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The Late Oligocene–Early Miocene Himalayan belt Constraints deduced from isotopic compositions of Early Miocene turbidites in the Bengal Fan

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Abstract

We present a mineralogical and isotopic study of Early Miocene turbidites from the Bengal Fan, which are the oldest sediments recovered during ODP Leg 116. Clay fractions are dominated by illite and chlorite and have low $\delta^{18}O$ (11–16‰). The clays are dominantly derived from a metamorphic precursor by physical erosion, and have undergone only minor low-*T* water–rock exchange and chemical weathering. Sr and Nd isotope analysis of silt and clay fractions and coarse muscovite, biotite and feldspar fractions are remarkably similar to those of the presently exposed High Himalaya Crystalline (HHC) sequence. The data show that a close analogue of the HHC was already subaerially exposed to active erosion during Early Miocene. Rb–Sr data on the biotite separates has been used to evaluate the time elapsed between cooling through the closure temperature for Sr in biotite in the HHC (ca. 325°C) and final sedimentation in the Bengal Fan. Despite the large uncertainties in the initial $^{87}Sr/^{86}Sr$ values of sedimentary mixtures, our estimates of the elapsed time between cooling and deposition are short (4–14 Ma). Assuming a transport time scale ($\leq$1 Ma), deduced exhumation rates are in the same range of modern values (1–3 mm/yr) since ca. 30 Ma. Given that (a) the rocks exposed at the surface, (b) the style of weathering, and (c) rates of exhumation were similar to the present, we infer that the factors controlling erosion of the Early Miocene Himalayan belt were also similar to the present. The data suggest that the Early Miocene Himalayan belt had significant relief and induced orographic effects on precipitation similar to the modern mountain range. It appears that the thrusting along the Main Central Thrust (MCT) or similar structures has uplifted metamorphic basement analogous to the present HHC at sufficiently high rate to maintain steep relief throughout Miocene time, despite high average erosion rates.

1. Introduction

Current ideas about the tectonic and structural evolution of the Himalaya are based in large part on studies of structures, metamorphism and intrusions that have been active or emplaced during the last 25 Ma. A number of studies have evaluated patterns of Himalayan unroofing rates and tectonic style during this interval (e.g., Hubbard and Harrison, 1989; Hubbard et al., 1991; Hodges et al., 1992). However the timing of initiation of crustal thickening and inverted metamorphism through lithospheric thrusts in the Indian plate remains poorly defined. Based on the

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age of detrital sediments, Najman et al. (1994) concluded that Himalaya existed as a mountain range 35 Ma ago, but most pre-Miocene features of the tectonic history have been overprinted by younger deformation and/or metamorphism, or removed by erosion. In this paper we use the sedimentary record of clastic debris from the Himalaya to infer some of the features of Himalayan geology in the earliest Miocene to late Oligocene, an interval for which direct information from outcrop is rare. With this approach, in place of analyzing minerals extracted from a single metamorphic or magmatic sample, we must analyze detrital sediments which are complex mixtures of eroded material. Mineralogy and isotopic tracers of sediments cored in the Bengal Fan during ODP Leg 116 (Fig. 1) have been used to characterize the source and weathering history of eroded Himalayan formations (Bouquillon et al., 1990; Yokoyama et al., 1990; France-Lanord et al., 1993). Geochronological studies of these sediments (Copeland et al., 1990; Corrigan and Crowley, 1990) have constrained unroofing rates and transport time. However, these studies did not focus on the oldest sediments recovered during ODP Leg 116 and the Early Miocene sedimentation in the Bengal Fan remains poorly documented.

In this paper we present new Sr, Nd and O isotopic data from the oldest levels cored in the Bengal Fan during ODP Leg 116 in order to identify the sources of Early Miocene sediments. We also analyzed hand-picked biotite from four distinct stratigraphic levels from ODP Leg 116. Rb–Sr geochronologic data from biotites allow a crude estimate of the Himalayan exhumation rate during the Early Miocene and Late Oligocene. Mineralogical and oxygen isotopic data on clay fractions are used to estimate weathering intensity during erosion and transport. These data constrain the tectonic evolution of the Himalayan belt since the Late Oligocene and the style of erosion and alteration in the Early Miocene in the Himalayan basin.

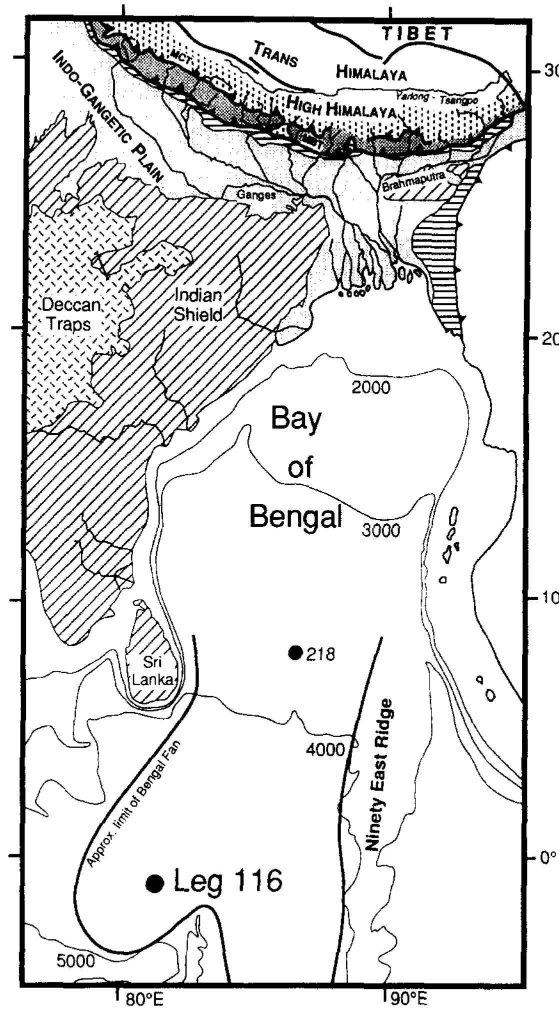

Fig. 1. Location of ODP Leg 116 Sites in the Bengal Basin. Main potential sources of the Bengal Fan turbidites are also shown: Indian shield, Deccan traps and Himalayan range divided in Lesser Himalaya, High Himalaya Crystalline, High Himalaya Sedimentary Series and Trans Himalaya.

2. Age and mineralogy

Sediments of Holocene to Early Miocene age were recovered from the distal Bengal Fan by ODP Leg 116 (Fig. 1). Samples for this study were taken from the bottom of Hole 718C between 800 and 935 m below sea floor (mbsf), the oldest interval cored during Leg 116. The age of these sediments is not well constrained, but a minimum is given by a biostratigraphic pick of 16.2 Ma at 778.8 mbsf (Gartner, 1990). The presence of *Spherolithus heteromorphus* (minimum age ca. 17.1 Ma) near the bottom, and the absence of *Sp. belemnos* (17.4 Ma) suggested that the maximum age of Hole 718C was not older than 18 Ma (Gartner, 1990). Given that these sediments were deposited well below the carbonate compensation depth, it is possible that corrosion of carbonate tests has destroyed such evidence. The nannofossil biostratigraphy is not well-preserved at Site 718, especially below 800 mbsf where only one core recovered calcareous ooze (core 94X). This core shows some bioturbation, and the carbonates are dominantly inorganic (Cochran et al., 1989) and derived from dissolution–recrystallization of biogenic carbonates (Boulègue and Mariotti, 1990). Therefore, it is possible that the upper age limit of 18 Ma for the bottom of Hole 718C estimated from the available nannofossil data is too young. In fact, such a young age requires that sedimentation rates prior to 16.2 Ma must have been significantly higher than the mean rate from 16.2 to 11 Ma of 26 m/m.y. (Curray, 1994). A simple linear extrapolation of sedimentation rates from above the well-defined 16.2 Ma datum suggests an age around 22 Ma for the deepest core of Hole 718. Curray (1994) has recently proposed a similar extrapolation of stratigraphic ages for the distal Bengal Fan based on sedimentation rate evolution. Thus, while the stratigraphic age of the lowest sediments recovered in Hole 718C is uncertain, we take 20–22 Ma as a working 'best' estimate.

All the analyzed samples are silt or clayey silt from facies I of Stow et al. (1990). The mineralogy of both the coarse fraction and silt is dominated by quartz, feldspar, micas and vermiculite, which is very similar to that of younger sediments (Bouquillon et al., 1990). The heavy mineral fraction contains metamorphic minerals including garnet and epidote (Yokoyama et al., 1990). X-ray diffraction data from <2 μm size fractions show little variation, with a typical analysis yielding 25% chlorite, 45% illite, 10% mixed layers, 12% smectite and 8% kaolinite.

3. Methods

Monomineralic separates were prepared from cored material by gently desegregating samples in distilled water and hand-picking grains. Silt (2–50 μm) and clay (<2 μm) fractions were separated by cation exchange resin dispersion and flocculation following procedures described in Bartoli et al. (1991). All fractions used for Sr and Nd analysis were leached with 10% acetic acid to remove biogenic carbonate and adsorbed cations. Chemical separations were performed as described in Michard et al. (1985). Isotopic compositions were measured on a Finnigan-MAT 262© in static mode (CRPG, Nancy). Sr isotopic ratios were normalised to $^{86}Sr/^{88}Sr = 0.1194$, mean value of NBS-987 = 0.710180 during period of analysis. Nd isotopic ratios were normalised to $^{146}Nd/^{144}Nd = 0.7219$, mean value of La Jolla Nd std. = 0.511857 during period of analysis. Because of small sample sizes (<2 mg) of the biotite fraction, total chemistry blanks were measured routinely along with samples. Sr blanks were 200–300 pg, and the isotopic composition of blanks was 0.709–0.715. Nd blanks were ~60 pg. Rb/Sr ratios and Sr isotopic compositions of biotites have been corrected using the blank measured during the period of analysis. Oxygen from silicate sites on clays were extracted by fluorination following the technique of Clayton and Mayeda (1963). CO_2 gas was analyzed on a VG 602D mass spectrometer and results are expressed with respect to V-SMOW. All extractions were duplicated and average reproducibility is ±0.3‰.

4. Sources of Early Miocene sediments

Nd and Sr isotopic data from a variety of mineral phases and grain size fractions yield results that are essentially identical with those obtained from higher stratigraphic levels in the Bengal Fan (Table 1, Fig. 2). For the silt and clay fractions, $^{87}Sr/^{86}Sr$ ratios corrected to the biostratigraphic age of deposition (Sr^*) are between 0.733 and 0.756. ε_{Nd} values range from -14.3 to -16.8-(correction of ε_{Nd} to the age of deposition is a trivial change for sediments this young). Monomineralic separates (muscovites and feldspars) yield Sr^* ratios from 0.725 to 0.775, with ε_{Nd} from -14.7 to -17.8. Silt and clay fractions have systematic differences, with lower Sr^* ratio, and higher Sm/Nd ratios and ε_{Nd} in clay than in silt.

The major lithologic groups in the modern Himalaya (Lesser Himalaya – LH; High Himalaya Crystalline – HHC; Tibetan Sedimentary Series – TSS) define distinct domains in Sr^*–ε_{Nd} space (Fig. 2). Sr and Nd isotopic compositions of the oldest (Early Miocene) sediments from the Bengal Fan are similar to those of the present HHC and recent sediments. The data imply that a Miocene analogue of the HHC was already exposed to erosion by 20 Ma, and further was the dominant source of sediments delivered to the Indian Ocean (Fig. 2). These results, along with those of France-Lanord et

Table 1
Isotopic data from Early Miocene sediments (ODP Site 718C) and feldspar separates from all the ODP Leg 116 sites

Sample	Fraction	Depth (mbsf)	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{143}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}	$\delta^{18}O$ SMOW (‰)
Hole 717C												
2H1.80-81	*F*	*16*	*155*	*110*	*2.01*	*0.74874*						
2H1.80-81	F	16	142	122	2.45	0.74452	1.7	0.3	0.114	0.511753±11	−17.3	
84X2.101-103	*F*	*763*	*139*	*83*	*1.69*	*0.73554*						
Hole 718C												
49X1.66-67	*F*	*466*	*104*	*43*	*1.17*	*0.73330*						
79X CC27-28	*F*	*760*	*39*	*28*	*2.04*	*0.75999*						
80X1.36-37	2–50 μm	762	60	104	4.94	0.75668	19.8	3.7	0.119	0.511780±14	−16.7	
80X1.36-37	<2 μm	762	65	279	12.10	0.73849	38.5	8.0	0.131	0.511899±10	−14.41	15.8
87X2.30-31	2–50 μm	830	56	83	4.24	0.75494	21.0	3.9	0.117	0.511818±5	−16.0	
87X2.30-31	<2 μm	830	62	289	13.17	0.75265	32.3	6.2	0.122	0.511885±7	−14.7	11.3
88X4.30-31	2–50 μm	842	65	148	6.49	0.75767	25.8	4.7	0.116	0.511834±5	−15.7	
88X4.30-31	<2 μm	842	63	223	9.99	0.73603	34.5	6.9	0.126	0.511898±7	−14.4	
89X CC13-14	2–50 μm	855	65	91	3.97	0.75307	32.3	5.9	0.116	0.511796±14	−16.4	
89X CC13-14	<2 μm	855	68	237	9.87	0.74161	37.5	7.4	0.124	0.511906±7	−14.3	
89X CC13-14	F	855	40	36	2.56	0.75269	7.6	1.5	0.122	0.511276±7	−17.8	
90X2.44-45	2–50 μm	858	65	104	4.58	0.75085	29.4	5.3	0.114	0.511778±15	−16.8	
90X2.44-45	<2 μm	858	80	217	7.64	0.73683	46.1	8.7	0.120	0.511873±12	−14.9	
96X1.31-32	Mu	908	70	339	13.83	0.77921	2.0	0.4	0.138	0.511794±30	−16.5	
97X CC10-11	2–50 μm	925	64	111	4.86	0.75175	20.4	3.8	0.119	0.511816±8	−16.0	
97X CC10.11	<2 μm	925	62	234	10.70	0.74060	35.9	6.7	0.118	0.511895±10	−14.5	12.3
97X CC10-11	F	925	79	33	1.19	0.72534	10.9	2.1	0.125	0.511821±7	−15.9	
97X CC10-11	Mu	925	172	276	4.54	0.73464	3.9	0.7	0.116	0.511847±12	−15.4	

Notes: Mu = muscovite, F = feldspar, 2–50 μm: silt fraction and <2 μm: clay fraction. Data in italics are from Bouquillon et al. (1990).

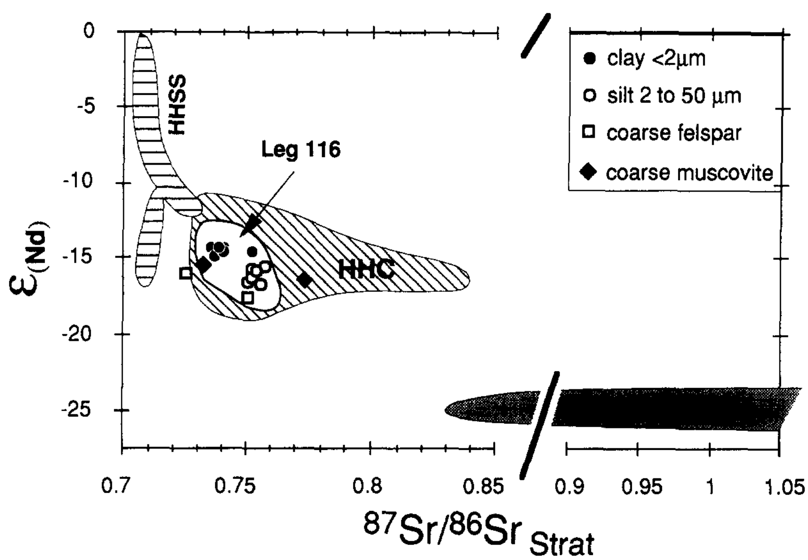

Fig. 2. Sr and Nd isotopes compositions of Early Miocene silt, clay fraction, coarse muscovite and feldspar compared to fields of major Himalayan formations and Middle Miocene to Holocene sediments recovered in ODP Leg 116 (France-Lanord et al. (1993) and references therein). Early Miocene sediments have the same source than the younger ones which is a close analogue of the present High Himalaya crystalline.

al. (1993) imply that the sediment provenance has changed little since ca. 20 Ma.

These conclusions are somewhat at odds with those reached by heavy mineral provenance studies. Yokoyama et al. (1990) and Amano and Taira (1992) argued that the 17–15 Ma interval was dominated by detritus derived from the Lesser Himalaya. While there is an apparent increase in some types of heavy minerals possibly derived from this unit (garnet, epidote), such an increase itself does not imply a major change in provenance. It merely requires that some part of the Lesser Himalaya underwent significant erosion during this interval. Erosion rates are presently very heterogeneous in the Himalaya (e.g., Zeitler, 1985), and almost certainly always have been (Copeland et al., 1987; Copeland, 1993). An interpretation based on the relative abundance of heavy minerals alone does not satisfy the requirement of isotopic mass balance in the sediment mass, and is not consistent with other evidence (see discussion by Copeland (1993)).

While the Sr and Nd values for all samples are within the range defined by the HHC, slight and systematic differences exist between isotopic compositions of silt and clay fractions. Clay fractions (<2 μm) have slightly lower Sr^* and higher ε_{Nd} than the coarser fraction. There are several possible sources of this heterogeneity. Variations in the relative proportion of minor sources between the different fractions is one possibility. For instance, a 10% LH contribution in silt fraction would reduce ε_{Nd} by 1 to 2 units and increase the Sr^* ratio by 0.008 to 0.100. Variation of mineralogical composition could also introduce a shift of isotopic composition between different size fractions. Pedogenic minerals (vermiculite, smectite, kaolinite) are more abundant in clay fractions than in silts. These secondary minerals have their Sr in equilibrium with surface waters of the Indo-Gangetic flood plain, where dissolved Sr derived from carbonate dissolution is important (Krishnaswami et al., 1992). Consequently,they typically have lower Sr^* ratios than the 'primary' mineral assemblage (Derry and France-Lanord, 1996) and 20 to 30% of smectite/vermiculite with an Sr^* ratio of 0.720 would account for the observed contrast. However, this cannot account for ε_{Nd} variations (e.g., Goldstein, 1988). The detailed suite of analyses of isotopic and elemental compositions of different size fractions throughout the Leg 116 cores defines the presence of a small component with low Sr^* and high ε_{Nd} found in the <2 μm fraction (Derry and France-Lanord, 1996). The source of this component has not been uniquely identified, but it is probably derived from weathering of volcanic rocks from either the Deccan traps or the volcano-detritic series from the Himalaya such as the Giumal formation. A small amount of this component (ca. 10%) in the <2 μm fraction is sufficient to account for the observed difference in Sr and Nd isotopic compositions between silt- and clay-sized fractions, while accounting for only ca. 1% of the total sediment volume of the fan. We emphasise that the isotopic variability between size fractions is relatively small compared to the difference between possible end member sediment sources. The Nd and Sr data from all size fractions are consistent with the HHC or closely analogous unit as the dominant source of sediment in the Early Miocene. We infer that by the time of deposition of the oldest strata recovered on Leg 116, rocks with isotopic systematics very similar to the modern HHC were already subareally exposed and undergoing rapid erosion.

$\delta^{18}O$ measurements from clay (<2 μm) separates are 11.3 to 15.8‰ (Table 1). These values are only slightly shifted from unaltered Himalayan micas (typically 8 to 10‰, after France-Lanord et al. (1988)) from igneous and high-grade metamorphic units. $\delta^{18}O$ values in clays equilibrated during weathering typically are ≥20‰, depending on the source of water in the weathering environment. Some stratigraphically higher units in the Bengal Fan sequence contain abundant smectite and kaolinite, have $\delta^{18}O$ of 17.7 to 22.6‰, and are interpreted to have undergone extensive floodplain weathering (France-Lanord et al., 1993). In the oldest Bengal Fan sediments, the slight increase in $\delta^{18}O$ from unaltered micas to clays is caused by the presence of a small component of weathering products with heavy $\delta^{18}O$ values in the <2 μm fraction. The XRD data from Early Miocene <2 μm samples typically show 15 to 25% kaolinite±smectite, which is consistent with this interpretation. Thus even in the fine (<2 μm) fraction, most of the Early Miocene material is derived from high-temperature metamorphic sources and has undergone relatively little low-temperature alteration during weathering and transport.

5. Oligocene–Miocene exhumation rate of the Himalaya

In an attempt to establish rates of exhumation of the Himalaya during the Early Miocene, biotite separates from bottom of Hole 718C, Hole 717C were analyzed for Rb and Sr isotopes (Table 2 and Fig. 3). Biotite separates of similar sizes prepared from a paragneiss sample taken from outcrop in the HHC (NL 59, France-Lanord et al. (1988)) were also analyzed as a control for the effects of blank corrections and uncertainty in initial $^{87}Sr/^{86}Sr$ ratio. The samples from the Leg 116 cores were each hand-picked from a single 1 cm interval of core, and thus represent a very short time interval of sedimentation. Despite the small size of these samples (0.5 to 2 mg) blank corrections were small, and do not introduce a significant error for the proposed interpretation. These biotite samples were also analyzed for Nd isotopes (Table 2). All compositions fall in the range of Nd data from Leg 116 (France-Lanord et al. (1993); Table 1) which imply that the coarse biotites are derived from the same sources as the other material in the sediment.

In order to determine cooling ages from the Rb–Sr systematics of biotite separates, it is necessary to know the initial Sr isotope ratio $(^{87}Sr/^{86}Sr)_i$ of the biotites. However, our samples are composed of

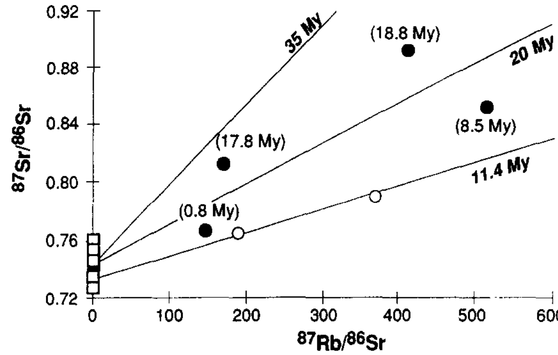

Fig. 3. Rb–Sr isochron graph of coarse biotite separates (•) from several stratigraphic ages (indicated into bracket) in ODP Leg 116. Feldspar separates (□) data indicate a range of Sr_i of the source rocks of the biotites. The isochron lines were calculated using an Sr_i of 0.743. Two aliquots of biotite from HHC paragneiss (○) show the accordance of data even for small samples (1–2 mg). The actual isochron includes whole-rock analysis from Deniel et al. (1986).

50 to 500 grains of biotite, each from a distinct source rock of unknown and variable initial Sr isotope ratio. Two points suggest a resolution of this problem. First, each biotite separate can be considered as an average of the multiple sources. The mean $^{87}Sr/^{86}Sr$ ratio obtained on multiple feldspar separates (0.743 ± 0.012; Table 1) gives a reasonable estimate of the initial $^{87}Sr/^{86}Sr$ ratios associated with these biotite separates. Secondly, the large error

Table 2
Rb–Sr and Sm–Nd isotope data for biotite separates

Hole	717	717	718	718	NL 59	NL 59
Core/Sec.	20X 01	82X 01	86X 02	88X CC		
Interval	76–77	24–25	102–103	"9–10"		
Depth (mbsf)	151.3	740.74	820.8	844.7		
Strat. age (Ma)	1	8.5	18.5	18.8		
Nd (ppm)	3.2	17.3				48.1
Sm (ppm)	0.6	2.4				
$^{143}Nd/^{144}Nd$	0.511890	0.511784	0.511812			0.511838
±	0.000024	0.000015	0.000023			0.000009
ε_{Nd}	−14.6	−16.7	−16.1			−15.6
Sr (ppm)	13.8	5.2	11.5	3	1.3	6.3
Rb (ppm)	710.5	926.4	680.6	409.8	168.8	412
$^{87}Rb/^{86}Sr$	149.9	518.2	172.4	414.5	369.7	191.1
$^{87}Sr/^{86}Sr$	0.7654	0.8509	0.8121	0.8906	0.7897	0.7654
Age[a] (Ma)	10.5	14.7	28.2	25.1	8.9	8.2
±	5.7	1.7	4.9	2.0	2.3	4.5

NL 59 WR from Deniel et al. (1986) gives an $\varepsilon_{Nd} = -15.1$ and $^{87}Sr/^{86}Sr = 0.7331$ which implies an WR/biotite age = 11.4 Ma.
[a] Cooling ages have been calculated assuming $^{87}Sr/^{86}Sr_i = 0.743 \pm 0.012$.

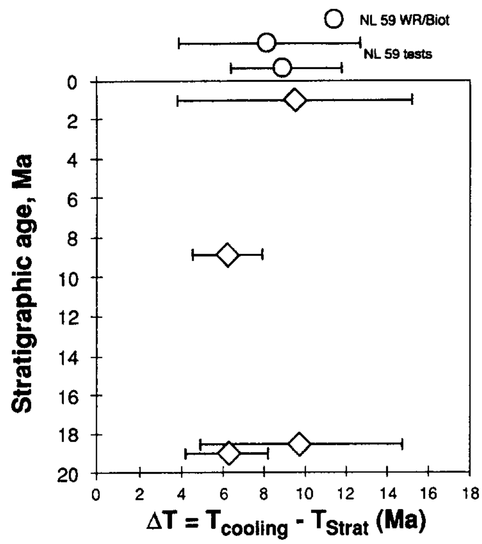

Fig. 4. Exhumation and transport time versus stratigraphic age calculated from Rb–Sr data on biotites. Ages were calculated using $Sr_i = 0.743 \pm 0.012$. Ages obtained for each biotite separate of NL 59 sample are not significantly different from the age calculated from WR/biotite. The larger error bars are due to lower $^{87}Rb/^{86}Sr$ ratios. Despite these uncertainties, the Early Miocene biotites were metamorphosed in a similar way than those actually outcrop in High Himalaya crystalline. The exhumation rate is still high in Himalaya in Late Oligocene/Early Miocene.

due to the uncertainty in the $(^{87}Sr/^{86}Sr)_i$ is to some degree offset by the very high ^{87}Sr enrichment produced in biotites with high Rb/Sr ratios over the time scale of interest. Using our estimate of $(^{87}Sr/^{86}Sr)_i$ obtained from the averaged feldspar data, the ages calculated for each biotite separate from the outcrop sample NL 59 are not significantly different from the age calculated from whole-rock biotite data (Table 2, Deniel et al. (1986)). While the uncertainties in the calculated cooling ages (T_{cool}) for the Early Miocene sedimentary biotites are large, the data indicate that all four biotite samples cooled through their blocking temperatures (300–350°C, Purdy and Jäger (1976)) 4.5 to 14 Ma prior to their biostratigraphic age of deposition (T_{strat}) in the Bengal Fan (Fig. 4).

The interval between the cooling ages and age of deposition ($\Delta T = T_{cool} - T_{strat}$) for the biotite samples comprises the time necessary to unroof and erode the sample (T_{ex}), and the transport time from outcrop to depocenter (T_{trans}). A minimum estimate for total exhumation and transport time ($\Delta T = T_{ex} + T_{trans}$) is given by the $^{39}Ar/^{40}Ar$ dates on single feldspar grains in the Bengal Fan (Copeland and Harrison, 1990). While there was a large spread in single grain ages from any given stratigraphic interval, at all intervals measured there was at least one sample with an Ar cooling age indistinguishable from the biostratigraphic sedimentation age in the fan. Thus, at least some material was exhumed and delivered to the fan on a time scale less than the combined uncertainties in the Ar thermochronology and the biostratigraphy ($\Delta T \leq 1$ Ma in this case). Nevertheless, the mean transport time between the Himalaya and the distal part of Bengal Fan is unknown and probably variable (France-Lanord et al., 1993). Estimates of the residence time of detrital zircons in the Indus River (Cerveny et al., 1988) and K-feldspars in Tsangpo River (Copeland and Harrison, 1990) are less than 1 Ma. However, this period corresponds only to the riverine part of the transport cycle and does not include residence in intermediate basins or transport by submarine turbidity currents. Pinet and Souriau (1988) used a global compendium of various hydrologic and geomorphologic parameters to model the erosional cycle. Using their model, the transport time scale of the present Ganga–Brahmaputra basin is estimated at ca. 2–2.5 Ma. These various estimates collectively suggest that the mean transport time is currently not negligible, but still relatively small compared to the time scale of exhumation. Biotite separates of different stratigraphic age yield comparable results for ΔT, suggesting that the interval between metamorphism and subaerial exposure due to erosion±tectonic denudation has been broadly similar since Late Oligocene time. Zeitler (1985) proposed several models of geothermal gradient for the Himalaya using a monotonic increase of temperature with depth for temperatures lower than 350°C (also shown by Hodges and Silverberg (1988) and estimated a thermal gradient of 31°C/km. If the transport time is taken as ≤1 Ma, the exhumation time scale can be estimated as $T_{ex} \approx \Delta T - 1$. For a geothermal gradient of 31°C/km the average exhumation rate of material later deposited as sediment in the Bengal Fan was of the order of 1 to 3 mm/yr.

6. Exhumation styles in the Himalaya since Late Oligocene

The sedimentological and geochemical data from the Bengal Fan show several close similarities between the Early Miocene erosional system and that of the present day. Specifically, (1) the primary provenance for both Early Miocene and recent sediments was the HHC or a geochemically analogous unit, (2) the degree of weathering of both Early Miocene and recent sediments are anomalously low compared to other deep sea clastics, and (3) mean rates of exhumation in the Early Miocene were comparable to present rates. However, these similarities do not necessarily imply that Himalayan tectonic activity during the Miocene was directly comparable to the present. For example, during the Early Miocene, north-directed low-angle normal faulting was active and responsible for a significant part of the exhumation of the HHC metamorphic rocks (Pêcher, 1991). Hodges et al. (1992) have estimated that movement along the Southern Tibet Detachment Zone (STDZ) resulted in a minimum tectonic unroofing rate of 2 mm/yr between 22 and 19 Ma. Such movement would be sufficient to exhume rocks that were at 350°C within 6 Ma without any additional erosional unroofing. If this local estimate is extrapolated to the whole Himalaya and if average Early Miocene total exhumation rates did not exceed ca. 3 mm/yr, then erosional denudation must have been relatively less important than at present. However, the rate of deposition in the Bengal Fan and the prevalence of physical erosion versus chemical weathering imply that during Miocene, exhumation was not only due to tectonic unroofing. Biostratigraphic uncertainty for the Early Miocene sediments may also mean that calculated ΔT values are too long, if the actual sedimentation ages are older than estimated. Older sedimentation ages would imply increased total exhumation rates, and increased erosion rates (non-tectonic denudation). The fact that the Bengal Fan had prograded to 1°S in the Indian Ocean, 2500 km south of the current mouths of the Ganges, by the Early Miocene, suggests that erosion and sediment transport were significant in Late Oligocene–Early Miocene time (Curray, 1994).

Another source of uncertainty in comparing biotite cooling histories from Early Miocene and Quaternary or Recent sediments is that the sedimentary biotite mixtures integrate variations in exhumation history over the previous several million years. For example, it is likely that between 7 and 1 Ma the erosion rates were lower than the present ones (Burbank et al., 1993; France-Lanord et al., 1993; Derry and France-Lanord, 1996). Thus, estimates of ΔT and exhumation rates obtained from biotites in late Quaternary sediments may be lower than Recent exhumation rates in the Himalaya. Based on the modern erosional load of the Ganges–Brahmaputra (1.9×10^9 ton/yr, Summerfield and Hulton (1994)) and assuming that 80% is derived from the HHC, the current erosional denudation rate is 5 ± 2 mm/yr. The uplift estimated by topographic levelling measurements (Jackson and Bilham, 1994) is around 5 ± 1 mm/yr. Thus short-term late Quaternary erosion rates appear to be higher than long-term Plio-Pleistocene or Early Miocene averages as recorded by the Rb–Sr systematics of detrital biotites. A better knowledge of the sedimentation rates in the Bengal Fan, along with data on exhumation rates (such as zircon fission track) that is integrated over shorter time intervals, are necessary to examine the relative proportion of erosion and tectonic denudation with time.

7. Conclusions

Nd and Sr isotopic data show that Early Miocene detrital sediments from the Bengal Fan are dominantly derived from an analogue of the present High Himalayan Crystalline sequence. Clay mineralogy and oxygen isotope data indicate that erosion processes were sufficiently dynamic to allow physical erosion to strongly dominate over chemical weathering. Rb–Sr model ages of detrital biotite separates imply that the time scale of exhumation from depths of 10–11 km and transport of material from the source area to the Bengal Fan has been 6 to 10 Ma since Oligo-Miocene time. These rates are consistent with mean exhumation rates of 1 to 3 mm/yr. at all intervals examined here. Because the detrital biotite Rb–Sr systematics integrate over a time scale of several million years, they do not provide a history of specific tectonic events in the Himalaya. Rather they demonstrate that the processes of metamorphism and rapid exhumation were initiated at least by the Late Oligocene, and have had comparable rates since. A Late Oligocene age for metamorphism and rapid exhumation is consistent with other evidence for activity of the Main Central Thrust by that time (Le Fort, 1986; Harrison et al., 1992). Rapid erosion rates in high grade metamorphic rocks (similar to the modern HHC) recorded in the Bengal Fan during the Early Miocene also implies that the Himalaya front range had already developed considerable relief. The evidence for a high and actively eroding Himalayan range by the Early Miocene has some implications for models of the development of the Tibetan Plateau, and requires an early age for the development of crustal thickening in the region. Sedimentary evidence for the initiation of Himalayan metamorphism and denudation is to be found in deeper parts of the Bengal Fan and foreland basins, where terrigenous sedimentation rates were high since the Late Eocene (Curray, 1994).

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