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REPLY

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This article is a reply to a comment by Chen et al. (2018), https://doi.org/10.1029/2018JB015536.

Key Points:

- Early Cretaceous *ophiolite*, *seamount*, or *oceanic plateau* are vaguely defined, and their crystallization ages are poorly constrained
- Latest marine deposits across the suture zone are quite younger than the initial collision age
- Arc-related magmatic rocks do not necessarily form in a continental arc; paleomagnetic constraints are mutually conflicting

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Reply to Comment by W.-Y. Chen et al. on "Sedimentary and Tectonic Evolution of the Southern Qiangtang Basin: Implications for the Lhasa–Qiangtang Collision Timing"

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1. Introduction

We thank Chen et al. (2018) for their critical comments on our recent publication, which provides us an opportunity to further discuss our preferred sedimentary and tectonic scenario of the Jurassic southern Qiangtang basin and Bangong-Nujiang suture zone. Chen et al. (2018) use evidence from ophiolites, marine successions, arc-related magmatism, and paleomagnetism to argue that the Bangong-Nujiang ocean did not close until mid-Cretaceous time (~100–90 Ma), thus challenging our preference for Middle Jurassic Lhasa-Qiangtang initial collision at ca. 166 Ma (Ma et al., 2017). Chen et al. (2018) propose that this early event (ca. 166 Ma) was related to subduction of oceanic highs. This is disfavored by Ma et al. (2017) because magmatism, uplift of forearc floor, and recycling of older forearc strata, which are held to be associated with flat subduction induced by subduction of oceanic highs (see a review by Ridgway et al., 2012), were not recorded in the southern Qiangtang basin (Ma et al., 2017). In this Reply, we check all of these pieces of evidence reported by Chen et al. (2018) separately and eventually conclude that their provided observations do not prove the existence of a Cretaceous Bangong-Nujiang ocean and do not invalidate our preferred scenario of Lhasa-Qiangtang initial collision in the Middle Jurassic.

2. Discussion

2.1. Ophiolite Complexes

Chen et al. (2018) maintain that widely reported Upper Jurassic-Lower Cretaceous ophiolite fragments from the Bangong-Nujiang suture zone indicate that the Bangong-Nujiang ocean was wide open in the late Early Cretaceous. This claim may be countered as follows.

First, *ophiolite*, *seamount*, and *oceanic plateau*, actually consist of an association of igneous and sedimentary rock types, including at least gabbro, diabase, basalt, and chert, are too vaguely defined in the Comment and articles cited therein. Besides mid-ocean ridge and oceanic interior settings preferred by Chen et al. (2018) in the Comment, mafic rocks can form in diverse tectonic settings, such as intraplate and arc settings. Chert can be deposited on oceanic crust (preferred in the Comment) or on continental crust (McBride & Folk, 1979) in deep water, so its age constrained by radiolarian biostratigraphy should not be considered as ophiolite formation age if its contact with ocean floor basalt is unclear. The ocean island basalt (OIB)-like mafic rocks, extending for about 800 km along the Bangong-Nujiang suture zone from west to east, display positive Nb–Ta anomalies. Provided they are indeed Early Cretaceous in age (ca. 132–108 Ma; Bao et al., 2007; Fan et al., 2015; Zhang et al., 2014; Zhu et al., 2006), they can be interpreted to result from the upwelling-enriched asthenosphere due to oceanic slab break-off beneath the Bangong-Nujiang suture zone after Lhasa-Qiangtang collision (Zhu et al., 2016). This interpretation is consistent with the conclusion of a thickened crust after closure of the Banggong-Nujiang ocean (P. Hu, Zhai, et al., 2017), which is supported by Lower Cretaceous felsic plutonic and volcanic rocks occurring within the Bangong-Nujiang suture zone in Dongqiao, Nima, and Gaize (P. Hu, Zhai, et al., 2017; Kapp et al., 2005) and by continental red beds in Nima and Gaize (Kapp et al., 2005).

Second, we are doubtful about the validity of crystallization ages of mafic rocks listed in the Figure 1 in Chen et al. (2018), as constrained by zircon U–Pb dating and mineral or whole rock $^{40}Ar/^{39}Ar$ dating. Zircons of the

Early Cretaceous ages reported by Bao et al. (2007), Liu et al. (2014), and Zhu et al. (2006) show narrow bands of oscillatory zoning in cathode-luminescence images (Figure 5 on p. 665, Figure 5 on p. 434, and Figure 4 on p. 1317, respectively). The thin zoning in cathode-luminescence images is typical of zircons crystallizing from felsic rather than from mafic igneous lavas, because the latter contains crystallizing zircons of broader bands (Rubatto & Gebauer, 2000). And in the Zhonggang oceanic island, the foreign zircon ages older than the Cretaceous occupy 74% in number and display multiple peaks (Fan et al., 2015). This fact indicates contamination of continental crust materials and cannot reconcile with the truth of an oceanic island which is too far away from continent crust to be contaminated. Chen et al. (2018) cited Xu et al. (2014) to support the existence of an Early Cretaceous open Bangong-Nujiang ocean, but the sample was collected in the Shiquanhe-Yongzhu-Jiali ophiolitic belt rather than in the Bangong-Nujiang suture zone (Xu et al., 2014).

As far as $^{40}Ar/^{39}Ar$ ages are concerned, they reflect cooling of the rock below the closure temperature of the K–Ar isotope system (usually lower than 550 °C). Therefore, the $^{40}Ar/^{39}Ar$ ages cited in the Comment (127–110 Ma; whole rock, plagioclase, or clinopyroxene ages; from basalt, plagiogranite, or gabbro) cannot be certainly interpreted as crystallization ages of the host rocks (crystallization temperature usually higher than 600 °C) without discussion, especially considering that several major felsic magmatic events occurring along the Bangong-Nujiang suture zone during the Early Cretaceous (e.g., 118–113 Ma in Dongqiao reported by P. Hu et al., 2017; 116–107 Ma in Gaize reported by Kapp et al., 2005) have with all likelihood reset the K–Ar system. The radiolarian data collected by Chen et al. (2018) are taken directly or indirectly from the 1:250,000 geological-mapping report. Neither photos of radiolaria, stratigraphic contacts, nor Global Positioning System coordinates were provided, which makes these data far from convincingly documented.

2.2. Latest Marine Strata

Chen et al. (2018) suggest that the Lhasa and Qiangtang blocks did not collide until the late Early Cretaceous based on the reported mid-Cretaceous marine succession in the southern Qiangtang basin, in the Bangong-Nujiang suture zone, and in the northern Lhasa subterrane. As discussed in section 7.4.3 in Ma et al. (2017), however, at the early stage of two continents collide, marine environments keep across the suture zone due to inherited space, which is the rule in mountain belts around the world (X. Hu et al., 2016). For example, India and Asia collided at ~59 Ma, whereas marine sedimentation in intervening seaways extended to the Lutetian (43–41 Ma) or even to the late Priabonian (34 Ma; X. Hu et al., 2017).

We fully agree with Chen et al. (2018) that marine sedimentation in the Lhasa block extended to the early Cenomanian (~99 Ma), as indicated by foraminifera from the Langshan shallow-marine limestone (Boudagher-Fadel et al., 2017). However, there seem to be no marine strata younger than the Late Jurassic in the southern Qiangtang basin, where the Suowa Formation, representing the youngest marine lithostratigraphic unit in the southern Qiangtang basin, is Callovian in age (~164 Ma) according to ammonites (Ma et al., 2017; Yin, 2016). In the Bangong-Nujiang suture zone, the Mugagangri Group mélange is overlain by the shallow-marine limestones and sandstones of the Shamuluo Formation, which were deposited during Late Jurassic time (ca. 163–152 Ma), as constrained by coral and foraminifera biostratigraphy and the U–Pb zircon age of porphyritic granitoid intrusions (Ma et al., 2018). The *J–K* turbidite unit (as young as ~125 Ma) mentioned by the Comment was reported further south in the southern Nima basin by Kapp et al. (2007). It is too young to be included in the Mugagangri Group and may have been deposited on the Lhasa terrane and controlled by an unknown different, younger tectonic process.

2.3. Arc-Related Magmatism

Middle Jurassic to Upper Cretaceous felsic plutonic and volcanic rocks (ca. 175–100 Ma) with arc-related geochemical features (e.g., depleted in high field strength elements and enriched in incompatible elements) have been widely reported in recent years along the southern margin of Qiangtang, with a magmatic gap between 140 and 130 Ma (see a review by Zhu et al., 2016). Magmatic rocks with arc-related geochemical fingerprints, however, do not necessarily form in a continental arc during ongoing subduction of oceanic lithosphere. For example, the Linzizong volcanic rocks of the Gangdese Belt, characterized by arc-related geochemical signals (Mo et al., 2008), were emplaced largely after initiation of the India-Asia collision (Zhu et al., 2015). In fact, Lower Cretaceous magmatic rocks of arc-related geochemical features on the southern margin the Qiangtang were interpreted to have formed during slab rollback following the Lhasa-Qiangtang collision (Zhu et al., 2016).

2.4. Paleomagnetic Data

Paleomagnetic data suggest that the Lhasa and Qiangtang blocks initially collided during the Late Jurassic (~162 Ma; Yan et al., 2016) or suggest that the two blocks had already collided by the Early Cretaceous west of 87° E (Bian et al., 2017; the longitude of Biluoco area in Ma et al., 2017 is ~89° E). This is not mentioned by Chen et al. (2018) and does not support their interpretation. Considering the papers cited by Chen et al. (2018), paleomagnetic information gathered so far is mutually conflicting and insufficient to robustly constrain the timing of the Lhasa-Qiangtang collision.

3. Concluding Remarks

Chen et al. (2018) do not offer any direct geologic evidence to support their oceanic-highs subduction model. The indirect data they cite and discuss, including the age of supposed ophiolite complexes and of the latest marine deposits, arc-related magmatism, and paleomagnetic data, do not prove the persistence of the Bangong-Nujiang ocean in the Early Cretaceous and do not invalidate our preferred conclusion of Lhasa-Qiangtang initial collision during late Middle Jurassic time. Chen et al. (2018) tentatively relate the lack of syn-kinematic magmatism in the Biluoco Formation with temporary choking of the subduction zone by subduction of oceanic highs. However, in the basin, not only magmatism but also uplift of forearc floor and recycling of older forearc strata which are held to be associated with flat subduction induced by subduction of oceanic highs (see a review by Ridgway et al., 2012) were not recorded, as discussed in section 7.4.1 of Ma et al. (2017).

In conclusion, our favored scenario for late Middle Jurassic initial collision between the Lhasa and Qiangtang blocks during the late Middle Jurassic still holds. However, as we stated in section 7.4.3 of Ma et al. (2017), the upper-plate tectonic position of our study area makes the tectonic interpretation open to the possibility of oceanic-highs subduction as well as of an early microcontinent-Qiangtang collision preceding the final collision between the Lhasa and Qiangtang blocks.

As a final remark, diachronic tectonic processes may exist along strike, as Chen et al. (2018) also mention. The current level of geological information is insufficient to constrain such a hypothesis, and more work along the Bangong-Nujiang suture zone and in the Lhasa and Qiangtang blocks is required to better understand the evolution of the Lhasa-Qiangtang collision in space and time and its impact on the crustal growth of central Tibet.

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