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This article is a reply to comment by *Yi et al.* [2017] doi:10.1002/2017JB014353.

Key Points:
- Zongpu and Zongshan carbonate rocks in the Gamba area of southern Tibet were chemically remagnetized
- Remagnetization was induced by oxidization of pyrite to authigenic magnetite long after carbonate deposition
- Paleomagnetic results from Zongpu and Zongshan carbonate rocks should not be used for tectonic reconstruction

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Reply to comment by Z. Yi et al. on "Remagnetization of the Paleogene Tibetan Himalayan carbonate rocks in the Gamba area: Implications for reconstructing the lower plate in the India-Asia collision"

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Abstract In their comment on our publications on pervasive remagnetization of Jurassic-Paleogene carbonate rocks of the Tibetan Himalaya (Huang et al., 2017, *Journal of Geophysical Research: Solid Earth*, *122,* doi: 10.1002/2016JB013662 and 122*,* doi: 10.1002/2017JB013987), Yi et al. (2017) questioned our fold tests applied to their published paleomagnetic results from the Paleogene Zongpu and latest Cretaceous Zongshan carbonate rocks (Patzelt et al., 1996, *Tectonophysics*, *259*(4), 259–284; Yi et al., 2011, Earth and Planetary Science Letters, 309(1), 153–165). They argued that authigenic magnetite pseudomorphic after pyrite, which is the dominant magnetic carrier within these carbonate rocks as indicated by our thorough rock magnetic and petrographic investigations, was formed during early diagenesis and that the primary natural remanent magnetization (NRM) is retained by these carbonate rocks. However, their statement for the invalidity of our fold tests is based on unrealistic assumptions that these carbonate rocks carry primary NRM and that the upper Zongpu Formation was deposited on a 10° primary dip. Their argument for immediate oxidization of pyrite to authigenic magnetite after carbonate deposition onto the continental passive margin ignores that sulfate-reducing conditions were prevailing during early diagenesis, it is also inconsistent with the timing of the secondary remanence acquisition in remagnetized carbonate rocks elsewhere. As previously demonstrated, and agreed upon by Yi et al. (2017), the Zongpu and Zongshan carbonate rocks in Gamba are remagnetized; here we argue that the timing of remagnetization cannot be demonstrated to shortly postdate sedimentation. These data should therefore not be used for tectonic reconstructions.

1. Introduction

Tibetan Himalayan carbonate rocks exposed in the Tingri and Gamba areas in southern Tibet have been intensively studied to determine the paleolatitudes of the northern margin of the India [*Besse et al.*, 1984; *Appel et al.*, 1991; *Patzelt et al.*, 1996; *Appel et al.*, 1998; *Tong et al.*, 2008; *Yi et al.*, 2011; *Ran et al.*, 2012; *Liebke et al.*, 2013; *Huang et al.*, 2015a]. Of the investigated Jurassic to Paleogene carbonate strata, only the Zongpu (62–52 Ma) and Zongshan (71–65 Ma) Formations near the Gamba County were believed to carry a primary remanent magnetization [*Patzelt et al.*, 1996; *Yi et al.*, 2011]. Paleomagnetic results from these two formations were therefore widely used to constrain the size of Greater India and the initiation of the India-Asia collision [e.g.*,* *Patzelt et al.*, 1996; *Dupont-Nivet et al.*, 2010; *Yi et al.*, 2011; *van Hinsbergen et al.*, 2012; *Lippert et al.*, 2014; *Huang et al.*, 2015b]. In our recent papers [*Huang et al.*, 2017a, 2017b], we investigated the rock magnetic and petrographic properties of previously studied Jurassic to Paleogene carbonate rocks in the two areas, i.e., both Tingri and Gamba. Our investigations showed that these carbonate rocks with magnetite as the dominant magnetic carrier share similar characteristic rock magnetic properties of "wasp-waisted" hysteresis loops, suppressed Verwey transitions, extremely fine grain sizes, and strong frequency-dependent magnetic susceptibility, which typically fingerprint remagnetization in carbonate rocks. Our scanning electron microscopy and energy-dispersive X-ray spectrometry further visually and chemically characterize that magnetite grains in carbonate rocks are pseudomorphs of early diagenetic pyrite with detrital magnetite rarely preserved. Therefore, we suggested that oxidation of early diagenetic iron sulfide to authigenic magnetite likely caused pervasive chemical remagnetization of the Tibetan Himalayan carbonate units. In addition, we reanalyzed fold tests of the paleomagnetic directions reported and argued that they do not conclusively show prefolding magnetizations (the main point challenged in the comment)—and even if they did, that would only constrain the acquisition timing of the NRM to sometime after deposition and sometime prior to folding. Thus, we conclude that the latest Cretaceous and early Paleogene latitudes of the Tibetan Himalaya and size of Greater India have yet to be determined paleomagnetically and the initiation of collision cannot yet be precisely dated by paleomagnetism alone. Our finding thus allow a larger Greater India (3500 km) that is required for a ~ 59 Ma onset of the collision suggested by, e.g., sedimentological and stratigraphic data [e.g., *Hu et al.*, 2016], but which is incompatible with the previously reported Zongpu and Zongshan poles.

2. Authigenic Magnetite Formation Long After Carbonate Deposition

Based on our comprehensive rock magnetic and petrographic results [*Huang et al.*, 2017a], *Yi et al.* [2017] agree that the magnetic carrier of the Zongpu carbonate rocks is authigenic magnetite. However, they argue that these authigenic magnetite grains were formed at the very early diagenetic stage with no significant lapse of time between of the deposition and remanence acquisition. This deduction is speculative and, we argue, unlikely in the light of the following arguments. First, the Tibetan Himalayan carbonate rocks were deposited onto a passive continental margin represented by the Tibetan Himalayan sequence with reasonably high organic carbon contents. Sulfate-reducing conditions were therefore probably prevailing during early diagenesis, which induced dissolution of detrital magnetite/hematite and formation of pyrite with the primary paleomagnetic record being erased [*Roberts et al.*, 2013]. This is supported by our petrographic observations which show that pyrite, magnetite pseudomorphic after pyrite, and rutile pseudomorphic after detrital magnetite are widespread within the carbonate rocks, whereas occasional detrital magnetite that survived the diagenesis is only identified in the Zongshan carbonate rocks in Gamba [*Huang et al.*, 2017a, 2017b]. Oxidation of pyrite to authigenic magnetite, as well as the acquisition of the secondary remagnetized NRM, must have happened in another, later, diagenetic stage when these carbonate rocks were subjected to suboxic to even oxic conditions, caused by, e.g., tectonic uplift, or oxidizing fluid circulation, or both. Second, immediate remanence acquisition after deposition requires redox conditions within the buried sediments to have changed all the time from oxidation (to oxidize pyrite to magnetite in the lower strata) to sulfate reduction (to produce pyrite in the higher strata) before the deposition of any new sediments throughout the depositional time interval of the Zongpu carbonate rocks of 10 Myr. We see no arguments to support such a scenario of flipping redox conditions during sedimentation. Third, the Tibetan Himalayan carbonate rocks have rock magnetic and petrographic characteristics similar to those of the remagnetized carbonate rocks in North America and Europe with authigenic magnetite as magnetic carrier [e.g., *Jackson*, 1990; *Katz et al.*, 2000; *Weil and Van der Voo*, 2002]. While acquisition of remanence in these remagnetized carbonate rocks is commonly suggested to have happened long after deposition, there is no compelling argument to suggest that the remanence carried by authigenic magnetite in the Zongpu carbonate rocks in Gamba was acquired shortly after the deposition. Another good example is from the Jurassic carbonate rocks in the Tingri area, which share similar rock magnetic and petrographic properties to the Zongpu carbonate rocks in Gamba with remanence probably acquired long after deposition, in the Late Cretaceous [*Huang et al.*, 2015a, 2017b]. Fourth, *Liebke et al.* [2013] (with an author of the comment of *Yi et al.* [2017]) argued for a secondary remanence acquisition at 48 Ma to explain the remagnetization recognized in the Zongpu carbonate rocks in the Tingri area. Those carbonate rocks share the same rock magnetic and petrographic characteristics as the Zongpu carbonate rocks in the Gamba area [*Huang et al.*, 2017a, 2017b].

Furthermore, *Kodama* [2012] has argued that if chemical remanence is acquired during an early diagenetic stage, then inclination shallowing induced by compaction would be observed within the carbonate rocks. Elongation/inclination analysis [*Tauxe*, 2005] applied to both Zongpu and Zongshan carbonate rocks, however, indicates negligible inclination shallowing [*Dupont-Nivet et al.*, 2010]. This may thus indicate a secondary origin of the remanence acquired long after lithification without compaction induced inclination shallowing within the rocks.

Finally, a primary origin of the NRM of Zongpu carbonate rocks in Gamba is challenged by the fact that NRMs are mostly of reversed polarity with only one short normal polarity zone defined from few specimens and correlation to GPTS that misses 26Cn [*Yi et al.*, 2011]. In situ NRMs of the few specimens with normal polarity are actually very close to the present-day geomagnetic field direction at the sampling locality, suggestive of recent overprint [*Huang et al.*, 2017a]. A similar recent overprint is also identified from the top of lower Jidula quartz sandstones, which contain large amounts of authigenic hematite in addition to detrital magnetite as indicated by our rock magnetic and petrographic investigations [*Huang et al.*, 2017a, Figure S2].

3. Inconclusive Positive Fold Tests for the Zongpu Carbonate Rocks

As we have previously, we argue that the remanence in the Zongpu and Zongshan carbonate rocks is thus of secondary origin. To support that the remanence is at least of a prefolding age, *Yi et al.* [2017] question the validity of the fold tests in our reanalyses of the published paleomagnetic results from the Zongpu carbonate rocks in the Gamba area. Their fold tests applied to carbonate rocks from Member I, Members II–IV, and Members I–IV of the Zongpu Formation, no matter on individual specimen level or site level, are also negative, which are similar to our results. However, *Yi et al.* [2017] argue that these negative fold tests are inconclusive because they fail the F test [*McElhinny*, 1964]. This argument is not persuasive, however, because failure of the F test could well have been caused by the limited bedding variation within Member I and Members II–IV carbonate rocks. This is supported by the fact that K_{max}/K_{min} value of the DC fold test applied to Members I–IV is much closer to the corresponding critical F value than DC fold tests applied separately to the Member I and Members II–IV. Indeed, k_g/k_s of our nonparametric fold test applied to Members I–IV is 1.22 [*Huang et al.*, 2017a], which is just above F [294, 294] = 1.21 [*McElhinny*, 1964]. *Yi et al.* [2017] further suggest that these negative fold tests may be caused by northward latitude shift of the Tibetan Himalaya during the deposition of Member I and Members II–IV carbonate rocks. First and foremost, this argument is based on the assumption that the NRM would be primary. Second, the authors do not take into account the error bar of the mean inclination from Member I and Member II–IVs carbonate rocks. For example, the Tibetan Himalaya would have moved northward ~540 km in ~3 Myr within the depositional time of Member I carbonate rocks, corresponding to ~10° of inclination increase, which is just within the statistical uncertainty of the mean inclination (ΔI = 5.6°) of Member I carbonate rocks. Third, if the argument of primary remanence acquisition during a northward shift of Tibetan Himalaya is valid, then variation induced by progressive latitude shift should also exist within the data set of Member I carbonate rocks, and the best grouping of the remanence directions from Gamba and Tukson should be reached at less than 100% untilting rather than around 100% untilting as the authors presented. Individual remanence directions of the Member I carbonate rocks in Tukson were not published by the authors, and we can neither evaluate when best grouping is reached nor estimate the paleolatitude where the remanence was acquired. In any case, the calculated ~3°N paleolatitude of *Yi et al.* [2017] is questionable because they apply a 100% untilting of the bedding.

To explain why the mean dip of Members II–IV is ~10° shallower than that of Member I, *Yi et al.* [2017] argue that Member II–IV carbonate rocks were deposited on a forebulge, which has slightly tilted Member I carbonate rocks before the deposition of Members II–IV carbonate rocks. This argument is, however, against the geological observation that an unconformity exists between Member III and Member IV carbonate rocks, whereas Members I–III were deposited continually on a carbonate ramp [*Li et al.*, 2015], which could not have been deposited at a 10° primary dip, as this would lead to massive slope failure. While the Tibetan Himalaya must have migrated through a forebulge prior to arrival in the trench, we consider it unlikely that this flexural wave caused the 10° dip difference within the rocks deposited on the carbonate ramp of the Zongpu Formation, instead, this difference in bedding attitude between Member I and Members II–IV carbonate rocks was probably caused by later tectonic activity. Together with the negative fold tests from the Zongpu Formation near the Gamba County, it is then reasonable to argue that remagnetization happened during early tectonic activity associated with arrival to the suture zone, which induced bedding attitude variation within the Zongpu carbonate rocks. After the acquisition of the secondary remanence, regional folding developed near the Gamba County and Tukson. The apparent ~10° higher inclination of the Member II–IV than the Member I carbonate rocks can be best explained by applying a shallower bedding attitude to the in situ remanence directions of the Members II–IV carbonate rocks for tilt correction, which are actually indistinguishable from that of the Member I carbonate rocks [*Huang et al.*, 2017a].

4. Summary

Yi et al. [2017] agree with our assessment that the carbonate rocks of the Zongpu and Zongshan Formations are remagnetized. The debate then focuses on the timing of the remagnetization. *Yi et al.* [2017] argue that the fold tests of the Zongpu Formation may be interpreted as positive, assuming primary dips of up to 10° in the carbonate rocks. They also assume that remagnetization happened during early diagenesis and suggest that the remanence from these formations may be seen as (quasi-)primary. Their interpretation of an early diagenetic stage for authigenic magnetite formation after pyrite is, however, hard to reconcile with a logical evolution of the redox conditions during deposition of Himalayan carbonate rocks. It is also inconsistent with the timing of the remanence acquisition argued for many remagnetized carbonate rocks elsewhere. With few detrital magnetite grains preserved and ubiquitous and overwhelming authigenic magnetite within the rocks, it is very likely that the primary depositional remanent magnetization carried by detrital magnetite within the latest Cretaceous Zongshan carbonate rocks in Gamba has been significantly biased by the secondary chemical remanent magnetization carried by authigenic magnetite [*Huang et al.*, 2017b]. Even if the fold test would be positive, which can only be argued for by assuming a steep primary dip for the carbonate successions, this still leaves the timing of prefolding remagnetization undetectable. We emphasize here that the Zongpu and Zongshan carbonate rocks in the Gamba area are remagnetized and that the timing of remagnetization cannot be demonstrated to shortly postdate sedimentation (i.e., during early diagenesis). These data should therefore not be used for tectonic reconstructions.

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