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Mantle kinematics driving collisional subduction: Insights from analogue modeling

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A B S T R A C T

Since several decades, the processes allowing for the subduction of the continental lithosphere less dense than the mantle in a collision context have been widely explored, but models that are based upon the premise that slab pull is the prominent driver of plate tectonics fail. The India–Asia collision, where several episodes of continental subduction have been documented, constitute a case study for alternative views. One of these episodes occurred in the early collision time within the Asian plate where continental lithosphere not attached to any oceanic lithosphere subducted southward in front of the Indian lithosphere during its northward subduction that followed the oceanic subduction of the Tethys ocean. This process, known as collisional subduction, has a counter-intuitive behavior since the subduction is not driven by slab pull. It has been speculated that the mantle circulation can play an important role in triggering collisional subduction but a detailed, qualitative analysis of it is not available, yet. In this work we explore the southward subduction dynamics of the Asian lithosphere below Tibet by means of analogue experiments with the aim to highlight how the mantle circulation induces or responds to collisional subduction. We found that during the northward oceanic subduction (analogue of Tethys subduction) attached to the indenter (Indian analogue), the main component of slab motion is driven vertically by its negative buoyancy, while the trench rolls back. In the mantle the convective pattern consists in a pair of wide convective cells on both sides of the slab. But when the indenter starts to bend and plunge in the mantle, trench motion reverses. Its advance transmits the far field forces to two upper plates (Asian analogues). The more viscous frontal plate thickens, and the less viscous hinterland plate, which is attached to the back wall of the box, subducts. During this transition, a pair of sub-lithospheric convective cells is observed on both sides of the Asian analogue slab, driven by the shortening of the frontal plate. It favors the initiation of the backwall plate subduction. Such subduction is maintained during the entire collision by a wide cell with a mostly horizontal mantle flow below Tibet, passively advecting the Asian analogue slab. Experimental results suggest that once the tectonic far-field force related to the forward horizontal motion becomes dominant upon the buoyancy forces, trench advancing and the transmission of the tectonic force to the upper and backwall plates are promoted. This peculiar condition triggers the subduction of the backwall plate, despite it is light and buoyant.

1. Introduction

Continental subduction has been proposed for decades as a key process occurring during the long-lasting collision between India and Asia, with a northward motion of India at a rate in excess of 50 mm/yr since ∼50 Ma (e.g. Patriat and Achache, 1984; Molnar and Stock, 2009; van Hinsbergen et al., 2005), allowing the subduction of the continental lower crust attached to the lithospheric mantle while the upper crust thickens and forms the Tibetan plateau (e.g. Mattauer, 1986; Tapponnier et al., 2001). However, only recently some evidence of such process has been collected. The fact that the continental lithosphere could subduct has first been hypothesized from the seismicity within the continental collision framework of the Pamir and Hindu Kush at the western extremity of the collision system, which reveals two subduction zones of opposite vergence (Chatelain et al., 1980; Burtman and Molnar, 1993). However, the nature of the lithosphere, continental or oceanic, remained speculative, as well as

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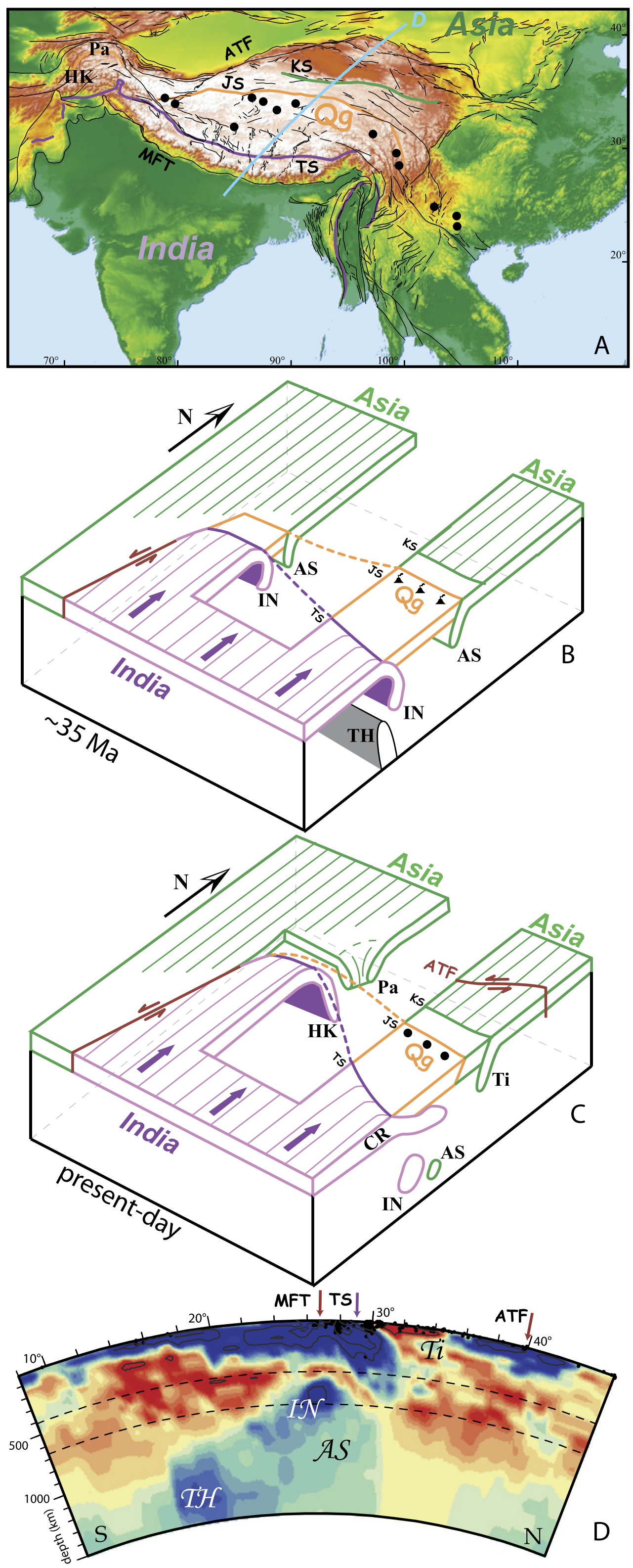
the slab length. Global P-waves tomography allows to discuss the maximum depth extent of the two distinct slabs (Negredo et al., 2007): the Indian slab deepens northward almost vertically down to ~600 km beneath the Hindu Kush, and the Asian lithosphere is seemingly deepening southward down to ~400 km beneath the Pamir (Fig. 1). The maximum depth of seismicity has been modeled and shown to be compatible with continental lithosphere subduction (Negredo et al., 2007). Recent seismic studies of the Pamir–Hindu Kush region show details of the lithospheric structure of such slabs (Mechie et al., 2012; Kufner et al., 2016), revealing a strong evidence of their continental nature by showing the subduction of light continental lower crust on top of denser continental upper lithosphere down to ~400 km depth (Schneider et al., 2013). Although less documented, the Asian lithosphere in central Tibet is inferred to subduct southward down to 300 km, with no related seismicity (Kind et al., 2002; Replumaz et al., 2013). During the early Tibetan collision stage, a first episode of subduction of the Asian lithosphere likely occurred beneath Qiangtang, as recorded by Cenozoic volcanics between 50 and 30 Ma in the Qiangtang block (e.g. DeCelles et al., 2002; Spurlin et al., 2005; Goussin et al., submitted for publication) (Fig. 1). This slab detached, and sunk, and is possibly revealed by a positive P-wave speed anomaly in the lower mantle (Replumaz et al., 2013) (Fig. 1).



Beneath the Himalaya, it has been proposed that at present-day the Indian lower crust, attached to its lithospheric mantle, is bent and is underplated below southern Tibet (Nábělek et al., 2009) (Fig. 1). A possible additional process that may help the subduction of continental plates it eclogitization. During the bending of the Indian plate beneath the Himalaya, its density could be close to mantle density, which favors underplating below southern Tibet (Hetenyi et al., 2007).

However, a dynamic explanation of continental subduction is still lacking, mostly because it is in principle less dense than the mantle (in the absence of secondary processes like eclogitization). Deciphering its contribution to the formation of the Tibetan plateau where this under-explored process is possibly important (Mattauer, 1986; Tapponnier et al., 2001; Spurlin et al., 2005; Replumaz et al., 2013; Goussin et al., submitted for publication). But above all, this observation calls for to go beyond the paradigm of slab pull as a unique driver of plate tectonics. Alvarez (2010) already pointed to the fact that protracted collisions require support from mantle tractions; sustained continental subduction is even more difficult to sustain under the premise that slab pull is the prominent, if not unique, tectonic engine.

A low-density contrast between the continental lithosphere and the mantle facilitates the subduction of the continental lithosphere attached to a dense oceanic slab (Capitanio et al., 2010; Bajolet et al., 2013), but it cannot trigger the subduction of the Asian lithosphere which is not attached to a dense slab (Fig. 1). At the lithospheric scale, analogue models show that the initiation of continental subduction in a context of convergence occurs with a low degree of coupling at the plate interface and with an inclined plate contact (while vertical boundary favor buckling of the lithospheres) (Luth et al., 2010; Willingshofer et al., 2013). At the mantle scale to date, only two models attempt to quantita-

Fig. 1. (A) Topographic map of the collision zone between India and Asia. The Indian crust is separated from the Asian crust by the Tsangpo suture (TS, in purple). In central Tibet, Cenozoic volcanic rocks between 50 and 30 Ma (black dots) are observed north of the Qiangtang block (Qg), located south of the Jinsha suture (JS, in orange). KS: Kunlun suture, Pa: Pamir, HK: Hindu Kush. (B) Three-dimensional schematic view of the lithospheric structure (middle-lower crust and lithospheric mantle) below Tibet in the early collision time. The Indian lithosphere (IN) subducted northward facing the Asian slab (AS) beneath Qiangtang (Qg). Both slabs detached from the continents and have sunk down to the lower mantle since then. The same color code used for the different plates is applied to experimental data. (C) Three-dimensional schematic view of the lithospheric structure at present-day as inferred from global tomographic cross section (Replumaz et al., 2013) shown below, showing to the southwest, the Indian lithosphere (in purple) subducting northward beneath the Hindu Kush (HK) down to the transition zone (~600 km), facing the Asian lithosphere (in green) subducting beneath Pamir down to 300–400 km. In central Tibet, the Asian lithosphere (Ti, in green) is subducting southward down to 300 km along the Kunlun suture (KS), facing the Indian craton (CR) underplating south Tibet. (D) Cross-section along line shown on A of Pwave global tomographic model, with positive anomalies interpreted as slabs subducted during the collision (Replumaz et al., 2013). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)