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Laser $^{40}Ar/^{39}Ar$ age constraints on Miocene sequences from the Bengal basin: Implications for middle Miocene denudation of the eastern Himalayas

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[1] Petrographic, mineral-chemistry and subsurface studies reveal that orogenic sedimentation had already begun in the Bengal basin by the early Miocene. Laser $^{40}Ar/^{39}Ar$ age determinations were made for detrital muscovite grains (145 total, among 4 samples) from the lower-to-middle Miocene Bhuban Formation. The laser fusion ages range from circa 12 Ma to 516 Ma, and thus suggest derivation from a combination of sources: the Himalayas, Indo-Burman ranges and possibly the Indian shield and Tibetan plateau. Modes of circa 16 Ma, 18 Ma, 26 and 40 Ma in the age distributions of these samples are most consistent with unroofing of the Higher Himalayas since the early Miocene. Detrital micas of such an early age (16 Ma) for the Bhuban Formation are interpreted to indicate that little time elapsed between the isotopic closure of ^{40}Ar in the muscovite and its ultimate deposition in middle Miocene strata. The detrital ages of circa 16 and 22 Ma in this study, most prominent in the highest stratigraphic levels sampled in this study, are younger than those previously reported in the western Himalayan foreland basins. These younger detrital ages are consistent with rapid middle Miocene unroofing and erosion as has been proposed for crystalline rocks of the eastern Himalayas. The minimum $^{40}Ar/^{39}Ar$ ages for muscovite in a particular sample seem proportional to the stratigraphic level sampled, i.e., younger ages tend to occur for samples of higher stratigraphic level. These results support earlier studies indicating that detrital geochronology can be used as an effective tool in evaluating stratigraphic ages.

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1. Introduction

[2] The collision of India with Eurasia provides a spectacular display of plate tectonics. The timing of initial collision of the Indian plate with Eurasia has been debated [*Cochran*, 1990; *Butler*, 1995] (also see discussion from *Uddin and Lundberg* [1998]). Data bearing on the timing of collision come mainly from areas west of the central Himalayas [e.g., *Beck et al.*, 1995; *Najman et al.*, 1997]. Although most workers suggest that the leading edge of India began to collide with Eurasia in a so-called "soft" collision around 55 Ma [i.e., *Sclater and Fisher*, 1974], others propose an earlier collision at about 70 Ma [i.e., *Yin and Harrison*, 2000]. Continent-continent "hard"collision however may not have occurred until the Eocene/Oligocene boundary (~34 Ma) [*Aitchison et al.*, 2007].

[3] In the eastern Himalayas, Eocene sandstones from Assam (northeast India) are orogenic [*Uddin et al.*, 2007] suggesting uplift and denudation of the Himalayas had taken place by the Eocene. The Paleogene units of onshore delta of the Bengal basin are however still debatable, as they vary compositionally from being primarily quartzose non-orogenic [*Uddin and Lundberg*, 1998] to orogenic in character with meta-sedimentary lithic fragments [*Johnson and Nur Alam*, 1991; *Najman et al.*, 2008]. A lower Neogene uplift of the Himalayas is confirmed along all segments of the Himalayas from west [e.g., *Beck et al.*, 1995] through central [e.g., *DeCelles et al.*, 2004] to the east [e.g., *Uddin et al.*, 2007]. Distal eastern equivalents of the molassic Siwalik sequences have been studied in the Bengal fan, in seismic surveys [*Curray*, 1991] and on two drilling legs (Deep Sea Drilling Project Leg 22 and Ocean Drilling Program Leg 116) [*Ingersoll and Suczek*, 1979; *Amano and Taira*, 1992]. Drilling has recovered strata as old as about 18 Ma, and detrital geochronology and isotopic studies on these strata indicate that orogenesis had begun prior to this time [e.g., *Copeland and Harrison*, 1990; *Galy et al.*, 1996; *White et al.*, 2002; *Hodges et al.*, 2005; *Szulc et al.*, 2006].

[4] Compared to the western Himalayas, the timing of geological events has not been studied as extensively in the eastern Himalayas or in the foreland basins to the south. In order to add constraints to our understanding of sediment

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provenance and to further outline the exhumation history of the eastern Himalayas, we have analyzed detrital minerals from Cenozoic strata of the Bengal basin. Specifically, we have determined laser $^{40}Ar/^{39}Ar$ ages for single crystals of detrital muscovite grains from Miocene sandstones in select drill cores from the basin. Major goals of our study have been to trace the source terranes that contributed clastic sediments to the Himalayan-Bengal system and the changes in these sources through time. We have also compared our results with data on well-characterized sequences in other segments of the Himalayas and on Miocene and younger deposits of the distal Bengal fan, in order to evaluate along-strike and downstream changes in sediment provenance.

1.1. Rationale for Evaluating Orogenic Sediments by $^{40}Ar/^{39}Ar$ Dating of Detrital Muscovite

[5] If a grain of muscovite is weathered from uplifted bedrock, transported, and ultimately deposited in a sedimentary sequence, the $^{40}Ar/^{39}Ar$ age of that grain should provide a proxy for the time of cooling of its source through the closure interval for argon retention in muscovite, provided that no additional radiogenic ^{40}Ar is lost during transport or after deposition [e.g., *Hodges et al.*, 2005; *Burbank et al.*, 2007]. Sediment thickness and thermal gradients are moderate in the Bengal basin and $^{40}Ar/^{39}Ar$ studies in the foreland basin deposits and the distal Bengal fan have not been compromised by thermal resetting [*Copeland and Harrison*, 1990]. The details of argon diffusion and closure temperature in muscovite are not critical to the present study, as grains contained within a single sandstone are likely to have differing cooling histories, and differing closure temperatures are likely to be represented in a population of detrital mineral ages. Many studies refer to a range of 300–400°C for the argon closure temperature of muscovite [e.g., *Hodges*, 1991]. Empirical studies of argon diffusion in muscovite [e.g., *Hames and Bowring*, 1994; *Kirschner et al.*, 1996] indicate a relatively low diffusivity for argon in muscovite and a somewhat higher closure temperature (~375–425°C for a range of typical grain sizes and cooling rates). On the basis of direct measurements for natural diffusion gradients, we suggest the physical grain size and radius (measured parallel to (001), i.e., a cylinder geometry for diffusion) are most appropriate for modeling diffusion in muscovite (for an alternative treatment) [see *Harrison et al.*, 2009]. The grain size ranges for samples of the present study are represented in the auxiliary material.[1]

[6] Detrital muscovite crystals from a single sedimentary sample typically exhibit a range of $^{40}Ar/^{39}Ar$ mineral ages that is far greater than the precision of individual measurements, and may yield a complex distribution with multiple age modes. Protracted and complex age distributions could reflect a history of slow cooling or polymetamorphism in a given source region, or even specific outcrop (c.f. laser single-crystals studies of muscovite in slowly cooled and polymetamorphic rock) [e.g., *Hames and Hodges*, 1993; *Hodges et al.*, 1994]. Perhaps more commonly in the relatively young and rapidly unroofed settings of the crystalline Himalaya, age distribution with multiple modes is an indication of multiple source regions. In any case, the youngest mode of a detrital mineral age distribution has particular sedimentological significance: the difference between its age and the depositional age of the sample represents the maximum duration of transport from source to depocenter. For many Miocene-Pliocene foreland-basin samples of the Siwalik molasse and the Bengal fan, this interval is statistically indistinguishable from zero, indicating that sediment residence times in fluvial systems on the southern flank of the Himalayas are remarkably brief [*Copeland and Harrison*, 1990]. To the extent that rapid transport is related to high relief in the source region, this phenomenon may indicate a well-developed Himalayan orogenic “front” existed and uplift and unroofing ages may come close to be the depositional ages of the clastic wedges [*Hodges et al.*, 2005; *Brewer et al.*, 2006].

1.2. Regional Geology of the Himalayan-Bengal System

[7] The Himalayan-Bengal delta and fan, in the eastern part of the Himalayas, represent the largest active orogenic depositional system (Figure 1). The Himalayan-Bengal system developed due to collision of India with Eurasia and has an orogen-to-basin linkage via two major drainage networks, the Ganges to the west and the Brahmaputra to the east (Figure 1). The Bengal basin of Bangladesh and the West Bengal State of India is a large delta-dominated basin that comprises the proximal, eastern portion of the immense foredeep of the Himalayas comprised of Cenozoic sequences derived from both the eastern Himalayas and the Indo-Burman ranges. The Bengal basin is over 20 km deep and spreads over 130,000 km^2, and is filled by synorogenic sediments. Sediment is ultimately transported by turbidity currents to the deep-sea Bengal fan [*Curray*, 1991]. The Bay of Bengal is a remnant portion of an ocean basin that closed by subduction eastward beneath the Indo-Burman ranges and the Andaman and Sunda outer arc [*Ingersoll and Suczek*, 1979]. The mountains of the Indo-Burman ranges are east of the Bengal basin, and to the north lies the Shillong plateau, a 1 km-high horst block that exposes Precambrian basement rocks [*Johnson and Nur Alam*, 1991]. A monocline along the southern Shillong plateau borders the Bengal basin along the prominent east-trending Dauki fault, a south-vergent thrust fault (Figure 1). *Johnson and Nur Alam* [1991] suggested that 28 to 80 km of dip-slip displacement have lifted the Shillong plateau to its present elevation since the Miocene, and that this uplift forced the Brahmaputra to shift 300 km westward from draining over the Sylhet trough from the northeast during the Miocene to its present position at west of the Shillong plateau (Figure 1) [*Johnson and Nur Alam*, 1991; *Uddin and Lundberg*, 1999].

[8] The mammoth proximal portion of this system acts as a repository of stratigraphic information on the Himalayan orogeny. Although much of the delta remains buried, most of the basin's depositional history is represented in exposed stratigraphic sequences of marginal uplifts. Present-day sediment fill of the Bengal foredeep is asymmetric and extremely thick, with thickness increasing to the south and east. *Curray* [1991] reinterpreted seismic refraction and reflection data in the Bay of Bengal to suggest a minimum thickness of sedimentary deposits greater than 22 km beneath the Bengal

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/jb/2009jb006401/. Other auxiliary material files are in the HTML.

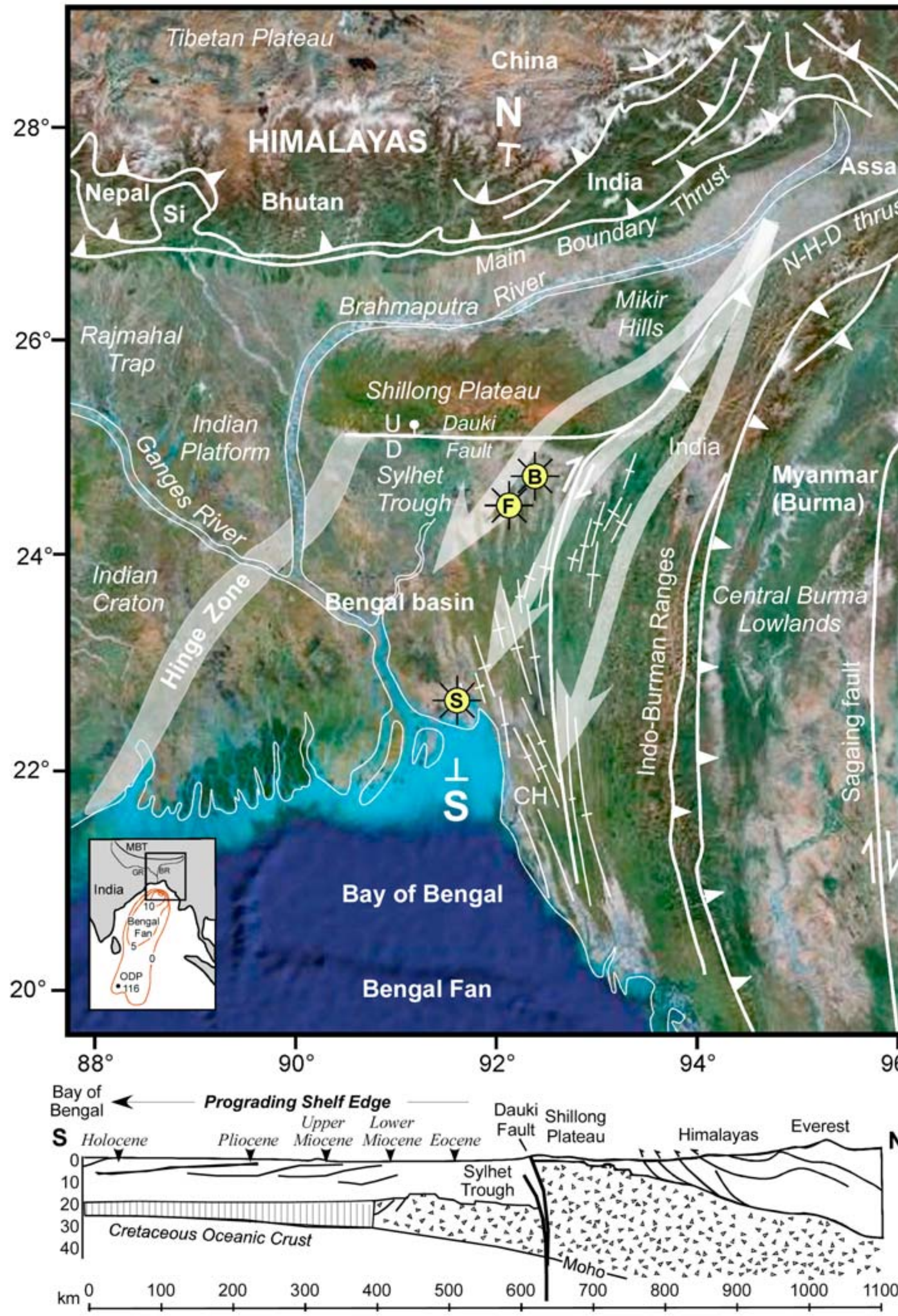

Figure 1. Location and tectonic map of the Bengal basin showing sample sites for $^{40}Ar/^{39}Ar$ dating [after *Uddin and Lundberg*, 1998]. The NE-SW trending hinge zone separates the eastern part of the Bengal basin from the northwest Indian platform. The deeper part of the Bengal basin is truncated at the Chittagong hills at the east with complexity of fold belts increasing toward the Indo-Burman ranges further east. B – Beanibazar 1X; F – Fenchuganj 2; and S – Sitakund 1. Beanibazar 1X and Fenchuganj 2 wells are located in the gas-rich Sylhet trough. Sitakund 1 is located toward the south, in the Chittagong hills area (CH). A north-south cross-section shows 20-km crustal relief at the Dauki thrust fault between the uplifted Shillong plateau and the subsided Sylhet trough. Shelf-edge progradation toward south since the Eocene is illustrated in the cross section [after *Uddin and Lundberg*, 2004]. Sample location of *Harris et al.* [2004] in Sikkim-Darjeeling area is shown as Si, just north of the Bengal basin. White shaded arrows suggest location and flow directions of the Miocene paleo-Brahmaputra [after *Uddin and Lundberg*, 1999] before its shifting to its present location west of the Shillong plateau. N-H-D thrust: Naga-Haflong-Disang thrust. Google Earth imagery (c) Google Inc. Used with permission.

Geologic time	Unit		Thickness (m)
Late Miocene to Pliocene	Tipam Group	Tipam Sandstone	80-1100
~~Unconformity~~~			
Middle to Late Miocene	Surma Group	(Upper Marine Shale) Boka Bil Formation	300-1400
Early to Middle Miocene		Bhuban Formation	250-1700
~~Unconformity~~~			
Oligocene	Barail Formation		45-1600

Figure 2. Miocene stratigraphy of the Bengal basin, showing the position of the lower-to-mid Miocene sediments. The Bhuban and Boka Bil sediments that constitute the Miocene Surma Group are bounded by unconformities. These primarily deltaic deposits range in thickness from 150 m in the Indian platform region to as high 3 km in the eastern deeper and Chittagong hills part of the Bengal basin. These sediments primarily compose of bedded to rippled, alteration of sandstones and mudrocks. The Upper Marine Shale represents the last marine transgression in the Miocene [*Holtrop and Keizer*, 1970; *Uddin and Lundberg*, 1999].

continental shelf, with the lower 6 km or so comprising Cretaceous and Paleocene pre-collisional strata and the overlying 16 km derived from the collision. A NE-trending tectonic hinge zone separates the deeper facies strata of the foredeep in the southeast from a relatively thin "Indian platform" region of northwest Bengal basin [*Uddin and Lundberg*, 2004]. The Sylhet trough, an important tectonic element within the deeper facies of the basin, developed through rapid subsidence and has a 20-km structural relief with the Shillong plateau to the north (Figure 1). This basin is petroliferous, and stratigraphic information is well documented from petroleum exploration. Intensity of folding increases toward the southeast of the Bengal basin due to east-west compression of the Indo-Burman ranges. The folded flank of the Bengal foredeep comprises largely Sub-Himalayan molasse, folded tightly along north-trending axes, known as Chittagong hills (Figure 1). The sediment that has been carried into this system and which has not been trapped in this delta has been transported farther south to form the Bengal deep-sea fan, the largest submarine fan in the world. Many studies have been done on drill cores collected during research expeditions in the more distal regions of the Bengal fan through the Ocean Drilling Program (ODP) [e.g., *Copeland and Harrison*, 1990].

1.3. Stratigraphic Facies and Depositional Age of the Bhuban Formation

[9] The stratigraphy of the Bengal basin was established by lithostratigraphic correlation to type sections in neighboring Assam, northeastern India (Figure 1) [*Evans*, 1964; *Khan and Muminullah*, 1980]. The present stratigraphic framework of the Bengal basin has been refined by subsequent studies of palynology [e.g., *Reimann*, 1993], micropaleontology [e.g., *Banerji*, 1984], seismic stratigraphy [e.g., *Lindsay et al.*, 1991] and magnetostratigraphy [*Worm et al.*, 1998]. The Bhuban Formation is stratigraphically positioned between the Oligocene Barail unit and the middle-to-upper Miocene Boka Bil Formation (Figure 2) [*Uddin and Lundberg*, 1999]. A laterite unit serves as the unconformable boundary between the Miocene Bhuban Formation and Oligocene Barail Formation. The Bhuban-Boka Bil contacts are conformable.

[10] The Miocene Surma Group, comprising the Bhuban and Boka Bil formations, is well developed in the eastern fold belts and deeper parts of the basin, with a thickness of about 3 km in the northern Chittagong hill tracts and in the Sylhet trough. In the northwestern stable shelf area, the Surma Group is much thinner (150 m to 1.3 km) [*Khan and Muminullah*, 1980]. Of the three units within the Bhuban Formation, the lowermost and uppermost are mainly light-gray to light-yellow siltstone and fine-grained sandstone, alternating with bluish-gray, bedded mudrock, whereas the middle unit is composed mainly of blue to yellowish-gray silty and sandy mudstone. *Johnson and Nur Alam* [1991] interpreted Bhuban sequences as prodelta and delta-front deposits of a large mud-rich delta system, similar to the modern Ganges/Bengal delta. In the Chittagong Hill tracts however, several Bhuban sequences have been identified as turbidite deposits [*Akhter et al.*, 1998]. The overlying Boka Bil Formation is generally composed of shale, siltstone and sandstone that were deposited in subaerial to brackish environments, based on presence of mudcracks and pollen types (*Hystrichosphraedis*) [*Holtrop and Keizer*, 1970]. A shaly upper member of the Boka Bil Formation has been designated by *Holtrop and Keizer* [1970] as the "Upper Marine Shale," representing the last Miocene transgression before the deposition of non-marine sediments of Pliocene and Pleistocene age (Figure 2).

[11] Fossil foraminifera from the Bhuban Formation have been interpreted to indicate a middle Miocene age [*Reimann*, 1993]. *Rahman and Faupl* [2003] determined incremental heating $^{40}Ar/^{39}Ar$ ages for multigrain samples of muscovite from drill core samples of the Miocene Surma Group that tended to range between 25 to 36 Ma. The multigrain (bulk sample) incremental heating approach for $^{40}Ar/^{39}Ar$ dating, used by *Rahman and Faupl* [2003], is problematic for detrital samples, because age variations in hydrous phases tend to homogenize (for studies of muscovite, see *Hodges et al.* [2005]). Also, the depths of samples were not specified in

the work by *Rahman and Faupl* [2003]. We consider the minimum ages they obtained to provide meaningful estimates of the maximum possible ages for their study units. *Uddin and Lundberg* [1998] interpreted all of the available data to indicate that the Bhuban Formation is of lower-to-middle Miocene age and the Boka Bil Formation ranges from middle-to-upper Miocene age.

2. Methods

[12] We were granted limited access to subsurface core samples obtained during petroleum exploration, curated by Bangladesh Petroleum Exploration, Inc. Samples used in this study were chosen from lower to middle Miocene Bhuban Formation because this is the oldest unit that has been penetrated in most petroleum exploration in the eastern part of the Bengal basin. Three wells were chosen for this study: Beani Bazar-1X, Fenchuganj-2 and Sitakund-1 (Figure 1). Two out of four samples were chosen from Fenchuganj-2 (FG 2–18; 4540 m to 4549 m and FG 2–22; 4721 m to 4730 m); one each from Beani Bazar 1X (BB 1–11; 3408 m to base, approximately 4018 m) and Sitakund-1 (SKND 1–20; 2793.7 m to 2799.9 m). These well locations belong to the folded flanks of the Chittagong hills and Sylhet trough of the eastern Bengal basin (Figure 1).

[13] The use of material from exploratory drill cores placed constraints on the amount and number of samples available for this study. Four representative samples were selected for $^{40}Ar/^{39}Ar$ study of detrital muscovite (each sample was about 0.5 kg and is representative of the respective interval). The abundance and grain size of muscovite varied among these samples, with the result that it was possible to separate and analyze ~20–60 crystals from each. The samples available limited our strategy to identify the dominant age peak(s) for a given sample [c.f. *Burbank et al.*, 2007], and we do not imply that we define all possible characteristics of the age distributions to a high level of certainty [c.f. *Vermeesch*, 2004]. Once prepared, muscovite samples were irradiated at the McMaster nuclear reactor facility in Hamilton, Ontario, Canada. Samples were analyzed at Auburn University in the Auburn Noble Isotope Mass Analysis Laboratory (ANIMAL). ANIMAL is equipped with a low-volume, high sensitivity 10-cm radius sector mass spectrometer and automated sample extraction system (based on a CO_2 laser) for analysis of single-crystals (additional facility information is provided in the data repository). The Fish Canyon Tuff (28.02 ± 0.16 Ma) [*Renne et al.*, 1998] was used as the primary standard in this study. Uncertainties reported are the standard deviation, representing the precision of analysis, and do not include systematic errors arising from uncertainties in the decay constant or monitor age. All analyses represent single crystals and total fusion of muscovite with a CO_2 laser. Sample BB 1–11 contained the coarsest muscovite, typically 2–3 mm in diameter, resulting in ~5×10^{-16} mol $^{39}Ar_K$ per analysis and a typical precision of about 1%. In contrast, sample SKND-1 contained much less muscovite, and crystals were generally less than 0.5 mm in diameter, with the result that uncertainty in individual analyses tends to be several times greater for this sample. Representative photomicrographs of crystals from each sample along with complete data tables for monitors, and representative analyses of air and analytical blanks, are presented in the data repository.

3. Results and Interpretations

3.1. Laser Single Crystal $^{40}Ar/^{39}Ar$ Age Determinations

[14] The samples collectively show a considerable spread of muscovite ages (circa 11 Ma to 516 Ma; see Figure 3 and Data Set S1) as would be expected for sediments derived from terranes of complex history or various sources. All fifty-nine of the single muscovite crystals analyzed from Beani Bazar (BB 1–11) are younger than 70 Ma, with conspicuous modes at circa 26, 22, 18 and 16 Ma (Figure 3). Roughly half of the BB 1–11 muscovite analyzed yielded ages of circa 15–17 Ma. Sample SKND 1–20, collected far to the south in the Chittagong Hills (the more distal local seems also to be reflected in the finer grain size of this muscovite) yields ages generally similar to those from BB-11, with the addition of three single-crystal ages of circa 40 Ma. Note that BB 1–11 and SKND 1–20 were collected from present-day depths in the basin that are roughly comparable (~3408 and 2793 m, respectively). The remaining two samples are from the single Fenchuganj core, drilled close to the location of BB 1–11, but from considerably greater depth. Most of the ages obtained in FG 2–18 (~4540 m) are between 20 and 40 Ma, and three of the twenty analyses were for crystals from a pre-Cenozoic source with ages greater than 100 Ma. Similarly, most of the ages for FG 2–22 (~4721 m) are between about 20–40 Ma, but with a higher proportion of older ages and six of the thirty with ages greater than 100 Ma.

[15] Muscovite ages of 38 to 40 Ma may correspond to an “Eocene-Himalayan” source [e.g., see *Hodges et al.*, 1994]. Twelve out of 145 fusion dates for the lower Miocene Bhuban sandstones are between 50 and 550 Ma. It seems likely that these earlier stratigraphic sequences had source terranes that include lithologies as old as the Cambrian rocks of the Lesser Himalayas [e.g., *DeCelles et al.*, 2004].

[16] The majority of the samples, however, yield age modes that are indicative of orogenic belts of the Himalayas and possibly the Indo-Burman ranges. The Indo-Burman ranges are made up mainly of Cretaceous to Eocene pelagic strata overlain by thick Eocene to Oligocene turbidites and upper Miocene to Pleistocene molasse (Figure 1) [*Brunnschweiler*, 1966]. At the present level of erosion, white mica $^{40}Ar/^{39}Ar$ ages of the High Himalayan Crystalline rocks and the south Tibetan Himalayas cluster between 13.7 and 25 Ma [e.g., *Guillot et al.*, 1994; *DeCelles et al.*, 2004]. The Main Central Thrust (MCT) was active by 24–21 Ma as the MCT hanging wall was deforming at ~22 Ma [*Hubbard and Harrison*, 1989]. *Harrison et al.* [1997] however, suggest a much later (late Miocene) date of deformation. Monazites from graphic schists in the Lesser Himalayas revealed a range of early to mid-Miocene age (15.8–11 Ma) [*Catlos et al.*, 2001]. Cooling ages of detrital muscovites from two catchment areas in Nepal also provided age ranges between 11 to about 20 Ma, having the upper ages that drained from the top of the Higher Himalayas and the Manaslu Granite [*Brewer et al.*, 2006]. Fission track and U/Pb studies provide evidence for widespread cooling in the Nepalese Himalaya at about 16.0 ± 1.4 Ma, that is likely related to a combination of tectonic and erosional

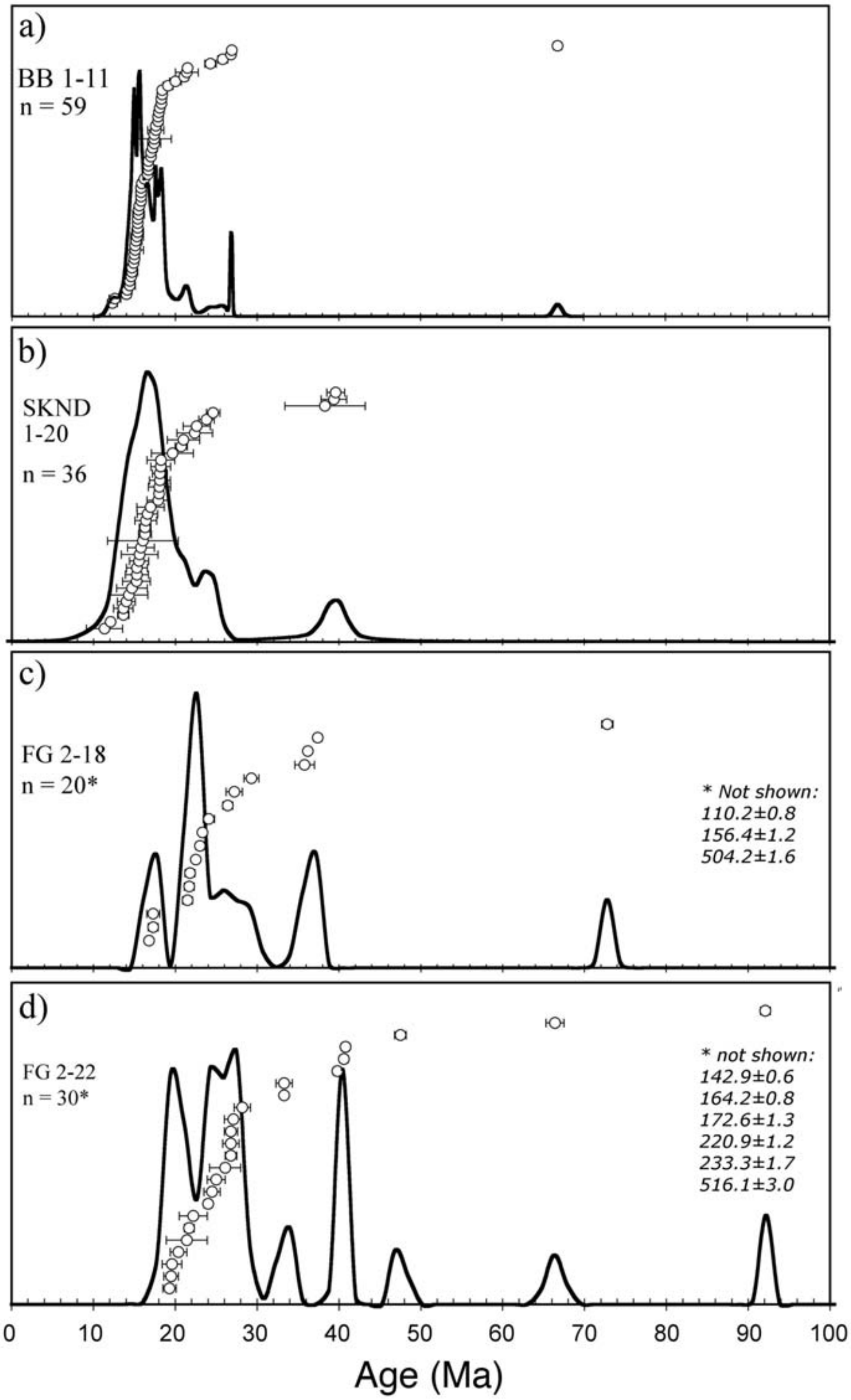

Figure 3. Frequency and probability plots for $^{40}Ar/^{39}Ar$ ages of muscovite crystals analyzed in this study. (a) Muscovite crystals from the Beani Bazar (BB 1–11) core (depth 3408 m approximately 4018 m) are typically younger than 28 Ma, with prominent modes at circa 16 and 18 Ma. Two to three times as many muscovite crystals were separable from this relatively coarse grained, muscovite-rich sandstone than the other study samples. (b) Muscovite crystals from the Sitakund core (SKND-1-20) (depth 2793.7 m to 2799.9 m) vary considerably, but with a single mode at circa 16 Ma. This is the only sample collected from the southeast Bengal basin. (c) Muscovite crystals from the upper core sample from Fenchuganj (FG 2–18) (depth 4540 m to 4549 m) vary considerably, with modes at ~16 and 22 Ma, and about one fourth of the crystals yield ages older than 40 Ma. (d) Muscovite crystals from the lower core sample from Fenchuganj (FG 2–22) (depth 4721 m to 4730 m) vary more than the other samples, with ages generally older than 18 Ma, and about one third of the crystals yield ages older than circa 40 Ma.

activity, including movement on MCT and Southern Tibetan Detachment System [*Bernet et al.*, 2006; *van der Beek et al.*, 2006]. Many of these tectonic units may potentially have contributed to the Bengal basin detritus used in this study. *Copeland et al.* [1995] studied the rocks of the Gangdese batholith in the southern Tibetan plateau (Figure 1) and found crystallization ages in the range of 94 to 42 Ma. The plutonic rocks of the Gangdese batholith, comprising granite, granodiorite, and tonalite, have a range of crystallization ages from ~120 to 40 Ma [*Harris et al.*, 1988]. The batholith also shows two distinct periods of plutonism that are broadly 120–90 and 70–40 Ma [*Copeland et al.*, 1995]. *Chung et al.* [1998] found evidence for tectonic and magmatic activity in the Tibetan plateau (as recorded by potassic volcanic rocks) from 30 to 40 Ma.

[17] Among all four study samples, more than one-third of the ages are circa 16–18 Ma suggesting rapid uplift and denudation of Lesser and Higher Himalayan rocks. One prominent candidate for a source of muscovite with this age is the Sikkim Himalayas along the Main Central Thrust [*Harris et al.*, 2004]. *Harris et al.* [2004] document 11–7 kbar of decompression in the high-grade crust of Sikkim Himalayas (just north of the Bengal basin; marked "Si" in Figure 1) in the 7 m.y. interval from 23 to 16 Ma. This may imply that the ~16–18 Ma micas in the Bhuban Formation could be from Sikkim-Darjeeling area, and also implies that the remaining 7 kbar over those source rocks was removed before their Miocene erosion and deposition in the Bengal basin. This implies that the denudation rates in the Himalayas during the middle Miocene were extremely rapid. High uplift and erosion rates of 2.2 to 8.3 mm/yr with an average of 5.5 mm/yr are known from Taiwan [*Fuller et al.*, 2003]. Similar average rates of erosion have also been determined in the Nanga Parbat, the western syntaxis of the Himalayas [*Zeitler et al.*, 2001]. As the lower Miocene (~25 to ~11 Ma) sediments in the Bengal basin show a dominance of 16–18 Ma muscovite grains, the uplift and exhumation rates during the lower Miocene in the eastern Himalayas seem to be comparable to rates determined for Taiwan and the Nanga Parbat.

[18] An alternative scenario with more moderate rates of exhumation may be indicated if the Bhuban stratigraphy and our study samples are not as old as previously suggested. An upper Miocene to Pliocene age for the Bhuban sediments would imply that significant time had elapsed between the episodes of cooling and subsequent sedimentation of mica grains in the Bengal basin. Compositional study [*Uddin and Lundberg*, 1998] of these sandstones suggests the first substantial presence of sedimentary and low-grade metamorphic assemblages (orogenic) following a predominance of quartzarenites in the Oligocene. Denudation and the earliest orogenic sediments are reflected in the Bhuban Formation of the Bengal basin. Paleodrainage systems (like the paleo-Ganges and paleo-Brahmaputra) had developed by the Miocene time to carry clastic wedges from the uplifted Himalayas to the Bengal basin [*Lindsay et al.*, 1991; *Uddin and Lundberg*, 1999]. The stratigraphic position of the Bhuban Formation between the Oligocene Barail and middle-to-upper Miocene Boka Bil Formation, along with palynological, paleontological, compositional study and orogenic history of the eastern Himalayas suggest that this stratigraphic unit is post-Oligocene and most likely, belongs to lower-to-middle Miocene age [*Khan and Muminullah*, 1980]. Thus, we interpret the predominance of 16–18 Ma ages for detrital muscovite in this study to reflect increased erosion of Himalayan sequences, perhaps in the same event that caused deep crustal decompression in the crystalline rocks of the Sikkim area [*Harris et al.*, 2004]. This study reveals abundance of 16–18 Ma muscovite grains from all three wells in northeast to southeast side of the Bengal basin. Based on subsurface facies data, *Uddin and Lundberg* [1999] proposed major sediment plume systems draining in these two areas from northeast India (Figure 1). These two sediment flow path might have represented separate distributary networks of a major Miocene delta located at the eastern part of the Bengal basin. The predominance of 16–18 Ma muscovite in these two separate geological provinces more than 350 km apart suggest that denudation, transportation and depositional phases were broadly synchronous, and that detrital geochronology can be used as an effective tool in evaluating stratigraphic ages in these foreland basins system where continental depositional facies preclude assemblage of key dateable fossils. Our ability to interpret the data distributions for these samples is somewhat compromised by the maximum number of crystals we could obtain for analysis from these limited drill core samples, and thus the differing numbers of analyses presented. However, it is clear (Figure 3) that the minimum radiometric detrital age for each sample, and the overall distributions of ages, tend to become younger with decreasing stratigraphic level in this study. This relationship is observed better in the FG (FG 2–18 and FG 2–22) samples.

3.2. Discussion of New Detrital $^{40}Ar/^{39}Ar$ Ages in the Context of the Himalaya-Bengal System

[19] Previous $^{40}Ar/^{39}Ar$ age determinations for detrital muscovite from the Miocene Surma Group from the Sylhet trough [*Rahman and Faupl*, 2003] were based on incremental heating of multigrain samples, with resulting age spectra characterized by initial ages of circa 25 Ma increasing to ages of circa 35 Ma for high-temperature increments. Farther south, in a distal section of the Bengal Fan turbidites, *Copeland and Harrison* [1990] found an average age for muscovite grains of circa 30 Ma (range from 23.4 to 88.2 Ma) in stratigraphic sequences of about 13 Ma. Thus, results of previous work can be interpreted to indicate that the average ages of detrital muscovite from the Sylhet trough and from the distal ODP marine sections of the Bengal fan are similar. Both studies have suggested a Himalayan contribution of the detritus. Based on thermochronometry, *Brewer et al.* [2006] show that modern sediment from the Higher Himalayan sequences yield muscovite ages of circa 4–10 Ma, indicating recent erosion rates of ~2 mm/yr or higher. The present study indicates there was a major influx of sediment to the Bengal basin at circa 16–18 Ma, consistent with the rapid unroofing event deduced by *Harris et al.* [2004] for the Sikkim Himalaya.

[20] Laser $^{40}Ar/^{39}Ar$ dating of individual detrital muscovite crystals from Oligocene and Miocene sequences along the western syntaxial area of the Himalayas have provided average cooling ages between 28 and 22 Ma suggesting that major unroofing of the Himalayas did not start until 28 Ma [*Najman et al.*, 1997]. The circa 25 Ma ages determined in the present study, as well as some older ages suggestive of an Indian craton source, are comparable to those reported by *Najman et al.* [1997]. However, a large

proportion of ages in the present study are much younger (16–18 Ma) than the results reported by *Najman et al.* [1997].

4. Conclusions

[21] Laser $^{40}Ar/^{39}Ar$ age determinations for detrital muscovite from the Bhuban Formation of the Bengal basin generally range from circa 16 Ma to 516 Ma, and thus were derived from a complex terrain or combination of sources that likely include the orogenic belts of the Himalayas, the Indo-Burman ranges, and the Indian craton. The detrital age modes at ~16 and 22 Ma are younger than generally reported in previous studies in the Bengal basin [*Rahman and Faupl*, 2003], Bengal fan [*Copeland and Harrison*, 1990] and in the foreland basins of the western Himalayas [*Najman et al.*, 1997]. The detrital mineral age distributions observed in the Bhuban Formation tend to become younger with decreasing stratigraphic age and to reflect an increasing prominence of Himalayan sources for ~16 Ma and ~22 Ma muscovite grains. The predominance of 16–18 Ma muscovite ages in the stratigraphically highest core samples is consistent with a major episode of unroofing in the interval from ~18–16 Ma as inferred for Himalayan crystalline rocks by *Guillot et al.* [1994] and *Harris et al.* [2004]. Dominance of synchronous $^{40}Ar/^{39}Ar$ dates (16–18 Ma) in all three wells is an indication that denudation, transportation and depositional phases acted essentially simultaneously. This result emphasizes the utility of detrital chronology (and the youngest ages determined for a particular sample) as a tool in evaluating stratigraphic age. Additional work on more samples may be able to provide a greater constraint on much needed basin-wide stratigraphy in the Bengal basin.

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