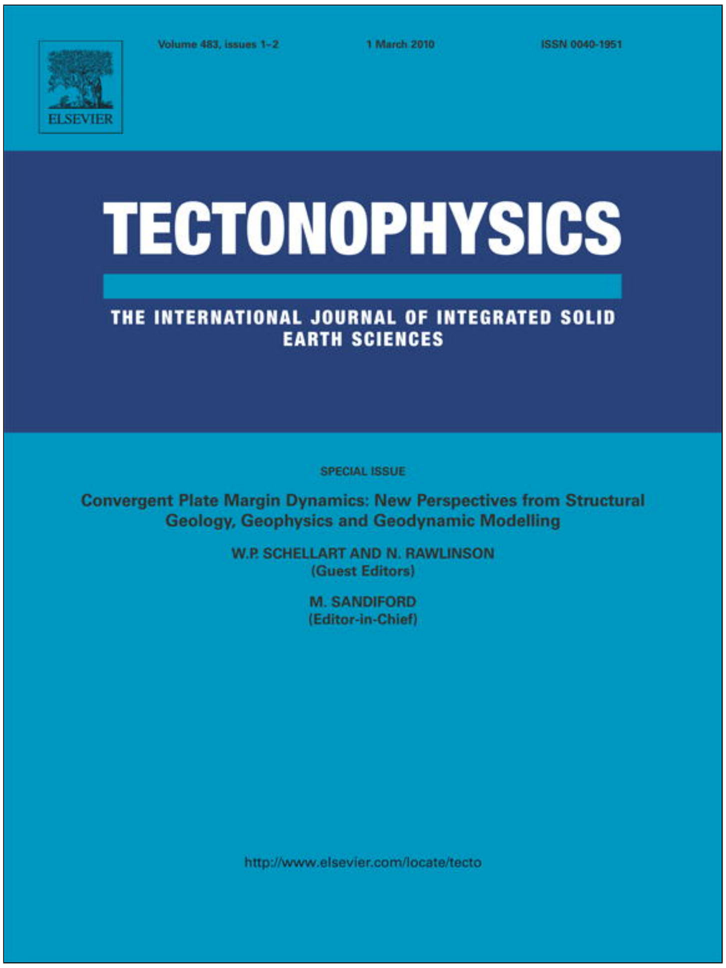

ELSEVIER
Volume 483, issues 1–2
1 March 2010
ISSN 0040-1951
TECTONOPHYSICS
THE INTERNATIONAL JOURNAL OF INTEGRATED SOLID EARTH SCIENCES
SPECIAL ISSUE
Convergent Plate Margin Dynamics: New Perspectives from Structural Geology, Geophysics and Geodynamic Modelling
W.P. SCHELLART AND N. RAWLINSON
(Guest Editors)
M. SANDIFORD
(Editor-in-Chief)
http://www.elsevier.com/locate/tecto

Tectonophysics 483 (2010) 125–134

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

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

Anne Replumaz [a,*], Ana M. Negredo [b], Stéphane Guillot [a], Antonio Villaseñor [c]

[a] Université Grenoble I, Joseph Fourier, CNRS, BP 53, 38041 Grenoble Cedex, France
[b] Dept. of Geophysics, Facultad CC. Físicas, Universidad Complutense de Madrid. Av. Complutense, 28040 Madrid, Spain
[c] Instituto de CC. de la Tierra 'Jaume Almera', CSIC, C/Lluís Solé i Sabarís, s/n. 08028 Barcelona, Spain

A R T I C L E I N F O

Article history:
Received 5 March 2009
Received in revised form 2 September 2009
Accepted 9 October 2009
Available online 18 October 2009

Keywords:
Continental subduction
Lithospheric extrusion
Tomography
Underthrusting
India/Asia collision
Convergence
Break-off
Andaman Sea
Burma

A B S T R A C T

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

* Corresponding author.
E-mail address: anne.replumaz@ujf-grenoble.fr (A. Replumaz).

0040-1951/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2009.10.007

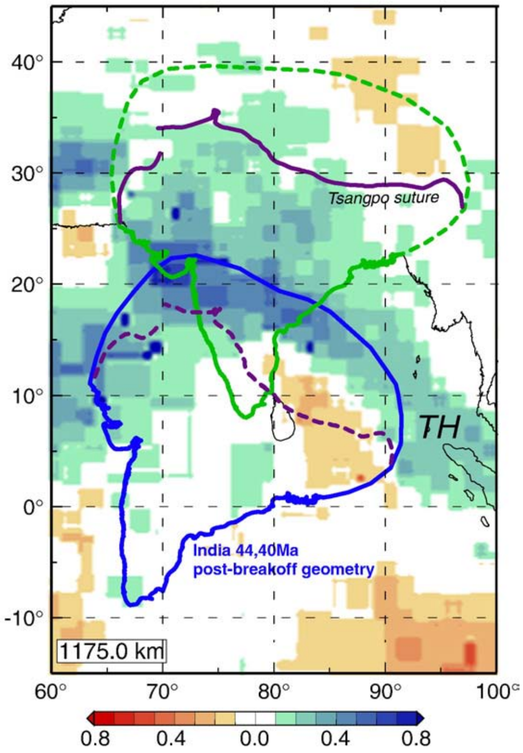


Fig. 1. horizontal section of the *P*-wave global tomographic model modified from Bijwaard et al. (1998). Anomaly TH is interpreted as marking the location of late Mesozoic TetHyan oceanic subduction until slab break-off at about 45 Ma. This anomaly has been used draw the geometry of continental India 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.

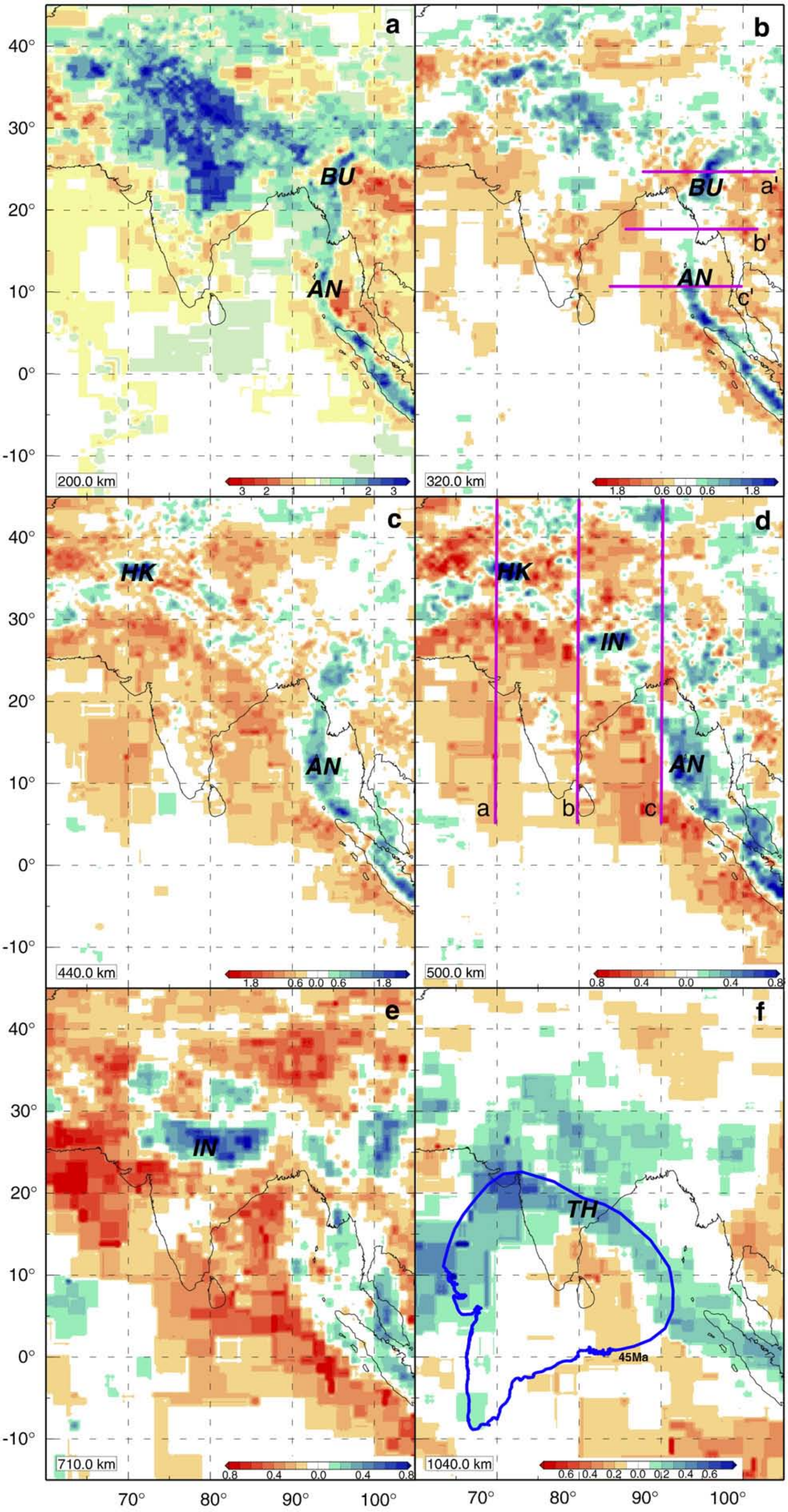
To constrain the timing of subduction onset we adopt the assumption that in the absence of significant lateral mantle advection, the tip of a steeply subducting slab sinks into the mantle without lateral migration (e.g. Uyeda and Kanamori, 1979; Heuret and Lallemand, 2005). The regional mantle advection 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.


a
b
c
d
e
f
BU
AN
a'
b'
c'
HK
IN
TH
45Ma
a
b
c
200.0 km
320.0 km
440.0 km
500.0 km
710.0 km
1040.0 km
40°
30°
20°
10°
0°
-10°
70°
80°
90°
100°

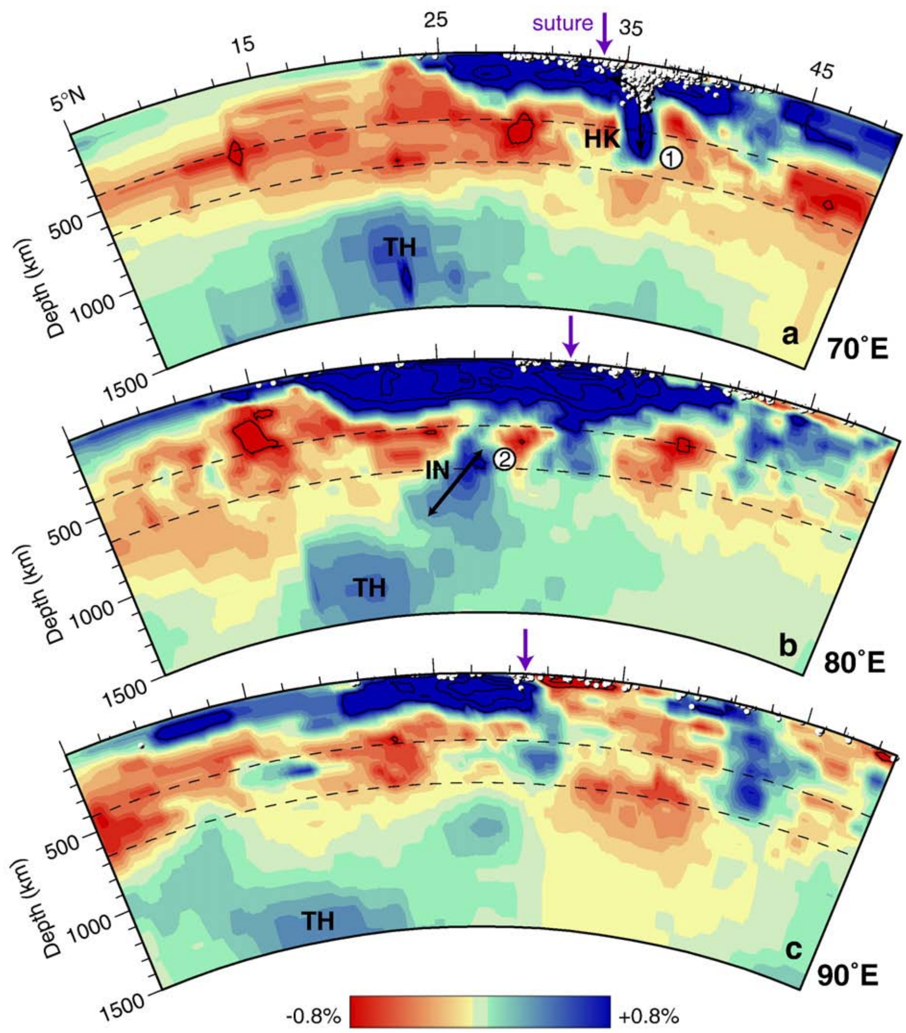


Fig. 3. tomographic cross-sections perpendicular to collision front (location on Fig. 2d), showing distinct anomalies from west to east. a: the on-going subduction of Indian lithosphere beneath the Hindu Kush (HK anomaly). b: the IN anomaly suggests a geometry of a slab dipping southwards. c: no anomaly is observed beneath India below 200 km. Shallow high wavespeed anomalies north of the Tsangpo suture (purple arrow) show significant underthrusting of India beneath the western Tibet (a and b) but not beneath the eastern Tibet (c).

the study region exhibits a high level of seismicity (see regional ray coverage maps in Replumaz et al., 2009). The long high wavespeed TH anomaly trends NW–SE (Fig. 2), and appears as laterally continuous along the entire plate boundary from at least 1600 km to 1100 km depths. Above the TH anomaly and north of it, there are several distinct high wavespeed anomalies labelled as IN, HK, BU and AN in Figs. 2–4. These anomalies appear laterally unconnected with each other, which reflects the complex evolution of subduction processes during India/Asia collision (Fig. 5).

The HK anomaly (beneath Hindu Kush) occurs from the surface down to 600 km depth. This anomaly has been interpreted as related to the ongoing subduction of the Indian lithosphere under the Hindu Kush mountains (Van der Voo et al., 1999; Koulakov and Sobolev, 2006; Negredo et al., 2007). Hypocenters reach depths of about 300 km and describe a well-defined Wadati-Benioff zone (e.g. Chatelain et al., 1980; Burtman and Molnar, 1993; Fan et al., 1994; Fig. 3a). The seismically active portion of the slab is shallower than the extent of the ~600 km deep imaged slab, as it extends deeper than the fragile/ductile transition depth predicted by Negredo et al. (2007).

The IN anomaly (beneath India) occurs from ~900 km up to ~500 km depth. This anomaly is not visible at the top of the mantle transition zone. This anomaly appears unconnected both with the deep anomaly TH and with shallower high wavespeed anomaly interpreted as related to the Indian craton. In map view, the east–west anomaly extent is reduced by 50% at the top of the anomaly (Fig. 2d–e), as its vertical extent increases from west (300 km) to east (700 km). The vertical tomographic section through the anomaly suggests that it dips to the south (Fig. 3b).

The BU anomaly (beneath Burma) reaches depths of about 400 km, while hypocenters reach depths of about 200 km and describe a well-defined Wadati-Benioff zone (Fig. 4a). It has been interpreted as related to the ongoing subduction of the Burmese microplate (Ni et al., 1989; Li et al., 2008). Seismic tomography images indicate that this anomaly appears unconnected with the AN anomaly to the south, and also with shallower high wavespeed anomaly interpreted as related to the Indian craton to the west (Figs. 2 and 4).

The anomaly AN (beneath Andaman) occurs above 600 km. It is separated by a kink around 4°N, from the anomaly beneath Sumatra. At shallow levels (Fig. 2a–b), the anomaly below Andaman and northern Sumatra appears to be gently curved, whilst at depth (Fig. 2c–d) the anomaly forms a relatively sharp fold. The shape and position of this fold agree well with high wavespeed anomalies shown in previous studies (e.g. Pesicek et al., 2008). The high velocity anomalies are prominent and positive at depth (+1%) but change to relatively low and negative *P*-wave anomalies (−0.6 to −0.2%) above 200 km between 9.5 and 12.5 °N (Fig. 4c). This change to negative

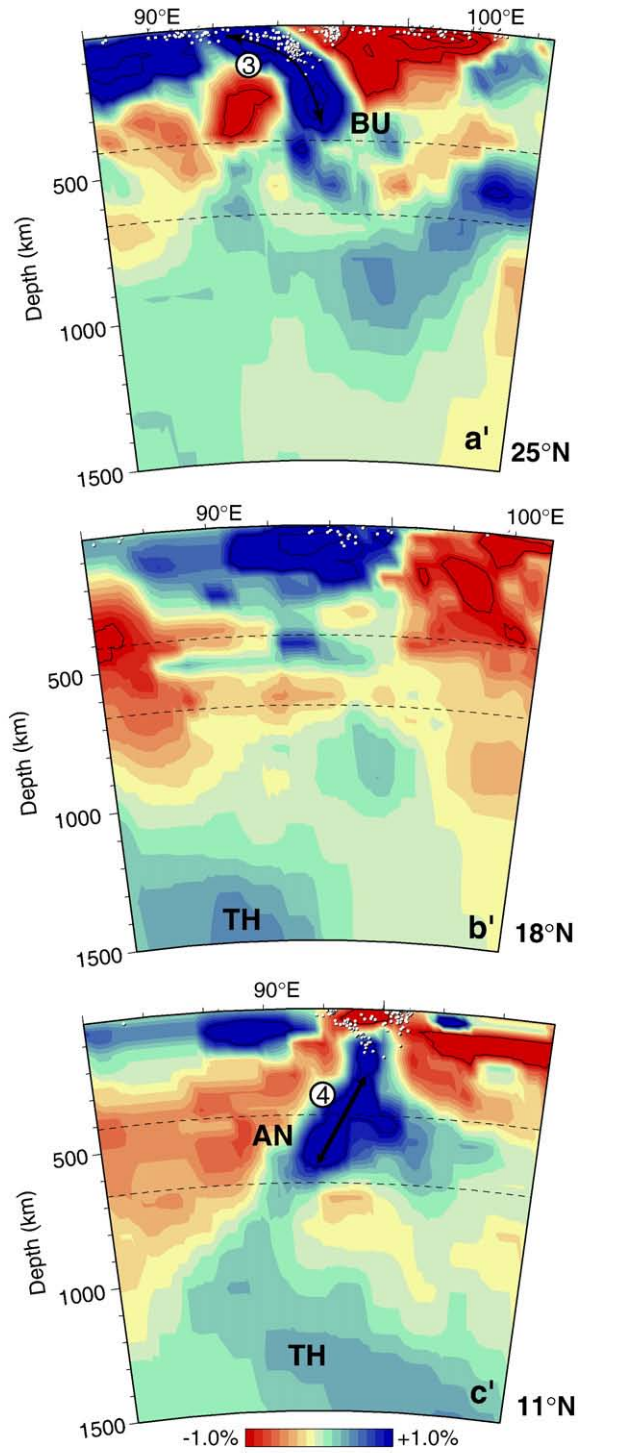


Fig. 4. tomographic cross-sections perpendicular to the Burma/Andaman trench (location on Fig. 2b), showing vertical extent of anomalies BU (a′) and AN (c′), and absence of subduction beneath the south of Burma (b′).

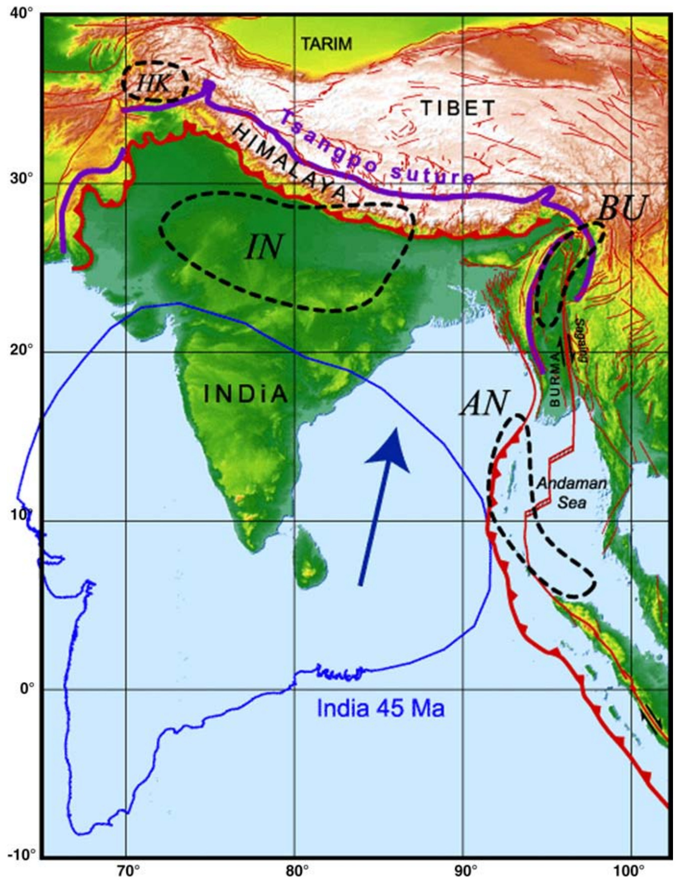


Fig. 5. black dotted lines: horizontal projection of tomographic anomalies north of the position of India at 45 Ma (in solid blue); purple lines: suture, representing the present-day boundary between Indian and Asian crusts; blue arrow: velocity vector of India approximately N20°, 5 cm/yr, with respect to stable Siberia. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

velocity anomaly, where one should expect an oceanic slab with a well-defined Wadati-Benioff zone to be present, has been recently interpreted as the subduction of the Ninetyeast Ridge, with a lithosphere thinner and warmer than surrounding oceanic lithosphere (Miller and Lee, 2008; Shapiro et al., 2008).

The shallow horizontal section at 200 km (Fig. 2a) shows fast *P*-wave propagation beneath India and western Tibet, and slow propagation beneath the eastern part of the Tibetan Plateau. Tomographic vertical sections across Tibet, also show shallow high wavespeed anomalies north of the Indus Tsangpo suture to the west (Fig. 3a–b), and slow below the northern part of the eastern Plateau (Fig. 3c).

4. Anomaly HK recording on-going Indian lithospheric subduction

Several geological and geophysical studies suggest the presence of two converging subduction zones in the western syntaxis of the India–Eurasia collision zone, with steep northward subduction of Indian lithosphere beneath the Hindu Kush and southward subduction of Asian lithosphere under the Pamir (e.g. Chatelain et al., 1980; Burtman and Molnar, 1993; Fan et al., 1994). The present-day ongoing subduction of the Indian lithosphere under the Hindu Kush is nearly vertical down to ~600 km (Van der Voo et al., 1999; Koulakov and Sobolev, 2006; Negredo et al., 2007). The timing of this subduction process has been investigated by Negredo et al. (2007). Considering a static position of the subduction hinge, they inferred that subduction began at about 8 Ma ago, when the northern boundary of India reached the location of HK anomaly (Fig. 6a). A velocity of subduction under Hindu Kush as high as 5 cm yr^{-1} during the last 8 Ma is then required to reproduce the observed length of the Indian slab. This high velocity implies that all the recent convergence between India and Eurasia in the Hindu Kush region would be accommodated by subduction of the Indian lower crust and lithospheric mantle.

Recent studies suggest an ongoing process of slab break-off either on the basis of tomographic vertical sections between 71 and 73°E showing slab thinning at about 250 km depth (Koulakov and Sobolev, 2006) and on the basis of the analysis of a cluster of intermediate-

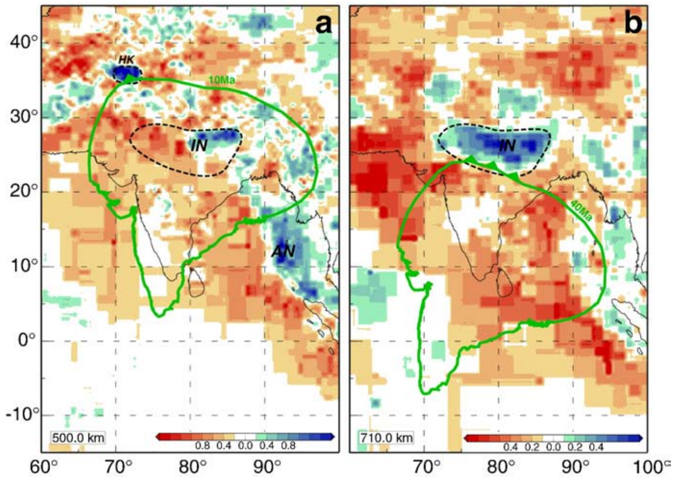


Fig. 6. a: horizontal section at 500 km. The northern boundary of India reaches the HK anomaly at ~10 Ma (green contour). b: horizontal section at 710 km. The northern boundary of India reaches the IN anomaly at ~40 Ma (green contour). Only the ~1500 km long portion of the continent overlapping anomaly IN was subducted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

depth earthquakes suggesting the presence of ductile faults bounding an elongated boudin (Lister et al., 2008).

5. Anomaly IN recording past Indian lithospheric subduction

Positive IN anomaly has been interpreted as mapping a fragment of slab of Indian continental lithosphere (Van der Voo et al., 1999; Chemenda et al., 2000; DeCelles et al., 2002). In particular the study by Replumaz et al. (2009) provides quantitative constraints for the spatio-temporal evolution of the related subduction process. We briefly summarise here their results and then discuss them in the context of overall post break-off evolution of the collision zone. After the first break-off at about 45 Ma, they suggest that a new phase of subduction of India lithosphere took place north of the former oceanic subduction locus. By comparing the position of the northern boundary of India at different times with the position of the base of the IN anomaly (Fig. 6b), they have inferred that subduction of a 1500-km-long portion of the northwestern Indian margin started at about 40–30 Ma. They have interpreted that this subduction phase ended by a second slab break-off process, evidenced by the interruption of IN anomaly at the top of the mantle transition zone. On the basis of rough estimates of slab length and dip along different tomographic cross sections they suggest that slab tearing started at ~25 Ma at the western end of the slab and propagated eastwards until complete break-off at ~15–10 Ma.

It is interesting to compare present-day subduction under the Hindu Kush with the postulated subduction associated with IN anomaly, as present-day slab tearing proposed by different authors can be similar to the IN slab break-off process. The absence of deep seismicity beneath the Himalaya is in contrast with the continuous seismic zone reaching a depth over 300 km beneath the Hindu Kush (e.g. Pegler and Das, 1998; Negredo et al., 2007), thus suggesting the absence of present-day steep subduction under the Himalaya.

Furthermore, vertical slab sinking on the Hindu Hush slab is assumed to be consistent with a static position of the subduction hinge. In contrast, our interpretation of roll-over geometry of the Indian slab is compatible with the India/Asia plate boundary advancing northward (e.g. Tapponnier et al., 2001; DeCelles et al.,

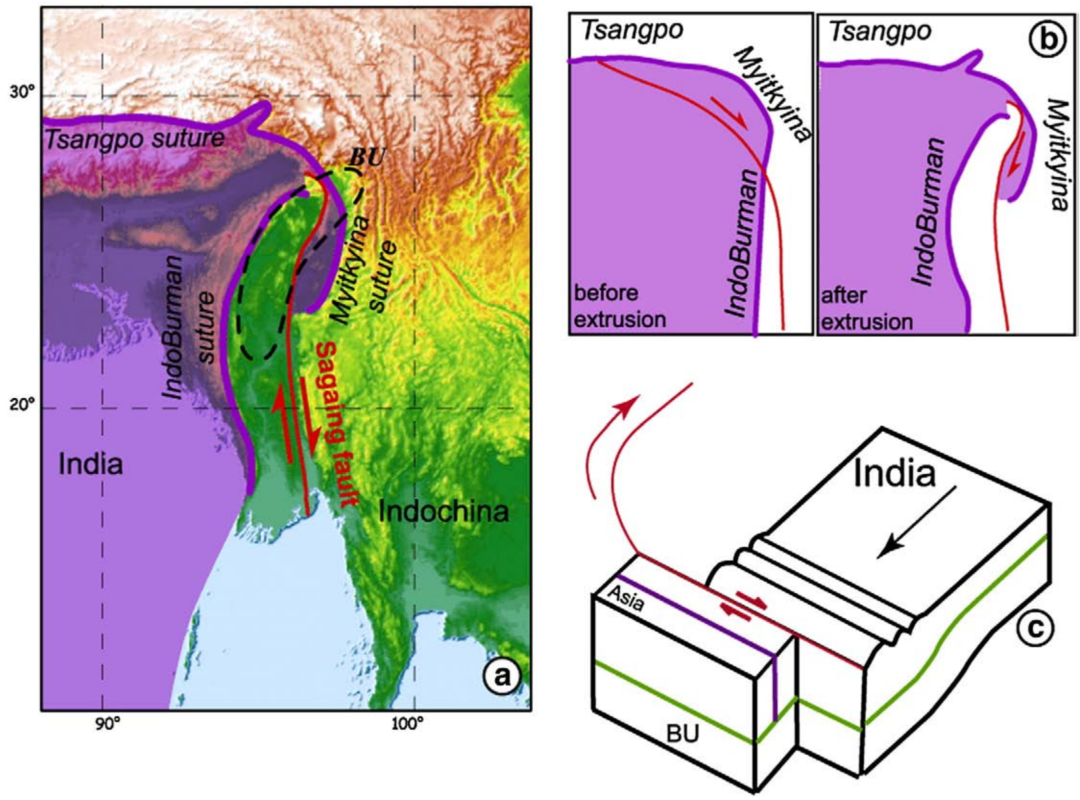


Fig. 7. a/ map of the peculiar geometry of the suture (purple line) between India (in shaded purple) and Asia in northern Burma. The area between the Myitkyina suture and the Sagaing Fault corresponds to a portion of Indian crust. b/ Before the extrusion of Indochina, this portion of Indian crust slid was most likely initially located along the northern margin of India, bounded by a continuous plate boundary, with the Myitkyina suture being located between the Tsangpo and the Indo-Burman sutures. It slid along the Sagaing fault, most probably during the extrusion of Indochina. c/ We propose here that the Burmese microplate belonged to the northern margin of India and slid southwards, in a similar way to the portion of Indian crust. Green line: intracrustal decollement.

2002; Replumaz and Tapponnier, 2003). This motion, combined with the hypothesis of the no lateral migration of the tip of the slab, should lead to this kind of overturned geometry (Fig. 3b). Similar roll-over slab geometries have been obtained in numerical models (Manea and Gurnis, 2007) and laboratory experiments (Schellart, 2005; Heuret et al., 2007).

6. Anomaly BU recording recent Indian lithospheric extrusion

The BU anomaly is located at the northeastern corner of the Indian plate (Fig. 5). Its horizontal projection is roughly located between the Sagaing Fault and the Indo-Burman suture (Fig. 7). The low wavespeed zone between the BU anomaly and the fast anomaly corresponding to the Indian craton further to the west (Fig. 2a), leads to the interpretation that this microplate is independent and unconnected with the craton. This anomaly has been interpreted in terms of the subduction of the Burmese microplate (Ni et al., 1989; Huang and Zhao, 2006; Li et al., 2008). Furthermore, tomography images showing fast anomaly interruption to the north of the Andaman Sea (Figs. 2b and 4b; Miller and Lee, 2008; Shapiro et al., 2008) indicate that the Burmese microplate appears also to be unconnected with the slab imaged by AN anomaly.

According to regional geologic studies by Le Dain et al. (1984) and Armijo et al. (1989), the area between the Myitkyina suture and the Sagaing Fault corresponds to a portion of Indian crust. They proposed that this crust slid southwards along the Sagaing Fault, most probably during the extrusion of Indochina (between about 30 and 15 Ma; Briais et al., 1993; Leloup et al., 2001). This portion of Indian crust was most likely initially located along the northern margin of India, bounded by a continuous plate boundary, with the Myitkyina suture being located between the Tsangpo and the Indo-Burman sutures. This process is illustrated in a schematic way in Fig 7b. Consistently with this interpretation, we propose here that the Burmese microplate belonged to the northern margin of India and slid southwards as it was shifted out-of-the-way of the northwards path of India, in a similar way to the Indochina block. Following our interpretation, the Burmese microplate was detached by a strike-slip fault and turned around the eastern syntaxis (Fig. 7c). After this shifting, subduction of the lithospheric mantle of the Burmese plate happened as it was confined between India and Indochina. It is worth noting that the crustal portion extruded does not coincide with the BU anomaly location, thus suggesting a possible decoupling between the crust (or at least the upper crust) and the lithospheric mantle.

7. Anomaly AN recording past Indian lithospheric extrusion

The AN anomaly is separated by a kink around 4°N from the anomaly beneath Sumatra. Provided that this kink marks not only a change in the strike and dip of the anomalies, but also a dramatic change in their length, we interpret that they map two different slabs. In contrast Pesicek et al. (2008) interpret that both anomalies map a laterally continuous but strongly folded slab. It is worth noting that a number of tomographic studies consistently show that fast seismic anomalies mapped east of about 95°E beneath Sumatra and Java penetrate into the lower mantle (Van der Voo et al., 1999; Hafkenscheid et al., 2001; Replumaz et al., 2004; Richards et al., 2007), whereas fast anomaly under the Andaman Sea reaches only about 600 km depth (Fig. 4c). Therefore we suspect that a different kind of process is responsible for each anomaly.

A comparison between the geometry of AN anomaly and reconstructed positions of India at different times indicates that this anomaly (at least its northern half) strikes parallel to the path of the northeastern corner of India (Fig. 8). This is also the case for BU anomaly. This differs significantly to the scenario proposed here relating IN anomaly to frontal subduction of northwestern, as IN

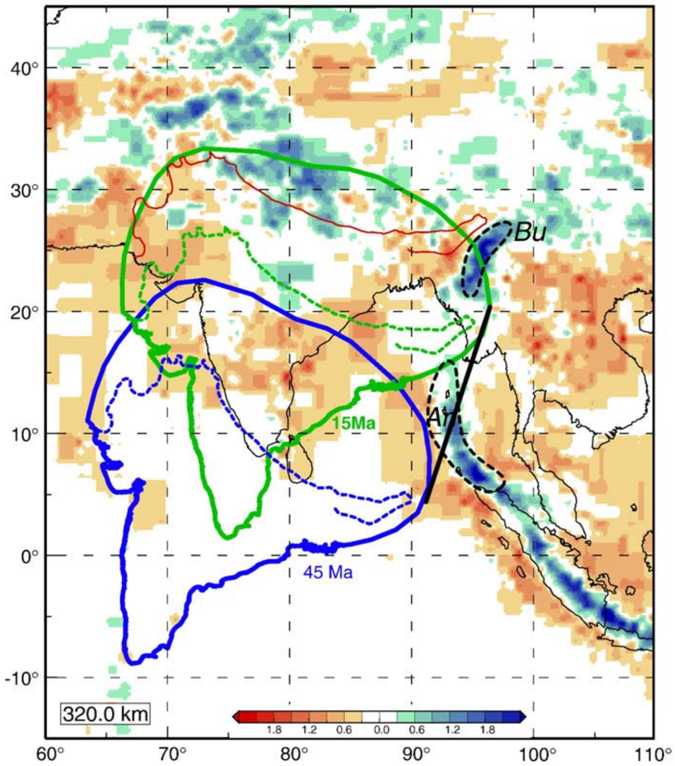


Fig. 8. horizontal tomographic section at 320 km. A comparison between the geometry of AN anomaly and reconstructed positions of India at different times indicates that this anomaly (at least its northern half) strikes parallel to the path of the northeastern corner of India (black line). This is also the case for BU anomaly. The position of anomaly AN compared to India position at 15 Ma is similar to the position of the anomaly BU compared to the present-day position of India. We propose that the AN anomaly corresponds to a portion of Indian lithosphere extruded southeastwards before the extrusion of the portion corresponding to slab BU.

anomaly is oriented perpendicular to the motion of India. Therefore we prefer to discard a similar kind of process.

In contrast we suggest that a similar process interpreted as responsible for BU anomaly likely cause anomaly AN. In this sense, it is worth remarking that the position of anomaly AN compared to India position at 15 Ma is similar to the position of the anomaly BU compared to the present-day position of India. We therefore propose that the AN anomaly corresponds to a portion of Indian lithosphere extruded southeastwards before the extrusion of the portion corresponding to slab BU (Fig. 9).

The relatively low *P*-wave above 200 km between 9.5 and 12.5 °N (Fig. 4c) has been recently interpreted as the subduction of the Ninetyeast Ridge, with a lithosphere thinner and warmer than surrounding oceanic lithosphere (Miller and Lee, 2008; Shapiro et al., 2008). The high *P*-wave velocity of the anomaly below 200 km depth suggests that another type of lithosphere subducted before the Ninetyeast Ridge. Following our interpretation this lithosphere corresponds to a portion of Indian lithosphere. The vertical length of the thick anomaly, probably corresponding to the continental portion of the slab, is of about 300 km (Fig. 4c).

8. Discussion: Indian subduction, underthrusting, and extrusion budget

As we mentioned in the introduction section, the area comprised between the tomographically inferred northern boundary of India at ~45 Ma (after being rotated on the sphere up to the present; green dashed contour in Figs. 1 and 10) and the location of continental suture provides an estimate of the total amount of Indian lithosphere consumed since ~45 Ma. Possible mechanisms to consume this

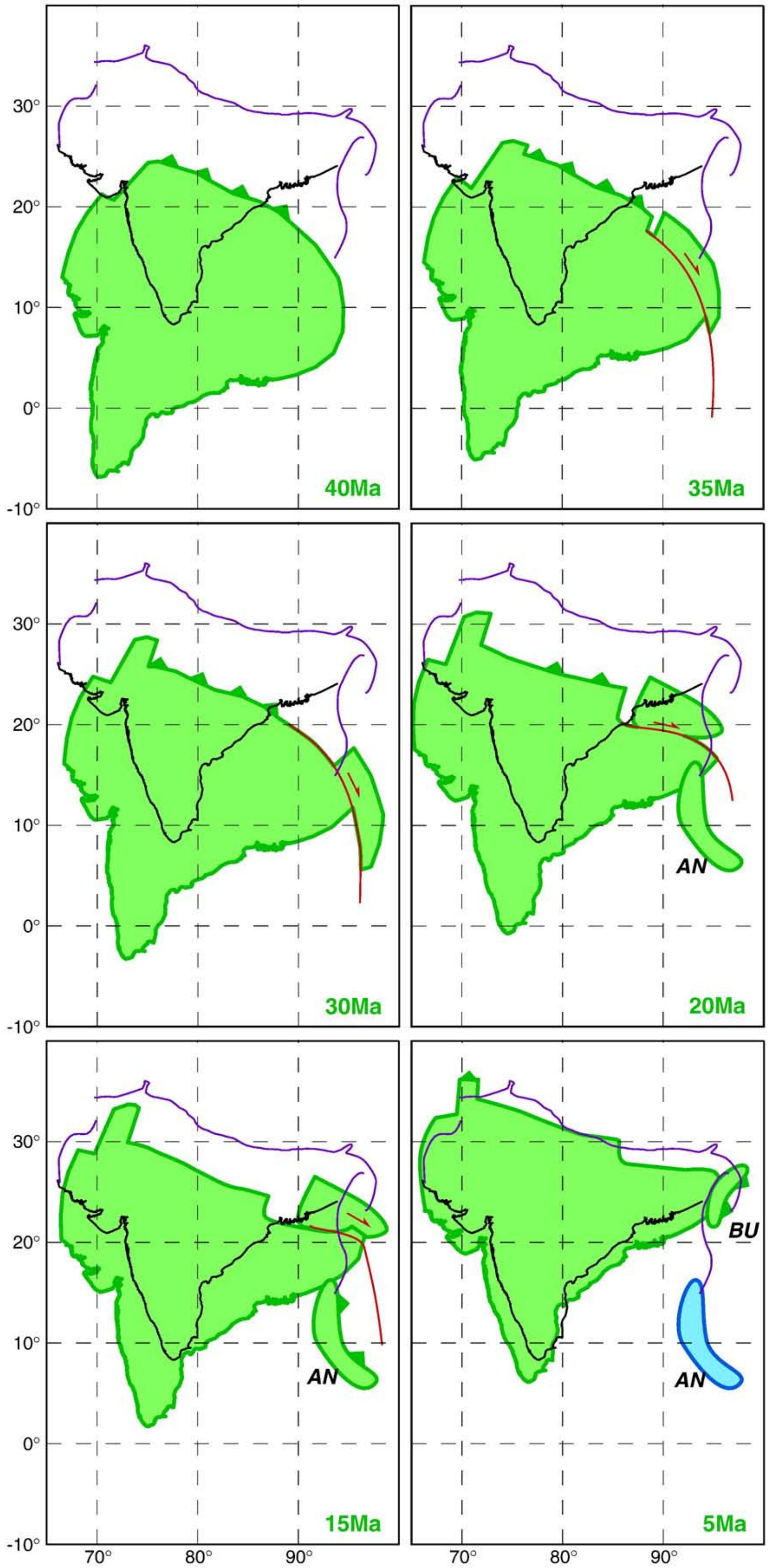


Fig. 9. Spatio-temporal evolution of multiple episodes of continental subduction related to tomographic anomalies HK, IN, BU and AN. To the western part of the collision zone, two successive episodes of steep subduction of the northern margin of India occurred. To the east of the collision zone, two successive episodes of southeastward extrusion followed by subduction occurred. Both extruded portions were initially located along the northern margin of India.

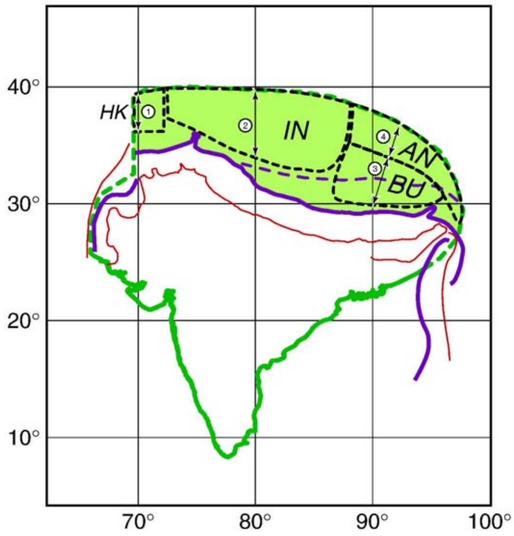


Fig. 10. the area (green shaded area) comprised between the tomographically inferred northern boundary of India at ~45 Ma (after being rotated on the sphere up to the present; green dashed line) and the location of continental suture (purple line) provides an estimate of the total amount of Indian lithosphere consumed since ~45 Ma. Anomalies HK, IN, BU and AN are interpreted as the result of successive continental subduction episodes, which successively removed a portion of the northern margin of Indian lithosphere (black dotted lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

'missing' India (green shaded area in Fig. 10) are subduction, underthrusting or extrusion.

Anomalies HK, IN, BU and AN are interpreted as the result of successive continental subduction episodes, which were preceded by southeastwards extrusion in the case of slabs under Burman and Andaman Sea (Fig. 9). Each episode successively removed a portion of the northern margin of Indian lithosphere. We have measured along different sections the anomalies interpreted in this study (Figs. 2–4) and have represented them in Fig. 10. The portions corresponding to HK and IN anomalies cover most of the western part of this 'missing' India. We therefore conclude that subduction mainly consumed Indian lithosphere under the western Tibetan Plateau (Fig. 10). The non-covered area can be attributed to the portion of northern India most likely consumed by underthrusting after slab break-off at ~15 Ma. According to our interpretation, the portions corresponding to BU and AN anomalies, presently trending north–south, were initially roughly oriented east–west along the northern margin of India (Fig. 9). For this reason, they are represented with this orientation in Fig. 10. The amount of Indian lithospheric mantle interpreted to have been removed by extrusion covers the entire eastern part of this 'missing' India, which leads us to infer that extrusion was the main mechanism to consume Indian lithosphere in the eastern part of the collision zone. Southeastwards extrusion thus appears as a plausible mechanism alternative to normal dip subduction and to underthrusting (including low angle subduction).

Shallow seismic tomography has not yet provided unequivocal constraints on the present-day northward extent of underthrusting beneath Tibet. Some surface wave studies reveal fast wave propagation beneath much of Tibet (e.g., Shapiro and Ritzwoller, 2002; Priestley et al., 2006) and suggest that the entire plateau is underlain by a relatively cold lithospheric mantle (to 225–250 km depth). In contrast, the *P*-wave tomographic model presented here and the one by Li et al. (2008) consistently find fast *P*-wave propagation beneath western Tibet, and slow one beneath the eastern parts of Tibet (Fig. 2a). Our inferences are consistent with *P*-wave tomographic models and with recent lithospheric modelling (Jimenez-Munt et al., 2008) as they provide support for the absence of significant underthrusting under central and eastern Tibet. Aside from these discrepancies between different tomographic models, they consistently find no evidences of steep frontal subduction in the upper mantle beneath central and eastern Tibetan Plateau (Huang and Zhao, 2006; Priestley et al., 2006; Li et al., 2008).

This study highlights the fundamentally different evolution at lithospheric scales of the western and eastern parts of the collision zone. This lateral variation in the processes that accommodated convergence is in contrast with the continuity of the Tsangpo suture, which represents the boundary between India and Asia at crustal level (Fig. 5). This suggests a strong decoupling between the Indian crust and lithospheric mantle.

Acknowledgements

On the French side, the project is funded by INSU-CNRS grants grants and by the Ministère des Affaires Etrangères et Européennes (Partenariat Hubert Curien-Picasso d'Egide). On the Spanish side, this work was funded by the Spanish Plan Nacional of MEC projects CTM200613666-C02-02/MAR and CTM2005-08071-C03-03/MAR; by UCM Research Groups; and by HF2008-0089. This is a contribution of the Consolider Ingenio 2010 team CSD2006-00041 (TOPO-IBERIA). Tomographic images have been made with the graphic program P developed by Wim Spakman. Thanks to Paul Tapponnier and Rob van der Hilst from fruitful discussions, encouragements and advices. We thanks two anonymous reviewers as well as associated editor WP Schellart for constructive comments that help us to improve our manuscript.

References

Armijo, R., Tapponnier, P., Tonglin, H., 1989. Late Cenozoic right-lateral strike-slip faulting in southern Tibet. J. Geophys. Res. 94, 2787–2838.

Bellahsen, N., Faccenna, C., Funiciello, F., 2005. Dynamics of subduction and plate motion in laboratory experiments: insights into the "plate tectonics" behavior of the Earth. J. Geophys. Res. 110, B01401. doi:10.1029/2004JB002999.

Behounkova, M., Cizkova, H., 2008. Long-wavelength character of subducted slabs in the lower mantle. Earth Planet. Sci. Lett. 275. doi:10.1016/j.epsl.2008.07.059.

Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. J. Geophys. Res. 103, 30055–30078.

Billen, M.I., Hirth, G., 2007. Rheologic controls on slab dynamics. Geochem. Geophys. Geosyst. 8. doi:10.1029/2007GC001597.

Briais, A., Patriat, Ph., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea, implications for the Tertiary tectonics of SE Asia. J. Geophys. Res. 98, 6299–6328.

Burtman, V.S., Molnar, P., 1993. Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. Spec. Pap.Geol. Soc. Am. 281, 76.

Chatelain, J.L., Roecker, S.W., Hatzfeld, D., Molnar, P., 1980. Microearthquake seismicity and fault plane solutions in the HinduKush region and their tectonic implications. J. Geophys. Res. 85, 1365–1387.

Chemenda, A.I., Burg, J.P., Mattauer, M., 2000. Evolutionary model of the Himalaya–Tibet system: geopoem based on new modelling, geological and geophysical data. Earth Planet. Sci. Lett. 174, 397–409.

Christensen, U.R., 1996. The influence of trench migration on slab penetration into the lower mantle. Earth Planet. Sci. Lett. 140, 27–39.

DeCelles, P.G., Robinson, D.M., Zandt, G., 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. Tectonics 21. doi:10.1029/2001tc001322.

Engdahl, E.R., van der Hilst, R., Buland, R., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull. Seismol. Soc. Am. 88, 722–743.

Enns, A., Becker, T.W., Schmeling, H., 2005. The dynamics of subduction and trench migration for viscosity stratification. Geophys. J. Int. 160, 761–775. doi:10.1111/j.1365-246X.2005.02519.x.

Fan, G., Ni, J.F., Wallace, T.C., 1994. Active tectonics of the Pamirs and Karakorum. J. Geophys. Res. 99, 7131–7160.

Guillot, S., Garzanti, E., Baratoux, D., Marquer, D., Mahéo, G., de Sigoyer, J., 2003. Reconstructing the total shortening history of the NW Himalaya. Geochem. Geophys. Geosyst. 4. doi:10.1029/2002gc000484.

Hafkenscheid, E., Buiter, S.J.H., Wortel, M.J.R., Spakman, W., Bijwaard, H., 2001. Modelling the seismic velocity structure beneath Indonesia: a comparison with tomography. Tectonophysics 333, 35–46.

Hafkenscheid, E., Wortel, M.J.R., Spakman, W., 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. J. Geophys. Res. 111. doi:10.1029/2005jb003791.

Heuret, A., Lallemand, S., 2005. Plate motions, slab dynamics and back-arc deformation. Phys. Earth Planet. Inter. 149, 31–51. doi:10.1016/j.pepi.2004.08.022.

Heuret, A., Funiciello, F., Faccenna, C., Lallemand, S., 2007. Plate kinematics, slab shape and back-arc stress: a comparison between laboratory models and current subduction zones. Earth Planet. Sci. Lett. 256, 473–483. doi:10.1016/j.epsl.2007.02.004.

Huang, J.L., Zhao, D.P., 2006. High-resolution mantle tomography of China and surrounding regions. J. Geophys. Res. 111. doi:10.1029/2005jb004066.

Jimenez-Munt, I., Fernandez, M., Verges, J., Platt, J.P., 2008. Lithosphere structure underneath the Tibetan Plateau inferred from elevation, gravity and geoid anomalies. Earth Planet. Sci. Lett. 267, 276–289. doi:10.1016/s0012-821x(04)00070-6.

Kohn, M.J., Parkinson, C.D., 2002. Petrologic case for Eocene slab breakoff during the Indo-Asian collision. Geology 30, 591–594.

Koulakov, I., Sobolev, S.V., 2006. A tomographic image of Indian lithosphere break-off beneath the Pamir-Hindukush region. Geophys. J. Int. 164, 425–440.

Le Dain, A.Y., Tapponnier, P., Molnar, P., 1984. Active faults and tectonics of Burma and surrounding regions. J. Geophys. Res. 89, 453–472.

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., Manickavasagam, R.M., 2005. The onset of India–Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. Earth Planet. Sci. Lett. 234, 83–97. doi:10.1016/j.epsl.2005.02.038.

Leloup, P.H., Arnaud, N., Lacassin, R., Kienast, J.R., Harrison, T.M., Trong, T.T.P., Replumaz, A., Tapponnier, P., 2001. New constraints on the structure, thermochronology, and timing of the Ailao Shan-Red River shear zone, SE Asia. J. Geophys. Res. 106, 6683–6732.

Le Pichon, X., Fournier, M., Jolivet, L., 1992. Kinematics, topography, shortening, and extrusion in the India–Eurasia collision. Tectonics 11, 1085–1098.

Li, Chang, van der Hilst, D., Meltzer, A.S., Engdahl, E.R., 2008. Subduction of the Indian lithosphere beneath the Tibetan Plateau and Burma. Earth Planet. Sci. Lett. 274. doi:10.1016/j.epsl.2008.07.016.

Lister, G., Kennett, B., Richards, S., Forster, M., 2008. Boudinage of a stretching slablet implicated in earthquakes beneath the Hindu Kush. Nat. Geosci. 1, 196–201. doi:10.1038/ngeo132.

Manea, V., Gurnis, M., 2007. Subduction zone evolution and low viscosity wedges and channels. Earth Planet. Sci. Lett. 264, 22.

Mattauer, M., 1986. Intracontinental subductions in tertiary mountains belts of Asia — relationships with strike–slip faults. Bull. Soc. Geol. Fr. 2, 143–157.

Miller, M.S., Lee, C.T.A., 2008. Possible chemical modification of oceanic lithosphere by hotspot magmatism: seismic evidence from the junction of Ninetyeast Ridge and the Sumatra–Andaman arc. Earth Planet. Sci. Lett. 265, 386–395. doi:10.1016/j.epsl.2007.10.039.

Molnar, P., England, P., Martinod, J., 1993. Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon. Rev. Geophys. 31, 357–396.

Najman, Y., Carter, A., Oliver, G., Garzanti, E., 2005. Provenance of Eocene foreland basin sediments, Nepal: constraints to the timing and diachroneity of early Himalayan orogenesis. Geology 33, 309–312.

Negredo, A.M., Replumaz, A., Villasenor, A., Guillot, S., 2007. Modeling the evolution of continental subduction processes in the Pamir-Hindu Kush region. Earth Planet. Sci. Lett. 259, 212–225. doi:10.1016/j.epsl.2007.04.043.

Ni, J.F., Guzman-Speziale, M., Bevis, M., Holt, W.E., Wallace, T.C., Seager, W., 1989. Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone. Geology 17, 68–71.

Patriat, P., Achache, J., 1984. India Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature 311, 615–621.

Pegler, G., Das, S., 1998. An enhanced image of the Pamir-Hindu Kush seismic zone from relocated earthquake hypocenters. Geophys. J. Int. 134, 573–595.

Pesicek, J.D., Thurber, C.H., Widiyantoro, S., Engdahl, E.R., DeShon, H.R., 2008. Complex slab subduction beneath northern Sumatra. Geophys. Res. Lett. 35. doi:10.1029/2008GL035262.

Priestley, K., Debayle, E., McKenzie, D., Pilidou, S., 2006. Upper mantle structure of eastern Asia from multimode surface waveform tomography. J. Geophys. Res. 111. doi:10.1029/2005jb004082.

Replumaz, A., Tapponnier, P., 2003. Reconstruction of the deformed collision zone between India and Asia by backward motion of lithospheric blocks. J. Geophys. Res. 108. doi:10.1029/2001jb000661.

Replumaz, A., Karason, H., van der Hilst, R.D., Besse, J., Tapponnier, P., 2004. 4-D evolution of SE Asia's mantle from geological reconstructions and seismic tomography. Earth Planet. Sci. Lett. 221, 103–115. doi:10.1016/s0012-821x(04)00070-6.

Replumaz, A., Negredo, A.M., Villaseñor, A., Guillot, S., 2009. Indian continental subduction and slab break-off during collision, in review Terra Nova.

Ribe, N.M., Stutzmann, E., Ren, Y., van der Hilst, R., 2007. Buckling instabilities of subducted lithosphere beneath the transition zone. Earth Planet. Sci. Lett. 254, 173–179. doi:10.1016/j.epsl.2006.11.028.

Richards, S., Lister, G., Kennett, B., 2007. A slab in depth: three-dimensional geometry and evolution of the Indo-Australian plate. Geochem. Geophys. Geosyst. 8. doi:10.1029/2007gc001657.

Rowley, D.B., 1996. Age of initiation of collision between India and Asia: a review of stratigraphic data. Earth Planet. Sci. Lett. 145, 1–13.

Schellart, W.P., 2005. Influence of the subducting plate velocity on the geometry of the slab and migration of the subduction hinge. Earth Planet. Sci. Lett. 231, 197–219. doi:10.1016/j.epsl.2004.12.019.

Schellart, W.P., 2008. Subduction zone trench migration: slab driven or overriding-plate-driven? Phys. Earth Planet. Inter. 73–88. doi:10.1016/j.pepi.2008.07.040.

Shapiro, N.M., Ritzwoller, M.H., 2002. Monte-Carlo inversion for a global shear-velocity model of the crust and upper mantle. Geophys. J. Int. 151, 88–105.

Shapiro, N.M., Ritzwoller, M.H., Engdahl, E.R., 2008. Structural context of the great Sumatra–Andaman Islands earthquake. Geophys. Res. Lett. 35. doi:10.1029/2008GL033381.

Stegman, D.R., Freeman, J., Schellart, W.P., Moresi, L., May, D., 2006. Influence of trench width on subduction hinge retreat rates in 3-D models of slab rollback. Geochem. Geophys. Geosyst. 7. doi:10.1029/2005GC001056.

Tapponnier, P., Peltzer, G., Armijo, R., 1986. On the mechanics of the collision between India and Asia. In: Ramsay, J.G., Coward, M.P., Ries, A.C. (Eds.), Collision Tectonics. Geological Society Special Publication, vol. 19. Geological Society, London, pp. 115–157.

Tapponnier, P., Xu, Z.Q., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., Yang, J.S., 2001. Oblique stepwise rise and growth of the Tibet plateau. Science 294, 1671–1677.

Uyeda, S., Kanamori, H., 1979. Back-arc opening and the mode of subduction. J. Geophys. Res. 84, 1049–1061.

Van der Voo, R., Spakman, W., Bijwaard, H., 1999. Tethyan subducted slabs under India. Earth Planet. Sci. Lett. 171, 7–20.

Villaseñor, A., Spakman, W., Engdahl, E.R., 2003. Influence of regional travel times in global tomographic models. EGS–AGU–EUG Joint Assembly, Nice.