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Rise of the Himalaya: A Geochronologic Approach

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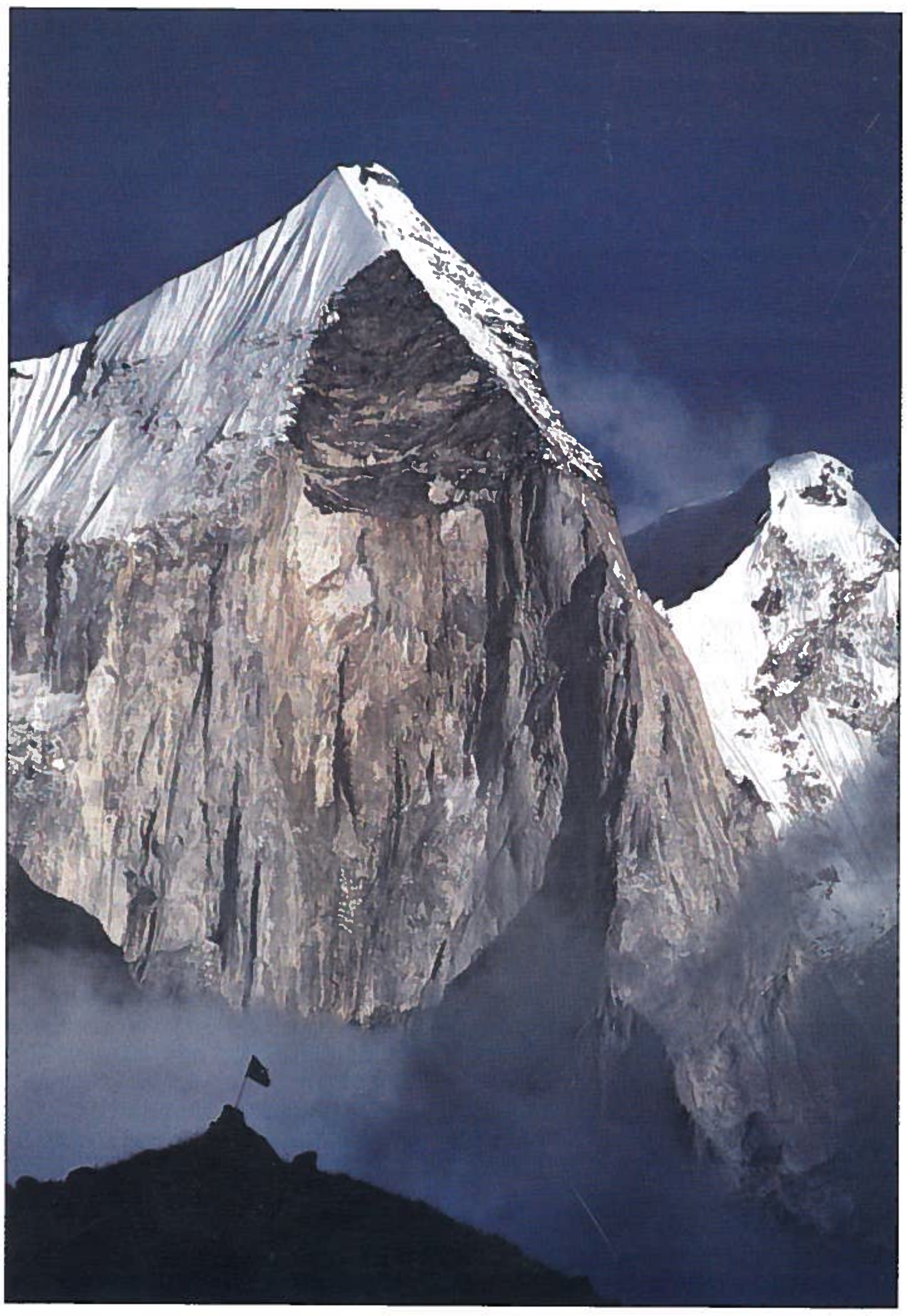

Bhagirathi leucogranite of the Higher Himalaya (Garhwal region, India) intruding the Tethyan sedimentary series. This is one of several postcollisional Tertiary leucogranites of the Himalaya (see Table 1 for the age data). Photos by Mugs Stump.

ABSTRACT

Recent geochronologic and geologic data shed new light on the pattern of tectonic evolution of the Himalaya. Following the continent-continent collision between the Indian and Asian plates in early Tertiary time, the Proterozoic-Cambrian rocks of the leading edge of the Indian plate were reactivated during the Himalayan orogeny. Postcollisional events include a complex history of deformation, metamorphism, plutonism, large-scale thrusting, north-south compression and extension, and the uplift and unroofing of the Himalaya. Hornblende K-Ar and $^{40}Ar/^{39}Ar$ ages from amphibolite-facies Higher Himalayan crystalline (HHC) rocks indicate two regional metamorphic events: one in the Eocene after the collision, and the other in the early Miocene during intense activity of the Main Central thrust. U-Pb (zircon) and Rb-Sr isochron ages demonstrate that postcollisional intrusions of leucogranites occurred in four phases: in the Eocene (50–35 Ma) in the northwest Higher Himalaya; early-middle Miocene (24–15 Ma) in the Higher Himalaya; middle–late Miocene (15–7 Ma), in the northern Himalaya (within the Tethys Himalaya in south Tibet); and 7–2.5 Ma in the Nanga Parbat massif. Different mechanisms probably were responsible for the generation of these leucogranites from the partial melting of the HHC rocks. Most of the leucogranitic intrusions seem to have occurred in the Miocene. Within the Higher Himalaya, compression along the Main Central thrust and extension along the detachment fault between the metamorphic sequence and overlying Tethyan sedimentary sequence (South Tibetan detachment system) occurred simultaneously at least at some point in the early Miocene. Geochronologic and sedimentologic data indicate three prominent phases of uplift-denudation in the Himalaya: early Miocene (21–17 Ma); late Miocene (11–7 Ma) and Quaternary. The early Miocene phase reflects the intense activity of the Main Central trust, the South Tibetan detachment system, a rapid pulse of uplift and denudation of HHC rocks, development of the Siwalik basin, and increase in clastic flux from the Higher Himalaya. The late Miocene phase seems to have encompassed the beginning of the Main Boundary thrust, another major pulse of clastic sediments to the Siwalik Range, and the Indus and Bengal fans, and was coeval with onset of monsoon seasonality. Present seismicity, fission-track analysis, geodetic studies, antecedent river profiles with deep gorges, and enormous sedimentation in the Indo-Gangetic plains, Arabian Sea, and Bay of Bengal provide evidence for the ongoing dynamism, uplift, and unroofing of the Himalaya, expressing its "morphogenic phase."

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INTRODUCTION

The growing interest in the evolution of the Himalaya stems in part from the majestic dimensions of this mountain belt and in part from the unparalleled opportunity it provides for studying continent-continent collisional orogenesis as part of a complex set of processes acting both beneath and on the surface of Earth. The upheaval of the Himalaya represents a significant event in the Cenozoic history of our planet, not only for its geological implications, but also for the impact it has had on the ecology of Asia. Throughout its 2500 km arcuate length, the Himalaya epitomizes the Huttonian tenet of modern geology—dynamism of the solid Earth. Three significant aspects of orogenesis—magmatism, metamorphism, and tectonism—are well illustrated in the Himalaya, where tectonic and erosional forces currently compete, and crystalline rocks that were once deep-seated are now exhumed and occupy lofty levels (Fig. 1—see p. 88).

Following recognition in the context of plate tectonics that the Himalaya is a classic example of continent-continent collisional orogeny (Dewey and Bird, 1970), several models have been proposed for its geologic evolution (e.g., Powell and Conaghan, 1973; Le Fort, 1975, 1989; Molnar and Tapponnier, 1975; Fuchs, 1981; Gansser, 1981; Valdiya, 1984; Molnar, 1984; Searle et al., 1987). Fundamentally, all these plate-tectonic models agree on the northward drift of India in the Mesozoic, the consumption of the Tethyan ocean along the Indus-Tsangpo suture zone in the Cretaceous–early Tertiary, and the India-Asia collision and its attendant compression and deformation in the Cenozoic, giving rise to the Himalaya. However, on a

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detailed scale, disputes on the tectonics are numerous. In this short article, we do not intend to probe the particulars of differing thoughts on the Himalayan orogeny. What we emphasize here is *time,* the essential element not only in understanding the geohistory of the Himalaya, but also in testing the tectonic models. To understand *how,* we must also know *when.* Although the review papers cited above have used some geochronologic data in their discussion, we have attempted to synthesize the age data comprehensively and to analyze them in the light of current discussions on Himalayan geology. These data, together with geologic evidence, suggest an *episodic* uplift-denudation history of the Himalaya throughout Neogene and Quaternary time.

TIMING OF MAGMATISM AND METAMORPHISM IN THE HIMALAYA

The time of continental collision between India and Asia has been estimated to be 65–45 Ma, on the basis of paleomagnetic data from the Indian Ocean, peninsular India, and the Trans-Himalayan magmatic belt. This was not necessarily a synchronous event but perhaps occurred with an oblique geometry, the northwestern part of the Indian plate colliding first around the Cretaceous-Tertiary (K-T) boundary and the collision terminating in the eastern Himalaya toward the end of the Eocene (Patriat and Achache, 1984; Besse et al., 1984; Klootwijk, 1984; Jaeger et al., 1989; Klootwijk et al., 1992; Treloar and Coward, 1991).

The Higher Himalayan crystalline (HHC) rocks constitute the backbone of the Himalaya. Toward the north, the HHC rocks form the basement (infrastructure), which is overlain by Tethyan sedimentary rock. The contact between these has been recognized in places to be an extensional normal fault (the South Tibetan detachment system; Burchfiel et al., 1992). Toward the south, the HHC rocks were emplaced over the Lesser Himalayan sediments in the form of nappes and klippen (i.e., Outer crystalline rocks) along the Main Central thrust (Fig. 1). Available Rb-Sr whole-rock isochrons and U-Pb zircon ages from the HHC and Outer crystalline rocks date back to Proterozoic-Cambrian (Fig. 2), indicating that these rocks belonged originally to the Indian shield, but were reactivated during the Cenozoic Himalayan orogeny.

Postcollisional events within the Himalaya encompass a complex history of deformation, crustal thickening and shortening, metamorphism, leucogranitic intrusion, thrusting of regional dimension, extensional tectonism between the HHC and overlying Tethyan sedimentary rocks, and uplift-denudation of the Himalaya.

The polyphase deformation and metamorphism of the Himalayan package have been reviewed by Thakur (1980), Windley (1983), Le Fort (1986), and Hodges et al. (1989). An important problem has been the timing of regional metamorphism(s) related to the Himalayan orogeny. Amphibolite-facies metamorphism has affected the HHC rocks. Except for their lower parts, which are slightly metamorphosed, most of the Tethyan sedimentary strata have escaped the Himalayan regional metamorphism (Gansser, 1981; Le Fort, 1989). Hornblende K-Ar and $^{40}Ar/^{39}Ar$ ages (with closure temperatures of 500–550 °C) provide time constraints on the metamorphic history of the high-grade HHC rocks (Fig. 3). The ages from Nepal cluster around 20–24 Ma, but those from the northwest Himalaya date back to the Eocene. Treloar and Rex (1990) and Sorkhabi et al. (1992) have suggested that the thermal peak of the Barrovian-type (intermediate pressure and temperature) regional metamorphism in the northwestern HHC rocks predated 40 Ma, and thus took place not long after the continental collision if the metamorphism was related to the India-Asia collision and crustal thickening. On the basis of concordant hornblende $^{40}Ar/^{39}Ar$ and sphene U-Pb ages from an amphibolite, Hodges et al. (1991) inferred that the regional metamorphism in the Nepalese part of the HHC rocks occurred at 22–21 Ma.

These age differences reflect the polymetamorphic nature of the HHC rocks as discussed by Hodges et al. (1989), who distinguished between an early Barrovian-type metamorphism that took place after the collision, and a later regional (essentially Buchan-type [high temperature, low pressure]) metamorphism that occurred during the Main Central thrusting. According to Le Fort (1986), however, the second event was an inverted Barrovian-type metamorphism related to the Main Central thrusting and was followed by a secondary retrograde metamorphism. Obviously more isotopic age data with higher closure temperatures obtained from various parts of the HHC rocks are necessary to detect the signatures of polymetamorphism throughout the Himalaya, and attempts to model the Himalayan metamorphic history based on "age guessing" or "extrapolating age data" from one area to another may be misleading.

Copeland et al. (1991) determined very young (<5 Ma) hornblende, mica, and K-feldspar $^{40}Ar/^{39}Ar$ ages from near the Main Central thrust in central Nepal and have interpreted them to be the result of resetting by hot fluids channeling along the thrust after migrating upward through the Lesser Himalaya, and having originated from the movement in early Pliocene time of the Main Boundary thrust.

Radiometric data have revealed postcollisional timing of plutons in the Higher Himalaya. These two-mica (commonly tourmaline-bearing) leucogranites have high initial Sr and Pb ratios, low Nd isotopic ratios, and a high range of $\delta^{18}O$ (Table 1; Le Fort et al., 1987, and references therein). Nd model ages yield crustal residence times of 1.1 to 2.3 b.y. (Allegre and Othman, 1980). Available age data from central and eastern parts of the Himalaya suggest that the leucogranites, although chemically similar, can be classified into two groups: the Higher Himalaya belt leucogranites (especially those between the Higher Himalayan metamorphic rocks and the overlying Tethyan sedimentary rocks in Nepal), which were emplaced earlier (24–15 Ma); and the northern Himalayan belt leucogranites (within the Tethys Himalaya in southern Tibet, also called the Lhagoi Kangari Belt by Chinese geologists), which yield younger emplacement ages (15–4 Ma).

The origin of the postcollisional leucogranites, although they are volumetrically a minor component of the Himalaya, is controversial. Le Fort (1975, 1986) and Le Fort et al. (1987), concentrating on the central parts of the Himalaya, suggested that the Himalayan leucogranites were generated by partial melting of the Tibetan slab gneisses induced by fluids (H_2O and CO_2) rising from devolatizing footwall rocks during the overthrusting of the hot Tibetan slab over the cold Lesser Himalaya along the Main Central thrust. This widely accepted model, however, seems to be only part of a complicated story. In Pakistan, Zeitler

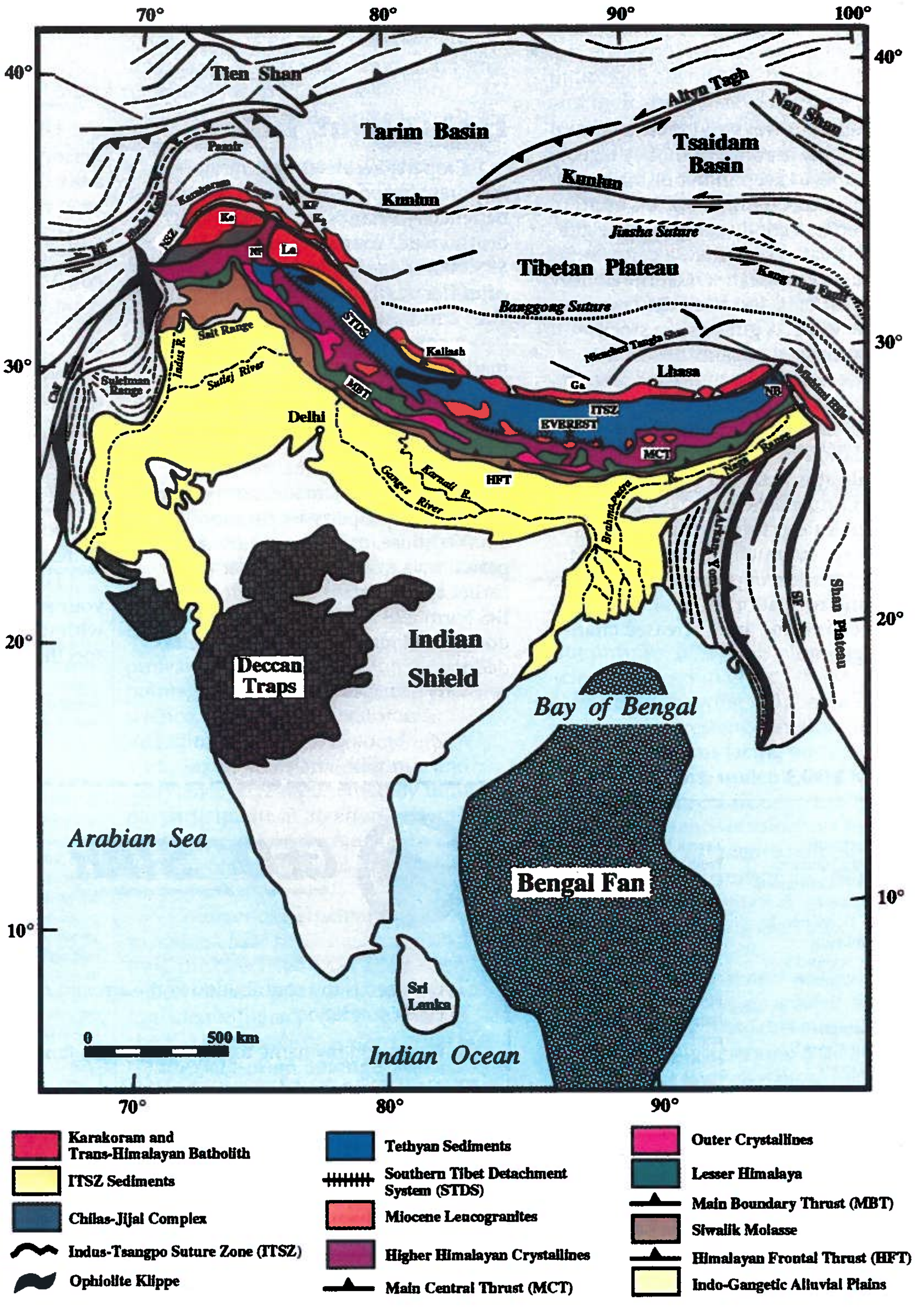

Figure 1. Geologic map and regional tectonic framework of the Himalaya (after Molnar and Tapponnier, 1975; Gansser, 1981; Windley, 1983, and other sources). The Himalaya seems to be the last of a series of collisions of the Gondwana fragments with Eurasia. Older accretions have occurred along the Jinsha and Bangong-Nujiang sutures (e.g., Şengör, 1981). The Indus-Tsangpo suture zone (ITSZ) represents the initial boundary between the Indian and Asian plates, along which the Neo-Tethyan ocean was consumed to give rise to the Trans-Himalayan magmatic arc. The thrust contact between the Himalaya and the ITSZ has been variously called the Main Mantle thrust in Pakistan, the Zanskar thrust in India, and the Gandese thrust system in Tibet. Geologically, the Himalaya is divisible into four longitudinal belts: (1) the Tethys (Tibetan) Himalaya encompassing the shelf and shelf-edge sediments of Neo-Tethys deposited from late Proterozoic–Cambrian to Late Cretaceous–early Eocene time on the passive continental margin of the Indian plate; (2) Higher Himalayan crystalline (HHC) rocks, also called Central crystalline rocks, Great Himalaya, and Tibetan slab, which includes various metamorphic and granitic rocks; the boundary between the HHC rocks and the Tethys Himalaya has recently been found to be a normal fault of extensional mode and shear sense (Pecher, 1991, and references therein), called the South Tibetan detachment system (Burchfiel et al., 1992); (3) the Lesser Himalaya, which comprises sedimentary and low-grade metasedimentary rocks of early Paleozoic and Precambrian age and is separated from the HHC rocks by the Main Central thrust (MCT) system; and (4) the Sub-Himalaya, or Siwalik molasse of middle Miocene to Pleistocene age, separated from the Lesser Himalaya by the Main Boundary thrust (MBT) system to the north, and from the Indo-Gangetic alluvial plains by the Himalayan frontal thrust (HFT) to the south. These morphotectonic units decrease in altitude from north to south, and their thrust boundaries are north dipping. ChF—Chapman fault; Ga—Gandese; HF—Herat fault; KF—Karakoram fault; Ko—Kohistan; La—Ladakh; NB—Namche Barwa (7755 m); NP—Nanga Parbat (8125 m); NSZ—Northern (Shyok) suture zone; SF—Sagaing fault. All the rivers shown have their sources in places close to Mt. Kailash.

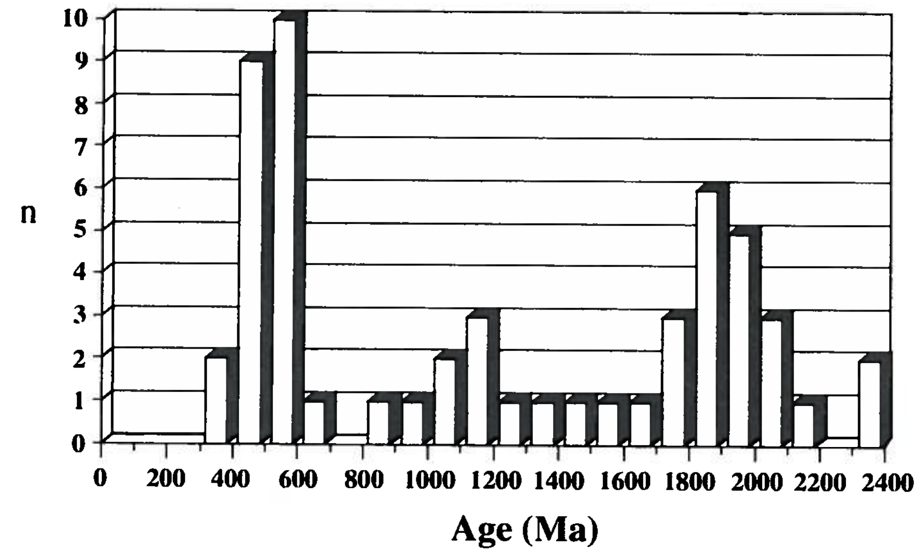

Figure. 2. Histogram of Rb-Sr isochron and U-Pb zircon ages reported in the past two decades from the gneisses and granites of the HHC and their klippen and nappes in the Lesser Himalaya (i.e., Outer crystallines). Rb-Sr ages reported before 1977 have been recalculated using the currently agreed constants. Where more than one age was available for a sample, the latest one was used. Most of these data have been reported from the Indian parts of the Himalaya, and the references are in Bhanot et al. (1980) and Sorkhabi (1991). The ages range from 400 to 2300 Ma, with two distinct peaks—one at 400–600 Ma and the other at 1800–2000 Ma—straddling a slight peak at 1000–1100 Ma. Very high initial Sr ratios point to their derivation from still older continental crust. These ages are similar to those found for the crystalline rocks of the Indian shield (Sarkar, 1980), indicating that the crystalline rocks in the Higher Himalaya and Lesser Himalaya were originally the northerly extension of the Indian shield but were involved in the Cenozoic Himalayan orogeny. The peaks at 1800–2000 Ma and the slight peak at 1000–1100 Ma indicate Precambrian magmatic events. Le Fort et al. (1986) argued that the 500 Ma peak represents a thermal episode that has affected not only the Himalayan edge of India, but also in part most of the other fragments of Gondwana through zones of crustal extension and thinning along which substantial amounts of lower crustal material melted. This episode is part of the Pannotios Cycle of Stump (1987).

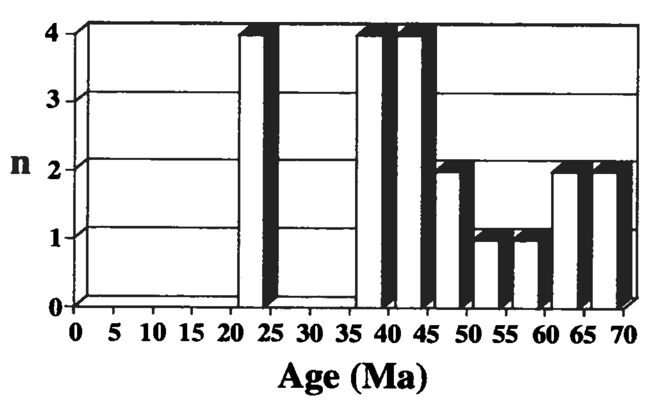

Figure 3. Histogram of hornblende K-Ar and $^{40}Ar/^{39}Ar$ ages from the Higher Himalayan metamorphic rocks (Pakistan, India, Nepal), recording paleotemperatures of 500–550 °C. (Data from Saxena and Miller, 1972; Krummenacher et al., 1978; Maluski and Matte, 1984; Hubbard and Harrison, 1989; Treloar and Rex, 1990; Chamberlain et al., 1991; Sorkhabi, et al., 1992.)

TABLE 1. RADIOMETRIC AGES FROM POSTCOLLISIONAL LEUCOGRANITES IN THE HIMALAYA

Pluton	Method, material*	Age (Ma)	Source†
Pakistan			
Swat	U-Pb (zr)	~35	Zeitler and Chamberlain (1991)
Naran	"	~50	"
Nanga Parbat	"	2.3, 5, 7	"
India			
Zanskar	Rb-Sr (ms)	17 ±0.2	Searle and Frye (1986)
Bhagirathi	Rb-Sr (5 points)	64 ±11	Stern et al. (1989)
	Rb-Sr (minerals)	21.1 ±0.9	
	K-Ar (ms)	18.9 ±1.3	
Nepal–S. Tibet			
Mustang	K-Ar (bt)	15, 24	Krummenacher (1971)
Manaslu	Rb-Sr (7 points)	29 ±1	Hamet and Allegre (1978)
	Rb-Sr (wr-ms; 6 points)	15.3–20.5	Vidal et al. (1982)
	Rb-Sr (11 points)	18.1 ±0.5	Deniel et al. (1987)
	U-Pb (mo)	25	"
	Rb-Sr (ms)	14.9–21.4	"
	K-Ar (ms)	13–16.1	"
	Ar/Ar (ms, bt)	13.3–18.4	Copeland et al. (1990)
	Ar/Ar (ks)	3.4–10.7	"
Makalu-	K-Ar (bt, ms)	14.4–16	Wager (1965)
Lhotse-	K-Ar (bt)	18.7, 19	Krummenacher et al. (1978)
Nuptse-	Rb-Sr (6 points)	92.7 ±9.4	Kai (1981)
Rongbuck	Rb-Sr (bt)	14.1 ±0.2	"
	Rb-Sr (4 points)	52 ±1	Ferrara et al. (1983)
	Rb-Sr (wr-mineral)	13.7–17.3	"
	U-Pb (mo)	21.9, 24	Scharer (1984)
	U-Pb (mo)	22–25	Copeland et al. (1987)
	Ar/Ar (ms, bt, ks)	16.2, 17.1, 16.2	"
	Ar/Ar (ms)	16.5 ±0.4	Hubbard and Harrison (1989)
	Ar/Ar (ks)	15.5 ±1.8	"
	U-Pb (mo)	20.6 ±0.2	Parrish (1990)
	Ar/Ar (ms,bt)	15.3–15.8	Villa (1990)
Bhutan			
Chekha	Rb-Sr (bt)	11, 10	Gansser (1983)
Gophu La	Rb-Sr (bt-ms)	15, 14.4	Ferrara et al. (1985)
	Ar-Ar (orthoclase)	~18	Villa and Lombardo (1986)
SE Tibet–Bhutan			
Lhozhag	Rb-Sr (wr-ms)	15.1, 15.8	Debon et al. (1983)
	K-Ar (ms)	13.3 ±1	Debon et al. (1985)
Kula Kangari	Ar-Ar (bt, ms)	10.7–11.4	Maluski et al. (1988)
South Tibet			
Nyalam	K-Ar (ms)	12, 12.5	Zhang et al. (1981)
	U-Pb (mo)	16.8 ±0.6	Scharer et al. (1986)
	Ar-Ar (ms, bt)	14.8, 16.6	Maluski et al. (1988)
Gabug	Rb-Sr (7 points)	43 ±3	Wang et al. (1981)
	K-Ar (ms)	14.7	"
	K-Ar (ms)	18.4, 20.1	Zhang et al. (1981)
Gyirong	K-Ar (ms, bt)	21.1–20.4	"
North Himalayan Belt (Tibet)			
Gyaco La	K-Ar (2bt-2ms)	13.3 ±0.4	Debon et al. (1985)
	Rb-Sr (wr-bt-ms)	7.1, 8.4	Debon et al. (1986)
Kari La	K-Ar (3wr-3bt)	10.8 ±0.8	Debon et al. (1985)
Maitia (Maja)	U-Pb (mo)	9.8, 9.2	Scharer et al. (1986)
	Ar-Ar (ms, bt)	6.4, 5.8	Maluski et al. (1988)
Lhagoi Kangari	U-Pb (mo)	15.1 ±0.5	Scharer et al. (1986)
	Ar-Ar (ms, bt)	12.3, 10.7	Maluski et al. (1988)
Kung Co	Ar-Ar (ms, bt)	15	"

*bt: biotite; ks: K-feldspar; mo: monazite; ms: muscovite; wr: whole rock; zr: zircon.

†Referenced in Krummenacher et al. (1978); Zhang et al. (1981); Ferrara et al. (1983); Scharer et al. (1986); Debon et al. (1986); Le Fort et al. (1987); Castelli and Lombardo (1988); Maluski et al. (1988); Hubbard and Harrison (1989); Stern et al. (1989); Zeitler and Chamberlain (1991). The scattering of data on emplacement ages is due to the fact that these leucogranites were generated from older crustal material, and thus Pb inheritance in zircon and heterogeneous Sr isotopic ratios make them difficult to date precisely.

and Chamberlain (1991) found two leucogranites of 35 and 50 Ma (U-Pb zircon ages) in the Swat-Nayan region, lying to the west of Nanga Parbat massif, rocks that may have resulted from melting in the lower parts of the crust induced by tectonic thickening of the Indian continental plate as suggested by England and Thompson (1984). Such an origin is consistent with hornblende $^{40}Ar/^{39}Ar$ cooling ages of 45–38 Ma from metamorphic rocks surrounding the leucogranites. Given the similarity in the metamorphic history of the Swat region (Pakistan) (Treloar and Rex, 1990) and the Zanskar region (northwest India, farther east of Nanga Parbat) (Sorkhabi et al., 1992), we suspect that such Eocene leucogranites may also exist in northwest India.

Zeitler and Chamberlain (1991) also found very young leucogranites of 2.3, 5, and 7 Ma (U-Pb zircon) within the Nanga Parbat massif. They have interpreted these to have formed by decompressional melting during rapid exhumation that has affected the Nanga Parbat massif in the past 10 m.y. In fact, as Zeitler and Chamberlain (1991) mentioned (see also Castelli and Lombardo, 1988), it is possible that such a mechanism was partially responsible for the generation of the early–middle Miocene anatectic leucogranites in Nepal—e.g., Makalu and Manaslu—which also cooled and have been exhumed very rapidly, as thermochronologic data show (Table 1). Given the early Miocene age of the South Tibetan detachment system (discussed below) and its prominent role in the exhumation of the HHC, formation of the early to middle Miocene leucogranites appears to be synchronous with the beginning of extension within the Higher Himalaya. Note that these leucogranites are located close to the South Tibetan detachment system (Fig. 1).

EPISODIC TECTONIC-EXHUMATION HISTORY OF THE HIMALAYA

Various geochronologic and geologic evidence indicates that the uplift-denudation of the Himalaya since the continental collision has *not* been a *uniform* event throughout time, but rather has occurred in an *episodic* manner. A synthesis of available information points to the following scenario.

Early Miocene (21–17 Ma) Phase of Uplift-Denudation

This major phase of uplift-denudation has been suggested by several geologists (e.g., Gansser, 1981; Valdiya, 1984) and has been elaborated with geochronologic data emphasizing the formation of the Tibetan plateau by Harrison et al. (1992).

Throughout the Himalaya, during the late Eocene and almost the entire Oligocene, there seems to be a hiatus in sedimentation and the development of laterite and karst surfaces (Wadia, 1975; Powell and Conaghan, 1973; Johnson et al., 1985; Le Fort, 1989). However, starting in early Miocene time, the Murree and Siwalik fluvial sediments were deposited in a basin that formed in front of the rising Himalaya (Gansser, 1981; Johnson et al., 1985). Further evidence for this marked uplift-denudation episode is provided by the stratigraphy of the Bengal Fan—the world's largest—which has been formed increasingly since the early Miocene from sediments derived from the Himalaya (Curray, 1991), the HHC rocks being the main source (France-Lanord et al., 1992). Whiting and Karner (1991) also reported a sharp increase in subsidence rates on the western margin of India beginning at ~25 Ma, which they ascribed to Indus Fan loading.

Fission-track analysis of detrital zircons from the Siwalik Group in Pakistan (Cerveny et al., 1988) and in India (Sorkhabi, unpublished data), $^{40}Ar/^{39}Ar$ analysis of detrital muscovite and K-feldspar from the Bengal Fan (Ocean Drilling Program Leg 116) by Copeland and Harrison (1990), and fission-track analysis of apatite from the same core samples (Corrigan and Crowley, 1993) indicate that the Hima-

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laya has been unroofing at fast rates for the past 18 m.y. (inferred from the fact that radiometric mineral ages are zero to only a few million years older than depositional ages, and from distribution of fission-track lengths).

Other evidence comes from the record of seawater $^{87}Sr/^{86}Sr$. The flux of dissolved Sr transported by rivers originating in Himalaya-Tibet accounts for about 25% of the global Sr budget. By calculating the Sr isotopic evolution curve for the past 100 m.y., Richter et al. (1992) showed that riverine Sr flux increased after the India-Asia continental collision in the early Tertiary, with a rapid increase at ~20 Ma. Krishnaswami et al. (1992) also showed such an increase of the Sr flux in the Ganga-Brahmaputra river system during the past ~20 m.y.

The thermal history of the HHC rocks in the northwest Himalaya as determined from K-Ar and $^{40}Ar/^{39}Ar$ dating of mica and from fission-track ages (Zeitler, 1985; Treloar and Rex, 1990; Sorkhabi, 1991) also indicates that cooling of the rocks during the early–middle Miocene was very fast (~30 °C/m.y.). Given that the cooling of the rocks occurred because of their uplift to surface (unroofing), rapid cooling of the HHC rocks in the early Miocene is indicative of rapid unroofing in the Himalaya, consistent with the sedimentation history discussed above.

In a histogram of mica cooling ages determined in the past three decades for various parts of the Himalayan metamorphic and granitic rocks, the majority of cooling ages are early–middle Miocene, with a peak at 18–16 Ma (Fig. 4). These cooling ages correspond to paleotemperatures of 300–350 °C (closure temperatures of mica), and indicate at least 10 km of unroofing of the Himalayan rocks since 17 Ma.

The unroofing of the HHC rocks has been due to erosion as well as to motion along faults bounding it: the Main Central thrust shear zone to the south was intensely active in early–middle Miocene time (Gansser, 1981; Valdiya, 1984; Le Fort, 1989), as was the South Tibetan detachement system to the north. Available data indicate that the detachment system was very active in the early Miocene. Hodges et al. (1992) suggested that normal faulting in the Everest region occurred between 22 and 19 Ma, on the basis of U-Pb ages of accessory minerals from an amphibolite in the footwall and an undeformed granite cutting across the fault, and that it was simultaneous with the compression along the Main Central thrust zone. In the Zanskar region (India), discordant mica K-Ar ages from the footwall and hanging wall of the normal fault also indicate early Miocene activity (Sorkhabi, 1991). Treloar et al. (1991) argued that the Main Mantle thrust separating the Kohistan block from the Higher Himalaya in Pakistan (Fig. 1) was originally a south-verging thrust, but later became a north-side-down extensional structure. On the basis of fission-track ages reported by Zeitler (1985) which yield similar apatite ages (~15 Ma), but discordant zircon ages across the fault, Treloar et al. (1991) inferred that the extension took place before 15 Ma, and was active during the period 23–20 Ma.

The Trans-Himalayan Xuxu pluton, near Lhasa, which was intruded at 42 Ma, was rapidly cooled and unroofed at 21–18 Ma, as demonstrated by $^{40}Ar/^{39}Ar$ dating of biotite from rocks collected from a vertical profile (3600–4600 m) (Copeland et al., 1987), the $^{40}Ar/^{39}Ar$ age spectrum analysis of a single-grain K-feldspar sample (Richter et al., 1991), and the fission-track analysis of apatites (Pan et al., 1992). Furthermore, Copeland and Harrison (1990) obtained a cluster of $^{40}Ar/^{39}Ar$ ages at 15–20 Ma from detrital K-feldspars from the Tsangpo River near Lhasa. In Kailash, results of $^{40}Ar/^{39}Ar$ age spectrum on a K-feldspar from a cobble show very rapid cooling between 19 and 18 Ma (Harrison et al., 1991). Miocene Kargil molasse in Ladakh (lying to the west of Kailash) (Thakur, 1980) is also probably the sedimentary product of rapid denudation. However, whether rapid uplift-exhumation during the early–middle Miocene affected plutonic rocks along the whole of the Trans-Himalayan batholith is yet to be resolved.

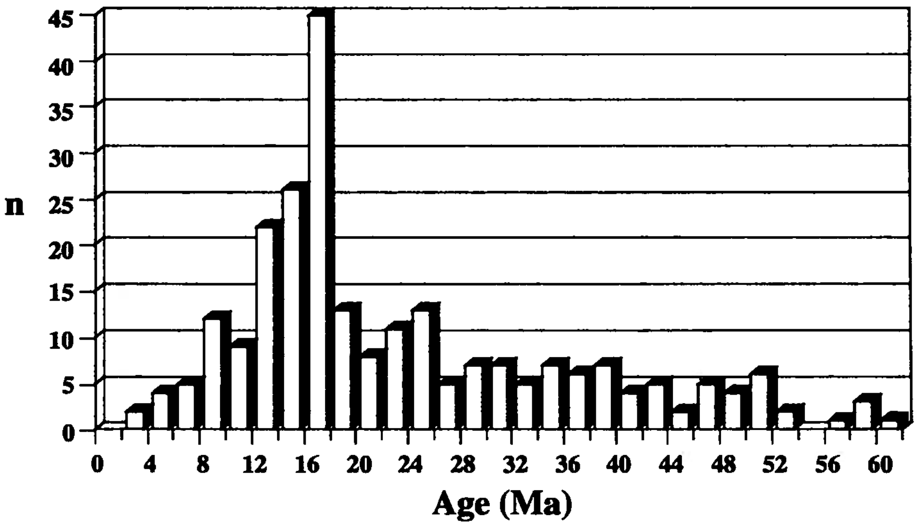

Figure 4. Histogram of 247 Cenozoic cooling ages of the HHC and Outer crystalline rocks determined by Rb-Sr (biotite), and K-Ar and $^{40}Ar/^{39}Ar$ (biotite or muscovite) methods, corresponding to paleotemperatures of 300–350 °C. Pre-Cenozoic ages, especially on biotite, carrying excess argon or incomplete resetting, were excluded from the histogram. Most of the younger ages (<8 Ma) are from the Main Central thrust zone. A period of rapid cooling and a major pulse of exhumation in the Himalayan occurred at 18–16 Ma. Many sources have been used for this histogram. The references up to 1979 are given in Mehta (1980). Other major sources include Honegger et al. (1982), Ferrara et al. (1983), Maluski and Matte (1984), Zeitler (1985), Debon et al. (1986), Maluski et al. (1988), Hubbard and Harrison (1989), Copeland et al. (1991), Treloar and Rex (1991), Sorkhabi (1991, and unpublished data), and references therein.

Late Miocene (11–7 Ma) Phase of Uplift-Denudation

From the mass accumulation rates of terrigenous clastics from eleven Ocean Drilling Project (ODP) sites in the Indus and the Bengal fans, Rea (1991) found that during 9–6.5 Ma the clastic flux increased by a factor of 2.5 to 13. Independently, Amano and Taira (1992) studied sedimentary strata drilled from the Bengal Fan (ODP Leg 116) and found that the sedimentation rate increased abruptly between 10.9 and 7.5 Ma. In another study farther west, in the northwest Indian Ocean, ODP Leg 117 scientists discovered that until ~10 Ma the sedimentary deposits were siliclastic, but since 10 Ma and especially since ~7 Ma, biogenic deposits have dominated, and they commonly contain opal and microfossils (various radiolaria and foraminifera), which are associated with the monsoon through the process of upwelling. These data indicate that development of the Himalayan barrier to the monsoon is correlated to the 11–7 Ma phase of uplift (Ocean Drilling Program Leg 117 Scientific Drilling Party, 1988a, 1988b).

On the basis of a comparison of more than 20 sections of the foreland basins in the Himalaya dated by magnetostratigraphy, Burbank (1991) also detected a pronounced increase in regional subsidence at ~11 Ma. By studying a 2800 m section of the Siwalik strata in Pakistan, Johnson et al. (1985) found that at about 11 Ma (the time boundary between the lower and middle Siwalik Group) the sedimentation rate increased from 0.12 to 0.30 mm/yr and simultaneously blue-green hornblende appeared, which is attributed to rapid uplift of the Nanga Parbat region and the associated erosion of ultramafic rocks in northern Pakistan. Several horizons of the 2550 m Baikya section of the Siwalik Group in Nepal have been investigated by Copeland et al. (1992), who determined $^{40}Ar/^{39}Ar$ ages on 91 detrital K-feldspars to be only 3 m.y. older than their age of deposition (8.4 to 6.7 Ma), indicating rapid unroofing throughout this period.

Carter et al. (1992), studying the sedimentation record of the Siwaliks in Nepal, found that a disruption occurred at ~7.5 Ma due to the initiation of the Main Boundary thrust; uplift within the foreland at this time is recorded by local intraformational breccia and erosional unconformities, and it coincided with the monsoon seasonality in the Indian subcontinent. In Langtang National Park, central Nepal, on the basis of $^{40}Ar/^{39}Ar$ cooling ages of muscovite, Macfarlane et al. (1992) detected two major periods of movement of the Main Central thrust as a duplex structure: an early, ductile phase at 20–15 Ma, and a late, brittle phase after 9–7 Ma, coeval with the development of the Main Boundary thrust to the south.

Fission-track apatite ages of 10–5 Ma obtained from the HHC rocks in the Kaghan-Babusar region of Pakistan (Zeitler, 1985), the Zanskar region of northwest India (Sorkhabi, 1991), and various parts of the Higher Himalayan belt in India (Ball, 1981) indicate an unroofing of at least ~4000 m since late Miocene time. Unfortunately, absence of fission-track length measurements on these samples (due to their low track density) does not give information on the pattern and rapidity of cooling and exhumation. (Sorkhabi is working on this problem.)

In southern Tibet, along the Nyainqentanglha Range, Pan and Kidd (1992) found a low-angle ductile detachment structure along which movement occurred at 8–6 Ma, shown by $^{40}Ar/^{39}Ar$ ages on mica.

Quaternary Phase of Uplift-Denudation

Gansser (1983) emphasized this phase of uplift, which he called the “morphogenic phase.” Studies by D. W. Burbank and his co-workers on the intermontane basins of Kashmir and Peshawar in the northwest Himalaya have provided valuable information on the Quaternary uplift-denudation history. These basins formed because of activity of the Main Boundary thrust. The Kashmir basin formed at 5–4 Ma with the rise of the Pir Panjal Range to its south. Sedimentation continued in the basin until the middle Pleistocene; since then, these lacustrine and deltaic deposits have been uplifted 1400–3000 m at a rate of at least 4 mm/yr (Burbank and Johnson, 1983). Sedimentation in the Peshawar basin began ~2.8 Ma through uplift of the Attock Range along the southern margin of the basin. Widespread sedimentation was terminated after 0.6 Ma by the rapid rise of the Attock Range, at an average uplift rate of 0.5 mm/yr for the past 0.6 m.y. (Burbank and Tahirkheli, 1985).

Similar intermontane basins exist not only in Nepal (Takkhola, Pokhra, and Kathmandu basins), but also in the Trans-Himalaya (e.g., Skardu basin in Pakistan and Kargil basin in India), where detailed investigation is needed to infer their neotectonics. Farther south, active faulting has been occurring along the Himalayan frontal thrust, which separates the Pleistocene Siwalik sedimentary rocks from the Indo-Gangetic alluvial plains (Nakata, 1989) (Fig. 1). These data support the idea that the Quaternary morphogenic phase of uplift has affected all zones of the Himalaya.

The Nanga Parbat massif in Pakistan presents the most notable example of Quaternary uplift in the Himalaya. Pioneering fission-track studies of this massif by Zeitler et al. (1982; Zeitler, 1985) have revealed very young apatite ages, ranging from 0.4 to 2.8 Ma, corresponding to an average unroofing rate of 5 mm/yr for the Nanga Parbat massif during the Quaternary.

The antecedent drainage pattern in the Himalaya is a classic example of its kind (Holmes, 1965) and has been studied by, e.g., Seeber and Gornitz (1983). Most of the rivers flowing through the Himalaya originate to the north and cut deep gorges through the loftier Himalaya; the present topography of the Himalaya postdates the river courses. The Indus gorge at Nanga Parbat is the most remarkable one. The elevation difference between the river (1100 m) and the Nanga Parbat peak (8125 m) is >7000 m over a distance of only 21 km (Gansser, 1983). Along the Indus Valley, at Jalipur, Misch and Raechl (1935) found that very young (Pleistocene?), little-consolidated sandstones were steeply folded and transgressed by the Indus River terraces.

Rapid uplift-denudation of the Himalaya during the Quaternary is also recorded in the stratigraphy of the Indus and Bengal fans, where Rea (1991) detected a pulse of clastic input that began between 3.7 and 2.5 Ma and lasted for 2 m.y. Amano and Taira (1992) found a prominent increase in the contribution of sediments to the Bengal Fan around 0.9 Ma.

Geodetic surveys in the Himalaya not only demonstrate uplift of the Himalaya but also provide some idea about the current rates of the uplift. Measurements made across the Siwalik Range in India reveal an uplift rate of 0.8 mm/yr (Narain, 1975). North–south leveling in Nepal during the past 15 years indicates active uplift of the Lesser Himalaya and Higher Himalaya at 2 and 4 mm/yr, respectively (Jackson et al., 1991). Finally, seismicity along the Himalayan thrusts and its syntaxial bends on the west and the east gives evidence for its ongoing dynamism and upheaval.

SUMMARY AND CONCLUSIONS

The episodic history of the Himalaya outlined above commenced with an early–middle Miocene phase of uplift-denudation. Here the question arises, What exactly happened in the early Miocene that produced such intense tectonic activity, upheaval, and exhumation? To answer this question, one must consider the fact that the Himalaya is the product of the India-Asia convergence and that the convergence may have been accommodated in several ways. Lateral extrusion of the Indochina block along the Red River fault (a left-lateral, ductile strike-slip shear zone) during the Oligocene–early Miocene is a case in point, and several lines of evidence supporting this have been elaborated by Tapponnier et al. (1986) and Harrison et al. (1992). However, this should not prevent us from looking to tectonic accommodation within the Himalaya itself prior to the Miocene. For example, we do not know exactly when the Main Central thrust began (though it had an active phase in the early Miocene). Did it form in the Eocene (Dewey et al., 1988) or the late Oligocene (Hodges et al., 1989)?

The idea that the early Miocene extension and detachment between the HHC rocks and the overlying Tethyan-Tibetan sedimentary sequence occurred as a result of the gravitational collapse of a topographical high (Burchfiel et al., 1992) implies crustal stacking within the Himalaya to produce such a relief before Miocene time. Given that the Himalayan frontal thrust, the Main Boundary thrust, and the Main Central thrust become older from south to north, one can envision the existence of an even older thrust between the Indus-Tsangpo suture zone and the Main Central thrust. Perhaps the South Tibetan detachment system was originally a thrust fault that later became an extensional normal fault. Studies establishing the extensional tectonics of this normal fault do not preclude such a possibility. Treloar et al. (1991) considered this to be the case with the Main Mantle thrust, and Jain et al. (1992) argued that extensional deformation in Zanskar was superposed on an earlier phase of ductile shearing with a top-to-southwest sense of thrust movement. Valdiya (1989) considered the detachment normal fault as a reactivated structure, which has accommodated part of the India-Asia convergence.

In summary, the Himalaya has undergone a complex and episodic tectonic history. The available geochronologic data and geologic evidence demonstrate that 21–17, 11–7, and 2–0 Ma mark pulses of major uplift-exhumation and events associated with the tectonism of the Himalaya. There is the possibility of other local or regional pulses, however, and further studies will refine the episodic history on a detailed scale. It is appropriate to recall the words of Eduard Suess, who almost 100 years ago wrote in his first article on Tethys: "Our scholars will some day know more than their masters do now; so let us patiently continue our work and remain friends."

Acknowledgments

The data synthesized and analyzed in this article have been obtained through invaluable efforts of numerous geologists and geochronologists. We salute all of them and apologize that lack of space did not allow us to present a detailed list of references. Sorkhabi thanks many Indian and Japanese friends who have helped him in numerous ways with the study of the Himalaya. We thank Sue Selkirk for preparing the figures, and two anonymous reviewers for their critical, constructive comments.

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NACSN Asks for Recommendations

The North American Commission on Stratigraphic Nomenclature passed a resolution at its October 28, 1992, meeting in Cincinnati, Ohio, to "solicit opinion from the profession as to whether or not to amend the 1983 North American Stratigraphic Code so as to provide for formalization of sequence-stratigraphic units." A committee that will make recommendations on this matter was established at the same meeting.

All workers concerned with sequence stratigraphy are invited to communicate their opinions and specific recommendations to Donald E. Owen, Chairman, NACSN, Department of Geology, Lamar University, P.O. Box 10031, Beaumont, TX 77710, (409) 880-8234, fax 409-880-8007.

Opinions are solicited as to whether sequence-stratigraphic units should be considered a special type of Allostratigraphic Unit, as defined in the existing North American Stratigraphic Code (*AAPG Bulletin*, 1983) and how sequence-stratigraphic units relate to the Unconformity-Bounded Units (Synthems) of the ISSC (*GSA Bulletin*, 1987). Recommendations on exactly what kind of sequence-stratigraphic units and surfaces (sequences, parasequences, marine-flooding surfaces, condensed zones, etc.) that should be formalized or remain informal are solicited also. Comments will be considered until July 31, 1993, but earlier submittal of opinions and recommendations is encouraged. ■

Call for Papers—Engineering Geology

Contributions are being solicited for a volume on clay and shale slope instability which will be submitted to the Geological Society of America for publication in the Reviews in Engineering Geology series. It is anticipated that the volume will cover a wide range of topics pertaining to clay and shale slopes, including characterization of shear strength and other engineering properties; aspects of hillslope hydrology related to slope stability; mechanical analyses of slope stability; the influence of structural and stratigraphic details on slope stability; regional and local hazard assessment; and case histories of both failures and remedial efforts. Papers that integrate both geological and engineering aspects of clay and shale slope instability are especially welcome. Manuscripts will be subjected to peer review and revision, if necessary, before acceptance. A guide for authors is currently in preparation. Target date for submission of manuscripts, along with the names and addresses of at least two qualified reviewers, is June 1, 1993.

For additional information, please contact either of the two co-editors: William C. Haneberg, New Mexico Bureau of Mines and Mineral Resources, Campus Station, Socorro, NM 87801, (505) 835-5808; Scott A. Anderson, Department of Civil Engineering, University of Hawaii, Holmes Hall 383, 2540 Dole Street, Honolulu, HI 96822, (808) 956-9859.

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