doi: 10.1111/j.1365-3121.2010.00945.x

Indian continental subduction and slab break-off during Tertiary collision

Anne Replumaz,[1] Ana M. Negredo,[2] Antonio Villaseñor[3] and Stéphane Guillot[1]

[1]*Université de Grenoble I Joseph Fourier, CNRS, BP 53, 38041 Grenoble Cedex, France;* [2]*Department of Geophysics, Facultad CC. Físicas, Universidad Complutense de Madrid. Av. Complutense, 28040 Madrid, Spain;* [3]*Instituto de CC. de la Tierra 'Jaume Almera', CSIC, C/Lluís Solé i Sabarís, s/n. 08028 Barcelona, Spain*

ABSTRACT

High wavespeed seismic anomalies in the transition zone and uppermost lower mantle beneath the India-Asia collision zone, imaged by body-wave seismic tomography, have been interpreted as subducted fragments of continental material. In this study, we focus on the prominent anomaly located beneath India between depths of about 450 and 900 km. By combining the location of this anomaly with palaeogeographical positions of India, we constrain the timing of the subduction event probably related to this anomaly. We infer that a large portion of the north-western margin of India initiated subduction at 35 ± 5 Ma along a 1500-km-long WNW–ESE striking zone and ended with a progressive slab break-off process. This break-off started most probably around 25 Ma at the western end of the slab and propagated eastwards until complete break-off around 15 Ma. This study helps to constrain better the amount of convergence between India and Asia absorbed by continental subduction.

Terra Nova, xxx, 1–7, 2010

Introduction

High wavespeed anomalies are commonly interpreted as remnants of slabs, with deeper anomalies representing older subduction events (e.g. van der Hilst *et al.*, 1995; Bijwaard *et al.*, 1998). Beneath the zone where India collided with Asia, an elongated, continuous, NW–SE-trending anomaly at depths between 1100 and 1600 km is thought to record the location of late Mesozoic oceanic subduction (marked as TH for TetHys in Fig. 1f; van der Voo *et al.*, 1999; Replumaz *et al.*, 2004; Hafkenscheid *et al.*, 2006; Richards *et al.*, 2007). Beneath India, this anomaly vanishes at depths shallower than about 1000 km, indicating a slab break-off process. By combining the form of the anomaly, the palaeoposition of India and the length of the Indian slab as it is now subducting beneath the Hindu Kush, Negredo *et al.* (2007) inferred the geometry of India at the time of break-off (blue contour in Fig. 1f) and estimated that the age of break-off was about 45 Ma. This age is in agreement with previous studies (e.g. Chemenda *et al.*, 2000; Kohn and Parkinson, 2002). A number of geological studies indicate that the oceanic crust had been consumed by this time (Rowley, 1996; Guillot *et al.*, 2003; Leech *et al.*, 2005; Najman *et al.*, 2005). Accordingly, shallower positive anomalies (at depths < 1100 km) have been interpreted as fragments of slabs of continental nature subducted after 45 Ma (van der Voo *et al.*, 1999; Chemenda *et al.*, 2000; DeCelles *et al.*, 2002). The purpose of this study was to provide quantitative constraints for the spatio-temporal evolution of the related subduction process. Here, we focus on the large anomaly extending from the uppermost lower mantle to the top of the transition zone beneath India (anomaly marked as IN, for INdia, in Fig. 1). We combine tomographic images, palaeogeographical positions of India and elements of subduction kinematics to characterize the subduction process that originated this anomaly.

Correspondence: Anne Replumaz, Université de Grenoble I Joseph Fourier, CNRS, BP 53, 38041 Grenoble Cedex, France. Tel.: 33 4 76 63 59 19; e-mail: anne.replumaz@ujf-grenoble.fr

Mantle structure under the collision region

We use an update of the P-wave global tomographic model of Bijwaard *et al.* (1998) augmented with additional well-located earthquakes at teleseismic and regional distances (Villaseñor *et al.*, 2003). The new dataset consists of approximately 14 million P-wave travel times from 300 000 well-recorded earthquakes. This is approximately twice the data used by Bijwaard *et al.* (1998), and the most significant increase is for travel times recorded at regional distances that sample the shallow mantle.

To gain a better insight into the 3D mantle seismic structure beneath the collision zone, we combined horizontal and vertical tomographic sections (Figs 1 and 2).

The most common approach to obtain an estimate of the resolving power of the dataset is to conduct synthetic reconstruction tests. The synthetic (checkerboard) models used here consist of well-separated spikes with alternating ± 5% velocity anomalies with respect to the reference model ak135 (Kennett *et al.*, 1995) shifted laterally and in depth. We have used spike amplitudes of ± 5% because they lead to a signal-to-noise ratio of the synthetic delays that is similar to that of real data when 0.5 s Gaussian noise is added (Amaru, 2007). Figure 3 shows the results of the synthetic reconstruction test for 3° × 3° spikes at different depths. The reconstruction is very good for all regions north of 20°N and decreases in southern India because of the lack

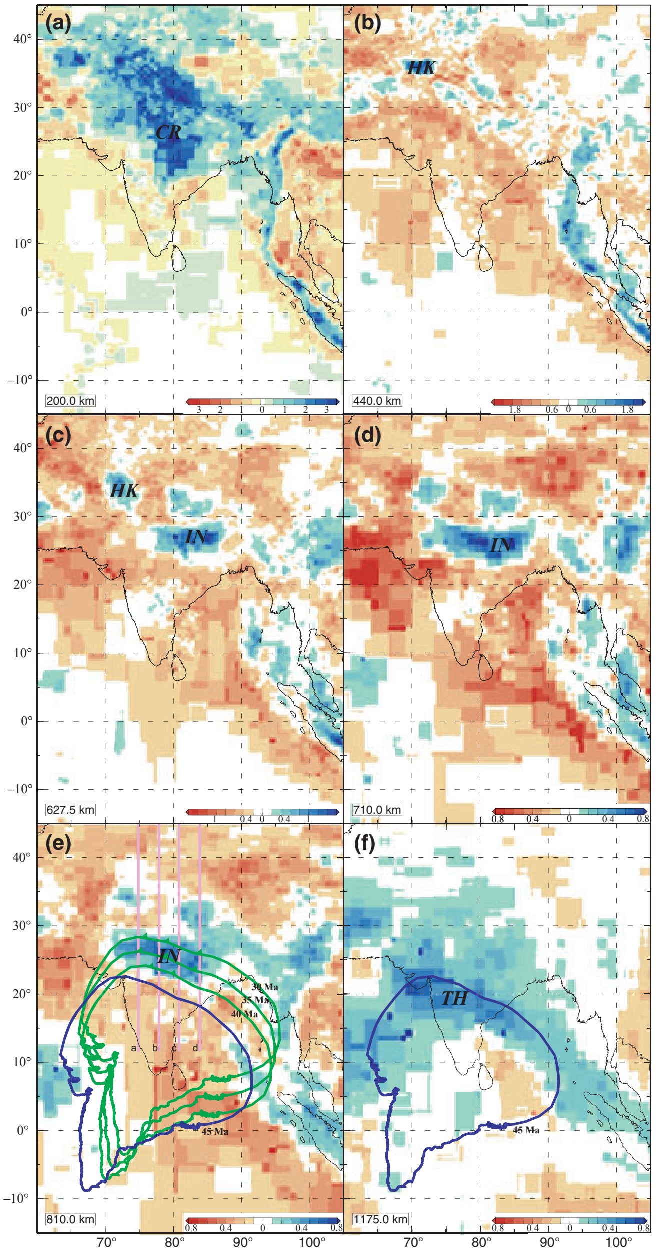

Fig. 1 Horizontal sections at different depths of the P-wave global tomography model used in this study. Anomaly HK is related to the Indian continental slab under the Hindu Kush. Anomaly CR is related to the Indian craton (section a). Sections c and d show the prominent IN anomaly, whereas section b shows that this anomaly disappears at the top of the transition zone. Blue line (in sections e and f) indicates the geometry inferred by Negredo *et al.* (2007) for continental India at about 45 Ma. This geometry of India is further rotated about poles given by Patriat and Achache (1984) to obtain positions at 40, 35 and 30 Ma (green lines in section e). Section f shows anomaly TH, which is interpreted as marking the location Tethyan oceanic subduction.

of stations and earthquakes. The anomalies interpreted in this study are also shown in Fig. 3 as black outlines, illustrating that their size and location are sufficiently well resolved by our travel time dataset.

Figures 1 and 2 show that anomaly IN occurs between depths of about 450 and 900 km and appears to be unconnected from anomaly TH farther south. This anomaly IN is not visible at the top of the transition zone (Fig. 1b), so it is apparently not connected to strong anomalies of high wavespeed at shallow depths (labelled CR, for Indian CRaton, in Figs 1 and 2). The east–west extent of IN decreases by about a factor of two from the bottom (Fig. 1e) to the top of the anomaly (Fig. 1c). The anomaly shows an apparent southward dip that becomes more clear as the vertical extent of anomaly IN increases from west to east (Fig. 2).

The IN anomaly attenuates and enlarges in the lower mantle. The anomaly smearing and the partial loss of visibility of slabs as they penetrate into the lower mantle are common features of deep subduction zones (e.g. van der Hilst, 1995; Bijwaard *et al.*, 1998; Ricard *et al.*, 2005). Moreover, it is well known that travel time tomography (seismic tomography using arrival times of body waves) underestimates the values of the seismic anomalies. Therefore, in the interpretations made in this study, we only make use of the geometry of the high-velocity seismic anomalies and not of the values of the anomalies' amplitudes.

Indian continental subduction during collision

We interpret that anomaly IN, located at depth shallower than 1100 km, represents a slab of continental material subducted after the large-scale slab break-off at *c.* 45 Ma. The shallower high wavespeed anomaly CR is commonly interpreted as related to the Indian craton (e.g. van der Voo *et al.*, 1999). We infer that the gap between anomalies IN and CR is an evidence of a second slab break-off event. Therefore, we propose that after the first break-off at about 45 Ma, a new phase of subduction of India lithosphere took place north of the former oceanic subduction locus, this phase originating the slab mapped by anomaly IN, and finished by a second slab break-off (Fig. 4). The interpretation of the continental nature of this slab is consistent with the large IN anomaly thickness, similar to the anomaly mapping subducted continental lithosphere under the Hindu Kush mountains (e.g. Negredo *et al.*, 2007), and much broader than the anomaly mapping oceanic subduction under Indonesia (Replumaz *et al.*,

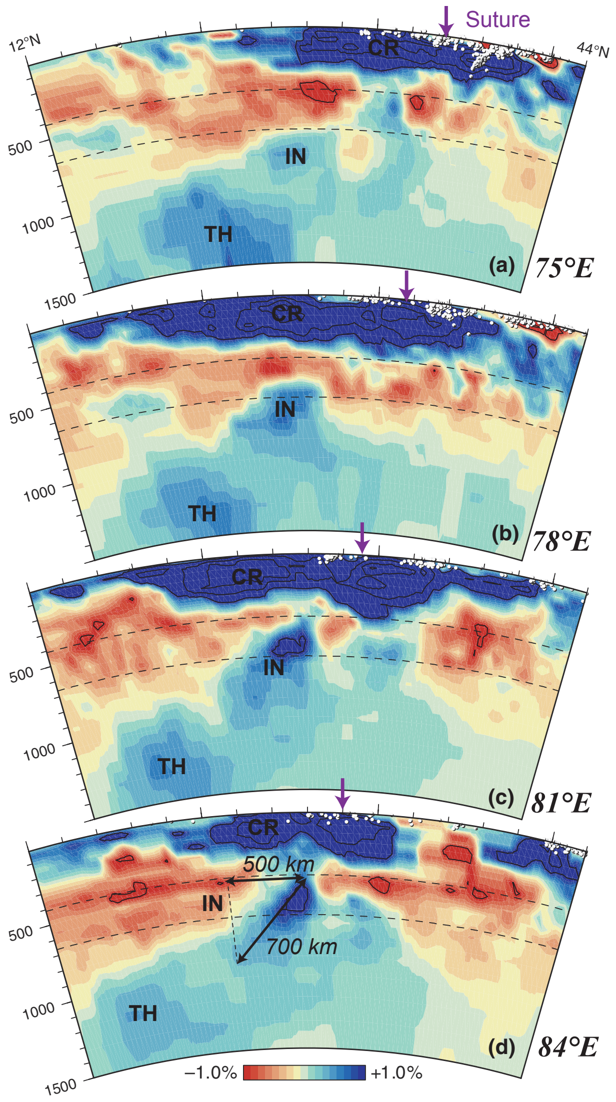

Fig. 2 Vertical sections across the IN anomaly (location in Fig. 1e). Vertical extent of the anomaly increases from about 300 km along section a, to about 700 km along section d.

2004). However, caution must be taken when discussing anomalies' thicknesses, because of the aforementioned limited resolution of tomographic images.

We assume 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). Therefore, the dip of the slab is related to the hinge displacement. The geometry of IN anomaly suggests a southward dipping slab. This interpreted roll-over slab geometry is compatible with the India/Asia plate boundary advancing northwards (e.g. Tapponnier *et al.*, 2001; DeCelles *et al.*, 2002; Replumaz and Tapponnier, 2003) combined with the lack of lateral motion of the tip of the slab (Fig. 4). Similar roll-over slab geometries have been obtained in numerical models (Manea and Gurnis, 2007) and laboratory experiments (e.g. Schellart, 2005; Heuret *et al.*, 2007) for oceanic slabs. The recent study by Capitanio *et al.* (2010) is focused on subduction in the India/Asia collision zone. They show by means of dynamic simulations that a continental slab eventually overturns under increasing trench advance, when subduction is driven by a combination of slab pull and ridge push. We suggest that the trench advance in the central part of the collision zone was probably enabled by the extrusion of the Indochina block, pushed eastwards away from the Indian path (e.g. Replumaz and Tapponnier, 2003).

The existence of the second break-off implies the absence of present-day steep subduction in the area. This is consistent with the absence of deep seismicity beneath the Himalaya. It is also consistent with the inferred location of the northern edge of Indian lithosphere under Tibet (e.g. Hetenyi *et al.*, 2007; Li *et al.*, 2008) about 500 km north of the IN anomaly, which implies that the previously subducted Indian lithosphere was probably detached and left behind (Fig. 4). Both the eastward increase in the slab length and the decrease in the gap between the slab and the Indian craton (Fig. 2) suggest a progressive eastward migration of the slab detachment to the site of its complete break-off (Fig. 5). Other examples of progressive slab tearing are described in the Mediterranean (van der Meulen *et al.*, 1998; Wortel and Spakman, 2000) and in central Mexico (Ferrari, 2004).

Initiation of Indian continental subduction

To estimate when subduction started, we have used the procedure described by Replumaz *et al.* (2004) and Negredo *et al.* (2007). We assume that for steep subduction, the deepest part of the anomaly roughly marks the locus of subduction initiation (Fig. 4). By comparing the palaeoposition of the northern boundary of India at different times (using the rotation poles by Patriat and Achache, 1984) with the position of the anomaly at 810 km, we infer that the northern boundary of India matches the southern and northern edges of the IN anomaly at about 40 and 30 Ma respectively (green contours, Fig. 1e). We thus propose that this subduction process initiated at 35 ± 5 Ma. The IN anomaly is overlapped at this time by a 1500-km-long WNW–ESE striking segment at the western part of the northern margin of India (Fig. 1e), thus suggesting that only this western part of the margin underwent subduction. The parallel

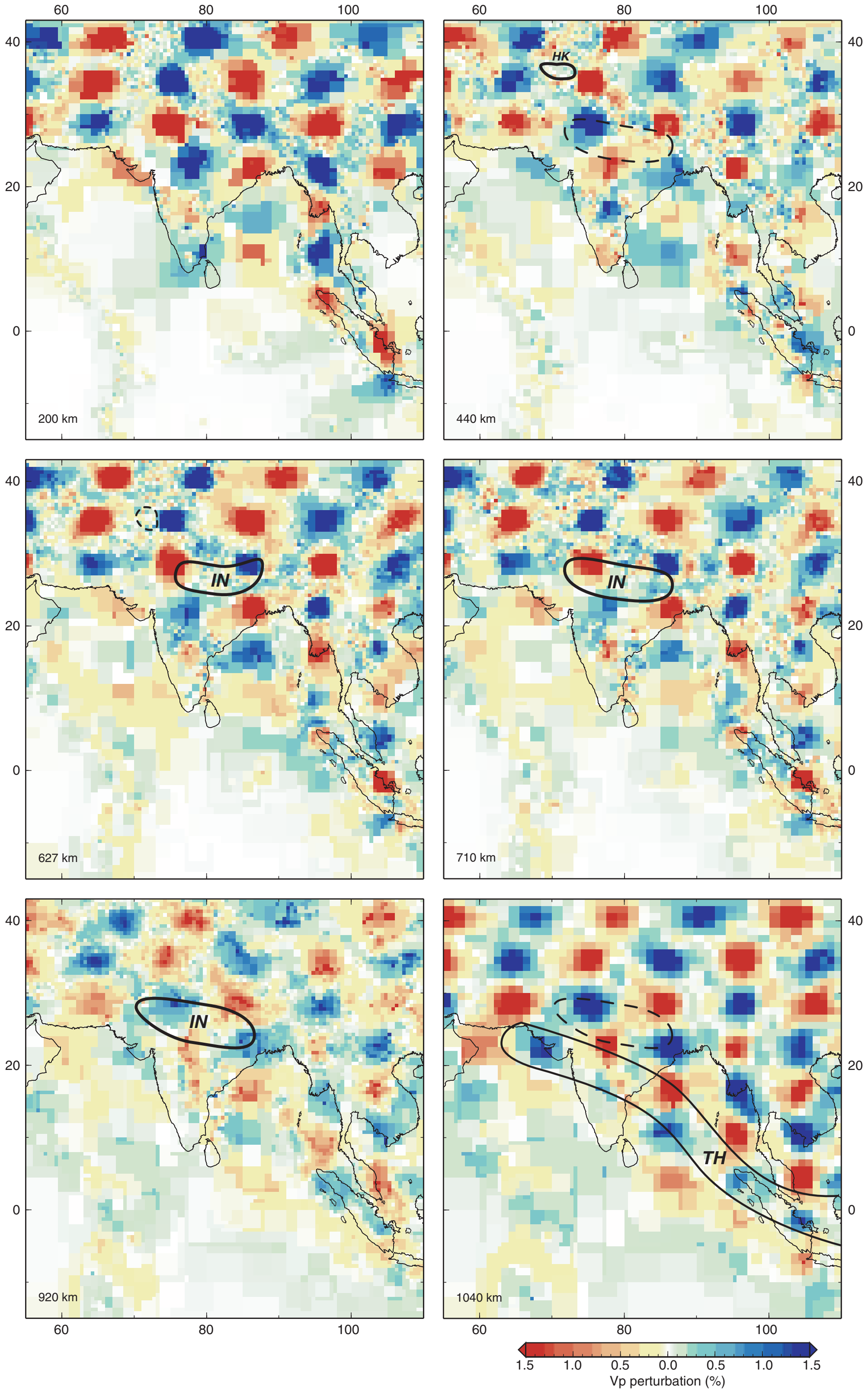

Fig. 3 Synthetic reconstruction tests for 3° × 3° spikes at different depths (same depths as in Fig. 1 except for the two deepest sections, as depths are chosen to cross the input anomaly roughly at its centre). We have used spike amplitudes of 5% because they lead to a signal-to-noise ratio of the synthetic delays that is similar to that of real data when 0.5 s Gaussian noise is added (Amaru, 2007). These tests show that the anomalies interpreted in this study (black outlines) are well resolved by our travel time dataset.

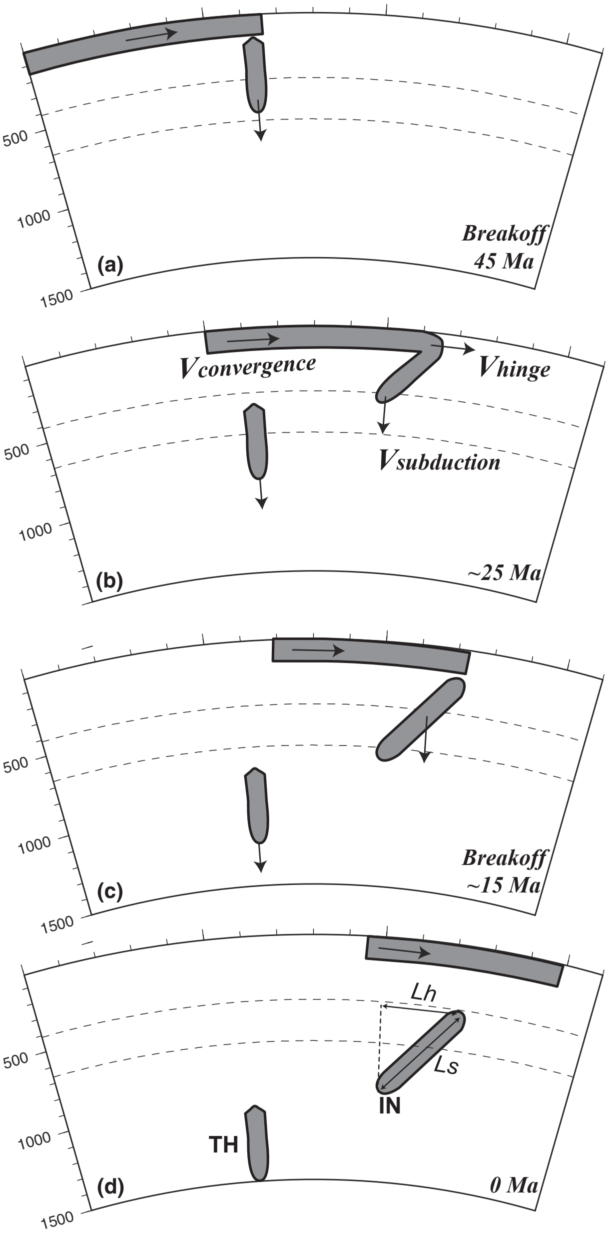

Fig. 4 Proposed schematic evolution of the subduction process and break-off of Indian continental lithosphere. Panel a illustrates a vertical slab with no advancing subduction hinge. Panels b to c illustrate that the interpreted overturned geometry of the slab is probably the result of the combination of advancing subduction hinge and anchoring of the tip of the slab.

trends of the anomaly and the northern boundary of the continent suggest that this subduction initiated roughly simultaneously along this 1500-km-long zone.

Timing of slab break-off

We calculate first-order estimates of subduction duration using common values of convergence velocity and estimates of slab lengths. At lithospheric scale, the convergence velocity V_c is equal to the Indian subduction velocity V_s plus the hinge velocity V_h (see scheme on Fig. 4):

$$V_c = V_s + V_h = \frac{L_s + L_h}{\Delta t_s},$$

where L_s is the estimated length of the Indian slab, L_h is the displacement of the hinge (given by the horizontal projection of the slab; Fig. 4), and Δt_s is the duration of the subduction episode. We use a mean convergence velocity V_c for the last 45 Ma of 5 cm a^{-1} (e.g. Guillot *et al.*, 2003). To provide a first-order estimate of slab length, we adopt the simplifying assumption that it behaves as a relatively rigid slab, and measure the down-dip extent of IN anomaly. The values of L_s and L_h estimated in this way for the easternmost part of the slab (Fig. 2d) are 700 and 500 km, respectively, which result in a subduction duration Δt_s of about 25 Ma. This duration in turn gives velocities of subduction and hinge motion of about 3 and 2 cm a^{-1} respectively. For the cross-section *a*, we assumed L_s and L_h to be about 40% of the values of section *d*, which corresponds to a subduction duration of about 10 Ma. As the estimated age for the initiation of subduction is around 35 Ma, we infer that tearing of the slab began in the western part at around 25 Ma and propagated eastwards until complete break-off at around 10 Ma.

The uncertainty associated with this timing is largely due to the contribution of different uncertainty sources. First, the propagation of the uncertainty of about 10 Ma in the timing of subduction initiation must be considered. Second, the estimates of slab length are subjected to the limited resolution of tomographic images. Moreover, imaging a continuous seismic structure throughout the transition zone may be hampered by decreased seismic velocity–temperature sensitivity and varying phase transition depths (Goes *et al.*, 2004; Ricard *et al.*, 2005). Third, slab penetration into the lower mantle could lead to thickening or buckling of weak slabs (e.g. Christensen, 1996; Ribe *et al.*, 2007), which adds potential uncertainties to our analysis.

The timing of break-off estimated in this study can be further constrained by comparison with independent geological indications. From the composition and age of magmatic and metamorphic rocks, Chemenda *et al.* (2000) and Maheo *et al.* (2002) proposed a slab break-off event occurring at about 25 Ma along the Western Himalaya. Mugnier and Huyghe (2006) suggested that sedimentation in the Ganges foreland basin is compatible with a regional isostatic rebound at about 15 Ma in the Central

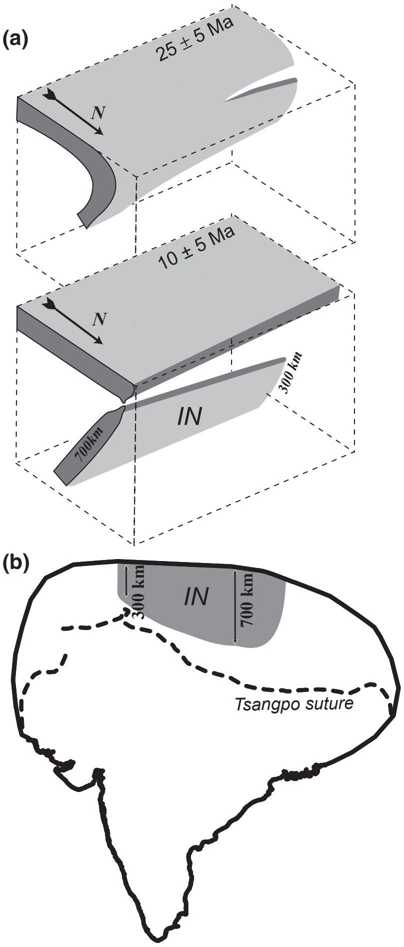

Fig. 5 (a) Schematic 3D diagram illustrating a progressive eastward migration of the slab detachment, from the beginning of tearing at 25 ± 5 Ma to complete break-off at 10 ± 5 Ma (inspired from Wortel and Spakman, 2000). (b) Geometry of continental India rotated to the present. The northern outline represents the northern boundary of India at 45 Ma (Fig. 1f, Negredo *et al.*, 2007) after rotation. The shaded area represents the portion of India consumed by subduction, as interpreted from the analysis of anomaly IN.

Himalaya, probably caused by slab break-off. These observations are in agreement with the eastwards propagation of the break-off proposed in this study and suggest that most probably slab break-off started at about 25 Ma at the western end of the slab and ended at the eastern part at about 15 Ma (Fig. 5a). An additional indication of slab break-off being completed by 10 Ma is that this is the minimum time required (after slab break-off and considering V_c of 5 cm a^{-1}) by the northern edge of India to advance until its present location about 500 km north of the top on IN anomaly (Fig. 2d and Li *et al.*, 2008).

Did continental subduction accommodate all the Indian-Asian convergence?

Possible lithospheric processes acting during India/Asia collision to absorb the convergence are subduction, underthrusting or extrusion. To discuss their relative roles, we considered the geometry inferred for India at about 45 Ma by Negredo *et al.* (2007) (blue contour in Fig. 1f) and rotated it on the sphere to the present (Fig. 5b). The region comprised between the rotated northern boundary and the location of suture should be regarded as the portion of India absorbed during collision since 45 Ma. The shaded region in Fig. 5b corresponds to the portion of subducted Indian lithosphere, as inferred in this study from the analysis of anomaly IN. It almost reaches the Tsangpo suture and leads us to infer that subduction was the main mechanism to consume Indian lithosphere under the western Tibetan Plateau. Further east, recent seismic tomography studies consistently find no evidence of large-scale steep subduction, but the amount of Indian underthrusting under Tibet remains a matter of debate. Recent surface wave studies suggest that the entire plateau is underlain by a relatively cold lithospheric mantle (Priestley *et al.*, 2006). In contrast, the P-wave tomographic models by Li *et al.* (2008) and that used in the present study suggest no underthrusting in the eastern part of Tibet north of the Tsango suture (Fig. 1a). Extrusion of Indian lithosphere has been proposed as an alternative mechanism to subduction or underthrusting in this eastern part (Replumaz *et al.*, 2010).

Acknowledgements

The project was funded by the Integrated Actions Program HF2008-0089 by the Spanish and French Foreign Affairs Ministries (Egide-Picasso). Additional support was provided by the Spanish Plan Nacional; MEC projects CTM2006-13666-C02-02/MAR, CGL2009-13103; and funding for the UCM Research Groups. This is a contribution of the Consolider-Ingenio 2010 team CSD2006-00041 (TOPO-IBERIA). Tomographic images were made using the graphic program P developed by Wim Spakman. We thank the editor Jason P. Morgan, an anonymous Associated Editor and anonymous reviewers for their thorough reviews, which greatly improved the manuscript.

References

Amaru, M., 2007. *Global Travel Time Tomography With 3-D Reference Models*. PhD thesis, Utrecht University, Utrecht.

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

Capitanio, F.A., Morra, G., Goes, S., Weinberg, R.F. and Moresi, L., 2010. India-Asia convergence driven by the subduction of the Greater Indian continent. *Nat. Geosci.*, **3**, 136–139, doi: 10.1038/NGEO725.

Chemenda, A.I., Burg, J.P. and 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. and Zandt, G., 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau. *Tectonics*, **21**, 1062–1087, doi: 10.1029/2001tc001322.

Ferrari, L., 2004. Slab detachment control on mafic volcanic pulse and mantle heterogeneity in central Mexico. *Geology*, **32**, 77–80, doi: 10.1130/G19887.1.

Goes, S., Cammarano, F. and Hansen, U., 2004. Synthetic seismic signature of thermal mantle plumes. *Earth Planet. Sci. Lett.*, **218**, 403–419, doi: 10.1016/S0012-821X(03)00680-0.

Guillot, S., Garzanti, E., Baratoux, D., Marquer, D., Maheo, G. and de Sigoyer, J., 2003. Reconstructing the total shortening history of the NW Himalaya. *Geochem. Geophys. Geosyst.*, **4**, 485–506, doi: 10.1029/2002gc000484.

Hafkenscheid, E., Wortel, M.J.R. and Spakman, W., 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. *J. Geophys. Res.*, **111**, 35–46, doi: 10.1029/2005jb003791.

Hetenyi, G., Cattin, R., Brunet, F., Bollinger, L., Vergne, J., Nabelek, J. and Diament, M., 2007. Density distribution of the India plate beneath the Tibetan plateau: geophysical and petrological constraints on the kinetics of lower-crustal eclogitization. *Earth Planet. Sci. Lett.*, **264**, 226–244, doi: 10.1016/j.epsl.2007.09.036.

Heuret, A. and 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. and 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.

Kennett, B.L.N., Engdahl, E.R. and Buland, R., 1995. Constraints on seismic velocities in the earth from travel-times. *Geophys. J. Int.*, **122**, 108–124.

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

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L. and 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.

Li, C., van der Hilst, R.D., Meltzer, A.S. and Engdahl, E.R., 2008. Subduction of the Indian lithosphere beneath the Tibetan Plateau and Burma. *Earth Planet. Sci. Lett.*, **274**, 157–168, doi: 10.1016/j.epsl.2008.07.016.

Maheo, G., Guillot, S., Blichert-Toft, J., Rolland, Y. and Pecher, A., 2002. A slab breakoff model for the Neogene thermal evolution of South Karakorum and South Tibet. *Earth Planet. Sci. Lett.*, **195**, 45–58.

Manea, V. and Gurnis, M., 2007. Subduction zone evolution and low viscosity wedges and channels. *Earth Planet. Sci. Lett.*, **264**, 22–45, doi: 10.1016/j.epsl.2007.08.030.

van der Meulen, M.J., Meulenkamp, J.E. and Wortel, M.J.R., 1998. Lateral shifts of Apenninic foredeep depocentres reflecting detachment of subducted lithosphere. *Earth Planet. Sci. Lett.*, **154**, 203–219.

Mugnier, J.L. and Huyghe, P., 2006. Ganges basin geometry records a pre-15 Ma isostatic rebound of Himalaya. *Geology*, **34**, 445–448.

Najman, Y., Carter, A., Oliver, G. and 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. and 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.

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

Priestley, K., Debayle, E., McKenzie, D. and Pilidou, S., 2006. Upper mantle structure of eastern Asia from multimode surface waveform tomography. *J. Geophys. Res.*, **111**, 1–20, doi: 10.1029/2005jb004082.

Replumaz, A. and Tapponnier, P., 2003. Reconstruction of the deformed collision zone between India and Asia by backward motion of lithospheric blocks. *J. Geophys. Res.*, **108**, 1–25, doi: 10.1029/2001jb000661.

Replumaz, A., Karason, H., van der Hilst, R.D., Besse, J. and 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., Guillot, S. and Villaseñor, A., 2010, Multiple episodes of continental subduction during India/Asia convergence: insight from seismic tomography and tectonic reconstruction. *Tectonophysics*, **483**, 125–134, doi: 10.1016/j.tecto.2009.10.007.

Ribe, N.M., Stutzmann, E., Ren, Y. and van der Hilst, R.D., 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.

Ricard, Y., Mattern, E. and Matas, J., 2005. Synthetic tomographic images of slabs from mineral physics. In: *Earth*'s Deep Mantle, Structure Composition, and Evolution, Vol. 160, Geophysical monograph (R.D. van der Hilst, J. Bass, J. Mattas and J. Trampert, eds), pp. 283–300. AGU, Washington.

Richards, S., Lister, G. and Kennett, B., 2007. A slab in depth: three-dimensional geometry and evolution of the Indo-Australian plate. *Geochem. Geophys. Geosyst.*, **8**, 1–11, 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.

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

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

Villaseñor, A., Spakman, W. and Engdahl, E.R., 2003. *Influence of Regional Travel Times in Global Tomographic Models*. EGS–AGU–EUG Joint Assembly, Nice.

van der Hilst, R.D., 1995. Complex morphology of subducted lithosphere in the mantle beneath the tonga trench. *Nature*, **374**, 154–157.

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

Wortel, M.J.R. and Spakman, W., 2000. Geophysics – subduction and slab detachment in the Mediterranean-Carpathian region. *Science*, **290**, 1910–1917.

Received 20 December 2008; revised version accepted 17 March 2010