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The Indo-Asian continental collision: A 3-D viscous model

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ABSTRACT

The large-scale physical process of the Indo-Asian continental collision and the formation of the Himalayan–Tibetan Plateau have been simulated in various viscous thin-sheet models, but the thin-sheet simplification also kept some important issues from being fully explored. Among these issues are the role of strike-slip fault zones in facilitating large-scale lateral translation of lithospheric blocks (the escaping tectonics) during the collision, and the speculated lateral flow of the ductile middle–lower crust under the Tibetan Plateau. Here we present a fully three-dimensional finite element model to simulate the Indo-Asian continental collision. The model includes major boundary faults to simulate the escaping tectonics, and vertically variable rheological structures to model lower crustal flow. The collisional process is constrained by the history of the Indo-Eurasian plate convergence and the present crustal thickness and topography of the Tibetan Plateau. Our results indicate that the restrictive boundaries of the Tibetan Plateau, including the rigid Tarim and South China blocks, largely control the spatiotemporal patterns of crustal deformation in the collision zone. As the Indian indenter moves toward the Tarim block, higher strain rates and topography developed in the western part of the collision zone than in the eastern part, causing the northward migration of the deformation front to gradually change to eastward migration in the past 10–20 Myr, broadly consistent with the initiation of widespread E–W extension in the Plateau. These restrictive boundary blocks also force the crustal and mantle materials in the collision zone to flow coherently, hence providing an alternative explanation for the apparently vertically coherent deformation in Tibet. Assuming that the crust weakens as it thickens, our model predicts the lateral expansion of the Tibetan Plateau, an important feature of the Tibetan tectonics that is missing in previous models with constant rheology.

1. Introduction

The Himalayan–Tibetan Plateau, created mainly by the Indian–Eurasian continental collision in the past ~65–50 Myr (Molnar and Tapponnier, 1975, 1977; Yin and Harrison, 2000), is the best-studied example of collisional tectonics (Patriat and Achache, 1984). The collisional process and the resulting large-scale continental deformation have been simulated in viscous thin-sheet models (England and Houseman, 1986, 1988; Houseman and England, 1993, 1996). The thin-sheet approximation reduces the three-dimensional (3-D) lithospheric deformation to 2-D, hence greatly simplifies computation. These models have illustrated some of the basic physics of continental collision, including the northward migration of crustal thickening and uplift, and the balance between gravitational potential energy resisting crustal thickening and the viscous stress from convergent plate boundaries that drives crustal shortening and thickening (Houseman and England, 1996). However, the 2-D simplification also keeps some important issues from being fully explored.

One such issue is the lateral motion of lithospheric blocks along major strike-slip fault zones, the so called escaping tectonics (Peltzer and Tapponnier, 1988; Tapponnier et al., 1982). Geological evidence indicates that, in and around the Tibetan Plateau, strain has been localized along major fault zones and large amounts of fault slip, up to hundreds of kilometers or more, have been accumulated along some of these faults during the Indo-Asian collision (Peltzer et al., 1989; Replumaz and Tapponnier, 2003). This suggests that lateral extrusion of lithospheric blocks may have played a major role in accommodating the Indo-Asian collision. Such escaping tectonics cannot be simulated in the viscous thin-sheet models, which do not include internal fault zones in the finite strain calculations.

Another issue is the role of lower crustal flow during the continental collision and mountain building (Royden et al., 1997). Extrapolation of rock mechanics data suggests for a weak middle–lower crust for most continental lithosphere (Brace and Kohlstedt, 1980), and a weak middle–lower crust in eastern Tibetan Plateau has been inferred from some seismological studies (Royden et al., 2008). Large-scale lateral flow of the weak ductile middle–lower crust under Tibetan Plateau may explain the flatness of the plateau (Zhao and Morgan, 1987), topographic gradients across the margins of the plateau (Clark and Royden, 2000; Clark et al., 2005), and many other geological features of Tibetan tectonics (Beaumont et al., 2001). The lower crustal flow and other

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depth-dependent deformational processes cannot be simulated in viscous thin-sheet models and require models with three-dimensional rheological structures.

Lechmann et al. (2011) did a detailed comparison of continental collision in a viscous thin-sheet model with that in a three-dimensional viscous model, using a simple geometry of a Cartesian box. They have shown some importance difference in results from these two models, especially near the indenter and around its corners. We have developed a three-dimensional finite element model with specific model geometry, boundary conditions, and rheological structures to calculate finite strain evolution during the India–Eurasian collision. In a previous report, we used this model to explore the time-dependent partitioning of the shortened crustal material between thickening and lateral extrusion (Yang and Liu, 2009). In this paper we use this model to systematically explore how boundary fault zones and 3-D variations of rheological structure of the Eurasian crust affect the crustal deformation and mountain building in the Tibetan Plateau and surrounding regions.

2. Tectonic background

The Indo-Asian collision initiated ~70–45 Myr ago and has continued to today at an average rate of 40–50 mm/yr. (Avouac, 2007; Molnar and Stock, 2009; Patriat and Achache, 1984; Yin and Harrison, 2000). The history of the Indo-Asian collision and the development of the Himalayan–Tibetan Plateau can be found in many review papers (Molnar and Tapponnier, 1975; Replumaz and Tapponnier, 2003; Royden et al., 2008; Tapponnier et al., 2001; Yin and Harrison, 2000) (Fig. 1). These and other papers show significant advance of our knowledge of the collisional tectonics from intensive studies of the Himalayan–Tibetan Plateau in the past few decades, yet some major questions remain. Here we highlight some of them that further insights may be obtained from 3-D finite strain calculations.

One question is how the Tibetan Plateau developed over space and time as a consequence of the Indo-Asian collision. The viscous thin-sheet models predict crustal thickening and uplift that propagate northward as the Indian plate indent into the Eurasian continent (England and Houseman, 1986, 1988). Now it is clear that the uplift history of the Tibetan Plateau is more complicated. Crustal shortening and uplift in northern and northeastern part of the Tibetan Plateau may have started as early as Eocene and Oligocene (see (Clark et al., 2010; Molnar et al., 2010; Yin, 2010) and references therein); uplift of the eastern Tibetan Plateau is believed to have occurred more recently (Clark et al., 2005), yet new evidence shows earlier (30–25 Ma) and multiple phases of uplift in eastern Tibet (Wang et al., 2012). It is also clear that the overall strain pattern over the Tibetan Plateau had a major shift around 10–20 Ma, as the dominantly N–S contraction was replaced by widespread E–W extension. Some workers attributed the E–W extension to gravitational collapse (England and Houseman, 1989; Liu and Yang, 2003), others linked the extension to the development of V-shaped conjugate strike-slip faults in central Tibet (Yin and Taylor, 2011). The cause of the change from N–S contraction to E–W extension, however, is not clear.

Another question is how the Tibetan Plateau has grown laterally. Molnar and Lyon-Caen (1988) have showed that, theoretically, the gravitational potential energy in a rising mountain belt tends to cap the elevation of the mountain belt and force it to grow laterally instead. Although the uplift history of the Tibetan Plateau seems complicated, the young and active deformation is concentrated near the margins of the Plateau (Clark et al., 2004; Yin, 2010), attesting its lateral growth. However, the Plateau is surrounded by the rigid Tarim, Ordos, and the South China (Sichuan) blocks that experienced little internal deformation through the Cenozoic (Fig. 1). How these

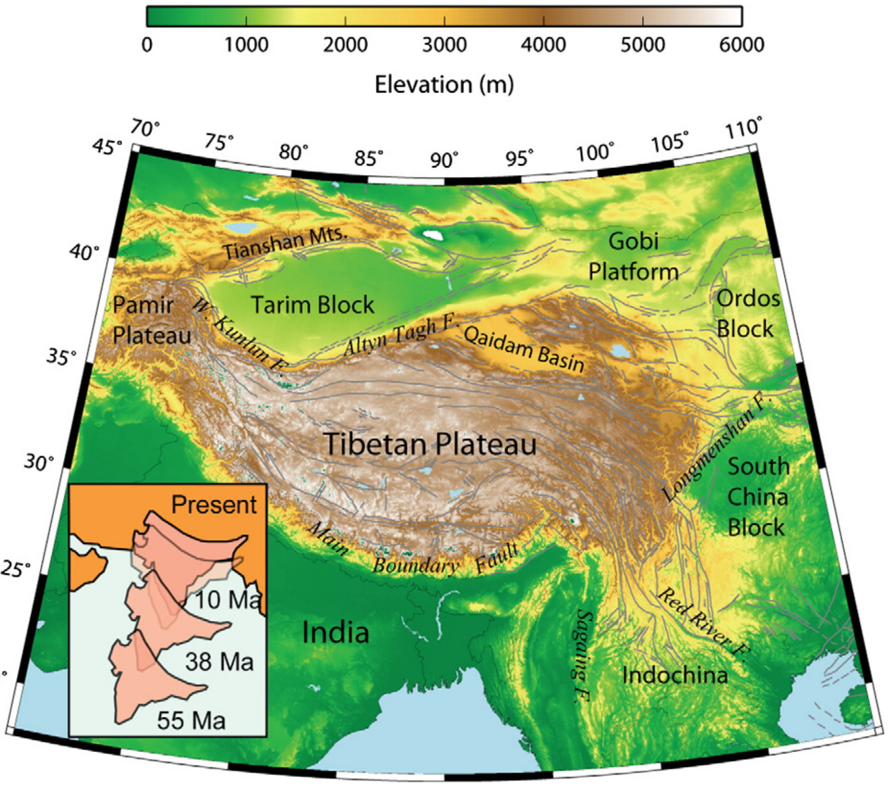

Fig. 1. Topographic map of the Himalayan–Tibetan Plateau and the surrounding regions. Gray lines are faults. The inset shows that the approximate trajectory of the Indian plate moving toward Asia in last 55 Myr (from "*This Dynamic Earth*" by the US Geological Survey).