Solid Earth Discuss., 7, C307–C314, 2015
www.solid-earth-discuss.net/7/C307/2015/

Solid Earth
Discussions
Open Access

Interactive comment on "Tectonic evolution and high-pressure rock exhumation in the Qiangtang Terrane, Central Tibet" *by* Z. Zhao et al.

Z. Zhao et al.

zhongbao.zhao@ifg.uni-tuebingen.de

Received and published: 30 March 2015

We thank the reviewer for the comments and suggestions. Our reply is given first (in blue) and changes to the manuscript are listed at the end of this reply.

1. Comments and replies

'(1) The new idea of this paper is the southward oceanic subduction under the SQT terrane around 240 Ma, which stopped after a certain time, and then reverse the movement. Based on most of the data, the evidence for this is not very convinced. The melt activity may be mainly related to the slab breakoff as many previous authors suggest. If the authors of this ms want to continue using this model, I suggest write an independent section/paragraph to summarize and highlight the evidences for this short

southward subduction.'

All authors in favour of an ocean between NQT and SQT agree on northward subduction underneath the NQT. Fewer authors have mentioned a possible slab that subducts southwards underneath the SQT. This was already suggested by Sengör et al. (1988) and explicitly proposed by Liu et al. (2011, their fig. 11), based on the occurrence of Late Permian to Triassic andesites and dacites in both the NQT and SQT (Zhai and Li, 2007; Wu and Lang, 1990). A problem, of course, is that large areas of the SQT are covered by Jurassic and younger deposits. The evidence for arc magmatism that indicates northward subduction underneath the NQT was given on page 342, beginning of section 3.5.

'(2) Another main problem I am concerning is that the proposed model is kind of very artificial, especially for the transition from single to double subduction, and then changed back to single subduction again (Fig 6a-c). What are the conditions for the first transition, from single to double? I can imagine that the increase of plate push may contribute in a certain degree. Otherwise the slab pull driven subduction is almost impossible to evolve like those shown in Fig 6b.'

Although modern and fossil cases of double divergent subduction zones are known (and cited in the text), they have received relatively little attention in the literature. There is, therefore, to our knowledge no general theory on the formation of such systems. One possibility is that there is subduction on both sides of a spreading ridge (common scenario) after which the (deactivated) ridge is subducted. As soon as there is no spreading between the two sutures, they must converge by rollback. Another mechanism could be that a subduction zone becomes curved leading to subduction in opposite directions in a 2D cross section. This requires significant rotation of sections of the subduction zone relative to each other, for which there seems to be no indication in case of the Qiangtang terranes.

'I am also quite curious about the conditions discussed in the manuscript for the second transition: the larger slab pull from longer slab that contribute to pull the shorter subducted slab returning back. Since the shorter southward subduction under the SQT terrane is a key character of the proposed model, used for the explanation of HP rocks formation and exhumation, thereby, could you try to discuss the conditions of this in more details, although I understand it may be difficult.'

A full discussion of the conditions leading to slab extraction would indeed be difficult, as it requires a full manuscript, which is actually in preparation. Two diverging subduction zones without a spreading ridge in between exert mutual slab pulls. As long as the sutures are far apart, friction will dissipate these forces and the two subduction zones roll back independently. This inevitably leads to the two converging to a distance where they each "sense" the other's pull. If the two forces are equal, the net remaining force leads to further convergence and finally collision of the overriding plates. However, in case of distinct asymmetry, one pull will increasingly dominate, leading to the shortest subducting plate being pulled up by the other, as we envisage. The lack of evidence for strong arc activity in the SQT is an indication that the southward subducting slab was not very well developed, possibly because it formed later. Another possibility is slab break-off, which would suddenly shorten one of the slabs. This appears to be currently happening with the Adria plate underneath central Italy. It should be noted that we do not pretend to have direct evidence for the southward subducting slab. However, we invoke it, as it is to us the most plausible mechanism to high-pressure rocks in contact with non-metamorphic sediments and mélange. This aspect is now highlighted more in reply to the suggestions by the first reviewer.

'(3) As discussed in the manuscript, there are mainly two previous models for the HP rock in central Qiangtang terrane: southward underthrust model by subduction in the JSS suture, as well as northward subduction in the Shuanghu suture. For the second model, you show one problem (Line 515-518) which is from Kapp etal, who is the proposer of the first model. Are there any other problems for the second model? Or your model just solved the problem, proposed by Kapp et al for the second model,

by adding a short southward subduction in a certain period of the main northward subduction? Could you compare your model and the previous two models.'

One problem with publications on northward subduction underneath the NQT ("second model") is that they do not clearly specify a mechanism for the exhumation of high-pressure rocks, because they are mostly based on igneous rocks as evidence for northward subduction. The main argument against the rather vague exhumation mechanism is that it requires major erosion and sedimentation, as was already pointed out by Pullen and Kapp (2014), which we therefore cite.

'(4) A key debate in this region is the existence, or not, of an ocean between north and south Qiangtang terrane. Are there any geological evidences for the subduction related Arc and back-arc system around the Shuanghu suture? Could you give some discussion on this?'

This was addressed in section 5.2, but perhaps too briefly. We extended section section 5.2 to address this.

'(5) Figure 1 included many data. They are from your own, or others. It is better to show clearly in the captions. Same for Figure 2.'

Both in figures 1 and 2 we have now added references to the data shown in these figures.

'(6) Section-3.2: After late Triassic, the NQT and SQT joined together. Therefore, the stratigraphic groups after that may not be needed to describe separately.'

The reviewer is correct here. However, the terms NQT and SQT are still useful as a geographic reference frame, which is why we maintain the use of these terms even after assumed amalgamation of the terranes. It is also useful, as there are distinct trends from south to north in terms of sedimentation/volcanic activity and onset of sedimentation. We therefore prefer to keep the section as is. We added the text "Amalgamation of North and South Qiangtang terranes" to figure 2, to highlight the moment where the two terranes joined.

'(7) The conclusion is very long, with many details already discussed in the main text. Could you shorten it and highlight the main ideas.'

We have almost completely rewritten and shortened the conclusions

'(8) Line 120-121: the age of suture zone closing AND exhumation of the high-pressure rocks; Do they have the same age? It seems not consistent with that discussed in the references.'

The zircon U-Pb ages of volcanics on the southern margin of the NQT range between 216-205 Ma (Zhai et al., 2013a; and references therein). As these authors note, this age range overlaps with the 40Ar/39Ar ages (222-203 Ma, Kapp et al., 2000; 2003b; Zhai et al., 2013a) of white mice in HP-rocks, interpreted as the age of retrogression of eclogites, and hence their exhumation. So yes, the ages are, within resolution, roughly the same.

'(9) The ms should be polished more carefully in order to fix small errors (not only as I show):' We apologise for this and carefully corrected the whole manuscript.

2. Changes made to manuscript

p. 342, after line 27, insert: Whereas abundant arc-related Permo-Triassic activity is documented in the NQT, relatively little evidence for such activity is documented in the SQT. Wu and Lang (1990) reported Late Permian andesites and dacites in the SQT, which led Liu et al. (2011) to propose both subduction to the north underneath the NQT, but also to the south underneath the SQT.

p. 348, lines 13-16 replaced with: Most authors invoke Permo-Triassic arc-related igneous activity, mainly in the NQT, as evidence for the former existence of the Shuanghu-Tethys between the NQT and SQT (Peng et al., 2014; Yang et al., 2011; Zhai et al., 2011a; Zhang et al., 2013). With few exceptions (Q, Wang et al., 2008), these authors interpret the igneous activity to result from northward subduction of this

ocean underneath the NQT. Further indications for a former ocean between the NQT and SQT are the ophiolitic mélange and high-pressure rocks with oceanic affinity (Zhai et al., 2007; 2013a) in the SQT.

page 349, add after line 4: If, as argued here, the mélange and high-pressure rocks were not exhumed by core complex-like doming, their presence within the SQT is difficult to reconcile with any model other than the former presence of an ocean between the NQT and SQT.

p 349, lines 6-9, rewritten to: The presence of high-pressure rocks is one of the arguments to invoke subduction to the south or north of the NQT. The southward underthrust model of Kapp et al. (2003b) provides a clear mechanism of exhumation of the high-pressure rocks: metamorphic core complex-like doming. This requires all mélange to have experienced high-pressure conditions, which contradicts our findings. The sequence of basement rocks at the base, overlain by ophiolitic mélange and high-pressure rocks, sedimentary mélange and sediments cannot be reconciled with the proposed exhumation in a core-complex, in which the autochtonous basement rocks should lie above the mélange.

p. 349, add after line 17: Exhumation of high-pressure rocks in the orogenic wedge also does not explain how the high-pressure rocks are brought into contact with non-metamorphic sediments and sedimentary mélange as is observed in the Rongma area.

p. 349, add after line 26: A key observation that needs to be explained is that the exhumed high-pressure rocks were brought into direct contact with originally overlying non-metamorphic sediments and mélange.

p. 351, lines 9-13, replace with: As long as the two sutures are far enough apart, each operates independently from the other. In the absence of spreading in between, the two sutures must converge by rollback. This inevitably leads to the two sutures converging to the point where the slab-pull of one subduction zone starts to affect the other. At some point in this scenario, the slab pull of the long (northern) slab will override the opposite pull of the short (southern) slab, which results in the short one being pulled up and towards the north (Fig. 6c). This scenario is similar to the current situation of the Adria plate,. . .

Section 6, Conclusions, rewritten and shortened to: Subduction mélange and high-pressure rocks in the Qiangtang Terrane record an important stage in the evolution and formation of the Tibetan Plateau, which has consequences for the location of different former oceans. Our mapping and structural analysis of the Rongma area in the centre of the metamorphic belt leads to the following main conclusions: 1. The North and South Qiangtang terranes were formerly separated by an Ordivician-Triassic ocean. 2. Metamorphism in the Central Qiangtang Metamorphic Belt occurred in two unrelated stages. The first, lower greenschist facies event occurred in Pre-/Early-Ordovician times and affected the Precambrian basement. A second event produced the high-pressure rocks that exhumed in the Triassic as a result of the closure at the Longmu Co-Shuang Hu suture zone between the North and South Qiangtang terranes. 3. The pre- to syn-collision lithologies (>210Ma) can be grouped into three main units: (1) Carboniferous and older basement, (2) non-metamorphic ophiolitic meÌĄlange, and (3) non-metamorphic sedimentary meÌĄlange with large rafts and sheets of non- metamorphic Permian sediments and high-pressure rocks (mostly blueschists). 4. To explain the current structural relationships of the units, we propose that the high-pressure rocks were exhumed by extraction of a short south-dipping slab from underneath the South Qiangtang terrane, bringing them in contact with the sedimentary meÌĄlange and Permian margin sediments. This unit was subsequently thrusted on top of the ophiolitic meÌĄlange. Upon final collision of the North and South Qiangtang terranes, both units were placed on top of the Paleozoic South Qiangtang basement. The whole tripartite stack was subsequently further shortened into a south-verging fold and thrust belt. This may have been a consequence of the amalgamation of the two terranes, or later (Jurassic–Paleogene) events. 5. After closure of the Longmu Co-Shuanghu suture zone, Upper Triassic sedimentation commenced in the south in a foreland setting and progressively extended to the north where extensive bimodal volcanic activity

occurred, which is interpreted as the result of mantle upwelling due to the final sinking of the paleo-Tethys slab. This study is based on a large study area in the centre of the Qiangtang terrane, which, however, extends over almost 2000 km. We hope that this study encourages more work, including detailed mapping and structural analysis, in the whole terrane to confirm or reject the former presence of an ocean between the North and South Qiangtang terranes, as well as investigate the consequences in terms of presence and size of other oceans between the various terranes that form the Tibetan Plateau.

references added: Şengör, A., AltÄśner, D., Cin, A., Ustaömer, T., and Hsü, K.: Origin and assembly of the Tethyside orogenic collage at the expense of Gondwana Land, Geological Society, London, Special Publications, 37, 119-181, 1988.

Added at end of Figure 1: Numbers in brackets refer to the following references: (1) Li et al. (2007); (2) Zhai et al. (2010); (3) Zhai et al. (2013b); (4) Wang et al. (2008); (5) unpublished data; (6) Zhai et al. (2009); (7) Zhao et al. (2014); (8) Kapp et al. (2003b); (9) Zhu (2005).

Added at end of Figure 2: Sources: (1) Li et al. (2007) and (2) Wang et al. (2008).

Interactive comment on Solid Earth Discuss., 7, 329, 2015.