# Provenance of Eocene foreland basin sediments, Nepal: Constraints to the timing and diachroneity of early Himalayan orogenesis

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## ABSTRACT

**In contrast to Eocene Himalayan foreland basin sedimentary deposits in India and Pakistan, coeval sedimentary rocks of the Bhainskati Formation in Nepal contain scant petrographic evidence of orogenic input. Such data have been used as evidence to promote models of diachroneity of India-Asia collision. In this paper we document orogenic input into the Eocene foreland basin rocks of Nepal, from fission-track analyses of detrital zircons. Our data provide evidence that significantly reduces the possible duration of any diachroneity of collision, and brings the interpretation of the sedimentary record into better agreement with ages of early thrusting and metamorphism in the orogen. We also use our detrital fission-track data to bolster previous age determinations of the overlying Dumri Formation, confirming the basin-wide occurrence of a major unconformity. Comparison of our data set with that from coeval along-strike rocks in India suggests that there is no evidence of diachroneity in early stages of the orogen's exhumation.**

**Keywords:** Himalayas, foreland basin, Nepal, fission tracks, detrital zircons, provenance.

## INTRODUCTION AND RATIONALE

Knowledge of the timing and diachroneity of India-Asia collision is required for accurate documentation of shortening, critical to models of crustal deformation and accommodation of convergence. The most often quoted age of collision is 55–50 Ma (de Sigoyer et al., 2000; Klootwijk et al., 1992; Searle et al., 1997), but the degree of diachroneity is disputed (Rowley, 1996, 1998; Searle et al., 1997). A number of parameters have been used as indicators of collision. Provenance indicators that show the first arrival into the foreland basin of material eroded from the orogen, or the first appearance on the Indian margin of material derived from the Asian plate, provide minimum constraints to the timing of collision.

Petrographic studies of foreland basin sedimentary rocks in India and Pakistan (Table 1; Fig. 1) document orogenic-derived detritus in Eocene strata (Critelli and Garzanti, 1994; Najman and Garzanti, 2000; Pivnik and Wells, 1996). By contrast, coeval sedimentary rocks of the Eocene Bhainskati Formation along strike to the east in the foreland basin in Nepal show scant petrographic evidence of orogenic input (DeCelles et al., 1998a). In Nepal and farther east in the Bengal Basin, Bangladesh (Uddin and Lundberg, 1998), the earliest clear evidence of erosion from the Himalaya is found in Miocene rocks. Such data open the potential for substantial along-strike diachroneity of collision (e.g., Najman and Garzanti, 2000; Uddin and Lundberg, 1998). The principal aim of this paper is to assess the evidence for early orogenic detritus in the Eocene foreland basin sedimentary deposits of Nepal by using different provenance techniques than have been applied to these strata in the past. Our data contribute primarily to the assessment of the degree of diachroneity of collision as determined by the first arrival of orogenic detritus along the length of the foreland basin.

Our data extend into the overlying poorly dated Miocene strata in the foreland basin (Table 1). We use our data from these rocks to bolster previous age determinations for the base of the succession in Nepal. We seek to confirm that the regional unconformity, already identified in the foreland basin in Pakistan and India (Najman et al., 2001, 2004), exists throughout the basin. Such information contributes to our quest to understand the cause of this unconformity, for which hypotheses ranging from slab breakoff to movement of a peripheral forebulge have been proposed (DeCelles et al., 1998a; Guillot et al., 2003; Kohn and Parkinson, 2002; Najman and Garzanti, 2000; Najman et al., 2004). Our second use of the data in the Miocene part of the sediment succession is, by comparison with similar data along strike in India, to search for evidence of diachroneity in the early exhumation of the mountain belt.

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TABLE 1. SUMMARY TABLE OF FORELAND-BASIN STRATIGRAPHY IN PAKISTAN, INDIA, AND NEPAL

| Age | Pakistan | India | Nepal |
|---|---|---|---|
| Middle Miocene to Holocene | Siwalik Gp | Siwalik Gp | Siwalik Gp |
| Late Oligocene to early Miocene? | Kamlial Fm | Kasauli Fm | Dumri Fm |
| | Murree Fm | Dagshai Fm | |
| Oligocene | unconformity | unconformity | unconformity |
| Eocene | Patala Fm | Sabathu Fm | Bhainskati Fm |

*Note*: References as in text.

## OVERVIEW OF HIMALAYAN GEOLOGY

The Himalaya (Fig. 1) are the result of early Tertiary closure of the Tethys Ocean and consequent collision between India and Eurasia. The line of collision is the Indus-Tsangpo suture zone, which contains molasse, mélange, and ophiolitic material. To the north of the suture zone, the Late Cretaceous to early Tertiary Trans-Himalaya represents the originally Andean-type continental margin of Eurasia (Scharer and Allegre, 1984). To the south of the suture zone, Indian plate rocks of the Tethys Himalaya (Gaetani and Garzanti, 1991; Garzanti, 1999), metamorphosed Greater (Higher) Himalaya (Pecher, 1989; Vannay and Hodges, 1996), and unmetamorphosed Lesser Himalaya (Sakai, 1983; Upreti, 1996) are found. In Nepal, the Eocene–lower Miocene foreland basin sedimentary rocks, discussed in more detail here, are located in the Lesser Himalaya. South of the Lesser Himalaya is the sub-Himalayan zone, consisting of Neogene fluvial foreland basin sedimentary deposits of the Siwalik Group (DeCelles et al., 1998b).

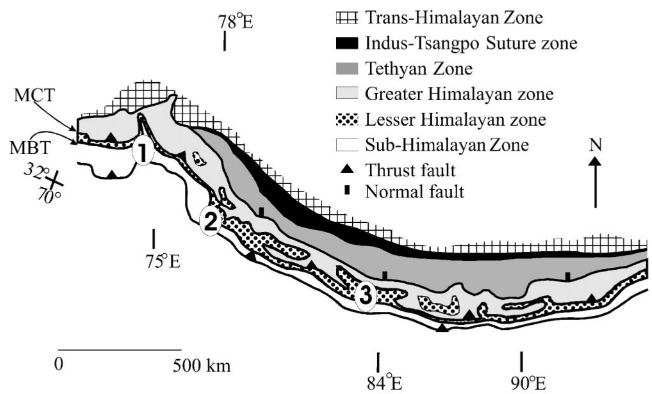


**Figure 1. Geological map of Himalaya (from Searle et al., 2003), showing study area and locations of along-strike studies discussed in text. 1—Study by Critelli and Garzanti (1994), Patala Formation, foreland basin, Pakistan. 2—Study by Najman and Garzanti (2000), Subathu Formation, foreland basin, India. 3—Location of this study, Bhainskati Formation, foreland basin, Nepal. MCT—Main Central thrust, MBT—Main Boundary thrust.**

## SUMMARY OF THE PRE-SIWALIK FORELAND BASIN STRATIGRAPHY IN NEPAL AND ALONG-STRIKE EQUIVALENTS

Our section of study in Nepal lies along the Bhainskati Khola (Table 1; Figs. DR1 and DR2[1]). The Eocene–lower Miocene foreland basin rocks are above the fluvial-deltaic Amile Formation of the Lesser Himalaya (Sakai, 1989). The age of the Amile Formation is loosely bracketed between Cretaceous and early Eocene. The contact between the Amile and overlying marine Bhainskati Formation is conformable (Sakai, 1989; Sakai et al., 1992). Sakai (1983) used middle Eocene fauna to date the Bhainskati Formation. An early to middle Lutetian age (P10-P11 zones, corresponding to 49.0–43.5 Ma; Zachos et al., 2004) is indicated by the Nummulite fauna found by Matsumaru and Sakai (1989) ~50 m above the base of the Bhainskati Formation (L. Hottinger, 2004, written commun.). Blondeau et al. (1986) and Fuchs and Frank (1970) suggested ages for the Bhainskati Formation only as young as the base of the middle Eocene and early Eocene, respectively. An oxisol marks the unconformable contact between the Bhainskati Formation and the sandstones and mudstones of the overlying alluvial Dumri Formation (DeCelles et al., 1998a; Sakai, 1989). The Dumri Formation was dated by magnetostratigraphy as ca. 21–16 Ma (unpublished data of T.P. Ojha, quoted in DeCelles et al., 2001) and by Ar-Ar dating of detrital micas as younger than 20 Ma (DeCelles et al., 2001).

To the west, in the Subathu subbasin of the foreland basin in India, the marine Subathu Formation, dated as upper Paleocene to lower middle Eocene (Batra, 1989; Mathur, 1978), is equivalent to the Bhainskati Formation. The overlying alluvial Dagshai Formation red beds and younger Kasauli Formation (Bhatia, 1982) are dated as younger than 30 Ma at the base of the succession (Najman et al., 2004) and younger than 22 Ma nearer the top (Najman et al., 1997).

In the foreland basin in Pakistan, marine facies equivalent to the Bhainskati Formation have a variety of local names (Shah, 1977), e.g., the Patala Formation, dated as 53–55 Ma (Critelli and Garzanti, 1994). Overlying the regional unconformity are the red beds of the Murree Formation (Bossart and Ottiger, 1989), dated as younger than 37 Ma (Najman et al., 2001), and the younger Kamlial Formation, dated as 18–14 Ma (Johnson et al., 1985).

## FISSION-TRACK DATA FROM THE FORELAND BASIN SEDIMENTARY ROCKS OF NEPAL: RESULTS AND INTERPRETATIONS

We collected samples spanning the complete section, from precollisional (Cretaceous) to postcollisional (Neogene) depositional age, in order to obtain detrital zircons for fission-track analysis. Of seven samples collected (located in Fig. DR2; see footnote 1) four were found to have sufficient yields and large enough grains to be suitable for analysis. Results are shown in Figure 2 and summarized in Table 2 (the full data listing is in Table DR1; see footnote 1).

We collected illite crystallinity data from 17 mudstone samples in the section in order to assess the postdepositional temperatures to which the rocks were subjected; these data allowed us to determine whether the fission-track ages represent detrital or reset ages. The <2 μm fraction of the mudrock was analyzed

[1]GSA Data Repository item 2005051, Figures DR1 and DR2, and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301–9140, USA.

TABLE 2. SUMMARY TABLE OF DETRITAL ZIRCON FISSION-TRACK ANALYSES

| Sample and formation | No. of grains | Principal age components |
|---|---|---|
| DB02-21J: Dumri | 62 | 30 ± 1 (69%); 304 ± 34 (18%); 117 ± 15 (7%); 61 ± 9 (6%) |
| DB02-21F: Dumri | 50 | 32 ± 1 (84%); 355 ± 56 (8%); 77 ± 8 (8%) |
| DB02-21N: Bhainskati | 32 | 343 ± 40 (59%); 119 ± 18 (21%); 45 ± 5 (20%) |
| DB02-21Z: Amile-Bhainskati transition | 38 | 72 ± 7 (42%); 266 ± 31 (26%); 60 ± 8 (24%); 107 ± 20 (6%) |

*Note*: Samples located in Figure 2.

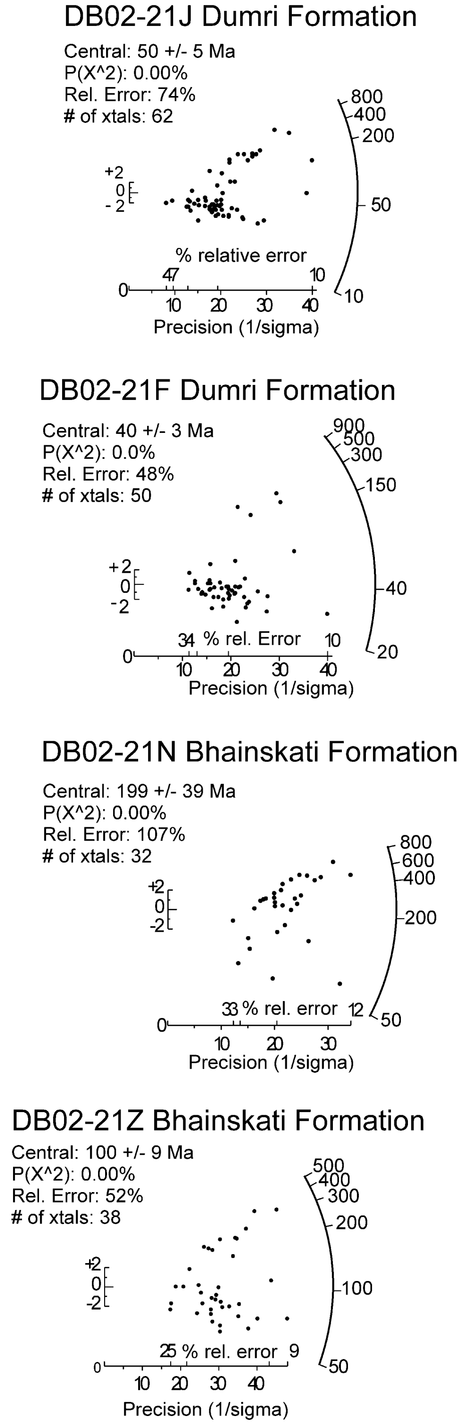


**Figure 2. Radial plots (Galbraith, 1988) showing distribution of detrital zircon fission-track ages as summarized in Table 2. Radial axes in Ma.**

in order to obtain information from the diagenetic rather than detrital component. Analyzed samples are located in Figure DR2; full results are given in Table DR2 (see footnote 1). The results do not show evidence of significant postdepositional reheating above 200 °C (Blenkinsop, 1988; Kubler, 1967), the lower boundary of the zircon partial annealing zone (Tagami et al., 1998). These data, plus the lack of evidence for any systematic lowering of fission-track age modes between samples (some modes are common to all), make partial resetting of fission-track data unlikely. Thus, zircon fission-track data in our study represent the timing of cooling through 200–370 °C in the source region.

The data set shows a number of zircon populations in each sample, indicating mixed provenance. In this paper we concentrate on the youngest age populations in the Bhainskati and Dumri Formations. The 45 Ma zircon population found in the Bhainskati Formation can be used to constrain the age of the upper part of the formation as younger than 45 Ma, and to determine provenance of the rocks. Zircons with such cooling ages could have been derived from the Trans-Himalayan arc north of the suture or from Indian plate Himalayan rocks south of the suture, exhumed by thrusting during the early stages of continental collision and crustal thickening. Either provenance requires the Indian and Asian plates to have been in contact by the time of deposition of these grains in the Eocene Bhainskati Formation rocks, and thus for inception of collision to have occurred. We consider the data to be cooling ages resulting from exhumation subsequent to crustal thickening of the Indian plate, because the majority of U-Pb ages, analyzed from zircons collected from the same rock sample, are of Precambrian–Cambrian age. These are interpreted as having been derived from Himalayan rocks south of the suture zone (DeCelles et al., 1998a, 2004). Our interpretation of the Eocene Bhainskati Formation as syncollisional brings the sedimentary evidence in Nepal into agreement with other lines of evidence that indicate that thrusting and metamorphism began soon after collision, in the Eocene (Godin et al., 1999; Ratschbacher et al., 1994; Searle et al., 1997).

The youngest zircon population in the Dumri Formation shows that the base of this formation is younger than 30–32 Ma. This provides clear evidence that the major unconformity with underlying Eocene strata, as documented in Pakistan and India (Table 1), is basin wide. Models that seek to explain this unconformity must invoke an orogen-wide rather than regional explanation. Consistent with metamorphic provenance as deduced from petrography (DeCelles et al., 1998a) and Ar-Ar ages of detrital micas (DeCelles et al., 2001), we interpret these zircon grains as derived from rocks exhumed after early stages of Himalayan metamorphism ca. 35–30 Ma (e.g., as documented by Hodges et al., 1996; Godin et al., 2001).

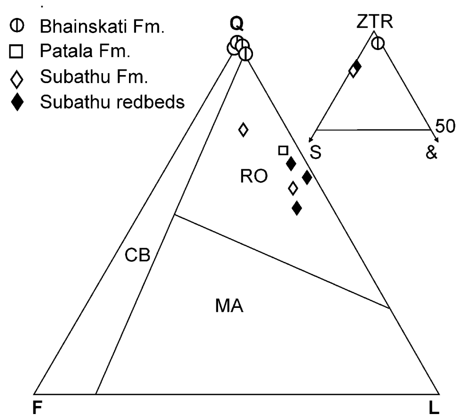


**Figure 3. Detrital modes and heavy minerals of early Himalayan foreland basin sandstones. Q—quartz, F—feldspar, L—lithic fragments, RO—recycled orogenic provenance field, CB—continental block field, MA—magmatic arc field, ZTR—ultrastable minerals zircon, tourmaline, rutile, S—chrome spinel, ampersand—other heavy minerals (brookite, garnet, sphene, anatase, apatite). Data are from Critelli and Garzanti (1994), Najman and Garzanti (2000), and DeCelles et al. (1998).**

## IMPLICATIONS FOR THE DIACHRONEITY OF COLLISION AND EXHUMATION

In contrast to the highly quartzose composition of the Bhainskati Formation, approximately coeval foreland basin rocks in India (Subathu Formation) and Pakistan (Patala Formation) show petrographic indicators of orogenic input. The rocks plot in the recycled orogenic provenance field of the standard QFL plot (Dickinson, 1985) (Fig. 3), contain felsic volcanic fragments likely derived from north of the suture zone, and chromian spinels of arc-ophiolitic provenance (Critelli and Garzanti, 1994; Najman and Garzanti, 2000). These data indicate inception of collision in the west by this time. Our new data set from the Bhainskati Formation, showing first evidence of orogenic input into the foreland basin of Nepal in Eocene rather than Miocene time, significantly reduces any possible degree of diachroneity of collision to span, at most, the duration of the early-middle Eocene. Our data therefore strongly support the recent work of DeCelles et al. (2004) who, based on U-Pb ages of detrital zircons and presence of chromian spinel in the Bhainskati Formation, concluded that in spite of the quartzose nature of the rocks, they represent syncollisional rather than precollisional facies.

We ascribe the marked eastward increase in detrital quartz in the foreland basin rocks (Subathu Formation, India: Q 62 ± 9, P/F 70 ± 16; Najman and Garzanti [2000]; Bhainskati Formation, Nepal: Q 96 ± 3, P/F 6 ± 11; DeCelles et al. [1998]) to significantly wetter subequatorial conditions in the east. The India-Asia collision took place at low northern paleolatitudes in the west, and equatorial paleolatitudes in the east (Besse and Courtillot, 1988; Bossart et al., 1989; Klootwijk et al., 1985). Prior to postcollisional counterclockwise rotation of India by as much as 33° (Dewey et al., 1989), the difference in paleolatitude between the foreland basin in Pakistan and Nepal may have been several degrees greater than at present. Therefore, in the east, whereas ultrastable minerals such as quartz, zircon, and Cr spinel survived extreme weathering (Fig. 3), less resistant minerals and rock fragments indicative of orogenic erosion are no longer preserved in the Eocene sedimentary record.

The youngest zircon fission-track age population analyzed from a sample at the base of the Dumri Formation may be compared with that from the coeval Dagshai Formation, along strike in India. Both formations are composed of similar petrographies and represent the earliest stages of exhumation of the metamorphosed Himalaya. The fact that the Dumri Formation zircon population age is nearly identical to that of the population at the base of the Dagshai Formation >500 km along strike in India (fission-track age 31 ± 1.6 Ma; Najman et al., 2004) suggests that there is no evidence of diachroneity of early exhumation; however, our data set is small.


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