Crustal thickening and lateral extrusion during the Indo-Asian collision: A 3D viscous flow model

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A B S T R A C T

The ~2000 km crustal shortening from the Indo-Asian collision in the past 40–70 million years has been accommodated mainly by crustal thickening in the Himalayan–Tibetan Plateau and lateral extrusion of blocks of Asian continents. However, the spatiotemporal evolution of crustal thickening and lateral extrusion, hence the far-field impact of the Indo-Asian collision on Asian tectonics, remains controversial. Here we present a 3D viscous flow model that simulates the partitioning of crustal material between thickening and lateral extrusion during the Indo-Asian collision. The model assumes conservation of crustal mass, and is constrained by the history of the Indo-Asian plate convergence and by the present-day topography of the Himalayan–Tibetan Plateau. The results show that much of the early collision was absorbed by crustal thickening within the Himalayan–Tibetan plateau. However, lateral extrusion of crustal material has gradually become dominant in the past ~10–20 Myr, indicating increasing influence of the Indo-Asian collision on Asian tectonics.

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1. Introduction

The Indo-Asian collision in the past ~40–70 Myr has caused about 2000 km crustal shortening (Yin and Harrison, 2000). Some collision was accommodated by crustal thickening in the Himalayan–Tibetan Plateau and surrounding regions (England and Houseman, 1986); the rest may be accommodated by lateral extrusion of blocks of Asian continent along numerous strike-slip fault systems (Tapponnier et al., 1982; Peltzer et al., 1989; Replumaz and Tapponnier, 2003) and by ductile lower crustal flow out of Tibet (Clark and Royden, 2000) (Fig. 1).

How the shortened crust was partitioned between crustal thickening and lateral extrusion during the Indo-Asian has important implications for the diffuse Asian tectonics, yet the answers from previous studies are inconclusive. In a continuum mechanical model that approximates the Asian continent as a viscous thin sheet indented by a rigid Indian plate, England and Houseman (1986, 1988) have shown that the collision is accommodated mainly through crustal thickening in central Asia, mostly within the Himalayan–Tibetan plateau. Conversely, using an analogue experiment of indentation of a plasticine Asian continent, Tapponnier and co-workers show far-reaching influence of the collision through lateral extrusion of blocks of Asian continent (Tapponnier et al., 1982). Subsequent studies have narrowed the gap between these end member models (Houseman and England, 1993), and the perceptions of how crustal thickens and extrudes have evolved. The lateral extrusion could occur in forms of both discrete translation of crustal blocks and distributed extrusion of crustal material (Kong and Bird, 1996), or by lateral flow of lower crustal material out of the collision zone (Clark and Royden, 2000). On the other hand, the Himalayan–Tibetan Plateau may have risen in discrete steps (Tapponnier et al., 2001). Nonetheless, the partitioning of strain between crustal thickening and lateral extrusion, and more importantly, the spatiotemporal evolution of such strain partitioning, remain controversial (Tapponnier et al., 2001; Wright et al., 2004).

The tectonic implications can be profound. When most of the Indo-Asian collision is absorbed by crustal thickening in the Tibetan Plateau, its impact would be limited to the plateau and surrounding regions (England and Molnar, 1997). Conversely, when the collision is accommodated mainly by lateral extrusion of Asian continent, its impact on Asian tectonics would be immediate and far reaching. Hence how the crustal shortening is partitioned between crustal thickening and lateral extrusion controls both the rise of the Himalayan–Tibetan Plateau and Cenozoic tectonics in much of the central and eastern Asia.

In this study we first estimate the amount of crustal shortening and the portion accommodated by crustal thickening in the Himalayan–Tibetan plateau, based on the history of the Indo-Asian collision and the present crustal volume in the plateau. We then use a three-dimensional (3D) viscous flow model to simulate the spatiotemporal partitioning of the shortened crust between crustal thickening and lateral extrusion.

2. The amount of crustal shortening and thickening

The relatively well-defined plate convergence history and the present-day crustal volume of the Himalayan–Tibetan Plateau permit some estimation of the portioning of crustal mass between thickening...
and lateral extrusion during the Indo-Asian collision (Dewey et al., 1989; Le Pichon et al., 1992; Molnar et al., 1993). If we use the present-day Himalayan–Tibetan Plateau as the control volume, we can estimate how much crustal material has been squeezed into this control volume since the beginning of the collision, and how much of the added crustal mass has been retained for plateau building. The rest must then be moved out of the control volume by lateral extrusion or other processes (see below).

The crustal volume of the present-day Himalayan–Tibetan Plateau is given by its surface area and the crustal thickness. At present the plateau may be defined along the Altyn Tagh fault (ATF) to its north, the Main Boundary Thrust (MBT) to its south, the Pamir plateau to its west, and the Longmenshan thrust and the Xiaojiang–Red River Faults to its east (Fig. 1). The area of the plateau so defined is \( \sim 3 \times 10^6 \) km\(^2\).

The crustal thickness within the Himalayan–Tibetan Plateau may be constrained by gravity and seismic results, which indicate that the plateau is generally in the Airy-type of isostasy (Housman and England, 1996; Fischer, 2002). Seismic tomography and deep seismic sounding show that the Moho reaches 70–74 km beneath the Tibetan plateau (Li et al., 2006; Sun and Toksoz, 2006). Receiver function analyses show that the crust thickens from 50 km beneath the Qaidam basin to 80 km beneath the south Tibet (Kind et al., 2002; Shi et al., 2004). However, the coverage of seismological studies is insufficient to constrain the crustal thickness of the entire plateau. So we use the elevation of the plateau and assume the Airy isostasy to estimate the crustal thickness; the total crustal volume of the present-day Himalayan–Tibetan Plateau thus calculated is \( 2.0 \times 10^8 \) km\(^3\), assuming 1) uniform crustal and mantle density of 2800 kg/m\(^3\) and 3300 kg/m\(^3\), respectively, and 2) initial elevation near the sea level (this serves as the upper bound for crustal thickening within the plateau).

This crustal volume of the present Tibetan Plateau includes the initial crustal mass, \( V_0 \), and crustal thickening from the collision, \( V_t \) (Fig. 2). \( V_0 \) would be \( 0.9 \times 10^8 \) km\(^3\) if the initial crustal thickness was 30 km, or \( 1.35 \times 10^8 \) km\(^3\) if the initial crustal thickness was 45 km. The initial crustal thickness is poorly constrained, but likely lies between 30 and 45 km, a range encompassing the crustal thickness of the India shield and most lowland Asian continent. Accordingly, \( 1.1 \sim 0.65 \times 10^8 \) km\(^3\) of crustal mass (\( V_t \) in Fig. 2) has been added to build today’s Tibetan Plateau.

The total volume of the crustal material pushed into the control volume by the Indian indenter during the collision (\( V_t \) in Fig. 2) may be estimated from the collisional history between the Indian and Eurasian plates, which is relatively well constrained from marine magnetic anomalies (Acton, 1999; Schettino and Scotese, 2005) (Fig. 1). Because the continental margin of the Indian plate before the collision is not well constrained, we define the northern edge of the Indian indenter along the MBT, the current collision front. Similarly, we assume the Altyn Tagh fault to be the northern boundary of the collision zone. In doing so, we have lumped the effects of continental margins of the Indian and the Asian plates, both poorly constrained, into the uncertainties of the initial crustal thickness. Uncertainties of other parameters, such as the inception time of the collision, probably have less impact than that of the initial crustal thickness. Assuming the crust was initially 30–45 km thick, we estimate that the volume of crust that has entered the control volume since 50 Ma is \( 1.8 \sim 2.7 \times 10^8 \) km\(^3\).

Given that \( V_t = 1.1 \sim 0.65 \times 10^8 \) km\(^3\), or 61–24% of the \( V_{in} \), the crustal mass entered the control volume, the rest 39–76% of \( V_{in} \) must be...
accommodated by lateral extrusion and other processes, which may include crustal thickening in the surrounding areas and erosion.

In this calculation we assumed mass conservation of the crustal material. Some studies have found evidence for eclogites in the bottom of crust beneath southern Tibet (Jackson et al., 2004; Hetenyi et al., 2007). The potential eclogitization may significantly reduce crust volume in old orogenic belts; however, eclogitization generally takes hundreds of millions of years, so the amount of crustal mass affected by eclogitization in young orogens like the Tibetan plateau is likely insignificant (Fischer, 2002). Similarly, although igneous intrusion or underplating may add crustal mass, their impact is likely small when compared with the large uncertainty in the pre-collision configuration of Indian and Tibetan continental boundaries and initial crustal thickness.

3. The 3D finite-strain flow model

To simulate the spatiotemporal partitioning between crustal thickening and lateral extrusion during the Indo-Asian collision, we developed a 3D viscous flow model (Fig. 3). This model approximates the Asian continent as a power-law viscous plate indented by a stiff Indian plate, similar to previous viscous thin-sheet models (England and Houseman, 1988). The model can include vertical variations of rheology. For this study we included a relatively weak lower crust 20-km below the surface to simulate the first-order effect of lower crustal flow (Royden, 1996; Clark and Royden, 2000). We also considered first-order rheological contrasts among the Indian indenter, the Himalayan–Tibetan orogenic zone, and the stiff Tarim and the South China blocks (Fig. 3). The major fault zones bounding these tectonic units are represented in the model with simplified geometry (Fig. 1) and simulated as weak zones using a special fault element (Goodman et al., 1988). The faults within the interior of the Tibetan plateau are not included. Their role is probably largely confined to the plateau (Kirby et al., 2007). The evolution of the finite strain is calculated using the finite element method (Yang et al., 2003).

The model includes only the crust, which is our primary concern here. The crustal material subducted into the mantle, if happened, is likely minor (Houseman et al., 2000). Deformation in the mantle has no major effects on the crustal volume of the Tibetan Plateau, although buoyancy forces in the mantle may have contributed to the elevation of the central-northern Tibet (England and Houseman, 1989; Molnar et al., 1993). Nonetheless, most part of the high Tibetan Plateau is isostatically compensated by crustal roots (Fischer, 2002).

The geological boundary conditions are simplified in the model (Fig. 3). The southern boundary moves northward at 40 mm/yr at the western end of the Indian indenter front, with a 0.22°/Myr counter clockwise rotation around a pole at the western end of the indenter. This is an approximation of the trajectories of the Indian plate derived from marine magnetic anomalies (Patriat and Achache, 1984; Ali and Aitchison, 2005). The western side of the model domain is fixed in the normal direction and free-slip in the tangential direction, reflecting geological conditions imposed by the Pamir plateau. The Himalayan–Tibetan Plateau is bounded by the Tarim block to the north and the South China block to the east, both assumed fixed in the model. Doing so is justifiable because their motion is insignificant in comparison to that of the Indian Indenter in the Cenozoic (Replumaz and Tapponnier, 2003). More importantly, it is the relative motion between the Indian plate and these bounding blocks that controls crustal shortening during the collision. On the surface and bottom of the model domain, the Winkler spring mattress (Desai, 1979) is applied to simulate topographic loading and isostatic restoring force (Williams and Richardson, 1991).

In this model, the Indian indenter bulldozes crustal material in the collisional zone, causing both crustal thickening in its front, and lateral extrusion in the form of crustal flow away from the collisional zone. Because of the rigid blocks surrounding the Himalayan–Tibetan Plateau, the main exits for the lateral extruding crustal mass are on the southwestern corner where crustal mass flows into Indochina, and on the northeastern side of the plateau (Clark and Royden, 2000). Accordingly, we used viscous-piston elements on these boundaries (indicated by pistons in Fig. 3), where the viscous resistance is proportional to the flow velocity at the boundaries. When the resistance coefficient is set to zero, most excessive crustal material would flow out of the collision zone. With a resistance coefficient of $2.8 \times 10^{10}$ Pa s/m or higher, these boundaries act like retaining walls that trap all crust material within the plateau. We adjusted the viscous resistance of these elements to preserve the right amount of crustal material required by that of today’s Himalayan–Tibetan Plateau. In most cases the required resistance coefficient is $5 \times 10^3$ Pa s/m at the Indochina boundary and $2.8 \times 10^5$ Pa s/m on the Gobi boundary.

The initial configuration of the collision zone is constructed by restoring the location of the Indian indenter relative to the Asian continent (Fig. 3). Given the uncertain initial crustal thickness of the collision zone (Yin and Harrison, 2000), we tested different values ranging from 30 km to 45 km in the model.

The model assumes the rheology of the power-law fluid. We explored different rheology with the power index varying between 1 and 10. The optimal models have a power index of 3 and effective viscosity of $6 \times 10^{22}$ Pa s (defined at the strain rate of $10^{-15}$ s$^{-1}$) for the upper crust (top 10 km), $4 \times 10^{22}$ Pa s for the middle crust (10–20 km depth), and $1 \times 10^{18}$–$4 \times 10^{22}$ Pa s for the lower crust, within the collision zone. For the Indian indenter, the Tarim block, and the South China block, we used a high effective viscosity of $4 \times 10^{23}$ Pa s for the entire crust. The boundary faults are simulated as 20-km wide zones of a relatively low viscosity, $3 \times 10^{19}$ Pa s in most cases. Increasing the viscosity of the fault zone would simulate strong coupling across the fault. The fault zone would be effectively shut off (fully locked), if its viscosity takes the value same as that of the ambient crust. Geological studies indicate that the Altyn Tagh fault and the Longmenshan fault were active at the early stage of the Indo-Asian collision (Yin et al., 2002; Burchfiel et al., 2008), so we included these faults from the beginning of the modeling. On the other hand, the Main Boundary Thrust was probably formed quite late, but is included from the beginning. This simplification may lead to overestimate of the role of strike-slip during the early stages of collision.

4. Model results

Based on the history of plate convergence, we conducted a series of forward models to simulate the partitioning of crustal material between
Fig. 4. Snapshots of the simulated Indo-Asian collision and the rise of the Himalayan–Tibetan Plateau. For this case the viscosity is $1 \times 10^{21}$ Pa s for the lower crust in the orogenic zone; other rheological values are given in the text. All fault zones bounding the Tarim and Shichuan-South China block, and the Main Boundary Fault are simulated with a 20 km wide zone of low viscosity ($1 \times 10^{20}$ Pa s). Viscous resistance at the exit boundaries (shown by pistons in Fig. 3) is proportional to the velocity at the boundaries; the resistance coefficient is $5 \times 10^3$ Pa s/m at the Indochina boundary, $2.8 \times 10^5$ Pa s/m on the Gobi boundary. The inset in (c) compares the predicted topography (thick lines) with that of present Tibetan plateau.
thickening within the Himalayan–Tibetan Plateau and lateral extrusion. The acceptable models should reproduce the present-day crustal volume and general topography of the Himalayan–Tibetan Plateau. Fig. 4 shows snapshots of one of the simulations. As the Indian plate collided with the Asian continent, crust was thickened near the Indian indenter and then spread northward, as in previous thin-sheet models (England and Houseman, 1986; England and Houseman, 1988). Because of the collisional zone narrows to its west (a shorter than average distance between the western Indian indenter and the Tarim block), the western portion of the Himalayan–Tibetan Plateau rises faster and higher, and spreads eastwards. Lateral extrusion, in the form of crustal flow out of the collisional zone, depends on the crustal viscosity and the boundary conditions. We found that flow in the weak lower crust is instrumental in reproducing the strikingly flat Tibetan plateau (Fig. 4c), as suggested by Zhao and Morgan (1987).

In the model the Indian indenter moves at a constant rate of 40–51 mm/yr, thus its 2700-km long northern edge moves 3.7–5.4 km3 of crustal material per year toward today’s Himalayan–Tibetan Plateau, depending on the assumed initial crustal thickness (30–45 km in the model). Over the past 50 Myr, this process has squeezed out $1.8-2.7 \times 10^8$ km$^3$ crustal mass (Fig. 5a), as in the aforementioned estimation. The portion accommodated by crustal thickening in the present Tibetan Plateau by a given time during the collision can be calculated by volume integration over the area enclosed by the Pamir, the ATF, the Longmenshan Fault and the MBT, whose positions were traced in the model. The total amount of the added crustal mass for plateau building, however, is constrained by today’s crustal volume ($2.0 \times 10^8$ km$^3$). Depending on the initial crustal thickness, in the model the viscous resistance along the “exit” boundaries (shown as pistons in Fig. 3) is adjusted to retain the right amount of crustal mass. We found that, within the range of 30–45 km thick initial crust, crustal thickening absorbed much of the collision in the early history of the collision, but its role has gradually declined with time. The relative proportion between crustal thickening and lateral extrusion depends on the initial crustal thickness. A thicker initial crust would require less crustal thickening within the Himalayan–Tibetan Plateau, and consequently more lateral extrusion in the later periods, but the same time-dependent trend of partitioning between thickening and lateral extrusion are independent of the initial crustal thickness.

The influx of crustal material not accommodated by plateau building must be absorbed by lateral extrusion, either by translation of continental blocks along strike-slip faults or by crustal flow out of the Tibetan Plateau, and by other processes, mainly erosion. This part has increased with time (Fig. 5a). The contribution from erosion is difficult to determine, but some rough estimates may be derived from Cenozoic sediments in basins around central Asia (Metivier et al., 1999) (Fig. 5b). Subtracting the contribution from erosion gives the estimate of lateral extrusion. Fig. 5c shows the proportion of crustal thickening, lateral extrusion, and erosion at selected time intervals from a model with 35 km initial crustal thickness. Given the uncertainties of initial crustal thickness and the rate of erosion, Fig. 5c is meant only to illustrate the general trend of partitioning among the various processes. The outflow of crustal mass was less than 13% of the inflow in the first 10 Myr but over 100% in the last 5 Myr. The negative contribution from crustal mass added to the plateau in the past ~5 Myr means that the total crustal volume of the Himalayan–Tibetan Plateau, as defined in Fig. 1, is shrinking as the indentation continues to shrink the surface area enclosed by those boundary faults in Fig. 1. However, the loss of surface area and crustal volume does not necessarily mean lose of crustal thickness and elevation. Because within the plateau, either adding new crustal mass from outside or having internal shortening can both lead to crustal thickening and hence uplift.

The predicted uplift history of the plateau is shown in Fig. 6. Everywhere within the Tibetan Plateau, the uplift accelerated with time. The uplift history varies from place to place; it was fastest in the western part and slowest in the northeastern part of the plateau. Nonetheless, most part of the plateau rose above 3 km about 10–20 Myr ago, broadly consistent with the timing of initiation of the widespread north-trending grabens in the Tibetan Plateau (Coleman and Hodges, 1995; Yin, 2000).

5. Discussion

The 2000–2500 km northward motion of the Indian plate relative to Eurasian plate in the past 40–70 Ma implies that up to $2.7 \times 10^8$ km$^3$ crustal material between the two plates has been telescoped. About 61–24% of this crustal mass have been accommodated by thickening within the Himalayan–Tibetan Plateau, the rest has to be moved out of the collision zone, either by lateral translation of blocks of the Asian continent or by crustal flow out of the Himalayan–Tibetan Plateau, and by other processes such as erosion.
The current crustal motion in the Himalayan–Tibetan Plateau and surrounding regions are shown by the Global Positioning System (GPS) measurements (Fig. 7). The GPS velocities represent mainly short-term strain rates, and it is unclear how the crustal motion varies with depth. Nonetheless, if we take the GPS velocities as an approximation of the average motion of the whole crustal blocks, we may estimate the crustal mass flux in and out of the Himalayan–Tibetan Plateau enclosed by the simplified boundaries in Fig. 7. Through each boundary segment the mass flux is given by the product of the length of the segment, the local crustal thickness, and the velocity of crustal motion normal to the segment, extrapolated from the GPS data. We found that the total influx of crustal material from the Himalayan front is 3.3–3.7 km³/yr, depends on the average crustal thickness of the Indian indenter; the total efflux from other sides of the Tibetan Plateau is 54–70% of the influx, close but lower than our estimated rate of extruding crustal mass (Fig. 5c). One possible explanation is the faster lower crustal flow than at the earth’s surface. In our model the rates of lower crustal flow can be orders of magnitude higher than at the earth’s surface.

Fig. 6. Predicted uplift history of selected locations (shown in inset) in the Tibetan Plateau.

Fig. 7. GPS velocity relative to stable Eurasia (data from Zhang et al. (2004)). The error ellipses are 95% confidence intervals. The line segments enclose the plateau over which the influx and efflux of crustal material are calculated. See text for details.
magnitude higher that the surface velocity. Royden and co-workers appealed to such lower crustal flow to explain the rise of eastern Tibet where surface shortening is insufficient (Clark and Royden, 2000; Royden et al., 2008).

The spatiotemporal partitioning of the telescoped crustal material is simulated in a viscous flow model, constrained by 1) the history of the Indo-Asian convergence, and 2) the topography (or the crustal volume) of the present Himalayan–Tibetan Plateau. Satisfying these constraints requires trade-offs between free or less constrained model parameters. For example, weakening the boundary fault zones in the model would enhance lateral extrusion, but then higher viscous resistance must be applied at the Indochina and the Gobi boundaries (indicated by pistons in Fig. 3) to retain enough crustal material to reproduce the present Tibetan topography.

Our finite strain model is a first-order approximation. Many parameters are poorly constrained and may change the details of the model predictions. One major uncertainty is the initial crustal thickness of the collision zone. Some part of the Tibetan Plateau probably stood high with a thick crust at the beginning of the Indo-Asian collision (Murphy et al., 1997; DeCelles et al., 2002; Rowley and Currie, 2006; Yin, 2006). In this case less of the telescoped crustal material would be needed to build the present Tibetan Plateau, consequently more lateral extrusion would be predicted. The effects of many other uncertainties, such as the initial geometry and structure of the margins of the Indian indenter and the Asian continent, as well as the paleo-positions of the Indian indenter (Ali and Aitchison, 2005), can be lumped into the large range of initial crustal thickness explored in the model. As shown in Fig. 5a, while the details vary with the different initial crustal thickness, the general trend of partitioning of crustal mass between thickening and lateral extrusion remains the same.

Other uncertainties include the boundary conditions. In the model we hold both the South China and the Tarim blocks fixed, although they both have moved away from the Indo-Asian collisional zone through the Cenozoic. However, their moving histories are not well constrained. Besides, their motion is of second order relative to that of the Indian indenter, thus their impact on the model is limited. Erosion is not included in the model, and the estimated rates of erosion are associated with large intrinsic uncertainties (Metivier et al., 1999). We included erosion in Fig. 5 to show the complete partitioning of the telescoped crustal material. Additionally, some of the lower crust of the Indian plate may have experienced eclogitization and subducted into the mantle (Le Pichon et al., 1992). The amount, while hard to constrain, is unlikely to be significant to alter the general results in this study.

With all the uncertainties, the model consistently predicts that most of the Indo-Asian collision was accommodated by crustal thickening within the Himalayan–Tibetan Plateau during the early stages of the collision. However, the role of crustal thickening declines with time, and is gradually replaced by lateral extrusion of crustal material. The underlying physics for this trend is straightforward. In the model, the driving force for lateral crustal flow is the gradient of gravitational potential energy between the Tibetan Plateau and the surrounding lowland. As the Tibetan Plateau rises, the gravitational force increases, hence the lateral crustal extrusion intensifies (England and Molnar, 1997; Kong et al., 1997). Furthermore, crust thickening increases the flow channel of the weak lower crust, hence promoting lateral extrusion.

The increasing role of lateral extrusion is generally consistent with initiation of widespread north–trending grabens in south and central Tibet (Armiho et al., 1986; Blinski et al., 2001), which has been explained either as gravitational spreading of the elevated Tibetan Plateau (Dewey, 1988; Liu and Yang, 2003) or as a consequence of lateral extrusion of the Tibetan crust (Yin, 2000). Note that in our model lateral extrusion is defined as crustal material flowing out of the presently defined Tibetan Plateau. Thus it includes both lateral translation of rigid blocks of Asian continents along strike-slip faults, and ductile flow of crustal material that may have contributed to crustal thickening in other parts of Asia. We cannot distinguish these two processes from modeling. It is conceivable that, when the Tibetan crust was relatively thin and strong during the early stages of collision, crustal flow is ineffective and block motion along strike–slip faults was the main form of extrusion. This may help explain early fault slips along some of the faults within and around the plateau, such as the late Oligocene to early Miocene slip along the Red River fault (Gilley et al., 2003). As the crust become thicker and presumably weaker, ductile flow in the lower crust would become more effective (Clark and Royden, 2000). The increasing role of lower crustal flow is consistent with late Miocene and younger uplift in eastern Tibet (Royden et al., 1997; Schoenbohm et al., 2006). Rapid changes of lithospheric rheology and boundary conditions, such as delamination or convective downwelling of mantle lithosphere under Tibet (England, 1993), could cause departure from the gradual change of crustal thickening and lateral extrusion predicted in this model (Tapponnier et al., 2001).

The existence of a weak, ductile lower crust under the Tibetan Plateau and its role in the plateau building have been challenged by recent results of consistent GPS velocities and the fast polarization direction of split SKS waves (Flesch et al., 2005; Wang et al., 2008). The apparently vertical coherence of deformation near surface and in the uppermost mantle has been interpreted as evidence for a strong crust–mantle mechanical coupling that is unfavorable for the existence of a weak lower crust (Bendick and Flesch, 2007; Wang et al., 2008). We suggest that the vertical coherence of lithospheric deformation within the Tibetan Plateau may simply result from the tectonic boundary conditions. The Tarim block and the South China blocks are rigid structures with high seismic velocities extending to >200 km depth (Liu and Jin, 1993; Huang and Zhao, 2006), with the Indian plate indenting from the south and southwest, the crustal and mantle mass is forced to extrude southwestward and northeastward (Fig. 1). Hence the coherent surface and mantle deformation cannot exclude the existence of a weak lower crust. Royden et al. (2008) have shown clearly reduced S wave velocities in the lower crust under eastern Tibet that are indicative of a weak lower crust.

The increasing role of lateral extrusion may also explain tectonics in many regions in central and eastern Asia where early Cenozoic tectonics show no clear link to the Indo-Asian collision (Northrup et al., 1995), whereas the impact of the collision in these regions is clear today (Avouac and Tapponnier, 1993; Zhang et al., 2003).

6. Conclusions

Major conclusions we may draw from this study include the following:

1) In Indo-Asian collision has telescoped up to $2.7 \times 10^8$ km$^3$ crustal material between these two plates. About 61–24% of the shortened crustal material has been accommodated by crustal thickening within the Himalayan–Tibetan Plateau; the rest has been accommodated by lateral extrusion, either in form of lateral translation of blocks of the Asian continent or by ductile flow in the lower crust, and by other processes such as erosion.

2) Most of the Indo-Asian collision was accommodated by crustal thickening within the Himalayan–Tibetan Plateau during the early stages of collision. The plateau rose from south to north at the beginning, and then from west to east. Most part of the Tibetan Plateau likely reached an elevation of 3 km or more about 15 million years ago.

3) As the Himalayan–Tibetan rises, lateral extrusion has gradually become the dominant way to accommodate the Indo-Asian collision in the past 10–15 Ma. The increasing role of lateral extrusion implies broader and stronger impact of the Indo-Asian collision on Asian tectonics.
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