Ganges basin geometry records a pre-15 Ma isostatic rebound of Himalaya

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ABSTRACT

The Tertiary continental strata of the Himalayan foreland basin are subdivided into two groups, but the meaning of this subdivision was previously unclear. From the analysis of drill holes, seismic lines, dated sections, outcrops, and balanced cross sections, we find that the southward migration rate of the depositional pinch-out of the younger group is 19 ± 5 mm/yr and equals the Himalayan shortening rate. This equality shows that the flexural foreland basin development is mainly controlled by the motion of the thrust load. The long-term pinch-out migration rate was slower for the older synorogenic group. Erosion locally occurred at the end of its deposition, due to tectonic reactivation of lineaments of the Indian shield. We suggest that this change in the basin development is linked to the detachment of the subducted Indian lithosphere that decreased the slab pull and increased the mean compressive stress within the Indian plate, whereas the plate motion remained constant. The most important implication of our work is that the associated isostatic rebound could have increased the Himalayan elevation prior to 15 Ma.

Keywords: Himalaya, flexure, foreland basin, relief, slab break-off, tectonic reactivation.

INTRODUCTION

The timing of the rise of the Himalaya is important because it is the best example for understanding the relation between mountain belt tectonics and paleoclimate (Molnar et al., 1993; Zhisheng et al., 2001; Spicer et al., 2003). However, the rise is debated because there is no direct measurement of paleoelevation. Therefore, geodynamical models that take into account the role of isostasy and horizontal stresses are important in deducing the evolution of the relief of a mountain belt (Molnar et al., 1993). In this paper we hypothesize that the overall foreland basin geometry of the Ganga basin is controlled by flexural subsidence related to the neighboring Himalayan belt evolution. The basin geometry is used to specify the evolution of the stress that affected the Indian shield and to propose an evolution of the lithospheric root and relief of the Himalayan belt.

GEOLOGIC SETTING

The Indian shield was affected by several tectonic events before the convergence of India and Asia. Its northern part was strongly affected by the formation of a Proterozoic fold belt and the Proterozoic to Cambrian Vindhyan basin (Shukla and Chakravorty, 1994). Therefore, the crust beneath the Ganga basin (Fig. 1) is affected by inherited tectonic lineaments. These lineaments delineate, from NW to SE, a succession of spurs and depressions in the Tertiary Ganga basin (Raiverman et al., 1994) and are oblique to the structural trend of the Himalayan thrust belt (Powers et al., 1998). This thrust belt induces a flexural subsidence that is the prime control of the foreland basin development (Burbank et al., 1996). The depocenter was located close to the front of the collision belt (Fig. 2) and the sediment pinch-out migrated outward (Lyon-Caen and Molnar, 1985) due to the motion of the thrust wedge (Huyghe et al., 2001).

The pre-Siwalik and the Siwalik groups define the synorogenic continental sediments of the foreland basin (Burbank et al., 1996; Najman et al., 2004). The lithostratigraphic distinction between the continental strata of the pre-Siwalik and Siwalik groups was defined early (Meddlicott, 1884), and the main distinction is the extent of the sedimentation domains. The base of the Siwalik group is ca. 13 Ma in India (Najman et al., 2004) and older than 15.5 Ma in Nepal (Gautam and Fujiwara, 2000).

DEPOSITION PINCH-OUT MIGRATION RATE AND HIMALAYAN SHORTENING RATE DURING THE SIWALIK STAGE

A previous estimate of the pinch-out migration rate was obtained from eight drill holes (Lyon-Caen and Molnar, 1985). This result is revisited from a compilation of 26 drill holes (Valdiya, 1980; Acharyya and Ray, 1982; Raiverman et al., 1994; Shukla and Chakravorty, 1994; Srinivasan and Khar, 1996; Bashial, 1998; Powers et al., 1998) and 5 outcrops of the Tertiary basal unconformity (Valdiya, 1980; Shresta and Sharma, 1996; Sakai et al., 1999) (Data Repository Table DR2[1]). Furthermore, 10 balanced cross sections of the outer belt (Srivastava and Mitra, 1994; Srinivasan and Khar, 1996; Powers et al., 1998; Lavé and Avouac, 2000; Mishra, 2001; Mugnier et al., 2004) are used to estimate the dis-

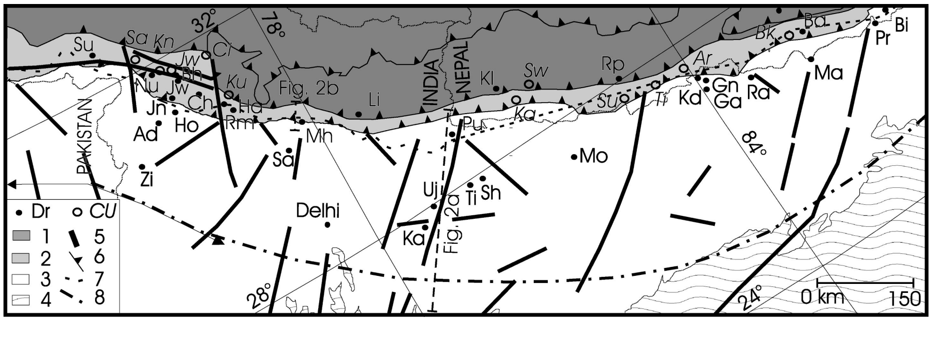

Figure 1. Structural sketch of Himalaya and its foreland basin. Key for abbreviations in Tables DR1 and DR2; see footnote 1. *Cu*—Magnetostratigraphic studies of Tertiary units. Dr—Drill holes (or outcrops) of base of Tertiary sediments (Table DR2; see footnote 1). 1—Himalaya; 2—sub-Himalaya; 3—foreland basin; 4—Indian shield; 5—lineaments beneath Ganga foreland basin (from Raiverman et al., 1994; Srinivasan and Khar, 1996); 6—Main Himalayan thrusts; 7—pinch-out of pre-Siwalik group (from Department of Mines and Geology, 1990; Shresta and Sharma, 1996; Srinivasan and Khar, 1996; Raiverman et al., 1994); 8—southern edge line of basin from Lyon-Caen and Molnar (1985).

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[1] GSA Data Repository item 2006088, Table DR1, age of the Tertiary lithostratigraphic units inferred from magnetostratigraphic studies and other methods; Table DR2, the migration of the pinch-out of the Tertiary basin; and Table DR3, shortening rate estimate through the central Himalaya, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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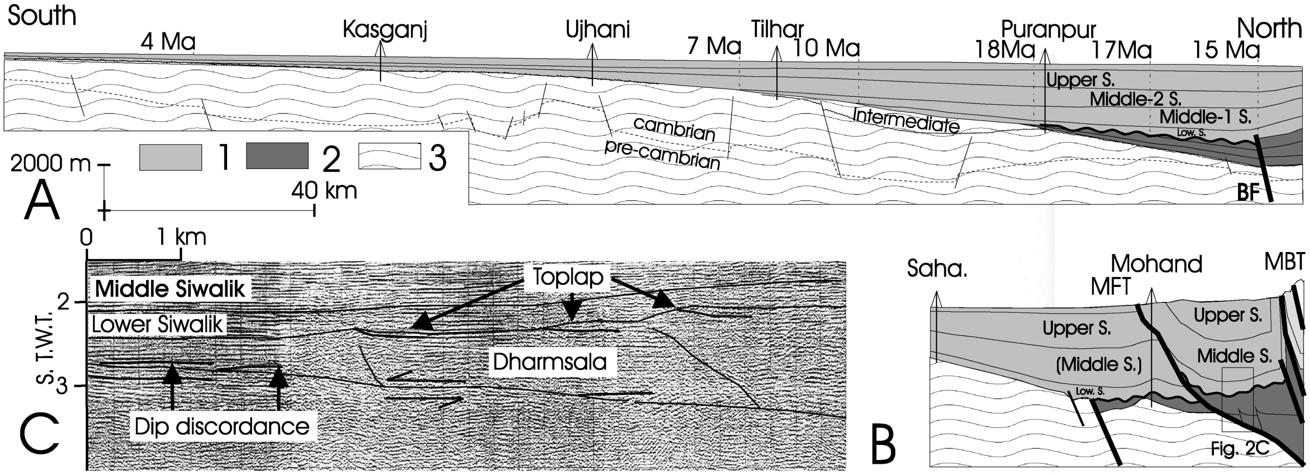

Figure 2. Cross sections through Tertiary sediments. Vertical scale is magnified by 5. A: Cross section through foreland basin. Ages refer to pinch-out: 1—Siwalik group; 2—Tertiary pre-Siwalik group; 3—pre-Tertiary sequences. BF—Reactivation of Indian shield lineament. Northern part of Tertiary basin is from Raiverman et al. (1994) and southern part is from Shukla and Chakravorty (1994); intermediate sequence is from Srinivasan and Khar (1996); basement structures are from Shukla and Chakravorty (1994). B: Structure of Tertiary sediments beneath sub-Himalayan belt of Dehra-Dun area from Raiverman et al. (1994) and Powers et al. (1998). MFT: Main Frontal thrust; MBT: Main Boundary thrust. Same scale for cross section A and B. Thickness of pre-Siwalik sediments varies greatly close to Mohand drill hole. C: Zoom of seismic profile (location in Fig. 2B). Beneath sub-Himalayan belt, toplaps occur beneath unconformity at base of Siwaliks. Paleorelief is preserved beneath lower Siwaliks at hanging wall of steep faults. These faults are cut and transported by basal décollement of sub-Himalayan zone. S.T.W.T.—seconds two-way traveltime.

placement of the thrust sheets. The method of analysis is detailed in Table DR2. The Siwalik group is informally subdivided into lower, middle, and upper lithostratigraphic units (Lyon-Caen and Molnar, 1985), and the age of the Siwalik units in the drill holes is estimated from the nearest, among 11, magnetostratigraphic studies (Fig. 1; Table DR1) (Burbank et al., 1996; Gautam and Rosler, 1999; Brozovic and Burbank, 2000; Gautam and Fujiwara, 2000). Nonetheless, these lithostratigraphic boundaries are diachronous at a local scale (Brozovic and Burbank, 2000; Huyghe et al., 2005) and along cross sections transverse to the foreland basin (Lyon-Caen and Molnar, 1985). We take into account this diachroneity to estimate the age uncertainty (Table DR2), leading to a smaller uncertainty for the pinch-outs located close to the dated sections.

The pinch-out migration rate varies laterally for the Siwalik period. It is 19 ± 5 mm/yr in front of the central part of Himalaya and only 12 ± 3 mm/yr in the western part (Fig. 3). This lateral variation mimics the variation of the shortening rate: in the central Himalaya, the shortening rate is 20 ± 5 mm/yr (De Celles et al., 2002; Mugnier et al., 2004) (Fig. 3; Table DR3 [see footnote 1]), and in the western part is 14 ± 4 mm/yr (Powers et al., 1998).

Our data sets are based on independent estimation procedures of the shortening and pinch-out migration rates and confirm their equality (previously postulated by Lyon-Caen and Molnar, 1985). Therefore our work reinforces the hypothesis that flexural behavior of the lithospheric plate links the evolution of the Ganga basin to the translation of the Himalayan belt. Furthermore, the mean slope and the topography of the belt have probably not changed greatly since at least 15 Ma, because the Himalayan wedge migrates only if its taper is maintained (Dahlen and Barr, 1989).

EVOLUTION OF THE BASIN PRIOR TO THE SIWALIK DEPOSITION

The pre-Siwalik group is formed of continental strata dated as between 13 Ma and younger than 30 Ma (Sakai et al., 1999; Najman et al., 2004). The pre-Siwalik basin is restricted to the very northern part of the Ganga plain (Raiverman et al., 1994), to the footwall of the basal décollement of the sub-Himalaya zone (Powers et al., 1998), and to the top of few tectonic Himalayan slices (Najman et al., 2004). An intermediate sequence (Fig. 2A) beneath the Ganga basin was initially interpreted as part of the Tertiary group (Lyon-Caen and Molnar, 1985), but further work suggests that it consists of Vindhyan deposits (Srinivasan and Khar, 1996).

The southward migration rate of the pinch-out for the pre-Siwalik group (Fig. 3) is less than the migration rate for the Siwalik group. We discuss the following six different hypotheses to explain this change: (1) variation of the rigidity of the flexed plate (Waschbuch and Royden, 1992); (2) onset of a thrusting event (Fleming and Jordan, 1990); (3) internal thickening and narrowing of the thrust belt (Sinclair et al., 1991); (4) change in the shortening rate; (5) erosional unloading of the topographic wedge (Burbank, 1992); and (6) loss of the heavy roots of the orogen (Sinclair, 1997).

A variation of the rigidity of the flexed plate is unlikely, because the rigidity was already great during the pre-Siwalik stage, due to the older than 500 Ma thermotectonic age of the Indian lithosphere (Burov and Diament, 1995). Furthermore, flexural modeling of the

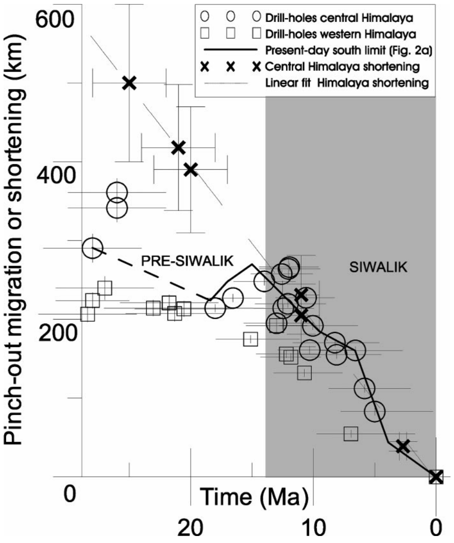

Figure 3. Plot of age of base of Tertiary sediments vs. distance from edge of Ganges basin. Circles, squares, and continuous and hachured lines refer, respectively, to drill holes east of E78° and west of E78°, and to cross section of Figure 2B (Table DR2; see footnote 1). Thick × symbols refer to plot of time vs. Himalayan shortening (Table DR3; see footnote 1) and hachured line is linear fit for these data.

Eocene–early Miocene foreland basin indicates a flexural rigidity $>7 \times 10^{23}$ Nm (De Celles et al., 1998), a value close to the present-day rigidity in central Himalaya (Lyon-Caen and Molnar, 1985).

EROSION AND TRANSPRESSION AT THE BASE OF THE SIWALIK GROUP

The fault activity evidenced beneath the foreland basin is used to test the other hypotheses proposed for the change of the migration rate.

Seismic data beneath the Ganga plain and the sub-Himalayan thrust belt (Department of Mines and Geology, 1990; Shukla and Chakravorty, 1994; Srinivisan and Khar, 1996; Raiverman et al., 1994) indicate that the partitioning of the Ganges basin in a succession of spurs and depressions is controlled by basement fault reactivation (Raiverman et al., 1994; Bashial, 1998). These spurs influenced the thickness and the southern depositional limits of the pre-Siwalik group (Raiverman et al., 1994).

Locally, the south boundary of the upper subgroup is located to the north of the pinch-out of the underlying subgroup (Raiverman et al., 1994). This apparent backward migration is due to erosion that had removed the southern part of the upper subgroup (Figs. 2A, 2B) beneath unconformities (Fig. 2C) at the top of the pre-Siwalik subgroup. This retrogradation causes the reduction of the long-term pinch-out migration rate, although the instantaneous Eocene–early Miocene and late Miocene–Pliocene migration rate could be similar (De Celles et al., 1998).

These unconformities, though largely extended (Pascoe, 1964), are discontinuous laterally (Raiverman et al., 1994). The erosion seems mainly expressed above the basement faults, and the complex pattern of the sedimentary bodies suggests a left-lateral transpressional tectonic regime along the lineaments oblique to the Himalayan trend. Normal faults, parallel to the Himalayan trend, throw down toward the north the base of the Tertiary strata (Raiverman et al., 1994) (Fig. 2B). They are related to the reactivation of Indian shield lineaments due to the negative curvature of the flexed lithosphere during the pre-Siwalik stage (Powers et al., 1998), and positive structural inversion (Gillcrist et al., 1987) leads to basement folding at their hanging wall at the end of the pre-Siwalik stage. Therefore, a phase of fault reactivation is synchronous with local erosion or deposition of the uppermost pre-Siwalik sequence and predates 15.5 Ma in Nepal and 13 Ma in India. This phase was linked to an increase of the mean horizontal forces applied by the plate motion close to the orogen area and/or a decrease of the bending moment that controls the curvature of a flexed plate.

FLEXURE OF THE INDIAN PLATE: THE ROLE OF CRUSTAL LOADING OF THE THRUST WEDGE VS. LITHOSPHERIC SLAB BREAK-OFF

Onset of a thrusting event and internal thickening of the thrust belt would change the geometry of the crustal thrust wedge (Fleming and Jordan, 1990; Sinclair et al., 1991), leading to a retrogradation of the pinch-out and an increase of the curvature of the flexed lithosphere. Such a curvature increase does not match a stress increase, and we therefore exclude these hypotheses for the transition between the pre-Siwalik and Siwalik stages.

The shortening rate during the pre-Siwalik stage was 20 ± 8 mm/yr (Fig. 3). Choosing the lower value of 12–14 mm/yr would keep the shortening and migration rates equal. Therefore, an increase of the shortening at the end of the pre-Siwalik stage would explain the stress increase. We do not favor this interpretation because it is associated with a constant convergence between India and Eurasia (DeMets et al., 1990) and an increasing erosion of Himalaya (Clift et al., 2004; Bernet et al., 2005).

This regional increase of the erosion could drive an erosional unloading (Burbank, 1992) at the Siwalik–pre-Siwalik transition. Nonetheless, erosional unloading would imply that erosion exceeded the volume of rocks moved by tectonics above the Indian plate. A lower bound for the rate of tectonic loading is the product of the lower estimate of the shortening (12 mm/yr) by the lower estimate of the thrust thickness (20 km). Therefore, the erosion would have to exceed 240 m^3/yr for a swath of 1 m, or 0.5 km^3/yr for the whole Himalaya, i.e., to be as great as the Pliocene–Quaternary erosion estimated by Métivier et al. (1999). No data suggest such a regional peak of erosion by that time.

We suggest that a lithospheric slab break-off increased the relief and consequently the erosion. This slab break-off increased the stresses within the Indian plate through two processes. (1) The loss of the mantle lithospheric roots decreases the additional forces exerted at the trailing edge of the flexed lithosphere (Lyon-Caen and Molnar, 1985) and decreases the curvature of the plate. (2) The loss of the continental mantle lithospheric roots increases the mean horizontal deviatoric forces applied by the orogen area and surrounding lowlands to one another (Molnar et al., 1993). Tomographic analysis (Van der Voo et al., 1999) suggests that several detached portions of the lithospheric mantle are located beneath Tibet and Himalaya, due to a delamination of the Indian continental mantle and its break-off. Such a break-off (Fig. 4) fits with the Neogene magmatic evolution of southern Tibet (Mahéo et al., 2002). We suggest, from the timing of the fault reactivation beneath the foreland basin, that the break-off was achieved before 15.5 Ma in the central Himalaya and propagated progressively westward over several million years.

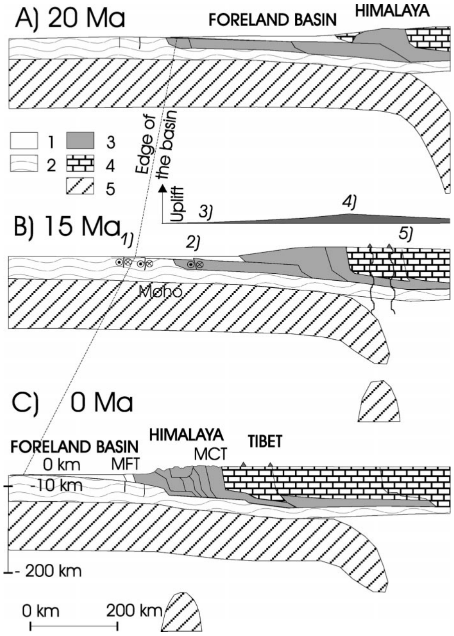

Figure 4. Sketch of Ganges basin–Himalaya–Tibet evolution. Vertical scale is magnified by 5 for uppermost crust (shallower than 10 km) to see foreland basin and Himalayan relief. Lithospheric structures are not vertically magnified. 1—Tertiary foreland basin; 2—crust of Indian shield; 3—Himalaya; 4—Tibetan zone; 5—Indian lithospheric mantle. MFT: Main Frontal thrust; MCT: Main Central thrust. A: Geometry ca. 20 Ma. B: Geometry ca. 15 Ma. Lithospheric mantle break-off induced (1) increase of stresses and (2) fault reactivation in Indian shield, (3) local erosion of foreland basin, (4) increase of altitude of Himalaya (uplift profile adapted from Buiter et al.; 2002), and (5) volcanism in southern Tibet. C: Present-day state.

Numerical models (Buiter et al., 2002) indicate that the break-off–related uplift zone is much larger than an uplift zone at the hanging wall of any megathrust fault (Beaumont et al., 2001), but it is much smaller than the width of Tibet. The Tibetan uplift is probably linked to several processes, and the slab break-off could be one of them. It induced a kilometer-scale increase of the altitude of the very southern part of the Tibetan plateau and led to topographic emergence of a discrete Himalaya belt with respect to the Tibetan plateau prior to 15 Ma.

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