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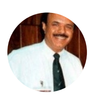

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Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion

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Abstract. Within the syntaxial bends of the India-Asia collision the Himalaya terminate abruptly in a pair of metamorphic massifs. Nanga Parbat in the west and Namche Barwa in the east are actively deforming antiformal domes which expose Quaternary metamorphic rocks and granites. The massifs are transected by major Himalayan rivers (Indus and Tsangpo) and are loci of deep and rapid exhumation. On the basis of velocity and attenuation tomography and microseismic, magnetotelluric, geochronological, petrological, structural, and geomorphic data we have collected at Nanga Parbat we propose a model in which this intense metamorphic and structural reworking of crustal lithosphere is a consequence of strain focusing caused by significant erosion within deep gorges cut by the Indus and Tsangpo as these rivers turn sharply toward the foreland and exit their host syntaxes. The localization of this phenomenon at the terminations of the Himalayan arc owes its origin to both regional and local feedbacks between erosion and tectonics.

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1. Introduction

One of the important outcomes of the plate tectonic model is the manner in which the chemical and mechanical evolution of the oceanic lithosphere can be understood in terms of the dynamics of mantle convection and plate motions. In contrast, the petrological response of the continental lithosphere to plate dynamics remains poorly resolved. Conceptual and numerical models have been put forth that by tracking particle paths through a deforming orogen, elegantly explain the broad evolution of collisional zones [e.g., *England and Thompson*, 1984; *England and Houseman*, 1986; *Beaumont et al.*, 1992; *Koons*, 1987, 1990; *Willett et al.*, 1993]. However, these models do not explain the specific ages and distribution of igneous and metamorphic rocks exposed in real mountain belts, and a number of additional factors have been proposed, including shear heating along major structures [e.g., *Molnar and England*, 1990], variations in crustal rheology [*Zhao and Morgan*, 1985; *Royden et al.*, 1997; *Axen et al.*, 1998], variations in thermal conductivity [*Jaupart and Provost*, 1985], thermal buffering or deformation associated with melting [*Hodges et al.*, 1988; *Hollister and Crawford*, 1986], shuffling of metamorphic terranes in thrust slices [e.g., *Treloar et al.*, 1989a; *Harrison et al.*, 1999], and the influence of preexisting crustal structure [e.g., *England and Searle*, 1986].

Much of this attention in both formulating and testing models of collisional orogenesis has been focused on the Himalayan-Tibet system, which although less well explored than older orogens, has been widely taken as the type example of continental collision and which has seen increasing use as a natural laboratory in which to examine a variety of active collisional processes [e.g., *Nelson et al.*, 1996; *Royden et al.*, 1997; *Yin et al.*, 1999]. Consideration of this young, still-active system raises several key issues in collisional tectonics and metamorphism: the importance of dynamic, significant topography to tectonics; the significance of widespread edge effects along lithospheric plate boundaries; and the spatially and temporally variable nature of regional metamorphism. The first-order relevance of exhumation has been recognized for some time [e.g., *England and Richardson*, 1977], as has the role of spatial variations in erosion [e.g., *Koons*, 1990], but the deep incision and locally strong geomorphic gradients associated with dynamic Himalayan topography beg a closer look. Effects at plate edges are an equally important consideration: one can make a reasonable case that the two Himalayan syntaxes occupy a significant fraction of the collisional system's area (Figure 1) and that evolving, three-dimensional, out-of-plane effects in these zones [*Koons*, 1994, 1995; *Enlow and Koons*, 1998] undermine the applicability of traditional two-dimensional models. Finally, the variability observed in Himalayan metamorphism raises the question of how to reconcile our "event-based" under-standing of current exposures in older orogens with observations of an active system which expresses ongoing collisional dynamics through exposures of rocks and structures developed over >50 million years.

This paper summarizes results from a multidisciplinary study of the Nanga Parbat massif of the northwestern Himalaya. (Below, we use the expression "Nanga Parbat-Haramosh Massif" (NPHM) when referring to the entire assemblage of Precambrian gneisses and younger cover that extend northward from Babusar Pass to the Asian plate rocks located north of the peak Haramosh (Figure 2). We use the expression "Nanga Parbat massif" to refer to that portion of the NPHM to the southwest of the Astor River (Figure 3). Finally, we use the expression "core of the massif" to refer to crystalline basement to the southwest of the Astor River immediately around and to the north of the topographic summit massif of the mountain Nanga Parbat itself.) Our work was aimed at understanding some of the specific causes that lead the continental lithosphere to become pervasively reworked during collision. In a region of exceptional topographic relief, Nanga Parbat exposes extremely young metamorphic and igneous rocks and is thus an ideal place to explore crustal reworking, as it offers an opportunity to relate current rock exposures closely with ongoing processes. Over the past 5 years an ~5000 km^2 area of the central Nanga Parbat massif has been the focus of our Nanga Parbat Continental Dynamics Project, which involved coordinated work in the areas of geochronology, petrology, structural geology, geomorphology, seismology, remote sensing, geomorphology, dynamical modeling, geochemistry, magnetotellurics, and neotectonics. Together with a number of petrologic, structural, and geomorphic studies carried out by other groups, we now have a much improved understanding of the extent, nature, and context of the young metamorphic anomaly at Nanga Parbat. We propose that both surficial and tectonic processes and feedbacks between them at local scales have been key elements in the recent evolution of the Nanga Parbat massif. In addition, incorporating preliminary data reported from Namche Barwa in the eastern syntaxis [*Burg et al.,* 1997], we argue that the syntaxial origin of the Nanga Parbat and Namche Barwa massifs is a predictable outcome of the topographic evolution of the Himalayan orogen.

2. Geology

2.1. Setting and Context

The Nanga Parbat-Haramosh Massif (NPHM) is a structural half window of Indian plate gneisses [*Misch*, 1949; *Tahirkheli et al.*, 1979; *Coward et al.*, 1986] located within the western Himalayan syntaxis (Figure 1). Unlike the more crisply defined eastern syntaxis, the western syntaxis expresses only a diffuse manifestation of the shear associated with the western boundary of the Indian plate, showing a broad general deflection of orogenic structures, little geomorphic expression of closely spaced strike-slip valleys, and a gentle apparent deceleration of plate velocities near the

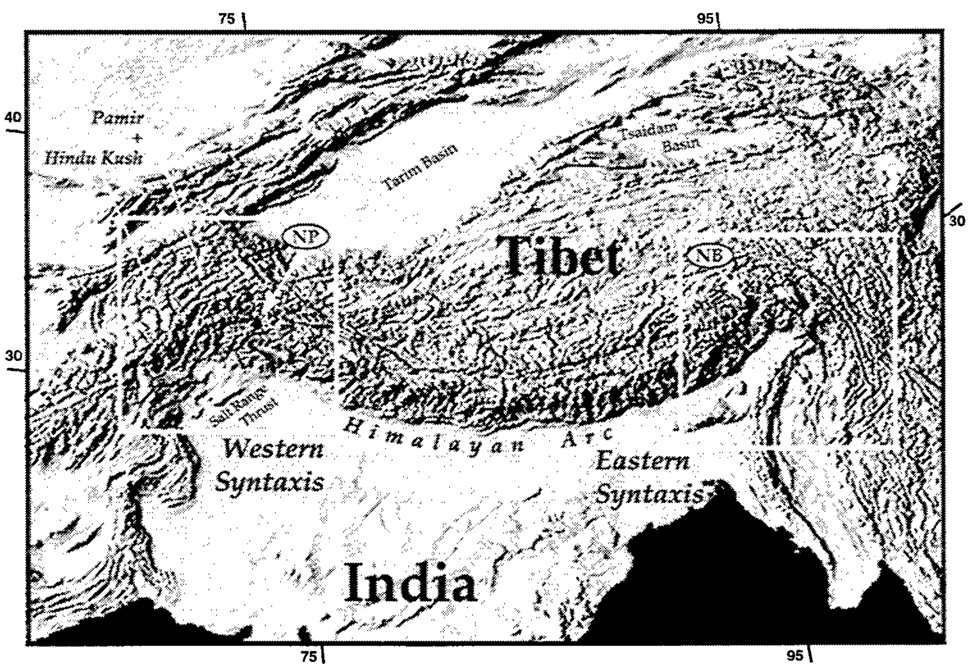

Figure 1. View of India-Asia collision zone, showing locations of eastern and western syntaxes and syntaxial metamorphic massifs (NP, Nanga Parbat; NB, Namche Barwa). Topography is from GTOPO30 data.

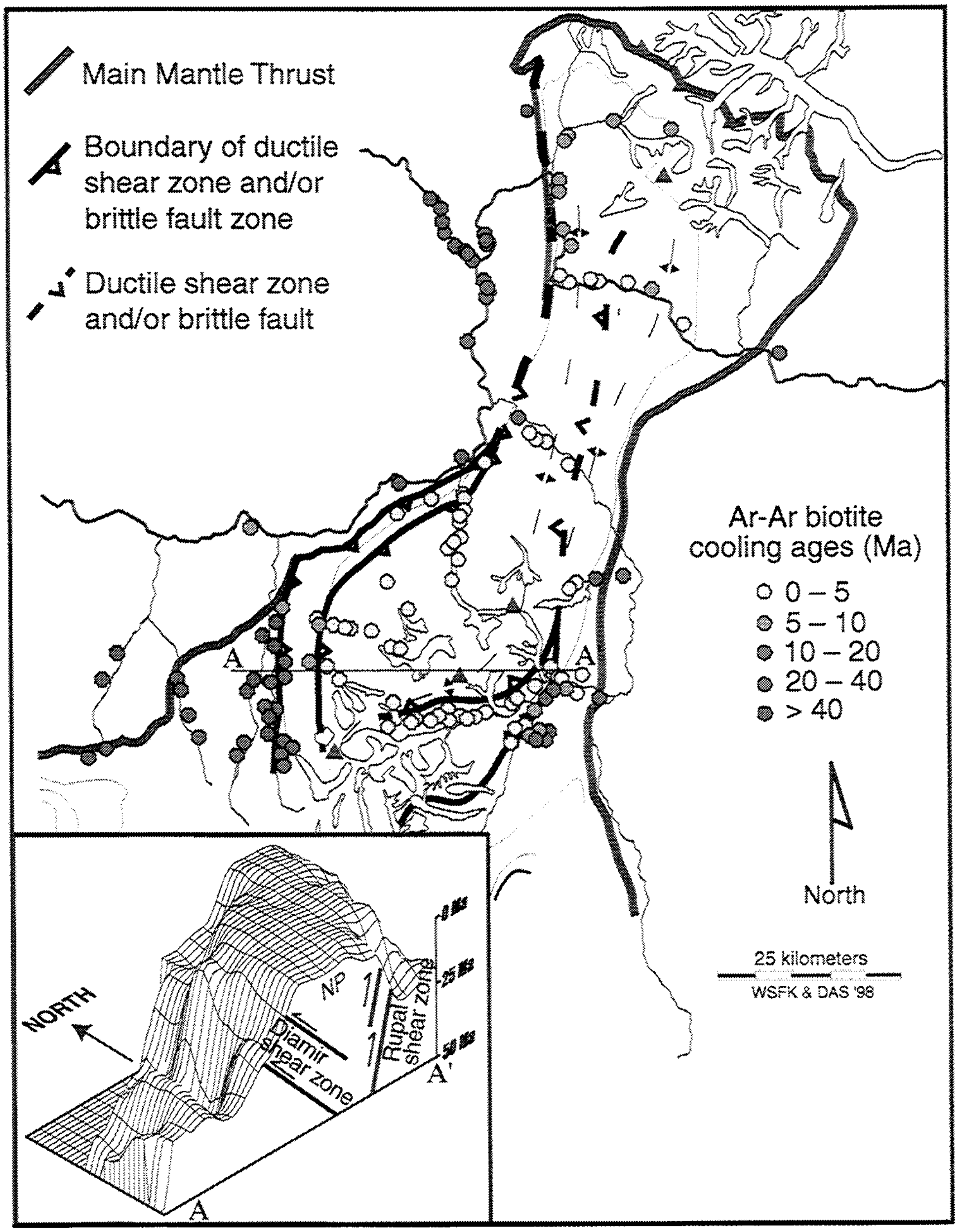

Plate 1. The $^{40}Ar/^{39}Ar$ biotite cooling ages from within and near the Nanga Parbat massif. Bulk of the data are from *Schneider* [1999]; some additional data are from *Zeitler* [1985], *Treloar et al.* [1989b], *Zeitler et al.* [1989], *George et al.* [1995], *Winslow et al.* [1996], *Whittington* [1996], and *Reddy et al.* [1997]. Biotite cooling ages (T_c ~350°C at high local cooling rates) define major structural breaks around Nanga Parbat massif, and mimic the pattern seen in metamorphic grade (Plate 2b) and microseismicity (Plate 2d). Inset shows "thermochronologic morphology" of massif taken approximately along swath A-A'.

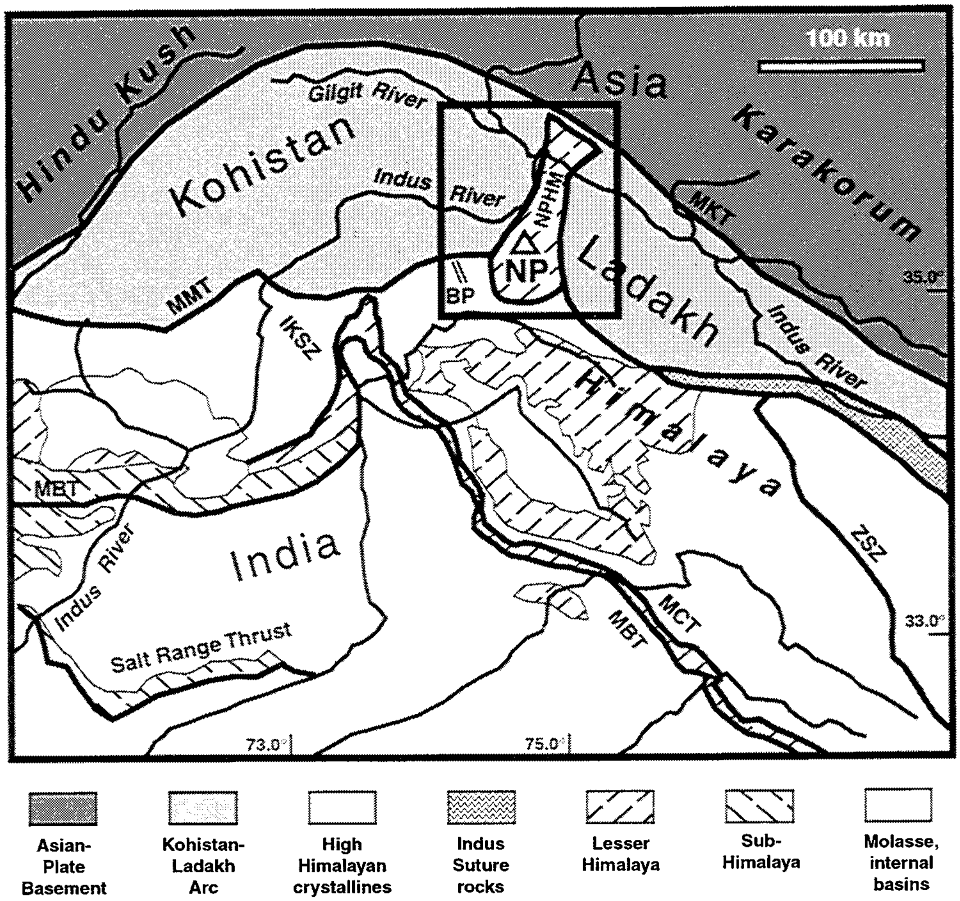

Figure 2. Regional map of NW Himalaya, showing tectonic context of Nanga Parbat-Haramosh Massif (NPHM). NP, Nanga Parbat; BP, Babusar Pass; MKT, Main Karakorum Thrust (northern branch, Indus Suture Zone); MMT, Main Mantle Thrust (southern branch, Indus Suture Zone); MCT, Main Central Thrust; MBT, Main Boundary Thrust; ZSZ, Zanskar Shear Zone; IKSZ, Indus-Kohistan Seismic Zone.

plate edge [e.g., *Holt et al.*, 1995; *Koons and Zeitler*, 1997; *Bernard et al.*, 2000].

The Nanga Parbat massif is flanked to the west and east by rocks of the Mesozoic Kohistan-Ladakh arc terrane and to the north by rocks of the previous Asian continental margin. The massif was overthrust from the north by mafic to intermediate volcanic and plutonic rocks of the Kohistan terrane [*Tahirkheli et al.*, 1979; *Coward et al.*, 1986; *Chamberlain and Zeitler*, 1996], presumably during collision of the Indian continental margin and Kohistan at 55 Ma or before [*Klootwijk et al.*, 1992; *Smith et al.*, 1994; *Beck et al.*, 1995; *Searle et al.*, 1999]. Most recently, Nanga Parbat basement has been exhumed by NW directed thrusting and development of what has generally been described as a large north-south oriented antiform (Figure 2) [*Gansser*, 1964; *Coward et al.*, 1986; *Butler and Prior*, 1988; *Madin et al.*, 1989; *Zeitler et al.*, 1989; *Treloar et al.*, 1991; *Schneider et al.*, 1999a].

2.2. Structure and Tectonics

The NPHM is a polyphase basement massif [*Treloar et al.*, 1991; *Wheeler et al.*, 1995] which records evidence of both Precambrian and Tertiary structural and metamorphic overprinting. The antiformal massif is bounded by young reverse faults with opposing dips, thus defining a crustal-scale popup structure having a dominant vergence to the northwest (Figure 3) [*Schneider et al.*, 1999a]. Active faulting is common within the massif and includes the substantial northwest directed Raikhot thrust system (Figure 3), which places basement over Pleistocene gravels [*Butler and Prior*, 1988; *Madin et al.*, 1989; *Shroder et al.*, 1989] and is currently propagating to the northwest into the adjacent Kohistan terrane [*Schneider et al.*, 1999a]. The Raikhot Fault defines the western margin of the NPHM and in part cuts out the trace of the Main Mantle Thrust, the original suture between Kohistan and India, but elsewhere, this contact is preserved, although overprinted by the Raikhot Fault along the northwest NPHM margin. The southeastern structural margin of the massif is defined by the southeast directed Rupal-Chichi Shear Zone, which occurs as a broad ~5 km swath of S-C mylonites; zircon and monazite U-Pb and biotite Ar-Ar age data imply that this ductile shear zone began significant activity at or shortly before 10 Ma [*Schneider et al.*, 1999b]. Overall, the NPHM's eastern boundary with adjacent rocks of the Kohistan terrane is sharp, with the Main Mantle Thrust zone preserved unmodified except for being

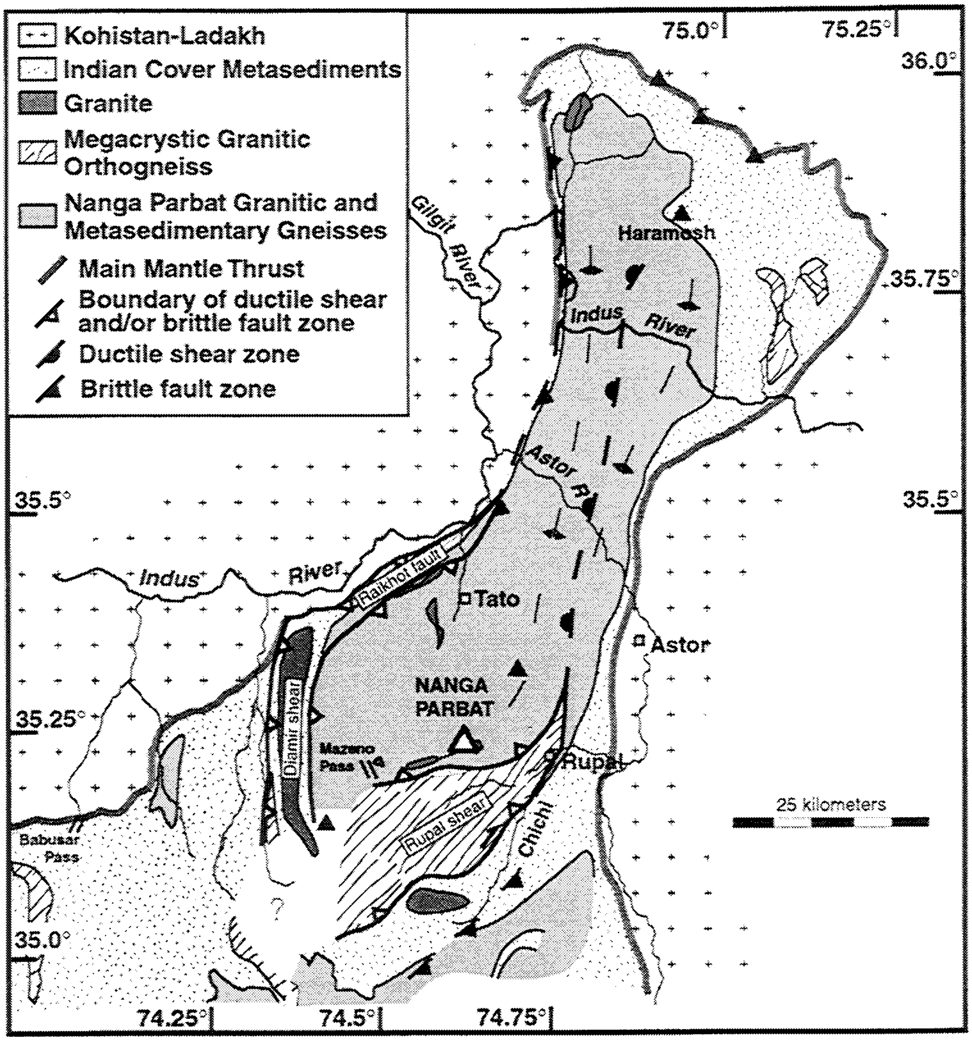

Figure 3. Geological sketch map of the Nanga Parbat-Haramosh Massif (after *Schneider* [1999]), showing main rock units, structures, and localities referred to in text.

folded upward by the rise of the NPHM antiform [*Schneider et al.*, 1999a]. To the southwest the boundary between Nanga Parbat gneisses and largely cover rocks of the Indian plate occurs as the Diamir Shear Zone, a continuation to the southwest of the Raikhot Fault. The shear zone comprises dominantly plutonic rocks of the Jalhari biotite granite intruded into pelitic and calcareous metasediments, all cut by pervasive thrust-sense shear zones and faults [*Schneider et al.*, 1999a; *Edwards et al.*, 2000]. There is a pronounced metamorphic gradient developed across the Diamir shear, from cordierite-K-feldspar grade within the massif to staurolite-garnet to the west, requiring significant excision of metamorphic section [*Poage et al.*, 2000].

Within the Nanga Parbat massif, cooling ages of biotites range between 1 and 5 Ma and, on all of the massif's sides, define sharp boundaries coincident with young or active structures; biotite ages within the core of the massif are <3 Myr (Plates 1 and 2a) [*Winslow et al.*, 1996; *Schneider*, 1999; *Schneider et al.*, 2001]. Over the past several million years the massif has experienced (and continues to experience) locally WNW-ESE directed shortening, possibly related to radial spreading of the greater Himalayan arc [*McCaffrey and Nabelek*, 1998; *Seeber and Pecher*, 1998] or, alternatively, transpression associated with strike-slip displacement along the Karakorum fault system [*Seeber and Pecher*, 1998; *Schneider et al.*, 2001]. This shortening is superimposed on the dominant N-S convergence being experienced in the western Himalaya [*Holt and Haines*, 1993; *Bernard et al.*, 2000], and decoupling of some sort presumably occurs at depth [e.g., *Seeber and Armbruster*, 1979].

It is important to emphasize that no significant tectonic exhumation younger than ~20 Ma has been documented within or near the Nanga Parbat massif, as discussed by *Edwards* [1998], *Schneider et al.* [1999a], and *Edwards et al.* [2000]. While logistical and physical limitations curbed our efforts short of complete coverage, we trekked into and mapped lithologies and structures in most valleys entering the Nanga Parbat massif. Our mapping also incorporated careful examination of a Landsat thematic mapper image [seven-band, 30 m resolution] which has zero cloud cover and an exceptionally high snow line. The geographic distribution of our ground observations and isotopic cooling age samples are quite sufficiently well distributed relative to the overall Nanga Parbat structure for us to be very confident that we have not missed an unknown shear zone or fault of any first-order significance, either of normal or of thrust sense. Evidence for tectonic exhumation to the west-southwest of Nanga Parbat near Babusar Pass [*Hubbard et al.,* 1995] most likely is related to a period of extension experienced along the Main Mantle Thrust zone [*Treloar and Coward,* 1989] and, in any case, is constrained by geochronological data to be no more recent than ~20 Ma [*Chamberlain et al.,* 1991], too early to be relevant to the Neogene metamorphic event at Nanga Parbat.

Within the Raikhot-Diamir system along the northwestern side of the massif (Figure 3), brittle moderately to steeply east dipping faults with clear east side up slickenfibers overprint a wide ductile shear zone, which also has moderate to steeply east dipping foliation with highly consistent east side up shear-sense indicators. That the biotite cooling age gradient is localized across this zone and indicates rapid cooling in the 5-1 Ma age range suggests that these structures are congruent and that the ductile zone is not rotated relative to the faults. We think the most plausible hypothesis is that the whole Raikhot-Diamir shear zone and faults are a progressive response to upward and approximately west-northwestward thrust movement of the core of the Nanga Parbat massif.

Along the southeastern side of the massif the oblique thrust and dextral strike-slip ductile shear zone defined by the S/C mylonites of the Rupal-Chichi shear zone (Figure 3) has a metamorphic contrast across it, similar to that for the Diamir shear zone portion of the western side of the massif, from cordierite–K-feldspar in the higher parts of the northwest Rupal Valley wall to staurolite-kyanite within and east of the Rupal-Chichi shear zone proper. It is important to recognize that the metamorphic contrast, like that across the Diamir zone, is not observably abrupt on the scale of a few meters to a few hundred meters, such as is common for large normal-sense low-angle detachments, nor does it anywhere involve a metamorphic grade decrease to greenschist facies or no-grade sedimentary rocks, also characteristic of original large normal-sense detachments. Again, the major and significant part of the biotite cooling age gradient for the southeast side of the Nanga Parbat massif coincides with this shear zone, from 1 or 2 Ma on the northwest side to 10 Ma and older outboard of the shear zone. Since staurolite-grade rocks represent temperatures well above 300°C and occur outboard of the shear zone, it seems to us implausible that the Rupal-Chichi Shear Zone could have been a normal-sense detachment, at least for the growth of the NP massif, which is constrained by our isotopic ages to have been largely a product of the last 10 Myr.

2.3. Petrology, Geochronology, and Geochemistry

2.3.1. Protolith and early metamorphic history. Nanga Parbat exposes mostly monotonous, highly foliated tonalitic biotite gneisses, with minor amounts of more heterogeneous, marble- and pelite-bearing metasediments and a few bodies of younger granitic gneisses. U and Th contents of gneisses within the core of the massif rocks are quite high (~28 ppm Th and 7 ppm U) and nearly a factor of 2 higher than rocks in the cover sequence (~15 ppm Th and 4 ppm U). Most metamorphic units give consistent U-Pb zircon ages of ~1850 Ma with some indication of an older ~2600 Ma component [*Zeitler et al.*, 1989; *Zeitler and Chamberlain*, 1991; *Schneider et al.*, 1999b, 1999c, 2001]. At one locality, zircons from the granitic Shengus gneiss yield an age of ~500 Ma and strong evidence for a ~2600 Ma inherited component [*Zeitler et al.*, 1989]; *Schneider et al.* [1999a, 2001] report similar results from granitoid units along the eastern parts of the NPHM. Nd-Sm analyses of mafic dikes that cut basement fabrics in several parts of the NPHM [*Treloar et al.*, 2000a] suggest the dikes are of Proterozoic age and confirm the inference from U-Pb zircon ages [*Zeitler et al.*, 1989] that the massif represents a polymetamorphic terrane that experienced an early, pre-Himalayan high-grade metamorphism. Additional Nd-Sm measurements [*Whittington et al.*, 1999a] show that for the most part, Nanga Parbat gneisses are a high-grade expression of the Lesser Himalayan sequence and are not correlative with the metamorphic sequence developed in the Higher Himalayan Crystalline Series, as has been widely assumed [e.g., *Le Fort,* 1989].

NPHM gneisses experienced an early high-pressure metamorphism [*Misch*, 1949; *Chamberlain et al.*, 1989; *Winslow et al.*, 1995; *Pognante et al.*, 1993; *Kattak*, 1995; *Whittington*, 1997; *Whittington et al.*, 1998, 1999b; *Poage et al.*, 2000], the origin of which is uncertain and could encompass episodes of either Precambrian age [e.g., *Treloar et al.*, 1991; *Wheeler et al.*, 1995; *Treloar et al.*, 2000a], Tertiary age [*Chamberlain et al.*, 1989; *Smith et al.*, 1992], or, almost certainly, both. Recent discovery [*Schneider et al.*, 1999b] of a 22-24 Ma granite pluton immediately adjacent to the Nanga Parbat massif and early Tertiary garnet Nd-Sm ages from within the NPHM [*Foster et al.*, 1999a, 1999b] provide unequivocal evidence for occurrence of "typical" Himalayan age metamorphism here in the far northwestern Himalaya. In summary, Nanga Parbat basement is of Lesser Himalayan affinity, has high radiogenic heat production, and is polymetamorphic, showing evidence for a 2600 Ma protolith, a major 1850 Ma overprint, and "Himalayan" metamorphism and granite emplacement, all a prelude to the Neogene and Recent (?) metamorphic event discussed below.

2.3.2. Neogene granites and granulite overprint. Over the past several million years the central portions of the Nanga Parbat antiform have experienced a distinctive petrological overprint involving pervasive fluid flow, granite intrusion, granulite-facies metamorphism, and migmatization [*Misch*, 1949; *Smith et al.*, 1992; *Zeitler et al.*, 1993; *Chamberlain et al.*, 1995; *Khattak*, 1995; *Winslow et al.*, 1995; *Butler et al.*, 1997; *Whittington*, 1997; *Whittington et al.*, 1998, 1999b; *Poage et al.*, 2000]. Along and to the north of Nanga Parbat's summit massif, concentric isograds culminate in cordierite–K-feldspar–sillimanite grade (Plate 2b) [*Winslow et al.*, 1995; *Whittington*, 1997; *Poage et al.*, 2000]. In this central region of the massif a moderate number of undeformed granitoid dikes and pegmatites as well as a few small bodies of undeformed granite occur with ages ranging between 1 and 2 Ma [*Zeitler et al.*, 1993; *Schneider et al.*, 1999c]. Similar rocks also occur throughout the entire massif but outside the central region have ages ranging from 5 to 10 Ma [*Zeitler and Chamberlain*, 1991; *Schneider et al.*, 1999c,

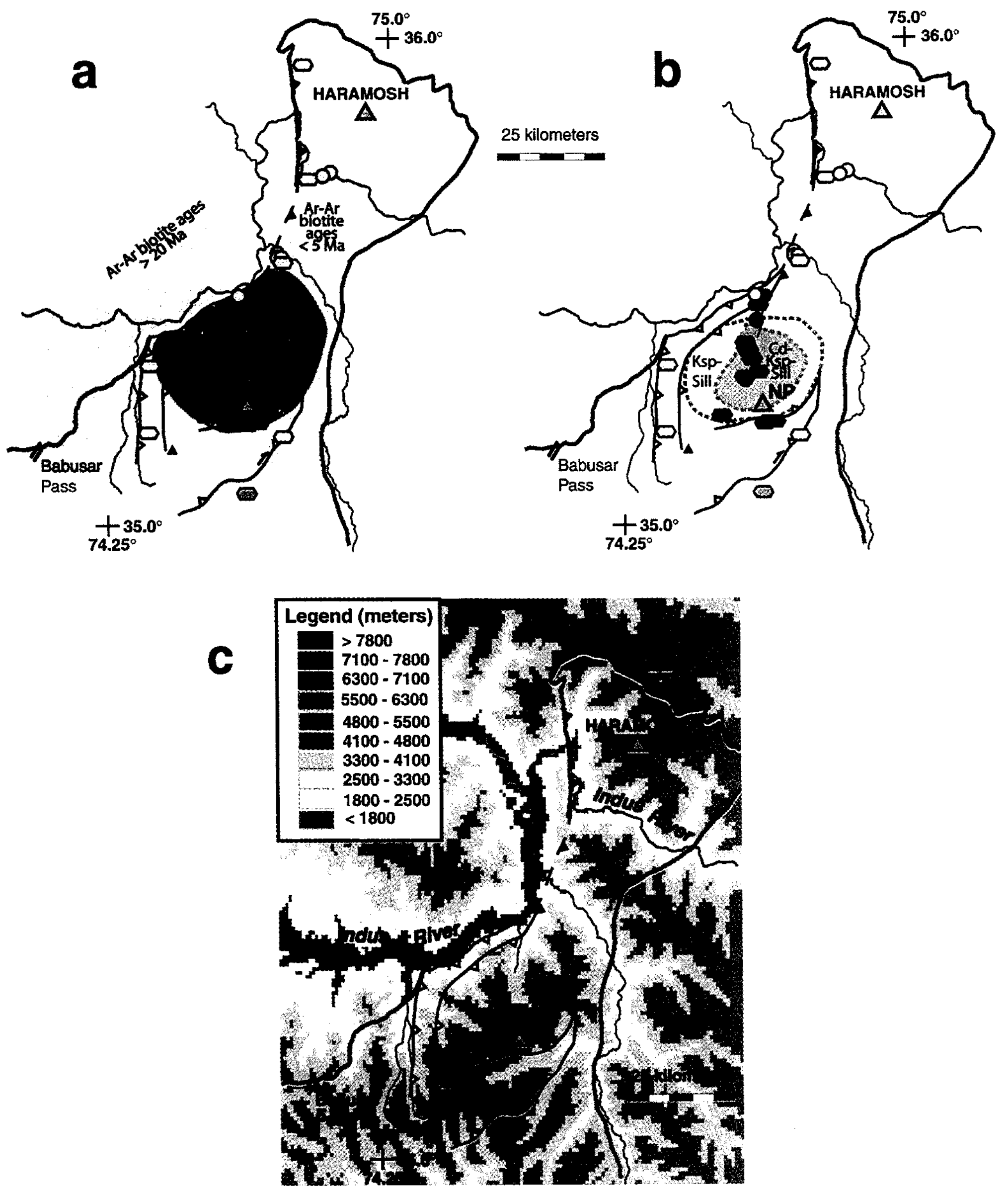

Plate 2. Comparison of key Nanga Parbat data sets showing coincidence of significant geological and geophysical anomalies within the core of the NPHM, near and just to north of the summit massif of Nanga Parbat. Sections shown in Plates 2d-2f are all to same scale. (a) Geochronological data. Ar-Ar biotite cooling ages are as follows: > 20 Ma, green; < 5 Ma, pink; < 3 Ma, red. U-Pb or Th-Pb ages on granite dikes and stocks are polygons. U-Pb and Th-Pb ages on metamorphic monazites are circles. All U-Pb and Th-Pb ages are as follows: red, ages < 2 Ma; yellow, ages 2 – 15 Ma; violet, ages > 15 Ma. Sources are *Schneider et al.* [1999a, 1999b, 1999c], *Schneider* [1999], *Zeitler and Chamberlain* [1991], *Smith et al.* [1992], and *Zeitler et al.* [1993]. (b) Location of high-grade metamorphic assemblages. K-feldspar–sillimanite (pale orange) and cordierite–K-feldspar–sillimanite (bluish green) are shown [*Poage et al.*, 2000]. U-Pb and Th-Pb geochronological data from Plate 2a are reproduced for comparison. (c) Topography around NPHM. Note significant erosional gap cut by Indus River to the northwest of the NPHM. Source is GTOPO30 database. (d) Seismicity. Microearthquake epicenters, red dots; blue triangles, station locations. Source is *Meltzer et al.* [2001]. Section shows distribution of seismicity with depth, including sharp bottom cutoff and upward deflecting beneath region of maximum rapid exhumation as inferred from high-grade assemblages (see Plate 2b). (e) Tomography. Map view shows (in red) region of low P wave velocities in middle crust and (in yellow) region of high S-wave attenuation in middle crust. Section view shows region of crust having very high electrical resistivity of a minimum of 1000 ohm m (dashed line). Source is *Meltzer et al.* [2001]. (f) Section showing magnetotelluric results. Source is *Park and Mackie* [2000].

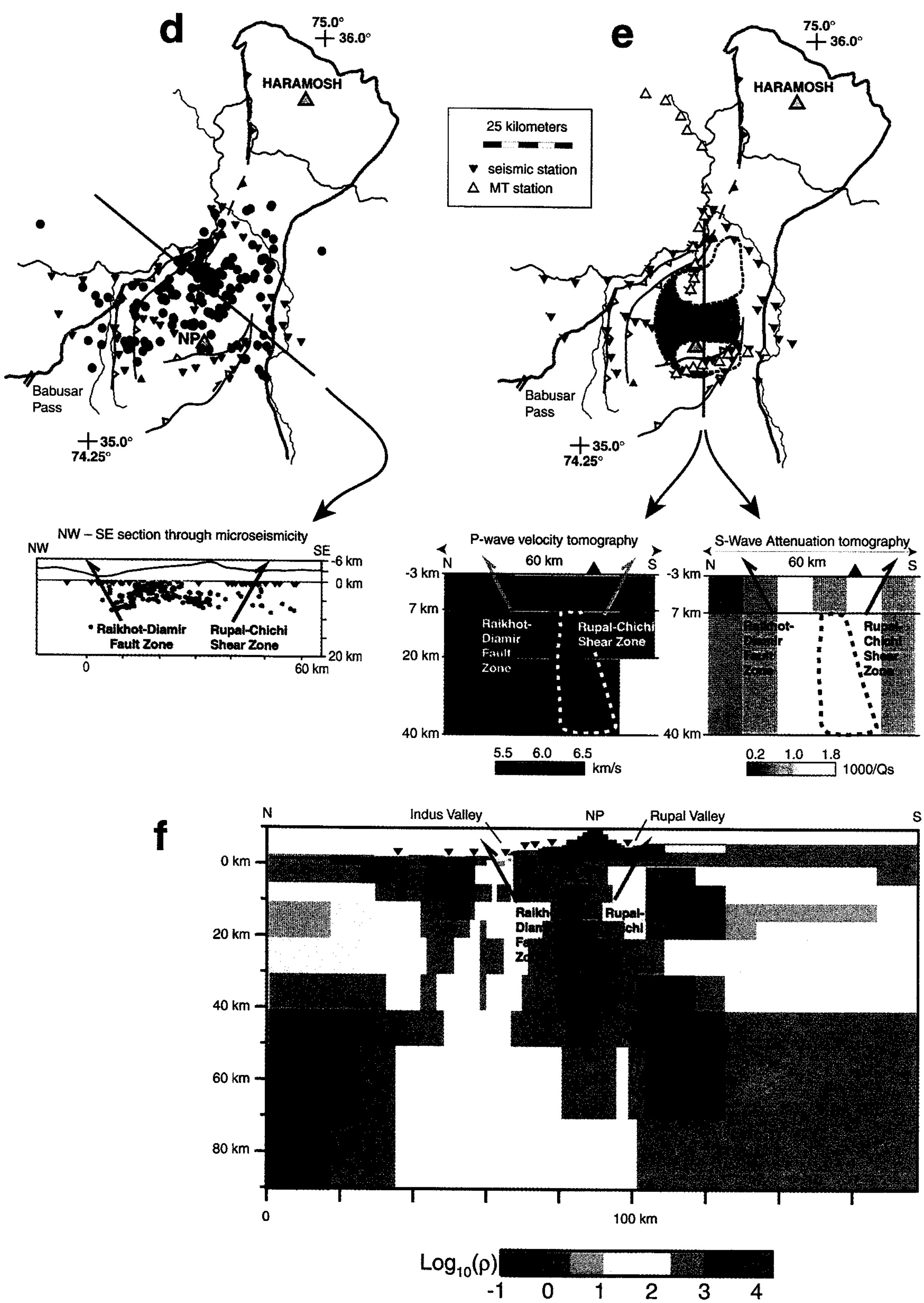

Plate 2. (continued)

2001]. Generally, within the NPHM and locally near the core of the massif, the ages of these igneous units young progressively toward the summit region. Monazite ages of as young as 3.3 Ma on migmatites of known *P-T* conditions suggest cooling rates for exposed surface rocks of well over 200°C/Myr and unroofing in the past 3 Myr of some 15-20 km at rates of ~5 km/Myr [*Zeitler et al.*, 1993; *Whittington*, 1996, 1997]. Thus, in at least several cases, granite emplacement took place during exhumation, leading to the suggestion that many of the young Nanga Parbat granites owe their origin to dehydration melting during decompression caused by erosion [*Zeitler and Chamberlain*, 1991; *Butler et al.*, 1997; *Whittington et al.*, 1999b].

The duration of the young overprint within the core of the NPHM is not well constrained. The young accessory mineral ages from this active region very likely reflect a continuum process (see discussion below) and thus would not provide a constraint on the start of the most recent metamorphic overprinting. *Treloar et al.* [2000b] have argued that many of the hornblende Ar-Ar ages of between 20 and 30 Ma from within the NPHM date cooling from an earlier Himalayan metamorphic episode, in contrast to the conclusion that these ages reflect incorporation of excess Ar and therefore are at best maximum ages [*Zeitler et al.*, 1989; *Smith et al.*, 1992]. If so, then these ages provide a maximum constraint on the age of the overprint, albeit not a tight one. On the basis of metamorphic-zircon depth-profiling data reported by *Winslow et al.* [1996], metamorphic monazite data from NPHM gneisses reported by *Smith et al.* [1992], and granite and shear-zone accessory-mineral data reported by *Schneider et al.* [1999b, 1999c, 2001], *Schneider et al.* [2001] have argued that the NPHM experienced doming and some anatexis beginning sometime in the interval 15-10 Ma, with subsequent magmatic activity and deformation migrating progressively inward toward the presently active core of the massif.

2.3.3. Fluid inclusions and fluid flow. The Nanga Parbat massif hosts a dual fluid-flow system, as shown by fluid-inclusion data, field observations, and Sr, O, and H isotopic measurements [*Craw et al.*, 1994, 1997; *Winslow et al.*, 1994; *Chamberlain et al.*, 1995; *Gazis et al.*, 1998; *Poage et al.*, 2000]. The upper crustal portion of this system extends as deep as ~5 km below mean surface elevation and is dominated by flow driven by steep topographic gradients and downward infiltration of meteoric water. Hydrothermal activity associated with this shallower flow, manifested as fossil and active hot springs, is widespread, although the absolute amounts of fluid are not high and the chemistry of the waters is rock dominated. Magnetotelluric data (see below) suggest that locally along major shear zones, fluids may be driven to considerable depths [*Park and Mackie*, 1997], and unusual cordierite-rich seams within the core of the massif record localized melting or metasomatism due to local penetration of fluid into rocks at depths of ~10 km [*Whittington et al.*, 1999b; *Whittington*, 1997], although the source of this fluid has not been established.

Deeper flow, driven in part by temperature gradients associated with upwards advected isotherms within the massif, is dominated by CO_2-rich fluids. The water-dominated system is confined to the core of the massif, and the CO_2-dominated portion occurs along its margins, particularly to the east. *Poage et al.* [2000] interpret this distribution as reflecting the tectonic history of these exposures, with the core of the massif exhibiting fluids associated with the current metamorphic overprint, and the margins exhibiting fluids associated with Himalayan (or older) metamorphism.

Fluid inclusion studies provide additional information on the recent crustal environment within the core of the massif. *Winslow et al.* [1994] estimated thermal gradients in the top ~3 km of the crust to be as high as 100°C/km and, combining fluid inclusion pressure-temperature (*P-T*) estimates with $^{40}Ar/^{39}Ar$ biotite cooling ages, determined exhumation rates over the past 1 Myr to be 3-6 km/Myr Within the core of the massif, fluid inclusions are found which indicate the presence of both boiling and dry-steam zones [*Craw et al.*, 1994, 1997; *Poage et al.*, 2000], consistent with expectations based on the high rates of exhumation. In this region, brittle fractures which cut young structures have primary fluid inclusions with homogenization temperatures up to ~415°C, whereas inclusions in veins showing ductile deformation indicate temperatures of ~450°C. On the basis of these data, the brittle-ductile transition beneath the core of the massif should occur at temperatures centered around 400°C, at a depth below the surface of ~5 km (see section 2.5.1).

2.4. Geomorphology

The Indus River cuts a tight east-west canyon directly across the northern Nanga Parbat-Haramosh Massif, maintaining grade across the active Raikhot Fault system, after which its flow is augmented significantly at its confluence with the Gilgit River (Plate 2C). The modern Indus then turns toward the south, directly along the active northwestern thrust front of the Nanga Parbat massif at a relatively low elevation of ~1000 m (Plate 2c), excavating a deep valley between Nanga Parbat and the adjacent Kohistan terrane, establishing extreme local relief, and providing for highly efficient removal of detritus from the region. The evolution of the ancestral path of the Indus is not certain and may have been influenced by both local and regional tectonics. Upstream of Nanga Parbat, the thick fluvial sediments of the Bunthang Sequence [*Cronin et al.*, 1989] suggest that for at least the past million years, uplift along the Raikhot fault may have ponded the Indus at times. At a more regional scale it is generally accepted that the Indus is antecedent with respect to the development of the NPHM, given the way it has maintained its course directly across the Nanga Parbat antiform. It has been suggested that the river's current turn toward the south reflects relatively recent capture, with the ancestral river having taken a more circuitous route to the foreland by first flowing to the west-northwest through the Gilgit Valley before turning southwest toward Afghanistan [*Brookfield*, 1998]. Direct evidence for this speculation has not yet been identified, and it is equally plausible that the river has followed its current course for at least several million years.

The great relief defined by Nanga Parbat and the adjacent Indus River (~7000 m) is associated with unroofing rates averaging at least 5 mm/yr over the long term, as documented at several timescales by geomorphic, petrologic, and fluid inclusion studies [*Zeitler et al.*, 1993; *Gardner and Jones*, 1993; *Craw et al.*, 1994; *Winslow et al.*, 1995; *Craw et al.*, 1997; *Whittington*, 1997; *Shroder et al.*, 1999; *Shroder and Bishop*, 2000]. Fluvial incision rates have been measured along the Indus River where it crosses the NPHM and are among the highest in the world, reaching 12 mm/yr [*Burbank et al.*, 1996]. Denudation of small high-elevation alpine basins reaches several millimeters per year [*Shroder et al.*, 1999], and fluvial flushing rates are extremely high, locally achieving rates of several centimeters per year [*Shroder et al.*, 1998, 2000; *Shroder and Bishop*, 2000]. Recently, *Finlayson et al.* [2000] have calculated erosion indices for catchments along the entire southern flank of the Himalaya, and they conclude that erosion potential within the interiors of the Himalayan syntaxes, along the Indus near Nanga Parbat, and along the Tsangpo at Namche Barwa should be up to 3 times greater than along the central portions of the range.

Exhumation processes at Nanga Parbat have been dominated by mass movement, glaciation, and river incision for at least the past 55 kyr. Glaciation has been much more widespread spatially and has been monsoon driven and temporally asynchronous to Northern Hemisphere ice sheet volumes [*Phillips et al.*, 2000]. Diverse field measurements of local, short-term incision rates average 2.2 cm±1.1 cm/yr at lower valley mouths [*Shroder and Bishop*, 2000; *Bishop and Shroder*, 2000]. Slopes in the region are steep at both high and low elevations, averaging some 32° and having a mode of 37° [*Burbank et al.*, 1996; *Bishop and Shroder*, 2000]. *Burbank et al.* [1996] argued that these slopes reflect the angle of internal friction of local bedrock, with landsliding keeping pace with rapid downward incision along the Indus and major tributaries. All in all, the lack of evidence for tectonic exhumation [*Schneider et al.*, 1999a; *Edwards*, 1998] dovetails with studies of denudation around the massif which indicate that erosional processes are sufficient to provide the exhumation required by petrologic and other studies.

2.5. Geophysics

Seismic and magnetotelluric studies undertaken as part of the Nanga Parbat project provide new constraints on the dynamics of the Nanga Parbat massif and provide a view into crust that is likely to be undergoing high-grade metamorphism at the present time. Seismic work included a 4 month PASSCAL deployment of a dense 50 station array of short-period instruments (Plate 2d), distributed over an approximately 75 x 75 km area in and around the central Nanga Parbat massif, augmented with several broadband stations distributed locally and regionally [*Meltzer et al.*, 2001]. The array recorded some 380 well-located local events and some 1500 associated events in total. The magnetotelluric (MT) studies involved two orthogonal transects though the central portions of the Nanga Parbat massif (Plate 2e), made with station spacings of between 2 and 10 km and recordings made over periods ranging from 0.008 to 1024 s [*Park and Mackie*, 1997, 2000].

2.5.1. Microseismicity. Around Nanga Parbat, microseismicity is laterally confined almost entirely within Indian plate rocks of the central NPHM itself (Plate 2d) [*Meltzer et al.*, 2001]. Vertically, seismicity is delineated by an abrupt cutoff at shallow depths. Approximately 90% of the microseismicity is observed at depths ≤ 2 km below sea level (bsl) (~5-6 km below the average topographic surface). Two thirds of these events locate above sea level. The base of seismicity forms a prominent antiformal shape beneath the massif and exhibits considerable structural relief, ~3 km in a lateral distance of 12 km. The apex of this antiform occurs at 5 km depth bsl and is offset ~10 km northwest of the core of the massif's topographic ridge crest, where petrological and cooling age studies suggest the locus of most rapid advection and exhumation is located (Plate 2a,b), and where a corresponding upward deflection of isotherms would be expected. The base of seismicity deepens to 8 km bsl to the northwest and southeast, mapping a thermal boundary and a transition between brittle and plastic deformation. There is no seismicity deeper than 8 km depth (bsl) beneath the massif. The transition between brittle and plastic deformation takes place over an ~3 km thick zone extending upward from the base of seismicity and corresponds to a region where temperatures reach 400°-450°C [*Meltzer et al.*, 2001]. This interpretation is consistent with fluid inclusion studies from veins with brittle fractures cutting young structures in the core of the massif. The fluid inclusions include a vapor-rich phase that homogenized at temperatures up to 415°C [*Craw et al.*, 1994, 1997; *Winslow et al.*, 1995]. Fluid inclusions from veins showing ductile deformation are inferred to have equilibrated at 450°C.

2.5.2. Tomography and other constraints. P and S wave velocities immediately below the central portions of the Nanga Parbat massif are as much as 10% lower in comparison to Indian plate rocks of the surrounding massif (Plate 2) [*Meltzer et al.*, 2001]. Three-dimensional joint inversion for hypocenter location, V_p, and V_s indicates that low velocities apply to the entire crust as well as the uppermost mantle and the region of anomalously low velocity corresponds to a zone of high attenuation, 3 times larger than surrounding areas. Preliminary analyses yield a depth to Moho beneath the massif of only ~40 km. These tomographic results suggest essentially isothermal conditions in the middle to lower crust beneath the core of the massif.

Neither seismic velocities nor waveforms show evidence for an extensive body of melt located beneath the Nanga Parbat massif, although local travel time delays and anomalous waveforms may indicate small zones of partial melt. Although many of the local events recorded by the array show impulsive arrivals, a number of other arrivals have a harmonic character much like those seen in active hydrothermal systems.

2.5.3. Magnetotelluric results. Magnetotelluric surveys [*Park and Mackie*, 1997, 2000] show that the deeper crust beneath Nanga Parbat is electrically homogeneous and, surprisingly, that the middle and lower portions of the crust directly beneath the central Nanga Parbat massif are quite electrically resistive to depths of at least 50 km below sea level, with minimum values of resistivity of 1000 ohm m (Plate 2f). In contrast, above 1 km bsl the shallowest parts of the crust are quite conductive. The Raikhot Fault Zone appears as a conductive zone extending to 10 km below sea level, and to the south of Nanga Parbat and the Rupal valley, inversion of the MT data also locates a highly conductive zone in the middle crust. Although this conductor lies outside the area surveyed, sensitivity tests suggest that the feature is robust.

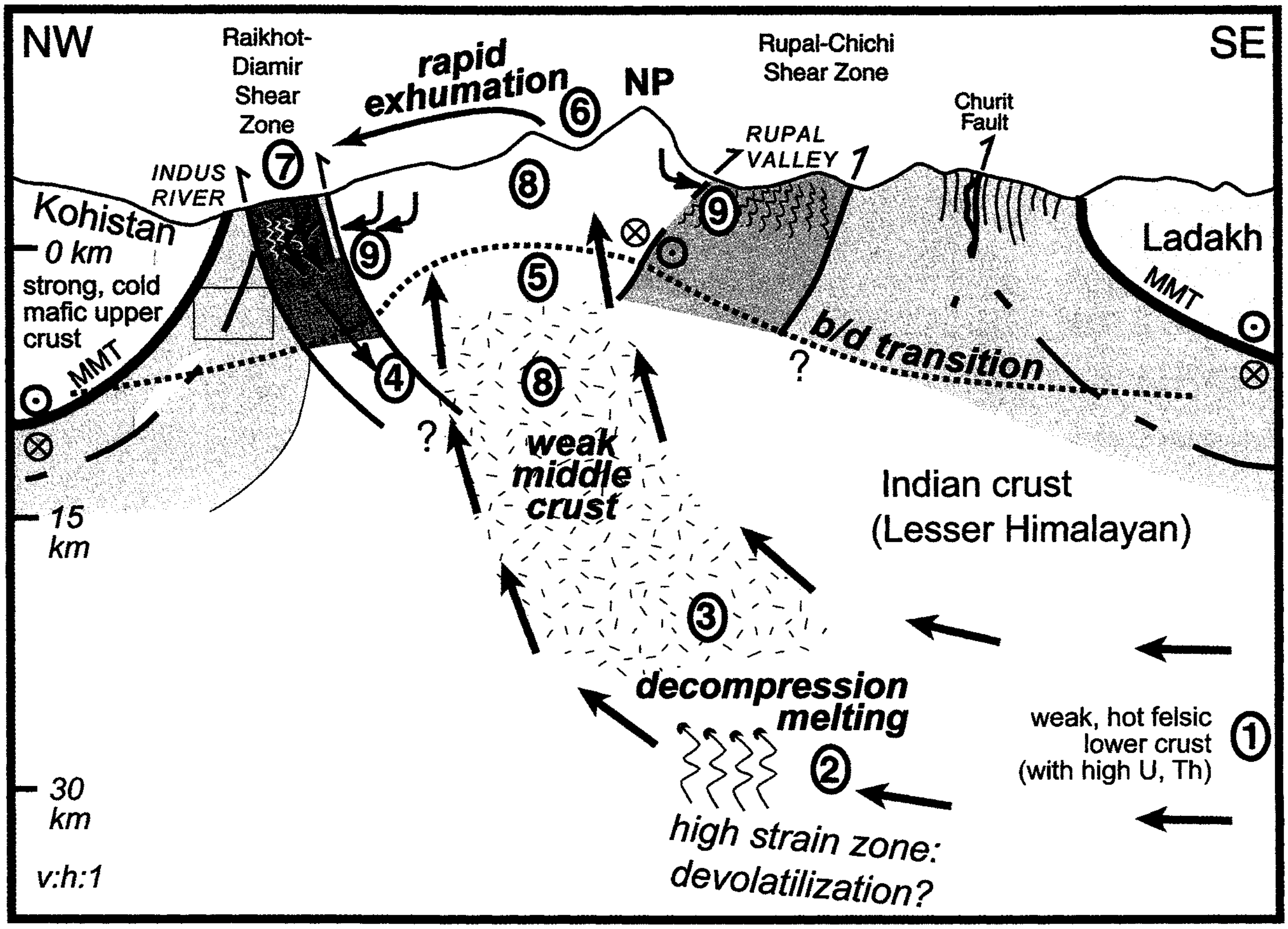

Plate 3. Sketch illustrating erosional-rheological coupling manifested as a tectonic aneurysm at Nanga Parbat. Incision of a large-magnitude river gorge into rheologically heterogeneous crust significantly weakens the crust and causes positive feedbacks to develop as crust flows into weak zone; rapid advection of material here builds mountain over weak crust, at point of maximum exhumation rate, as river continues to remove material and maintain topographic gap. Specific features are as follows: (1) warm, previously metamorphosed crustal material enters the system and (2) passes through a high-strain zone and further devolatilizes. (3) Dehydrated rock enters region of rapid exhumation where decompression melting occurs (shallower, water-saturated melting also can occur where rock encounters water, possibly kneaded into massif along shear zones (4)). Focusing of strain leads to rapid advection and (5) elevation of isotherms and the brittle-ductile transition (as well as localization of microseismicity above this zone); weakening of the upper crust (potentially a positive feedback); (6) counterintuitive localization of high topography over the weak zone, aided by efficient erosion (7); (8) exposure of low-pressure/high-temperature migmatites showing a strong decompression path; and (9) development of strong meteoric circulation systems.

The MT data rule out the presence of an extensive body of hydrous melt as well as large volumes of interconnected fluids: beneath Nanga Parbat the measured resistivities amount to at most 0.004% interconnected hydrous fluid in the middle and lower crust. Such resistive values are unique for the middle crust, which has generally been found to be relatively conductive. The observation of enhanced conductivity at shallow levels and along the Raikhot support the inference from stable isotope and fluid inclusion data that Nanga Parbat hosts a dual hydrothermal system (see above).

2.5.4. Synthesis of geophysical data. Together, our seismic and magnetotelluric studies show no evidence for a volumetrically significant hydrous magma, ruling out contact metamorphism and large-scale plutonism at Nanga Parbat as an explanation for the heat flow, radiometric age, petrologic, and fluid flow anomalies evident at the surface. If partial melt or magma bodies are present, they are of small extent and are not associated with interconnected aqueous fluids. The most direct interpretation of our geophsyical data is that the core of the Nanga Parbat massif and its significant topography are developed above dry, hot, thin, weak crust, consistent with the inference that the very young Nanga Parbat granites owe their origin to decompression melting, [*Zeitler and Chamberlain*, 1991; *Whittington*, 1997; *Whittington et al.*, 1999b].

2.6. Summary of Geological and Geophysical Data: Is Nanga Parbat Anomalous?

The picture that emerges at Nanga Parbat is of a polymetamorphic basement massif that has been and is undergoing an episode of pronounced but focused crustal reworking; by this we mean pervasive deformation, young metamorphism and limited melting, widespread fluid flow, rapid and pronounced erosional exhumation, and shaping of the crust into spectacular, steep topography. Within or near the Nanga Parbat's summit massif are found the massif's most extreme topography and relief, exposures of very young cordierite-bearing granulite-grade migmatites, the crest of a young and active crustal-scale antiformal popup structure, young 1-2 Ma granitoids, abundant seismicity with sharp bottom and lateral cutoffs, widespread upper crustal hydrothermal activity involving dry steam, steep near-surface thermal gradients, and rapid denudation documented across a wide range of time scales, and all these features are developed above a volume of crust that is hot and dry, as suggested by low seismic velocities, high attenuation of seismic wave propagation, and high electrical resistance (Plate 2).

In our view, the Nanga Parbat massif exhibits several anomalous features which set it apart from other high-grade terranes in the Himalaya: it has experienced a Neogene metamorphic and anatectic event not reported elsewhere (with one exception; see discussion about Namche Barwa later in this section). Certainly, significant, steep relief is common along the Himalayan arc, and other occurrences have been reported from the High Himalaya of high-grade migmatites intruded by dehydration melts correlated to decompression [e.g., *Davidson et al.*, 1997]. However, what distinguishes Nanga Parbat are (1) Neogene anatexis and metamorphism imprinted on Lesser Himalayan crust, (2) at quite local scale, the geographic coincidence of these phenomena with the active structures of the Nanga Parbat antiform, and (3) the rapid and recent exhumation of these young granites and migmatites by erosional processes not low-angle normal faulting, erosional processes that are likely to be several times more energetic than in the central Himalaya [*Finlayson et al.*, 2000]. Because the degree to which the Neogene metamorphic event at Nanga Parbat is anomalous bears directly on the model we discuss below, a comparison to other high-grade exposures deserves some attention.

To the southwest of Nanga Parbat in Indian plate rocks of the Himalaya of Pakistan, the Barrovian series metamorphism nowhere reaches levels attained at Nanga Parbat [*Desio*, 1977; *Treloar et al.*, 1989a; *Chamberlain et al.*, 1991; *DiPietro*, 1991; *Pognante anad Spencer*, 1991; *Pognante et al.*, 1993; *Smith et al.*, 1994; *O'Brien et al.*, 2000], and only extremely minor exposures of anatectic melts have been reported [*Zeitler and Chamberlain*, 1991]. The age for this generally higher-pressure metamorphism is early to mid-Tertiary [*Zeitler and Chamberlain*, 1991; *Tonarini et al.*, 1993; *Smith et al.*, 1994; *DiPietro et al.*, 1999]. Cooling age patterns [*Zeitler*, 1985; *Zeitler et al.*, 1989; *Treloar et al.*, 1989b] clearly show that significant young exhumation is limited to the Nanga Parbat massif and immediate vicinity, as underscored by biotite cooling age patterns immediately around Nanga Parbat (Plate 1).

Elsewhere in the Himalaya, ages of metamorphism are also considerably older, the abundant leucogranites are mostly ~22-24 Ma in age, and as has been noted in Pakistan [*Treloar et al.*, 1989a], the inverted metamorphic sequences are probably controlled by postmetamorphic thrust stacking [*Harrison et al.*, 1998, 1999]. Recent work has documented some younger regional metamorphism not associated with early movement on the Main Central Thrust or extensional collapse [e.g., *Harrison et al.*, 1997], but the ages of ~6 Ma and older are greater than those seen at Nanga Parbat, and inferred rates of long-term exhumation would be correspondingly greater as well. Further, a key element in the metamorphic evolution of the Higher Himalayan Crystallines in the central Himalaya is the presence of the Southern Tibetan Detachment System [*Burchfiel and Royden*, 1985], which has been responsible for a considerable degree of tectonic exhumation [*Hodges et al.*, 1993] that has been invoked as a cause for the dehydration melts [*Harris and Massey*, 1994] and decompression textures [e.g., *Davidson et al.*, 1997] observed in the High Himalaya.

One other locality in the Himalaya does appear to share a number of attributes with Nanga Parbat, the Namche Barwa massif located within the core of the eastern Himalayan syntaxis (Figure 1). Recent studies [*Burg et al.*, 1997; *Liu and Zhong*, 1997] describe Namche Barwa as a north plunging antiformal structure which exposes young 2-3 Ma, rapidly cooled, low-pressure granulites and migmatites which have overprinted Indian basement of Precambrian age. Bounded by active shear zones and replete with hot springs, the Namche Barwa massif is traversed by a major river, the Tsangpo, which together with Namche Barwa and related peaks, defines a gorge with nearly 7 km of local relief as it turns toward the foreland through the eastern Himalayan syntaxis, much in the way that Nanga Parbat and the Indus River define over 7 km of local relief within the western syntaxis.

3. Discussion: Origin of Active Himalayan Metamorphic Massifs

The ensemble of young, active phenomena observed at Nanga Parbat is not predicted by conventional mechanical models of collision zones. It has been argued that some features at Nanga Parbat, for example, the young cooling ages and perhaps even the dehydration melting, merely reflect rapid erosion of a thrust slice or "crustal-scale fold" [*Treloar et al.*, 1991; *Wheeler et al.*, 1995; *Butler et al.*, 2000]. However, the features that mark the core of the NPHM as well as the symmetric and, to our knowledge, unique presence of active metamorphic massifs within both Himalayan syntaxes suggests that more is involved in their genesis than passive if rapid erosion.

3.1. Regional Considerations

At first glance, it is not clear what shared features in the Himalayan syntaxes might be responsible for the similar crustal anomalies at Nanga Parbat and Namche Barwa. In contrast to the diffuse western syntaxis [e.g., *Bernard et al.*, 2000], the eastern syntaxis is a well-defined, crisp "indentor corner" generated by changes in velocity conditions at the eastern edge of the Indian indentor [*Koons*, 1995; *Holt et al.*, 1991; *Royden et al.*, 1997]. Its tectonics, geomorphic expression, and kinematics are quite different from those of the western syntaxis, which *Koons and Zeitler* [1997] have proposed to be a "rheological corner" dominated by variations in the geology of the northwestern Indian plate (i.e., rigid Kohistan block; foreland underlain by evaporites).

Despite significant differences in their mechanics, what the eastern and western syntaxes do share are major orogen-traversing rivers. Both the Indus in the west and Tsangpo in the east turn sharply from the Tibetan Plateau to head south into the foreland and, as they do, they cut deep cross-strike gorges, establishing extreme local relief, and facilitating highly efficient evacuation of detritus out of the local system. The cutting of these gorges may be very recent; for both the Indus and, especially, the Tsangpo, the possibility has been raised that river capture within the syntaxes has dramatically diverted these rivers within the past few million years [*Seeber and Gornitz*, 1983; *Koons*, 1995; *Brookfield*, 1998; *Shroder and Bishop*, 2000].

3.2. Suggested Model: Erosionally Facilitated Thermal-Mechanical Coupling ("Tectonic Aneurysm")

A number of authors have suggested how mechanical interactions between erosion and orogenic deformation might occur at many scales, with erosion shifting the dynamics of deforming regions by shifting or eliminating crustal loads [e.g., *Beaumont et al.*, 1992; *Norris and Cooper*, 1997; *Pavlis et al.*, 1997]. The structural response to unloading is often viewed as passive, being either broadly isostatic in nature or involving crustal flow in response to pressure differentials [e.g., *Wdowinski and Axen*, 1992]. On the basis of our observations at Nanga Parbat we propose a dynamical model that incorporates such local-scale feedbacks between erosional unloading and tectonics, such as changes in thermal structure and in crustal rheology due to metamorphic evolution and advection.

Our model operates as follows (see Plate 3). Consider a volume of late orogenic crust that is characterized by high radioactive heat production and has experienced some metamorphism and possibly melting early in collision (e.g., crust of the sort proposed by *Zhao and Morgan*, [1985], *Nelson et al.* [1996], and *Royden et al.* [1997]). This would be the hot, relatively dry protolith for the young metamorphic processes we are trying to explain and, in fact, represents our estimate for conditions prior to development of the Nanga Parbat anomaly. In a syntaxial setting at a plate edge, considerable, varied and ongoing deformation of this warm crust would be expected [*Koons*, 1995; *Seeber and Pecher*, 1998]. Such a syntaxial setting is also likely to see entrainment of a large, orogen-crossing river as it exits from the hinterland to the foreland, excavating a deep set of valleys and gorges as it does so [*Koons* 1995; *Brookfield*, 1998].

If incipient strain within such crust coincides with a deep valley cut by a big river, the crust will tend to deform or fail at this point, where the load is less. This will draw material toward the valley, in proportion to the valley's magnitude, assuming some minimum threshold has been reached in terms of locally diminished crustal load. The immediate consequence of this crustal flow will be to locally weaken the crust still further because as hot lower crust is advected toward the surface, isotherms will rise in it, thermally thinning the normally strong upper crust. Metamorphism and, in particular, limited dehydration melting will also accompany sufficiently rapid decompression of advected lower or middle crust, further altering local rheology and weakening the local crustal column. This will encourage additional deformation and focus strain into the thermally weakened zones, setting up a positive feedback.

In addition, rapid advection will lead to the development of high topography and the development, in concert with the adjacent large river, of significant, steep relief capable of sustaining rapid erosional exhumation. Thus, at least locally, surface and tectonic processes will be in positive feedback in which rapid erosional exhumation facilitates rapid crustal advection, and this rapid advection supports maintenance of the local relief, which in turn drives exhumation. The presence of a large, orogen-crossing river is important in this model in that it possesses sufficient power to establish a low local base level and to evacuate any eroded crustal material completely away from the local system.

The resulting thermal and petrological anomalies associated with this exhumation and concentration of strain would mark what could be thought of as a "tectonic aneurysm." Such a feature could evolve to be quasi-stable as the feedbacks between erosional exhumation, strain focusing, and weakening of the crust come into play. One of the nonintuitive outcomes of such erosional/thermal coupling would be the generation of very large mountains of limited spatial extent perched above weak crust.

3.3. Application of Model to Nanga Parbat

Applied specifically to Nanga Parbat, such a model provides a framework with which to synthesize our observations (Plates 2 and 3). One can view our data in two reference frames, that of material moving into and through the local system (the moving "petrological" reference frame) and that of the crustal column at the present moment (the fixed "geophysical" reference frame). Because of the young and still-active nature of the massif, Nanga Parbat provides a unique opportunity to reconcile observations made from these two vantages, assuming one makes the reasonable assumption that the state of the lower crust today is still germane to the surface geological observations we made of material 1-3 Myr in age.

Material moving toward the Nanga Parbat massif from the east-southeast first enters a high-strain zone below the massif in which already metamorphosed crustal rocks of the Indian plate may undergo additional metamorphic dehydration reactions and devolatilization at depth (Plate 2) [*Koons et al.*, 1998]. Past this point, rocks undergo rapid uplift and decompression as a result of rapid erosional exhumation. They enter a zone characterized by sillimanite-facies stability and dehydration melting, generating small amounts of relatively dry melts which can rise into the massif to relatively shallow levels, as observed at Nanga Parbat [*Schneider et al.*, 2001]. Further rapid exhumation and decompression brings rocks into contact with sufficient fluids at shallower depths of 12-15 km to generate additional melts in the form of the cordierite-bearing granitic seams that are unique to Nanga Parbat [*Whittington*, 1997; *Whittington et al.*, 1998]. Finally, rocks enter what amounts to a thermal boundary layer in which isotherms and the zone of transition from ductile deformation to brittle failure are compressed. At Nanga Parbat, the steep gradients in topography, temperature, and strain rate, as documented by fluid inclusion and seismic data [*Craw et al.*, 1994; *Winslow et al.*, 1995; *Craw et al.*, 1997; *Meltzer et al.*, 2001), are potent forces for redistribution of fluids, manifested in the meteoric-dominated hydrothermal system that is present in the upper crust of the massif core, local penetration of fluids to considerable depths along active faults, and shallow emplacements of melts [*Craw et al.*, 1994, 1997; *Chamberlain et al.*, 1995; *Winslow et al.*, 1995; *Butler et al.*, 1997; *Whittington*, 1997; *Whittington et al.*, 1999b; *Edwards et al.*, 2000].

This model is also consistent with geophysical data from Nanga Parbat which offer the perspective of the fixed reference frame. The zone of high electrical conductivity to the south of Nanga Parbat (Plate 2f) [*Park and Mackie*, 1997, 2000] would correspond to the point where crustal material dehydrates as it encounters high-strain zones. The unusual observation from the MT data that the middle to lower crust below Nanga Parbat is resistive corresponds to the model prediction that lower crustal material will have been dehydrated and contain insufficient connected fluid phase to be electrically conductive. Seismic tomography shows that a lower-velocity lozenge of crust extends to depth beneath the core of the Nanga Parbat massif [*Meltzer et al.*, 2001], consistent with the advective crustal flow patterns predicted by the aneurysm model. Finally, the shallow, upward bowed cutoff in microseismicity (Plate 2d) located where we have inferred greatest amounts and rates of exhumation (Plates 2a and 2b), provides evidence for the upward deflection of the brittle-ductile transition and existence of a thermal boundary layer.

As we noted earlier, the presence of the Indus, a very large, orogen-traversing river, plays a key role in this model. Most directly, the Indus works together with rapid rock uplift rates to establish the extreme relief which can efficiently exhume crust via mass wasting, as the Indus has sufficient power to move any such exhumed material away from the massif. In terms of the evolution of the Nanga Parbat massif, it is widely accepted that the Indus was antecedent to the uplift of the NPHM. In our model, incipient deformation of dehydrated NPHM basement left warm by high radiogenic heat production and the thermal effects of earlier Himalayan metamorphism set the stage for the Indus to amplify deformation and facilitate subsequent petrologic effects by means of rapid erosional exhumation.

3.4. Broader Implications

Within the northwestern Himalaya the Neogene activity within the core of the Nanga Parbat massif is clearly an anomaly that stands out from background patterns in metamorphic facies and timing (see earlier discussion). The exposures of low-pressure granulites and melts at Nanga Parbat thus emphasize the complexities that can be present in an evolving orogen in terms of the distribution and timing of metamorphism and demonstrate that tectonic and geomorphic phenomena associated with plate edges can play a significant role in reshaping the continental crust. An important challenge will be to understand how the signatures of such processes are retained since structures like Nanga Parbat and Namche Barwa might not be preserved in older orogens that have experienced further deformation and regional unroofing to deeper levels. Gneiss domes share a number of similarities with the overall features of Nanga Parbat and are potential candidates as older examples of erosional-thermal coupling [*Koons, 1998*; *Schneider et al.*, 2001].

Another issue that calls for further examination is the local tectonic response that can be brought about by regional-scale coupling between collisional plate edge dynamics and the evolution of large river systems. Stream capture of "outboard," orogen-parallel rivers [*Koons*, 1995] associated with enhanced headward cutting in the Himalayan syntaxes might have done more than just facilitate metamorphism and may, in fact, have played an active role in triggering the formation of the Nanga Parbat and Namche Barwa aneurysms: the timing of development of the Nanga Parbat and Namche Barwa massifs is generally in line with the inferred timing of stream capture for the Indus and Tsangpo, if this, in fact, occurred. Although documenting and dating capture of this magnitude in a rapidly eroding terrain would be difficult, it should be possible, and the relationship between the evolution of big rivers and big mountains could be better established. In this regard, it is worth noting that at ~7.9 Ma, there is a marked increase in the input of high $^{87}Sr/^{86}Sr$ of detrital carbonate in the Siwaliks of Pakistan [*Quade et al.*, 1997]. Since these paleosols represent deposits along the ancestral Indus River, we suggest that it is possible that the increase of high $^{87}Sr/^{86}Sr$ calcite represents the timing of exposure of high $^{87}Sr/^{86}Sr$ calcite-bearing rocks [*Gazis et al.*, 1998; *Blum et al.*, 1998] found in the core of Nanga Parbat.

4. Concluding Remarks

We propose that local, suborogen-scale erosional exhumation at Nanga Parbat (and, we suspect, at Namche

Barwa), far from being overrated [*Whittington*, 1996], is, in fact, of first-order importance in facilitating the metamorphic, topographic, and structural evolution of the interiors of the Himalayan syntaxes. Such pervasive structural and metamorphic overprinting of old basement rocks is a fundamental geodynamic process in its own right. Ultimately, the dynamics of syntaxial metamorphic massifs may be reconciled with broader orogen-scale collision processes through the feedbacks between deformation, topographic evolution, and erosion that lead to the channeling of major river systems through syntaxes [*Koons*, 1995; *Brookfield*, 1998]. Our results contribute to the growing appreciation of the importance that surficial processes and crustal rheological variations have on controlling the shape, dynamics, and evolution of mountain belts, at many scales.

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