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Interactive comment on "Plio-Quaternary tectonic evolution of the southern margin of the Alboran Basin (Western Mediterranean)" *by* Manfred Lafosse et al.

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This paper deals with the recent tectonic evolution of part of the southern margin of the Alboran Basin (and not the whole southern margin as wrongly stated in the title). Actually, the authors focus on the offshore southernmost part of the Trans-Alboran Shear Zone (TASZ) representing a broad area of deformation which is not as well

documented as other areas in the Alboran domain. The interest of the work is to further document this area with new, high-quality seismic data of high to very high resolution and to better assess and/or discuss the reasons for the fast stress changes that occurred since Pliocene. As a whole, this contribution appears stimulating and rather convincing and is worth to be published.

However, several limitations appear in the way the authors reports previous studies and discuss their interpretations; furthermore, the bad organization of the ïňĄgures and the poorly written English make the paper quite difïňĄcult to read.

Actually, I have identiïňĄed an important weakness: an important point supported by the authors is to suggest that besides the well-assessed processes of indentation in the central Alboran domain and extrusion of the Rif, the major change of tectonic style in the study area is related to a clockwise rotation of the Alboran tectonic domain instead of a change in the Eurasia/Africa plate convergence vector. The reality is that (1) uncertainties on kinematic data (DeMets at al., 2015) prevent from assessing any signiïňĄcant change in the obliquity angle or in slip direction in the study area since the Messinian, although Nubia-Eurasia angular velocities estimated from geodetic and geologic observations appear to differ signiïňĄcantly. (2) the block rotation model proposed by Meghraoui and Pondrelli (2013) is a large-scale model ("restraining bend") based on the assumption of a right-lateral deforming zone with large fault systems in the offshore domain: in my opinion, the fault geometry, sense of motion and continuity are far from being clearly assessed, preventing from concluding ïňĄrmly that a block rotation model (either bookshelf or pinned) is responsible for the change in tectonic style. It results from (1) and (2) that the choice made by the authors is quite questionable, in my opinion. Other parameters such as, for instance, changes of body forces during crustal thickening of the South Alboran Ridge or even further south, or transpressive fold propagation (as suggested, lines 403-404), or also effects of propagation of the Al-Idrissi fault on strain distribution, should be included in the discussion on this challenging question.

We agree with the reviewer and thank him for his constructive comment. He highlights issues that might represent critical weakness in our paper. From the results of DeMets et al., (2015), the Africa-Eurasia convergence azimuth 95% confidence interval is approximatively around +/- 7° at 2Ma; the error on the velocities are inferior to 1mm/a. More important is that the trends of the velocity and the azimuth are stable since 6Ma. Estimates of local changes in stress direction since 5.33Ma are around 12-15° (based on structural data, Martínez-García et al., 2013). This is the same order than the amount of rotation from pinned block model (Meghraoui and Pondrelli, 2013) and in the same order of magnitude of strain rotation in Palano et al. 2013, but also in the same order of rotation in the Betic-Rif orogenic arc (Crespo-Blanc et al., 2016). A well-described 20° difference exists between the direction of Africa/Eurasia convergence given by GPS and kinematic models (e.g,. Bougrine et al., 2019). Calais et al., (2003) propose that a change in Africa/Eurasia kinematic after 3.16 Ma may explain it. As discussed in DeMets et al. 2015, a recent (maybe younger than a few hundred thousand years) changes of kinematic can explain the discrepancy between long-term kinematic model and GPS data. Yet, it implies rapid changes in moments of forces that could be impossible.

We would like the referee to consider the following reasoning: any change of the Africa-Eurasia rates and directions of convergence that is recorded in the tectonic structures of the Alboran Basin must be recorded in similar structures within the Mediterranean Basin. Considering that Nubia is a rigid block, we argue that any changes (i.e,. period <5My) of Eurasia/Nubia convergence direction or important change in angular velocities must lead to a tectonic reorganization at the scale of the Mediterranean. Sedimentary basins must record such a tectonic reorganization. If indeed, some pieces of evidence of rejuvenation of vertical motion along East Mediterranean basins exist around the Mid-Pleistocene Revolution in the Eastern Mediterranean (Gawthorpe et al., 2018; de Gelder et al., 2019; Schattner, 2010), it is difficult to relate those changes to a change of Africa/Eurasia convergence. It is out of the scope of this paper to discuss if such reorganization exists at the scale of the whole Mediterranean Basin, and

if it exists, if it linked to plate tectonic, to change of slab behavior in the mantle or to climate change.

Some published and unpublished 3D numerical models (Le Pourhiet et al., 2014) demonstrate that, in a transpressive setting, main shear zones rotate until new better-oriented shear zones start to nucleate, as proposed from analytical models of blocks rotations (Nur et al., 1986; Ron et al., 2001). Following the Occam's razor principle, we assume that the tectonic reorganization in the Alboran basin occurring during the Pleistocene is linked to local tectonic evolution and rotation of the Alboran tectonic domain, rather than a change of kinematic. A similar model is also proposed from onshore field studies (Crespo-Blanc et al., 2016).

On the second point, we agree that the geometry of the model of Meghraoui and Pondrelli (2013) is far from being evident. Yet, their estimations are close to estimates of block rotation from other studies (Crespo-Blanc et al., 2016; Platt et al., 2003). The geometry of the right lateral fault is not to be demonstrated. A right-lateral strike-slip fault zone exists onshore in the Beti,c accommodating the extrusion of the Betic-Rif tectonic domain (Galindo-Zaldivar et al., 2015; Gonzalez-Castillo et al., 2015). The continuity of this right lateral fault zone toward the East is complex because it seems to form a triple junction with the Carboneras and Palomares fault zones. Its left lateral behavior is evidenced by GPS data (Galindo-Zaldivar et al., 2015). A right-lateral strike-slip structure occurs offshore further South, from the Adra fault zone to the Yusuf Fault and then to the Algerian Margin (e.g,. Estrada et al., 2018; Martínez-García et al., 2011). The northern segment of this structure is younger than 1.1Ma (Perea et al., 2018). On a regional scale, it draws a poorly continuous shear zone from the External Units in the Betic Belt to the Algerian Margin.

Furthermore, we agree with the referee, changes of body forces may have occurred. However, we must then examine the causes of such changes. A first change could be the Messinian Salinity Crisis. An isostatic response to the 1500m change of water level must have some consequences on the local tectonic. It is not clear how changes of vertical stress overtime in the lithosphere modify the local compressive tectonic and to our knowledge, this is not known. Another cause of change of body force can be upper-lithospheric mantle and/or lower crustal delamination associated to sinking lithospheric material (e.g. Calvert et al., 2000; Levander et al., 2014; Petit et al., 2015) and lithosphere tearing at STEP fault (Hidas et al., 2019). Slab rollback as the main driving force is likely to have ended or to be a considerably weak force during the Pliocene as the age of youngest evidence of accretion in the Rif is Upper-Miocene (Capella et al., 2016). Upper mantle and lower crust delamination can occur below the Betico-Rifian tectonic domain (Petit et al., 2015). It can influence the velocity field as demonstrated for thermomechanical modeling (Le Pourhiet et al., 2006), thought viscous coupling (Perouse et al., 2010; Petit et al., 2015). Regional-scale changes of buoyancy force through changes of coupling or delamination can indeed happen from the Pliocene, yet it would have produced a change of vertical motion pattern along the Rifian arc.

To our opinion, uplift and radial extension in the central Rif can evidence such a Pliocene change of body forces. It is possible that this mechanism contributes to the regional stress-field and to WSW-ENE extrusion of the Rif. In addition to the extrusion, body forces can contribute to the localization of the Al-Idrissi fault along an area of a strong gradient of crustal thickness. By decoupling the deformation across the Alboran Ridge, the inception of the Al-Idrissi Fault during the Quaternary zone can trigger a latter change of strain portioning and pure compression along the SAR and the NAR. It might be possible to demonstrate it by thin shell modeling. This is part of an ongoing investigation using the method described in Pérouse et al., (2012), and a complete discussion of this last mechanism is out the scope of the present paper.

I have other comments below: - The introduction part is full of unclear statements (i.e., lines 79-80, 81-82, 129-130, etc. . .), so that facts are often confused and mixed with interpretations. I recommend carefully check the reported assessments in order to clarify between what is established and what is an hypothesis. –

We agree with the referee. We modified the introduction to do a clear distinction be-

tween hypothesis and data.

The term "inversion" is systematically used throughout the paper; however, it appears that not only inversion is actually occurring, but merely reactivation, or tectonic reorganization. I urge the authors to distinguish a true tectonic inversion of structures (or of the margin) from other types of tectonic changes (for instance, from a strike-slip to an extensional strain change).

We agree with the referee. Indeed, we used the word inversion too often. We rephrase to avoid such terminology when needed. We would like to clarify the following point. The Alboran Basin is a fore-arc basin during the Miocene times (Duggen et al., 2008; Peña et al., 2018). The studied area is the southern termination of the WAB, which corresponds to the STEP fault. The exact geometry of this STEP when the slab-roll back slows down is yet not well known. This topic is the subject of a new paper already submitted to Tectonics. The tectonic reorganization described in this paper is, however, younger than the tectonic inversion that starts during the Miocene around 8Ma.

I also urge the authors to better highlight the new features and facts they bring compared to previous studies instead of speculating too much on a possible cause of strain re-organization.

We agree with the referee. According to referee 1 and to the referee 2, in the revised version, we propose a synthesis of the tectonic events in the Betico-Rifian arc and Alboran basin. This allows a better comparison with the recent papers published on the neotectonics of the Alboran Basin.

For instance, the clear change of strain pattern (both in tectonic style but also in strain expression) shown on Figure 9 between Pliocene and Quaternary is an excellent example of strain superimposition at short time scale on a same geological structure and deserves for instance a comparison with the well-expressed NW-SE set of diffuse, secondary faults identiïňĄed between the Carboneras fault and the north Alboran Ridge further north (Perea et al.,Marine Geology, 399, 23-33, 2018).

The referee is right. The dataset in Perea et al., (2018) allows proposing a timing of propagation of secondary NW-SE dextral strike slip faults of the Yusuf fault system, which fits well with our results. These authors propose that early Pliocene subsidence occurred in the Djibouti plateau. After a period of tectonic quiescence, strike-slip faulting starts during the Quaternary. The propagation of NW-SE strike-slip faults occurs around 1.1 Ma. It fits with our proposition that the inception of the deformation along the AIF is younger than 1.8 Ma and should start around with the rapid transgression of the shelf in the Nekor basin after 1.12 Ma. In our interpretation, fault localization along present-day active segments of AIF occurs after 0.8Ma (Lafosse et al. 2017). We modified the discussion according to the referee's comment.

- The role of volcanism in the tectonic evolution is only quickly mentioned but not enough discussed: in some way, the big and small Al-Idrissi volcanoes seem to play the role of "nucleation" points and to focus strain: is it what you suggest? How to explain the occurrence of such a volcanic activity during the major compressional phase?

The referee is right, yet following the comment of referee one, the length of our discussion is already too important. We suggest that poorly dated volcanism occurred in the Early-Pliocene. The volcanism could occur as a response to the crustal thinning (Duggen et al., 2008) or it could also be a response to changes of body forces after the Messinian Salinity Crisis (Sternai et al., 2017). Gravity anomaly interpreted as incipient faults in Galindo-Zaldivar, et al. (2018) could also correspond to underplated magmatic material following pre-existing tectonic corridors. Yet, we believe that this discussion is out of the scope of the present paper. We can hypothesis that local volcanism occurs in response to mantle delamination and to an early-inception of strike-slip faults. We can only conjecture that the volcanism localizes along tectonic features as in another context (e.g. the North Sea graben, Quirie et al., 2018).

How do you imagine to inïňĄll the syncline axis during folding (l. 300)?

We interpret that volcanic activity and the subsequent deposition of volcanoclastic sed-

iments are guided by the geometry of the fold NE-SW trend.

Why do you suspect the same age for volcano-clastic deposits and volcanics north of the Alboran Ridge (l. 302).

We suspect the same ages because the volcanism North of the Alboran Ridge, which seems to have similar chemistry than the samples studied in the Francesc Pages high, is dated from early Pliocene (Duggen et al., 2008). It corresponds to the stratigraphic age constraints that we have for the volcanism of the studied area. However, we agree that is speculative.

In Fig. 15b, you suggest subsidence initiation along the big Al-Idrissi volcano: is it linked to the syncline formation during folding?

We thank the referee for his remark. From our interpretation, the subsidence is linked to normal faulting. Before 1.8Ma, the basinward motion of the shoreline and the normal regressive geometry of the shelf argue for progradation driven by sediment supply. Sedimentation rates outpace the rates of relative sea-level rise (positive accommodation) at the coastline (Catuneanu et al., 2011). It is likely that the overall regressive trend is linked to positive accommodation space during syncline formation. However, the later Pleistocene transgression is clearly linked to the normal faulting. We modified the text according to the reviewer comments.

I have a problem to clearly identify the left–lateral deïňĆections of the hinge axis of the Pliocene folds (l. 235) in Fig. 10: it is not so obvious from your drawing. The differences between this structural sketch and the ones on Fig. 15a and 15b are large. This is important because this pattern is assumed to support the left-lateral transpression in the SAR.

We agree with the reviewer comment, interpretations of left lateral deflection of the hinge axis are difficult. However, we can simply show that Pliocene folds are oblique to the general N065° of the Alboran Ridge. To convince the referee, we can also compute from our drawing the azimuth of the hinge axis folds at each vertex (Figure 1 below). The resulting figure illustrates the change of orientation of the hinge axis. From analogue model experiments, oblique fold patterns occurred in transpressive/strike-slip shear zones (Richard, 1991). The amount of rotation evolves through time if a function of the mode of transpression (pure/simple shear, Fossen et al., 1994), as demonstrated elsewhere (Tadayon et al., 2018). In figure 15, we draw the simplified fold axis to help the reader.

Although the left-lateral transtension along the AIF is well evidenced, the southward propagation of the AIF toward the Nekor fault is claimed by the authors but not documented in their study: the role played by this propagation in the change of strain pattern in the area is not a new feature and has been already described in previous studies. For these reasons, I recommend publication after major revision.

We agree with the referee, and modify the text accordingly, by adding a table of the tectonic event at a regional scale. However, there is two recent papers demonstrating that the Al-Idrissi fault is recent (i.e. Pleistocene) feature (Galindo-Zaldivar et al., 2018; Gràcia et al., 2019) and one paper proposing a model explaining the strain pattern (Spakman et al., 2018). None of those papers proposes new pieces of evidence showing how the Al-Idrissi fault is different from the Trans Alboran Shear Zone in the SAR region. The Miocene to Quaternary tectonics in the NAR and Yusuf fault is described in Martínez-García et al., (2013) and (2017). We propose an age of the Bokkoya fault in Lafosse et al. 2017. To our knowledge, this paper is the first study integrating the data along the AIF and the SAR.

A rewriting of the manuscript is also necessary to improve the English and to address the many mistakes left behind (sentences without verbs or with two verbs, incorrect gram-mar, etc. . .; confusion between terms: compressive or extensive for compressional and extensional, register for recording, channels for drifts, mass transport complex for MTD with a complex internal structure, northern for western in Figure 14 caption,. etc).

We modified the text according to the referee's comments.

Figures must be logically presented and all line positions must appear on Figure 3.

We modified the figure accordingly.

A Table is also needed at the end in order to summarize the time line and main tectonic and volcanic events with respect to the main structures of the area.

We added the table according to the referee comment.

Figure 15 should clearly display opposite left-lateral double arrows and mention in Figure 15a the Nekor fault and the SAR.

We modified the figure accordingly.

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Fig. 1. : Azimuths of the hinge axis of the folds along the SAR area. Azimuths tend toward the E-W direction at the center of the folds and toward a N065 direction toward the tips of the folds, therefore demonstrating the left lateral deflection. Computations of the strike of the folds hinge axis are done using MatLab.