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Solid Earth Discussions

Interactive comment on "Spatial evolution of Zagros collision zone in Kurdistan – NW Iran, constraints for Arabia–Eurasia oblique convergence" *by* S. Sadeghi and A. Yassaghi

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I would like to thank Dr. P.B. Ballato for his thorough and constructive review of this manuscript. We found his comments very useful in improving the content of the MS. Below, please find reply to the comments which he had raised during the review of the MS. For convenience; the corrected parts of the manuscript are highlighted using track changes and its file is also attached as aux. file.

General Comments:

1) The concept of strain partitioning should clarified (please see my comment on Page

2736, lines 10-11), because it sounds different from that one commonly used in the literature (at least to me). Reply: The concept of strain partitioning is addressed in replies to comments: Page 2736, lines 10-11; Page 2746, line 14; Page 2746, line 15; Figure 8.

2) The relative chronology of dip and oblique slip in the Radiolarite zone with respect to the two dominant deformation processes (obduction and collision) are poorly constrained (please see my comment on Page 2746, line 14). Reply: As replied to comment Page 2746, line 14, the early stage structures (related to obduction, discussed in section 5.1) developed in Late Cretaceous as transpressional deformation which is partitioned in Radiolarite zone between two different dextrally deformed and reverse domains while in the Bisotoun and NE margin of the Radiolrite zone they developed as dextral-reverse faults. The late stage strike-slip faulting occurred in late Tertiary (e.g. the Mrekhil-Ravansar fault system) cut the early structures across the Radiolarite and Bisotoun zones are proposed as collision zone related structures (discussed in section 5.2).

3) The way the balanced cross section was constructed needs to be better explained (e.g., how did you get the length of the Radiolarite Basin; please see comment on Page 2744 on lines 25-26 and following page). The implications of that section should also be discussed; for example what can we learn from those numbers? Reply: Explanation as to construction and restoration of the cross section is presented in reply to comment Page 2744 (lines 25-26) and page 2745 (lines 1-3). Implication of the x-section construction and restoration is given to sections 5.1 and 5.2 and also in conclusion section. It is explained that more than 79% of the shortening is occurred by obduction related to the Early stage of deformation in Late Cretaceous and only 16.5% of the shortening is due to the effect of the Late Tertiary.

4) A broader vision of the topic is missing; including it could lead to a more solid manuscript, which may be cited by other people working in different mountain belts; in other words what can we learn from your study area that could be exported in other

regions? Reply: A broader vision of this manuscriptthat that is mainly focused on Iranian Kurdistan part of the Zagros is for the Arabia–Eurasia oblique convergence during all stages of Zagros orogeny since the Late Cretaceous. This is constrained by the Neo-Tethys reconstruction since Middle Jurassic. This proposition is added to the last sentences of the section 5.3.

5) The language needs to be really improved. Reply: The MS language is improved through English editing by Professor Ferguson (that is greatly acknowledged) as the other reviewer.

Specific Comments:

Comment: Title: You address both spatio and temporal evolution but the title you report only "Spatial". The other point is that I will replace collision zone with suture zone, because collision would imply a larger area (basically from the Caucasus to the Zagros). Reply: Though we used structural relations to differentiate obduction related structures from the later one (e.g. the Marekhil-Ravansar fault system), but since no quantitative data as to temporal evolution of the structures are presented therefore the term " temporal" is not used on the title. As to replacement of the term "collision zone" we would like to emphasis though the collision zone can be used for the whole Arabia-Eurasia, but we have shown that we are working on Zagros part of collision zone in the Kurdistan. If we use suture zone it only refer to small zone between the internal and external parts of the Zagros orogeny, but our study covers areas from both parts.

Comment: Page 2736, lines 10-11, what do you mean with partitioning? To me oblique slip on a fault is not partitioning; strain partitioning occurs when oblique shortening is accommodated through dip and strike slip either on the same fault or on adjacent faults. Please have a look at the paper of Jackson et al., (Geoph. J. Int., 2002). Reply: The sentences are rewritten to remove its writing style problem that causes misunderstanding of the readers. The main purpose of this paper is to show oblique convergence in both Radiolarite and Bisotoun zones. This oblique convergence in

radiolarite zone is partitioned into dextral and reverse domains whereas in Bisotoun domain is occurred along dextral-reverse faults. Comment: Page 2736, lines 18-19, According to plate tectonic reconstructions (McQuarrie et al., Geoph. Res. Letter, 2003) from at least ca. 56 to 20 Ma, plate convergence vectors should have been perpendicular to the plate margin (you may also check out the recent update published in McQuarrie and Van Hinsbergen, Geology 2013). Please verify it. Reply: lines 18-19 in page 2736 are rewritten upon the suggested references in the comment.

Comment: Pages 2736, (line 25) and 2736 (lines 1-2), You may be more precise about the supposed timing of the continental collision (even reporting different opinions). Cenozoic is a long period (65 Myr) and I guess that the ïňĄrst half of it can be easily excluded; about the citations, a lot of work has been done from different authors in the last years; for example N. McQuarrie has reviewed her previous work publishing an updated version in 2013 (McQuarrie and Van Hinsbergen, Geology 2013). Reply: lines 25-26 in page 2736 and lines 1-2 in page 2737 are rewritten upon the suggested references in the comment

Comment: Page 2738, lines 12-14, It is ïňĄne to use new terms but they should not confuse readers; for example the term collision zone is generally thought to include the entire zone from the Caucasus to the suture or the Zagros Fold and Thrust Belt; I would suggest to use a different name for the Sanandaj-Sirjan, Gaveh rud etc... zone (for example some authors used the name "crush zone", but I am not sure if it applies here). Reply: the used terms" Sanandaj-Sirjan, Gave Rud etc." are well known for Zagros in the literature. Therefore as the reviewer is also concern the word "crush zone" might not apply for the study area that covers the Zagros suture zone and some parts of its external and internal.

Comment: Page 2738, lines 15-17, I suppose that with "accumulated" you imply "tectonic emplacement" Please verify it. As it is one could interpret it in terms of sedimentary processes (i.e, sediments accumulation). Reply: in lines 15-17 in page 2738, the term "accumulate" is replaced by the term "emplaced".

Comment: Page 2738, lines 19-23, In which kind of sedimentary basin, the Gaveh Rud unit is thought to be deposited? What is the depositional age of these volcaniclastic deposits? It may be good to mention brieïňĆy for readers that are not familiar with the geology of the Zagros. I would also refer to the paper of Agard et al., (International Journal of Earth Science, 2005. Reply: in lines 19-23 of the page 2738, explanation as to tectonic setting of the Gave Rud unit within the Zagros is added to the text as suggested.

Comment: Page 2738, lines 19-23, Not clear; as it is it seems that the Sanandaj-Sirjan zone accommodated signiïňĄcant Cenozoic collisional deformation. Is that the case? I also doubt that we could call the Sanandaj Sirjan zone the metamorphic core of the Zagros; if you look at mountain belts like the Alps where you have metamorphic rocks in the axial zone, you will see that these rocks experienced signiïňĄcant exhumation during orogenic processes (most of them experienced HP or ultra HP metamorphism). Exhumation in the Sanadaj Sirjan zone does not seem to be the case, and the age of metamorphism appears to be pre Jurassic or so, except few localized area where core complexes are thought to have developed during the Cenozoic, most likely before continental collision (and in that case rock cooling and uplift will be associated with tectonic denudation with little contribution of erosional exhumation; see Verdel et al., GSA Bull 2007). Reply: We agree with the reviewer that the Sanandaj-Sirjan zone does not show extensive evidence of “HP or ultra HP metamorphism” and this study is not going to discuss on the metamorphic process and its exhumation in the zone, thus we removed the term “metamorphic core” that is driven from the literature and then we rewritten the sentence.

Comment: Page 2739, lines 3-6, In which unit is the basal decollement and where are the intermediate decollements; It may be worth mentioning it. Reply: The sentence is reworded to show the differences in the type of the basal decollements in the Lorestan and Dezful Embayment as well the absence of the Middle decollements (e.g. Dashtak Formation) in the Southern part of the Dezful Embayment.

Comment: Page 2740, lines 25-27, I found this sentence a bit disconnected, especially in a section entitled "Stratigrahy of the Zagros collision zone"; please explain it better or move it for this section. Same for the ïňĄgure. Reply: The sentence is reworded to provide better explanation as to presentation of the growth strata in Campanian-Maastrichtian rocks of the Gurpi Formation that is used to show the effect of this event in the study area as this event is also constrained (by Karim et al., 2011) in Iraqi Kurdistan.

Comment: Page 2744 (lines 25-26) and page 2745 (lines 1-3), How did you estimate the distance between L2 and L3, which is basically the length of the radiolarite basin? That estimate will have a profound impact on your total shortening. As you wrote above the line-length technique cannot be applied there, probably because you miss cutoff angles in footwall and hanging wall. Please provide an explanation for that estimation. Reply: explanation as to estimation of the shortening in the Radiolarite zone using area balancing and as to sedimentary cover and Bisotoun zone using line-length balancing are added to the text. Remind here that area balancing is done using depth of basement and exposure of the Radiolarite zone from the cross section as well as the zone thickness from its stratigraphy in the literature.

Comment: Page 2745, lines 23-25, Did we have subduction until late Miocene? I think that more recent publications pointed out that subduction should have lasted until Early Miocene (20 Ma; and possibly earlier). You may check out more recent publication of the three authors you mention here (among others) like: Allen and Armstrong, 3P 2008 Mouthereau et al., Tectonophysics 2012 McQuarrie and Von Hinsbergen Geology 2013 Reply: Timing of the subduction upon the recent publications is corrected and more recent publications are replaced with the old one as suggested.

Comment: Page 2746, line 14, The Radiolarite zone has experienced Cretaceous (obduction related) and Tertiary (collision related) deformation. You nicely show that strike-slip faulting is younger than thrust faulting. However it is not clear to me if these thrust faults in the Radiolarite Zone accommodated only transpressional (oblique slip) or also

dip slip (pure thrusting) deformation and when (Cretaceous or Tertiary)? For example, if you had only transpressional deformation in the Cretaceous I would totally agree with the oblique obduction. On the other hand, if you had both oblique and dip-slip, how can you say that oblique motion (transpressional deformation) has occurred only in the Cretaceous while pure thrusting must reïňĆect a more recent regime (Tertiary)? For the moment I am sure if you are reporting convincing data that could help in establishing a chronology of dip and oblique slip. Please clarify it A way to distinguish the kinematic regime associated with the obduction from that one associated with collisional deformation, could be to look at deformation processes in the Gaveh Rud; this unit is younger than Cretaceous and hence should have recorded only collisional deformation. Reply: In late Cretaceous, the oblique convergence in the Radiolarite zone occurred as two different dextrally deformed and reverse domains which show partitioning of oblique convergence in parallel side domains (Fig.8b). In the Bisotoun zone and NE margin of the Radiolrite zone, however, the oblique convergence is shown by development of dextral-reverse faults. Thus, the oblique convergence as stated in the comments occurred in the late Cretaceous as transpressional deformation which is partitioned in Radiolarite zone between two different dextrally deformed and reverse domains while in the Bisotoun and NE margin of the Radiolrite zone it developed as dextral reverse faults. We have to emphasis that late stage strike-slip faulting occurred in late Tertiary (e.g. the Mrekhil-Ravansar fault system) and cut the early structures across the Radiolarite and Bisotoun zones.

Comment: Page 2746, line 15, My understanding of partitioning is different. Please see comments in the Abstract: strain partitioning occurs when oblique shortening is accommodated through dip and strike slip either on the same fault or on adjacent faults. Please have a look at the paper of Jackson et al., (Geoph. J. Int., 2002). Reply: As replied to the last comment, partitioning of oblique deformation in the Radiolarite zone is accommodated on two adjacent reverse domain (as dip slip) and dextral domain (as strike slip). However, in the Bisotoun zone this oblique convergence occurred along dextral-reverse fault (both dip and strike slip) on the same fault. Thus, Partitioning of

oblique deformation is only occurred in the Radiolarite zone.

Comment: Page 2748, line 8, Why late stage of orogeny? Do you mean early stage? Reply: Thanks to the reviewer attention, the text is corrected.

Comment: Page 2748, line 12, You should check out plate tectonic reconstructions and include them in the discussion. Reply: References as to plate tectonic reconstructions are included to the last sentences of section 5.3.

Comment: Page 2748, lines 16-18, This point is not really discussed in the manuscript; it is cited but not discussed. If you consider it as one of your major conclusions it should be documented before. Reply: This point is somehow addressed in the first paragraph of section 5. To have similar wording in both discussion and conclusion, the conclusion section is rewritten.

Comment: Page 2748, lines 19-21, Please see my comment above on chronology of faulting in the Radiolarite zone. Reply: Reply to this comment is presented in replies to comment Page 2746, line 14 as well as to comment Page 2746, line 15.

Comment: Page 2749, lines 1-4, Please see my comment on shortening estimates. Reply: As stated in reply to comment Page 2744 (lines 25-26) and to comment page 2745 (lines 1-3), estimation of the shortening in the Radiolarite zone is done using area balancing. Remind here that area balancing is done using depth of basement and breadth of the Radiolarite zone from the cross section as well as the zone thickness is estimated from the literature. Explanation as to this is added to the relevant section.

Comment: Figure 2: What is the color for the Qom Formation? The scale in the middle of the ïňĄgure does not look nice; why do not put it on a corner (for example the NW one?) Reply: The color of Qom Formation is corrected and the scale bar is replaced as suggested.

Comment: Figure 3, I would probably add the orientation of these stratigraphic Sections (SW-NE from left to right or?) Adding a ïňĄfth column on the left showing the

stratigraphy of the Sanandaj-Sirjan Zone may be also useful. What is the meaning of the colors? Please explain in a legend or in the ïňĄgure caption. Reply: The orientation of stratigraphic sections (SW-NE from left to right) is added to figure 3. As replied to comment Page 2738, lines 19-23, the deformation of Sanandaj-Sirjan zone does not addressed in this study, thus we prefer not to present its stratigraphic column. The colors of the stratigraphic section are presented in order the readers more easily differentiate an correlate the rock units in different columns.

Comment: Figure 7: I suppose that the 3 black great circles are fault planes with associated sense of motion. Do they represent the major fault zone (for example in different locations), or are they different planes? Please clarify. The read great circle represents the mean direction of the High Zagros fault zone in your study area? Please write it down in the ïňĄgure. On how many measurements are based the arrows showing the fault kinematic of the red plain? It may be good to know it, to have the ïňĄlling on the robustness of these kinematic data. Reply: the stereogram is refined to show more clear information as to the kinematics of the High Zagros fault zone. The read great circle represents the mean direction of the High Zagros fault zone. The numbers of measurements are also added to show quantity of the data. Caption to the figure is also rewritten.

Comment: Figure 8, I am not sure if I understood correctly what you mean with "kinematically different domains". From what I can see on ïňĄgure B you considered folds as result of shortening (dip or oblique slip?) and strike slip faults as result of a wrenching tectonic (pure strike slip?). Are these conclusions just based on the pattern of structures on map view or is part of your results? What is the sense of motion of those faults that do not have strike-slip symbols but are located next to your black arrows? Please clarify it. Reply: As replied to comment Page 2746, line 14, the figure 8 shows partitioning of dextrally deformed domains (pink) and reverse domains (violet) in the Radiolarite zone during oblique convergence. The kinematics of these domains are not concluded “just based on the pattern of structures on map view” but interpreted

using minor folds (stereograms on Fig.11a and b for kinematics of dextral domains, while Fig.11-c for kinematics of reverse domains). In response to the comment stated as “What is the sense of motion of those faults that do not have strike-slip symbols but are located next to your black arrows?” this is to clarify that this faults are late stage strike-slip faults that are printed on the earlier dextrally deformed and reverse domains. For better explanation on kinematics of the early structures, Fig 8.b is refined to show only kinematics of the early stage structures.

Comment: Figure 9 What is the meaning of the green area? Different unit? Reply: The green area remover from the Figure.

Comment: Figure 11, I am not sure if the stereoplot of ïňĄgure A shows layer parallel shearing; the fold axis is perpendicular (trend of line NNE) to the shear plane (strike of plane WNW); that means that the shear planes are perpendicular to the fold limbs. Or? Moreover, in the text you write: “plunging inclined folds (Fig. 11b) and reclined folds (Fig. 11a) in the dextrally deformed domains and horizontal inclined folds (Fig. 11c) in reversely deformed domains.” I am wondering if the fold of ïňĄgure C can be deïňĄned as "horizontal inclined" considering that the axial plane is dipping to the NE and is not vertical. To me it would be plunging inclined like ïňĄgure B. In case you may argue that ïňĄgure B is closer to "horizontal inclined" giving that the axial plane could dip ca. 80 to the NNE. Reply: Fig.11 presents the kinematics of dextral and reverse domains in the Radiolarite zone. The presence of spectacular minor folds in this zone provides constrains for kinematics of these domains. In the stereoplot of ïňĄgure A, reclined folds (both fold axis and axial plane are inclined), the trend of fold axis is perpendicular to the trend of the shear direction but the trace of axial plane is parallel to the trend of shear direction and also parallel to the trend of bedding (refer to part A of the attached 3D sketch). Thus, it shows strike-slip kinematics or in the Radiolarite zone dexterally deformed domain. However, in the stereoplot of ïňĄgure C, horizontal inclined fold (fold axis is horizontal but axial plane in inclined), drawn for the reverse domains, the domain is deform reversely and the fold axis

and the trace of axial plane are parallel to the trend of bedding but perpendicular to the shear direction (refer to part C of the attached 3D sketch). In the stereoplot of ïňĄgure B, plunging inclined fold (fold axis is plunging and axial plane in inclined), is closer to the Stereoplet of figure A and thus interpreted for dexteral reverse domains.

Please also note the supplement to this comment:
http://www.solid-earth-discuss.net/7/C1724/2016/sed-7-C1724-2016-supplement.zip

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