# Synchronous anatexis, metamorphism, and rapid denudation at Nanga Parbat (Pakistan Himalaya)

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## ABSTRACT

**The Nanga Parbat–Haramosh massif of the western Himalaya is a north-trending half-window of Indian crust that provides spectacular exposures of Precambrian basement gneisses that have been overprinted by Himalayan metamorphism. We report here petrologic data and U/Pb dates on zircon and monazite which document that Nanga Parbat gneisses underwent a Pliocene-Pleistocene episode of high-grade metamorphism and anatexis during an interval in which the Nanga Parbat massif was undergoing rapid denudation at mean rates of ~5 mm/yr. We speculate that by initiating decompression melting, this denudation may be at least partly responsible for the anatexis and high-grade metamorphism.**

## INTRODUCTION

Recent advances in analytical techniques and in conceptual models have made it feasible to interrelate the metamorphism of crustal rocks with their tectonic history (England and Thompson, 1984, among many others). In general, models show that during and after continental collision, metamorphism occurs over a protracted period of time (tens of millions of years) as perturbed geotherms return to equilibrium. However, in detail, the metamorphism and anatexis of the continental crust are complicated phenomena that result from the interplay of numerous tectonic processes. Recently, for example, structural and petrologic studies have shown that extensional collapse of mountain belts following crustal thickening can have a profound effect on metamorphic evolution (Selverstone, 1985; Ruppel et al., 1988). These studies show that rapid denudation during extension results in nearly isothermal decompression and abrupt discontinuities in the array of pressures and temperatures recorded in surface rocks. In this paper, we present evidence that (1) an episode of high-grade metamorphism and anatexis observed in central parts of the Nanga Parbat–Haramosh massif (Pakistan High Himalaya) occurred within the past 10 m.y. during a phase of rapid denudation and (2) these events were a direct result of neither late extensional collapse nor the crustal thickening that accompanied Late Cretaceous or early Tertiary collision of the Indian and Asian plates.

## GEOLOGIC SETTING

In Pakistan, the Indian plate is bordered on the north by the Kohistan-Ladakh island arc. Early Tertiary convergence of these terranes was accommodated along the Main Mantle thrust (Butler, 1986) and resulted in deep burial and metamorphism of the leading edge of the Indian plate before ~40 Ma. After following "clockwise" *P-T* paths toward peak metamorphism (Treloar et al., 1989; Chamberlain et al., 1991), rocks in the Indian plate were thrust southward between 40 and 25 Ma, resulting in metamorphic discontinuities across thrust faults. Following thrusting, rocks of the Indian plate cooled rapidly in the interval 25 to 20 Ma, possibly because of tectonic denudation of the Indian plate along normal faults as Kohistan moved northward relative to the Indian plate (Chamberlain et al., 1991; Treloar et al., 1991a, 1991b).

Although this scenario is applicable to rocks of the footwall of the Main Mantle thrust throughout much of northern Pakistan, it is unclear whether it applies to the Nanga Parbat–Haramosh massif. The massif is a north-trending extension of Indian crust that projects from the foothills of the Himalaya into the Karakoram (Misch, 1949; Butler and Prior, 1988). Within the Nanga Parbat–Haramosh massif are 1850 Ma tonalitic basement gneisses (Iskere Gneiss), at least one younger unit (~500 Ma; Shengus Gneiss), and cover rocks of unknown age (Butler and Prior, 1988; Zeitler et al., 1989; Madin, 1989). Draped around the massif are plutonic, volcanic, and metasedimentary rocks belonging to the Kohistan-Ladakh island arc.

The massif is delineated along its western and eastern margins by the Main Mantle thrust, which is well exposed along the eastern boundary (Treloar et al., 1991a, 1991b; Butler et al., 1992). Along the western edge of the massif, however, the trace of the Main Mantle thrust has been faulted away, exposing the Indian plate rocks that make up the Nanga Parbat–Haramosh massif. This fault, referred to as the Liachar thrust or Raikhot fault (Butler and Prior, 1988; Madin et al., 1989), has been active both at shallow crustal levels, as shown by the presence of brittlely deformed cataclasites, and at relatively deep crustal levels, as evidenced by ductile shear zones. S-C fabrics, mica fish, asymmetric feldspar augen, and stretching lineations in the fault zone show a consistent northeast sense of motion, which suggests that the Nanga Parbat–Haramosh massif has moved upward and northward relative to Kohistan (Butler and Prior, 1988; this study).

Two lines of geochronologic evidence suggest that the western boundary of the Nanga Parbat–Haramosh massif has been active recently. First, there are deformed granitic dikes within this fault zone, and similar but undeformed dikes within the massif give U/Pb zircon ages between 2 and 7 Ma (Zeitler and Chamberlain, 1991). Second, there is a concentric pattern of young fission-track ages around the massif which shows that denudation of the massif has accelerated over the past 10 m.y., culminating in rates possibly as high as 7 mm/yr (Zeitler, 1985).

## PETROLOGICAL AND GEOCHRONOLOGICAL RESULTS

The metamorphic and structural relations found within the Nanga Parbat–Haramosh massif are exposed along a traverse extending south from the Indus River, past Tato village, and on into what we refer to informally as the "core" of the massif, near and below the summit of Nanga Parbat itself (this section defines the greatest continental relief on Earth, some 7 km of relief in 15 km; Fig. 1). The Liachar thrust, juxtaposing the Kohistan terrane and the massif, is exposed at the northern end of this traverse, along the Indus River.

Three metamorphic zones are exposed along the Tato traverse. In the region between the Liachar thrust and Tato village (Fig. 1), pelitic rocks contain the assemblage kyanite + garnet + muscovite + quartz. To the south of Tato village the metamorphic gradient steepens sharply, metamorphic conditions changing over a distance of <10 km from kyanite + muscovite to sillimanite + muscovite, followed by a sillimanite + potassium feldspar + cordierite zone (Fig. 1). The pelitic rocks in the core of the massif are highly migmatized and show abundant stringers (1–5 cm thick) of leucogranite (former melt). Pelitic wall rocks contain the granulite-grade assemblage sillimanite + potassium feldspar + cordierite. The melts consist of the typical S-type anatectic assemblage quartz + plagioclase feldspar + potassium feldspar + biotite + sillimanite +

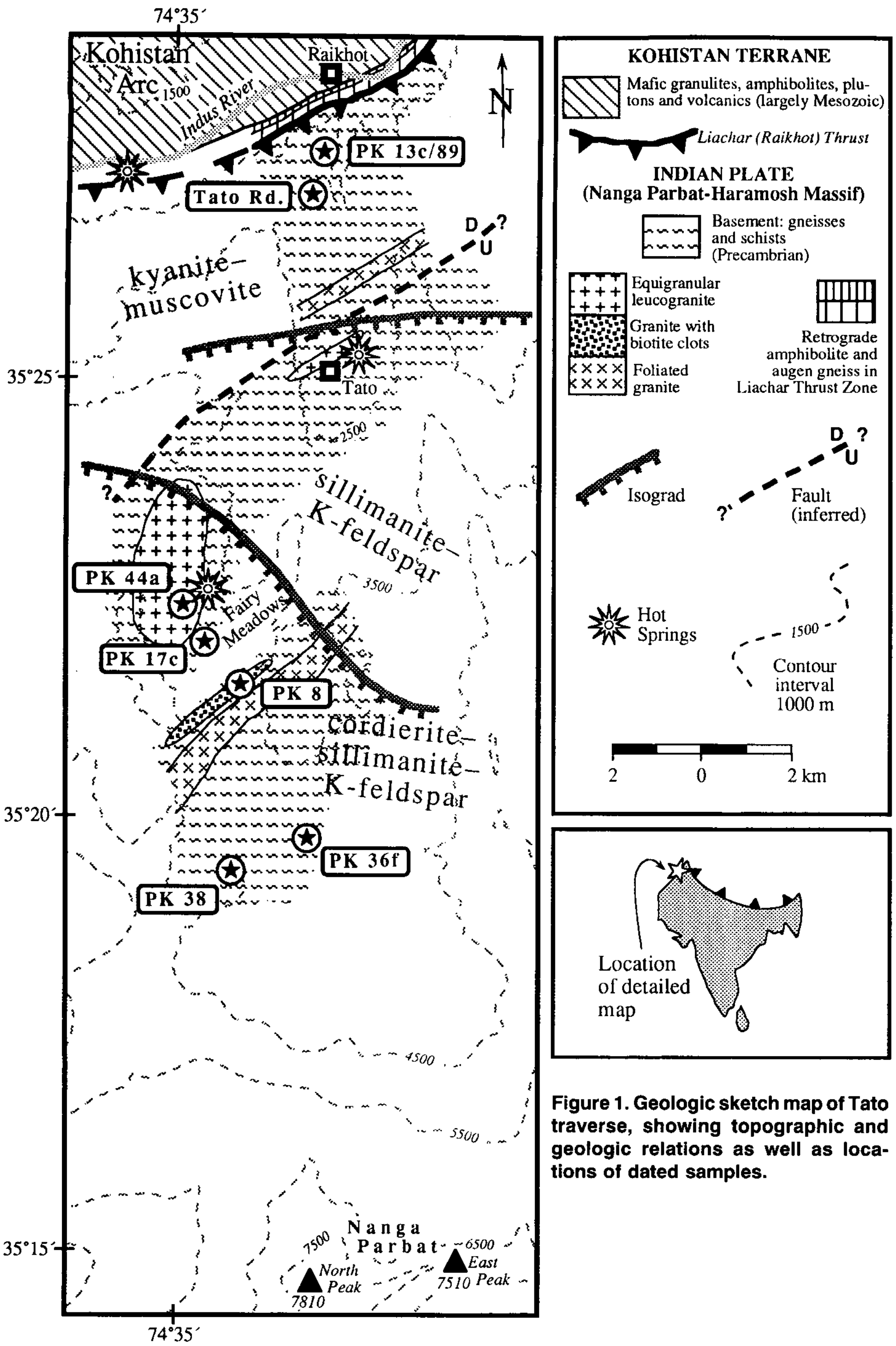

**Figure 1. Geologic sketch map of Tato traverse, showing topographic and geologic relations as well as locations of dated samples.**

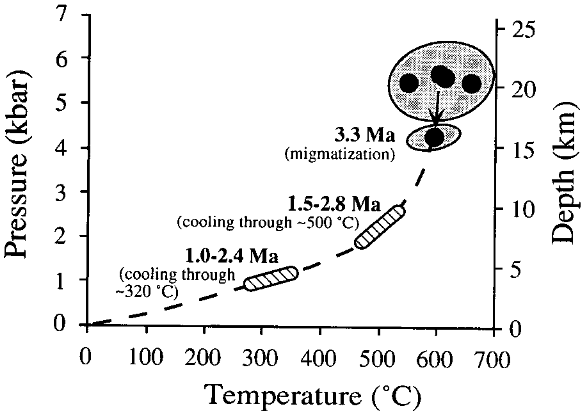

**Figure 2. Pressure and temperature estimates for metamorphic conditions in core of Nanga Parbat–Haramosh massif. Points show individual determinations and ellipses show precision (1 $\sigma$). Each $P$-$T$ point is average of two or three estimates made from different coexisting garnet, biotite, and plagioclase grains in given thin section. Also shown are inferred $P$-$T$ path for rocks currently exposed in core of Nanga Parbat–Haramosh massif and time limits on this metamorphic history.**

cordierite + garnet + tourmaline. Similar leucogranite dikes and melt stringers are observed along strike in northern areas of the Nanga Parbat–Haramosh massif (Butler et al., 1992).

To quantify $P$-$T$ conditions within the core of the massif, we applied the well-calibrated garnet-sillimanite-plagioclase-quartz barometer (Newton and Haselton, 1981) and the garnet-biotite thermometer (Indares and Martingnole, 1985) to four pelitic rocks and one melt sample of garnet-cordierite-sillimanite, all from the highest grade zone along the Tato traverse. Our calculations included corrections for nonideality of Ti and Al solution in biotite (Indares and Martingnole, 1985), nonideality of Ca in garnet (Newton and Haselton, 1981), and nonideality of Ca in plagioclase (Orville, 1972). Taken at face value, our measurements suggest that the highest grade metamorphism occurred at temperatures of ~650 ±50 °C and pressures of 6 ±1 kbar and that the melt sample formed or was injected at slightly lower temperatures of ~600 °C but significantly lower pressures of 4.1 ±1 kbar (Fig. 2). It appears that rocks in the core of the massif underwent isothermal decompression after peak metamorphism. Uncertainty in this $P$-$T$ path stems from the possibility of continued cation diffusion between minerals after peak metamorphism, which might result in lower recorded temperatures, and errors inherent in the thermobarometers. Neither of these problems should significantly affect the trend of the $P$-$T$ path shown in Figure 2 because (1) closure effects during cooling will simply displace the apparent $P$-$T$ path to lower temperatures (assuming equilibrium is maintained during cooling; see Selverstone and Chamberlain [1990] for discussion) and (2) comparative thermobarometry eliminates the systematic errors inherent in the thermobarometer calibrations. Ideally, it is possible to resolve $P$-$T$ differences between samples of tens of bars and tens of degrees (Hodges and McKenna, 1987).

To ascertain the timing of melting and metamorphism along the Tato traverse, we measured U/Pb ages on zircons from six units, using the scanning high-resolution ion microprobe (SHRIMP) (Fig. 3): migmatite containing melt stringers (PK 38); fine-grained granite from a kilometre-sized stock (PK 44a); fine-grained granite containing clots of biotite and present as metre-thick sheets (PK 8); fine-grained granite from a dike (PK 36f); and two tourmaline-bearing pegmatites from the core (PK 17c) and the northwestern flank (Tato Road) of the massif. All samples contained numerous xenocrystic zircons giving ages of ~1 850 Ma and therefore probably derived from the Iskere Gneiss; all samples but the migmatite also

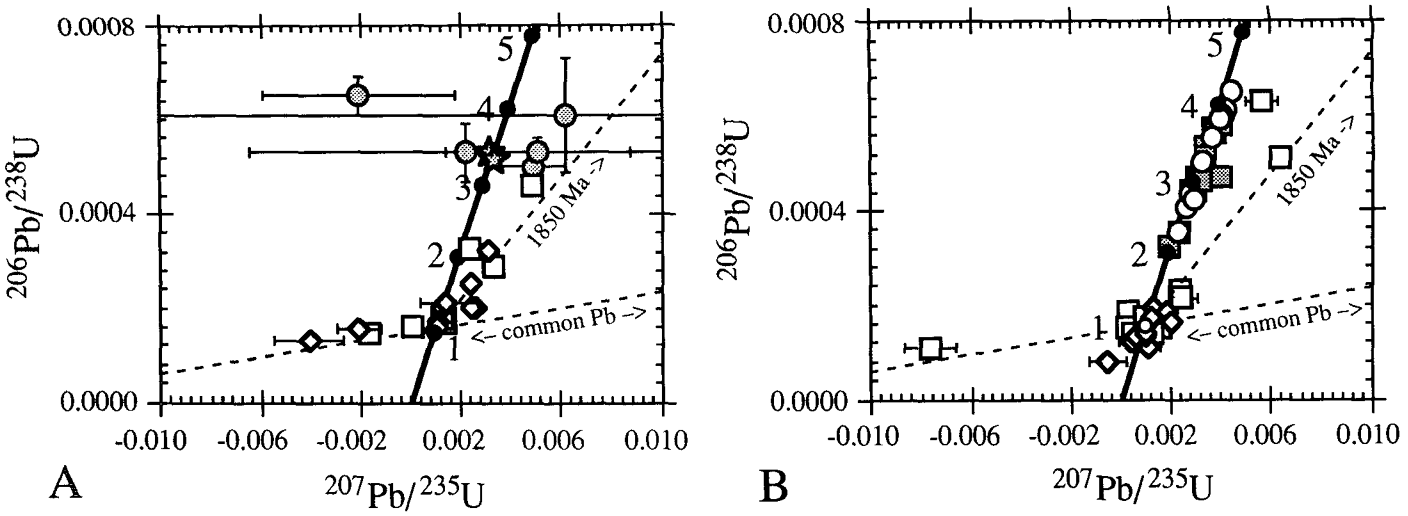

**Figure 3. A: Concordia diagram showing U/Pb analyses of zircons obtained from igneous units. All samples are from core of Nanga Parbat–Haramosh massif. Only young ages are shown; many zircons contained cores giving $^{207}Pb/^{206}Pb$ ages of ~1850 Ma. Dashed reference lines show inheritance trend toward 1850 Ma and common-Pb correction trend. Error bars (1 σ) reflect counting statistics, interelemental calibration, and common-Pb correction. Circles = migmatite (PK 38); diamonds = leucogranite stock (PK 44a); squares = granite sheets (PK 8); stars = monazite U/Pb analyses for sample PK 38. B: U/Pb results for dikes. Diamonds = tourmaline-bearing pegmatite from core of Nanga Parbat–Haramosh massif (PK 17c); open squares = fine-grained granite from core of massif (PK 36f); gray squares = tourmaline-bearing pegmatite from western flank of massif (Tato Road); open circles = tourmaline-bearing pegmatite from western flank of Nanga-Parbat–Haramosh massif (PK 13c/89; data from Zeitler and Chamberlain, 1991). For older pegmatite dikes, youngest ages are taken as best estimate for time of emplacement. Muscovite and K-feldspar from sample PK13c/89 yield saddle-shaped $^{40}Ar/^{39}Ar$ age spectra with minimum ages, respectively, of 1.4 and 2.7 Ma; biotite from surrounding schists yields $^{40}Ar/^{39}Ar$ ages of 2.8 to 3.5 Ma; monazite from sample Tato Road is reverse discordant with $^{207}Pb/^{235}U$ age of 2.4 ±0.2 Ma.**

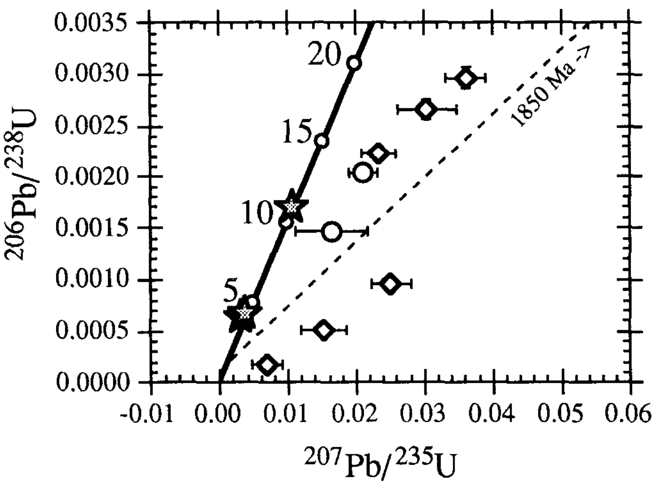

**Figure 4. U/Pb results, ion-microprobe drilling analyses of rims of metamorphic zircons from Iskere Gneiss, Tato traverse (circles and diamonds). Also shown are U/Pb analyses of monazite from two schist samples from Tato traverse (stars). Samples taken from northwestern flank of Nanga Parbat–Haramosh massif, north of Tato village (see Fig. 1).**

contained discrete euhedral grains of high-U igneous zircon (1%–4% U). The pegmatites contained distinctly blue, high-U zircon, as noted in other pegmatite samples from the massif (Zeitler and Chamberlain, 1991). Analytical and data-reduction procedures followed those given in Compston et al. (1986). Analyses were corrected for common Pb by using measured $^{208}Pb$ and common Pb the same age as that of the zircon (Williams and Claesson, 1987); our analyses were not corrected for the effects of U-series disequilibrium (Barth et al., 1989), because corrections would be smaller than the uncertainties in our data.

In every case, igneous grains are young. Four samples from the core of the Nanga Parbat–Haramosh massif yielded $^{206}Pb/^{238}U$ ages of about 1 ±0.1 Ma; although the $^{207}Pb/^{235}U$ uncertainties are large, the analyses appear concordant. The scatter and most outliers in the data are consistent with (1) inheritance from an 1850 Ma component (cores are common in the igneous grains) and (2) overcorrection and undercorrection for common Pb. The one pegmatite sample from the flank of the massif yielded results similar to previous analyses, and we estimate its age to be ~2.2 Ma. Finally, zircons from the migmatite are overgrown by relatively high U rims, which yielded ages that, although imprecise, are clearly younger than 5 Ma.

Other data are available from the Tato traverse that constrain the timing of anatexis and metamorphism. First, two monazite fractions from migmatite within the core of the massif are concordant at 3.3 ±0.1 Ma (sample PK 38; Fig. 3A). Second, metamorphic monazites obtained from two samples of kyanite + muscovite zone metapelites yield ages of between 4.0 and 10 Ma (Smith et al., 1992). Third, SHRIMP drilling-mode analyses have revealed Iskere Gneiss zircons from the Indus River section through the massif to have micrometre-scale, high-U rims with ages of 2–11 Ma (Zeitler and Williams, 1988). Similar analyses of zircons from two gneiss samples from the Tato traverse are less conclusive, although these Proterozoic grains are also clearly mantled by high-U zircon that is less than 5 Ma in age (Fig. 4). Finally, amphibole float taken from the base of the summit wall in the core of the massif yields saddle-shaped $^{40}Ar/^{39}Ar$ age spectra having minima of 1.5–2.8 Ma, and biotite samples from the core yield $^{40}Ar/^{39}Ar$ ages of 1.0–2.4 Ma. These results confirm that along the Tato traverse, the core of the Nanga Parbat–Haramosh massif has undergone a recent metamorphic episode culminating in extensive partial melting as recently as ~1.0 Ma.

## DISCUSSION AND CONCLUSIONS

Our data document a recent anatectic event within the Nanga Parbat–Haramosh massif, far younger than reported elsewhere in the Himalaya and far removed in time from the early Tertiary, collision-related metamorphism observed elsewhere in the Pakistan Himalaya (Treloar et al., 1989; Chamberlain et al., 1991). Our petrological and geochronological data also allow us to determine directly a denudation rate for rocks within the core of the massif; our $P$-$t$ estimate for migmatization of 4.2 ±1 kbar and 3.3 ±0.1 Ma (U/Pb on monazite) leads to a mean denudation rate of 4.5 ±1.1 mm/yr. This value follows from equating the U/Pb age of monazite with the timing of high-grade metamorphism, a reasonable assumption given recent studies of monazite (Smith and Barreiro, 1990); careful examination of Nanga Parbat monazites suggests that they are metamorphic phases in equilibrium with the main assemblage, not hydrothermal or inherited in origin (Smith et al., 1992).

The denudation rate calculated here bears on the nature of uplift and unroofing in mountain belts. We observe rapid denudation in an area where no tectonic denudation has been recorded. We also find an episode of high-grade metamorphism and anatexis to be coeval with rapid denudation. The rapid uplift of rocks at Nanga Parbat can no longer be viewed as a process manifested only in relatively cool rocks near the surface, widely separated in time from Himalayan high-grade metamorphism (Butler and Prior, 1988). At Nanga Parbat, processes governing metamorphism, melting, and uplift are undeniably coupled.

Currently, we can only speculate about causes for the young metamorphic, anatectic, and tectonic episode focused on the massif. One novel possibility is that rapid uplift may have been the cause of melting and metamorphism in the core of the massif. In response to rapid denudation in the late Neogene, partially dehydrated lower-crustal rocks could have melted by decompression (Zeitler and Chamberlain, 1991), and rising melts would have transferred heat to shallower levels, resulting in the young metamorphic episode of which we see evidence. In such a scenario, melts were intruded throughout the uplift phase and caused both the higher pressure–higher temperature metamorphism (650 °C, 6 kbar) and the later lower-pressure metamorphism at 1–4 Ma (600 °C, 4 kbar).

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