Comment on egusphere-2022-1166

Víctor Tendero Salmerón (Referee)

Referee comment on "Oblique rifting triggered by slab tearing and back-arc extension: the case of the Alboran rift in the eastern Betics" by Marine Larrey et al., EGUsphere,
https://doi.org/10.5194/egusphere-2022-1166-RC1, 2023

General comments:

The study presents a collection of previous structural, geological and marine data (seismic reflection profiles) plus some new data to provide a complete explanation for the extension of the Internal Zones of the Betic Cordillera. The authors raise the model of the STEP fault, which is a proper model to explain the westwards displacement of the Alboran Domain, to interpret the shear deformations of the central-eastern Betics basins (Almanzora Corridor, Alpujarras Corridor, Alhabia Basin, Huércal-Overa basin, Tabernas basin) and the exhumation of the main metamorphic domes (Sierra Nevada, Sierra de los Filabres, Sierra Alhamilla). The article is well presented and new data are provided to propose a geodynamic model based on both land and sea data. The model of a STEP fault that affects the Internal Zones can explain the extension and location of strike-slip faults in the area, as well as part of the exhumation of the metamorphic complexes of the Internal Zones and the structuration of the main basins of the study zone.

However, the final model needs to be more accurate. The use of previous structural data, such as the stretching lineations, is sometimes simplified (see specific comments). Some of the parts of the model and hypothesis need clarification. In addition, it is a model to explain the extension of Miocene age, but the previous models that have been raised since the late 80s, and that have been modified and discussed until nowadays, are not properly discussed. I would like that the authors include a better discussion of alternatives. Because of that, I suggest major revisions, because I think these models and previous data that may not support the STEP model should be better discussed and considered.

Altogether, the geodynamic proposal is very interesting and the manuscript is a valuable contribution, but it is not the only model in a very discussed and complex region. These others proposals need to be more discussed and some data/arguments should be clarified.

We warmly thank you for your review. We provide a detailed answer below.

Specific comments:

In section 1, lines 62-76, authors speak about the current deformation patterns. I would like to suggest some clarifications to be mentioned. First, it is true that the strike-slip and normal faulting are active and coeval in the cordillera, but there is a zonation (see, for example, Tendero-Salmerón, 2022, and references therein). In central Betics, normal faulting is predominant, while in the eastern Betics is strike-slip, so they operate synchronously but in different areas, which may respond to different evolution stages of the cordillera.

Second, regarding to the GPS displacements to the west of the cordillera, the authors might find interesting the work of Pérez-Valera et al. (2017) that propose a shear deformation in the olistostromic units of the Guadalquivir basin.

Third, the authors stated that there are a current transtensional deformation on the Betic Cordillera, in general. This can be discussed: this is also congruent with a combination of extension (roll-back) orthogonal to compression (convergence) and there are zonation into the cordillera. The western Betics present compression, as well as Rif, while the eastern one present trans-compression, which is far from the transtensional general state proposed. In fact, in the northern part of the EBSZ, works as Borque et al. (2019) show transpression as predominant and it is not congruent with an oblique extension pattern.

Here we answer to the comments of the reviewer that are broadly concerned with the same set of problems.

According to geodetic data, the eastern termination of the EBSZ strain is transpressional, it is purely compressional (indentation) eastward and extensional to the West (Borque et al., 2019). Borque et al. 2019 show that EBSZ is currently accommodating strike-slip movement along its southern segment while the component of shortening is shown to increase at the NE termination of the EBSZ (not our study area). This is not contradictory with the content of the paper. Indeed, the shortening that prevails in the East is not in contradiction with the extrusion model West of EBSZ where extension and right-lateral shearing are dominant. This expected in the case of extrusion.

In our study area, which is located to the West of the EBSZ and represents 80% of the Betic Cordillera, we reiterate that deformation is dominated by extension and strike-slip (see also the review provided by Guillermo Booth-Rea CC2). Extension is well documented by GNSS velocities (Palano et al., 2015) showing westward increasing directed velocities and also increasing southward (Sierra de los Filabres vs. Gador and Sierra Nevada vs. Malaga), implying right lateral shear. Therefore in the Betics (Central Betics where the metamorphic domes are) strike-slip and extension are synchronous. We infer that transtension does dominate the strain regime the area west of the EBSZ. On the "free border" of the escaping Alboran block compression (Gibraltar) is expected but this is outside of the scope of the present study.

We have modified the text to better indicate the location of the study area (central Betics with the metamorphic domes) to be mistaken with the region east of the EBSZ. We have also added in the introduction relevant informations regarding the complex tectonic setting associated with extrusion (shortening in the east-indentation and west, strike-slip localised across the EBSZ and distributed extension and strike-slip in our study area).

Lines 93-102, and also in other sections like lines 282-287. The basins analyzed in the work fits well in a model controlled by strike-slip; in fact, they are located along major strike-slip faults of the cordillera (or related to their terminations, as Huércal-Overa basin). But, can this model be applied for other significant basins like Granada basin or the Campo de Dalías area, where normal faults are the main active structures? Is it suitable for the Galera fault, in the Baza basin and its relation with the Baza normal fault? (See, for example, Medina-Cascales et al., 2020 and references therein). Then, maybe the model presented is not suitable for all the region and this should be discussed, or to specify that works well for some those basins.

In this part we introduce the topics and recall that in models of highly oblique margin, basins like Baza are predicted. Considering the strike-slip nature of the tectonic regime, these normal faults are predicted to be parallel to the direction of shortening. These basins are integrated in the discussion. For instance we wrote : "The NW-SE/NNW-SSE sedimentary basins (Guadix, Baza, Alhabia; **Fig. 5**), in contrast, are extensional basins formed parallel to the direction of the regional compression (Sanz de Galdeano and Vera, 1992; Larouzière et al., 1988). E-W strike-slip corridors, aligned in the direction of the domes, and NW-SE normal faulting patterns are both key features consistent with predictions from models of oblique extension at transform margin (**Fig. 3**)."

Normal faulting locally expresses the dominant strain regime but importantly this deformation is consistent with the large-scale distributed dextral transtensional deformation. In any case, the pattern of W-directed GPS velocities in the study area implies both extension parallel to extrusion toward the West and right-lateral strike-slip shear. So the question is not whether strike-slip shearing exists but instead how highly oblique extension is partitioned between normal faulting and strike-slip faulting.

Lines 185-187. Stretching lineations approximately show E-W orientation in the Nevado-Filábride Complex, but in the Alpujárride Complex there are more orientations. Which lineations are those mentioned here? In Figure 5 only those of the Nevado-Filábride Complex are shown, but in the text Sierra Gádor is cited as an example, although this range is part of the Alpujárride Complex and present lineations with different orientation (e.g., Orozco et al., 1998). If only Nevado-Filábride Complex is considered, is it the only complex affected by the STEP fault proposed? I think this needs to be clarified.

Yes in Fig. 5 we present lineations only from the NF complex. And you are also correct about Gádor. Therefore we have removed the mention to Gádor in the text as only the AJ complex is exposed in Gádor. Note that in this section we review previous works dealing with Miocene deformation, especially extension and strike-slip, and more specifically the tectonic relationships between domes and basins. We do not intend to discuss the link with STEP faulting here.

On the other hand, these lineations and the evidence of shear deformation are well-known on the literature, but other models have been proposed to explain them (like orthogonal compression, or compression while the exhumation was ongoing, or recent hypothesis that considers the Nevado-Filabride part of the Iberian margin and not of Alboran Domain, which led to a quick exhumation after slab tearing). These models are not properly discussed in the following sections.

Indeed, EW stretching lineations are well documented and to our knowledge there is a consensus to interpret them as reflecting EW ductile stretching not orthogonal compression. Discussions exist and models differ about EW extension but when it is associated with brittle deformation. We think that our short review summarises pretty well the main interpretations regarding the Miocene tectonic evolution of the metamorphic domes based on publications from 1990 to 2021.

"The domes are extension-related features interpreted either as 1) EW-metamorphic domes resulting from the exhumation in the footwall of a regional W-directed extensional low-angle detachments, later folded during post-Tortonian N-S contraction (e.g. Montenat & Ott d'Estevou, 1990; Sanz de Galdeano and Vera, 1992; Sanz de Galdeano and Alfaro, 2004; Martínez-Martínez et al., 2002; Martínez-Martos et al., 2017; Pedrera et al., 2010, 2007) or 2) Miocene metamorphic domes formed by constrictional ductile strain regime accompaniying W-directed stretching of the Alboran domain and trench retreat, with limited overprint by the Tortonian contraction ca. 8 Ma (Augier et al., 2013; Augier et al., 2005; Augier et al., 2005b; Galindo-Zaldivar et al., 2015; Jolivet et al., 2021b; Martínez-Martínez et al., 2002)."

The fact that Alboran Domain (NF Complex) was part of Iberia is not an issue and this is actually conform with our kinematic reconstruction (Angrand and Mouthereau, 2021) that view Alboran as continental block rifted from Iberia in the Jurassic. So NF belong to Alboran which is also Iberia. We made this point clearer also based on remark by Guillermo Booth-Rea (CC2) when presenting the kinematic model of Fig. 4.

Figure 4. The position of lithospheric tear faults is discussed and most of the literature located the limit of the tearing of the slab of the

Iberian margin below central Betics (near of the change of the topography from high ranges to low ranges). Why is it located to the west? Maybe, the authors could add a reference in the figure caption of which work has used to locate the tear faults.

These tear faults refer to those roughly positioned regionally in Jolivet et al. (2021). We also added black stars corresponding to slab rupture defined in Mancilla et al. (2015a). These references have been added.

In the stereoplots of Figure 8, for σ_2 there are more horizontal data that vertical ones, although vertical ones are mentioned as significant and used as an evidence for the STEP model. Maybe a percent of how many NW-SE/WNW-ESE horizontal and vertical ones are could help.

Pure extension (σ2 horizontal) also fits with the development of highly oblique rifted margin above a STEP fault (see Fig. 3). So we do not base the STEP fault model only on the strike slip stereo plots (σ2 vertical). Anyhow the remark is sounding and we added percentages. Results are : 73% are pure normal faulting and 27% of strike-slip faulting. Note that we propose an explanation for the lack of strike-slip fault : "The reason why strike-slip faulting is less apparent in the field than expected in models in **Fig. 3** is likely to reflect the fact that oblique extension is not fully partitioned between normal and strike-slip components and is actually distributed along oblique structures. Moreoever, where strike-slip faults are found they are associated with narrow basins or near the contact betwen the cover and basement but not in the center of HOB or TB."

Section 4.1.2. Do the NW-SE normal faults cut the E-W strike-slip faults as they cut the E-W folds of the main ranges?

We have not seen the NW-SE faults cutting E-W strike-slip faults but are indeed cutting E-W-directed structure. Considering strike-fault zone are highly discontinuous this is not surprising.

Lines 392-395. Authors considered that extension and strike-slip regimes occurred synchronously in a large scale tectonic process. This is suitable for the studied area, but not for the whole cordillera nor Alboran Domain. There are other areas where this is not observed, like the normal faults systems of the central Betics, or the western Betics. This should be discussed and why the main evidences are located there. Is the STEP fault deformation only shown in this part of the

Betics? Could it be related to the movement to the west of the central and western Betics, while the eastern Betics (Prebetic Arc, Águilas Arc, Campo de Cartagena basin, Alhama de Murcia fault area, etc.) were stuck against the Iberian Margin?

It is important to remember that the present-day kinematics tells us that the Central Betics (not western Betics) are undergoing both extension and dextral shearing (see above Fig. 3 and text) so yes we can extend our results to the Central Betics. Large active NNW-SSE normal faults are bounding the Sierra Nevada. This is related to the extrusion kinematics which is linked to indentation in the easternmost Betics east of the EBSZ. STEP faulting related to slab retreat that occurred under regional N-S convergence is likely the main explanation for the extension and strike-slip. As slab detached in Central and Eastern Betics, tectonic inversion of the rifted margin and indentation by the EAB occurred. This is a late process that triggered the current extrusion toward the SW and therefore probably explain part of the extension we observe through NW normal faulting. Anyhow we think they are all connected in space and time.

We have modified the implication section to make this clear :

"Only recently, around 8 Ma, as the slab detached, indendation of the rifted margin by the magmatic crust of the EAB started in the eastern Betics. This caused shortening east of EBSZ associated with indentation of the Águilas Arc (Ercilla et al., 2022), and amplification of the metamorphic domes in the vicinity of the EBSZ (e.g. Alhamilla) (**Figure 18**). The strike-slip deformation model in the Betics has the advantage to explain the N-S crustal thinning while back-arc extension is oriented E-W, in a continuum of deformation from the Miocene to the present. In this model, ductile stretching and ductile detachment associated with the development of the domes are the expression of oblique E-W extension. It provides a coherent scheme linking the formation of EW-directed basins in the brittle field associated with strike-slip faulting, and NW-SE/NNW-SSE sedimentary basins (Guadix, Baza, Alhabia) formed in transtension during the Tortonian. As such, the oblique extension, which is closely associated with STEP faulting required by slab retreat, is overall a characteristic feature of the regional NW-SE/NNW-SSE convergence since at least the Miocene. "

Figure 13. The fault that cut the crust in the left edge of the figure (northwards of the Carboneras fault) cannot be seen in the profile and it is partially drawn outside the profile. It should be removed or authors should enlarge the seismic profile, or better explain why it can be interpreted.

Agreed. We removed the continuity of the fault outside of the seismic profile.

Lines 523-525. This can be explained by different crustal domains proposed in the cited works of the article. The rigid East Alboran Basin is less deformed and transfer the deformation to the thin continental crust located to the north, which is less rigid. It has also been proposed for the transpression in the EBSZ (Borque et al., 2019) and for the Águilas Arc (Ercilla et al., 2022).

We agree the EAB is clearly indenting the Iberia margin. The reason why this occurs still needs to be explored because the EAB is not necessarily the more rigid although the crust is mafic. Indeed, the lithosphere and crust are the thinnest in this region. Prexisting weak fault zones might also be involved. We added ref to Ercilla et al. 2022 which as lacking in the previous version.

Implications.

Line 539, this was already known, the main thinning episode of the Internal Zones has been considered of Early Miocene to Middle Miocene, so it does not seem a new contribution.

There must a misunderstanding here. Our sentence is : "…crustal thinning occurred under oblique extension and was not restricted to the post-Tortonian evolution". We explicitly indicate that crustal thinning occurred by oblique extension (new) and that oblique extension is long term process (new). This last point is important because this means oblique extension as seen in the geodetic data can be extrapolated in time.

Line 539, If STEP fault operated mainly since Middle Miocene, then it operated over an already thinned crust, according to bibliography and the timing of the extension of the Internal Zones. Later, in line 568, it is said that the thinning started at 23 Ma, which is Early Miocene, so, did the STEP fault start then? In line 579 authors said since Miocene, this needs to be more accurate. The ages of the proposed STEP are not clear and authors could clarify this for the potential readers.

To be exact we have written l 539 : "… oblique rifting possibly operated **since at least** the middle Miocene, as the slab retreat started in the Alboran basin and is therefore kinematically associated with STEP faulting." This being said, you are right we need to be more specific. We think it is also a major question in the Betics because when reading the literature, the geochronological and stratigraphy data suggest formation of the Alboran basin in the Aquitanian-Burdigalian at the earliest. This is outlined by exhumation of metamorphic rocks to the surface and deposition of Burdigalian deposits.

We have reworked this part to make things clearer : "Ductile thinning associated with the formation of metamorphic domes and exhumation of HP rocks is dated to 23 to 16 Ma (Platt et al., 2006; Booth-Rea et al., 2015). This provides time constraint for the beginning of oblique extension and westward slab rollback. Deformation at the future location of the tear fault was probably initially diffuse and resulted in an immature oblique rift system in the South, combined with thrusting in the external zones to the North (**Figure 18**). In the Langhian-Serravallian (14-13 Ma), accompanying slab steepening, localization of slab tearing, and propagation of thrusting in external zones, oblique extension spread over the whole central Betics. At this time, metamorphic domes exhumed to upper crustal levels and recorded the transition from ductile shearing to brittle faulting (**Figure 18**)."

In short, the conditions for tear faulting were established progressively from the early Miocene to the middle Miocene. Our observations in the sedimentary basins reflect conditions that were achieved when STEP faulting localised in the middle Miocene.

Line 565-567: this is very relative, the inversion is important next to the Carboneras and Palomares faults, but it is also important in other areas as it is shown by the elevation of the main ranges as antiforms (Sierra Nevada, Sierra de las Estancias, Sierra Gádor, Sierra de los Filabres) and the nearby basins. It is expected in an area such as the EBSZ, it does not support unequivocally the model of the STEP.

We did not intend in this paper to quantify the effect of shortening on the elevation of the main sierras. Deep-seated mantle processes can equally be proposed to explain the topography of those sierras. From our experience the amount of shortening has remained relatively modest west of the EBSZ. Amplification of dome topography likely occurred by shortening but when and how much it is yet to be quantify. Note that this part the text has been modified.

Figure 18. I would appreciate some extra indications in this figure. Is the fault that crosses from Betics to Africa a simplified representation of the Trans-Alboran Shear zone? Also in the stage of post 8 Ma, the model shows some similarities to the indentation model of central Alboran Sea (Estrada et al., 2018). What represents the northern boundary? Is the contact between Internal and External zones? In the post 8 Ma stage, the northern margin does not work as a strike-slip fault, as said in the text and shown by seismicity and other works. In fact, in the eastern Betics, the Internal- External zones contact is a backthrust. At least the symbol of thrust of the previous stages should not disappear.

Yes this is the TASZ. We keep the thrust symbol.

Lines 573-576. The N-S crustal thinning can be explained without STEP fault. For example, the models that consider a curved slab that was initially attached to both African and Iberian margins (e.g., Chertova et al., 2014, Spakman et al., 2018). In that case, the curved slab generated an opening of the Alboran basin with radial extension, or, at least, N-S extension in some stages while the slab is still attached to the Iberian margin. This is another point that authors should discuss, why the model they present explain better the geodynamic evolution than the alternative models.

Yes they are many models that can explain the N-S crustal thinning. The type of geodynamic models you are referring to are not designed to reproduce details of the tectonic features we document in our paper. However, these models explain the N50-60E extension documented in the central-eastern Betics by the differential absolute motions between Iberia and the slab decoupled from Iberia by slab tearing (Spakman et al., 2018). We consider that it is can be envisaged that in addition to the dominant westward slab rollback, mantle-derived slab dragging contributed to the late extensional stage, from 14-13 Ma, when slab tearing localized. We have modified the text accordingly. Our model and slab-dragging model are likely to be complementary.

Technical comments:

Line 22: type error, “confirms” instead of “confirm”. Done. Line 24: please, consider eliminating “found” in “The extension is found associated”. Done

Figure 1, caption: please, replace “Palomeras” by “Palomares” in all text, the fault name is Palomares. Done

Figure 1: please, consider changing the color of the trace of seismic profile MSB08, being in red could make hard to identify its location due to the red polygon under it. Done.

Figures 1 and 2: please, consider adding the names of Betics and Rif to the main maps, or enlarge them. In the Figure 1, I would also suggest to add the “Gibraltar Arc” in the strait area. In the inset of Figure 2, I would add a scale and/or a square in the main map to show that areas. Done.

Line 172: type error in “rather” Done

Line 195: please, add a coma after “structures” Done

Line 202: type error, eliminate the “(“ before “Sanz de Galdeano” Done

Line 226: type error, eliminate the “(“ before “Martínez-García” Done

Line 232: type error, it is just one figure, so “Fig. 5” instead of “Figs. 5”. Done

Line 245: please, consider replacing “they” by these deposits, or basins, to clarify the sentence. Done

Figure 6. I would suggest to the authors to explain the use of the colors in the stratigraphic columns in the legend of the figure.

We removed colors from this figure.

Line 282: please, check whether Figure 5 should be cited in that line. It cannot clearly be seen in Figure 5 the asymmetry of the basins nor gravity measurements. We removed the reference to Fig. 5

Line 327: “Sierra Limaria” is no shown in any map or figure, I would consider to include it. Done

Line 357: Could it be “Sierra Alhamilla” instead of “Sierra de los Filabres”? Sierra de los Filabres is continuous in the Alhabia basin borders and it is not cut by normal faults that interrupt its continuity in that zone.

This is indeed the Sierra de los Filabres. More precisely this is the southern flank of the Filabres that is discontinuous. We corrected this.

Line 389: type error, the direction of the extension: “NNE-“, I guess it is “NNE-SSW”. Corrected.

Line 422: the reference “Peña et al., 2018” it is incorrect, I think. It should correspond to the works of “Gómez de la Peña et al. (2018)” that are cited in the following sections. The list of references should be corrected because the works of Gómez de la Peña appear as “Peña, L. G.” instead of “Gómez de la Peña, L.”. True. Corrected.

Line 495: type error, eliminate the “(“ before “Martínez-García”. Done. Line 521: type error, there is not Figure 19, I think it corresponds to Figure 17 in this line. Corrected

Line 533: Is section 7 or section 6? corrected. Line 557: figure 18 caption: please, replace “is showing” by “shows”. Done Line 564: please, consider eliminating “found” in “are found associated”. Done Line 583: type error: orogenic. Done Line 587: please, add a coma after “roll-back”. Done Line 589: please, replace “an other” by “another”. Done

Comment on egusphere-2022-1166

Anonymous (Referee)

Referee comment on "Oblique rifting triggered by slab tearing and back-arc extension: the case of the Alboran rift in the eastern Betics" by Marine Larrey et al., EGUsphere, https://doi.org/10.5194/egusphere-2022-1166-RC2, 2023

This manuscript presents an oblique rifted margin model for the Alboran Basin northern margin. This oblique rifting is understood as the consequence of a STEP fault and slab retreat. This model is supported by a compilation of results, both onshore and offshore. Taking into account that most studies in the area are focused either onshore or offshore, this is a valuable contribution. The manuscript is well written, and the results are clearly presented. However, from my point of view, further discussion is needed in order to strengthen the conclusions of this study. In my opinion, there are two major points that should be tackled before the publication of this manuscript:

We thank the reviewer for his/her very useful comments.

1) The authors discussed crustal thinning. Considering the complex structure of this region, in which different crustal types coexist, I believe that crustal thinning is approached in a too simple way. This is especially true in section 5.2, in which crustal variations along a N-S section are compared. While onshore the Betics the crust is formed by a stack of different domains including the Alboran domain, offshore in the south Iberian margin the crust is (most probably) only formed by the Alboran domain. Further south, in the East Alboran Basin, there is a totally different crust with a different origin, the magmatic crust. Although these different crustal types are mentioned in the manuscript, they are not described or discussed in any detail. The authors state that the margin thins from 35 km (onshore) to 20 km in its distal part (north Alboran Basin), assuming a constant and homogeneous crust before the thinning. Prior to this statement, further

discussion on the crustal structure and how and why it is comparable from the proximal to the distal margin is needed.

Thank for this comment. It is true that we did not discuss in sufficient details what the existence of crusts with different composition imply for our tectonic model. In our view the magmatic crust of EAB is the continuation of the Alboran margin intruded by voluminous arc magmas. The section 5.2 has been modified to incorporate such a discussion. References to Booth-Rea et al., 2018 and Gómez de la Peña et al. 2020 have been added.

2) Also, further discussion on how the presented data support or not previous models is needed. Although it is discussed how the data can be explained with the proposed oblique rifting model, I think that a discussion that includes previous models of the area is also necessary. Several models have been proposed in this area, some of them including slab retreat and slab tearing. Thus, discussing these models in light of the compilation of data presented will strengthen the conclusions of this study.

A similar comment is raised by RC1. We have modified our implication section “Section 6” to implement comparison with other models, especially model from Spakman et al., 2018.As a minor comment, I think that the discussion of the timing of the extension offshore can be improved, especially as the age of extension is included as one of the conclusions of the manuscript. The age of the tectonic activity is well described for the onshore data (sections 3 and 4). However, for the offshore sections the description is focused on the sediments, and the fault activity description can be improved (section 5).

We have modified both sections 5 and 6 to better implement our conclusions on the timing of faulting and magmatism that help strengthening our tectonic scenario.

Comment on egusphere-2022-1166

Guillermo Booth-Rea (Referee)

Referee comment on "Oblique rifting triggered by slab tearing and back-arc extension: the case of the Alboran rift in the eastern Betics" by Marine Larrey et al., EGUsphere, https://doi.org/10.5194/egusphere-2022-1166-CC2, 2023

The manuscript “Oblique rifting triggered by slab tearing and back-arc extension: the case of the Alboran rift in the Eastern Betics” presents new field data and interpretation regarding the late Miocene evolution of the Eastern Betics. The extensional structures are set in the context of the evolution of a STEP fault setting during the late Miocene to Present. In general, it is well written, although it requires some reorganization, with a proper introduction separated from a geological setting. There is text that should be transferred to the discussion section. Furthermore, it has missing references and requires a careful review of some of its findings. It needs major corrections. I include an annotated version of the PDF file and I also include some detailed corrections below.

We thank the reviewer for his time and insightful comments.

Abstract:

Although the abstract does not have references, I include them below to support the comments I make. They may be used in the main body of the text.

Line 15: much of the extension observed in the Betics is not “backarc”, because it occurs in a forearc position respect to the volcanic arc. Actually, STEP faulting and associated extension in the Betics, and in other western Mediterranean regions propagates into the continental nappe and FTB domains (e.g. Mancilla et al., 2015; Booth-Rea et al., 2018b. Please correct.

This statement is neither wrong nor true, because it depends on what we consider as the arc. Overall it is very interesting and allows us to clarify our thoughts. Considering the Betic Cordillera developed above a STEP fault during the Miocene, the Betic Cordillera is not an arc and the extension we document in the Betics is instead related to the west-directed retreat of the Alboran slab. Therefore the extension in the Betic Cordillera is backarc for the Gibraltar arc.

A second argument is that the East Alboran volcanic arc is Tortonian in age and therefore much younger than the age of the onset of extension (Burdigalian) in Alboran. This means arc volcanism occurred in an already thinned crust. It therefore rather reflects “backarc arc magmatism” not a true suprasubduction volcanic arc. This certainly needs to be discussed but considering the logic of the paper we think the oblique extension we are looking at is backarc relative to Gibraltar arc. Anyhow we change the title because we think “Oblique rifting" is a little redondant with backarc extension and its connection with slab retreat process is the main message of the paper.

Line 18: current deformation patterns determined from GPS data show two contrasting settings in the Betics. Whilst extension is dominant in the central Betics, shortening and strike-slip deformation occurs in the Eastern Betics (e.g. Palano et al., 2013). This pattern has worked probably since the Messinian (e.g. Giaconia et al., 2014; 2015; Gómez de la Peña et al., 2022).

We modified the text following comments by RC1. Just to precise for the reader that what your indicating as eastern Betics actually refer to the region east of the East Betic Shear Zone, where there are actually no metamorphic domes.

Line 29: The slab did not detach instantaneously at 8 Ma. Slab detachment propagates in time and is probably still occurring in the western Betics. Different work has proposed different rates of slab detachment from very fast rates in the order of 35 cm/yr to 160 mm/yr

(García-Castellanos and Villaseñor, 2011; Boonma et al., 2023) to rates of approximately 32 mm/yr (de Lis Mancilla et al., 2015) to 50 mm/yr if tearing initiated under the Balearic promontory in the middle Miocene as proposed by Moragues et al. (2021).

Agreed. We have indicated the age used in the literature for the initiation of slab detachment. We made it clearer in the text.

Tear faulting and oblique….

This section is very long and confusing. Please separate information in a classic introduction and a geological setting.

We understand your point. However the Betics is a well-known example for STEP faulting and extension. We think it makes sense to combine our current theoretical knowledge on STEP faulting with some geology of the Betics. This is an introduction not a geological setting. In this way, the reader is immediately provided with both an introduction to the processes we discuss in the ms and at the same time with key informations relevant to addressing our main issues: the tectonic relationships between STEP faulting and oblique rifting.

Line 45: Crustal thickness in the Betics is locally above 45 km (e.g. de Lis Mancilla et al., 2015)

We used the joint interpolation of deep seismic reflection constraints and receiver function estimations from Mancilla et al. 2015 published by Diaz et al. 2016. We guess this is the best model because it accounts for more constraints. However, considering the isocontours of crustal thickness plotted in Figure 2 each 5 km, we have added “>” to 35 km because the thickness in our study is larger than 35 km.

Line 52: These sentences are not precise. Please notice, several authors have differentiated two types of strike-slip faults in the Betics, those related to late transcurrent tectonics in the Eastern Betics (e.g. Bousquet, 1979; Weijermars, 1987; Booth-Rea et al., 2004; Giaconia et al., 2012a, b) and those working as transfer faults of the extensional system, related to the slab tearing or detachment mechanism (Martínez-Martínez et al., 2006; Rutter et al., 2012; Giaconia et al., 2014; de Lis Mancilla et al., 2015

Here we refer to strike-slip faults accommodating differential extension. In that respect there are transfer faults. We tried to make this clearer.

Line 55: Please do not use the term "corridor", fault or fault zone are more appropriate. The Torcal fault has been especially well described by Balanyá et al. (2012); Barcos et al. (2015).

Done. We added ref to Barcos et al. (2015) which is relevant.

Line 57: Slab retreat and its effects did not end simultaneously in all the Betics. It still produces active extension and intermediate seismicity in the Central and western Betics (e.g. González-Castillo et al., 2015; Heit et al., 2017; Madarieta-Txurruka et al., 2021)

It was not our intension to say slab retreat ended at the time along the strike of the Betics. We wanted to point out it started about 8 Ma ago. We modified the text.

Line 96: add other references (Booth-Rea et al., 2004; Rodríguez-Fernández et al., 2011; Giaconia et al., 2014).

In this sentence we cite papers that referred to the asymmetry of the intramontane basins. We agree that Giaconia et al. 2014 and Rodríguez-Fernández et al. 2011 do present cross-sections of intramontane basins from which one can infer the asymmetry of the basins but not Booth-Rea et al.(2004).

Caption Figure 2: GPS movement is not oblique to plate convergence in the Easternmost Betics.

Exact. We have corrected this.

Line 145: The eastern Alboran basin, and the transition to the Algerian basin formed later, mostly by late Miocene volcanic accretion in arc and backarc settings (Booth-Rea et al., 2007; 2018; Gómez de la Peña et al., 2020).

Agreed. We did not originally intend to introduce the Eastern Alboran Basin, but it makes sense to present it here as we present seismic lines later in the text. References added.

Line 158: Part of this paragraph is more suited for the discussion. This model, and the one proposed by Vergés and Fernández, 2012, have several serious problems including the provenance of the Alboran domain (African margin, in these models) respect to the detrital provenance signature of the Malaguide complex (top of the Alboran domain) that has a NE Iberian massif origin (Jabaloy et al., 2021). The direction of extension (E-W opening of the western Algerian basin) and slab tearing (NE-SW directed) is also highly oblique to the NW-motion they propose for the Alboran domain, especially during the last 14 Ma.

There should be a misunderstanding. There is no inconsistency with Iberian origin for Alboran. Our model (Daudet al., 2020; Angrand and Mouthereau, 2021) considers that the Alboran domain has been rifted from Iberia during the Jurassic. This is fully consistent with U-Pb data that suggest Alboran was attached to Iberia in the late Paleozoic (Jabaloy et al, 2021). But we also agree with Vergés and Fernández (2012) that nappe stacking occurred from south to north. The internal deformation of Alboran is well depicted by the chosen motion paths (black in Fig. 4) but is considered to be 110 km in the EW direction. This EW extension is contained in NW-motion of Alboran. Slab tearing is considered roughly parallel to the Betic trend (more ENE-WSW than it is in reality).

They should discuss other models that propose a more complex evolution and a link between the external Betics and the Balearic Promontory (Moragues et al., 2021). Even the direction of thrusting in the external Betics, shows problems with this NW-directed shortening, being more westwards directed (Pérez-Valera et al., 2017). Finally, the model in Figure 4 does not fit with biogeographic and palaeontological evidence that indicate an insular land connection between the Alboran domain and the Balearic Promontory in the Middle Miocene (see references in Moragues et al., 2021).

Our reconstruction is compatible with a connection between external Betics and Balearic promontory (probably more apparent in Daudet et al., 2020 than in Angrand and Mouthereau, 2021). And you are right this is a major difference from Vergés and Fernández (2012). The direction of thrusting in the external Betics is not easy to reconstruct because of the structural complexities arising from salt tectonics. In any case we agree with the findings of Pérez-Valera et al. (2017). The W-directed thrusting in external domains they document likely reflects the dextral component of deformation we emphasize in our study. We should however be caution because strain partitioning is expected in these strongly decoupled salt-bearing units. As mentioned above the connection between Alboran and Balearic promontory is accounted for in our model from the middle Miocene onwards. In fact they are both deforming with the same NW motion over this period (motion not shown for the Balearic promontory). A last comment however. Remember that we need to absorb 150 km of N-S convergence since the Oligocene between Iberia and Africa (Macchiavelli et al., 2017) which is unfortunately only rarely taken into account in most kinematic models of the region. We added references to other models that positioned Alboran domain to the south of the Balearic Promontory (e.g. Moragues et al., 2021; van Hinsbergen et al., 2014).

Miocene extension:

Line 220: Please notice that Martínez-Martínez et al., 2006 mentions that extension is still active in the Central Betics, whilst the related structures have been inverted towards the East. Furthermore, other authors propose NE-SW extension lasted until 7.5-7 Ma in the Eastern Betics (Booth-Rea et al., 2004; Giaconia et al., 2014). The change from extension to shortening was not instantaneous in all the Betics. It propagated through time, and is probably still occurring.

We made clearer in the new version that extension is still ongoing in the Central Betics. We modified the text and added the references.

Line 223: Regional uplift is not necessarily related to shortening. Other authors have proposed it is related to deep mantle mechanisms like slab tearing or delamination (e.g. Duggen et al., 2003; García-Castellanos and Villaseñor, 2011; Mancilla et al., 2015; Moragues et al., 2021).

Here, we originally did not intend to introduce the large scale driver. But we agree, we think placing the question of uplift in a larger perspective is interesting here. So we added a sentence and most references as suggested.

Line 236: strike-slip. Transcurrent is a particular type of strike-slip context, where the main stress axis is horizontal. In the Betic case, the transfer faults are not transcurrent faults, as they develop in an extensional setting (See Martínez-Martínez, 2006).

To us strike-slip deformation/fault/strain and transcurrent deformation/fault/strain express basically the same deformation process. Of course it should be differentiated from strike-slip state of stress or stress regime (s2 vertical). This means strike-slip faulting (or transcurrent fault) may occur in extensional stress regime; this is probably what you mean. In this sentence we are not referring to the stress regime but rather to faulting/deformation, which is transcurrent or strike-slip.

Line 240: Please, check this better. The eastern Betic basins contain Burdigalian and Langhian sediments. Also, the Serravallian-Tortonian is not 11-9 Ma!! The Serravallian starts at 13.82 Ma. See Giaconia et al., 2014; Gómez de la Peña et al., 2021)

In the pdf you provided you suggest remove the following sentence "The oldest sediments deposited unconformably on the Paleozoic-Triassic basement are red alluvial conglomerates and deltaic series dated from Serravallian to lower Tortonian". We don't understand why because this is what the geology (published and unpublished literature available) tells us. We are not aware of works mentioning older sediments. In addition, we have clearly observed that this sediments are resting in stratigraphic contact with the metamorphic basement. We modify the sentence to include the possibility that older sediments might be present somewhere.

The stratigraphy shown in fig. 2, fig. 4 of fig. 7 in Giaconia et al. does not show sediments older than Langhian-Serravalian. However in their Fig. 3 they do indicate Burdigalian strata. To support this they refer to Fortuin and Krijgsman (2003) but these authors do not refer to the occurrence of Burdigalian sediments in the Nijar basin. They also refer to Piller et al.(2007) but this citation does not seem to be relevant because it presents a synthesis at the scale of the para-tethys with no specific constraints from the Sorbas basin. It seems the only work suggesting possible occurrence of Burdigalian deposits in the eastern Sorbas is published in the PhD thesis of Barragán (1997). In our view, the biostratigraphic informations presented in this work are not sufficient and based on too few rock exposures to justify a profound modification of the first-order stratigraphy of the Sorbas basin. Anyhow, we think Burdigalian deposits once existed and were covering the Paleozoic basement in the region, but the subsequent exhumation of metamorphic rocks just removed them.

Line 246: The older sediments were not sourced from the Nevado Filabride. Only from the Tortonian onwards (Völk, 1967). The paleogeographic work you cite does not take into account the displacement over the Sierra Nevada extensional dome, which you indicated above had in the order of 100 km displacement…

Section 3.2 is about the Tortonian. It does intend to describe the tectono-sedimentary evolution before the Tortonian. Moreover based on our own field work and in conformity with previous data, Tortonian sediments do contain NF pebbles and are often found in stratigraphic contact with them, so the relationships between these sediments and their source (NF) is straightforward. The extension you mention is inferred from Martinez-Martinez et al. (2002) not from us. It is documented through based on the ductile deformation of the metamorphic complex.

Figure 6: please update the stratigraphy of the Sorbas basin that starts in the Burdigalian. Both the Tabernas and Sorbas basins include early to middle Miocene sediments. See Giaconia et al. (2014) for the stratigraphy of the Sorbas basin.

We have added a sentence indicating that Burdigalian deposits have been reported east of Sorbas Basin. However we think, as explained above, that the biostratigraphic informations available are not sufficient to justify a profound modification of the first-order stratigraphy of the Sorbas Basin shown in Figure 6.

Lines 568-582: it is difficult to reconcile end of ductile deformation at 16 Ma with HP/LT metamorphism at 13 Ma, no? Please, check missing references and be consistent with the data. Obviously, ductile deformation took place at the same time as brittle deformation in shallower levels of the crust (see Booth-Rea et al., 2015). Exhumation of the Sierra Nevada dome continued until Present.

Indeed, both brittle and ductile deformation are still active in the Betics. But this is not our point in this sentence. We just wanted to pointed out the timing of transition from ductile to brittle deformation during exhumation of the metamorphic domes. We modified the texte and added refs.