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Multiple episodes of continental subduction during India/Asia convergence: Insight from seismic tomography and tectonic reconstruction

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ABSTRACT

High wavespeed tomographic anomalies shallower than 1100 km beneath the India/Asia collision zone are interpreted as continental slabs subducted during collision. Combining anomaly positions with paleogeographic reconstructions of India, we constrain the spatio-temporal evolution of multiple episodes of continental subduction likely related to these anomalies. This study highlights the different evolution at lithospheric scales of the western and eastern parts of the collision zone. The evolution of the western part is characterized by two episodes of steep subduction of the northern margin of India. The first episode, involving an area with a lateral extent as large as 1500 km, started at about 40–30 and ended by a slab break-off process at ~15 Ma, The second episode consists on subduction beneath the Hindu Kush mountains since ~8 Ma. To the east of the collision zone, no anomaly related to steep subduction along the northern edge of India is found. We interpret two tomographic anomalies beneath the eastern border of the Indian plate, beneath Burma and beneath the Andaman Sea, as the result of two successive episodes of southeastward extrusion followed by subduction. We suggest that both extruded portions were initially located along the northern margin of India, and that they slid around the eastern syntaxis, then southward along the eastern boundary of Indian plate. Both portions subducted along the eastern border of India, south of the eastern syntaxis.

We provide a rough estimate of the amount of Indian lithosphere consumed during these subduction and extrusion episodes. By comparing this amount with the total amount of Indian lithosphere at the onset of collision, we conclude that these processes accommodated most of the India/Asia convergence during collision.

1. Introduction

The northward penetration of India into Asia since the Eocene deformed a vast area of both continents. For the upper crust, continental convergence was likely absorbed by crustal thickening, erosion and extrusion (Tapponnier et al., 1986; Le Pichon et al., 1992; Replumaz and Tapponnier, 2003). The quantitative partitioning of convergence absorption between these processes is a matter of debate. At lithospheric scale (excluding the upper crust) continental convergence was likely accommodated by subduction, underthrusting, delamination or extrusion (e.g. Mattauer, 1986; Molnar et al., 1993; Tapponnier et al., 2001; DeCelles et al., 2002). The existence of all these processes, as well as their relative role in accommodating convergence is also controversial.

The total amount of convergence between India and Asia has been estimated to range from 2000 to 3000 km, increasing eastwards, using the surface of the indentation mark, left by the impaction of India onto Asia (Tapponnier et al., 1986; Le Pichon et al., 1992; Guillot et al., 2003). The estimated partitioning of shortening between India and Asia depends on the location and geometry of the plate boundary at the beginning of indentation. Recently, the Early Tertiary plate boundary has been constrained on the basis of interpretation of seismic tomography images. High wavespeed anomaly observed beneath India from depths of ~1100 km down to at least 1600 km (labelled as TH, for Tethys, in Figs. 1–4) has been related to the continuous subduction of Indian Ocean beneath Southeast Asia since at least the Cretaceous (Van der Voo et al., 1999; Replumaz et al., 2004; Hafkenscheid et al., 2006; Richards et al., 2007). The TH anomaly vanishes at depths shallower that ~1100 km, which has been interpreted by Negredo et al. (2007) to reflect a slab break-off process at the onset of indentation of India. Therefore these authors used the outline of this high wavespeed anomaly at this depth to draw the geometry of the northern boundary of India at the time of break-off (blue contour in Fig. 1). Moreover, Negredo and co-authors estimated an age of break-off of ~45 Ma, on the basis of the

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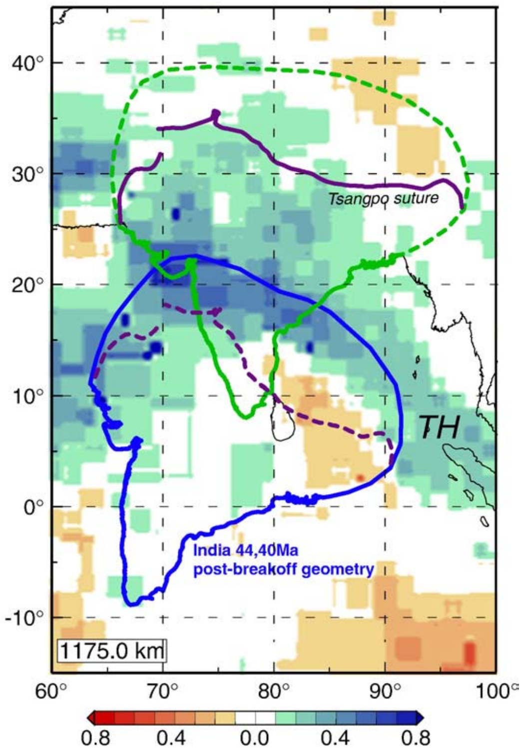

Fig. 1. horizontal section of the *P*-wave global tomographic model modified from Bijwaard et al. (1998). Anomaly TH is interpreted as marking the location of late Mesozoic TetHyan oceanic subduction until slab break-off at about 45 Ma. This anomaly has been used draw the geometry of continental India at the time of break-off (blue contour). Modified from Negredo et al. (2007). The region comprised between this Indian geometry at 45 Ma and the Indus Tsangpo suture should be regarded as the total amount of India consumed during collision in the last 45 Ma, either by subduction, underthrusting or extrusion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

combination of tomographic images and paleogeographic reconstructions of India at different times (Patriat and Achache, 1984). This estimated age of slab break-off is in agreement with the age of late Eocene K-rich magmatism observed in southeastern Tibet (Kohn and Parkinson, 2002) and with results of modelling of continental subduction (Chemenda et al., 2000). In the present study we focus on the post break-off evolution of the collision zone. We use seismic tomography images in the upper mantle and uppermost lower mantle to interpret the spatio-temporal evolution of processes that likely accommodated India/Asia convergence during the last ~45 Ma. The 0tomographically inferred northern boundary of India at ~45 Ma is an important constraint for our analysis, as the area comprised between this boundary (after being rotated on the sphere up to the present; green dashed contour in Fig. 1) and the location of continental suture provides an estimate of the total amount of Indian lithosphere consumed, either by subduction, underthrusting and extrusion.

2. Assumptions and approaches

We interpret high wavespeed anomalies imaged at depths shallower than about 1000 km as representing lithospheric material subducted after the mentioned large scale slab break-off at *ca.* 45 Ma. Our first assumption is that this material is of continental nature, in agreement with a number of studies (Van der Voo et al., 1999; Chemenda et al., 2000; DeCelles et al., 2002). Actually, the age estimated for the initial contact between the Indian and Asian continental margins is of about 55 Ma, deduced from the age of the Tso Morari eclogites, which formed when Indian continental crust arrived at the Transhimalayan trench (Guillot et al., 2003; Leech et al., 2005). Also the change from marine to terrestrial sedimentation at ~50 Ma (Rowley, 1996; Najman et al., 2005) indicates that oceanic crust was completely consumed by the time of slab break-off. This timing implies that a portion of subducted Indian continental lithosphere, pulled down by the dense oceanic lithosphere, was likely detached by this break-off process.

To constrain the timing of subduction onset we adopt the assumption that in the absence of significant lateral mantle advection, the tip of a steeply subducting slab sinks into the mantle without lateral migration (e.g. Uyeda and Kanamori, 1979; Heuret and Lallemand, 2005). The regional mantle advection has been inferred to be negligible in the region (Replumaz et al., 2004). We therefore infer that the map view of the deepest part of a high wavespeed anomaly roughly marks the location of the plate boundary at the time of subduction initiation. This procedure of combining tomographic anomalies at different depths with the reconstructed position of the plate boundary at different times has been shown by Replumaz et al. (2004, 2009) and Negredo et al. (2007) to be useful to constrain the timing and kinematics of different subduction episodes in the collision zone. Our hypothesis of negligible lateral migration of the deepest portion of the slab is in agreement with the predictions of dynamic experimental models of subduction in the upper mantle (e.g. Schellart, 2005; Bellahsen et al., 2005; Heuret et al., 2007; Schellart, 2008). These models consistently show that, regardless of the slab sinking trajectory related to trench migration (backward sinking for trench retreat and forward for trench advance, e.g. Schellart, 2008), significant lateral motion of the tip of the slab only occurs when it approaches the base of the upper mantle and is caused by the imposed condition of no-penetration into the lower mantle.

To constrain the duration of subduction processes we adopt the simplifying assumption of considering that the interpreted slabs behave as relatively rigid slabs, so experiencing little internal deformation. This is in agreement with recent numerical thermo-mechanical modelling, which indicates that once the slab sinks into the lower mantle, resistance to slab descent into the higher viscosity lower mantle leads to progressive decrease of slab dip due to bending, rather than to internal deformation of the slab (Billen and Hirth, 2007). Nevertheless, some complexities as significant buckling of weak slabs observed in numerical models of deep subduction (e.g. Christensen, 1996; Enns et al., 2005; Stegman et al., 2006; Behounkova and Cizkova, 2008) as well as in experimental approaches (Ribe et al., 2007) cannot be discarded. Such complexities generate potential uncertainties in our inferences for lower mantle slabs which are taken into account in the large uncertainty ranges associated with our estimates.

3. Mantle structure beneath the collision zone

To gain a better insight into the 3D mantle seismic structure beneath the collision zone, we combine horizontal (map views; Fig. 2) and vertical sections (Figs. 3 and 4) of the *P*-wave global tomographic model of Bijwaard et al. (1998). This model has been updated by Villaseñor et al. (2003) by including arrival times of earthquakes from 1995 to 2002 listed in the bulletins of the International Seismological Centre and reprocessed using the EHB methodology (Engdahl et al., 1998). The ray coverage provides a qualitative estimate of the resolution for the model. This resolution is good at all depths because

Fig. 2. Section *a* shows fast wave propagation beneath western Tibet, interpreted as significant underthrusting of India under the western Tibet, and slow beneath the central and eastern Tibet, interpreted as the absence of significant underthrusting of India under the central and eastern Tibet. Sections *b* to *e* show distinct high wavespeed anomalies that we associated with Indian continental slab fragments. Sections *f*: anomaly TH, interpreted as marking the Early Tertiary plate boundary between India and Asia.