Response to reviewers

We sincerely thank the three reviewers for their fair and constructive reviews. We appreciate the feedback given on the manuscript and carefully incorporated all points risen. Please find blow our answers for each comment in green coloured text. We re-arranged the discussion sections. While most of the text remained unchanged, we added some paragraphs related to the review comments.

We also modified the title, which now better summarised our findings.

New title:

Seismic evidence for failed rifting in the Ligurian Basin, Western Alpine Domain

Detailed responses to the referees:

Reviewer #1 (Laurent Jolivet)

This paper is a welcome complement to the current knowledge of the nature of the crust in the Mediterranean back-arc basins. A debate has been active for many years on the nature of the crust and the existence or not of true oceanic crust. Recent investigations in the Tyrrhenian Sea suggest that a large part of what was previously interpreted as oceanic crust would in fact be exhumed continental mantle. This new paper addresses this question on the example of the Ligurian Basin, the north-easternmost part of the Liguro-Provençal Basin. If oceanic crust was so far supposed to be present in the center of the basin, it was always described a atypical with large volcanic intrusions instead of a well-organized mid-ocean ridge. This new contribution shows clearly that along the entire profile, no oceanic crust is present and that exhumed mantle is found in the southern part. Whether there is or not true oceanic crust further south will remain debated but, at least for the Ligurian portion, the debate should now be closed. The paper is well written and easy to read. Although I am not a specialist of seismics I could understand the methodology and the discussion and the whole makes a convincing manuscript.

The only suggestion I have to address to the authors is to open the discussion to the more general point of back-arc rifting in the Mediterranean context. The findings described here have important consequences in terms of rifting dynamics. Why does true oceanic crust does not emplace in this sort of back-arc environment is an important question.

Indeed, a discussion on the back-arc rifting in the broader Mediterranean context would be interesting and worthwhile. We feel that we can provide only limited input on the raised question regarding the lack of oceanic crust in other back-arc environments in the Mediterranean solely based on the seismic profile P02 presented here. In fact, it is not known whether other back-arc environments show a similar structure as the Ligurian Basin. However, the presented new findings for the Ligurian Basin are of general interest in themselves and merit a presentation in a focussed way.
We added a more general introducing section to chapter 5.4 to show possible driving limits to the opening of the Ligurian back-arc basin:
"The opening of the Ligurian Basin in a back-arc position during late Oligocene and early Miocene that was driven by the south-east retreating Apennines-Calabria-Maghrebides subduction zone (e.g. Doglioni et al., 1997; Faccenna et al., 1997; Carminati et al. 1998; Rehault et al., 1984). The shift of active expansion from the Ligurian basin to the Tyrrhenian Sea is considered as a result of the Alpine collision that locked the Corsica-Sardinia drift towards the east and slab break-offs along the northern African margin and along the Apennines (Carminati et al., 1998). Thus, the opening of the Ligurian Basin was limited in time and space."

Reviewer #2 (Jean-Xavier Dessa)

1 General comments

The manuscript presents us with a study of crustal structures over a profile crossing along strike in the central Ligurian Basin, by means of seismic refraction and seismic reflection. The main finding of the paper is that a transition from thinned continental crust to unroofed mantle covered by thick sediments is observed from northeast to southwest along the profile. In other words, no mantle-derived oceanic crust seems to be observed in the "oceanic" part of the basin. On these grounds alone, the paper represents a very interesting contribution and is definitely worthy of publication. I have some comments on the manuscript, that can be ranked as minor but that are numerous though. I think addressing them thoroughly would help improve clarity and consistency.

2 Specific comments and suggested corrections

The line numbering in the word template is different to the created PDF, however, we think that we easily could find the sections pointed out.

• Line 60: Dessa et al., 2011 is not a relevant citation as far as the Corsican margin is concerned. Rollet et al.'s paper and perhaps a few others should rather be cited here.

Indeed, we changed the reference to Contrucci et al., 2001 and Rollet et al., 2002.

• Lines 102-103: Some more details would be welcome on the seismic source and its tuning. How many airguns? What minimum and maximum volumes? What depth of immersion? What frequency range? Considering the level of technical details provided on the GEOLOG data logger for instance, there is room for a bit more information here.

We included more details on the airgun system itself:

"A total of 1079 shots were fired by an ~89-liter (5420 inch^3) G-gun array, consisting of 2 sub-arrays. Each sub-array with a cluster of 2x8.5 litres (520 inch^3), followed by a cluster in the middle of 2x6.2 litres (2x380 inch^3, port) and 2x4.1 litres (2x250 inch^3, starboard), and the third cluster again of 2x8.5 litres for both sub-arrays. The array with a string distance of 12 m was towed at 8 m below the sea-surface and 40 m behind the vessel. A shot interval of 60 s resulted in a shot distance of ~123 m. The guns were shot at ~190 bar providing a dominant frequency band of approximately 5-70 Hz."

• Line 104: Still on the technical side, we are told that the symmetry of the direct arrival was used as a criterion to refine station locations. It makes perfect sense but it would be interesting to explain how this is done practically (i.e., how the position is updated from an observed asymmetry). Either a few words or a reference could be provided.

We included more details (Lines 110-113):

"For this purpose, the direct arrival was picked and the deviation between computed and real travel times was minimised by adjusting the OBS's position along the profile. Dislocation off-line cannot be corrected with this method. For 2D traveltime modelling, the stations were projected on to the profile."

• Line 120: Technical again, and I might be unfamiliar with some recent developments, but I fail to see how an atomic clock may control the sampling rate of an autonomous sea-bottom instrument. Should we understand that in other contexts (such as in a lab...), the data logger would have this capability to be fitted with an atomic clock?

Indeed, the internal clock used in some of the recorders is a clock, which is controlled by the oscillation frequency of atoms (i.e. caesium), giving very high accuracy, compared to quartz oscillators. On the other hand atomic clocks consume much more power (probably double the rate) than a usual simple quartz oscillator, which is a disadvantage for long term deployments.

• Line 142: Nitpicking a bit, but Figure 3 has no a) and b) panels and yet, a reference is made here to Fig. 3a (although the sense of it is clear).

The labels “a)” and “b)” have been too small. We enlarged it for better visibility and included a panel c).

• Line 149: The meaning of a “longer” Pg phase is unclear to me. Should we understand that it is observed along a larger range of offsets? It might be rephrased.

Re-phrased: *“Simultaneously, when phase Ps3 disappears (from OBS208 towards the north (compare to OBS209 (Fig. 2c), where Ps3 only occurs on the southern branch), an additional refracted phase (Pg) (green picks in Fig. 2c-2d) occurs with an increasing range of offsets observed on the stations and becomes longer northwards.”*

• Line 153-155: The text is a bit confused here. 1) Fig. 2b is invoked but does not correspond to a northern station, as the sentence seems to imply; 2) It is not clear to me that the critical distance is larger to the north (this may have a lot to do with the fact that labels along axes in Figure 2 are not readable, see my specific comment on this point below); 3) OBS208 is not labelled in any figure and the discussed change in gravimetric data is not even located below, but 20 km south if the text is to be believed. Why then not giving the actual location of said change in km along the profile rather than with respect to a remote OBS? On a sidenote, to the best of my understanding, this location would correspond to a distance of 50 km along the profile, where I was not able to identify any change in the free air anomaly. Are we talking about the decrease observed from 60 km onward? Confusing indeed …

We re-phrased this section in order to make it clearer to the reader:

1) Re-phrased the explanation of Ps3 (yellow phase, Figure 2) and then explain the slight changes from south to north.
2) We increased the axis labels on Figure 2 and adjusted a little bit the position of the phase labels. The difference in critical distance between the northern and the southern stations is very small (~5-10 km) and is maybe better to see in Fig. 2a.
3) OBS208 was wrong! Changed to OBS209. To follow the order of Figures we removed the link to Fig. 5. It was simply to give the reader a view to the second dataset to directly follow the changes, since they are very small. We do not want to change the order of figures, since the gravity modelling is based on the seismic results.

Yes, 60 km along the profile and onward towards the north, and it should be seen from OBS209. Indeed a profile KM will make the description much clearer. Added.

• Line 154: Same remark as for Line 142. No a) and b) panels in Figure 5. Note that this figure is referred to in the text before any reference is made to Figure 4. Normally, figures are numbered in the same order as that in which they are called in the text.

Figure 5 does not really have a panel (a) and (b) since for example the colour scale of the gravity model is at the top of the figure. We modified the text so that we now call the Figures in the correct order.

• Line 159: We are told that picking was made on hydrophone data rather than geophone. Is there a justification to this? One would arguably expect a better sensitivity of geophones. Is there any issue with data quality on geophones?

The data quality of the geophones is commonly controlled by the instrument coupling to the seafloor and thus varies largely between different study areas. Sometimes the geophone shows a similar or better S/N ratio than the hydrophone on our data set, also dependent on the offset range. While single instruments show a similar quality than the hydrophone, overall the hydrophone data was more robust for all stations along the profile. We included the following sentence on the data quality:

"The overall quality of the hydrophone data was slightly better compared to the vertical geophone channel, however, the vertical component was used for picking to confirm…"

• Line 161: I do not find it completely obvious that using multiples yields more information to confirm layer boundaries. Could the authors provide a citation or a bit of explanation to support this claim?

We inserted and explained in the text and gave a citation (Meléndez et al., 2014):

"The vertical seismometer component was used for picking to confirm and to complement the picks observed on the hydrophone channel. In addition, multiples were picked when above the noise level (because of constructive interference) and where primary waves are below the noise level (Meléndez et al., 2014)."

• Line 166: Some more details explaining how the set of additional starting models were generated would be most welcome. On what assumptions were they built? Do they span a large area in the model space? Etc. This might even warrant a figure if it can be made synthetic enough.

We added some text to clarify:

"To test the model space and its limits, starting models, ranging from velocities between 1.8 km/s and 2.5 km/s at the seafloor with different velocity gradients, and ranging from 4.5 km/s to 7.5 km/s at 12-13.5 km depth to mimic the different types of crust, were manually created using RAYINVR (Zelt, 1999)."

• Line 167: The use of 2 criterion begs the question of travel time uncertainties and how they were assessed. No information is given about that and that too would be most welcome. A 2 criterion of 1 only bears relevance if there is a rigorous and objective way to estimate uncertainties.

We included a sentence on the size of pick uncertainties that were assigned to the different picked phases (Lines 178-180):

"The picks were assigned pick uncertainties ranging from 20 ms for clear near offset phases (Ps1), 30 ms for intermediate offsets (Ps2 and Pg), and up to 50-70 ms for picks at larger offset (Pn and PmP) taking into account the decreased resolution due to the increased wave length of the seismic signal and the decreased signal-noise-ratio."

• Line 171 and 175: Standard deviation values are provided in s here, which does not make any sense ito me and is not coherent with Figure 4b an 4c, where they are given in km/s, as one would expect for a velocity model.

Corrected.

• Line 181-182: To back up the claim that lateral velocity variations are a consequence of the irregularity of the salt layer, it would be interesting to compare the wavelengths of these anomalies with those of the salt unit as imaged in MCS data. This would furthermore provide some added value to the MCS data which are practically of no use in the discussion of structures as it stands (let alone parasound data)—this point is discussed below (comment on Fig. 3).

We inserted a third panel (Fig. 3b) which compares the MCS data with the OBS data within the range of 300 traces and linked this figure to the text.

• Line 199: Error of reference: the histogram is not in Figure 5a (which does not exist), but in Figure 4e.

Changed.

• Line 217: The title of the section is wrong. “Discussion” rather than “Introduction” should feature here. The section title is likely inherited from the manuscript template...

Corrected - wrong copy paste into the template.

• Line 224: Same figure, same problem as in Line 199. Figure 5e instead of 4e.

Corrected.

• Line 267-268: It is not clear to me what the authors mean with a less evolved crust. Do they mean the thickness of it? Its nature? As a result, I find the meaning of the last two sentences of this paragraph rather enigmatic.

Changed "less evolved" to "less thick". Added that these observations indicate thickening continental crust towards the North.

• Line 309: I find the sentence about the preference of the authors for a magmatic origin to the observed magnetic anomalies rather than a relation with an unmapped spreading axis to be quite an understatement as their own results seem to completely rule out the possibility of a ridge axis (no oceanic crust is an overwhelming argument against the existence of any accretion axis at any time here I believe). More generally, I think this very interesting result and its implications are not highlighted enough in the discussion.

We changed the title in order to focus on our main finding. We changed the abstract and the style of the conclusion to bullet points to improve the visibility of our findings and highlight them.

• Fig. 1: A lot of features on the map, some not very visible, some practically invisible due to a poor choice of non-contrasting colors with respect to the bathymetric background or to the use of thin lines. Rollet et al. refer to “atypical oceanic domain” instead of “atypical oceanic crust”. Since the main result of this study is to rule out the existence of an oceanic igneous crust, the reference to an “Atypical Oceanic Crust” is a bit confusing here. I would suggest the same appellation as in Rollet et al.

Changed to atypical oceanic domain (AOD) in the figure. Reduced the contrast of the map and enlarged the contrast and thickness of the lines and objects of importance.

• Fig. 2: As mentioned above, labels along axes should be made readable for all data plots.

Axis labels enlarged and phase labels slightly adjusted.

• Fig. 3: Features in the MCS profile are barely visible and poorly discussed in the text. This observation holds even more true for parasound results which do not back results at all. I think dropping them could be considered.

We inserted a third part into the figure (Fig 3, panel b) that compares the undulations of the first arrival phase in the OBS with the MCS data. We like to keep this figure, since it provides a good impression on the complexity of the shallow portion of the subsurface and shows the entire data range acquired along this profile.

Reviewer #3 (Manel Prada)

1 General comments

• The manuscript "Oligocene-Miocene extension led to mantle exhumation in the central Ligurian Basin, Western Alpine Domain" by A. Dannowski and co-authors present new constraints on the petrological nature of the basement in the Ligurian Basin from new wide-angle seismic data and travel-time tomography. The authors show that rather than oceanic crust, as previously interpreted in the area, the northwestern region of the basin experienced crustal thinning and later mantle exhumation. However, I found the occurrence of mantle exhumation difficult to reconcile with the velocity structure of the uppermost mantle presented here. Considering that the mantle is fully exposed to the seawater during the opening of the basins, I found strange that the top of the mantle does not show the typical velocity gradient of exhumed mantle regions, in which Vp increases progressively from ~4.6 km/s (100 % alteration) to 7.8-8.0 km/s (no alteration) (Minshull 2009; https://doi.org/10.1016/j.crte.2008.09.003; Prada et al., 2015 doi: 10.1093/gji/ggv271). While I agree that there is no oceanic crust, the lack of an exhumed mantle-like Vp vertical gradient implies that the mantle was not fully hydrated and thus, exhumed, possibly because of the presence of syn-rift sediments or the existence of hyperextended continental crust. In fact, this interpretation fits nicely with the model. Lower crustal velocities are > 5.5 km/s, which may well be indicative of tilted fault blocks and rotated syn-rift sediments (e.g. Bayracki et al., 2016, Nature Geoscience, DOI: 10.1038/NGEO2671). The top of the continental basement in these settings can be really rough, and thus difficult to identify in OBS data. The fact that you don't see it, doesn't mean it's not there. In addition, mantle Vp is close to 8 km/s in some regions (e.g. beneath OBS205), while it decreases in others to < 7.5 km/s. This pattern resembles the mantle structure underlying continental tilted blocks reported in other rifted margins such as Galicia (Bayracki et al., 2016) and the Porcupine Basin (Prada et al., 2017 EPSL; http://dx.doi.org/10.1016/j.epsl.2017.06.040). Such pattern is attributed to the fault-controlled water influx to the mantle during rifting (Bayracki et al., 2016). In light of these observations, I advise the authors to reconsider their interpretation. Apart from this aspect, I also found some issues during the modelling and in section 5.4 that, if tackled, can help to improve the robustness of the final model, and thus, strengthen the paper. I discuss them the bellow.

We agree that the concept of mantle exhumation poses some interesting aspects and thank the reviewer for pointing these out. Indeed our data may not provide the information if sediments are underlain by thinned continental crust or exhumed mantle. We now discuss both scenarios. Exhumed mantle does not necessarily imply to be exposed directly on the seafloor as we mentioned in lines 270-275. We now additionally clarify this in the discussion by adding extra paragraphs in sections 5.1 and 5.2. We re-phrased the manuscript at several places to open up the discussion about the continental material (thinned continental crust or exhumed subcontinental mantle) underlying Ligurian Basin.

In contrast to the Tyrrhenian Sea we observe a strong in amplitude PmP reflection, which indicates a high velocity contrast at the crust-mantle boundary. The nature of the velocities >5.5 km/s can be debated and we cannot distinguish between fast sediments and left over rotated continental crust blocks (rotated the orthogonal direction to the profile). Sediments have to play a role during rifting and mantle serpentinisation (Ruepke et al., 2013), else we would observe a much higher rate of mantle serpentinisation, we agree, also in areas with remnant blocks of continental crust.

We changed the manuscript title to: *"Seismic evidence for failed rifting in the Ligurian Basin, Western Alpine Domain"*

Regardless of these issues, the paper unequivocally demonstrates that there is no oceanic crust in this region of the Ligurian Basin, and that is of great relevance for the community working on the

Mediterranean region. This study fits nicely with the goals of Solid Earth, and thus, I strongly encourage the authors to tackle all these aspects and resubmit the manuscript for its publication.
Best regards, Manel Prada
Major issues:

• The authors use forward modelling, I presume, to explore the lateral consistency of the seismic phases observed in each receiver. Then, they use this preliminary model as input for the tomography. However, it is confusing the way the authors describe and apply the layer stripping strategy. The authors say, "In a first step only near offset picks with distances smaller than 15 km were inverted." This is rather confusing. It seems that the authors have inverted the travel times within 15 km of offset from each receiver, independently of the seismic phase they correspond to. It would be better to explicitly mention the type of seismic phases that the authors have included in the first step, which I guess by Figure 4, are all sedimentary and crustal phases, plus PmP.

We removed the sentence since it is rather confusing and not necessary to explain the modelling strategy for the final average velocity model. This actually was a process that allowed us to get better acquainted with the data and the model behaviour and which will not be visible in the final results. But indeed, in first steps we only selected picks up to 15 km offset to image the uppermost sediments.

• One would also appreciate more details on the layer stripping strategy. Did the authors overdamped the result of the crustal layer when inverting for mantle phases?

We overdamped the model and included this in the text.

• On the other hand, the authors follow some sort of Monte Carlo analysis to assess the space of possible solutions but they only use 17 models for the crustal level and even a lower number for mantle phases, 12. The final standard deviation is low in Fig. 4. My concern is that given the low number of realizations tested the initial standard deviation (which one would appreciate seeing in the supplementary material) might below as well. I suggest testing at least 100 models for each layer, which is what is commonly done in this type of study to assess the uncertainty of model parameters. The outcome of this uncertainty analysis in its present form is not convincing which may lead to skepticism of the final interpretation.

In contrast to 100 or even 1000 different models, to call it Monte Carlo analysis, we preferred to calculate a smaller set of models to test a wider model space. In contrast to the commonly performed automated generated Monte Carlo models with velocity perturbations of a few percent from an already well fitting starting model, we set up the starting models by hand and tested limits of the model space until the model still converged. In the statistics, we included only starting models which converged to a low chi². The two outlying models (now shown in Fig. 4c), "fast" and "slow", would lose their weight if we would add even more automated starting models in the centre of the model space. Thus, we think the statistics based on a few manually created starting models are supporting a robust final average model although based on a lower number of starting models.

The starting models used were 1D hanging below the seafloor along the profile now shown in Figure 4 as (c) and we added a sentence on the 1D structure of the starting models in the text.

• In addition, the authors may want to provide more details on this type of statistical test, right now is a bit vague. How are the initial models? Are they randomly created or they are derived from the forward modelling? The authors could add figures of the initial models, initial standard deviation, as well as the results from forward modelling in the supplementary material. Do they add Gaussian random noise to the picks (I would encourage them to add this to the test)?

Added now in 4c and as inlay in 4d to better document what the input for the modelling is. Random Gaussian noise was not added, but during modelling re-picking of phases (fine adjustments to the wavelet) did not lead to major differences in the resulting velocity model. We added a sentence:

"Random Gaussian noise was not added, to the travel time picks, however, during modelling re-picking of phases (mainly fine adjustments to the picks) did not lead to major differences in the resulting velocity model."

• The gravity modelling could be also improved as well. The authors could show how the gravity response derived from a density model with a homogeneous mantle density of 3.3 g/cc compares with the model they have and the observed anomaly. That would help to discern between serpentinized mantle and non-altered mantle rock, which in turn would allow to strengthen the hypothesis of the paper.

The anomalies in the density have been related to the anomalies in seismic velocities. However, the influence of these localised anomalies that are buried by several kilometres of sediments is minor for the general trend of the model fit to the satellite-derived gravity data. Based solely on gravity data, we cannot judge if the mantle is serpentinised in these patches.

• Line 350-351 and all section 5.4: "seafloor spreading and formation of oceanic crust was not initiated during the extension of the Ligurian Basin.". I would be more cautious here, it seems that the authors are saying that there is no oceanic crust in the whole Ligurian basin. Extension in this basin increases from north to south and as in the Tyrrhenian formation processes may significantly change from the north (region imaged in this study) to the south.

The Ligurian Basin is the NE part of the Liguro-Provencial basin. The studied profile covers the SW part of the Ligurian Basin. Along the profile, we do not observe oceanic crust. Of course, oceanic crust may still occur in the larger Liguro-Provencial basin, but we rule out that there is any oceanic crust towards the NE, within the Ligurian Basin.

We carefully discuss this and point out that the COT might be nearby and oceanic crust occurs towards the S and/or SW as observed by Gailler at al. (2009).

Minor changes:

• Line 18: augmented -> complemented

Changed.

• Line 22-23: "exhumation of sub-continental mantle which eventually became serpentinised". According to the models of mantle exhumation crustal faulting initiates the hydration of the mantle during rifting. Thus, serpentinization occurs before the exhumation. The authors should modify this sentence accordingly.

Re-phrased.

• Section 3.2 The GEOLOG recorder. This section is a bit out of place since this is not a technical paper and thus, it distracts the reader from the main point. I suggest moving this section to supplementary material and briefly mentioning the GEOLOG recording system in section 3.1.

We keep this section in its place, since we cannot refer to a technical paper describing the data logger. The title describes clear what the reader can expect by reading this section and can jump to the next section if it becomes too technically. We included some more technical specifications on the airgun system as well (as recommended by reviewer #2) and hence give more background information on the data acquisition parameters.

• Line 154: The gravimetric data (Fig. 5a) show a change approx. 20 km south of OBS208. Please add the numbering of OBS in Figure 5a.

It is 20 km south of OBS209. Additionally, we now also give the corresponding profile kilometre for this change in the text. We added the OBS numbers as shown in Figure 2.

• Figure 1: There is a bracket missing in Rollet et al. (2002), and it would be good to see the numbering of the OBS/H shown in Fig. 2 instead of OBS/H 201-208-215.

We changed the numbering according to figure 2. Corrected the bracket.

~~Oligocene-Miocene extension led to mantle exhumation in the central Ligurian Basin, Western Alpine Domain~~
Seismic evidence for failed rifting in the Ligurian Basin, Western Alpine Domain

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Abstract. The Ligurian Basin is located in the Mediterranean Sea to the north-west of Corsica at the transition from the western Alpine orogen to the Apennine system and was generated by the south-eastward trench retreat of the Apennines-Calabrian subduction zone. Late Oligocene to Miocene rifting caused continental extension and subsidence, leading to the opening of the basin. Yet, it ~~still~~ remains enigmatic if rifting caused continental break-up and seafloor spreading. To reveal its lithospheric architecture, we acquired a ~~state of the art~~130-km long seismic refraction and wide-angle reflection profile in the Ligurian Basin. The seismic line was recorded in the framework of SPP2017 4D-MB, the German component of the European AlpArray initiative, and trends in a NE-SW direction at the centre of the Ligurian Basin, roughly parallel to the French coastline.

The seismic data were recorded on the newly developed GEOLOG recorder, designed at GEOMAR, and are dominated by sedimentary refractions and show mantle Pn arrivals at offsets of up to 70 km and a very prominent wide-angle Moho reflection. The main features share several characteristics (i.e. offset range, continuity), generally associated with continental settings rather than documenting oceanic crust emplaced by seafloor spreading. Seismic tomography results are ~~augmented~~ complemented by gravity data and yield a ~~7.5~~ ~6-8 km thick sedimentary cover and the seismic Moho at 11-13 km depth below the sea surface. Our study reveals that the oceanic domain does not extend as far north as previously assumed. Whether Oligocene-Miocene extension led to extreme thinned continental crust or exhumed subcontinental mantle with a low grade of mantle serpentinisation remains enigmatic. However, rifting failed before oceanic spreading was initiated, accompanied by the formation of mantle derived oceanic crust. ~~which is directly underlain by serpentinised mantle material at the south-western end of the profile. The acoustic basement at the north-eastern termination is interpreted to be c~~Continental crust is~~,~~ thickening towards the NE within the northern Ligurian Basin.

~~Our study reveals that the oceanic domain does not extend as far north as previously assumed and that extension led to extreme continental thinning and exhumation of sub-continental mantle which eventually became serpentinised.~~

1 Introduction

The Ligurian Sea is situated in the north-western Mediterranean Sea at the transition from the western Alpine orogen to the Apennine system. The geodynamic~~al~~ setting of the area is controlled by the convergence of the African and Eurasian plates (e.g. Dercourt et al., 1986). Despite the existing large collection of seismic and other geophysical data, the present-day crustal architecture of the Ligurian Basin is still under discussion and the kinematic boundaries are poorly resolved, in particular, the continent-ocean transition (COT) along the margins as well as its termination to the north-northeast. Imaging clear fault structures within the crust has proven~~d~~ challenging due to the presence of thick Messinian salt layers and due to the ~~time of arrival~~ masking effect of the first seafloor multiple which roughly coincides with the arrival of the reflection of the acoustic basement (Béthoux et al., 2008). Deep drilling data are lacking and the magnetic data are complex and anomalies discontinuous (Bayer et al., 1973). Based on integrated seismic and magnetic data, maps indicating the extent of the oceanic domain were created (i.e. Burrus, 1984; Gueguen et al., 1998; Rollet et al., 2002), however, no axial ridge was imaged near the centre of the basin (Rollet et al., 2002). To explain the mismatch between the expected oceanic domain and the observed seismic signal, t~~T~~he crust in the north-eastern basin was interpreted to be ‘atypical’ oceanic crust (Mauffret et al., 1995; Chamot-Rooke et al., 1997; Contrucci et al., 2001; Rollet et al., 2002)~~ to explain the mismatch between the expected oceanic domain and the observed seismic signal~~. A clear change from continental to oceanic crust was only shown for the southern area of the Ligurian Basin, in the Gulf of Lion and offshore Sardinia (Gailler et al., 2009). It is proposed that the oceanic domain is separated from the continental margins by a transitional domain characterised by a high-velocity lower crust (Fig. 1). An~~ good~~ overview of seismic experiments until 2002 is presented in Rollet et al. (2002). Furthermore, the area was revisited or data were re-analysed with modern seismic techniques including the CROP deep seismic profiles (Finetti et al., 2005), the TGS-NOPEC and the SARDINIA profiles (Gailler et al., 2009; Jolivet et al., 2015), as well as more recent studies along the French and Italian Riviera with the 3D seismic refraction GROSMarin project (Dessa et al., 2011) and an amphibious ambient noise study (Guerin et al., 2019).

In the frame of the LOBSTER project, we ~~add~~ obtained a new state-of-the-art seismic refraction line ~~to the database~~ (Fig. 1, red line with orange and yellow triangles). Here, we present the analysis of the seismic refraction ~~line in~~ data from the central Ligurian Basin, which is the extension of a pre-existing seismic profile (Makris et al., 1999), which we call MAKRIS (Fig. 1, black line). We aim to unravel the present-day crustal structure and its nature in the centre of the Ligurian Basin, map the depth of the crust-mantle boundary (seismic Moho), and reveal the styles of deformation during the last extensional phase. We investigate the hypothesis that~~ the~~ Oligocene-Miocene ~~extension~~ rifting led to either ~~hyper-~~extended continental crust or ~~serpentinised~~ exhumation of sub-continental mantle below post-rift sediments in the north-eastern Ligurian Basin. ~~A further objective is to provide a seismic velocity model as a contribution to an improved seismic event localisation in the offshore region.~~

2 Geological structures and geodynamics of the Ligurian Sea and the Corsica-Sardinia block

The Ligurian Sea has a width of ~150 km, reaching from the northern tip of Corsica to the Ligurian coast near the city of Sanremo. It widens towards the southwest to ~175 km between Calvi (Corsica) and Cannes. South of ~~the~~ an imaginary line between Ajaccio (Corsica) and Toulon, the ~~basin~~ Ligurian Sea is roughly 225 km wide~~. The basin~~ and opens entirely towards the Balearic Sea. The Ligurian Basin itself is smaller with a width of 70 km, 120 km, and 170 km, respectively, along the three dashed grey lines in Figure 1 and the seafloor reaches a depth~~s~~ of ~2700 m. The Ligurian margin is characterised by a narrow and steep slope (10-20 km) with a few listric normal faults (Finetti et al., 2005). The Corsica slope is wider (20-50 km) and the margin is characterised by several listric faults extending over a wider area (~~Dessa et al., 2011~~ Contrucci et al., 2001; Rollet et al., 2002).

The Ligurian Sea formed as a back-arc basin at the transition from the western Alpine orogen to the Apennine system (e.g. Doglioni et al., 1997; Faccenna et al., 1997; ~~Rehault~~ Réhault et al., 1984). The Alpine transition is characterised by a change in subduction polarity between the two orogens (Jolivet and Faccenna, 2000; Handy et al., 2010). The Ligurian Basin is the oldest back-arc basin in the Western Mediterranean Sea and developed from Late Oligocene to Early Miocene (Réhault and Béthoux, 1984; Roca and Desegaulx, 1992; Fernàndez et al., 1995; Jolivet and Faccenna, 2000; Rosenbaum et al., 2002; Finetti et al., 2005; Advokaat et al., 2014). The extension is related to the south-east trench retreat of the Apennines-Calabrian subduction zone initiated in the Oligocene (Montigny et al., 1981; Réhault and Béthoux, 1984; Vigliotti and Langenheim, 1995; Gueguen et al., 1998; Rosenbaum et al., 2002; Faccenna et al., 2001).

Rifting has initiated ~30 Ma ago at a rate of ~1 cm/yr in the NE and ~2 cm/yr in the SW (Rollet et al., 2002). The initiation is associated with magmatism on land along the western Ligurian margin (Rollet et al., 2002). At roughly 21 Ma, rifting terminated while an anticlockwise rotation of the Corsica-Sardinia block was initiated (Rollet et al., 2002; Speranza et al., 2002). During this phase, the commencement of oceanic spreading was proposed (Pascal et al., 1993; Contrucci et al., 2001; Rollet et al., 2002; Finetti et al., 2005). These authors referred to tholeiitic volcanic edifices to solidify their interpretation and interpreted the pattern of magnetic data (Bayer et al., 1973) to be a result of two main discontinuous volcanic lineaments, sub-parallel to the basin axis related to oceanic spreading and unroofing of mantle material. The opening of the Ligurian Basin ended ~16-15 Ma ago and was associated with a second calc-alkaline volcanic phase along the Corsican margin (Rollet et al., 2002) that is linked to the migration of the subducting lithosphere towards the E-SE. The extension of the Ligurian Basin ~~stopped~~ terminated and shifted to the Tyrrhenian Sea while the Apennines-Calabrian subduction zone continued to roll back further southeast until late the Messinian, ~6 Ma (Faccenna et al., 2001; Advokaat et al., 2014). The opening rate was calculated with 7.8-10.3 mm/yr (Moeller et al., 2013). In the north of the Tyrrhenian Sea, extension led to continental crustal thinning (Moeller et al., 2013), while further south in the centre of the Tyrrhenian Basin, the mantle was exhumed and serpentinised and intruded by Mid-Ocean-Ridge type (MOR-type and intraplate basalts) (Prada et al., 2016). Similar to the Ligurian Basin, the Tyrrhenian Sea shows distributed, non-linear magnetic anomalies (Cella et al., 2008). Anomalies often coincide with volcanic islands, seamounts or other morphological units of igneous composition. During the Ocean Drilling Project (ODP) Leg 107 at site 651, serpentinised mantle rocks were drilled forming the top of the basement (Bonatti et al., 1990). Gueguen et al. (1998) and Rollet ~~a~~et al. (2002) suggest that the central Ligurian Basin is comprised of oceanic crust. These authors divided the basin into different zones of continental and oceanic domains based on seismic, magnetic and gravity data (Fig. 1): (1) atypical oceanic crust with (2) transitional zones to (3) continental crust. The location of the northeast-southwest trending continent-ocean transition is proposed to be situated in the vicinity of the volcanic Tristanites Massif (Fig. 1) (Makris et al., 1999) (yellow ~~line~~bar perpendicular to the MAKRIS profile in Figure 1). Based on re-analysed expanding spread profiles (ESP), Contrucci et al. (2001) proposed a 40 km wide area of oceanic crust near the Median Seamount (Fig. 1).

3 Data acquisition, processing, and modelling

Data at different scales resolving the subsurface structure were acquired in the Ligurian Sea in February of 2018 during the cruise MSM71 aboard the German research vessel Maria S. Merian (Kopp et al., 2018). Active seismic refraction data were obtained along the centre of the basin. Our NE-SW trending seismic refraction and wide-angle reflection line is situated in the prolongation of an existing refraction profile in the northern Ligurian Basin (Makris et al., 1999) (Fig. 1)~~ and is presented here~~.

3.1 Data acquisition and processing

The active seismic data were simultaneously recorded on short period ocean bottom seismometers (OBS) and ocean bottom hydrophones (OBH) as well as on a short streamer (280 m long) that was towed behind the vessel ~~in~~ at 5 m water depth. Additionally, Parasound sediment echo sounding data were recorded along the profiles. The 127.5 km long refraction seismic profile consists of 15 OBH/OBS at a station spacing of ~ 8km (Fig. 1). A total of 1079 shots were fired by an ~~84~~ ~89-liter (5420 inch^3) G-gun array, consisting of 2 sub-arrays. Each sub-array with a cluster of 2x8.5 litres (520 inch^3), followed by a cluster in the middle of 2x6.2 litres (2x380 inch^3, port) and 2x4.1 litres (2x250 inch^3, starboard), and the third cluster again of 2x8.5 litres for both sub-arrays. The array with a string distance of 12 m was towed at 8 m below the sea-surface and 40 m behind the vessel. A shot ~~at an~~ interval of 60 s~~,~~ ~~resulting~~ resulted in a shot ~~interval~~ distance of ~123 m. The guns were shot at ~190 bar providing a dominant frequency band of approximately 5-70 Hz. The location of the stations on the seafloor was ~~estimated~~ determined using the symmetry of the direct water arrivals from the shots on both sides. For this purpose, the direct arrival was picked and the deviation between computed and real travel times was minimised by adjusting the OBS's position along the profile. Dislocation off-line cannot be corrected with this method. For 2D traveltime modelling, the stations were projected on to the profile. The airgun shots were recorded using newly developed GEOLOG data loggers~~,~~ designed at GEOMAR. All recorders ~~ran~~ operated reliably~~e~~ during the deployment of 2 days with a negligible absolute clock drift between -1.03 ms ~~to~~ and +0.72 ms. The sampling frequency ~~i~~was 250 Hz. The data processing included the conversion of the continuous data from GEOLOG format into the standard continuous SEG-Y format using the GEOLOG programming interface. Afterwards, the continuous SEG-Y data were converted into standard trace-based SEG-Y format (Fig. 2b). Simultaneously, the clock drift was corrected, a step important for OBS data, since the instruments cannot be continuously synchronized via GPS during deployment as commonly done onshore. A gated Wiener multi-trace deconvolution with an autocorrelation average of 51 traces was applied to the shot gathers to compress the basic wavelet, to leave the Earth's reflectivity in the seismic trace and to remove the source signature and the hydrophone and geophone responses.

3.2 The GEOLOG recorder

The GEOLOG is a 32-bit seismic data logger designed to digitise data from a three-component seismometer and a hydrophone. We recorded the hydrophone output on two channels (channels 1 and 5) at two different amplification levels providing well amplified long-range records (gain=16) and preventing clipped amplitudes from short-range airgun shots (gain=1) to minimise difficulties with amplitude restoration because no gain range was implemented. The gain for the three seismometer channels 2 to 4 was set to 16, which provided good signal to noise ratios for all record offsets without clipping of amplitudes. Two additional analogue pins can be used as general-purpose input/output (GPIO) for measuring power levels for example. 3.3 V and 5 V connectors can serve external devices. Sampling intervals between 50 Hz and 4 kHz are controlled either by an atomic clock or by a temperature compensated clock (SEASCAN). We used an external GPS receiver for synchronization of the internal clock prior and after deployment, which was driven by the GEOLOG itself. Our seismic data were stored on two micro SD cards with a volume of 32 GB each. The recorder has been tested and proved reliable for writing speeds and SD cards of up to 128 GB (larger capacities are possible). The low power consumption of 375 mW (average battery drain) allowed us to save batteries. We used only 8 alkaline batteries per station for our short-term deployment. Thus, using lithium batteries, long-term deployments of more than 9 months can be performed. Battery power can further be saved by a delayed start of recording up to 31 days after programming. We set the recording parameters, i.e. the number of channels, gain and sampling rate, using ~~the~~ a graphical user interface. The recorders can be programmed through any terminal program on a Windows or Linux operating system. The programming device was connected via RS232 using an RS232-USB adapter. A second RS232 interface can be used to drive external sensors (e.g. levelling of broadband seismometers). The GPS system used for the internal clock time synchronisation was developed together with the recorder and can operate with GPS, GLONASS, GALLILEO and QZSS enabling operation worldwide and in polar regions. Besides stable output of NMEA data (defined by the National Marine Electronics Association) and a PPS (pulse-per-second) time signal, the German DCF-77 code is also available. Moreover, the GPS system is available to deliver time or distance based trigger with TTL output, NMEA sequence and records of time stamps on an SD card.

3.3 Data description and analysis

The airgun shots can be followed for offsets up to 60 km on all 15 stations (Fig. 2). In general, the sections look very similar with clear sedimentary arrivals and wide-angle Moho reflections (PmP) as well as mantle phases (Pn) at a critical distance between 25 km and 35 km to the stations (Fig. 2a). Although phase arrivals show common features in all record sections (Fig. 2a), the characteristics of the seismic phases change slightly from south to north (Fig. 2b-2d).

As a result of decreasing water depth towards the northeast, the direct wave~~s~~ through water (Pw) arrive later at the southern stations than at the northern stations (Fig. 2a). ~~The picks~~Arrivals from a shallow sedimentary reflection phase (PsP) ~~arrive~~ occur approximately 0.5 s to 1 s after the direct ~~arrival~~ wave and result from the top of salts that become shallower towards the north (as imaged in the multichannel seismic data in Fig. 3a). The red picks (Ps1) and the orange picks (Ps2) (Fig. 2b-2d) are interpreted as refracted phases through Plio-Quaternary and older sediments, respectively. The apparent seismic velocity of the Ps2 is very constant at ~4.3 km/s to ~4.6 km/s. The phase shows many undulations and some shadow zones (Fig. 3b) caused by the salt unit that displays intense doming and is possibly disrupted by some volcanic structures that are imaged in the MCS (Fig. 3a) and the Parasound data (Fig. 3c). This phase continues as a secondary arrival (Ps3) with a similar apparent velocity of ~4.6 km/s at the southern stations but disappears at the northern stations. Based on the apparent velocity and forward modelling, we interpret phase Ps3 as a refracted phase through the sediments. Simultaneously, when phase Ps3 disappears ~~(~~from OBS208 towards the north (compare to OBS209 (Fig. 2c), where Ps3 only occurs on the southern branch), an additional refracted phase (Pg) (green picks in Fig. 2c-2d) occurs with an increasing range of offsets observed on the stations ~~and becomes longer~~ northwards. The phase has an apparent velocity of ~6.2 km/s. At an offset of about 25 km, an abrupt change in the apparent seismic velocity to ~8 km/s occurs for the first arrival~~ occurs to apparent velocities of ~8 km/s~~, as typically observed in the oceanic upper mantle. The yellow picks (Fig. 2b-2d) are refracted mantle phases (Pn) that ~~at the northern stations and~~ show a similar apparent seismic velocity of ~8 km/s at the northern stations. However, the critical distance at the northern stations moves to slightly larger offsets of ~~at about~~ up to ~30 km. Furthermore, an earlier very short reflection occurs at 20-25 km offset. ~~The gravimetric data (Fig. 5a) show a change approx. 20 km south of OBS208.~~ Pn phases at the southern stations are very weak, while the PmP is relatively strong compared to typical oceanic crust characteristics. The observed slight changes in the seismic signal are accompanied by slight changes in the free-air gravity anomaly around profile KM 60 (approx. 20 km south of OBS209), as discussed below.

3.4 P-wave traveltime tomography modelling strategy and parameters

A preliminary seismic velocity model was build using RAYINVR (Zelt, 1999) to (1) reveal the overall structure of the ~~data~~profile, (2) manually assign the picked phases to certain layers, and (3) serve as starting ~~model~~ point for the travel time tomography. Travel times were picked on the hydrophone channels using the interactive analysis tool for wide-angle seismic data PASTEUP (Fujie et al., 2008). The overall quality of the hydrophone data was slightly better compared to the vertical geophone channel, however, the~~The~~ vertical ~~seismometer~~ component was used for picking to confirm and to complement the picks observed on the hydrophone channel. In addition, m~~M~~ultiples were picked when above the noise level (because of constructive interference) and where primary waves are below the noise level (Meléndez et al., 2014).~~,~~ ~~in addition and~~ Picks of water layer multiple phases were used during the forward modelling approach to confirm the layer boundaries and seismic velocities. Thereafter, a travel time tomographic inversion (tomo2D from Korenaga et al., ~~(~~2000~~)~~) was applied to invert the seismic P-wave velocity model and yield model uncertainties. The picks were assigned pick uncertainties ranging from 20 ms for clear near offset phases (Ps1), 30 ms for intermediate offsets (Ps2 and Pg), and up to 50-70 ms for picks at larger offset (Pn and PmP) taking into account the decreased resolution due to the increased wave length of the seismic signal and the decreased signal-noise-ratio. ~~In a first step only near offset picks with distances smaller than 15 km were inverted.~~ Subsequently, all first arrivals and the mantle reflections were inverted with a set of starting models that converged to chi² values of less than 1 within 5 iterations. To test the model space and its limits, ~~the~~ starting models, ranging from velocities between 1.8 km/s and 2.5 km/s at the seafloor with different velocity gradients, and ranging from 4.5 km/s to 7.5 km/s at 12-13.5 km depth to mimic the different types of crust, were manually created using ~~rayinvr~~ RAYINVR (Zelt, 1999). ~~The starting models used in the analysis were 1D hanging below the seafloor (Fig. 4c).~~ To carefully evaluate the resulting velocity models, we used three criteria: (1) travel times need to fit the data (Fig. 2a), (2) travel time residuals, RMS misfit and chi² had to be low (i.e. ~~chi2~~ chi² ~ 1), and (3) the gravity response (calculated after a velocity-density conversion after ~~) (~~Korenaga et al., 2001) of the resulting density model must yield comparable results to the satellite gravity data. Based on ~~the~~ this evaluation, 17 models (Fig. 4c) were chosen to generate an average model for the crustal part (Fig. 4a, above the Moho) and the standard deviation was calculated (Fig. 4b). Overall, the standard deviation in the crust down to the acoustic basement is smaller than 0.15 km/s, indicating small differences between the inverted velocity models and hence an excellent resolution. Random Gaussian noise was not added, to the travel time picks, however, during modelling re-picking of phases (mainly fine adjustments to the picks) did not lead to major differences in the resulting velocity model. In a further step, the average model was edited by adding different 1D profiles with mantle velocities underneath the crust-mantle boundary (inlay in Fig. 4d). A set of ~~12~~ 14 mantle velocity starting models was used to invert for refracted mantle phases, while the model above the seismic Moho was overdamped. Again, an average model and the standard deviation for the mantle were calculated (Fig. 4~~c~~d). Standard deviations for the mantle P-wave velocities are small (<0.1 km/s), indicating a good resolution of upper mantle velocities. Lastly, the very short reflected phases interpreted to result from the top of continental crust were calculated as a floating reflector without implementing a velocity discontinuity into the model to confirm the top of crust, i.e. the crystalline basement.

4 Results

4.1 Seismic P-wave velocity distribution

In general, the average P-wave velocity along the profile (Fig. 4a) shows only minor lateral variations, mainly caused by the salt layers and the corresponding tectonic features at 4-6 km depth. The uppermost portion of the velocity model is characterised by a strong velocity gradient of ~1 s^{-1} that is laterally ~~very~~ constant. P-wave velocities increase from 2.2 km/s at the seafloor to 3.5 km/s approximately~~.~~ 1.3 km depth below the seafloor. We interpret this unit as Plio-Quaternary sediments mixed with the upper evaporite unit after Rollet et al. (2002), using their multi-channel seismic data profile MA24 (Fig. 1, inlay profile 6). The Plio-Quaternary sediments are imaged as horizontally layered strata in the multi-channel seismic data in Figure 3a. This high velocity-gradient layer thins towards the north, from 1.5 km to 1.2 km thickness~~, respectively,~~ and shows slightly slower velocities at the southern end (2.2 km/s) compared to the northern end (2.4 km/s) at the seafloor. Between ~4 km and 6 km depth, the velocities range from 3.5 km/s to 4.5 km/s, and there are areas where minor velocity inversions are observed. These low velocity units have a lateral extent of up to 10 km and a velocity contrast of up to ~0.2 km/s. We identify this section as the Messinian salt unit. From 6 km to ~10 km depth, the seismic velocities increase from ~4.5 km/s at the top to 5.7 km/s at the bottom. We interpret this section as ~~Pre-Messinian down to~~ syn-rift sediments, possibly ~~from~~ Aquitanian ~~related~~ according to Jolivet et al. (2015), to post-rift sediments, until Pre-Messinian.

~~The acoustic basement occurs at a depth from of 10 km to 11.5 km below the sea surface.~~ In the north-eastern half of the profile, starting roughly at profile KM 70~~ (Fig. 4a)~~, we determine the crystalline basement (CB) (red dashed line in Fig. 4a) at a depth of 10 km to 11.5 km below the sea surface. ~~the~~ The basement velocities increase from 5.8 km/s to 6.6 km/s (marked with “Y” in Fig. 4a); they are interpreted, based on absolute velocities, as continental crust, thickening towards the north. The acoustic basement here is at a depth of ~10 km below the sea surface. At the opposite southern half of the profile, we could not identify the CB in the OBS data. However, a strong velocity jump occurs from 5.7 km/s to ≥7.3 km/s~~. We interpret this part of the acoustic basement~~ that we interpret as the crust-mantle boundary (Moho). The uppermost mantle is characterised by seismic velocities >7.3 km/s that increase to ~8 km/s over a depth interval of 2-3 km. The histogram (Fig. ~~5b~~4f) images a gap in seismic velocities between 6.6 km/s and 7.3 km/s, which suggests that no fresh oceanic crust material (gabbroic rocks) is present along the profile.

4.2 Gravity modelling

To constrain the crustal structure along the profile, we calculated the gravity response (Talwani et al., 1959) of the final seismic velocity model and compared it to the free-air gravity anomaly derived from satellite data (Sandwell et al., 2014). The fact that the profile is situated in the centre of the basin allows us to assume that only minor 3D side-effects occur in our 2D-modelling approach, caused by topography. The velocity-depth distribution was used to assign densities by applying different density-velocity relations. The water layer is assumed to have a density of 1.03 g/cm³. Gardeners rule, $\rho = 1.74 * Vp^{0.25}$, valid for sediments between 1.5 km/s < Vp < 6.1 km/s (Gardner et al., 1974), was used for the sedimentary layers. For crystalline (non-volcanic) rocks the relation: $\rho = 0.541 + 0.3601 * Vp$ (Christensen and Mooney, 1995) was used. A density of 3.3 g/cm³ was assigned ~~for~~ to the mantle. In areas with reduced seismic mantle velocities, the mantle density was reduced to 3.15 g/cm³ (Carlson and Miller, 2003). The converted densities explain the observed free-air gravity anomaly for the part covered by our deployed instruments. We extended the profile further northeast ~~with~~ over the marine part of the MAKRIS line (Fig. 1, inlay profile 4). From profile KM 127.5 northwards, we related the gross density model structure to the results of the MAKRIS line (Makris et al., 1999). However, we removed a large step of 10 km in Moho depth and replaced it by a more gradually deepening Moho, which closely follows ~~closely~~ the top of the layer of underplating in the MAKRIS line. The fit of observed and calculated gravity data ~~is~~ reasonably well supports~~ing~~ the interpretation of a thickening continental crust towards the northeast.

5 ~~Introduction Section (as Heading 1)~~Discussion

5.1 Nature of the crust~~lithosphere~~

The seismic velocity model along our refraction profile (Fig. 4a) shows no common features ~~for~~ of oceanic crust. Oceanic crust typically consists of a high-velocity gradient in Layer 2 and a lower velocity gradient in Layer 3 (e.g. White et al., 1992; Grevemeyer et al., 2018; Christeson et al., 2019). The absolute seismic velocities are highly variable, however, for a gabbroic crust, velocities are typically between 6.7 km/s and 7.2 km/s (Grevemeyer et al., 2018; Christeson et al., 2019). The histogram in Figure ~~5e~~ 4f shows a gap for this range of velocities suggesting ~~that no typical oceanic crust and no thick layer of gabbroic rocks~~ ~~are~~ ~~is~~ ~~present along the profile~~. In any case, the lack of seismic velocities expected for oceanic crust does not support the occurrence of larger units of oceanic crust as observed in the Tyrrhenian Sea (Prada et al., 2014).

Continental crust is characterised by a low seismic velocity gradient throughout the crystalline crustal layers and shows typical velocities of ~5.8 to ~6.6 km/s (Christensen and Mooney, 1995). We observe this velocity range in the northern half of the profile, starting from profile KM 70, at a depth of 10 km to 13 km (marked with “Y” in Fig. 4a). The observed seismic velocities provide only ~~leave~~ two possible interpretations: (1) hyper-extended continental crust or (2) a laterally isolated magmatic intrusion within the sedimentary units feeding the volcanic extrusion observed in the MCS and Parasound data (Fig. 3c). Based on the gravity model (Fig. 5), we favour the first scenario of extremely thinned continental crust, ~~pinching out~~ which is decreasing in thickness towards the SW~~, leading~~ and may even lead to exhumed mantle during the rifting phase in the south~~ern half of the profile~~.

The velocity model for the southern half along our refraction profile is well constrained, however, the lower part (9 km to 11 km depth), above the Moho, shows higher uncertainty compared to the shallow, sedimentary units. The depth of the crust-mantle boundary is well constrained with an uncertainty range of ±0.25 km along the southern profile half in contrast to ±0.75 km along the northern profile half (Fig. 4b). We observe seismic velocities >5.5 km/s that we interpret as fast syn-rift sediments due to a missing crystalline basement reflection. Alternatively, the change from sediments to the crystalline basement might not be characterised by a high impedance contrast, and thus, not imaged in our refraction seismic data as a strong in amplitude reflection event (compare to Fig. 2) and is expressed in a high uncertainty of the determined CB at the northern profile end (Fig. 4). The MCS line MA24 (Rollet et al., 2002) (Fig. 1, inlay profile 6) records the acoustic basement at ~6.5 s two-way traveltime (stwt), while the seafloor occurs at 3.6 stwt (~2.7 km below sea surface). By means of a simple time to depth conversion using an average seismic velocity of 4.2 km/s, we estimate a minimum sedimentary thickness of ~6.1 km (2.9 stwt), resulting in an acoustic basement depth of ~8.8 km, as a most shallow approximation (drawn as a red dotted line in figure 4a). This line roughly fits the 5.5 km/s isoline accounting for a standard deviation of 0.2 km/s (Fig. 4b). For the southern half of our profile, this leaves a maximum continental crustal thickness of 2-2.5 km, thickening northwards.

Based on the refraction seismic data along our profile (southern half) we are not able to distinguish between sediments with high seismic velocities and extremely thinned continental crust. However, we can give a minimum and maximum continental crustal thickness, ranging from 0 km to 2.5 km. Based on the velocity model (Fig. 4a) it is not possible to distinguish whether the crystalline basement ~~there~~ is upper, middle, or lower continental crust. ~~A continental crustal thickening~~ towards the north-east is as well supported by the ~~modelling of the free air anomaly~~ (Fig. 5). Additionally, a thickening crustal layer supports the interpretation as continental crust, since we would expect the COT to be manifested in an abrupt change from oceanic to continental crust or to gradually thin out towards the NE, towards the rotational pole (Rosenbaum et al., 2002), depending on the ~~situation~~ position of the profile with respect to the proposed spreading axis.

An expanding spread profile (ESP) (Le Douaran et al., 1984; Contrucci et al., 2001) crosses the northern end of our profile (Fig. 1, inlay profile 5). There the crust-mantle boundary was defined at a depth of 13-15 km while the acoustic basement was observed at ~9 km depth. Contrucci et al. (2001) retrieved crustal velocities of 6.3 - 6.9 km/s for the basin centre, which in general, is in good agreement with our results. Based on MCS data (LISA01) (Contrucci et al., 2001) with an observed major step in the basement on the Ligurian margin, they interpreted the central basin as an oceanic domain. On the Corsica margin, this major step was not observed~~,~~; however, magnetic anomalies were used to constrain the interpretation. The MCS data resolve only the sedimentary portion of the crust and ~~give~~ yield no information on the internal structures of the crystalline basement itself. ~~,~~ T~~t~~hus, a different explanation for the major step in the basement near the Ligurian margin could be that upper-crustal blocks sit on top of continental mantle similar to the Galicia margin (Nagel and Buck, 2004). Our profile only provides information on the basin centre where the absolute velocities of Le Douaran et al. (1984) and Contrucci et al. (2001) fit continental crust velocities ~~very well~~ and support our interpretation of mantle material beneath thinned continental crust observations.

5.2~~3~~ Low degree of mantle serpentinisation~~Mantle exhumation and magmatic intrusions~~

~~The velocity model for the southern half along our refraction profile is well constrained (Fig. 5b).~~ Seismic velocities of ~7.3 km/s and higher are too fast for magmatic crust (Grevemeyer et al., 2018; Christeson et al., 2019). Seismic velocities of unaltered mantle are >7.8 km/s (Carlson and Miller, 2003; Grevemeyer et al., 2018). Based on the seismic P-wave velocities, we interpret the uppermost mantle to be serpentinised at a low grade, which is supported by the Pn phases that are weak in amplitude at the southern stations (Fig. 2). P-wave velocities of ~7.5 km/s in the south-western half of the profile (Fig. 4a) are in-line with up to ~20% serpentinisation (Carlson and Miller, 2003). From OBS204 to OBS207, the PmP phase is extremely high in amplitude and unusually clearly visible over a wide distance of up to 20 km (in ~10 km to ~30 km offset to the station). This area (profile KM_40-KM_60) is marked by Vp > 7.8 km/s directly underneath the basement ("Z" in Fig. 4a), possibly an area of unaltered mantle due to a left over (and possibly rotated) block of continental crust as observed in other magma-poor passive margins (Bayracki et al., 2016) or a result of a mafic intrusion. The fact that the mantle is only partly serpentinised ~~implies~~ suggests ~~that syn-rift sediments (nowadays showing high P-wave velocities)~~ ~~were~~ ~~may have been~~ ~~directly deposited on top of the mantle or brittle continental crust (Pérez-Gussinyé, 2013).~~ Thus, structurally, the Ligurian Sea is mimicking the Atlantic non-volcanic passive margins of Iberia (Minshull et al., 2014) and Goban Spur (Bullock and Minshull, 2005).

However, the fast mantle in the Ligurian Sea would support a much lower degree of serpentinisation when compared to the Atlantic margin.

In comparison to the ~~Tyrrhenian Sea~~, the P-wave velocities of the upper mantle in the Ligurian Sea are ~~high~~ (Fig. 4a). P-wave velocities of the upper mantle in the ~~Tyrrhenian Sea Domain #3~~ are significantly lower with 4.5 km/s at the top of the mantle (Prada et al., 2016). We observe significant differences between both basins: (1) Along the southern half of our profile we observe strong PmP reflections indicating a high-velocity contrast at the crust-mantle boundary, while in Domain #3 in the Tyrrhenian Sea PmP reflections are absent. (2) The Ligurian Basin has a thick sedimentary cover of ~6-8 km, while the Tyrrhenian Sea Domain #3 shows a sedimentary cover of ~1-2 km (Prada et al., 2014). Further, (3) the Ligurian Basin was stretched ~150 km during the ~16 million year opening phase, while the Tyrrhenian Sea was stretched ~300 km within 9-10 million years. Although the extension in the Ligurian Basin lasted longer and occurred earlier, the sedimentation rate is significantly higher compared to the Tyrrhenian Sea. Syn-rift sedimentation was recorded in MCS data (Fig. 1, inlay profile 3) in the Gulf of Lion (Jolivet et al., 2015). Sediments are known to reduce the permeability and thus, the amount of water that reaches the mantle rocks, necessary for serpentinisation (Ruepke et al., 2013). Two other factors can play a role for the degree of mantle serpentinisation in the Ligurian Basin: Ruepke et al. (2013) show in thermo-tectono-stratigraphic basin models the effects of sedimentary blanketing and low stretching factors on serpentinisation. Hence our seismic velocity model (Fig. 4a) can be well explained if mantle rocks have been partially exhumed from continental crust, without being directly exposed to sea water due to syn-rift sedimentation. However, also the interpretation of extremely thinned brittle continental crust requires syn-rift sedimentation since the stretching might open fluid pathways through the crust down to the mantle (Nagel and Buck, 2004).

5.3~~2~~ Continent-ocean transition and magmatic intrusions

The MCS line MA24 (Rollet et al., 2002) was shot along an ESP profile consisting of four ~~stations~~measurements with a spacing of ~35 km (Le Douaran et al., 1984). The two transects are crossing our profile at the southern end (Fig. 1, inlay profile 6). The MCS data resolve sedimentary units, while the seismic velocities retrieved along the ESP profile show no absolute seismic velocities similar to oceanic crust. Both transects do not map a spreading axis. Further west along the Ligurian margin, a multichannel seismic study (Jolivet et al., 2015) and a wide-angle refraction seismic study (Gailler et al., 2009) of the Ligurian margin (Fig. 1, inlay profiles 2a and 3), in the Gulf of Lion, show a wide continent-ocean transition zone. The travel time tomography model along the OBS profiles (Gailler et al., 2009) images a succession of three domains: (1) continental, (2) transitional, and (3) oceanic ~~domain~~ towards the basin centre, following the zonation of Rollet et al. (2002). The same succession was found for both continental margins, ~~however~~though, the Corsica margin's transitional zone is much narrower. The transitional domain is interpreted to consist of a mixture of continental crust, exhumed mantle, and magmatic intrusions (Gailler et al., 2009; Rollet et al., 2002). In contrast, Jolivet et al. (2015) interpret the transitional zone as exhumed lower continental crust overlying the continental mantle which is in the distal part exhumed and serpentinised. ~~The exhumation of~~

lower continental crust in the Gulf of Lion~~s~~ is still debated. For example, numerical modelling of continental rifting at the magma-poor Galicia margin showed that the lower crust is scarcely preserved or absent in the continental tip (Nagel and Buck, 2004). Our velocity model at the base of the continental crust is not well enough resolved (Fig. 4b) to distinguish between upper and lower continental crust, but we emphasize again, that we can exclude oceanic crust based on the seismic velocity ~~distribution~~ structure (Fig. 4f~~e~~) and the results of gravity modelling (Fig. 5) along our seismic profile. The oceanic domain on both conjugated margins in the Gulf of Lion (Fig. 1, inlay profile 2a) and offshore Sardinia (Fig. 1, inlay profile 2b) was ~~imaged in the travel time tomographic approach with the typical pattern observed at mid-ocean ridges (Gailler et al., 2009), with a high velocity gradient in the upper oceanic crust and a low velocity gradient in the lower crust.~~

The extension process in the Ligurian Basin stopped roughly 16 Ma and was replaced by the extension and opening of the Tyrrhenian Sea as the Apennines-Calabrian subduction zone continued to roll back. The magnetic data (Bayer et al., 1973; Cella et al., 2008) in both basins show a similar anomaly distribution with discontinuous, partially isolated anomalies. Prada et al. (2014) analysed a seismic refraction profile crossing the Tyrrhenian Sea from Sardinia to Italy mainland. Similar to the Ligurian Basin, the western margin is more elongated than the eastern margin. They~~ authors~~ divide the analysed profile into 3 different domains from Sardinia to the central basin: In domain #1 continental crust thins from 22 km to 13 km over a distance of 80 km. Domain #2 is interpreted as magmatic back-arc crust with blocks of continental crust and stretches over a distance of ~80 km on the Corsican side of the basin (Prada et al., 2014). The change from continental to magmatic crust is marked by an abrupt increase of seismic velocities to >7 km/s in the lower crust, similar to the observation of Gailler et al. (2009) on the Ligurian Basin side of Sardinia. Prada et al. (2014) interpret the seismic velocities, which are slightly lower than found in 0-7 Ma old-oceanic crust, to be a result of back-arc spreading close to the active volcanic arc. Domain #3 is interpreted to be composed of serpentinised mantle to a depth of 5-6 km with basaltic intrusions and shows a width of ~140 km. ~~The authors summarise~~ Prada et al., (2014) suggest that rifting in the Central Tyrrhenian Basin started with extension of continental crust, continued with back-arc spreading, followed by ~~nearby~~ mantle exhumation. Later, the area underwent magmatic episodes with magmatic intrusions into the sedimentary layer or cropping out, forming volcanoes. These volcanoes and magmatic intrusions could be related to magnetic anomalies (Prada et al., 2016). Using the Tyrrhenian Sea as an analogy, we suggest that many of the isolated magnetic anomalies in the Ligurian Sea are caused by magmatic intrusions or extrusions manifested as volcanic edifices (Median Seamount, Tristanites Massif, Monte Doria; see Fig. 1) (Rollet et al., 2002), rather than related to a spreading axis, ~~which was indeed not mapped~~ in MCS data so far. However, in MCS data, intrusions of volcanic sills into younger sediments were observed (Finetti et al., 2005). At the Monte Doria Seamount, 11-12 Ma old basalts with a calc-alkaline signature were sampled by dredges and submersible dives (Rollet et al., 2002; Réhault et al., 2012), clearly indicating post-rift magmatism. Further, volcanism related to the slab roll-back of the Apennines-Calabrian subduction zone was observed at the Ligurian continental margin and dated to the initiation of the rifting phase (Rollet et al., 2002). Volcanism was as well associated with the end of the opening of the Ligurian Basin and related to the trench retreat of the Apennines-Calabrian subduction zone (Rollet et al., 2002). This implies that volcanism also occurred during the rifting phase and could add to the discontinuous magnetic anomalies.

5.4 Opening of the Ligurian Basin

The opening of the Ligurian Basin in a back-arc position during late Oligocene and early Miocene was driven by the south-east retreating Apennines-Calabria-Maghrebides subduction zone (e.g. Doglioni et al., 1997; Faccenna et al., 1997; Réhault et al., 1984; Carminati et al., 1998). The shift of active expansion from the Ligurian Basin to the Tyrrhenian Sea is considered a result of the Alpine collision that locked the Corsica-Sardinia drift towards the east and slab break-offs along the northern African margin and along the Apennines (Carminati et al., 1998). Thus, the opening of the Ligurian Basin was limited in time and space. Two different conceptual scenarios of rifting could explain our observations: (1) Rifting causing continental crust to thin until continental lower crust and mantle are exhumed and afterwards oceanic spreading is induced as observed in the Gulf of Lion (Gailler et al., 2009; Jolivet et al., 2015). (2) Rifting causing continental crust to thin until back-arc spreading is initiated and the continuation of extension leads to exhumation of mantle with magmatic intrusions (Prada et al., 2016).

Depending on the scenario, our profile is situated in the Ligurian transitional domain #2 or in the Tyrrhenian domain #3. Rifting scenario (2) would imply that well developed oceanic back-arc crust should occur southeast and northwest of the profile. The transect reaches into the area of a 3D seismic study of the Ligurian margin offshore Sanremo (Dessa et al., 2011). The authors state that they were surprised not to see a distinct change in the velocity field at the COT. Dessa et al. (2011) could not ~~show~~ find clear evidence for a kind of back-arc crust as shown by Prada et al. (2014) or Gailler et al. (2009). However, continental crustal thinning is well imaged. Considering these aspects, we rather favour rifting scenario (1) which is also supported by the conceptual model described by Decarlis et al. (2017) for the evolution of magma-poor rifted margins. The model includes three phases of extension: (1) An initial stretching phase forming widely distributed half-grabens in the upper crust. Afterwards (2) a thinning phase leads to hyper-extended crust and is followed by (3) an exhumation phase during which subcontinental mantle rocks were exhumed.

Furthermore, the Ligurian Basin width in our study area (70 - 120 km) is much narrower than further south (~200 km) where domain #2 is ~~summing~~ cumulating ~~up~~ to ~100 km in length for both conjugated margins together, which ~~. This~~ would entirely fill the basin in our study area, leaving little or no space for oceanic spreading. This is i.e. supported by petrological and geophysical observations at the West Iberia margin, that suggest that a COT zone can reach a width of up to 200 km (Pérez-Gussinyé, 2013).

Additionally, the opening rate becomes ~~s~~lower towards the north and the amount of stretching becomes less, which is probably caused by the anti-clockwise rotation of the Corsica-Sardinia block. Stretching of the crust as a result of the opening of the basin becomes less intense towards the north and thus controls the NE termination of the ultra-thin continental crust. Further, the extension of the basin decreases towards the north and assuming oceanic crust to be present, the crust should become less thick towards the proposed ridge axis tip. However, our seismic data and gravity data indicate a gradual thickening of the crystalline crust, at least a gradual deepening of the mantle, indicating thickening continental crust northwards. This is as well supported by the magnetic data (Bayer et al., 1973), which do not show the typical oceanic crust pattern of magnetisation stripes, but rather a lateral patchy pattern of magmatic domains. ~~This could imply that oceanic spreading was not initiated during the Oligocene-Miocene extension in the northern Ligurian Basin, along the southern half of our~~ seismic ~~line~~. Continuing further north, extension ~~leads~~ led to extreme thinning of continental crust, but lasted not long enough to exhume mantle.

6 Conclusion

The P-wave velocity model determined in this study images the uppermost lithospheric structure of the ~~north-eastern~~ central Ligurian Basin. Syn- and post-rift sediments of ~~7.5~~~6-8 km thickness filled the basin during and after the 15 Ma long lasting opening phase. ~~The~~Based on the image of the seismic velocity distribution along the southern half of the profile ~~shows~~ it remains enigmatic if the mantle is overlain directly by ~~sediments~~ or by extremely ~~thinned~~ continental crust of up to 2.5 km. ~~contact between sediments and~~ The degree of mantle serpentinisation~~ed mantle~~ with up to 20% is low.~~, while t~~ The northern half of the profile indicates a northward thickening of continental crust and a deepening crust-mantle boundary from 11 km to 13 km. Based on the retrieved velocity distribution, gravity modelling and results of surrounding studies, we conclude that the extension of the Ligurian Basin led to:

(1) ~~hyper-e~~Extended and very thin continental crust ~~and~~ or exhumed, partially serpentinised mantle ~~and~~

(2) ~~a c~~Continental crustal thinning from north to south related to the increase of extension with increasing distance from the rotation pole of the anti-clockwise rotation of the Corsica-Sardinia block. ~~Further,~~

Furthermore, our study documents that:

(3) ~~s~~Seafloor spreading and formation of mantle-derived oceanic crust was not initiated during the extension of the Ligurian Basin.

Thus, we ~~assume~~ conclude that the oceanic domain does not extend as far north as previously stated and that the transition from the continental domain and the real oceanic domain with a potential spreading axis is situated south or south-west, ~~however, nearby~~ our seismic line.

Data availability. Seismic data are available on request from the first or second author and ~~will be made~~are available via the German marine data archive PANGAEA ~~upon acceptance of the manuscript~~at https://doi.org/10.1594/PANGAEA.910561.

Competing interests. The authors declare that they have no conflict of interest.

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(Hetényi et al., 2018) and is part of the German priority program SPP2017 4D-MB. Generic Mapping Tools (Wessel & Smith, 1998) were used to produce the figures. We thank the reviewers L. Jolivet, J-X. Dessa, and M. Prada for their fruitful comments.

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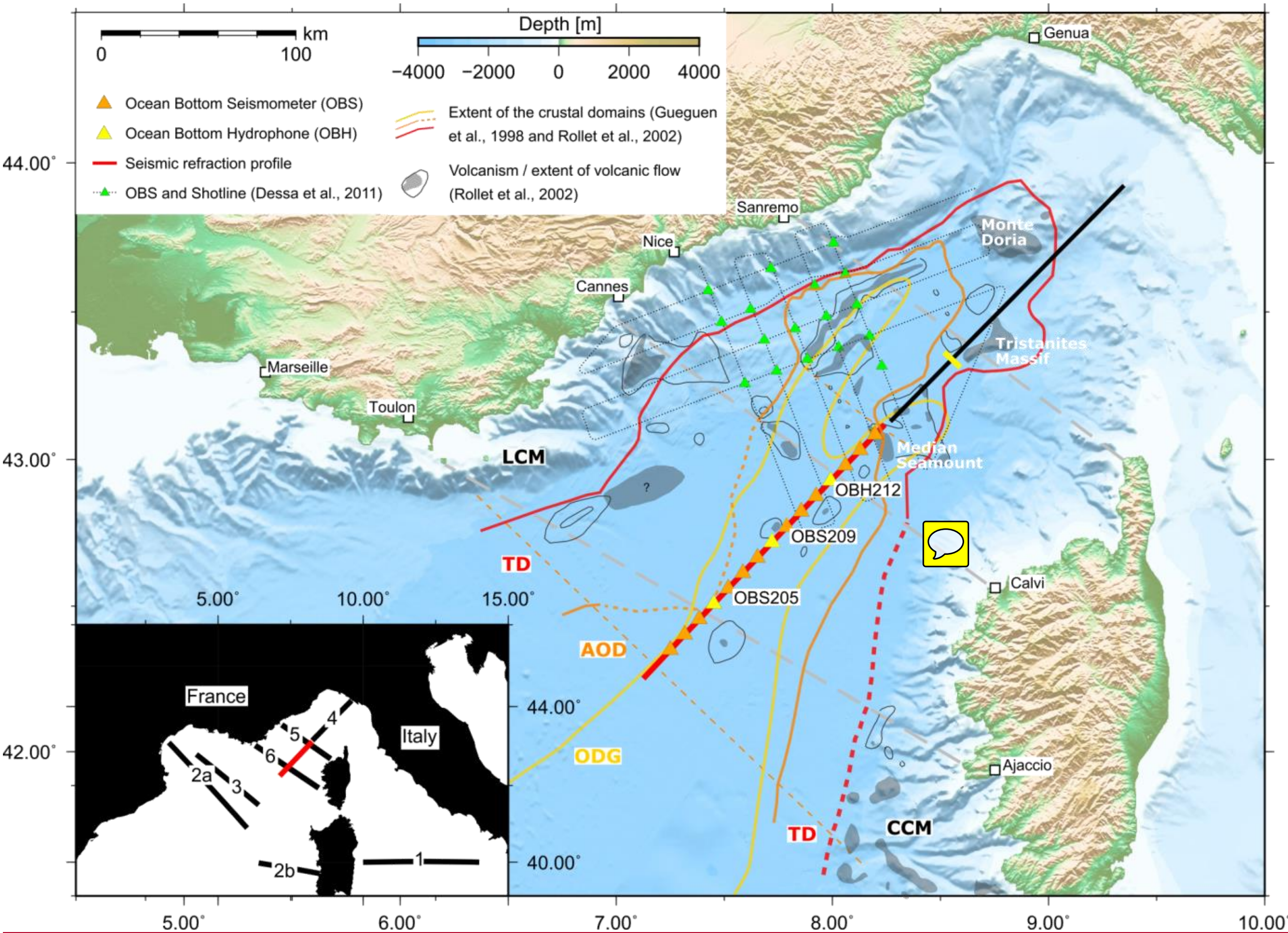

Figure 1: Relief map (GMRT data, Ryan et al., 2009)~~Map~~ **of the study area with the seismic refraction line (thick red line) and OBH/OBS locations** that ~~.~~extend the MAKRIS profile (thick long black line) (Makris et al., 1999). **Thin black** ~~lines~~ polygones **and grey shaded areas mark volcanic extrusion after Rollet et al. (2002). The different crustal domains (Rollet et al., 2002) are marked by thin orange and red lines and** are ~~labled~~labelled **with:** ~~AOC~~ AOD **- atypical oceanic** ~~crust~~domain**, CCM - Corsica continental margin, LCM - Ligurian continental margin, TD - transitional domain.** A t~~T~~**hin yellow line marks the oceanic domain (ODG) after Gueguen et al. (1998).** Thin r~~R~~**ed dashed lines show proposed fracture zones (Rollet et al., 2002).** Short thick yellow bar perpendicular to the MAKRIS profile marks the continent-ocean transition (COT) (Makris et al., 1999). **Green triangles and** thin **dotted** black **lines are the OBS locations and shot profiles of Dessa et al. (2011). The black and white inset in the lower left corner show previous seismic refraction and reflection lines: 1 - Prada et al. (2014), 2a/2b - Gailler et al. (2009), 3 - Jolivet et al. (2015), 4 - Makris et al. (1999), 5 - Contrucci et al. (2001), 6 - MA24 from Rollet et al. (2002).**

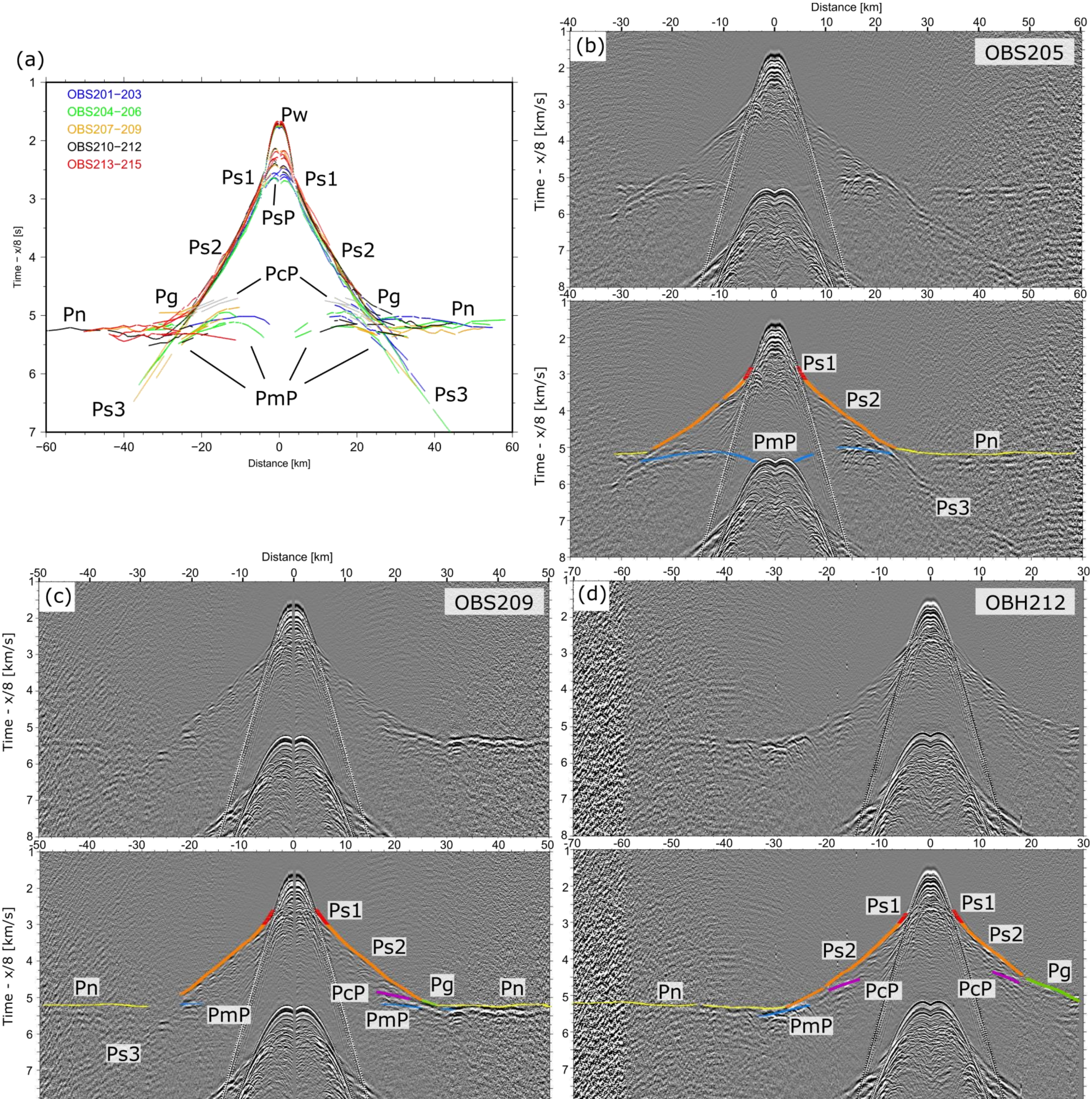

Figure 2: (a) Stacked travel time picks of all 15 stations showing very similar arrivals suggesting an almost 1D structure along the profile. (b) Record section of station OBS205 (time reduced with a velocity of 8 km/s). The lower panel shows the calculated travel time picks from the final velocity model superimposed on the seismic data. (c) Record section and calculated travel times of station OBS209 (d) Record section and calculated travel times of station OBH212.

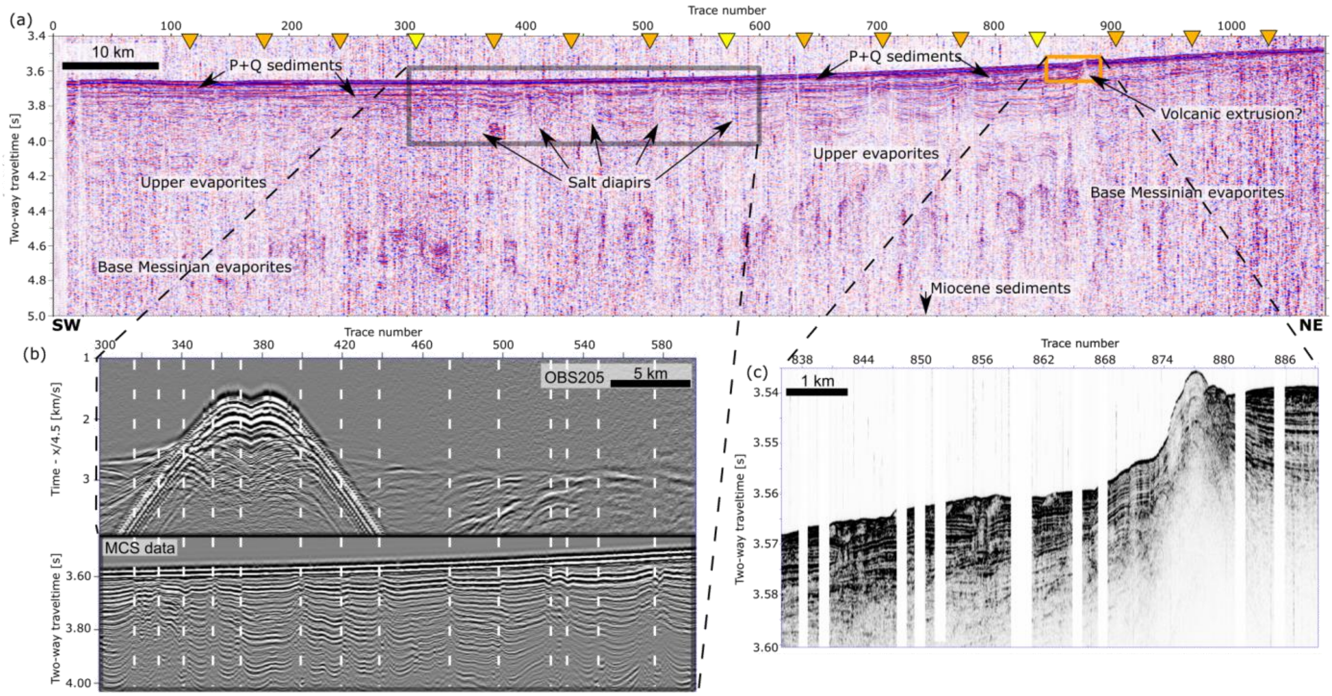

Figure 3: (a) Multi-channel seismic data (MCS data) simultaneously shot with the refraction seismic line. The orange/yellow triangles mark the OBS/OBH positions along the profile. (b) Upper panel shows OBS205 from shot point 300 to shot point 600 with a reduction velocity of 4.5 km/s. The lower panel is a zoom into the MCS section (black box in a). The white lines show that the undulations in the sedimentary phases fit well with faults and salt diapers. (c) Parasound sediment echo sounder data ~~from the~~ (orange box in 3a) ~~shown in the lower panel~~.

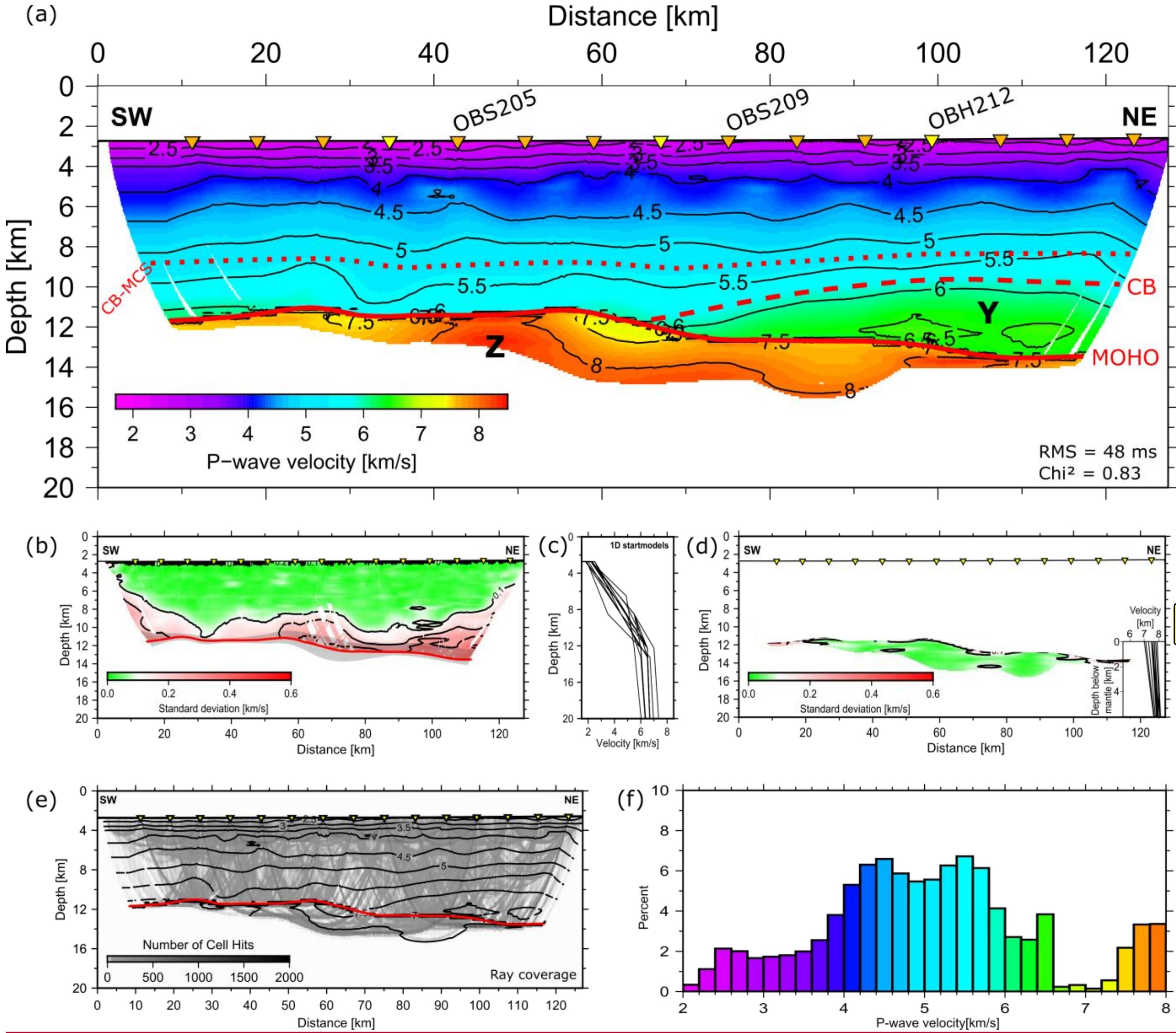

Figure 4: (a) Final velocity model based on the averaged velocities from the plausible starting models. The red dashed line marks the crystalline basement (CB) as determined from the refraction seismic data. ~~, t~~The red dotted line presents the CB inferred from MCS data (CB-MCS) crossing our profile (details given in the text). ~~, and t~~The solid red line marks the crust-mantle boundary (Moho); (b) Standard deviation for 17 inverted velocity models, covering the crustal part down to the Moho; (c) Starting models used in the inversion and to calculate the resulting average model in 4a. (d) Standard deviation for ~~12~~ 14 inverted velocity models (starting models in the inlay), covering the upper mantle up to the Moho; (~~d~~e) Ray coverage for the final average velocity model; (~~e~~f) Histogram with the velocity distribution of the final average velocity model.

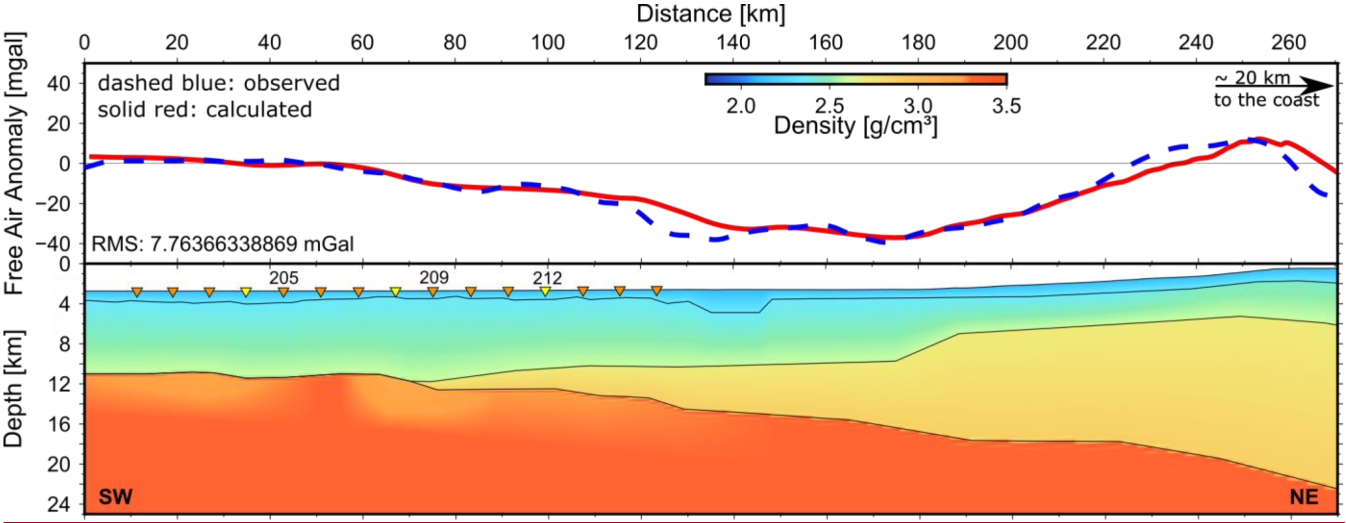

Figure 5: ~~Figure 5~~ **Density model (lower panel) converted from seismic velocities to densities (details given in the text) for the SW part covered by seismic stations. The profile was extended towards the NE using the marine part of the seismic refraction line of Makris et al. (1999). The upper panel shows the data fit between the** ~~observed~~ **satellite derived free-air anomaly data (Sandwell et al., 2014) (dashed blue) and the model response (solid red line).**