Dynamic ups and downs of the Himalaya

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ABSTRACT

Fast uplift and exhumation of the Himalaya and Tibet and fast subsidence in the foreland basin portray the primary Neogene evolution of the Indian-Eurasian collision zone. We relate these events to the relative northward drift of India over its own slab. Our mantle-flow model derived from seismic tomography shows that dynamic topography over the southward-folded Indian slab explains the modern location of the foreland depocenter. Back in time, our model suggests that the stretched Indian slab detached from the Indian plate during the indentation of the Eurasian plate, and remained stationary underneath the northward-drifting Indian continent. We model the associated southward migration of the dynamic deflection of the topography and show that subsidence has amounted to ~6000 m in the foreland basin since 15 Ma, while the dynamic surface uplift of the Himalaya amounted to ~1000 m during the early Miocene. While competing with other processes, transient dynamic topography may thus explain, to a large extent, both the uplift history of the Himalaya and subsidence of its foreland basin, and should not be ignored.

INTRODUCTION

Vertical ground motion at the Indian-Eurasian convergence (Fig. 1) during the Neogene is particularly exemplified by fast (yet disputed) kilometer-scale surface uplift of the Himalaya and south Tibet during early to middle Miocene time (for a review, see Molnar and Stock, 2009), and by the sudden increase of sedimentation rates in the adjacent Siwalik foreland basin starting at ca. 15 Ma (e.g., DeCelles et al., 1998; Mugnier et al., 1999). The timing of the morphotectonic and sedimentary events commonly suggests that the Himalaya and south Tibet were quickly uplifted and exhumed between ca. 20 Ma and 15 Ma, coeval with the onset of fast sedimentation in the Indo-Gangetic Plain. The associated change in the tectonic propagation of the orogenic wedge suggests that a common genetic cause relates the changes in elevation, exhumation, and sedimentation (e.g., Bernet et al., 2006; Mugnier and Huyghe, 2006). A common explanation for the fast surface uplift is the removal of the Tibetan mantle lithosphere that by virtue of gravitational unloading would have uplifted the lithosphere and surface toward crustal isostasy in the mantle-deprived lithosphere (e.g., Harrison et al., 1992; Molnar et al., 1993). On the foreland side, the elastic flexure of the Indian plate, loaded by the Himalayan belt, is often thought to have created the accommodation space for the Himalayan erosion products (e.g., Lyon-Caen and Molnar, 1983). While the timing of surface uplift has been relentlessly questioned during the past decades, by constraining paleoelevations, crustal growth, and exhumation rates, the canonical models for plateau uplift and subsidence in the foreland have surprisingly remained mostly unchallenged. Dynamic topography may be an alternative.

Here we refer to dynamic topography as the response of the surface to sublithospheric mantle flow, excited by density anomalies in the underlying mantle. Above subducting slabs, where mass anomalies are the largest in the mantle, topographic deflections possibly exceed 1000 m (e.g., Gurnis, 1992; Husson, 2006). Subduction of the Indian plate underneath Eurasia is not a steady process and therefore neither is dynamic topography. The slab deforms during the northern voyage of the Indian continent as it anchors in the underlying mantle (e.g., Replumaz et al., 2010), and the corresponding mass anomalies are constantly redistributed beneath the surface. In the reference frame of a given plate, dynamic deflections of the surface are therefore expected to grow and vanish above the moving anomalies. Here we explore the possibility that transient dynamic topography may alternatingly cause uplift and subsidence of different areas in the Indian-Eurasian collision zone, and thus reconcile most observations of exhumation, sedimentation, surface uplift, and subsidence.

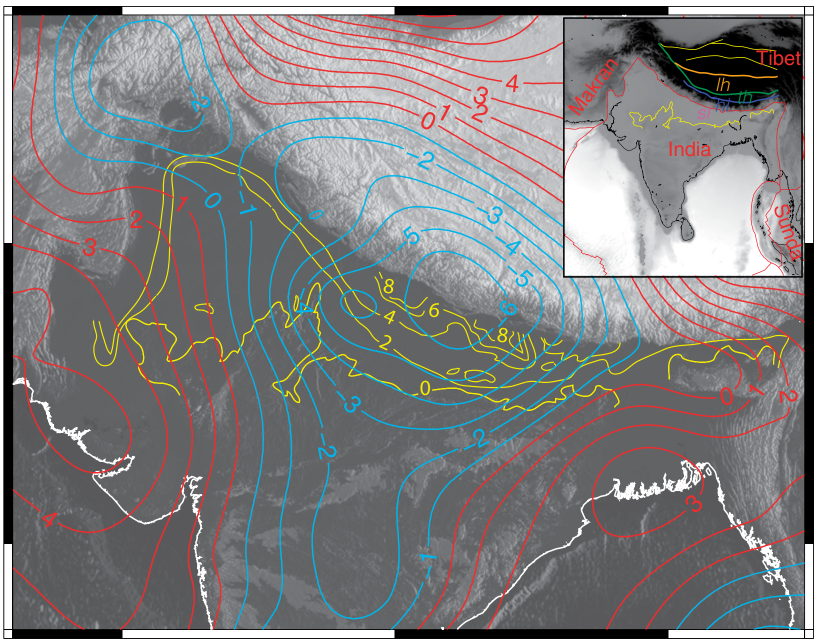

Figure 1. Indian-Eurasian convergence zone. Yellow contours show depth (in km) of the foreland basin below the Indo-Gangetic Plain (CGMW, 1982). Model-predicted dynamic uplift (red) and subsidence (blue) at present day (mantle flow model derived from seismic tomography). Values (in km) are given for a sediment-compensated deflection (Item DR1 [see footnote 1]). Inset: Plate boundaries are in red. lh—Lhasa; th—Tethys Himalaya; hi—Himalaya; si—Siwalik.

GEODYNAMICS OF THE INDIAN-EURASIAN COLLISION

Plate Kinematics

The convergence of India toward Eurasia during the Cretaceous and Paleogene is characterized by a long stage of subduction of the Tethyan oceans, interrupted by interludes of accretion

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of the Tibetan terranes (e.g., Van der Voo et al., 1999). Subduction pulled the Tethys oceanic plate down in the mantle until the Indian continent finally collided with Eurasia ca. 45 Ma (see Najman et al., 2010). Pulled from below and pushed from behind by the underlying mantle flow (Becker and Faccenna, 2011), the Indian continent moved northward. It gradually stepped over its own slab, flipped it, and folded it under itself in the mantle, several hundreds of kilometers to the south of the Himalayan belt (e.g., Van der Voo, 1999; Replumaz et al., 2010; Figs. 2A and 2B). Entrained by its oceanic precursor, the continental slab partially entered the subduction zone, and following its eclogitization, also actively contributed to its own subduction (e.g., Capitanio et al., 2010). However, its motion in the mantle was impeded by the three-dimensional nature of the subduction zone, where the indentation of the Indian continent worked in concert with the lateral subduction of the oceanic counterparts of the plate, underneath Makran to the west and in the Sunda Trench to the east. Over the past ~30 m.y., continental collision caused more than 1000 km of indentation (e.g., Patriat and Achache, 1984); meanwhile, the oceanic lateral counterparts did not change regimes, and their trenches stalled or even retreated (e.g., Replumaz et al., 2004; Fig. 2A). Kinematically, this is not feasible unless the Indian slab either breaks off or stretches by as much as the differential prograde motion between the continental and oceanic trenches, i.e., ~1000 km. By deciphering several global seismic tomography models (see Item DR1 in the GSA Data Repository[1]), we reconstructed the current structure of the lithospheric mantle in the light of these kinematic considerations. We interpret the fast-wave anomaly underneath the central Himalaya that fades out laterally at shallow depths, but resumes closer to the transition zone on both sides, as the remnant of the Indian slab. In order to reconstruct past geometries, we build upon the reconstructions and analysis in Replumaz et al. (2010) and establish a tectonic scenario based on the kinematic descriptions here. We suggest that the Indian slab detached at both ends of the Himalayan belt from the Indian plate ca. 15 Ma, and was then stretched by the progradation of the Indian continent with respect to the more stationary lateral counterparts and underlying mantle for the past ~30 m.y. (Fig. 2A). This mechanism would cause the tensional force to increase laterally, intensify stretching closer to the lateral boundaries of the Indian continent, and foster slab detachment at the edges of the Himalayan subduction zone. Forward motion of subducting slabs can only be a transient feature that accompanies forward trench migration (e.g., Husson, 2012); in our scenario, we assume that this episode possibly happened between 50 and 30 Ma. From that time onward, it gradually flipped over and detached (Figs. 2A and 2B), consequently altering the dynamic surface deflections.

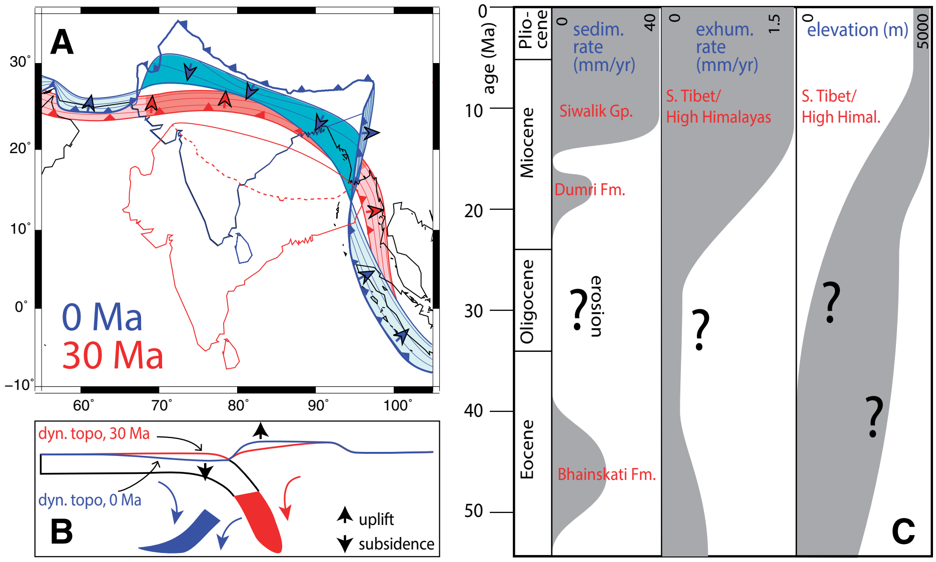

Figure 2. A: Position of India and Indian slab geometry (200 km isodepth contours) at 30 Ma and 0 Ma, relative to Eurasia. Arrows indicate vergence of the slabs (flipped at 0 Ma underneath India). Simplified versions of the darker domains are extracted for modeling (Fig. 3 and Item DR2 [see footnote 1]). B: Schematic dynamic uplift and subsidence above the drifting slab. C: Sedimentation, exhumation, and elevation histories (see reviews by Najman, 2006; Bernet et al., 2006; Molnar and Stock, 2009).

Morphotectonic and Sedimentary Framework

The Himalaya and south Tibet reached their present-day mean elevation of ~5000 m ca. 10 Ma following an episode of crustal thickening that raised the topography to ~4000 m, possibly between 45 and 20 Ma (Fig. 2C; for a review see Molnar and Stock, 2009). The extra topographic increase by >1000 m presumably occurred by a means other than crustal thickening. Evidence for surface uplift and erosion in the mountains is best illustrated by the change in tectonic regime ca. 15 Ma that accompanies the deposition and progradation of the Siwalik Group (e.g., Bernet et al., 2006), which unconformably overlies the condensed, partially eroded continental Dumri formations and older sedimentary sequences (Fig. 2C; Najman, 2006; DeCelles et al., 1998). Cooling rates also reveal a comparable timing: detrital apatite and zircon fission track data from the Siwalik Group in Nepal and India indicate that fast (>1.5 mm/yr) exhumation in the Himalaya started in the middle Miocene (Fig. 2C; Van Der Beek et al., 2006; Bernet et al., 2006). Prior to ca. 15 Ma, only the hiatus between the Siwalik Group and pre-Siwalik series indicates that earlier deposition was partially eroded, likely revealing an early to middle Eocene subsidence, followed by a late Eocene episode of surface uplift in the Himalayan foreland and renewed deposition from the middle Miocene onward.

PREDICTING DYNAMIC TOPOGRAPHY

Present-Day Dynamic Topography

Today, dynamic topography and its time dependence can be approximated with mantle flow models (for a review, see Flament et al., 2013) derived from seismic tomography, either globally, or more regionally, where density anomalies located in the upper mantle generate short-wavelength, high-amplitude deflections of Earth's surface. Seismic tomography reveals that the Indian plate is folded underneath itself (Van der Voo, 1999; Replumaz et al., 2010). Deriving dynamic topography from seismic wave speed in the mantle is not straightforward and, whether based on complex (e.g., Simmons et al., 2010) or simple (e.g., Husson, 2006) modeling protocols, relies on uncertain parameters. We opt for simplicity. Our attempt derives from Harper (1984), using the Stokeslets approximation (Item DR2). The density field is discretized into point masses, or point Stokes sinkers in an isoviscous fluid. Under these conditions, the deflection at a given surface location scales with the contrast between the density of the mantle and that of the material (air, sediments, or seawater) that counterbalances the vertical traction exerted by all Stokes sinkers. We derive the present-day mass distribution in the mantle from the global seismic tomography model of Li et al. (2008), assuming a linear conversion between seismic velocity anomalies and density anomalies (ignoring density anomalies shallower than 100 km).

[1]GSA Data Repository item 2014299, Item DR1 (reconstruction method for the Indian slab geometry during the Neogene), and Item DR2 (modeling dynamic topography), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

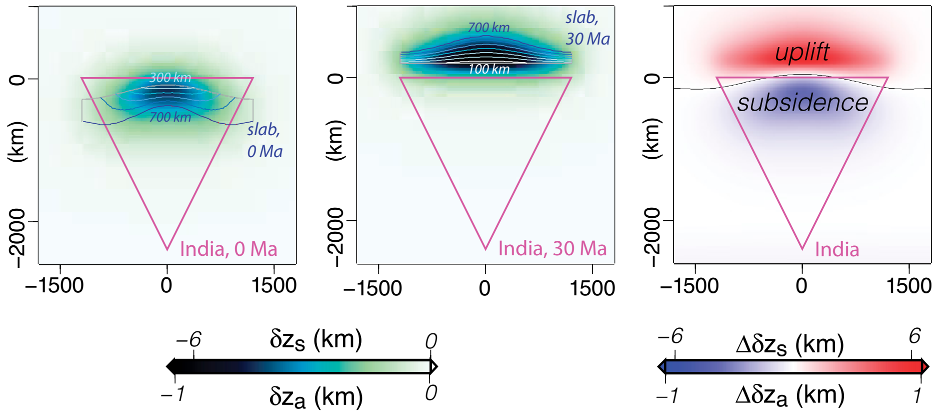

Figure 3. Map views of the dynamic topography at 0 Ma and 30 Ma (blue-green scale) for an idealized Indian-Eurasian subduction zone. Equivalent uplift and subsidence (bottom, blue-red scale) are given by the difference between the two. Pink triangle delineates an idealized India; slab 100 km isocontours are in blue. Scale indicates either an air compensation (δz_a) or a sediment compensation (δz_s) (Item DR1 [see footnote 1]).

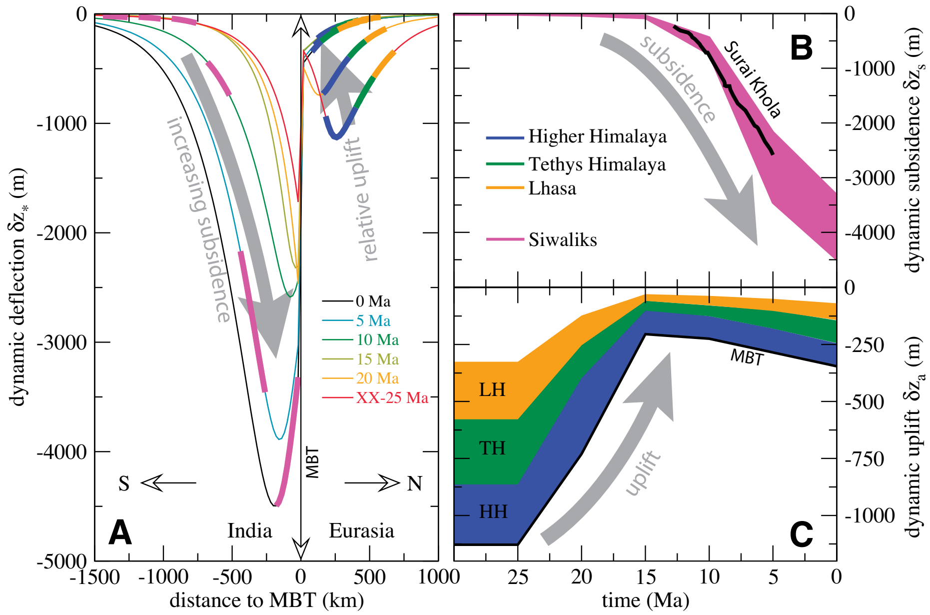

Figure 4. A: Dynamic component of the topography through time across the Himalaya. Differences between air compensation (δz_a) or sediment compensation (δz_s) to the north and south of the Main Boundary thrust (MBT), respectively, cause a discontinuity in the curves at 0 km. Thick color bars indicate the migrating locations of the Himalayan units (see Fig. 1 for location). The differential deflection inflates through time in the south and deflates in the north, causing net subsidence and uplift, respectively. B: Predicted dynamic subsidence in the Siwalik Group. Subsidence curve along the Surai Khola (e.g., Najman, 2006) is in black. C: Predicted dynamic uplift in the Himalaya and Tibet. Color key for units as in B.

The three-dimensional structure of the slab and mantle as inferred from seismic tomography is mirrored by the dynamic deflection at the surface (Fig. 1). This prediction can readily be compared to the geometry of the foreland basin: maximum predicted depression is located in the center of the Himalayan front, coincident with the foreland depocenter (Fig. 1). More generally, the shape of the dynamic deflection to the south of the Himalayan front approximately matches that of the foreland basin, which is focused on the central part. Assuming standard densities and conversion factors (see Item DR2), the sediment-compensated deflection, δz_s, reaches ~−6000 m in Nepal, which compares well with the thickness of the foreland series.

Dynamic Topography in the Neogene and Earlier

In order to predict past surface deflections, we use idealized reconstructions of the Indian slab as it is subducted into the mantle, based on the interpretation here of the Indian-Eurasian kinematics. Again, in order to compute the evolving dynamic deflection, we use isoviscous instantaneous Stokeslets models in an attempt to capture the prominent features (see Item DR2). With a 5 m.y. interval, the geometry of the slab is defined by a rotation, by a laterally variable stretching that defines the local dip of the slab, and by a detachment depth (Fig. 3). We assume that stretching and rotation of the slab underneath the Himalaya occur at an approximately constant pace. The slab is discretized into slablets (Ricard et al., 1993), the density excess of which with respect to the mantle is set to 60 kg m^{-3}. The integrated traction exerted by all slablets is counterbalanced by a deflection of the surface. In the foreland basin, that deflection is filled with sediments (see Item DR1). The prominent outcome of our model is the migration of the deflection from the overriding plate (Fig. 3) toward the subducting plate.

In the model, at 30 Ma, the corresponding δz_s forms a narrow, ~1500-m-deep foreland basin (Figs. 3 and 4A). As the slab gradually stretches, flips at ca. 15 Ma, detaches from the upper lithosphere, and sinks to be almost flat toward the transition zone, maximum deflection migrates southward to the Ganga plain between 20 and 10 Ma, where δz_s eventually increases to the present-day ~−4500 m (Fig. 4B). The comparison between the model and the geological record of the Siwalik Group can be made, provided that the trenchward migration of the Indian plate (set to 40 mm/yr from 0 to 10 Ma and 50 mm/yr earlier; e.g., Molnar and Stock, 2009) is accounted for (Fig. 4). This scenario explains the subsidence history of the Siwalik Group from ca. 15 Ma onward (Figs. 2C and 4B). The central part of the foreland gradually becomes more deflected, as also suggested by the tomography-derived model (Fig. 1). The fact that the dynamic deflection deflates as the mass anomaly gets deeper is largely compensated by the fact that it migrates to the south at a faster rate; in the foreland, the net result is a deepening of the deflection (Fig. 3). Overall, the characteristic geometries of both modeled present-day basins (derived from seismic tomography and from synthetic slabs, respectively) are comparable. This is further confirmed by the stratigraphic record that shows thicker series in the center, and also conformably shows increasing sedimentation rates ca. 11 Ma (e.g., Najman, 2006). Indeed, subsidence in central Nepal (Surai Khola section; Fig. 4B) is well reproduced by our models.

The overriding plate also records the southward translation of the dynamic deflection. Again, the comparison can be done provided that shortening in the upper plate is accounted for (herein set to 10 mm/yr between the Main Boundary thrust and the Tethyan Himalaya). At 30 Ma (and possibly before) mantle flow deflects the growing High Himalaya by a maximum of 1200 m (Figs. 3 and 4C). Between 25 and 15

Ma, the deflection δz_a is only ~−200m deep, which corresponds to a relative uplift of ~1000 m. The predicted timing of uplift thus matches the uplift and exhumation (Fig. 2C). The effect gradually vanishes northward in Tibet.

A remarkable longer-term feature of the foreland sedimentation is its oscillating style, with an early Eocene episode of sedimentation (Bhainskati Formation; Fig. 2C), followed by an episode of erosion, followed then by renewed sedimentation in the Siwalik Group. This early episode of sedimentation could be coeval with the subduction, breakoff, and southward motion (relative to India) of the Neo-Tethyan slab, which had a fate similar to that of the later Indian slab, as in the scenario in Replumaz et al. (2010). We therefore anticipate that dynamic topography evolved accordingly and that the southward drift of the Tethyan slab could have caused a precursor episode of subsidence and sedimentation in the Indian plate, recorded by the early Eocene sedimentation. We speculate that this alternating subsidence-uplift-subsidence scenario could mirror the overall geodynamic evolution of the Himalaya and south Tibet, where dynamic topography oscillates through time above the southward-drifting slabs. The unequivocal isotopic record of the early Paleogene uplift history could reveal that elevation did not grow at a constant pace, but instead also underwent alternating episodes of subsidence and uplift, caused by the transient dynamic topography over the drifting slabs.

DISCUSSION AND CONCLUSION

The efforts to constrain the paleoelevation, crustal growth rate, and exhumation by collecting data and observations during the last decades were not accompanied by any challenging of the purported dynamic processes that could explain the morphotectonic evolution of the Himalaya. Yet, those paradigms do not seem to satisfactorily explain the observations. For example, if the overriding Eurasian lithosphere had been deprived of its lithospheric mantle after its removal (e.g., Harrison et al., 1992; Molnar et al., 1993), the load that the overriding plate exerts to flex the Indian lithosphere should have decreased by an amount that equals that of the discarded mantle lithosphere, provoking an upward rebound of the foreland basin, not its subsidence. Similarly, if the Indian slab broke off at ca. 15 Ma, its flexural effect on the Indian plate would have decreased, and the foreland basin would have uplifted. The expected flexural response of the Indian lithosphere is thus an upward rebound, which is at odds with the increasing sedimentation rates in the foreland Siwalik series (e.g., Najman, 2006). Our results imply that the role of the lithosphere mantle on Himalayan and Tibetan uplift, as well as the many estimates of elastic thickness for the Indian plate, may be revised in order to account for dynamic topography.

Transient dynamic topography above the drifting Indian slab provides a comprehensive framework that reconciles many observations. However, there are uncertainties in the timing of the events; our reconstructions are oversimplified; and our modeling strategy bypasses a parameterization that is rendered complex by our poor knowledge of mantle properties. Yet, the good match between the observations and the magnitude and timing of our predicted dynamic deflections reveals the plausibility of the mechanism as a prominent control on the Neogene morphological evolution of the area. Our model can thus be viewed as a proof of concept that could be further explored.

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