India-Tarim Lithospheric Mantle Collision Beneath Western Tibet Controls the Cenozoic Building of Tian Shan

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Abstract The ongoing India-Asia collision principally regulates the Cenozoic tectonic deformation of the Asian interior, and builds a far-away but active spectacular intraplate orogen—Tian Shan. However, the deep processes and dynamics of far-field deformation propagation and the resultant Tian Shan building remain ambiguous. Here, we construct systematic numerical models with variable thermo-rheological properties of the orogen-featured blocks and convergence rates, which reveal that the far-field effect of India-Asia collision on the Tian Shan building is strongly controlled by the direct collision of Indian lithospheric mantle with the rigid Tarim block beneath western Tibet. The model results, together with the well-established geological and geophysical constraints, not only reconcile the first-order crustal delay are still poorly understood. In order to solve this problem, we constructed series of large-scale 2D thermomechanical numerical models, with considering the major lithospheric heterogeneities of the western Tibet-Tarim-Tian Shan-Junggar area. A novel mechanism for the Tian Shan building is proposed based on the comparisons of numerical models and multiple geological and geophysical observations. The new model indicates that the direct contact and collision between Indian and Tarim lithospheric mantles beneath western Tibet controls the Cenozoic building of the Tian Shan. The new finding links the Tibetan dynamics with far-field deformation in the Tian Shan range and sheds new light on the extensive continental deformation in the remote continental interior in response to plate tectonic forcing.

Plain Language Summary The present-day Tian Shan in the central Asia is one of the world’s greatest mountain ranges, and the India-Asia collision is generally invoked to account for its Cenozoic uplift. However, the Tian Shan range lies ~1,500 km to the north of the India-Asia plate boundary at the surface, and its major uplift in the Cenozoic is >30 Myr later than the onset of India-Asia collision. The physical mechanism for such a long-distance stress transfer and such a long-time delay are still poorly understood. In order to solve this problem, we constructed series of large-scale 2D thermomechanical numerical models, with considering the major lithospheric heterogeneities of the western Tibet-Tarim-Tian Shan-Junggar area. A novel mechanism for the Tian Shan building is proposed based on the comparisons of numerical models and multiple geological and geophysical observations. The new model indicates that the direct contact and collision between Indian and Tarim lithospheric mantles beneath western Tibet dominates the Cenozoic building of the Tian Shan. The new finding links the Tibetan dynamics with far-field deformation in the Tian Shan range and sheds new light on the extensive continental deformation in the remote continental interior in response to plate tectonic forcing.

1. Introduction

Tian Shan, as one of the world’s greatest mountain ranges, lies ~1,500 km to the north of the India-Asia plate boundary at the surface (i.e., the Indus-Tsangpo suture), indicating a long-distance orogenic effect due to the continuous Indian indentation (Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1979; Tapponnier et al., 1982; Figures 1a and 1b). The orogenesis of Tian Shan can be traced back to the Early Paleozoic, which recorded long-lived, subduction-induced accretions (Şengör, 1996; Şengör et al., 1993; Xiao et al., 2013). After continuous planation with the formation of series of Jurassic intermontane basins (M. Wang et al., 2015), the Tian Shan was eventually reactivated in the Cenozoic (Charreau et al., 2006; Hendrix et al., 1994; Yin & Nie, 1996) and is still uplifting at present (Charreau et al., 2017).

The Cenozoic building of Tian Shan attests to remarkable far-field tectonic effects of continental collision across central Asia, but the mechanism of the uplift remains ambiguous, with two major hypothetical models having been proposed. One prevailing model attributes it to the growing gravitational potential energy of the Tibetan plateau (England & Houseman, 1985; Molnar & Lyon-Caen, 1988; Molnar & Tapponnier, 1975),
with the corresponding stress leading to the reactivation of Tian Shan. Another model attributes it to the Arabia-Eurasia collision, which initiated series of strike-slip faults from the Zagros to Lake Baikal and contributed to the Tian Shan building (Yin, 2010). In addition, the southward subduction of Asian lithospheric mantle was also considered as a contribution to the diffuse deformation of Asian crust as well as the Cenozoic building of Tian Shan (Willett & Beaumont, 1994). Furthermore, the reactivation of Tian Shan is generally believed to occur >30 Myrs later than the onset of India-Asia collision (Charreau et al., 2006; Hendrix et al., 1994; Yin & Nie, 1996). The mechanism for such a long-time delay and the final triggering of Tian Shan building is still poorly constrained.

Aiming to understand the far-field effects of India-Asia collision and the Cenozoic deformation of Tian Shan, we perform systematic numerical experiments with varying thermo-rheological properties of multiple blocks and convergence rates, and provide a novel mechanism for the Tian Shan building. The new model, constrained by substantial geological and geophysical observations, highlights the crucial role of the Tibetan and Tarim lithospheric mantle collision beneath western Tibet in dominating the Cenozoic building of Tian Shan.

**Figure 1.** Geological and geophysical interpretation of the Tian Shan. (a) General topographic and tectonic map of the Tian Shan range and surrounding areas, with major tectonic blocks and faults (modified after Xiao et al. [2013] and Cowgill [2010]). Abbreviations: NTT, North Tian Shan fault; NTF, North Tarim Fault; TFSF, Talas-Fergana strike-slip fault; MPT, Main Pamir thrust. (b) Simplified large-scale tectonic map of the India-Asia collision zone and the Asian interior. The distribution of terranes and sutures are modified after Schwab et al. (2004), van Hinsbergen et al. (2011), and Yin and Harrison (2000). Detailed tectonic structure of the Tian Shan enclosed in the rectangle is shown in Figure 1a. Profile AA’ is the location of schematic cross-section in Figure 1c. Abbreviations: MBT, Main Boundary thrust; ITS, Indus-Tsangpo suture; BNS, Bangong-Nujiang suture; JS, Jinsha suture; AKMS, Anyimaqen-Kunlun-Muztagh suture; KF, Karakoram fault; ALT, Altyn Tagh fault. (c) Integrated schematic cross-section in the western Tibet-Tarim-Tian Shan region. The lithospheric structure of the Tibet-Tarim region is derived from the seismic data (Rai et al., 2006; Wittlinger et al., 2004; Zhao et al., 2010). Multiple lines of evidence supporting the India-Tarim collision beneath western Tibet are compiled in Figure 5. The lithospheric structure of the Tian Shan section is from J. Li et al. (2016).
2. Modeling Methods

The numerical modeling was performed with the I2VIS code (see Text S1 for the numerical methodology) (Gerya & Yuen, 2003a). The overall model setup is based on the tectonic evolution of the orogen-like Tibetan and Tian Shan regions as well as the adjacent craton-like Tarim and Junggar basins. It represents simplified inherited lithospheric heterogeneities from India to Junggar at the onset of India-Asia collision. Correspondingly, five continental blocks were integrated into the model, separately representing the Indian, Tibetan, Tarim, Tian Shan, and Junggar lithospheres from left (south) to right (north) (Figure S1). Detailed properties of the different rock types for these units are described in Tables S1 and S2.

The lithospheric thermal structure is simply adjusted with a prescribed initial Moho temperature ($T_{\text{Moho}}$). On the basis of the distinct tectonic evolution of the different geological units, a hotter thermal state (i.e., a higher $T_{\text{Moho}}$) is set for the orogen-featured Tibetan and Tian Shan units in the reference model, comparing to the rigid craton-featured Indian, Tarim, and Junggar lithospheres (Molnar & Tapponnier, 1981). Specifically, the Tibetan lithosphere is suggested to have experienced hydration- and partial melting-related weakening during multiple episodes of oceanic subduction and terrane accretion in the Mesozoic (Wu et al., 2016; Yin & Harrison, 2000), making it relatively hotter and weaker than the indenting Indian plate (Molnar & Tapponnier, 1981). As a simplification, all the accreted terranes are integrated as one weak Tibetan lithosphere. Similarly, the Paleozoic Tian Shan can be regarded as a long-lived scenario of multiple accretions of micro-continental fragments and arcs (Şengör, 1996; Şengör et al., 1993; Xiao et al., 2013), resulting in a rheologically weak Tian Shan region (Tapponnier & Molnar, 1979; Yin & Nie, 1996). In contrast, the Indian, Tarim, and Junggar units with Precambrian basements are generally regarded as rheologically strong blocks with relatively cold thermal profiles (Jagadeesh & Rai, 2008; Xu et al., 2015; Zhang et al., 2013). Accordingly, the $T_{\text{Moho}}$ of the craton-like domains is assigned to be 400°C in the reference model, with $T_{\text{Moho}}$ of the orogen-like Tibetan and Tian Shan lithospheres ($T_{\text{T}}$ and $T_{\text{TS}}$ henceforth) being 700°C (Figure 2). Six sensitivity models with variable $T_{\text{T}}$ and $T_{\text{TS}}$ (500–800°C) (Figures S2–S7) were further conducted. In addition, the sensitivity to increased density of the cratonic lithospheric mantle was also explored (Figure S10). Detailed model configuration and model limitations are given in Text S2 and S3.

The model domain has free-slip top boundary and sidewalls, with the bottom side as a mass-conservative permeable boundary. Continental convergence is driven by a pushing velocity within the Indian plate. An averaged convergence rate of 5 cm/yr is applied in the reference model (Lee & Lawver, 1995), and two sensitivity models with 3 and 7 cm/yr convergence rates were additionally built (Figures S8 and S9). Besides, with simplified erosion and sedimentation processes, the topography is calculated dynamically, whose evolution is based on the transport equation (Gerya & Yuen, 2003b).

3. Model Results

During incipient collision in the reference model (Figures 2a and 3a), the convergence first causes shortening and thickening of the Tibetan lithosphere that is the weakest section in the model. Thus, strain localization is observed at the southernmost Tibetan lithosphere, which is followed by the delamination of its lithospheric mantle (Figures 2a and 3a). Continuous convergence together with the delamination of Tibetan lithosphere results in a double-thickened Tibetan crust but obviously thinned lithospheric mantle (Figures 2b–2d). The remote Tian Shan region undergoes negligible deformation, until the indenting Indian lithosphere collides with the Tarim block beneath the Tibetan crust (Figures 3a–3d). Then, the plate-convergence stress acts directly on the rigid craton-like Tarim and transfers to the Tian Shan, initiating significant shortening deformation there (Figures 2d–2f and 3d–3f). The progressive underthrusting of the Indian lithospheric mantle beneath the thickened Tibetan crust shuts off the heat from the asthenosphere. Continuous indentation causes progressive crustal/lithospheric compression of the Tian Shan, eventually resulting in a bi-directional subduction of both adjacent lithospheres (Figures 2e and 2f). A crustal-scale flower structure with a thick lithospheric root is predicted after a convergence of 50 million years (Figure 2f).

The topographic evolution is characterized by an early growth of the broad Tibetan plateau and a delayed uplift of the narrow Tian Shan orogen (Figure 4a). The modeled Tibetan plateau is initiated during the delamination of the Tibetan lithospheric mantle and is ultimately underlain by the underthrusting Indian
Figure 2. Composition and temperature evolution of the reference model. (a–f) Composition evolution overlapped by isotherms. The model results indicate that continuous Indian plate indentation leads to delamination of the Tibetan lithospheric mantle, followed by the India-Tarim collision beneath the thickened Tibetan crust, which reactivates the Tian Shan. Different colors refer to different lithologies. Detailed properties of these rocks are shown in Tables S1 and S2. White numbered lines are isotherms plotted every 300°C starting from 100°C. Time and the amount ($\Delta x$) of convergence are given in each panel.
The modeled Tian Shan does not uplift, until the Indian lithospheric mantle begins to collide with the Tarim after the removal of Tibetan lithospheric mantle. The sensitivity model results indicate that the thermo-rheological properties of the Tibetan and Tian Shan lithospheres regulate the timing and pattern of intraplate deformation. A decrease of $T_{TS}$ to 600°C inhibits the reactivation of Tian Shan (Figures 4b, 4f, S2 and S6), whereas an increase of $T_{TS}$ to 800°C favors strain localization in the Tian Shan region, with a ~10 Myr earlier building of Tian Shan than the reference case (Figures 4c, 4g, S3 and S7). In addition, a relatively cold and strong Tibetan plate leads to the earliest uplift of Tian Shan (i.e., shortly after the India-Asia collision) but significantly delayed Tibetan uplifting (Figures 4d and S4). Increasing $T_{TP}$ to 800°C with keeping $T_{TS} = 700°C$, the model (Figures 4e and S5) shows rather similar result with the reference case.

**Figure 3.** Strain rate evolution of the reference model. (a–f) Evolution of the second invariants of strain rate ($\dot{\epsilon}_{II}$) with arrows indicating velocities. Colorbars for strain rate are shown on the right. The black, red, blue, and green triangles denote the crustal sutures between India-Tibet, Tibet-Tarim, Tarim-Tian Shan, and Tian Shan-Junggar, respectively. Time and the amount (Δx) of convergence are given in each panel.
Figure 4
The convergence rate and the density of cratonic lithospheric mantle could also modulate the mode of deformation propagation during collision. The model with a slow convergence of 3 cm/yr shows that the Tibetan crust absorbs larger convergence via crustal thickening and migrating (Figure S8), with the formation of a broader plateau, thus greatly restricting the uplift of Tian Shan (Figure 4h). In contrast, the convergence-induced deformation is rapidly propagated to the Tian Shan in the case with a fast convergence of 7 cm/yr (Figures 4i and S9). An increase of the Tarim and Junggar lithospheric mantle density favors decoupling of the lithospheric mantle from the overlying crust, resulting in long-distance underthrusting of the Tarim lithosphere beneath the Tibetan crust and thus postponing the Tian Shan uplift (Figure S10). However, the physical mechanism for the Tian Shan building has not been affected, which is still triggered by the India-Tarim collision (Figure S10).

4. Discussion

4.1. A New Model for the Cenozoic Building of Tian Shan

The Cenozoic India-Asia collision is generally invoked to account for the intraplate deformation in central-eastern Asia, including the Cenozoic building of the Tian Shan and Altai ranges (Molnar & Tapponnier, 1975; Tapponnier et al., 1982). Extensive numerical studies on the Tian Shan building have been performed over decades, but most of them focused on the magnitude of crustal deformation and the role of rigid Tarim basin (Dayem et al., 2009; England & Houseman, 1985; England & McKenzie, 1982; Neil & Houseman, 1997). Two hypotheses are proposed previously, emphasizing the role of northward crustal thickening (England & McKenzie, 1982) or the Arabia-Eurasia collision (Yin, 2010).

Alternatively, according to the systematic comparisons between the numerical models and the geological/geophysical observations from both the Tibetan and Tian Shan systems, we propose a new model that the direct collision of Indian lithospheric mantle with the rigid Tarim block controls the long-distance stress transfer and the final building of Tian Shan. In the new model, the Tian Shan was uplifted much later (>30 Myrs) than the initial India-Asia collision (Figure 2), which well accounts for the impressive time lag as observed by previous studies (Charreau et al., 2006; Hendrix et al., 1994; Yin & Nie, 1996).

4.2. Comparison With Lithospheric Structure and Cenozoic Magmatism of Western Tibet

The lithospheric structure of western Tibet (west of ~82°E) has been widely explored by multiple geophysical methods. Although several studies suggest that the Indian plate does not reach much farther than the Jinsha suture, leaving the northern Tibetan underlain by a hot and thinned lithospheric mantle (Matchette-Downes et al., 2019; Razi et al., 2016), a large number of geophysical images instead suggest that the Indian lithosphere has sub-horizontally underthrust the western plateau and directly collided with the Tarim lithospheric mantle beneath the West Kunlun range (compiled in Figure 5) (Gilligan et al., 2015; C. Li et al., 2008; Rai et al., 2006; Wittlinger et al., 2004; Zhao et al., 2010). The direct India-Tarim lithospheric contact was evidenced by the deep seismic reflection data (Gao et al., 2000), tomographic studies (Huang & Zhao, 2006; C. Li et al., 2008; Zhou & Murphy, 2005), receiver function analyses (Gilligan et al., 2015; Rai et al., 2006; Wittlinger et al., 2004; Zhao et al., 2010), extensive surface wave observations (Griot et al., 1998; Priestley et al., 2006), as well as the comprehensive geophysical-petrological-thermodynamic modeling (Tunini et al., 2016). Complete detachment of the Tibetan lithospheric mantle is required for the formation of this architecture, which is compatible with our recent numerical model (Huangfu et al., 2018) and this study; both of them indicate an entire removal of the western Tibetan lithospheric mantle. The expected...
lithospheric structure in western Tibet is in great contrast to the central-eastern Tibetan plateau with inefficient Sn propagation and low mantle seismic wave speed in the northern part (denoted in Figure 5; McNamara et al., 1995; Ni & Barazangi, 1983; Owens & Zandt, 1997), which may be attributed to remarkable lithospheric thinning and asthenospheric upwelling.

The numerical results allow important predictions for the thermal state of western Tibet. Despite only the crustal melting directly applied in the numerical model, episodes of magmatism with mantle sources, based on the pressure, temperature, and composition evolution, can still be predicted. The thermal evolution and partial melting are generally consistent with the spatiotemporal distribution of post-collisional magmatic rocks in western Tibet. First, delamination of the Tibetan lithospheric mantle (Figure 2c) is suggested to trigger magmatic clustering in northern Tibet since early Miocene time (Guo & Wilson, 2019). Then progressively northward underthrusting of the cold Indian lithospheric mantle gradually shut off the heat from the asthenosphere (Figures 2d–2f), resulting in the termination of magmatism in southern Tibet from ∼10 Ma to now (Chung et al., 2005; Guo et al., 2014). Thus, no igneous activity younger than that age occurs in southern Tibet, despite the existence of pervasive partial melting- and/or hydrous fluids-induced low velocity zones at mid-crustal levels (Yang et al., 2012), which also exhibits in the current model (Figures 2d–2f). During the India-Tarim collision, a narrow thermal flow channel still exists in the contact zone beneath northern Tibet (Figure 2f). Owing to this channel, partial melting of the sandwiched highly deformed lithospheric mantle as well as the overlying thickened crust can be triggered to produce the latest magmatism in the western Songpan-Ganzi terrane since ∼8 Ma (Guo et al., 2014). However, the extent of the magmatism in this episode is strongly restricted, compared with the contemporary magmatism in central-eastern Tibet (Chung et al., 2005; Guo & Wilson, 2019).

4.3. Comparison With the Cenozoic Tectonic Deformation of Tian Shan and Neighboring Blocks

Besides the India-Tarim contact beneath western Tibet, previous geophysical observations indicated bidirectional underthrusting of the Tarim and Junggar blocks beneath the Tian Shan (Koulakov, 2011; J. Li et al., 2016; Omuralieva et al., 2009; Zhao et al., 2003). This is consistent with the deformation pattern of the modeled Tian Shan and its lithospheric interplay with the two adjacent blocks (Figure 2f). Owing to the rheological contrast between the weak Tian Shan and the two neighboring strong cratonic basins, the
modeled Tian Shan is uplifted as a whole with simultaneous underthrust of both adjacent rigid blocks. In situ apatite fission track analyses from south and north of the Tian Shan agree with this model, both suggesting the concurrent unroofing of the South and North Tian Shan (Dumitrut et al., 2001; Hendrix et al., 1994).

In terms of crustal-scale deformation, the Tian Shan is featured with thrust faults on both flanks of the adjacent basins, as well as attendant fold and reverse fault zones along the range fronts (C.-Y. Wang et al., 2004; Yin et al., 1998). The current model reveals that the interior of the Tian Shan is first subjected to shortening, followed by the crustal overthrusting on the Tarim and Junggar blocks simultaneously (Figures 2e and 2f). Moreover, previous geophysical observations show that the Moho depth of the Tian Shan region ranges from 50 to 70 km, with the greatest depth in its middle part (J. Li et al., 2016), which is compatible with the modeled Tian Shan after a convergence of ~2,500 km (Figure 2f).

Field measurements and Global Position System data predicted a noticeable Cenozoic clockwise rotation of the Tarim basin (Avouac et al., 1993; Zhao et al., 2019). This rotation is interpreted to be driven by the India-Tarim contact beneath western Tibet (compiled in Figure 5), and accounts for distinct lithospheric interactions along the borders of Tarim Basin (Zhao et al., 2019). The kinematic feature of the Tarim block and the observed tectonic complexity along the boundaries provide additional constraints on the new model as proposed in this study. Specifically, the India-Tarim collision beneath western Tibet not only exerts a northward pushing on the western Tarim basin facilitating its rotation, but more importantly, allows long-distance stress transfer across the rigid Tarim block to build the Tian Shan.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The figures of numerical models are produced by MATLAB, with further compilation by CorelDRAW. Maps in Figures 1a and 5 are produced with GMT (Wessel et al., 2013). All related data of the numerical models are provided in Zenodo (https://doi.org/10.5281/zenodo.4818316).

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