Middle-late Miocene (>10 Ma) formation of the Main Boundary thrust in the western Himalaya

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ABSTRACT

Three independent data sets from northwestern India and Pakistan suggest initial displacement along >1000 km of the Main Boundary thrust prior to 10 Ma, at least 5 m.y. earlier than previously reported. Regionally extensive changes in the depositional characteristics and rates of the foreland-basin fill between 11 and 9.5 Ma are interpreted to reflect new hinterland loading due to the formation of the Main Boundary thrust. Sediment-accumulation rates, sandstone-siltstone ratios, and thickness and amalgamation of individual sandstone bodies all substantially increase after 11 Ma in well-dated stratigraphic sections from Pakistan to Nepal across the Indo-Gangetic foreland basin. In the Himachal Pradesh reentrant of northwestern India, a newly discovered 8.7 Ma conglomerate derived from the hanging wall of the Main Boundary thrust indicates that source-area uplift and denudation must have occurred prior to 9 Ma and probably prior to 10 Ma, assuming a gravel progradation rate of 3 cm/yr. Three apatite fission-track ages from structures at the leading edge of the Main Boundary thrust in the Kohat region of northwest Pakistan indicate that rapid cooling below ~105 °C between 8 and 10 Ma followed bedrock uplift and erosion that began ~1–2 m.y. earlier. These data indicate that the Main Boundary thrust in the western Himalaya formed synchronously along strike in the middle-late Miocene, has a displacement rate of ~10 mm/yr, and has a displacement history that is coeval with late displacement on the Main Central thrust.

INTRODUCTION

The Himalayan orogen is characterized by the activation and successive abandonment of intracontinental thrust faults whose lateral continuity and large inferred displacement identify them as primary zones of intracontinental thrusting during the Himalayan orogeny (Fig. 1) (Gansser, 1981; Molnar, 1988; Seeber et al., 1981). Along each of these thrusts, tens to hundreds of kilometres of the displacement between India and Asia have been accommodated (Gansser, 1981; Powell and Conaghan, 1973; Schelling, 1992; Seeber et al., 1981; Srivastava and Mitra, 1994; Treloar et al., 1992). From north to south and in order of decreasing age and structural position, they are (1) the Indus-Tsangpo suture, (2) the Main Central thrust, and (3) the Main Boundary thrust (Gansser, 1981; Seeber et al., 1981). Whereas the age of initiation and duration of thrusting on the Indus-Tsangpo suture and Main Central thrust have received considerable study, the history of the Main Boundary thrust is less well known owing to poorer exposure and fewer radiometric dates associated with it.

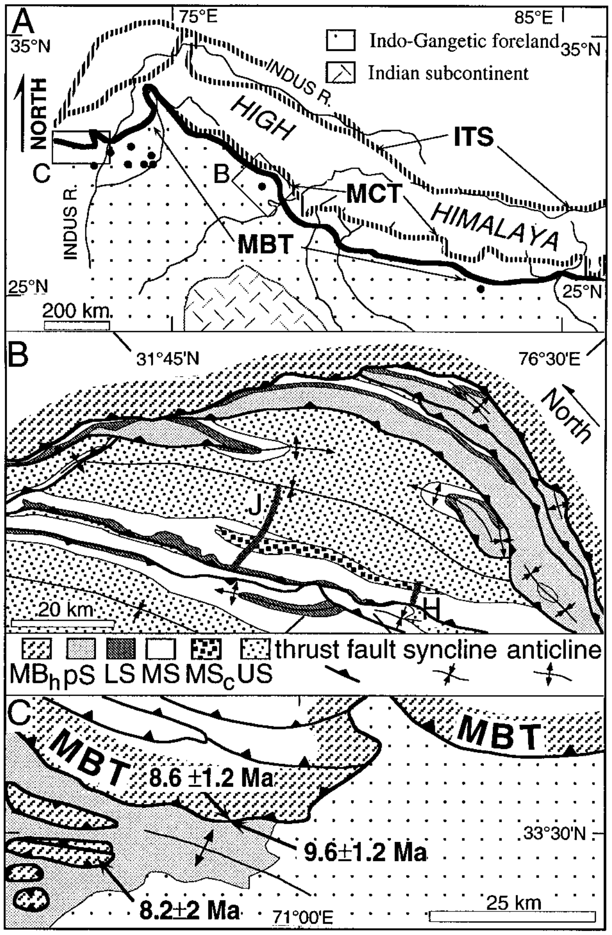

Figure 1. A: Map of western Himalaya showing Main Boundary thrust (MBT), Main Central thrust (MCT), and Indus-Tsangpo suture zone (ITS). Solid circles are locations of stratigraphic sections from which sediment-accumulation curves of Figure 2 were derived. B: Map of Himachal Pradesh reentrant with section location for Jawalamukhi (J) and Haritalyangar (H) magnetic sections. MB$_h$ = hanging wall of Main Boundary thrust; pS = pre-Siwalik strata; LS, MS, and US = lower, middle, and upper Siwalik, respectively; MS$_c$ = middle Siwalik conglomerates. (Modified from Raiverman et al., 1983.) C: Map of Himalayan foreland in northwestern Pakistan and eastern Afghanistan with sample sites and apatite fission-track ages. Units as in B, except for undivided Siwalik represented by open dot pattern.

The Main Boundary thrust is defined as the southernmost thrust that places metasedimentary rocks of the lesser Himalaya over unmetamorphosed clastic rocks of the Himalayan foredeep. Because it folds the Main Central thrust and cuts Quaternary sedimentary rocks preserved in the Himalayan foreland, the Main Boundary thrust must have formed sometime between the present and ~25–20 Ma (the age of formation of the Main Central thrust; Hodges et al., 1988; Macfarlane, 1993), although an older middle Paleocene age has been suggested (Srivastava and Mitra, 1994). The Main Boundary thrust cannot be directly dated because there are no overlapping or crosscutting relations that closely define its deformation history. Consequently, interpretation of stratigraphic, structural, and chronologic data must be used to define intervals of activity on the thrust. The oldest well-dated evidence (4–5 Ma) for Main Boundary thrust displacement comes from Pakistan and northwestern India (Burbank and Raynolds, 1988). Subsidence histories across the western Himalayan foreland, the provenance of a newly dated conglomerate, and new cooling ages from the leading edge of the Main Boundary thrust are herein interpreted to define

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its formation at >10 Ma along at least 1000 km of the Himalayan front.

GEOLOGIC DATA

Depositional Patterns Across the Himalayan Foreland

The subsidence history of the Himalayan foreland basin, the changing character of its fill, and regional paleocurrent patterns provide indirect evidence for the initiation of the Main Boundary thrust prior to 9.5 Ma. Based on a compilation of all published, magnetically dated sections spanning middle and upper Miocene strata (Burbank et al., 1994), sediment-accumulation rates show an apparent (up to 200%) regional acceleration between 11 and 9.5 Ma across the dated parts of the foreland (Figs. 1, 2). It is reasonable to interpret the sediment-accumulation curves as a proxy for regional variations in basin subsidence given (1) the large geographical separation of most of these sites from the coast and the resultant damping of eustatic effects, (2) modern topographic gradients on the actively aggrading foreland, (3) reasonable limits on permissible gradients in the past, and (4) high rates and amounts of accumulation with respect to likely changes in depositional gradients in the Miocene foreland (Burbank and Beck, 1991). The errors introduced by using assumed gradients are small compared to the magnitude of subsidence. Although some of the data could be interpreted to suggest an acceleration as young as 10 Ma, an older age minimizes the calculated rate changes. Furthermore, sediment-accumulation rates after ~11 Ma are statistically different from the average rate at the 95% confidence level in seven of the nine data sets. In many parts of the foreland, a major shift in sandstone-siltstone ratios from less than ~30% to greater than ~65% also occurs at ~11 Ma, when individual sandstone bodies become, on average, substantially thicker and more amalgamated. An overall pattern of axial drainage toward the east-southeast is seen in paleocurrent measurements spread along the foreland from Pakistan to Nepal (Burbank, 1992; Burbank and Beck, 1991; Burbank et al., 1994). Together, these observations can be interpreted to reflect an increase in loading and reorganization of the drainage system due to intensified hinterland deformation, specifically, formation of the Main Boundary thrust. Whereas comparable increases in subsidence could be generated by doubling or tripling the existing Miocene loads, it is more probable that formation of the Main Boundary thrust prior to 9.5 Ma caused accelerated subsidence within the foreland. Subsidence and drainage changes alone, however, do not uniquely fingerprint Main Boundary thrust formation.

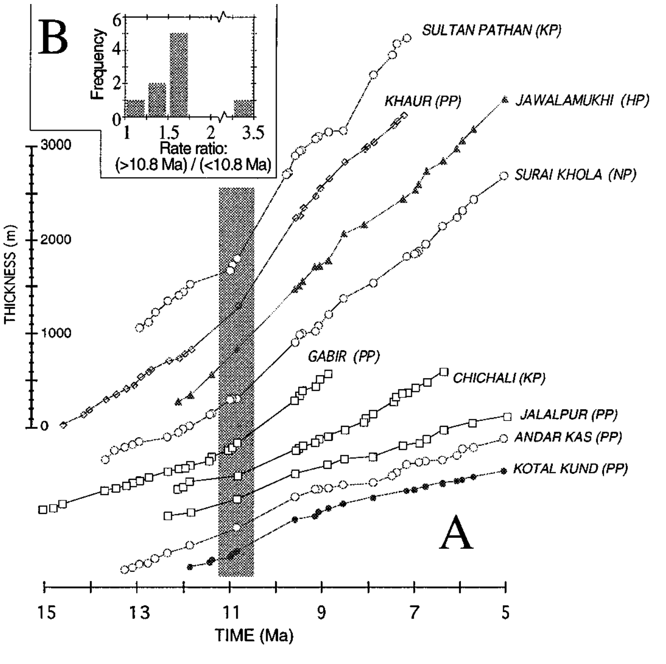

Figure 2. A: Sediment-accumulation curves for Himalayan foreland showing accelerated accumulation and inferred subsidence beginning at ~11 Ma (shaded band). Data are based on magnetostratigraphic studies that are correlated to magnetic time scale of Cande and Kent (1992). KP—Kohat Plateau; HP—Himachal Pradesh; NP—Nepal; PP—Potwar Plateau. Data sources: Andar Kas (Johnson et al., 1982); Chichali (Khan, 1983); Gabir (Johnson et al., 1985); Jalalpur (Johnson et al., 1982); Jawalamukhi (this study); Khaur and Kotal Kund (Johnson et al., 1982); Surai Khola (Appel et al., 1991); Sultan Pathan (unpublished data). For site locations, see Figure 1. B: Histogram of the ratio of sediment-accumulation rate for ≥1 m.y. intervals prior to and following 10.8 Ma vs. frequency. All rates increase, and five of the nine sections show increases between 50% and 75%.

Age and Provenance of a Middle Siwalik Conglomerate in Northwestern India

In a new, detailed litho- and magnetostratigraphic section of the Siwalik Group at Jawalamukhi in the Himachal Pradesh reentrant of northwestern India, the sudden appearance of a metamorphic- and plutonic-clast–dominated conglomerate in the middle Siwalik at ~8.7 Ma provides additional evidence for late Miocene uplift of the Main Boundary thrust (Figs. 1 and 3). The section is bounded at its base by the Jawalamukhi thrust fault and at its top by a thick boulder conglomerate. Total thickness of the section is ~3400 m, the longest published and dated section of Siwalik strata in India. It consists of 425 m of lower Siwalik, 1950 m of middle Siwalik, and 1025 m of upper Siwalik strata (Fig. 3). Six hundred paleomagnetic samples were collected at 134 sites. Following pilot demagnetization studies, the samples were thermally demagnetized at 400, 450, and 500 °C. Seventy percent of the samples yielded Class I sites (Fisher, 1953) ($k > 10$), and the resulting data pass the reversal test. Because of the uniform stratal dips through the section, the data fail the fold test. Correlation with the magnetic polarity time scale (Cande and Kent, 1992) is assisted by a preexisting magnetic section at Haritalyangar (Johnson et al., 1983), located ~30 km along strike to the southwest (Fig. 1B). We have extended that magnetic section downward through 600 m of strata, and in combination with associated faunal data (Johnson et al., 1983), we have documented the presence at Haritalyangar of chron 5n (9.59 to 10.83 Ma; Cande and Kent, 1992) (Fig. 3). Chron 5n is also seen in equivalent strata (as defined by strike-line mapping) in the Jawalamukhi section and provides a key correlation point. The Jawalamukhi section is interpreted to span ~7.7 m.y.: from ~12.3 Ma at the base within the lower Siwalik to ~4.6 Ma at the top within the upper Siwalik. An alternative correlation of the upper part of the Jawalamukhi section with the magnetic time scale is possible (Fig. 3). We prefer the correlation yielding slightly slower, but steadier, accumulation rates. This correlation is also more consistent with the Haritalyangar magnetostratigraphy, which we have recorrelated with the new time scale (Fig. 3).

Middle Siwalik deposition spans from 10.9 to 6.8 Ma with 500 m of conglomerate present between 8.7 and 7.2 Ma (Fig. 3) (0.38 mm/yr undecompacted sediment-accumulation rate). Clast types within the conglomerate include numerous pink quartzites that appear to be derived from the Deoban Formation, which is currently exposed in the Main Boundary thrust's hanging wall. Clast size averages 5–10 cm. Coarse stratification, broad scours, and imbrication are common. Paleocurrent directions ($n = 106$) from numerous clast imbrications and cross-beds indicate a mean paleoflow toward 250°, subparallel to the axis of the reentrant. Individual stories are typically 3–10 m thick and are >>200 m in width. These characteristics suggest braided-river deposition for the conglomerate. Its map distribution indicates a narrow conglomeratic facies belt ~40 km in

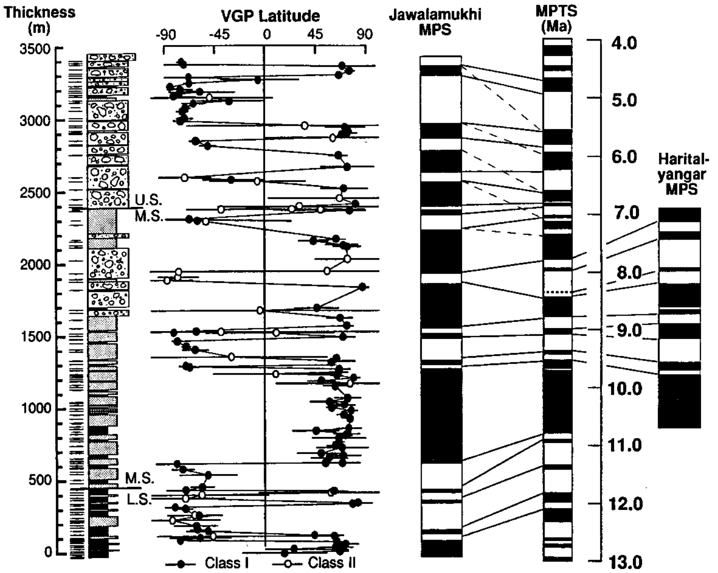

Figure 3. From left to right: Jawalamukhi lithostratigraphic column, site virtual geomagnetic polarities (VGP) with α_{95} error bars, local magnetic polarity stratigraphy (MPS), global polarity time scale (MPTS) of Cande and Kent (1992), and the Haritalyangar polarity stratigraphy (Johnson et al., 1983). Vertical distribution of samples for Jawalamukhi sites is given at left of lithostratigraphic section. Class I = $k > 10$, class II = $k < 10$ (Fisher, 1953). L.S., M.S., and U.S. = lower, middle, and upper Siwalik, respectively. Dashed lines show alternative (not preferred) correlation with time scale. Six hundred metres of new magnetic data have been added to Haritalyangar section (Johnson et al., 1983), and it has been recorrelated with the time scale. Close sample spacing at Haritalyangar reveals more detailed reversal pattern that apparently includes both cryptochron at ~8.3 Ma (Cande and Kent, 1992) and short reversal at ~8.8 Ma seen in other densely sampled Siwalik sections (Tauxe and Opdyke, 1982).

width and suggests that the channel belt was confined to a medial trough, parallel to the axis of the reentrant, for 1.3 m.y. This restricted-facies belt, trending at a high angle to the foreland margin, suggests that its distributary system was centrally focused by enhanced subsidence due to constructive interference between the convergent thrust loads on the flanks of the reentrant, by the surface morphology of prograding fans from the reentrant's sides, and by two subsurface basement ridges (Raiverman et al., 1983) that are oriented at high angles to the thrust front and that delineate the margins of the Kangra subbasin within the reentrant.

At present, the conglomerate at Jawalamukhi is located ~40 km from the Main Boundary thrust. Given the foreland-ward displacement of the Main Boundary thrust hanging wall since its inception, it is likely that the conglomerate facies had prograded >50 km into the foreland before arriving at Jawalamukhi. If the time encompassed by this progradation were known, it would be possible to determine the timing of initial uplift and erosion of the source area. Whereas there are no data on progradation in Himachal Pradesh, a similar conglomeratic progradation of a focused fluvial system in a structural reentrant occurred in the Jhelum reentrant during Pliocene-Pleistocene time (Burbank et al., 1988). A relatively rapid rate (3 cm/yr) of gravel progradation during diminished thrust loading is documented there. If similar progradation rates prevailed in Himachal Pradesh, the timing of source-area uplift would be >10 Ma, in agreement with the timing of displacement on the Main Boundary thrust inferred from the sediment-accumulation records.

Apatite Uplift Ages from Northwest Pakistan

A third, independent data set that places chronologic limits on the beginning of Main Boundary thrust deformation is provided by cooling and bedrock uplift ages derived from fission-track dating. Three samples were collected from the crests of en echelon, hanging-wall anticlines associated with the leading edge of the Main Boundary thrust system in Waziristan, northwest Pakistan (Fig. 1C). The samples were prepared and analyzed according to the methods outlined by Naeser (1979). These Cretaceous and Paleocene shelfal sandstones are currently at elevations of 1–2 km, but were previously buried to depths of >5 km below sea level. The apatite fission-track ages and track-length measurements (Table 1) indicate rapid cooling below ~105 °C between 8 and 10 Ma. We interpret this cooling to result from uplift and erosion of imbricates within the Main Boundary thrust system. Given the large vertical trajectory (>6 km) of these samples and their estimated maximum burial temperature of ~175 °C, it is likely that uplift began 1–2 m.y. prior to cooling through 105 °C.

DISCUSSION

Subsidence, lithostratigraphic, and geochronologic data independently suggest that the Main Boundary thrust formed before 10 Ma. It seems likely that this event had begun by ~11 Ma for the following reasons. First, some lag time between uplift of the hanging wall and the appearance of detritus in the foreland seems reasonable. The length of the lag time is difficult to calibrate. If it is essentially zero, then the thrust formed at 8.7 Ma at Jawalamukhi (Fig. 3). A more tenable position is that gravel progradation rates (~3 cm/yr; Burbank et al., 1988) dictate the duration of the lag time. Because the conglomerate lies >40 km southwest of the Main Boundary thrust now, a conservative estimate of the age of formation of the thrust (which neglects its even more northerly middle Miocene position) is at least at 10 Ma. Similar reasoning applies to the cooling ages from northwestern Pakistan. If the samples were instantaneously uplifted from below the 175 °C isotherm across the 105 °C isotherm, the age of initiation must be between 8.2 and 9.6 Ma (Fig. 1C). Alternatively, if the rocks were uplifting at a rate of ~1–2 mm/yr (given a geothermal gradient of ~30 °C/km), then formation of the thrust was at least 1–2 m.y. earlier, between 10 and 11 Ma. Formation of the Main Boundary thrust before 10 Ma, a period of displacement between 5 and 4 Ma (in northeast Pakistan and Kashmir; Burbank and Raynolds, 1988), and present seismicity on it at depth (Molnar, 1988) attest to the fault's longevity. If estimates of >100 km displacement on the thrust are correct (Molnar,

TABLE 1. APATITE FISSION TRACK AGES MEASURED FOR EACH SAMPLE

Sample	N	N_s	N_i	Pooled age (Ma)	N_d	N_{tl}	Mean length	Standard deviation
DA91-104	7	56	1264	8.6 ± 1.2	4184	2	15.32	
DA91-105	6	67	1357	9.6 ± 1.2	4184	9	14.67 ± 0.47	1.34
DA91-106	9	17	403	8.2 ± 2.0	4184	no confined tracks observed		

Note: N = number of apatite grains dated; N_s = number of spontaneous tracks counted; N_i = number of induced tracks counted; Pooled age = fission track age calculated assuming all grains come from a single population (calculated by using a weighted mean zeta calibration factor of 118.9 ± 3.6 relative to CN-1 glass); N_d = number of induced tracks counted for the CN-1 glass; N_{tl} = number of grains for track length measurement.

1988; Powell and Conaghan, 1973; Treloar et al., 1992), shortening rates of ~10 mm/yr are suggested by our data.

What can be said of regional spatial and temporal patterns of motion on the Main Boundary thrust? One significant problem in establishing a regional pattern is that the Main Boundary thrust is defined by the structural juxtaposition of lesser Himalayan rocks against foreland basin strata *rather* than by a single, mappable fault. As noted by many authors (Treloar et al., 1992), the "Main Boundary thrust" is a general term for a thrust zone that, in detail, is probably represented by a series of related individual thrusts along strike. Each of these individual thrusts roots downdip into the basal decollement of the Himalaya (Molnar, 1988; Schelling, 1992; Srivastava and Mitra, 1994). At the scale of our temporal resolution (±1 m.y.), the Main Boundary thrust began synchronously across >1000 km of the western Himalaya. There are no clear chronologic constraints on the Main Boundary thrust in central and eastern Nepal. A reasonable interpretation of the synchrony of the western Himalayan data is activation of the basal decollement beneath the Main Boundary thrust sheet by ~11 Ma. Although the data are too sparse to define its age more precisely at this time, it seems likely that individual imbricates mapped as the Main Boundary thrust and other faults related to this decollement are diachronous along strike. The range of cooling ages in northwestern Pakistan, the age of the conglomerate at Jawalamukhi, and the inferred 5 Ma age of cessation of thrusting on the Main Boundary thrust west of the Hazara syntaxis (Treloar et al., 1992) are all compatible with this inference.

The results of this study provide insight into the formation and successive abandonment of several of the principal decollements of the Himalayan orogeny. Detailed structural and geochronological studies in Nepal show at least three distinct phases of motion on the Main Central thrust between 25 and 15 Ma, between 9 and 7 Ma, and at ~2.3 Ma (Hodges et al., 1988; Macfarlane, 1993). The first period of motion coincides with a time when the Main Central thrust acted as the basal decollement (Burchfiel et al., 1992; Hodges et al., 1988), whereas the later two episodes occurred when the base of the Main Boundary thrust sheet was the basal decollement. Coeval motion on these two fundamental structures suggests that the underthrusting of India involved the gradual decrease of displacement rates on one decollement (the Main Central thrust) as major shortening shifted to a new, structurally lower one (the Main Boundary thrust). This evolutionary process involved broadly distributed deformation that is continuous at the time scale of the India-Asia collision, but is discontinuous at the time scale of the lifetime of individual thrusts. The relative temporal continuity of these processes has important implications for the formation and maintenance of orogenic topography, short-term sediment fluxes, uplift rates, and the age, location, and duration of metamorphic and structural events.

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