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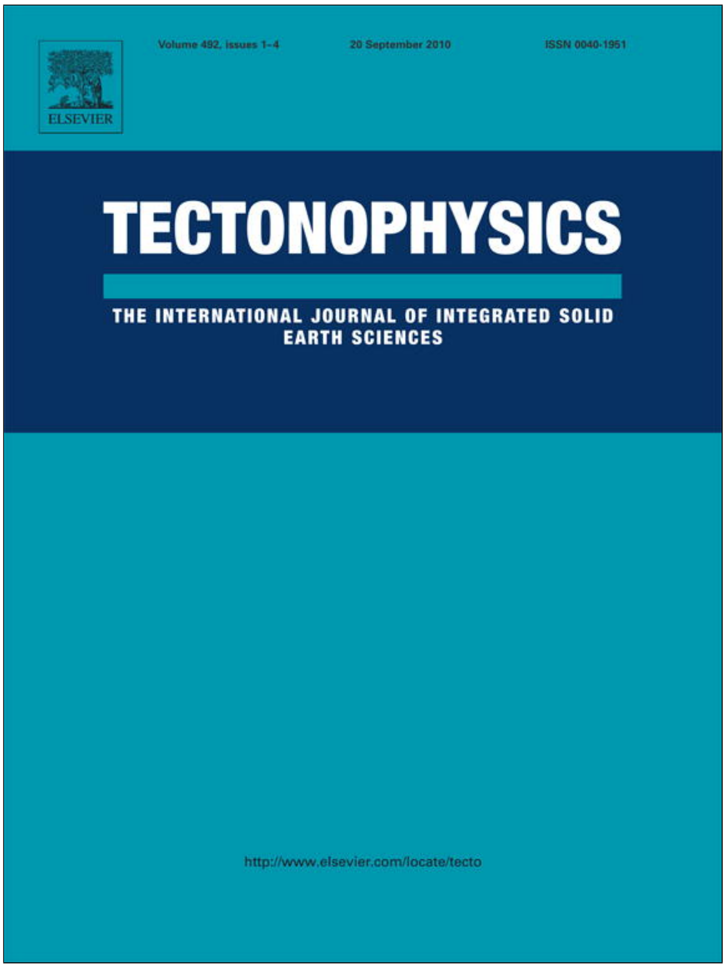

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Crustal mass budget and recycling during the India/Asia collision

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The long-lasting collision between India and Asia has resulted in crustal and lithospheric deformation of both continents, providing unequalled opportunities to evaluate their long-term mechanisms of deformation. We have quantified a crustal mass budget for the collision by comparing the present-day and initial crustal volumes of the Indian and Asian continents involved in the collision. Initial crustal thickness was estimated from the non-deformed parts of the continents, whereas their initial extent was mapped from their contours at the onset of collision, using seismic tomography. We quantify the portion of the initial crustal thickness of both continents stored within the currently thickened crust or redistributed due to extrusion. For the Indian continent, this portion amounts to about 19 km, far lower than the mean observed present-day crustal thickness of the Indian craton of about 38 km. We conclude that between 40 and 50% of Indian crust has been recycled into the mantle by continental subduction, corresponding to a decoupling level at about 15–19 km depth. For the Asian continent, the estimated crustal thickness stored during collision is about 33 km, close to the initial Asian crustal thickness. We estimate that only 3% of the Asian crust was recycled into the mantle. This corresponds to one episode of continental subduction, occurring most probably soon after the initiation of collision along the Bangong suture. We identify the related slab using seismic tomography. The strong contrast between India and Asia implies an age-dependent capacity of the continental crust to be recycled into the mantle. This result has to be taken into account for further analysis of global crustal recycling during Earth's history.

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1. Introduction

The indentation of Asia by India has resulted in crustal deformation of both continents, causing profound changes over immense areas and building the Earth's largest and highest topography (Fig. 1). This long-lasting collision between two continents provides unequalled opportunities to study the mechanics of continental deformation. Several models have addressed the question of the long-term strength of the continental lithosphere during the collision (for a review see Willett and Beaumont, 1994). One end-member model assumes that the entire lithosphere thickened as a thin viscous sheet, with broadly distributed shortening of both crust and mantle absorbing plate convergence (England and Houseman, 1989; Molnar et al., 1993). The other end-member model assumes that only the upper crust thickened, decoupled from a more plate-like behaviour of the underlying lower crust and mantle lithosphere, which did not thicken but was subducted (Meyer et al., 1998; Tapponnier et al., 2001; Replumaz et al., 2010a). Intermediate models allow the transfer of Indian crust below Asia (DeCelles et al., 2002; Hetenyi et al., 2007; Nábělek et al., 2009). The first model implies conservation of crustal mass during the collision, while the second allows a portion of the lower crust to be subducted into the mantle. Intermediate models allow transfer of crustal material between the two continents. In this paper, we aim to quantify the partitioning of crustal deformation between shortening through thickening, erosion and extrusion, and loss of lower crust into the mantle by subduction. This crustal mass budget on a continental-scale will assist in interpreting the long-term mechanics of continental deformation for young orogenic belts, such as the Asian continent, and ancient continental shields, such as the Indian subcontinent.

The position of the plate boundary between India and Asia at the onset of collision has been estimated previously using the present-day geometry of the indentation mark left by the impact of India onto the Asian margin, with a presumably linear geometry between Sumatra and the mouth of Indus (Fig. 1; Tapponnier et al., 1986; Le Pichon et al., 1992). The amount of thickening has been estimated in 2D, along north–south lines, using topography as an indicator of crustal thickness. Using the surface of the indentation mark as an indication of the total surface loss during the collision, the relative amounts of shortening and eastward extrusion of continental material have been discussed. Nowadays, the Moho has been imaged precisely beneath the collision zone and the crustal thickness is well-constrained

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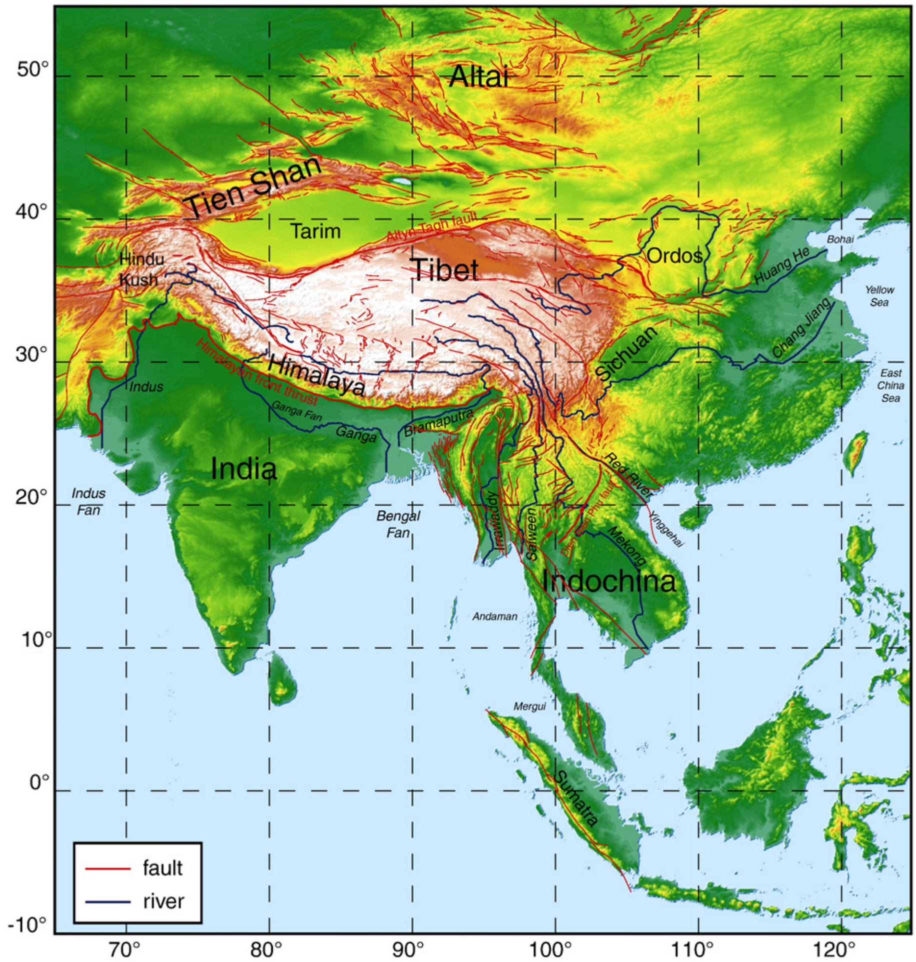

Fig. 1. Topographic map showing zones thickened during collision (brown and white) and zones not affected by the collision (green and yellow). Sutures (position from Valli et al., 2008), faults and rivers are portrayed.

(Mooney et al., 1998; Villaseñor et al., 2001; Li et al., 2006). Seismic tomography has been successful in mapping remnants of ancient slabs (e.g. van der Hilst et al., 1997; Bijwaard et al., 1998). The position of these can be compared to previous plate boundary positions, provided that the slabs sink vertically (e.g. van der Voo et al., 1999). We use those constraints to improve the previous 2D shortening estimations and to develop a crustal mass budget in 3D.

2. Present-day contour of continental blocks

Relics of the Tethys Ocean that used to separate the northern margin of India from the southern margin of Eurasia can be traced along the Indus–Tsangpo suture zone (in purple on Fig. 2). Considering the origin of the crust and the timing of deformation, we divided the collision zone in three blocks (Fig. 2). We call these Himalaya, Indochina and Tibet, although they are not identical to the current geographical extent of the Himalayan range, Indochina peninsula or Tibetan Plateau, respectively. The Himalayan block is the part of the Indian continent involved in the collision process, while the rest of the continent remained undeformed. The active deformation front migrated southwards during the collision, from the Indus–Tsangpo suture to the present-day Himalayan front (Robinson et al., 2001; DeCelles et al., 2002). North of the Indus–Tsangpo suture, the Indochina and Tibet blocks were parts of Asia when India collided. The Indochina block comprises the Indochinese peninsula and the southern part of the Tibetan Plateau. At the onset of collision, the Indochina peninsula was located partially in front of the collision zone, as deduced from the rotation pole of the peninsula (Briais et al., 1993) and tectonic reconstructions (Leloup et al., 2001; Replumaz and Tapponnier, 2003). It formed a compact block with the southern part of the Tibetan Plateau. To the west, this block has been thickened to form the southern Tibetan Plateau (Tapponnier et al., 2001), while to the east the Indochinese peninsula has been extruded southeastward between 30 and 15 Ma (Briais et al., 1993). It slid more than 700 km along a fault that extended from the South China Sea to the western part of the collision zone (Leloup et al., 2001). A portion of this fault has been preserved along the Red River from further deformation during the post-extrusion collision process, and is known as the Ailao Shan shear zone (Leloup et al., 2001). The Tibet block comprises the part of the Tibetan Plateau north of this extrusion fault. It was thickened since the Oligo-Miocene by thrusts propagating northward along the Altyn Tagh fault (Métivier et al., 1998; Meyer et al., 1998). Several hypotheses have been envisaged for the continuation of the extrusion fault within the Tibetan Plateau (Fig. 2): along the Jinsha suture (Tapponnier et al., 2001); the Bangong suture (Replumaz and Tapponnier, 2003; Leloup et al., 2001); or the Shiquanhe suture (Tapponnier et al., 1986). Each of the hypotheses for the limit between the Indochina and Tibet blocks leads to a different estimate of the partitioning of the Asian crustal mass between these blocks, which allowed us to discriminate between them.

3. Present-day thickness of continental blocks

We compiled a Moho depth map combining the contours obtained for China from seismic refraction/wide angle reflection profiles (Li et al., 2006), with the regional contours obtained from inversion of surface wave velocities (Villaseñor et al., 2001) (Fig. 3). The zones with a Moho depth greater than 50 km, i.e., the Tibetan Plateau, the Himalaya, the

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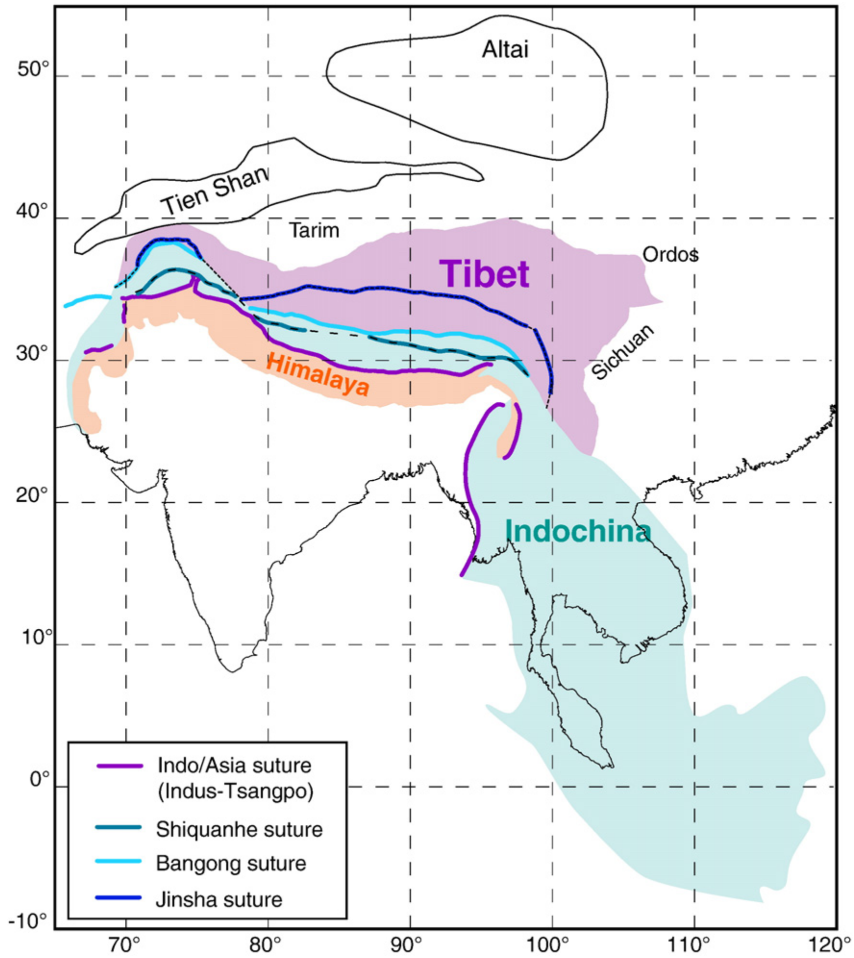

Fig. 2. Three continental blocks considered in this study, Tibet, Indochina and Himalaya. These blocks are considered homogeneous with respect to crustal origin and the timing of deformation. The separation between Tibet and Indochina could be along the Bangong, the Jinsha or the Shiquanhe sutures.

Tien Shan and the Altai ranges, have been thickened during the collision. By contrast, the zones around or in between them have not been thickened. To the south, the Indian craton has not been affected by the collision, and its crustal thickness is between 35 and 45 km (e.g. Gupta et al., 2003; Mandal, 2006). To the north, the Siberian craton was not affected either, and its crust is on average 38 km thick (e.g. Mooney et al., 1998). The Tarim and Ordos cratons north of the Tibetan Plateau, as well as the Sichuan craton to the east, have been translated and rotated during the collision, but were not deformed (Avouac et al., 1993; Yang and Liu, 2009). Those cratons have a crustal thickness between 42 and 44 km. East of the Sichuan craton, the Asian crust was not thickened during the collision. Its present-day crustal thickness is between 32 and 35 km (Li et al., 2006; Fig. 3). East of the Dien Bien Phu fault (Fig. 1), the Indochinese peninsula was not thickened during its eastward extrusion. The crustal thickness for this area is between 25 and 35 km, thinner where extensional basins occur southeast of the Indochina peninsula (Lebedev and Nolet, 2003).

The initial crustal thickness of the portions of the Asian and Indian continents that have been thickened during the collision is unknown. We hypothesise that the crustal thickness of these continents prior to collision is similar to that of their portions that have not been deformed. We estimate the initial crustal thickness of the Himalaya block to be about 38 km, similar to the present-day undeformed Indian continent. The Asian continent consists of tectonic units with strongly varying histories. The Ordos, Sichuan and Tarim cratons were not involved in the thickening process but the crustal thickness of those cartonic units is not a good estimate for that of the Tibetan Plateau prior to collision. We therefore use the undeformed portion of South China, east of the Sichuan craton and 34 km thick on average, as a better estimate of the crustal thickness of the northern Tibetan Plateau prior to the collision. The initial crustal thickness of the southern Tibetan Plateau is probably less than that and similar to the undeformed portion of the Indochinese Peninsula east of the Dien Bien Phu fault, 32 km thick in average. Those values are independent of the following calculations. They are used only to interpret our results.

4. Volume of thickened continental crust

For each block, we calculated the present-day volume of continental crust comprised between the topographic surface and the Moho. We used the GMT routine grdvolume (Smith and Wessel, 1990; Wessel, 1998; see Appendix A for script) to calculate for each block: the volume between the Moho and sea-level (V_{moho}); the volume between sea-level and the present-day topography (V_{topo}); the average elevation (H_{topo}); the average Moho depth (H_{moho}). The topographic dataset used is Gtopo30, with resolution reduced by half (pixel size of 1 min), which is sufficient for our purpose. The obtained values are reported in Table 1. The present-day average Moho depth is about 57 km for the Himalaya block, with an average elevation of 2600 m. With a boundary along the Bangong suture, the present-day average Moho depth is about 40 km for the Indochina block, with an average elevation of 740 m, and about 60 km for the Tibet block, with an average elevation of 4000 m. For each block, the average elevation is less than 10% of the average Moho depth.

We added the volume of material eroded and evacuated out of the block boundaries by the major rivers of Asia, which has been

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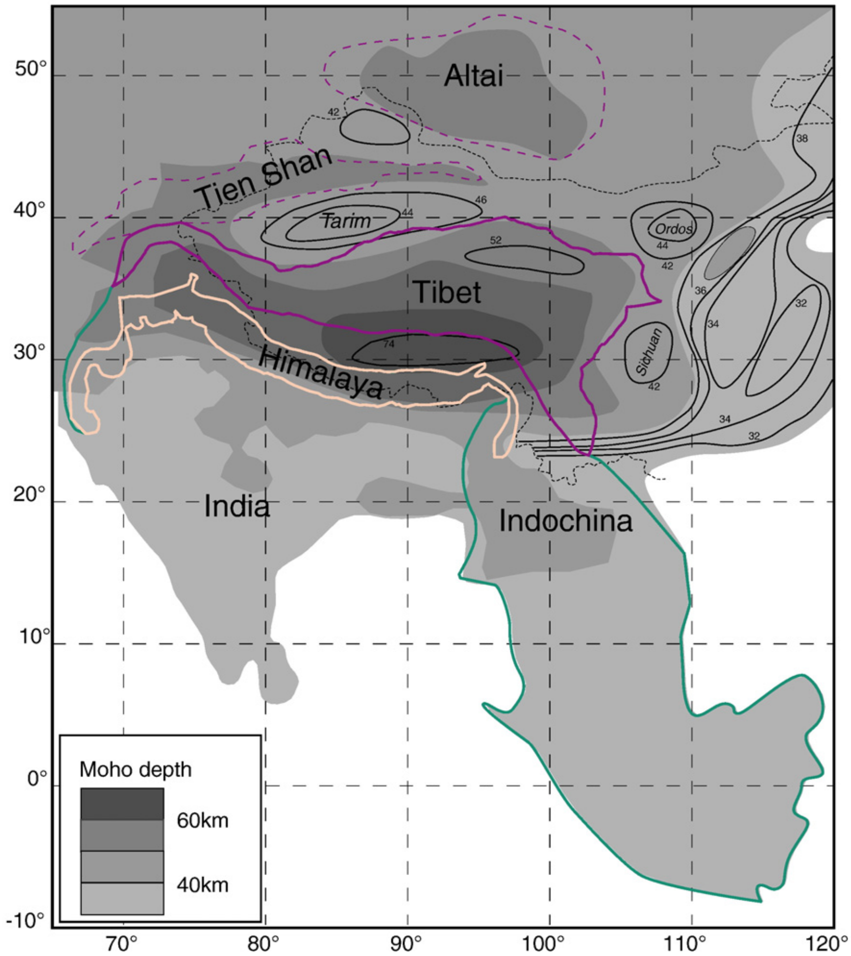

Fig. 3. Crustal thickness map (solid lines from Li et al., 2006; small dotted line China boundary) with contour of continental blocks (purple Tibet, green Indochina and orange Himalaya).

estimated by Métivier et al. (1999). We did not consider local erosion products trapped within the Tibetan Plateau by internal drainage (Métivier et al., 1998). As shown on Fig. 1, several major rivers are located in a single block (Huang He, Chang Jiang, Salween, Irrawaddy, and Ganga), but others are not. Both the Indus and Brahmaputra Rivers flow for half of their course along the Indus–Tsangpo suture, between the Himalaya block of Indian origin and the Indochina block of Asian origin. The partitioning of flux between source units has been deduced from the composition of sands (about 50% Asian and 50% Indian origin for the Indus river, but only 20% Asian origin for the Bengal fan deposits; Garzanti et al., 2004, 2005). The partitioning of flux between Tibet and Indochina for the Red River could not be deduced from sand composition, as petrographical and geochemical signatures of both blocks are comparable. From the partitioning of the drainage area, we infer 50% of Indochina block origin and 50% of Tibet block origin. The obtained volumes are reported in Table 2. For the Indochina and Tibet blocks, the eroded and evacuated volume is negligible compared to their crustal volume, about 2%. In contrast, for the Himalaya block, the volume of eroded material is important, especially in the Bengal fan (1.2×10^7 km^3, Métivier et al., 1999), and represents ~15% of its crustal volume. It is equivalent to 10 km of eroded topography considering the present-day area of the Himalaya block, or to 3 km considering the inferred initial area (see below). This is a reasonable amount considering the mean level of exhumation in the Himalaya (Einsele et al., 1996).

Table 1
For each block, present-day area (A0Ma), present-day volume between the Moho and altitude zero (V_{moho}), present-day volume between altitude zero and the topography (V_{topo}), average altitude (H_{topo}) and average Moho depth (H_{moho}), calculated using GMT routine grdvolume (Wessel, 1998; see Appendix A for script). The topographic dataset used is Gtopo30, with pixel size of 1′.

	$A_{0\,Ma}$ 10^6 km^2	V_{moho} 10^6 km^3	H_{moho} km	V_{topo} 10^6 km^3	H_{topo} km
Himalaya	0.83	47.6	57	2.2	2.6
Indochina (Bangong)	6.4	250.6	39	4.7	0.74
Tibet (Bangong)	2.2	132	59	8.8	3.9
Asia			44.5		1.6

Table 2
Volume of material eroded and evacuated out of the block boundaries (Métivier et al., 1999). Partitioning of flux among source units deduced from the composition of sands (Garzanti et al., 2004, 2005), or from drainage area. Internal drainage or basin inside the block boundaries has not be considered here.

River	Sediment volume 10^6 km^3	Indochina	Tibet	Himalaya
Indus fan	3.3	50%	50%	
Yinggehai	1.1	50%	50%	
Andaman	2.2	100%		
Mergui	1.1	100%		
East China Sea	1		100%	
Yellow Sea	0.52		100%	
Bohai	0.41		100%	
Bengal fan	12	20%		80%
Gange fan	0.75			100%
$V_{erosion}$ 10^6 km^3		7.9	4.13	10.4

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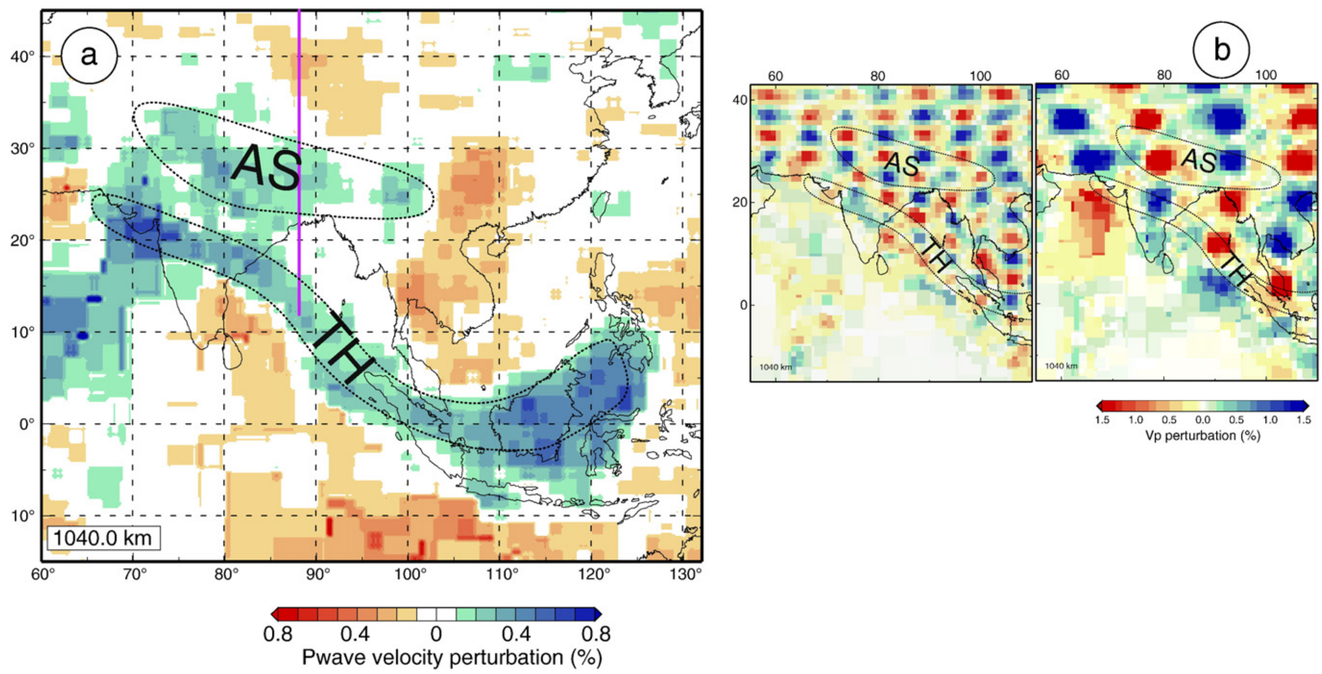

Fig. 4. Tomographic section at 1040 km depth. a) Position of anomalies TH and AS that map remnants of ancient slabs. b) Synthetic reconstruction tests for 2°×2° and 4°×4° spikes. These tests show that the anomalies interpreted in this study are well resolved by our travel-time dataset. Pink line shows cross-section of Fig. 6 (88 °E).

5. Block contours at the initiation of collision

We reconstruct the initial geometry of the blocks using seismic tomography and map remnants of ancient slabs showing previous block boundary positions (Fig. 4). 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 (Replumaz et al., 2010b). 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). Fig. 4b shows the results of the synthetic reconstruction test for 2°×2 and 4×4 spikes at the depth considered here, 1040 km. The reconstruction is very good beneath the continent, and decreases beneath the Indian Ocean, due to the lack of stations and earthquakes. The anomalies interpreted in this study are located in a well resolved zone, illustrating that their size and location are sufficiently well resolved by our travel-time dataset.

Beneath India, a continuous NW–SE trending high-wavespeed anomaly at depths below 1100 km has been interpreted as marking the locus of Tethyan oceanic subduction before the initiation of collision (anomaly TH, for TetHys, Fig. 4; van der Voo et al., 1999; Replumaz et al., 2004; Hafkenscheid et al., 2006; Richards et al., 2007). The Indochina block, as defined in this paper, extends east and south of the Indochinese peninsula, including Indonesia. Its eastern limit at the onset of collision is constrained by the deep anomaly TH, which marks the position of the convergent margin around Indochina before its extrusion (Replumaz et al., 2004; Fig. 5). This anomaly vanishes at depths shallower than about 1100 km (Fig. 6), which has been interpreted as marking Indian slab break-off at the onset of indentation. The high-wavespeed anomaly TH at this depth has been interpreted to outline the geometry of the northern boundary of India at the time of break-off (Negredo et al., 2007). The southern limit of India is given by the position of the continent deduced from the oceanic magnetic anomalies (Patriat and Achache, 1984). The total extent of India at the time of slab break-off depends on the chosen paleomagnetic position of India (cf. India contour in Fig. 5).

After slab break-off, India followed its northward motion. To the west of the collision zone, India resumed subducting under the Hindu–Kush (Western Syntaxis of the Himalaya), north of the break-off location. The length of this slab gives a constraint of the size of India after slab break-off. Negredo et al. (2007) match the length of the slab with the total extent of India deduced from the positions of India at different oceanic magnetic anomalies. They obtain a good match considering an age of break-off of 45 Ma. Therefore, we use in this study those

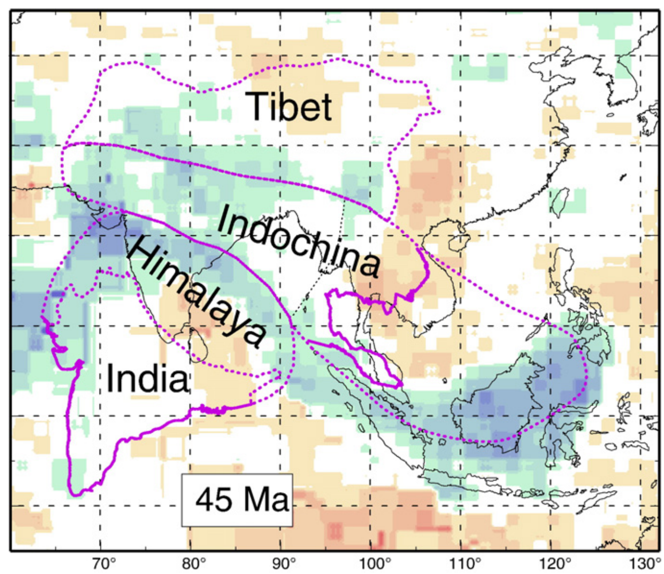

Fig. 5. Positions of block boundaries at the onset of collision inferred from remnants of ancient slabs mapped using seismic tomography: south, along the TH anomaly, boundary between India and Indochina, and north, along the AS anomaly, boundary between Tibet and Indochina.

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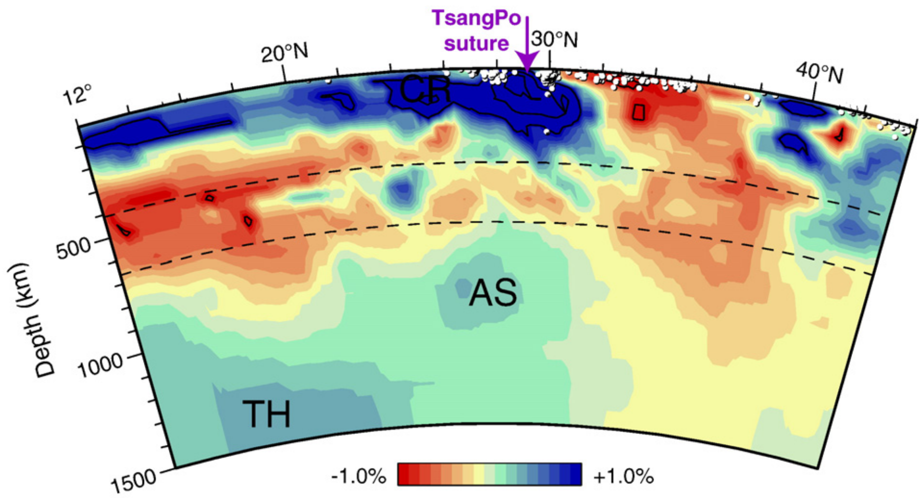

Fig. 6. Vertical section across the AS anomaly along 88 °E (location in Fig. 4).

reasonably well-constrained contours of the Indian and Asian continents at the estimated age of break-off, about 45 Ma (Fig. 5).

A second high-wavespeed anomaly of lower amplitude has been identified, located north of the TH anomaly and parallel to it (named AS, Fig. 4). Its horizontal length is about 3000 km, and its vertical extent is limited to about 200 km (Fig. 6). The AS anomaly has previously been identified by Hafkenscheid et al. (2006), but was not interpreted by these authors. As they pointed out, the AS anomaly cannot be an oceanic slab. It is located north of the Indus–Tsangpo suture at the onset of collision, represented by the top of the TH anomaly, and it is thus too far north to be a fragment of Tethyan slab subducted before collision (Fig. 5). It is also located above TH and thus not deep enough to be related to oceanic subduction during the accretion of Asia before collision (Fig. 6). We propose that this anomaly AS (ASian) is the remnant of an episode of Asian continental subduction. Such a process has already been proposed to partly absorb the northward motion of India within Asia, by successive episodes of subduction of unthickened continental lithospheric mantle north of the Indus–Tsangpo suture (Mattauer, 1986; Willett and Beaumont, 1994; Tapponnier et al., 2001).

The lack of vertical continuity of anomaly AS to the surface suggests that the slab was detached from the Asian continental crust and has sunk in the mantle since then. The anomaly is located between 1100 and 900 km depth, just above the top of the TH anomaly at 1100 km depth (Figs. 4 and 6). We suggest that this Asian continental subduction episode occurred soon after the break-off at about 45 Ma, related to the top of the TH anomaly. We associate the AS anomaly to the first episode of Asian continental lithosphere subduction. It should represent the initial boundary between the Indochina and Tibet blocks (Tapponnier et al., 2001). We use it to draw the geometry of the Indochina and Tibet blocks before thickening (Fig. 5).

6. Crustal mass preserved from subduction

We use the GMT routine grdvolume (Wessel, 1998) to calculate the area of the blocks at about 45 Ma ($A_{45\ \mathrm{Ma}}$). For each block, we divide its present-day crustal volume ($V_{0\ \mathrm{Ma}}$) by its area at 45 Ma to obtain a thickness ($\mathrm{HS}_{45\ \mathrm{Ma}}$):

$$HS_{45\ \mathrm{Ma}} = \frac{V_{0\ \mathrm{Ma}}}{A_{45\ \mathrm{Ma}}}.$$

This is equivalent to spreading the present-day thickened crustal volume over the initial area of the blocks (Fig. 7). The obtained thickness represents the portion of the initial thickness of the block that has been stored within the thickened crust during the collision. We consider that this thickness has been spared from subduction.

The present-day volume of crust was normalized to a mean crustal density of 2700 kg/m^3, using a simplified depth/density profile. We used this mean density for crust above 35 km depth, a density of 2900 kg/m^3 (7% more than the mean density) for the crust below

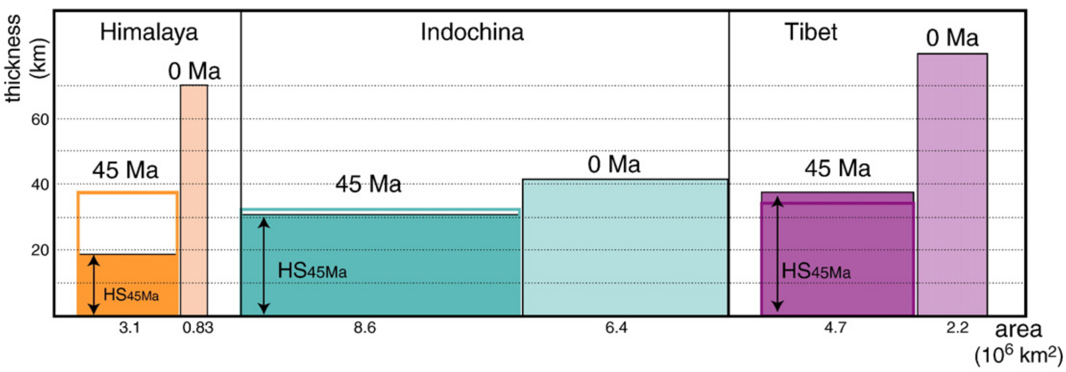

Fig. 7. Graph showing area along *x*-axis and average thickness along *y*-axis. For each block, the volume of continental crust comprised between the topographic surface and the Moho is divided by its present-day area measured on tomographic map (0 Ma thickness) or by its initial area deduced from tomography (45 Ma thickness). At 0 Ma, it illustrates that blocks are narrow and thick. At 45 Ma, the thickness represents the portion of the initial thickness of the block that has been stored within the thickened crust during the collision ($\mathrm{HS}_{45\ \mathrm{Ma}}$). Horizontal line indicates estimated initial thickness of crustal blocks (see text for discussion).

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35 km depth ($V_{depth>35\ km}$), and of 2250 kg/m^3 (17% less than the mean density) for the eroded and evacuated sediments ($V_{erosion}$).

$$V_{0\ Ma} = V_{topo} + V_{moho} + V_{depth\ >\ 35\ km}{}^{*}0.07 + V_{erosion}{}^{*}0.83.$$

During the collision, the northwest boundary of the Tibet block cannot be considered as fixed (Replumaz and Tapponnier, 2003) as part of the convergence of India is absorbed north of the Tibetan Plateau. The rigid Tarim basin has rotated clockwise since 11 Ma without deformation (Avouac et al., 1993). Part of the convergence is absorbed north of it, by shortening within the Tien Shan and Altai ranges (Fig. 1). In those ranges, the Moho reaches about 50 km, 10 km deeper than the surrounding cratons (Fig. 3). We chose to keep the northern edge of Tibet in a stable position to avoid uncertainty due to the reconstruction of its northward motion (Replumaz and Tapponnier, 2003). To take into account the northward motion of the northern edge of the Tibet block, we calculated the volume of crust thickened by its motion within the Tien Shan and Altai ranges, and added this to the crustal volume of Tibet (Table 3). The thickened volume is the total crustal volume of the Tien Shan and Altai ranges, calculated as for the Tibet block, minus their undeformed volume (block area*undeformed thickness). We used an underformed thickness of 38 km, corresponding approximately to the mean thickness of the crust in stable Siberia (Mooney et al., 1998).

The portion of the initial thickness of each block that has been stored within the thickened crust during the collision is shown in Table 3 and Fig. 7. For the Asian continent, adding the values of the Tibet and Indochina blocks, this portion is about 33 km thick. This thickness is comparable to the initial thickness of Northern Tibet, about 34 km, and of Southern Tibet, about 32 km, as previously estimated. We conclude that for the Asian continent almost the entire crust has been stored within the thickened blocks during the collision. The Asian continent has thus apparently been spared from massive continental subduction during the collision.

We obtain different results for the partitioning of the crust between Tibet and Indochina depending on the present-day location of the boundary between the two blocks (Fig. 2). With a boundary along the Jinsha suture (Tapponnier et al., 2001), the preserved thickness is about 28 km for Tibet and 36 km for Indochina. With a boundary along the Bangong suture (Leloup et al., 2001; Replumaz and Tapponnier, 2003), the preserved thickness is 37 km for Tibet and 31 km for Indochina. With a boundary along the Shiquanhe suture (adapted from Tapponnier et al., 1986), the preserved thickness is about 41 km for Tibet and 28 km for Indochina. Considering that an initial crustal thickness of 41 km for Tibet and of 36 km for Indochina are both excessively high, both the Jinsha and the Shiquanhe hypotheses appear improbable. We conclude that the Bangong suture represents the most probable boundary between the Tibet and Indochina blocks.

Table 3
For each block, its present-day crustal volume (V0Ma) is divided by its area at 45 Ma. It is equivalent to spread its present-day thickened crust volume over its initial area. The obtained length represents the portion of the initial thickness of the block that has been stored within the thickened crust during the collision ($HS_{45\ Ma}$). Partitioning of the Asian crust between Tibet and Indochina depending on the present-day location of the boundary between the two blocks is shown (favourite hypothesis along Bangong suture is shown in bold).

	V_{crust} 10^6 km^3	$A_{45\ Ma}$ 10^6 km^2	$HS_{45\ Ma}$ km
Himalaya	59.7	3.1	19
Asia (Tibet + Indochina)	438	13.3	33
Indochina (Bangong)	264	8.6	**30.9**
Tibet (Bangong)	174	4.7	**36.8**
Indochina (Jinsha)	306		35.8
Tibet (Jinsha)	131		27.8
Indochina (Shiquanhe)	242		28.3
Tibet (Shiquanhe)	195		41.3

For the Indian continent, we estimate that about 19 km of the initial crustal thickness has been stored by thickening during the collision within the Himalaya block. This value is far lower than the observed present-day mean thickness of the Indian craton of about 38 km (e.g. Gupta et al., 2003). Therefore, about half of the Indian crust must have been subtracted by another mechanism.

7. Discussion: amount of recycled crust during the collision

Possible mechanisms to absorb convergence are (1) thickening coupled with erosion, (2) extrusion, and (3) continental subduction, as part of the lower crust may remain attached to the lithospheric mantle and be pulled down with it. Previous budgets in 2D had two unknowns, the amount of extrusion and the amount of recycling (Tapponnier et al., 1986; Le Pichon et al., 1992). By considering the redistribution of mass between the present-day contour of Indochina and its contour before extrusion inferred from tomography (Fig. 5) together with the total thickening of the crust within the entire collision zone (Fig. 3), we quantify both the extrusion and the thickening processes. We are not able to discriminate between them in our budget. The only unknown is recycling of crust in the mantle by continental subduction. Our mass budget therefore represents a major improvement from previous budgets in 2D.

Our results show that during collision, the Asian crust was more or less preserved, while half of the Indian crust is missing (Fig. 7). Two mechanisms have been invoked to explain the large deficit of Indian crust, either the loss of lower crust into the mantle (Tapponnier et al., 1986; Le Pichon et al., 1992) or its transfer below Asian crust (DeCelles et al., 2002; Hetenyi et al., 2007; Nábělek et al., 2009).

To test if the transfer of Indian crust below Asia could restore the deficit, we try to estimate the volume of crust transferred. As recently imaged by Nábělek et al. (2009), the Indian lithosphere could currently underthrust the southern Tibetan Plateau, locally reaching the Bangong suture. About 15 km of Indian lower crust is eclogitized during the descent of the slab and stacked under Asian crust beneath 60 km depth, as modelled by Hetenyi et al. (2007). We calculated the volume of crust below 60 km depth beneath the Asian continent. We subtracted this volume from the Asian crustal volume and added it to the Himalaya block. We applied a volume increase of 22% to accommodate for the density of eclogite (3300 kg/m^3, 22% more than the average crustal density). The estimated volume is about 1.5×10^7 km^3 and increases the inferred preserved thickness of Himalayan block to 22 km, which is still much lower than the thickness of the Indian craton. On the other hand, the corresponding value of preserved initial crustal thickness of the Asian block decreases to 32 km. In this case, the volume of the subducted Indian crust is about 40% of the crustal volume of the Himalaya block. We conclude that at least 40%, and up to 50% considering no underthrusting, of the Indian crust involved in Himalayan collision has been recycled into the mantle. Such lower-crust subduction requires a decoupling level between 40 and 50% of the 38-km thickness of the Indian craton, that is, between 15 and 19 km. This depth corresponds approximately to the present-day depth of the Main Himalayan Thrust underlying the Himalayan mountain belt (e.g., Schulte-Pelkum et al., 2005; Nábělek et al., 2009).

Such a transfer of Indian crust below Asia could attenuate the deficit of Indian crust, but could not restore a regional equilibrium, as it would generate a deficit for the budget of Asian crust. This deficit should be compensated by the loss of Asian lower crust into the mantle. We have estimated the volume of subducted Asian crust corresponding to the slab of Asian origin related to the anomaly AS. The anomaly extends about 200 km vertically and 3000 km horizontally (Figs. 4 and 6). With a thickness of subducted lower crust between 15 and 19 km (as inferred for India), its volume can be

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roughly estimated between 1.1 and 1.4×10^7 km^3. This amount of subducted Asian crust is 3% of its total crustal volume, and is of the same order as the volume corresponding to the underthrusting of India beneath 60 km depth. It could restore the equilibrium of the Asian crustal budget. If a more significant transfer of crust from India to Asia is invoked to explain the large deficit of Indian crust, it would generate a large deficit for the budget of Asian crust. Such a deficit of Asian crust could not be compensated by observed subducted Asian lithosphere.

We show that both the Indian and the Asian continents experience continental subduction. This observation is in agreement with a plate-like behaviour of the lithospheric mantle of both continents (e.g. Meyer et al., 1998; Tapponnier et al., 2001). Transfer of Indian crust below Asia is compatible with our results if the volume transferred is small, of the order of a few percent of the total crustal volume of Asia. Such transfer has been imaged by seismic profiles (e.g. Hetenyi et al., 2007; Nábělek et al., 2009). The P-wave tomographic model presented here and the one by Li et al. (2008) consistently find fast P-wave propagation related to the Indian craton not far north of the Indus–Tsangpo suture, and slow one beneath Tibet (Fig. 6). It also suggests a small amount of underthrusting by Indian lithosphere in these regions (e.g. Li et al., 2008; Replumaz et al., 2010a). In contrast, our results are not compatible with the Indian plate underthrusting beneath the entire Tibet Plateau as suggested by some surface wave studies (e.g. Priestley et al., 2006). Such a significant transfer of crust from India to Asia reduces the large deficit of the Indian crust, but generates a large deficit for the Asian crustal volume.

8. Conclusion

During collision, both the Indian and the Asian crust were partly subducted in the mantle, which argues for a plate-like behaviour of the lithospheric mantle. A strong contrast between the geological histories of India, the lower plate composed of cratonic lithosphere, and Asia, the upper plate composed of younger orogenic belts, is reflected in the amount of recycling. 40 to 50% of the Indian crust involved in the Himalayan collision seems to have been recycled. This implies that during the continuous subduction of the Indian lower plate a decoupling level is located between 15 and 19 km depth on average. The long-term deformation of a craton such as India is thus characterised by such crustal-scale decoupling. For the upper plate, only 3% of the Asian crust was recycled into the mantle. This corresponds to one episode of continental subduction, most probably soon after the initiation of collision. This Asian subduction did not last long and did not recycle a large amount of Asian crust. It illustrates a negligible amount of recycling for young crust, such as the Asian continent. The strong contrast between India and Asia shows an age-dependent capacity of the continental crust to be recycled into the mantle. This result has to be taken into account for further analysis of global crustal recycling during Earth's history.

Appendix A

gmt script to calculate the crustal volume of the Indochina block

```
grdmask Indochina0Ma_XY.txt-GIndo0mask.grd-N0/1/1-I1m-R60/125/-10/40
grdmath TopoAsia.grd Indo0mask.grd MUL=IndoTopo.grd
grdvolume IndoTopo.grd-S-V-C0>TopoVolume
surface Moho_XYZ.txt-GMoho.grd-I1m-R-T0.25
grdmath Moho.grd Indo0mask.grd MUL-V=IndoMoho.grd
grdvolume IndoMoho.grd-Sk-V-C0>MohoVolume
```

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