Collaborative Research: Geodynamics of Indentor Corners

PROJECT SUMMARY

Across the northeastern margin of the Indian plate in southeastern Tibet, the Himalayan orogen terminates abruptly as collisional processes responsible for the elevation of Tibet and the tectonics of the main Himalayan range are replaced by the strike-slip tectonics of the eastern Himalayan syntaxis. The syntaxis occupies a sizeable portion of the diffuse India-Asia collision zone, and because it serves as the watershed for the largest rivers in Asia, its highly active tectonic and surface processes have a direct impact on over one billion people.

Modeling suggests that the syntaxis is a crustal manifestation of the complex lithospheric dynamics associated with an "indentor corner." Steep lateral velocity gradients mark the eastern margin of the Indian plate, and incoming Indian lithosphere is partitioned into at least two components: deeper Indian lithosphere that continues north beneath Tibet, and shallower lithosphere that decelerates and, together with overthrust Asian lithosphere, enters the clockwise deformation regime of the eastern syntaxis. Such corners are also sites of significant accommodation of crustal convergence by erosion and fluvial evacuation, and transfer of material between all these elements at high rates and short time scales.

We propose to use the eastern syntaxis of the Himalyan orogen to address key questions in the geodynamics of continental collisions: how do orogens and associated plateaus come to an end, how do tectonic and surficial processes interact to shape the crust during orogeny, and how is deformation partitioned at various scales? These issues, enigmatic in older orogens, are resolvable in young and active region such as the India-Asia collision. Our work will involve testing three linked hypotheses: (1) across the transition from Tibetan plateau to eastern indentor corner, changes in lithospheric rheology are an important control on changes in topography and lithospheric mechanics; (2) erosion plays an equally important role in controlling lithospheric dynamics, on par with crustal thickening and lateral accommodation, and feedbacks between the two ultimately shape the evolution of the orogen, and (3) within the syntaxial region, there is nearly complete decoupling between deformation in the upper crust and the deeper lithosphere. To test these hypotheses, we will track the magnitude, rates, and type of mass fluxes through the central region of the eastern Himalayan syntaxis. To do this we will use isotopic, geochronologic, geomorphologic, GPS, petrologic, seismologic, and structural techniques, fully integrated by three-dimensional modeling. The young structures and active processes in the region will permit us to meaningfully combine short-timescale measurements (e.g. seismological, GPS, geomorphic observations) with measurements made over a longer range of temporal scales (e.g. petrological, structural, geochronological observations) on material that is moving through the region and hence records a complex time-integrated pressure, temperature, and strain history.

This work will complement and integrate other NSF-supported studies of the diffuse India-Asia collision by examining mass transfer across one of the system’s fundamental yet poorly understood boundaries. Together with these other studies, our proposed project will help provide a coherent image of lithospheric structure and rheological variations for an orogen that remains the textbook example of collisional mountain building.

Important Note to Reviewers

The scientific rationale and objectives of this project are discussed in an integrated project description on pages C1 to C10. Discipline-specific discussions of experimental design and technical considerations occupy pages C11 to C27, and a summary of results from prior NSF support of Zeitler and Meltzer's participation in the Nanga Parbat project begins on page C28.

This multidisciplinary project involves 16 investigators from 6 institutions:

Lehigh University
- Peter Zeitler (geochronology, coordinator)
- Anne Meltzer (seismology)

Dartmouth College
- Page Chamberlain (petrology)

University of Washington
- Bernard Hallet (geomorphology)
- James Bardeen (surface modeling)
- David Montgomery (drainage-basin evolution)
- Bruce Nelson (isotope geochemistry)
- John Stone (cosmogenic isotopes)
- Alan Gillespie (remote sensing, neotectonics)

SUNY-Albany
- Bill Kidd (structural geology)

University of Otago
- Peter Koons (dynamical modeling, GPS)
- David Craw (fluid inclusions, petrology)

Chengdu Institute of Geology and Mineral Resources
- Liu Yuping (GPS, structural geology)
- Pan Guitang (tectonics)
- Geng Quangru (petrology)
- Zheng Lailing (petrology)

The total budget for this five-year project is ~$2.16 million and is distributed as follows (the amounts listed below include overhead, and the disciplinary breakdowns are approximate because of the integrated nature of our proposed work):

By Institution:		**By Discipline:**		**By Year:**	
Chengdu Institute	$105,250	Geochronology	$440,000	Year One	$371,832
Dartmouth College	$110,563	GPS	$170,000	Year Two	$565,463
Lehigh University	$1,082,099	Modeling	$65,000	Year Three	$680,436
MIT	$40,533	Structure	$170,000	Year Four	$258,945
Otago University	$78,400	Petrology	$110,000	Year Five	$285,607
Univ. of Washington	$575,394	Seismology	$615,000	**TOTAL**	**$2,162,283**
Albany	$170,044	Geomorphology	$490,000		
		Management	$100,000		

Geodynamics of Indentor Corners

OUTLINE OF CONTENTS

COLLABORATIVE RESEARCH: GEODYNAMICS OF INDENTOR CORNERS

Part I. INTEGRATED PROJECT DESCRIPTION

I – 1. Introduction and Overview

Perhaps the most prominent feature of the India-Asia continental collision is the highly diffuse plate boundary developed around and within Tibet. The ongoing collision of cold, strong Indian lithosphere with the relatively warm, weak lithosphere of the Asian plate has various manifestations over a broad portion of Asia (Figure 1), including growth of the Himalayan orogen, elevation of the Tibetan plateau, and development of extensive strike-slip faulting within both Tibet and the syntaxes that mark both ends of the Himalayan arc.

The Himalayan syntaxes comprise about a third of the India-Asia collision zone and encompass a substantial portion of the crustal deformation that occurs within the system (Figure 1). Some of the most active orogenic processes on Earth occur within these syntaxes. For example, a broad zone of active strike-slip deformation throughout a large part of southeast Asia (Royden et al., 1997; Wang and Burchfiel, 1997) is evident in a pronounced topographic grain dominated by the strong convergence and alignment of three of the great Asian rivers (Hallet and Molnar, in revision). More locally, embedded within their respective syntaxes, Nanga Parbat in the west and Namche Barwa in the east are antiformal basement massifs where the deep gorges of the Indus and Tsangpo rivers expose, uniquely, to our knowledge, some 7000 meters of actively deforming metamorphic rocks and granites as young as Pleistocene in age (Zeitler et al., in review; Burg et al., 1997).

A fundamental tenet of this proposal is that the active distributed deformation in the eastern Himalayan syntaxis arises from its position astride the lithospheric boundary between the northeastern edge of the Indian plate and southeastern Asia. At this "indentor corner" (see further discussion below), the eastern syntaxis is expressed in the crust as a clear rotation of topographic, structural, and geologic trends, whereas at depth we presume that the deeper, northward-moving Indian lithosphere experiences shear across its eastern boundary. Dynamical models predict that such corners are likely to be regions of complex lithospheric deformation marked by steep lateral velocity gradients, decoupling between the deep and shallow lithosphere, partitioning of crustal deformation into lateral and vertical components, significant accommodation of crustal convergence by erosion and fluvial evacuation, and transfer of material between various strain regimes at high rates and short time scales (Figure 2). Data verifying these model predictions are for the most part lacking, as the eastern syntaxis remains sparsely studied, particularly its deeper structure and its geomorphic evolution.

We argue that indentor corners are tectonic features of fundamental significance and are key to understanding the dynamics and boundary conditions of not only the India-Asia collision but continental collision in general. We also argue that southeastern Tibet and the central portion of the eastern Himalayan syntaxis provide an opportunity to document coupling between tectonic and surface processes in a region where the signals are exceptionally strong and clear. We propose to use the region as a natural laboratory in which to investigate three unresolved, interrelated issues that are fundamental to understanding indentor-corner dynamics and collisional orogenesis:

1. the important changes in the Tibetan Plateau’s surface morphology, crustal rheology, and lithospheric architecture, from central Tibet east to the indentor corner;

2. the nature of complex three-dimensional strain partitioning between the shallower (crustal) lithosphere and the deeper (mantle) lithosphere as material moves through the indentor corner;
3. the significance of erosional control on the three-dimensional pattern of crustal deformation within and around an indentor corner, on scales ranging from individual structures (i.e., the Namche Barwa antiform) to continental scale (Eurasia's accommodation of India's northward motion).

Our proposed research comprises tightly coordinated geomorphic, geodetic, seismic, petrologic, structural, geochronologic, and modeling studies designed to collect and integrate the data sets required to address these issues. By quantifying magnitudes, directions, and rates of lithospheric input and output near the indentor corner, we will also provide boundary conditions for this important element of the India-Asia collision that remains lightly studied and not well understood. In addition, our work will serve to integrate data obtained from recent and ongoing studies of southeast Asia and Tibet, thereby helping to provide a comprehensive understanding of distributed deformation associated with the India-Asia collision.

Below, we present our proposed work in the remaining portion of this project description. Part II of this proposal contains discipline-based discussions that relate specific measurements to our science goals and provide more detail about experimental design and technical issues. Part III summarizes relevant results from the Nanga Parbat Continental Dynamics project.

I – 2. Key Indentor-Corner Elements: SE Tibet, Eastern Syntaxis, Namche Barwa Massif

Before we discuss our proposed research, we review several aspects of Himalayan and Tibetan geology that provide the backdrop and motivation for our proposed work. We will focus on: (1) the structure and dynamics of the Tibetan lithosphere across the transition from the central plateau to the eastern syntaxis; (2) the crustal dynamics of the eastern Himalayan syntaxis and how these are related to the eastern indentor corner; and (3) the geology of the Namche Barwa massif and its associated knickpoint, which, although limited in spatial extent, are important features in understanding how both surface and tectonic processes have shaped the evolution of southeastern Tibet.

Background. Collision of the northern margin of the Indian continent with the accreted terranes forming the southern margin of Asia began as early as 50 Ma near the western syntaxis, with full involvement of the whole continental margin of India probably achieved by 42 Ma (Rowley, 1996, Harrison et al., 1992). Collisional convergence of a minimum of 2000 km (Molnar and Tapponnier, 1975; Patriat and Achache, 1984; Dewey et al., 1989) thickened the crust and elevated the Tibetan Plateau, raised the spectacular Himalayas, and thoroughly deformed southern Asia through a combination of extrusion tectonics and distributed shear (Peltzer and Tapponnier, 1988; Wang and Burchfiel, 1997), setting the stage for the modern dynamics that are the focus of this proposal.

Tibetan Lithosphere and Dynamics. Seismic and gravity data provide a clear picture of the general architecture of the orogen (Figure 3). Indian lithosphere descends beneath Asia at a relatively shallow angle (Chen and Molnar, 1981; Molnar, 1988; Jin et al., 1996; Ni and Barazangi, 1984). The crust in the southern part of the plateau is thick (65-75 km), has relatively low average P-wave velocities, relatively normal Poisson's ratios, and a high-velocity layer at its base (McNamara et al., 1997; Rogers and Schwartz, 1997; Zhao et al., 1996). To the north, the crust is thinner by 10-20 km, has higher average P-wave velocities, significantly higher Poisson's ratio (reflecting lower shear wave velocities), and lacks a high-velocity layer at its base (McNamara et al., 1997; Wittlinger, 1996; Owens and Zandt, 1997; Rogers and Schwartz, 1998). Indian lithospheric mantle is interpreted to extend beneath southern Tibet at least as far north as the central Lhasa terrane and perhaps as far north as the Bangong suture, based on the presence of high velocities in the lower crust (interpreted as Indian mafic lower crust) and normal Pn velocities indicating cold Indian lithosphere (Figure 3). Pn decreases beneath the northern portion of the Lhasa terrane and northern plateau. The northern plateau also shows inefficient Sn wave propagation and high Poisson's ratio in the crust, suggesting high temperatures beneath this region (McNamara et al., 1997; McNamara et al., 1995; Rogers and Schwartz, 1998; Zhao et al., 1993; Zhao et al., 1991), and leading Owens and Zandt (1997) to conclude that the Asian lower crust beneath northern Tibet is partially molten.

Initial results from Project INDEPTH (Nelson et al., 1996) suggested that a partially molten crust lies beneath the Yadong-Gulu rift in southern Tibet at 15-20 km depth. Seismic studies (reflection (Brown, et al., 1996; Makovsky, et al., 1996a,b) and receiver function analysis (Kind et al., 1996; Yuan et al., 1997)) suggest this partially molten layer is found beneath and north of the Indus Tsangpo suture. Magnetotelluric observations indicate the crust is electrically conductive beneath 10-20 km depth both north and south of the suture zone as well as several tens of kilometers both east and west of the rift (Chen et al., 1996), suggesting that the probable melt layer is not solely related to the rift itself. Strong P to S conversions in the wide-angle data and bright spots in the reflection data were used to infer that actual magma bodies, not just partial melt zones lie under part of southern Tibet (Nelson et al., 1996). An alternate interpretation suggests that the high-amplitude reflections observed in the INDEPTH data may be caused by aqueous fluids in the mid-crust rather than melt (Makovsky and Klemperer, 1998). Clearly, the mechanical properties of the crust would be substantially different in this case.

Geodynamic modeling suggests that plateau topography is supported by a weak crustal layer beneath the plateau and a strong crust along the plateau margins, and that the upper crust is decoupled from the lower crust so that the strain pattern observed at the surface does not extend into the lower crust and mantle (Royden et al., 1997). In this model, crust at the margins of the plateau is thickened from below by differential flow of the lower and middle crust from the center portions of the plateau toward the margins, rather than shortening and thickening by thrusting in the upper crust. This model is consistent with the suggestion of Owens and Zandt (1997) that the lower crust north of the Bangong suture is partially molten, weak, and flows, as well as with GPS results and geologic observations (lack of a distinct foredeep and fold-and-thrust belt; Royden et al., 1997) suggesting little extrusion of upper-crustal material to the east.

Modern Dynamics: Eastern Syntaxis. Mathematical models and physical experiments both predict that intense deformation should initiate near the original corner of a rigid indentor such as the Indian plate and that through time, this deformation will evolve and propagate, as steep velocity gradients arise adjacent to the original indentor's margins (e.g. Royden et al., 1997; Tapponnier et al., 1990; Enlow and Koons, 1998). This results in a simple, characteristic deformation pattern (Figure 4). As the indentor plows material into a two-sided orogen, material at the ends of the orogen slips around the indentor in a wake of strike-slip faulting and mountains of diminishing elevation, generating at shallow levels a well-defined crustal syntaxis that finds structural as well as topographic expression. This crustal expression, generated by changes in velocity conditions at the eastern edge of the Indian plate, is a manifestation of a complex whole-lithospheric structure that we refer to as an "indentor corner." Thus, we view the eastern Himalayan syntaxis to be an element of the eastern Himalayan indentor corner.

Considerable evidence supports the predictions about upper-crustal deformation made by these models and experiments. Much of the modern right-lateral shear motion of India relative to SE

China occurs by pervasive deformation distributed across a broad north-south zone some 1000 km wide, in part by slip on strike-slip faults and rotations of blocks about vertical axes (England and Molnar, 1997b, Royden et al., 1997). Although the tectonic setting of the eastern syntaxis is not without complexity, particularly with respect to the velocity of Burma and the dynamics of the Andaman subduction zone as it terminates near the syntaxial region (Curray et al. 1979; Holt et al. 1991; Widiyantoto and Van der Hilst, 1996), the region's overall velocity pattern clearly reflects the influence of the indentor corner (Holt et al. 1995; King et al., 1997). Overall, the predicted pattern of crustal deformation is compatible with observations from seismic moment analysis (Holt et al., 1991; Holt and Haines, 1993), neotectonic studies (England and Molnar, 1997b), GPS results (King et al., 1997; Royden et al. 1997), paleomagnetic studies (e.g. Huang and Opdyke, 1993), geologic studies (Wang and Burchfiel, 1997; Wang and Chu, 1988), and geomorphic analysis (Koons, 1995; Hallet and Molnar, in revision).

The deeper structure and kinematics of the lithosphere in and around the eastern indentor corner is unknown. Holt (2000) noted that in central Tibet crustal and mantle strains are correlated, but argued that the correlation reflects the influence of similar velocity boundary conditions influencing the crust and mantle lithosphere in this part of the orogen rather than coupling between the two. Given results showing that portions of the Himalayan and Tibetan crust can be quite weak (Nelson et al., 1996; Meltzer et al., in review; see discussion above), crustal and deep-lithospheric deformation are likely decoupled, with the mantle lithosphere and possibly parts of the crust continuing northward while upper-crustal material decelerates as it traverses the indentor corner and then begins to rotate and slough off to the east (Figure 3).

Modern Dynamics: Namche Barwa Metamorphic Massif. The active Namche Barwa metamorphic massif is nestled among the broader-scale tectonic and geomorphic features manifested in the eastern syntaxis (Figure 1). Namche Barwa shares with the Nanga Parbat massif in the western syntaxis a remarkable number of features (see Part III of this proposal for details about Nanga Parbat). Based on reports by Burg et al., (1997, 1998; Liu and Zhong, 1997), these include rapid exhumation of an antiformal massif which exhibits Pleistocene metamorphic and structural overprinting of Proterozoic Indian basement (Figure 5).

Both Nanga Parbat in the west and Namche Barwa in the east are being rapidly exhumed by a great orogen-scale Himalayan river (Indus and Tsangpo) as the river turns south and exits to the foreland through a syntaxis. To our knowledge, these active metamorphic massifs are unique to the Himalayan syntaxes. Based on results from Nanga Parbat, Koons et al. (in review) and Zeitler et al. (in review) have suggested that the presence of such a massif within each syntaxis is related to local feedbacks between tectonic and surficial processes: large-magnitude river incision can focus deformation of weak crust, leading to lower-crustal flow into the region; rapid erosional exhumation in response to the resultant enhanced advection further weakens the crust and results in a distinctive petrological, structural, and geophysical anomalies which can be thought of as a "tectonic aneurysm" (see Part III). In contrast, Treloar et al. (1991) and Burg (1997) proposed that the Nanga Parbat and Namche Barwa antiforms represent crustal-scale folds related in some way to syntaxial tectonics, with the major rivers being passively antecedent to these structures; based on finite-element modeling, Burg and Podladchikov (1998) suggested that such crustal-scale buckling requires deformation of cold, strong lithosphere. However, these alternative models do not provide an explanation of the observed petrological anomalies nor are they consistent with geophysical observations at Nanga Parbat which show the massif to be developed atop thin, hot, weak crust (Meltzer et al., in review; see Part III).

Where the Tsangpo crosses the Namche Barwa antiform (Figure 5), a spectacular knickpoint is developed (Figures 6-8). The drainage patterns in the region suggest that an ancestral Tsangpo-

Irrawaddy river was captured by the Brahmaputra network due to efficient headward cutting; this was likely caused by the river system's confinement within topography established by the tectonics of the eastern syntaxis (Koons, 1995). Brookfield (1998) suggests that this capture occurred a few million years ago based on comparison of stream profiles of the current Tsangpo with those of other major Himalayan rivers. The Namche Barwa knickpoint may be quite significant in controlling the geodynamic evolution of some 200,000 km^2 of the southern and southeastern Tibetan Plateau because it currently maintains the upper Tsangpo at a high base level above 3,000 meters (Figures 8 and 9).

I – 3. Outstanding Issues

With geological background in place, we return to the three interrelated issues that are the focus of this proposal.

Transition in lithospheric rheology and architecture across southeastern Tibet. The style of deformation in southeastern Tibet appears to depend on the lateral and vertical extent of weak zones in the lithosphere (e.g., Zhao and Morgan, 1985; Royden et al., 1997). An important geodynamic issue is the relationship between the weak, partially molten Indian crust (or aqueous fluids?) described by Project INDEPTH beneath southern Tibet (Nelson et al., 1996; Makovsky and Klemperer, 1998), the weak, partially molten Asian crust identified beneath northern Tibet (Owens and Zandt, 1997), and the strong, solid crust predicted to be located along the plateau's eastern margin (Royden et al., 1997). The recent seismic studies that have provided these first-order observations are primarily focused along a north-south profile across central Tibet, and little is known about transitions in lithospheric structure across eastern Tibet into the syntaxial region. The continuity and lateral extent of these features and the transition toward the east affect the mechanical response of the crust to deformation along the northeastern margin of the Indian plate, which in turn controls transitions in surface morphology (e.g., plateau vs. deeply incised) and local tectonics (e.g., presence or absence of N-S rifts).

Eastern indentor corner: 3D strain partitioning, and redistribution of mass. How the Tibetan, southeast Asian, and Indian lithospheres interact and partition strain is an open question. The broad clockwise rotation of upper-crustal material away from and through the eastern syntaxis has been well documented by GPS measurements, structural studies (King, et al., 1997; Wang and Burchfiel, 1997) and moment-tensor analysis (Holt and Haines, 1993). To what extent this continues at depth in the lower crust and mantle lithosphere is unknown. Based on geophysical observations made to the west, we predict that beneath the western portions of the eastern syntaxis, the mantle portion of the Indian lithosphere and possibly some portion of the lower crust continues north beneath the Tibetan Plateau.

Significance of the surficial mass flux. There is considerable controversy concerning the nature and extent of crustal deformation and transport along the eastern edge of the Himalaya-Tibet system, especially regarding the magnitude and timing of eastward extrusion of Tibetan crust via strike-slip faulting (e.g., England and Houseman, 1986; Houseman and England, 1996; Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; England and Molnar, 1990). Although erosion seldom figures in such studies, our and other's work at Nanga Parbat suggests that at least locally, a significant fraction of the crust can be rapidly removed by erosion from the interior of the orogen, and we suggest that efficient removal of material by large rivers at the indentor-corners is of fundamental significance at both local and regional scales in the Himalayan-Tibetan system.

The surficial mass flux from the eastern syntaxis is not well-documented. In SE Tibet and in the Three Rivers region in particular, the rugged landscape traversed by large rivers inset into deeply incised gorges strongly suggests that the area is undergoing significant erosion (Figures 7, 8), with the rivers acting as spatially extensive sinks of mass at the Earth's surface. This observation has not been taken into consideration in geodynamic models to date. Under these conditions, eastward motion of the thickened crust of Tibet to the side of the indentor does not have to propagate indefinitely to the east. Crustal motion could diminish eastward and the resulting crustal convergence could well be offset by surficial mass removal in the Three Rivers region (Figure 10a); this could be sustained indefinitely provided rock uplift is balanced by erosion. A simple mass-balance calculation suggests that quite a modest erosion rate of only 0.2 mm/yr could account for a significant component of the eastward mass flux (~10%), and 2 mm/yr would allow all the easterly advection from Tibet to be consumed by erosion. The relationship between both long-term and short-term erosion rates and current topography in the western Himalaya, (e.g., Zeitler, 1987; Burbank et al., 1996) suggests that erosion rates of millimeters per year and greater are likely to prevail within the eastern syntaxis; apatite fission-track ages of only 1-2 Ma from the Gongga Shan massif at the easternmost fringes of the Tibetan Plateau (Xu and Kamp, in prep.) are suggestive of similar erosion rates, at least locally. Thus we predict that quantitative assessment of these erosional fluxes will show them to be responsible for a significant fraction of the mass accommodation required for the India-Asia collision.

<u>Namche Barwa antiform and knickpoint</u>. Because the extreme knickpoint on the Tsangpo is developed right at Namche Barwa (Figures 6-8), the question arises as to whether the two features are related, or whether their co-location is mere coincidence. This issue has broader ramifications, because development of an erosionally mediated metamorphic massif requires rapid cutting of a significant gorge, perhaps only possible in regions with focused rock uplift and erosion such as an indentor corner. This would suggest a link between surficial and crustal geodynamics at two scales: at orogen-scale, to explain the localization of the great Tsangpo gorge within the eastern syntaxis, and locally, to explain the thermal-erosional weakening and extreme relief at Namche Barwa. If this is so, then the geomorphic, structural, and metamorphic evolution of the interior of the eastern syntaxis are genetically related.

Although their own origins may lie in control of regional drainage evolution by syntaxial tectonics, the Namche Barwa knickpoint and massif may in turn play an important role in large-scale Tibetan tectonics. Because regional-scale exhumation (or lack thereof) is an important control on the thermal and dynamical evolution of orogens, the Namche Barwa knickpoint may act as a first-order control on the geodynamic evolution of southern Tibet and the flanking eastern Himalaya by determining the base level of the upper Tsangpo. An important unanswered question would then be whether this knickpoint is evolving rapidly and actively cutting headward, or has long maintained a position centered on the Namche Barwa antiform due to feedbacks between uplift and erosion.

I – 4. Proposed Work

We believe that the eastern Himalayan syntaxis and the Namche Barwa metamorphic massif provide the best setting to study indentor-corner dynamics, the transitions at the margins of an orogenic plateau, and the interactions between active tectonic and surficial processes during orogeny, at both regional and local scales. We propose to integrate measurements from the fields of seismology, geodesy, geochronology, geomorphology, structure, petrology, and geodynamic modeling to (1) map the three-dimensional distribution of lithospheric deformation within and around the eastern indentor corner, (2) determine rates of erosion within the indentor-corner region, and fluvial evacuation of crustal mass from it, and (3) decipher the geomorphic and crustal evolution of the Namche Barwa metamorphic massif and its associated knickpoint:

1. Lithospheric deformation across the eastern syntaxis and SE Tibet. Geodynamic models (e.g. England and Houseman, 1986; Royden et al. 1997) make clear predictions of the distribution of strain around an indentor corner (Figure 4): horizontal compression, oriented nearly parallel to the displacement of the indentor, dominates the deformation field in front of it, but near its corners, compression is approximately radially oriented and deformation is relatively intense. As the indentor penetrates the deforming medium, shear on vertical planes parallel to the edges of the indentor and rotation become dominant. To assess these predictions, we propose to deploy a campaign-style GPS array across the eastern Himalayan syntaxis (Figure 11) as well as a regional seismic array augmented by dense coverage of the Namche Barwa massif itself (Figures 12, 13). The combination of earthquake location and GPS measurements will allow us to map in some detail the contemporary distribution of crustal strain in the region and provide tight geometric and kinematic constraints on our numerical models of lithospheric mass flow and deformation.

   While the effects of indentor-corner tectonics are most visibly expressed in upper-crustal development of syntaxial structures, the rheological state and the style and distribution of deformation in the lower crust and mantle in the immediate vicinity of the indentor corner are important constraints on lithospheric flow, especially given recent work suggesting that in central Tibet, the lower crust may be very weak (Nelson et al., 1996; Royden et al., 1997; Zhao and Morgan 1985; Owens and Zandt, 1997). In addition, determining patterns of asthenospheric flow around the plate edge will provide 3-D information about the relationship between the deeper lithosphere and sublithospheric structures. Our regional broadband seismic array will allow us to determine the structure, rheology, and fabric of the lower crust, lithospheric mantle, and underlying asthenosphere using receiver-function and shear-wave splitting techniques to identify significant structural boundaries and strain patterns.

   Our seismic and GPS arrays will also fill a gap by linking the INDEPTH and other results from central Tibet with past and proposed MIT efforts in the eastern syntaxis and with other geodetic studies in the Himalaya (Bilham et al., 1997; see Figure 12; see attached letter from Van der Hilst), constraining, for example, the lateral extent of the proposed melt layer within the Tibetan crust. Combined, these data sets will reveal the nature of active deformation across the entire margin of the eastern Tibetan Plateau. Integration of these data with existing, ongoing, and new geologic and geomorphic mapping will allow us to relate our short-term observations to longer-term deformation patterns.

2. Geodynamic consequences of exhumation at scales from 10^1 to 10^3 km and 10^0 to 10^6 years. Our preliminary modeling predicts that evacuation of crustal mass by erosion can have profound effects on crustal deformation at both local and regional scales. To test this, we propose to estimate exhumation and erosion rates at a range of scales using Ar-Ar and U-Th-He cooling ages, exposure ages, isotopic data and field studies of sediment yields. These estimates will complement one another, with the isotopic data providing longer-term temporal integration and the geomorphic data providing insight into dominant exhumation processes as well as a more spatially complete view of contemporary exhumation rates than can be obtained using point data. We will integrate these observational constraints and field studies with numerical modeling that links the evolution of landscapes dissected by realistic drainage patterns with broader-scale lithospheric deformation responding to tectonic forcing as well as surficial mass transfer.

3. Nature of crustal advection at Namche Barwa. We propose to fully document the recent deformation history and degree of metamorphic overprinting at Namche Barwa using petrologic, fluid inclusion, and structural analysis, integrated with seismic observations of the subsurface. This will allow us to calculate long-term denudation rates using high temperature geochronologic data coupled with *P-T* path estimates. Based on our work at Nanga Parbat, we found that integration of petrologic history with seismology is powerful means of probing active processes shaping the crust during deformation (see Section III). In conjunction with dating of metamorphic phases and small granite bodies within the massif, our goal is to construct detailed pressure-temperature-time paths which can be related to structural and geomorphic history. These *P-T-t* paths will be of critical importance in quantifying total depths of exhumation and long-term exhumation rates, as well as revealing conditions in the lower crust in the core of the syntaxial region.

   We will also study the geomorphic evolution of the Namche Barwa knickpoint. In concert with geologic studies of the massif, this will permit us to determine whether or not the knickpoint has been a stable feature. In concert with our studies of the significance of regional erosion, we will then be able to determine whether or not control of base level by the knickpoint has been a significant element in SE Tibetan geodynamics.

In summary, we stress that the focus of our proposed work is on an integrated understanding of the essential elements of indentor-corner dynamics, using the recent and modern dynamics of the Himalaya's eastern syntaxis as the best possible natural laboratory in which to investigate the coupling between exceptionally active surficial and tectonic processes at the ends of orogens. This is so because the youth and vigor of active structures and processes in the region will permit us to meaningfully integrate measurements made in the fixed, instantaneous reference frame (e.g. seismology, GPS, geomorphic observations) with measurements made over a broad range of temporal scales on material which is in the moving, time-integrated reference frame (i.e. petrology, structure, geochronology).

I – 5. Project Management And Logistics

Field Visit. In May, 1998, with support from the Continental Dynamics Program, PIs B. Hallet, A. Meltzer, and P. Zeitler traveled to China to meet with our counterparts at the Chengdu Institute of Geology and Mineral Resources (CIGMR), and to visit southeastern Tibet to assess logistics for fieldwork and become familiar with the local geology and tectonics. The trip was highly successful and productive. We spent four days in Chengdu having discussions with members of the Chengdu Institute (including its director, Pan Guitang), presenting our proposed work in some detail, learning about work and projects that the Chengdu Institute is carrying out in Tibet and at Namche Barwa, and discussing logistical arrangements, particularly those related to GPS and seismic studies. During this visit we also developed a cooperative agreement for our project (see attached letter and MOU). We next flew to Lhasa and spent a week with our colleagues reviewing the geological setting of Namche Barwa and the surrounding region, as well as becoming familiar with local geography and logistics. In September, 2000, we plan an additional trip to China and Tibet for further planning and geological reconnaissance.

Logistics and Work Plan. This eastern Himalayan syntaxis offers good access, and existing structural, GPS, and modeling studies provide an excellent regional context (e.g., Wang and Burchfiel, 1997; King et al., 1997; Holt et al., 1991, 1995; Royden et al., 1997). The region is accessible by a network of adequate roads and trails (Figures 11, 13). Field work will require some combination of travel by four-wheel drive vehicle and trekking. We anticipate no major difficulties, as members of our team have extensive experience working in mountainous terrane, including the Himalaya and Asia; they have, for example, carried out a successful, dense 60-station deployment of short-period and broad-band seismic instruments around Nanga Parbat.

Conditions at Namche Barwa itself are reputed to be remote and difficult, with the eastern side of the massif and the Big Bend of the Tsangpo being accessible only by treks. The terrain in the region certainly is steep and rugged, but fortunately, we found that the pass to the eastern portions of the massif nearly can be reached from a good jeep road, so that only a three-day trek is required to reach the Tsangpo on the eastern side of the massif. The Big Bend of the Tsangpo gorge can be reached by a straightforward two-day trek. Our Chengdu colleagues have visited all the places described above and feel that access is not a great problem. Based on our own experience in the area as well as discussions with others who have worked there, we concur, noting that sufficient footpaths exist along both sides of the Tsangpo to allow good, safe access to the interior of the massif, where we have identified sufficient outcrop exposures. Although it is true that the eastern syntaxis can be quite wet, much of our work will take place on the drier NW side of the massif, and sufficient tolerable weather occurs in May/June and September/October to permit the fieldwork we require. Finally, access to parts of the area is possible in winter months, and some of our lower-elevation work on the NW side of the massif, particularly that requiring low water levels, would best be carried out then.

Given the challenging terrain and the need to carefully scout sites for GPS and seismological studies over a broad region of SE Tibet, we are proposing a phased approach, as follows:

Year One:	Petrologic, geochronological, structural, and geomorphic studies, coordinated with scouting for seismic deployments and GPS campaign.
Year Two:	Initial GPS campaign, pilot seismic study, follow-up petrologic, structural, and geochronological work, geomorphic studies, and initial modeling
Year Three:	Further structural assessment and neotectonic studies, main seismic deployment (coordinated with MIT Eastern-Tibet deployment), geomorphic studies, numerical modeling using field-based constraints
Year Four:	Analysis and interpretation, follow-up field studies
Year Five:	Second GPS campaign, data synthesis, using coupled mechanical-landscape model

Collaboration and Coordination. We recognize that it is critically important that we have efficient and clear working relationships with Chinese counterparts. As discussed above, thanks to the assistance of Clark Burchfiel (who has had a long, successful, and productive relationship with the Chengdu group), we have established a firm and clear understanding with scientists at the Chengdu Institute of Geology and Mineral Resources (see attached MOU). Chengdu staff will play a fundamental role in our GPS work, and we will be coordinating our other studies with those being carried out under the auspices of Chengdu's project "Crustal deformation and deep processes of the region of Big Bend of the Yarlung Zangbo River and the relations to the uplift of the Qinghai-Tibetan Plateau." Chengdu scientists will accompany us in the field, and contribute to our work in petrology, GPS, seismology, and structure.

We have had discussions with Jean-Pierre Burg, at ETH, whose group carried out some of the first geological studies within the Namche Barwa massif. His group has been working on aspects of petrology, structural mapping, and high-temperature geochronology in the immediate Namche Barwa region. We have agreed to coordinate future work to avoid overlap and to complement our respective studies.

We have also talked with Rob van der Hilst, Robert King, Wiki Royden and Clark Burchfiel about coordinating our work with the MIT group's ongoing studies of eastern Tibet and surrounding regions, in particular their proposed seismic experiment (see attached letter). We will coordinate our field logistics, the timing of our experiments, and the training of Chengdu personnel in the field component of seismic deployments. We have also agreed to combine our seismic data sets to produce an integrated tomographic inversion of the eastern syntaxial region.

To obtain high-quality, up-to-date sediment-yield data in northern India, we have invited the collaboration of Christian France-Lanord, who has extensive experience using geochemical techniques to study sediment yields in the great Indian rivers, and most recently has worked on the upper sections of the Brahmaputra in India (see letter describing collaborative agreement). The sediment flux and geochemical data he will provide us from this area, when compared to corresponding data at the entrance of the Tsangpo gorge, will permit us to determine sediment production in the Namche Barwa region and thus the mean contemporary rate of erosion.

I – 6. Conclusions: Broader Significance of Expected Results

The modern record shows that complex, active geology occurs at transition zones along plate boundaries where changes from convergent to strike-slip motion define a plate corner. This is evident in both the Himalaya's syntaxes, at either end of the Aleutian Arc (Denali, Kamchatka), at the intersection of the Philippine and Indonesian Arcs with the Australian Plate (Papua New Guinea), and the intersection of the Caribbean and South American Plates. We feel that the eastern Himalayan syntaxis provides an excellent location in which to study important and fundamental aspects of plate collision: the transitions between differential plate motion, the range of geologic processes associated with plate boundaries at the edge of an orogen, and the simple question: how do orogens come to an end? The exceptionally active processes and excellent exposures in this region make it possible to meaningfully integrate data sets that in older or less well-exposed orogens are not easily compared. We emphasize that we are proposing to obtain a comprehensive view of contemporary and recent geodynamic processes within a well-defined indentor corner, in a region where geodynamic signals are strong; we are not proposing to catalog the long-term geologic history of the eastern Himalayan syntaxis as an exercise in descriptive Asian tectonics.

In the textbooks that we use to educate our students, the India-Asia collision zone is most often portrayed as the quintessential collisional orogen. In this regard our proposed study is timely as it will integrate well with other NSF-supported studies that have been or are being carried out on various elements of the India-Asia collision. These studies have provided important first-order observations on a range of orogenic processes from a range of locations scattered across a very broad and diverse collision zone. Our proposed study extends from central Tibet across the eastern indentor corner, providing a link between studies in central Tibet with those in eastern Tibet. Our work will provide a spatially continuous image of lithospheric structure and rheology across this transition zone, an examination of the degree of coupling and strain partitioning between the deeper mantle and the lithosphere in the eastern indentor corner, and an evaluation of the mechanisms and magnitude of mass transfer across this fundamental plate boundary, including the role of erosion and fluvial evacuation in the lithospheric mass budget. As designed, our proposed research is aimed at understanding how surficial and tectonic processes interact at scales ranging from individual crustal structures at the core of the eastern syntaxis to the whole of the lithosphere in southeastern Tibet, an interaction of great but in our view underestimated importance in both ancient and modern mountain belts. Finally, an improved understanding of the eastern indentor corner has significant societal relevance: the region we propose to study constitutes a large portion of the watershed for some of the most important rivers in Asia, and its active tectonic and surface processes directly impact the well-being of over one billion people.

Part II. DISCIPLINE-SPECIFIC DISCUSSION

II – 1. Seismology (Meltzer)

We propose to install both a regional broadband array and dense local short-period array deployed in nested fashion to provide regional coverage across the syntaxis and dense coverage around Namche Barwa itself (Figures 12, 13). The regional broadband array will be used to determine crustal and upper mantle structure and dynamics at the plate edge, to develop a more complete model of coupled crustal deformation and mantle flow in the syntaxial region. The focused short-period array at Namche Barwa will allow us to determine active fault kinematics and crustal structure and rheology beneath the massif. These details provide important constraints on petrologic and geodynamic models for development of metamorphic massifs (see Section III). Data analysis will include tomographic inversions for velocity and attenuation structure beneath the massif and the broader syntaxial region to constrain rheology, receiver-function analysis to determine primary structural boundaries, and earthquake location and focal-mechanism solutions, seismic moment analysis, and determination of shear-wave splitting parameters to look at strain and thermal structure.

Lithospheric structure: Initial observations constraining the general lithospheric architecture of the Himalaya came largely from studies of moderate to large magnitude (>5.5) seismic events within the Himalayan arc and from surface wave propagation across the Tibetan plateau (Chen and Molnar, 1981; Ni and Barazangi 1983; Hirn et al., 1984; Brandon and Romanowicz, 1986; Chun and McEvilly, 1986; Molnar, 1988). These data, recorded by global seismic stations located outside the plateau, hinted at structural complexities and lateral variations in the lithosphere and upper mantle beneath Tibet.

These initial observations have been confirmed and enriched as a more detailed picture of the orogen emerges from both passive and active seismic sources recorded by temporary portable arrays in Tibet. Fruitful collaborations with Chinese investigators lead to the 1991/92 deployment of IRIS/PASSCAL broadband instruments (Owens et al., 1993), a similar deployment by the French (Hirn, 1995; Wittlinger et al., 1996), and ongoing seismic studies conducted by the INDEPTH project (Zhao, 1993; Nelson et al., 1996). The seismic data recorded to date in Tibet point to lateral heterogeneity and complexities on both local and orogen scales (10s to 100s of km). The Tibetan plateau itself appears to be dissected into discrete tectonic blocks along structures developed prior to the Indian Asian collision (Wittlinger et al., 1996; Hirn et al., 1984; McNamara et al., 1996). These blocks with different inherited structures are likely responding to collisional processes in different fashions. These rich data sets continue to be mined by many investigators for insight into the rheology and structure of lithospheric and sublithospheric mantle structure beneath Tibet, and to important constraints for geodynamic models of the region and of orogenic evolution in general (Sandoval et al., 1997; Kosarve et al., 1999; Chen and Ozalaybey, 1998).

While these studies have provided significant first-order observations for central Tibet, they have primarily been focused on a north-south cross section across the central plateau (along the Lhasa-Golmud Road, Figure 3) and station spacing remains sparse for most of the passive source experiments. Very little is known about the lithospheric structure of eastern Tibet and the syntaxial region itself. Our proposed array will extend measurements and observations made in Central Tibet toward the east and toward the margin of the plateau where geodynamic models predict the crust should become strong in order to support the topography of the plateau. Our observations will assess the lateral extent of low velocity zones interpreted as melt within the upper and lower crust and assess the lateral variability of lithospheric structure and rheology particularly with respect to levels of decoupling within and at the base of the lithosphere.

Crustal Dynamics: Source parameters, focal mechanisms and moment release, determined for regional and local events recorded by portable arrays provide a rich data set for analysis of kinematics and style of deformation. While these events may not account for large moment release, they are more frequent and can make significant contributions to our understanding of regional tectonics by characterizing regional stress orientations. Analysis of focal mechanisms from 17 moderate to large (>5.5) magnitude events in the syntaxial region show a general trend of shallow dipping thrust events with hypocenters located within the upper 15-20 km of the crust (Molnar and Chen, 1983; Zhao and Helmberger, 1991; Molnar and Lyon-Caen, 1989; Baranowski et al., 1984). In general P axes change from a NNW orientation immediately west of the syntaxis to a NE orientation on the northeastern side of the syntaxis consistent with NNE direction of relative motion of India beneath an oblique boundary and perpendicular to the topographic gradient (Holt et al., 1991) (Figure 3). Right-lateral strike-slip occurs farther to the south. In detail the patterns are more complex. Temporary arrays with their ability to record smaller magnitude events have recorded a handful of events at depths of 70-90 km in the southern portions of the plateau (Zhu and Helmberger, 1996) supporting the notion that there are fundamental differences in the lithosphere beneath northern and southern Tibet. Straightforward time-domain moment-tensor inversion of regional events in the eastern syntaxis recorded by the 1991/92 PASSCAL experiment indicate complex faulting and steep spatial gradients in stress orientations within the eastern syntaxial region (Randall et al., 1995). Extensional, thrust, and strike-slip faulting all occur within 100-200 km of each other. While most events are shallow (<20 km), at least one event with a hypocenter just north the Namche Barwa massif occurred at a depth of 36 km, presumably within the underthrust Indian crust (Holt et al., 1991; Randall et al., 1995). This dataset (recorded in central Tibet ~500 km away from the syntaxis) recorded 9 well-resolved events (>Mw 4.0) in a six month period compared to the 17 events recorded over the 25 year period used in previous studies. We point out that our array at Nanga Parbat recorded over 400 local events within a four month period, illustrating the power of focused, short-term, dense array deployments for kinematic analysis.

Seismic Experiment. The seismic component of our project involves the deployment of a dense local array at Namche Barwa nested in a more broadly spaced regional array extending from central Tibet to the eastern syntaxis (Figures 12, 13). Our proposed regional array extends east-west across the southeastern edge of the Tibetan Plateau, capturing Indian lithosphere as it impinges on Asia, decelerates, delaminates, and flows into the syntaxial region. We are particularly fortunate that the MIT group is planning to add a seismic array to their ongoing studies in eastern Tibet and we are coordinating our array design, field logistics, and timing (see attached letter). The proposed MIT seismic array will nominally be co-located with the current MIT GPS array (Figure 11). The array will be deployed east of the syntaxis proper, crossing the edge of the plateau in a north-south direction; it will clearly image lithospheric structure in the strike-slip region associated with flow of material along the eastern edge of the indentor. Our regional array, when combined with the MIT array, provides a particularly exciting opportunity to capture a coherent snapshot of lithospheric structure and flow in the region of the indentor corner. While each project has distinct objectives and stands alone on its merits, the synergy is inescapable.

Feasibility: While establishing a dense temporary seismic network in the high Himalayas is logistically challenging, we have successfully carried out a similar campaign at Nanga Parbat in NE Pakistan. Access to the Namche Barwa region is quite good (Figure 11, 13). Adequate bedrock sites exist for deploying sensors so we can avoid station corrections due to low-velocity surface material. Regional seismicity is abundant (Figure 14). The Hindu Kush and subduction in the Andaman Sea are rich sources of deep events. At teleseismic distances, the subduction zones of the Pacific basin are prolific sources. On average 200-300 Mw=5.5 earthquakes occur within a six month period. Given that we will be able to record smaller magnitude events, we will have more than adequate sources for tomographic inversions.

Experiment Design. We have planned a phased approach for our seismic investigations that includes a small pilot project prior to a full scale deployment. We found this to be a particularly useful and effective approach at Nanga Parbat. For a relatively small cost we were able to record data yielding preliminary results and important insights for a larger, more involved deployment the following year and to work through the logistical details of deploying seismometers in rugged and remote terrain. The pilot experiment at Nanga Parbat made our work the following year considerably more efficient allowing us to maximize our recording time in the field and was an important part in the overall success of our experiment. We have planned our main deployment for 2003. This meets our project goals and meshes well with the IRIS/PASSCAL Instrument Schedule. As of this writing, the PASSCAL instrument pool is fully subscribed through 2002. Experiments requiring broadband instruments funded in the 2000 NSF fall review cycle will be scheduled for field work in 2003 and beyond (www.iris.iris.edu/passcal/BB02-03.html).

We are coordinating the seismic experiment with our colleagues at the Chengdu Institute. They will participate with both the field and data processing aspects of this work and will help with importation of instruments to the country. We have included funds to bring two colleagues to the US to work at the PASSCAL Instrument Center so that they can develop the required technical expertise in field operation, maintenance, and data-processing procedures to be full project participants.

In our first field season we will continue the scouting and logistics work begun on our reconnaissance trip. We will identify sites for installation of local dense array and explore the northern and eastern portions of the massif. This includes the Jiali–Parlung fault zone, mapped as a right lateral strike-slip fault that is clearly important in accommodating motion of material in the syntaxis (Figure 13). It is not clear what happens to this structure as it wraps around the syntaxial region connecting with north-south trending strike-slip faults in Burma and the Three Rivers region.

In our second field season we will deploy a small five-element short-period array (with either 2-Hz L22 or 10-second CMG-40T sensors, depending on availability in the instrument pool). These stations will be deployed in a cross pattern across the massif. Data will be recorded continuously for a 4 week period to evaluate microseismicity at Namche Barwa. This data set will give us an early opportunity to assess our model and evaluate triggering algorithms so we can develop the best deployment and recording strategy for the full deployment the following year. While the sensors deployed at Namche Barwa are recording data we will find sites and begin vault preparation for installation of the regional broadband array.

In our full-scale experiment in year 3, we will deploy a total of 70 PASSCAL instruments, a dense short-period array focused on the massif nested within a more regional broadband array deployed across southeastern Tibet. The short-period array will record for 5 months (May through October), and the 40-element regional broadband array will record for 12 months (Figures 12, 13).

The fourth and fifth years of the project include retrieval of the broadband array and data analysis. We propose to use two independent but complementary approaches to resolve the subsurface structure and fault kinematics at Namche Barwa. In the tomographic approach, velocity and attenuation structure are mapped by sampling seismic waves that have traversed a volume of material in the region of interest. In the source-mapping approach, fault kinematics is illuminated by hypocenter and slip geometry of earthquakes within the volume of interest. The data for both approaches are derived from simultaneous recordings at strategically located stations. Each technique provides unique but overlapping results (velocity and attenuation structure of the crust, location of structural discontinuities in the crust) which should be internally consistent. Simultaneous inversion for locations, velocity structure, and focal mechanisms by first motion and wave-form modeling will make full use of the digital 3-component data and provide the basis for a structural interpretation of local seismicity (Meltzer, et al., in review; Seeber et al., in prep). Results from local seismicity will play a crucial role in linking results from tomography of the regional ray paths with mapped surface structure. We will follow the tomographic inversion methods developed by Thurber (1988, 1993), Roecker et al. (1993), and Sarker and Abers (1998) that we are employing on our Nanga Parbat data set (Sarker et al., 1998 and in review). In addition long-period data from teleseismic and regional sources will be analyzed to determine receiver functions to look at structure. The abundance of data will allow stacking of the waveforms to improve results (Owens, et al., 1984; Priestly et al., 1988; Zhu et al., 1995; Dueker and Seehan, 1998).

Shear wave splitting parameters will be obtained using techniques developed by Karen Fisher at Brown with whom we are collaborating in analyzing our Nanga Parbat data set. These data will provide information on flow patterns in the sublithospheric mantle which is particularly important in the syntaxial region which should exhibit extreme shear. At Nanga Parbat we see shear-wave splitting of both the local and regional events and we are trying to uniquely quantify the crustal and mantle contributions to this splitting. The data we propose to acquire in Tibet should allow us to resolve this ambiguity on a regional scale particularly when combined with the MIT data set. Finally, moment tensor summation will be used to estimate seismically released strain and calculate short-term strain rates (Kostrov, 1974; Holt et al., 1991). Seismic strain rates can be used to calculate the velocity-gradient tensor field associated with earthquake deformation (Haines and Holt, 1993) providing an independent measurement that can be compared with GPS observations.

II – 2. GPS (Koons, King, Liu Yuping)

One of the primary goals of this study is to obtain a precise estimate of the convergence velocity and the spatial variation in the velocity field as a function of distance across the eastern Himalaya and the syntaxis. We propose a GPS survey across the region of greatest predicted vorticity (Figures 1, 4, 11) (Holt et al. 1995; Royden et al. 1997; England and Molnar 1997b; Koons and Zeitler 1997), extending westward the network established by the Chengdu Institute (CIGMR) and MIT in 1993 (King et al. 1997). In this region a transition occurs from dominantly north-directed collision at the edge of the Himalayan Front, to a zone of strike slip on generally east-directed dextral faults, and finally to the Xianshuihe Fault system of largely sinistral southeast-directed faults (King et al. 1997) (Figure 3). By linking into the existing GPS arrays in central Tibet and than extending along the eastern border of Tibet, the additional GPS sites we propose to establish will not only be of interest in connection with the indentor corner, but will also lead to a definition of the contemporary kinematics of a major portion of eastern Tibet.

Array Design. From our preliminary numerical modeling, seismological estimates (Holt et al. 1995) and existing GPS surveys (King et al. 1997) we predict northward velocities relative to Eurasia in excess of 20 mm yr-1 adjacent to the entrance of the Tsangpo Gorge. The predicted velocity depends upon the degree of strain concentration within the anticlinal structure of Namche Barwa region and could be substantially larger. Within the relatively undeforming region of SW Yunnan to the east, King et al. (1997) have determined southward velocities relative to Chengdu of ~10 mm/yr. Assuming that Chengdu moves southward relative to Eurasia at 0-5 mm/yr, we infer a difference in velocity across the 300 km of our network of ~30 mm/yr. From two GPS surveys spanning three years we can determined relative velocities within the region with uncertainties of better than 3 mm/yr at 95% confidence (e.g. Reilinger et al., 1997). Thus, with the expected gradients (0.1 mm/yr/km), we can differentiate the velocities of stations separated by about 30 km. Because the velocity gradient is unlikely to be uniform, we propose operating our campaign at a station spacing of ~50-100 km to the east and northwest of the massif reducing the spacing to ~20 km in the vicinity of Namche Barwa (Figure 11).

The predicted and observed velocity field with its large vorticity varies in both the north-south and east-west directions. Within the constraints imposed by access, we will attempt to observe the degree of curvature of the velocity field. As shown on Figure 11, our net is designed to extend as far south as terrain and political frontiers allow. With information from Indian continent GPS stations, velocities relative to India can be obtained although we will not be able to determine the north-south velocity gradient south of Namche Barwa. The eastern extent of our net is designed to overlap with the most recent western limits of the MIT/CIGMR surveys.

The first year of the project will involve locating optimum GPS sites within this region in conjunction with field mapping, petrological collection and identification of neotectonic activity. During Year 2, sites identified during the first year reconnaissance will be monumented and occupied by CIGMR and University of Otago GPS teams. We expect to have at least seven operating GPS receivers during the campaign and plan 48 hour occupation periods. We will rely upon primary monumentation for reoccupation but will establish adjacent secondary locations in the vicinity of each monument.

Data Analysis. Processing of the GPS data will be carried out at CIGMR by Liu Yuping and at MIT by Robert King using the GAMIT/GLOBK software developed by the MIT group (King and Bock, 1998; Herring, 1998). The velocities estimated for the Namche Barwa region will be combined with those from the CIGMR/MIT surveys of the eastern Tibetan plateau and data collected by the International GPS Service (IGS) to obtain velocities in a well-defined reference frame for the Himalayan syntaxis and surrounding area. Using techniques for surface deformation based on splines and polynomial surfaces (e.g. Haines and Holt, 1993; M. Henderson, unpublished) we will then produce a continuous velocity and strain field for our study region. Using simulated data from 23 prospective sites, we have calculated that we expect to be able to characterize the velocity gradients by a polynomial of up to 4th order with error less than 10^{-7} yr^{-1}. We will then use the velocity and strain rate surfaces as ground truth for our models.

II – 3. Geochronology (Zeitler, Stone)

Our work in geochronology will contribute to several of our primary research goals. We will document timing and longer-term rates of exhumation at a regional scale in coordination with geomorphic studies of sediment fluxes, and we will support study of the Namche Barwa antiform and the associated knickpoint in several ways, including (1) delineating significant structural breaks in coordination with structural and microseismic studies; (2) characterizing timing, patterns and rates of exhumation in and around the antiform and the Big Bend Gorge, in coordination with geomorphic studies; (3) dating of the higher-temperature petrological, and structural evolution of Namche Barwa and its immediate surroundings, in coordination with petrological studies, and (4) providing baseline age constraints for the protolith of the Namche Barwa gneisses as well as for rocks surrounding the massif proper. We will accomplish these tasks using comprehensive Ar-Ar and U-He dating supplemented by U-Pb analyses of zircon and monazite from selected samples, and cosmogenic-isotope dating of bedrock surfaces and other surficial materials.

Regional Exhumation. We have argued that the accommodation by erosion of any eastward extrusion of Tibetan crust has not been considered and is unconstrained. To provide a longer-term view of erosion rates that can be compared with contemporary sediment-yield data from gauging stations scattered through the region (see Section II–4), we will measure sets of Ar-Ar and U-Th/He cooling ages on a regional scale at localities selected to coordinate with sediment-flux data from existing gauging stations and existing geochronological data (e.g., Harrison et al., 1996). This work will require about 30 each of Ar-Ar mica and U-Th/He apatite analyses, as well as 10 detailed Ar-Ar analyses of K-feldspar.

Structural Breaks and Exhumation at Namche Barwa. The purpose of this work would be to provide a comprehensive picture of exhumation patterns around Namche Barwa for comparison to computed patterns of contemporary erosion rates and to provide a constraint on models for the massif, i.e., is there a broad exhumation gradient centered around Namche Barwa, or are there distinct steps in exhumation at the boundaries of the massif? At the Nanga Parbat massif, such a dataset illustrates that active deformation, exhumation, and thermal perturbation are essentially confined to the massif itself (Figure 15). Figure 15 also illustrates how cooling-age reconnaissance in rugged, vegetated, difficult terrain can help identify young, active structures of significant magnitude, allowing coordinated structural studies to be more efficiently focused.

Our main objective is a dense coverage of biotite Ar-Ar and apatite U-Th-He cooling ages measured on basement samples taken from throughout the northern Namche Barwa massif and its surroundings. Such ages record cooling through temperatures on the order of 300-400°C and 65°C (Zeitler et al., 1987; Wolf et al., 1996), providing, respectively, a crude proxy for time of passage through the brittle-ductile transition, and a record of passage through the shallowest crust that can be linked to geomorphic studies, particularly in areas of high exhumation rate like the Namche Barwa massif (clearly, when interpreting our data we will have to take into account the significant peturbations to local thermal structure introduced by rapid exhumation and significant relief). This coverage (about 100 laser total-fusion ages on biotite and 100 apatite U-Th/He ages) would be sampled to determine both the regional context in cooling-age patterns as well as offsets along particular structures closer to and within the Namche Barwa massif itself; 100 ages by each method will allow an adequate sampling of regional trends as well as focused transects across known or suspected structures. This work would be augmented with detailed K-feldspar thermochronology once the regional pattern of cooling ages is defined.

We will complement our dating of basement samples with a program of dating detrital mica samples taken from subbasins throughout the Namche Barwa massif. Figure 16 shows that by sampling streams exiting about 40 catchments, we could characterize the cooling-age distribution of a substantial fraction of the massif. This is important because the extreme terrain of the study area will make it hard to sample outcrops comprehensively. Elsewhere in the Himalaya, detrital-dating studies using minerals with low to moderate closure temperatures have proven to be of great value in deciphering the relationships between sedimentary units and the unroofing history of their source area (e.g., Zeitler et al., 1982; Cerveny et al., 1988; Copeland and Harrison, 1990). Our proposed work would have similar benefits, at a much more local scale in which the relationship of sediment to source is clear.

Metamorphic Timing. An essential component for understanding the evolution of the Namche Barwa massif and the stability of the Namche Barwa knickpoint will be knowledge of the rates and timing of events such as granite emplacement, partial melting, metamorphism, and large-scale exhumation. Complementing our cooling-age studies of shallow exhumation and in coordination with our petrological studies, we will use Ar-Ar ages on amphiboles and U-Pb ion-probe ages on zircon, monazite, and other accessory minerals (as discrete grains and as inclusions) to characterize the metamorphic, igneous, and high-temperature exhumation history of the massif. This approach will allow us to date fundamental cross-cutting relationships provided by the igneous units, as well as constrain the cooling history over the interval ~150 ˚C to over 800 ˚C (Zeitler, 1989).

Baseline Age Constraints. To provide a context for interpreting our metamorphic ages, and to provide a framework in which to better understand the tectonic evolution of Namche Barwa and the enclosing southeastern margin of Tibet, we will conduct U-Pb dating of zircons from several samples of basement gneisses as well as other lithologies. The lithological contrasts between Namche Barwa and its surrounding terranes is not always obvious, and such work is necessary to make certain that the protoliths of the metamorphic stratigraphy in and around the Namche Barwa massif are known.

Analytical Considerations. Based on our experience at Nanga Parbat, the work we propose is straightforward. Even the very young ages we expect do not present significant analytical difficulties, provided one is aware of U-series disequilibrium affecting U-Th-Pb ages (Schärer, 1984). We may need to compromise when dating young detrital micas, especially biotites: their typical atmospheric argon content, coupled with the young ages we expect of <5 Ma, may make it hard to obtain useful single-grain ages. If so, we will do our detrital work by total fusion of bulk separates, as in any case we are most interested in a reconnaissance cooling-age assessment of catchments. As mush as possible, however, we will attempt to do single-grain work. Finally, because parts of the Namche Barwa region are wet, warm, and vegetated, biotite weathering could be a concern, although high erosion rates mean that outcrop residence times will be quite low. We will characterize dated mica samples to ensure that they are fresh.

By the Ar-Ar method, we propose to analyze 130 biotite total-fusion samples, 30 amphiboles and micas by step-heating, 20 K-feldspars, and about 750 single-grain analyses of biotite or muscovite. By the U-Th/He method, we propose to analyze a total of 130 apatite samples. All the analyses will be done at Lehigh. The amphiboles, some biotites, and K-feldspars will be run as age spectra; in the case of the K-feldspars, detailed spectra will be run and modeled for thermal history inversion using code in place at Lehigh. We will analyze most biotite samples by total-fusion, on the grounds that it is better to devote the analytical effort to many samples, rather than many steps to a much smaller number of samples, given biotite's propensity to yield flat age spectra under any circumstance. Our experience at Nanga Parbat is that this is adequate for 1-2 m.y. resolution. We will perform full-stepheating experiments on some samples as a check, and on any group of samples showing anomalous or critical ages. For U-Th/He analyses, U and Th will be determined on the recovered aliquot analyzed for He to eliminate problems with heterogeneity introduced by sample splitting. The size and morphology of all grains in the apatite samples will be measured and our ages corrected for alpha-loss (Farley et al., 1996). Selected samples will be step-heated to assess their diffusion kinetics.

Our U-Pb work will be carried out on the Cameca ion probe at UCLA, where we have had excellent results and productivity (see letter of collaboration from Mark Harrison). We have budgeted for a total of 100 hours of probe time, which should be adequate for determining U-Pb ages or Th-Pb ages on some 15 zircon or monazite samples from granites or metamorphic units, plus reconnaissance of zircons ages in 10 basement samples. We will coordinate sampling of metamorphic units with our petrologists, and attempt at least some of the metamorphic accessory-mineral dating on grains *in situ* in thin sections.

Cosmogenic Dating. To investigate erosion on the 10^2-10^4 year timescale, we will use cosmogenic-isotope methods to date river incision and measure outcrop- and catchment-scale denudation rates. The incision rate of the Tsangpo, which is expected to set the tempo for erosion in this area, will be determined from exposure ages of strath terraces seen up to 50 m above river level during our 1998 exploratory trip. If incision rates are as high as 1 cm/yr (cf. Burbank et al., 1996) these may be as young as 5000 years. By using high sensitivity ^{36}Cl measurements on K-feldspar, we hope to obtain age resolution of 200-500 years, allowing us to track sub-millennial variations in incision rate from ledges and terraces at different heights. A connection between the ~10^4 year timescale and longer-term exhumation could be established if dating can be extended to flat-lying ridge sections up to hundreds of meters above river level observed during the reconnaissance trip. These are interpreted as former valley floor surfaces stranded by river incision. Dating will only be possible if well-preserved surfaces can be identified, requiring careful field work early in the project.

Erosion rates can be measured directly with cosmogenic isotopes, on outcrop and drainage basin scales (e.g. Nishiizumi et al., 1993, Granger et al., 1996, Bierman and Steig, 1996). These measurements apply to the ~2-3 m depth scale, hence bridge the short-term denudation rates derived from sediment yields and long-term rates from thermochronology. At erosion rates of ~1 cm/yr the time scale for cosmogenic isotope build-up is 2-300 years, which will result in extremely low cosmogenic isotope concentrations. To maximize sensitivity, we will measure ^{10}Be in large samples of quartz, and ^{36}Cl in K-feldspar. Cosmogenic isotope measurements on sediment will be carried out to help calibrate DEM-based erosion predictions; DEMs will be used to model spatial variations in erosion and isotope production in the catchments chosen for investigation (cf. Brown et al., 1995). Care will be taken to select catchments of appropriate scale and elevation to avoid sediments derived from glacial erosion because ice would shield them from cosmic rays to average the effects of intermittent sediment supply (e.g. from landsliding) and to minimize sediment storage.

II – 4. Geomorphology - (Hallet, Montgomery, Nelson, Gillespie)

Our geomorphic research will examine rates and spatial patterns of erosion as they pertain to the geodynamics of the Namche Barwa area and, more broadly, the extent to which sediment evacuation is significant as a spatially distributed sink of crustal material that could modulate the eastward crustal extrusion from the India/Eurasia collision. In particular, we intend to:

1. determine contemporary erosion rates in the Namche Barwa area by developing a sediment budget from measured sediment fluxes and from downstream variation in the composition of water and sediment along the Tsangpo/Brahmaputra.
2. develop maps illustrating the spatial variation of an index of erosion rate computed from digital data sets for the topography (DEM) and climate of SE Tibet. This index enables us to compare expected erosion rates in different areas underlain by similar bedrock. In particular, it shows that peak incision rates along the Tsangpo Gorge (Figure 8, 10c) are likely to exceed by far those along most other Himalayan rivers, including those along the Indus River (up to 12 mm/yr) reported by Burbank et al. (1996).
3. examine the linkage between rapid erosion and antiformal uplift that both appear to be centered on the steep portion of Tsangpo's great knick point.

Contemporary rates of erosion in the Namche Barwa region. We intend to use two independent but complementary approaches: deducing sediment flux directly from a sediment budget, in which the contribution of sediments eroded from the region is assessed from a measured downstream increase in sediment flux, and indirectly through geochemical tracking of river water and sediments.

Erosion rates deduced from sediment budget. We intend to determine the amounts of material currently entering and exiting the Tsangpo Gorge through ongoing suspended sediment flux measurements directly upstream of the gorge (Figure 17) and our proposed measurements along the upper Brahmaputra. The difference between the two amounts provides a direct estimate of the current sediment yield from Namche Barwa and the surrounding area for the duration of our study. In general this difference is ambiguous because it could be interpreted as a change in sediment storage in the intervening portion of the drainage basin. Fortunately, in this region of extreme relief and narrow steep-sided gorges floored by bedrock channels, the dearth of sediment stored in the basins makes it possible to derive basin-wide erosion rates with minimal ambiguity from the divergence of measured riverine sediment flux.

To define the total mass export from the Namche Barwa region, it is imperative that the Dihang section of the Brahmaputra in northern India be monitored, just before it spreads out into the plains because there is no sediment flux data for the uppermost Brahmaputra. This monitoring will be conducted under a collaborative agreement (attached at end) with Christian France-Lanord who has recently initiated research on the Dihang.

To determine how sediment flux changes along the Tsangpo, we also intend to monitor sediment flux in two relatively accessible areas of the Gorge where we expect some of the world's highest incision rates (Figures 7, 8), at the Big Bend and downstream at Medok (Figure 5). Sediment flux will be calculated from river discharge and suspended sediment concentration measured using robust sensor/data acquisition packages similar to those we have used in Alaskan glacial rivers (e.g. Merrand and Hallet, 1996). Each package consists of a data logger that records hourly for about one year input from a pressure transducer to monitor river stage, a turbidity sensor to provide a measure of suspended sediment concentration, a thermistor for water temperature and a rain gauge. The rating curve, relating stage to discharge, will be developed and the turbidity sensor calibrated using standard methods for each instrumented section; the channel geometry and bed roughness will be determined. Because of the remoteness of the sites, we are planning to augment electronic measurements at each site by hiring a local resident to collect water samples manually, record river stage and rainfall daily, and oversee the equipment to avoid tampering. The samples and observations will provide a cross check and year-long calibration for the electronic measurements, and in case of equipment malfunction, a partial patch for data gaps.

We also intend to use several decades of detailed sediment flux data available from SE Tibet and NE India to estimate erosion rates for the Namche Barwa area on a time scale longer than the duration of our study. We will seek a relationship between our measurements and data from established gauging stations in the region. Assuming this relationship is time invariant, it will enable us to infer the sediment flux exiting the Namche Barwa area from a relatively long time series of sediment flux in the Brahmaputra downstream of Ranaghat (Goswani, 1985; Barua et al., in revision).

Erosion rates deduced from radiogenic isotope and cation concentrations. To provide an independent estimate of suspended sediment flux, to estimate both the bedload (generally a minor but elusive component for larger rivers) and dissolved load in the Tsangpo, and to determine the relative sediment yields from sub-basins draining into the Tsangpo gorge, we propose to analyze water, and suspended and bedload sediment for Sm/Nd-Rb/Sr isotope and dissolved cation content at all sampled sub-basins (Figure 16).

In the Nepalese Himalayas and southern Tibet, where isotopic and chemical variability is regionally discrete and distinct much as in the Namche Barwa area, relative sediment yields from individual basins and relative fluxes of sediments transported, both mechanically and in solution, can be inferred from geochemical analyses of water and sediment (e.g., Galy 1999). For example, Harris et al. (1998) inferred major differences in erosion rates in different terrain from strong cation and isotopic gradients in water, and especially, in sediments from the Bhote-Kosi as it traversed from the Tibetan Sedimentary Series (relatively carbonate-rich, $^{87}Sr/^{86}Sr$ 0.725) to the High Himalayan Crystalline Series (HHCS) (carbonate-poor, $^{87}Sr/^{86}Sr$ 0.755). We expect similar contrasts along the Tsangpo where water isotopic ratios are low ($^{87}Sr/^{86}Sr$ 0.705-0.716) (Harris et al., 1998) prior to entering the more radiogenic HHCS in the gorge. Considerable erosion of HHCS must occur in the gorge to account for the $^{87}Sr/^{86}Sr$ of 0.719 measured in the upper Brahmaputra despite the dilution effect of two major tributaries (Dibang and Lohir) directly upstream that have large discharges of Sr-rich water with Sr ratios of .705-.708, based on reconnaissance sampling by France-Lanord (pers. communication, 2000). Tracking the isotopic composition of bedload sediments should be particularly reflective of input along the gorge because the confounding influence of mixing with bedload sediments from the Plateau is minimal, because they are largely trapped within the alluvial reach directly above the gorge. When combined with one independent measure of absolute sediment flux, such as that currently measured at the gorge entrance, the analyses can lead to direct estimates of absolute sediment fluxes both within and downstream of the gorge. Bruce Nelson will oversee the Sr, Nd, and cation analyses in Seattle and France-Lanord will conduct the carbonate analyses.

Digital maps of erosion rates in SE Tibet. We propose to develop an index of erosion rates to define how erosion varies spatially, using digital compilations of topography and precipitation, and simple relationships between erosion rates and drainage-basin parameters. These erosion rate indices can be calibrated using data on suspended sediment flux, as such data provide a direct empirical measure of basin-wide, admittedly short-term erosion rates. Sediment flux data are available from widely scattered hydrologic stations throughout this part of China (Hydrologic Bureau, 1982). We can also compare our calculated contemporary rates against our longer-term estimates of exhumation rates derived, in particular, from U-Th/He apatite dating, which should record the mean rate of removal of the last ~2 km of rock and require from 100,000 to 500,000 years near Namche Barwa. This comparison enables us to determine whether the long-term rate of rock removal may differ from current rates, and whether it is likely to include significant tectonic exhumation.

Physical intuition and considerable data suggest that both the fluvial bedrock incision rate (Stock and Montgomery, 1999), and the basin-wide erosion rate (Aalto and Dunne, 1998) scale with the amount of energy expended by rivers per unit time per unit channel area, or the shear stress developed on the river bed. These variables are functions of the local water discharge, Q, and the slope, S, of the river channel both of which can be assessed readily over an entire region from digital topography (DEM) and from digital compilations of precipitation estimates (Leemans and Cramer, 1992). Defining Q as the excess precipitation rate, P (precipitation reduced by evaporation) integrated over the upstream drainage basin area, A, we express the erosion index as:

$$e = K\, Q^m\, S^n \qquad (1)$$

Here e is corresponds either to the fluvial bedrock channel incision rate or basin-wide erosion rate. K, m, and n are empirical constants. K reflects erosion resistance of the bedrock and sediment supply; m and n take on different specific values depending on the river property that is assumed to control erosion (e.g. Slingerland, et al., 1998). We note that, in general, no simple connection exists between channel incision rates and basin-wide erosion rate. However, in areas of extreme bedrock-dominated relief, like around Namche Barwa, the rates must be similar to one another because slope erosion must keep up with river incision, lest rivers be found in deep notches or valley bottoms be flooded with sediment derived from hillslopes; any significant difference between the two would tend to be short-lived.

Maps of erosion rate index can be produced by applying equation (1), or its equivalent, throughout a river network. K can be assumed to be a constant for a region with bedrock that resists erosion similarly. We stress the distinction between the erosion rate index and the actual rates of erosion or incision, which would require generally unavailable knowledge of the resistance of the local bedrock to fluvial erosion and availability of local sediment stores. Recently, a similar erosion index approach has been validated and calibrated for crystalline and sedimentary rocks in the Himalayas of central Nepal by Lave and Avouac (2000; pers. communication); they compared erosion indices to depth of incision in dated strath terraces. Their work strongly supports the approach and highlights the need to survey river channel widths and to examine the bedrock and the bedload in the river channels, which we will do in the Namche Barwa area.

Methods for predicting local erosion rate indices are sensitive to algorithms used to extract drainage area and slope from DEMs, and to the grid size used in the analysis. Nonetheless, consistent application of such a model provides direct insight into spatial variation in expected erosion rates on all scales for which DEMs are available (Figure 10b,c). We stress that our main goal is a general constraint on erosion rates in SE Tibet for the purpose of constraining the short-circuit transport of crustal material out of the eastern syntaxis. We note that uncertainties in calibration are offset by the synoptic view that will be offered by a digital map of erosion index.

We have the ~1 km (30-arc second) DEM data in hand and have started to conduct initial analyses (Figure 8, 10c); we will incorporate better data as they become available. The successful February 2000 SRTM Shuttle mission is expected to produce a high resolution (1 arc second, ~30 meters) topographic data set of the world except for the high latitudes. These SRTM DEMs will become available to Montgomery and Hallet in the early phase of this project, as they are PIs on a study already included in the list of funded SRTM projects. Such DEMs will provide a consistent data set for quantitatively defining the erosion rate index along the Tsangpo and other big rivers in SE Tibet, and for comparing quantitatively the properties of slopes, rivers, and drainage basins in the Namche Barwa area with those in other parts of the region. The DEMs will enable us to calculate an integrated index of erosion rates (IIER, see Figure 10c) for the whole southeastern Tibet region with unprecedented resolution. This, together with existing riverine sediment flux data, will provide a firm basis for a major objective of this proposal, evaluating the extent to which the crustal pile-up at this corner of the India-Eurasia collision is alleviated by fluvial evacuation of lithospheric mass (Figure 10a).

Linkage between rapid erosion and antiformal uplift at Tsangpo's knick point. The Tsangpo knickpoint is remarkable for being the largest among the major knickpoints of Himalayan rivers (Brookfield, 1998; Figures 6 and 8), for its location atop a very active antiformal structure, for deposition immediately upstream of the knickpoint, and for the peak erosion indices being unsurpassed in the Himalayas, except for few reaches of the Arun River (Figure 10c).

A simple two-dimensional model of fluvial bedrock incision (Figure 18), based on equation (1), shows incision rates peaking in steep reaches, causing rapid upstream migration of the knickpoint in the absence of rock uplift. Such migration would only uncover relatively shallow rocks, which is <u>not</u> consistent with the observed exposure at Namche Barwa of rocks from considerable depth. Knickpoint migration can be essentially halted, however, by offsetting the erosion with uplift such as might be expected near the active Namche Barwa antiform and as would be predicted by our aneurysm model, in which local crustal advection and deep-gorge excavation are linked. In any case, the knickpoint would have to have been sustained and essentially stationary to erode the perhaps 15-20 km of crust that reconnaissance petrological and geochronological data (Burg et al., 1997) suggest has been removed locally over the past 3-4 m.y. This incision model can be improved by going to three dimensions and using high precision topographic data and an appropriate, well-calibrated erosion law. We intend to complement this with a calculation of the isostatic rebound caused by the deepening or propagation of the gorge, which was developed for the Olympics by Montgomery and Greenberg (2000). The incision model would permit calculation of the pattern of additional (tectonic) uplift required to maintain the river profile, thereby offering a useful constraint on the geodynamic analysis.

Therefore, as a next step we propose to use a three-dimensional model of landscape evolution (see Section II – 7) to explore the direct feedback between erosion and uplift, whereby the rapid erosion expected along steep reaches of big rivers naturally induces local antiformal uplift, or vice-versa. Specifically, we will use the model to study the evolution of the Tsangpo river profile, to determine whether the present-day knickpoint can be maintained over even short geological time scales, and to determine the likelihood and probable age of a river capture. The knickpoint may have been initiated relatively recently when the Tsangpo was diverted abruptly to the south away from the Luhit river by a steep tributary eroding headward from the south (e.g. Seeber and Gornitz, 1983; Brookfield, 1998). Insight into the timing and location of this capture would contribute to understanding the stability and rate of change of the Tsangpo knickpoint. A blend of image analysis (satellite imagery and aerial photographs) and field checking of key areas will be used to search for ancestral valley, stranded sedimentary fills, and degraded massifs, starting with the area where evidence of the capture has been found (Royden et al., 2000).

Summing up, this blend of geomorphic modeling studies and field work will help us understand the probable evolution of the Tsangpo river, which long ago probably wrapped around the syntaxis but now slices sharply through it. More generally, it will fundamentally improve understanding and appreciation of the links between lithospheric processes and erosion/fluvial evacuation at scales ranging from the center of the syntaxis to all of southeastern Tibet.

II – 5. Structure (Kidd, Pan Guitang)

The goals of the structural investigation are to determine the longer-term, overall kinematics and the large-scale structural geometry of the active antiformal Namche Barwa massif, and the relationship of this massif to regional structures of the eastern syntaxis. The structural work will focus on the following questions:

How are older large-scale structures deformed by young active structures within the syntaxis? Characterization of deformation of older structures in the syntaxis, by young structures exposed at the Namche Barwa massif and interaction with nearby large active structures (e.g. Jiali fault zone) will set limits on the amount and timing of large-scale mass flux from the region, and permit correlation between major structures and the local seismic and GPS results. In the core of the syntaxis the location of the Indus suture remains somewhat unclear. There are no exposures of ophiolitic rocks that mark the suture as in other parts of the orogen. Instead, relatively similar metasedimentary and granitoid rocks are juxtaposed across the Indus suture. No Tethyan cover metasediments are shown on the "Indian" side adjacent to the suture around Namche Barwa. Known major structures along strike westwards, specifically the

Gangdese thrust (Yin et al, 1994), the Zedong backthrust, the STDS detachment (Burchfiel et al, 1992), and general imbrication of the Tethyan cover, seem unlikely to be responsible for complete removal of all Tethyan metasediments; investigation of this issue may reveal new insights into some of the [elsewhere] still deeply buried parts of the Himalayan thrust system, and perhaps provide a constraint on how much lower crust was transported by it beneath the Lhasa block.

What are the kinematics and time of activity of Namche Barwa marginal faults and shear zones? While Burg et. al. (1997; 1998) and Liu and Zhong (1997) both describe the structure of the Namche Barwa massif as antiformal, they differ significantly in their interpretations of structures bounding the massif. Liu and Zhong (1997) suggest young strike-slip movement along the eastern margin of the massif, modifying the original ophiolite (Indus-Tsangpo) suture, and interpret a south directed thrust to place high-grade gneisses of the Namche Barwa core over the Tethyan (Himalayan) metasediments, whereas Burg et al. (1997; 1998) do not. Resolving the nature of these contacts and the relative timing of deformation along them are key components of the structural project. Folding of pre-existing major structures around a large-scale antiformal structure will reorient gently to moderately dipping thrust or normal displacement shear zones to steeply-dipping attitudes with apparent strike-slip kinematic indicators. It needs to be determined whether the strike-slip faults/shear zones on the western margin, and [according to Liu and Zhong] eastern margin, of Namche Barwa are the product of young strike-slip tectonics, or are the result of reorientation of older structures. This can only be done by structural and metamorphic field and sample investigation, in collaboration with dating of granitoid rocks structurally characterized with respect to the shear zone in which they occur.

Thrust- or folding-dominated structure? Although not identified by existing reconnaissance studies, we suspect that major, young thrust-sense shear zones, like those found at Nanga Parbat, and which are the dominant structures controlling exhumation there, may exist bordering and/or within the Namche Barwa massif. The cooling age pattern should help identify the likely sites for such shear zones. Structural and metamorphic definition and dating of such zones will be essential to understanding the growth of the structure and overall exhumation. Even if Burg et al. are correct that the "suture" along the eastern Namche Barwa margin has only been folded, as we discovered at Nanga Parbat (Edwards et al, 1996, 1997, 2000; Schneider et. al., 1999), this does not rule out one or more shear zone(s) of first-order significance within the massif. This part of the structural work, by linking timing of activity and shear sense, will contribute to testing the "tectonic aneurysm" model (Zeitler et al., in review; Koons, et al., in review), which requires focussing of strain during specific developmental stages.

Is there any tectonic denudation? Another goal of the structural investigation is to look for evidence of any major normal-motion detachment structure that would allow significant non-erosional exhumation of the massif, during some interval of its development. Burg et al (1998) remark that they saw little evidence of tectonic denudation, but much of the area has yet to be systematically mapped. The absence of such a structure at Nanga Parbat (Kidd et al, 1998; Schneider et. al., 1999) perhaps implies that one is unlikely to be present at Namche Barwa, but this must be determined by systematic structural mapping. This question is also linked to testing of the hypothesis of knickpoint arrest, since a similar pattern of alluviated valley upstream of the incised gorge can be seen at two localities farther west on the Yarlung Tsangpo where it is clear that members of the Neogene N-S rift system cross the river.

Proposed structural work and mapping will initially focus on characterizing the margins of the NB massif, particularly the kinematics of marginal ductile high strain zones, and an initial cross-section. The subsequent two field seasons will attempt to improve coverage of the massif, particularly to several cross-sections, to examine in more detail the relations between "basement" and "cover" metasediments, and to enlarge the area of structural investigation to allow comparison of the GPS and local seismic events to identified major structures. Burg et al. (1998) have already made some measurements of brittle fracture orientation and slip sense measurements; we plan to collect data at complementary sites. Any neotectonic fault scarps found will be mapped in detail, in cooperation with the geomorphology group, and integrated into the study of brittle features. Integration of the structural, isotopic dating, and metamorphic petrology is particularly critical for this project. The structural results should also contribute to the interpretation of the geomorphological, geodetic and regional seismic results. TM satellite images will be used for accurate field location, structural mapping and for construction of an overall geological compilation map derived from observations of members of all groups.

II – 6. Petrology and Fluid Inclusion Studies (Chamberlain, Craw, Geng, Zheng)

The specific objective of our petrologic and fluid-inclusion studies is to document the long-term, large-scale pattern of exhumation history in and around the Namche Barwa massif, using detailed pressure-temperature-time information obtained from crystalline rocks.

We plan to determine *P-T-t* paths for pelitic gneisses using a combination of thermobarometric techniques on inclusions in garnet, Gibbs-method analysis, and examination of metamorphic assemblages and textures. Previous studies show that pelitic gneisses at Namche Barwa range from amphibolite to granulite facies (Liu and Zhong, 1997) and contain high-aluminous assemblages suitable for petrologic analysis. The amphibolite-facies rocks consist of staurolite-plagioclase-garnet-sillimanite and/or kyanite-biotite-muscovite, and the granulite-facies rocks contain the assemblage plagioclase-garnet-sillimanite/kyanite-biotite-cordierite-spinel-rutile-ilmenite (Liu and Zhong, 1997). In many of the assemblages, garnet contains abundant inclusions suitable for thermobarometric analysis. Peak metamorphism of the granulites has been determined to be ~1.7 to 1.8 GPa and ~890°C (Liu and Zhong, 1997), with later nearly isothermal decompression to ~0.5 GPa and ~850°C (Liu and Zhong, 1997), consistent with a history of rapid exhumation.

The initial petrologic results of Liu and Zhong (1997) provide a framework for our *P-T-t* studies. What are needed, however, are: (1) estimates of *P-T* conditions of final equilibration along transects across key structural features; (2) *P-T* paths across key structural elements of the massif; and (3) detailed and combined petrologic and geochronologic results on the same samples to accurately define the *P-T* history. We have shown at Nanga Parbat that *P-T* paths, pressure and temperatures of peak metamorphism, and timing of metamorphism can and do change over relatively short distances. Such differences between *P-T-t* paths along transects in the massif have been instrumental in determining the tectonic history of the Nanga Parbat region and we have every reason to suspect that such differences will occur at Namche Barwa.

We realize that it is not trivial to construct meaningful *P-T-t* paths, particularly from granulite-facies rocks (e.g. Spear, 1991; Spear and Florence, 1992). Because these rocks have been subjected to relatively high temperatures we are concerned that homogenization of garnet compositions, retrograde Fe-Mg cation exchange reactions, and retrograde net-transfer reactions may influence the *P-T* paths we derive (Spear et al., 1990; Florence and Spear, 1991; 1993). Therefore, we will use a variety of approaches to characterize the *P-T* evolution of these rocks, such as the Gibbs method on zoned garnets (Spear and Selverstone, 1983; Spear, 1989; Spear et al., 1991; Kohn, 1993), *P-T* determinations on inclusions within garnet (St-Onge, 1987); and analysis of mineral reactions from reaction textures used in conjunction with petrogenetic grids (Chamberlain, 1986; Spear and Cheney, 1989; Spear et al., 1999). Use of several independent techniques will allow us in part to assess the quality of these *P-T* paths. The assemblages listed above have several well-calibrated thermobarometers, and in addition, we will determine pressures and temperatures using the pertinent reactions and thermochemical data sets for these assemblages (Berman, 1988). All of the *P-T-t* data will be done on sections fully characterized using petrographic. X-ray maps and backscattered electron images.

Timing of metamorphism along the *P-T* path can be calculated using monazite (Th-Pb), allanite (Th-Pb) , and zircon (U/Pb) ages (see Harrison et al., 1997; Catlos et al., 2000). Timing of near-peak metamorphic conditions can be calculated using matrix monazite, and portions of the prograde P-T path can be determined if monazite or allanite occur as inclusions in garnet (see Harrison et al., 1997).

The low-temperature portion of *P-T-t* paths can be quantified using fluid-inclusion studies. These studies are particularly useful for constraining near-isothermal uplift paths (Holm et al. 1989; Craw 1988; Craw et al., 1994) which we predict will be occurring within the Namche Barwa massif. To our knowledge, there have been no studies of fluid inclusions at Namche Barwa., and because the study of fluid inclusions in veins can yield invaluable, independent estimates of thermal gradient and, in combination with cooling-age studies, estimates of exhumation rate, it is important that we carry out such studies at Namche Barwa. We have used this approach in determining the recent exhumation history of Nanga Parbat with considerable success (Winslow et al., 1995). David Craw of the University of Otago has consulted and worked with the Nanga Parbat project on similar samples and has agreed to participate and work on this aspect of the project.

Quantification of the low-temperature portion of *P-T-t* paths is done by obtaining routine microthermometric data (homogenization and melting temperatures) on inclusions trapped at several stages during uplift of the rocks (Holm et al. 1989; Craw 1988, 1990; Craw et al., 1994). The key to success of these techniques is to collect samples for fluid-inclusion study from a variety of structural settings whose relative age is known. We will do this at Namche Barwa by carefully documenting the structural evolution of several generations of late-metamorphic minerals and quartz veins along our transects, and quantifying ages where possible using argon/argon dating of late-stage vein minerals (biotite, muscovite). Within individual samples, relative ages of fluid-inclusion generations can be obtained from petrographic examination, distinguishing primary from secondary inclusions, and analyzing different generations of late-stage secondary inclusions. From these data, the geothermal gradient, variations in this gradient with depth, and exhumation rate can be quantified (Holm et al. 1989; Craw et al. 1994; Winslow et al. 1994; Teagle et al. 1998).

II – 7. Modeling (Koons, Bardeen)

We propose an extensive numerical study involving closely linked models: one treating broader-scale lithospheric deformation responding to tectonic forcing as well as surficial mass transfer, and the other treating the evolution of landscapes dissected by realistic drainage patterns with high-spatial resolution. We refer to these models as the lithospheric model and the landscape model, respectively. The integration of both of these fully three-dimensional models will represent a significant advance in modeling active orogens, permitting us to examine the rich interactions of surface and lithospheric processes. Results from geological, geophysical, and geodetic investigations will serve as input and boundary conditions for modeling coupled surficial and tectonic processes. Integrating the results of our studies will allow us to incorporate rheologically distinct domains with representative geometries and physical properties to investigate local deformation and erosion anomalies that are unpredictable from analysis of a homogeneous material. Specifically, lithospheric modeling will identify zones of strain concentration and of strain-dependent changes in material properties that strongly influence erosional concentration (Koons, 1994; Koons et al., in review). Landscape modeling will be able to incorporate these effects and pass back information on surficial mass distribution for calculation of the stress and velocity fields. This coupled modeling approach will help us gain physically sound insight into the nature and relative importance of individual processes and links between processes responsible for the patterns of crustal evolution and geomorphic development revealed by field work. Ultimately, our integrated model should improve understanding of boundary conditions for the India-Asia collision and of the geodynamic evolution along irregular plate boundaries, both modern and ancient.

Lithospheric Model. Our models will be gridded at varying scales so that we can track particle behavior and the impact of local rheological and erosional variation on the dynamics at the larger orogen-scale. Particle-path characterization permits comparison of model pressure-temperature-time paths with those determined from our petrological and geochronological investigations. The upper surface and exhumation can be controlled by regridding procedures developed for work on the Southern Alps, New Zealand in which load removal and redistribution due to erosion are integral to the mechanical solution. The regridding procedures permit very large strains to be modeled, thereby reducing one of the weaknesses of Lagrangian formulations. Throughout the modeling, we will track deformation in the crust and lithosphere. The calculated strains within the upper mantle will be compared with seismic measurements of shear-wave splitting and those in the crust will be compared with observed strains in the crust.

The mechanical portion of our model will be based on existing numerical and analytical techniques for solution of three-dimensional deformation (e.g. Koons, 1994; Koons et al., 1998), using heterogeneous boundary conditions and rheological approximations. Initially we will employ a modified Lagrangian solution scheme based upon an ITASCA formulation (Cundall and Board, 1988), which provides flexibility in the use of rheological models, variable material geometry, variable exhumation rates, and permits tracking of individual packets through the deforming zone. Elastic/plastic and elastic/plastic/viscous rheologies are employed initially with the non-linear flow behavior defined by the degree of reaction/deformation coupling described more fully below. Preliminary models developed for this proposal used a Mohr-Coulomb upper crust resting on a Drucker-Praeger (plastic) lower crust, which in turn sits above a plastic, high-density mantle. We have previously used these techniques to investigate deformation- and thermally-driven fluid flow in active convergent zones (e.g. Koons et al. 1998).

To validate numerical solutions wherever possible and to clarify relationships among Cartesian stresses, principal stresses and failure orientations, we employ the eigenvector method for analysis of critical failure in three dimensions (Koons, 1994) and other analytical approximations (Enlow and Koons, 1998). Perturbation-derived analytical expressions have yielded considerable insight into the variables controlling strain partitioning in obliquely convergent orogens; we will expand this approach to modeling corner dynamics. Fault-plane solutions and moment-tensor solutions from the seismic data will be used to validate model predictions of failure orientations.

Within the core of the eastern syntaxis, the recent and rapid exhumation of deep crustal assemblages at Namche Barwa presents a relatively simple field example of the coupling of reaction and deformation without complexities introduced by later metamorphism. Observations at Nanga Parbat and the Southern Alps, New Zealand led us to examine rheological changes induced by coupled reaction/deformation. We hypothesize that mid- to deep-crustal metamorphic recrystallization affects the rheology of the crust in high-strain regions due to coupling among diffusion, reaction, and deformation (Koons et al., 1987). We link metamorphic recrystallization to the broader-scale deformation in which the extent of equilibration is a function of cumulative strain. Because reaction is a function of the strain-rate field in this formulation, the location and timing of metamorphism, fluid release and formation of melts may be defined within the mechanical framework (Koons 1996; Koons et al. 1998).

Consequently, our proposed work presents an ideal opportunity to test predictions made by this novel view of metamorphic equilibration. The *P-T-t* information derived for Namche Barwa by petrological and geochronological work and constraints on rheology and lithospheric architecture determined by our short-period seismic array will place limits on deformation and reaction timing and on the rheological properties of the massif. Our numerical solutions will use these rheological and temporal constraints to produce a kinematic solution that can be compared with strain observations from field mapping, seismic analysis, and the GPS survey. In addition, because of the strain control of the lower order harmonics of the topography (Koons 1994; 1995), the model of metamorphism we propose has significant implications for the complexity and evolution of topography. Our proposed geomorphological studies will provide information on topographic complexity and scale dependence, and so provide a test of metamorphic and geomorphic links.

Landscape Model. The higher-order harmonics of the topography and the drainage patterns in the eastern Himalaya and southeastern Tibet will be investigated by coupling the lithospheric model just discussed with an existing landscape evolution model (James Bardeen's "TerraForms"; http://www.phys.washington.edu/~bardeen/). In collaboration with Bardeen, two issues will be explored digitally: (1) the evolution of the drainage network, including the potential for stream capture and the dynamics of the Tsangpo knickpoint in the eastern syntaxis, and (2) the broader scale evolution of drainage networks in southeastern Tibet, starting from dendritic network that general drain toward the lowlands to the east to systems of river valleys that converge tightly and wrap around the syntaxis. TerraForms is well suited for these virtual explorations. It readily generates topologically correct fractal networks that can serve as initial networks prior to large crustal deformation It is then able to track the evolution of the landscape as the crust deforms according to the lithospheric model, and erodes by slope and fluvial processes according to rules similar to Equation 1. Diffusive slope processes, in which erosion depends on local slope and curvature rather than upstream drainage area, are included in the model and expressed as a function of altitude, representing the tendency for diffusive processes to prevail at low altitudes where soil increasingly mantles slopes. We intend to add algorithms to TerraForms that represent processes likely to facilitate river capture by reducing divides; in standard topographic evolution models, divides tend to persist indefinitely because erosion vanishes there, precisely where the drainage area also vanishes. Such processes include deep-seated bedrock failures and headwall retreat by cirque glacier erosion. The sensitivity of the long-term evolution of the landscape to the initial conditions can be determined. Erosion rates and distribution determined from the landscape simulations will serve as boundary conditions on the upper surface of the lithospheric model. The itterative coupling between lithospheric and landscape models will be completed by passing back the calculated vertical and horizontal crustal displacements that alter the surface into the landscape model.

Part III. RESULTS FROM PRIOR NSF SUPPORT – ZEITLER and MELTZER

EAR-9418849. $1,337,707. (Lehigh budget w/ various supplements; project budget $2.2 million) 1994-2000. "Collaborative Research: Crustal reworking during orogeny: an active-system Himalayan perspective." P. Zeitler, A. Meltzer, with co-PIs C.P. Chamberlain, J. Blum (Dartmouth), P.O. Koons (Otago), J. Armbruster, L. Seeber (LDEO) S. Park, R. Mackie (Riverside), W.S.F. Kidd (Albany), P. Le Fort and A. Pecher (Joseph-Fourier), J. Shroder, M. Bishop (Nebraska), J. Quade (Arizona) M.Q. Jan, M. Khattak, M.A. Khan, S. Hamidullah (Peshawar).

Overview and Status of the Nanga Parbat Project.
Our goal in this multidisciplinary project was to use the excellent exposure of lower-crustal rocks at Nanga Parbat to understand how continental crust is petrologically and structurally overprinted during collision. We used studies in seismology, magnetollurics, structure, geochronology, petrology, geochemistry, and geomorphology to assess the tectonic processes responsible for the young igneous and metamorphic activity and rapid exhumation observed at the massif. Field work is complete, data processing and synthesis are done, and most of our data have been presented for publication or are in review. We are currently working on a synthesis volume that will serve to disseminate our results in a comprehensive fashion, and we have also worked with video producer Doug Prose, who is making a science documentary that will disseminate results of the Nanga Parbat project to the public and to schools.

Detailed structural mapping and patterns of cooling ages show the massif to be a crustal-scale pop-up structure marked by active brittle faults and older shear zones into which relatively older granitoids were emplaced (Figures 15, 19; Schneider et al., 1999a, 1999b; Edwards et al., 2000). No evidence for significant extensional exhumation is present. Developed in Proterozoic basement, the massif was first overprinted by an earlier Himalayan metamorphism as shown by the presence of an ~18 Ma anatectic granite (Schneider et al., 199b). Widespread young granite dikes 1-3 Ma in age are confined to the topographically high core of the massif (Schneider et al., 1999c), where low-P/high-T cordierite/K-feldspar gneisses (Poage et al., in press) with metamorphic ages of ~3 Ma occur. Pervasive upper-crustal fluid flow occurs in the core region, as do steep thermal gradients of 60˚C/km or more as shown by fluid inclusions for the top 3 km of the crust. A sharp lower cut-off in microseismicity, bowed upward 3 km beneath the summit region, indicates the brittle-ductile transition is shallow at ~2-5 km bsl (Figure 20a; Meltzer et al., in review). This pattern, together with tomographic results showing very low Vp and Vs and higher attenuation throughout the crust in the region below the core of the massif, is consistent with rapid advection of hot crust at 5 mm/yr as indicated by petrological and geochronological data (Figures 15, 19, 20d-g; Meltzer et al., in review; Sarker and Meltzer, in review). This also suggests that the primary flow path of material into the massif is from depth rather than along a shallow detachment. MT and seismic data rule out large magma bodies as the cause of the observed petrological anomaly; variable seismic waveforms indicate small-scale heterogeneities in the shallow crust related to fluids (either partial melt or aqueous; Figure 20c), whereas the MT data surprisingly show the lower crust to be atypically resistive (Figure 20f; Park and Mackie, 1997, 2000; Meltzer et al., in review). These structural, geophysical, and petrological anomalies occur in a bulls-eye pattern around the summit massif and are associated with focused exhumation and concentrated strain (Zeitler et al., in review).

Using a coupled thermal/mechanical/erosional model (Koons et al., in review), we can show that in a deforming orogen, local rheological variations such as those that arise from deep and rapid incision (as seen at Nanga Parbat (Shroder and Bishop, 2000)), can strongly rearrange the regional strain pattern to one which departs significantly from that predicted using uniform rheological parameters and simple velocity boundary conditions (Figure 21). A weak area will focus particle paths such that movement of material within the orogen will be concentrated into the weaker zone. A positive feedback develops in which advection of material into this weakened zone results in concentrated exhumation and corresponding advection of isotherms, further weakening the upper crust. One outcome of such erosional/mechanical coupling is the development of very large mountains of relatively limited spatial extent perched atop hot, thin, weak crust.

The manifestations of such localized deformation are many (Figure 21c). Focusing of strain and rapid exhumation lead to substantial metamorphic and structural overprinting of the crust, as high-temperature lower-crustal rocks, possibly already partially molten, are isothermally decompressed and brought into communication with surface waters. The thermal and petrological anomalies associated with this exhumation and concentration of strain can be thought of as a tectonic aneurysm. This model provides an integrating framework for understanding the diverse suite of observations that we and other workers have collected at Nanga Parbat. Our view is that rapid erosion and excavation of a deep gorge by the Indus River has focused strain and triggered development of a tectonic aneurysm in crust initially weakened by thickening and having very high radioactive heat production. The emplacement of granites during recent erosional exhumation (~1-5 Ma), development and exposure of young low-pressure granulite-facies metamorphic rocks (3 Ma in age), development of structural relief via antiform growth and thrusting, formation of a vigorous metamorphic/meteoric hydrothermal system, shallow brittle to ductile transition, and generally hot resistive crust are all consistent with advection of deep crustal material into a relatively weak crustal zone.

We suggest that at Nanga Parbat (see Figure 21c), initial high-pressure metamorphic equilibration and volatile release occur within a high-strain zone located to the south of the massif. In this zone, mid- to deep-crustal metamorphic recrystallization occurs as non-equilibrium transitions driven by steep velocity gradients affecting the rheology of the crust. Rocks having passed through the high-strain zone have been dehydrated and contain insufficient connected fluid phase to serve as an electrical conductor so that the crust beneath the massif is resistive. Rapid decompression of water-poor, dehydrated gneisses generates vapor-absent granitic melts which are emplaced upwards into the massif (Zeitler and Chamberlain, 1991; Butler et al., 1997). These dry gneisses then pass into a lower-strain zone beneath the summit, advecting isotherms. During uplift the gneisses undergo decompression reactions, generating the lower-pressure and high-temperature granulite assemblages preserved in the center of the massif.

Our model also sheds light on the relationship between fluid flow and the evolution of the brittle/ductile transition at Nanga Parbat. Less than 1 m.y. after exhumation begins, a near-steady-state thermal pattern is established (Koons, 1987). Steep geothermal gradients are produced (approaching 100°C/km near the surface), elevating the 400°C isotherm and the position of the brittle/ductile transition to ~2-5 km depth bsl, as suggested by our petrologic, fluid inclusion, and seismologic observations at Nanga Parbat (Winslow et al., 1994; Craw et al. 1994; Figure 20g). Rock moving through this thermal boundary passes from predominantly ductile to predominantly brittle mechanical behavior. The thermal boundary layer is a dynamic zone of fluctuating ductile/brittle strain as fluid pressure cycles between lithostatic and hydrostatic. Brittle failure within this boundary layer can occur as shear failure at elevated fluid pressure, or as local hydrofracturing, and provides the source of some of our recorded microseismicity. At the elevated temperatures of the lower part of the thermal boundary (~450°C; Craw et al., 1994, 1997), the few fluids available undergo phase transformations from supercritical fluid in the ductile rock at lithostatic pressure to dry steam as the pressure is released to hydrostatic pressure. The total amount of fluid at the thermal boundary base is minor, with little cooling potential, and has both the thermal and isotopic signature of the rock. The upper part of the thermal/mechanical boundary layer is one of high geothermal gradients with vigorous free and forced convection systems connected to the surface. Fluids are dominantly meteoric (Chamberlain et al., 1995). Fluids recharge along high altitude shear zones in the massif and discharge along marginal shear zones within boiling hot springs (Craw et al., 1994; Chamberlain et al. 1995). Driving forces for fluid flow are a combination of topographic and thermal gradients in the upper 3-5 km.

Specific Outcomes. Our goal was to document and better understand the processes that have recently placed a strong structural and metamorphic overprint onto the Precambrian rocks of the massif. A significant portion of this project involved the comprehensive characterization of the massif's structure, petrological conditions, and geochronology, to document the extent of the anomalous conditions in the core of the massif and to determine the relationships of various data sets, as described above. This effort was essential. Prior to this study virtually all data from Nanga Parbat came from a single ~10 km traverse on the north side of the massif, augmented by a few studies along the Indus gorge. Our MT data and our dense seismic array have provided the first close-up look at an actively deforming metamorphic massif, linking the current state of the lower crust and deformation regimes in the crust with the petrologic and other observations made on surface exposures. Given the resemblance that Nanga Parbat shows to classic gneiss domes, our aneurysm model provides both a genetic mechanism and a tectonic setting for these features often seen in older mountain belts.

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*These are publications having either Lehigh investigators as authors, or other members of the Nanga Parbat project who are also co-PIs on this proposal. Other members of the project have published an additional 14 papers, and project members have presented over 50 abstracts at AGU & GSA meetings (1996-200); Himalayan-Karakorum-Tibet Workshops (Peshawar PK) 1998 and (Kloster Etal) 1999; Int. Symp. on Deep Profiling of Continents and their Margins, 1998. Results from the Nanga Parbat project were presented at a symposium on partial melting and orogenic evolution, 1998 Annual Meeting, GSA (M. Edwards, co-organizer) and at a special session we convened at the Fall 1998 Meeting, AGU: "Fire and Ice--The Geomorphology of Metamorphism: Mesoscale Linking Between Surficial and Crustal Processes." (P. Zeitler, C.P. Chamberlain, B. Hallet, co-convenors).

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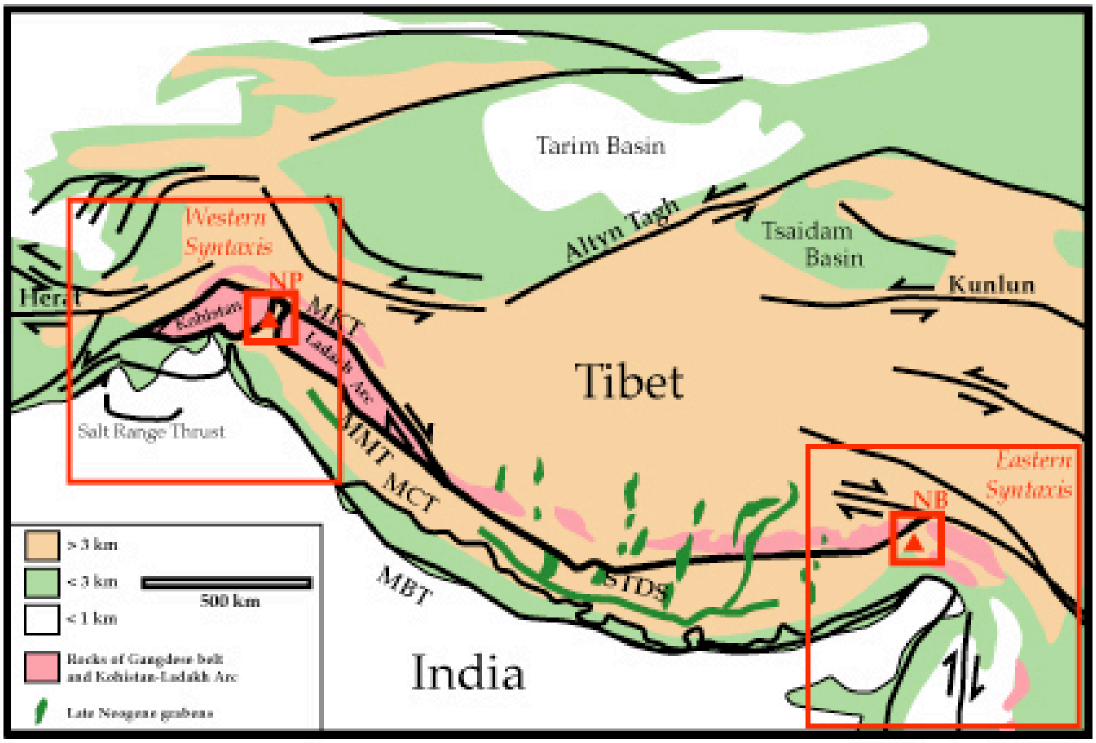
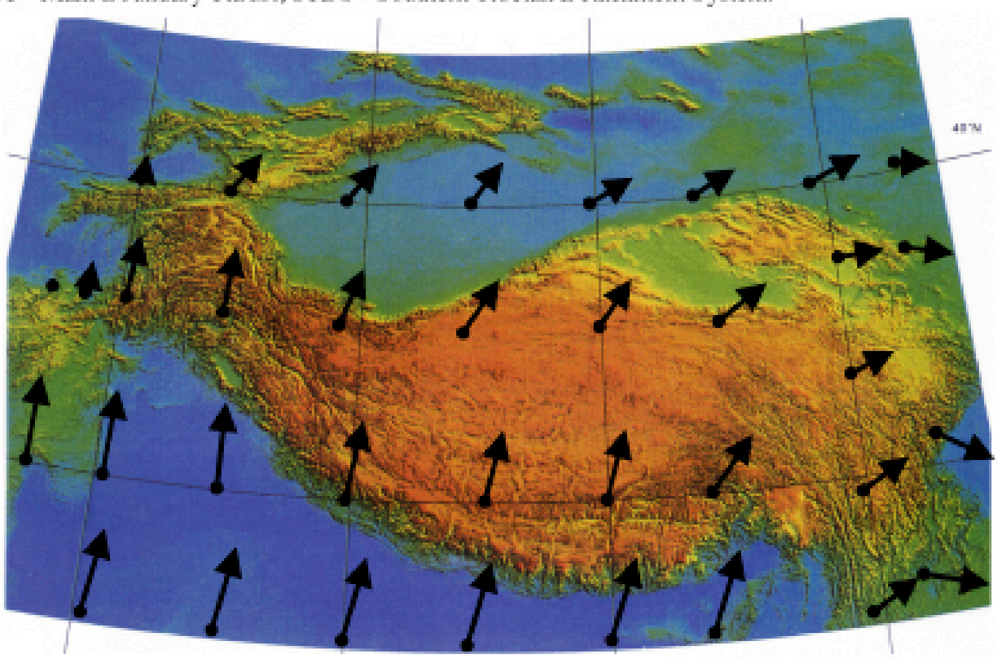


Figure 1a. Tectonic sketch map of the Indian-Asia collision (after Harrison et al., 1992). Approximate locations of the western and eastern Himalayan syntaxes are shown, as are locations of Nanga Parbat (NP) and Namche Barwa (NB) metamorphic massifs. MMT - Main Mantle Thrust; MCT - Main Central Thrust; MBT - Main Boundary Thrust; STDS - Southern Tibetan Detachment System.



Topography after Fielding et al. (1994)
Velocity vectors after Holt et al. (1995)

Figure 1b. Topographic consequences of the India-Asia collision (from Fielding et al., 1994). Also shown are velocity vectors derived from seismic moment analysis (Holt et al., 1995; Bernard et al., in press). Note the vorticity evident around the eastern margin of the collision zone, and apparently lacking along the western margin.

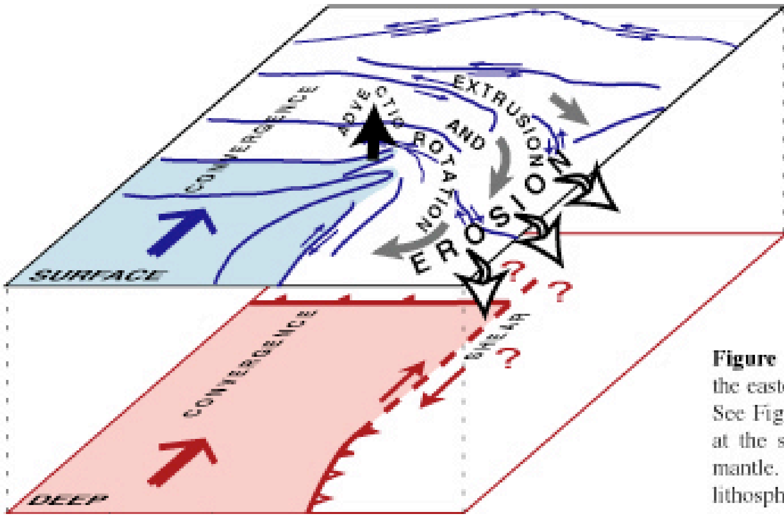


Figure 2. Conceptual illustrations of mass flux near the eastern Himalayan indentor corner (not to scale). See Figure 3 for orientation. Panels show dynamics at the surface and at depth within the lithospheric mantle. Blue, pink – Indian indentor; white – Asian lithosphere.

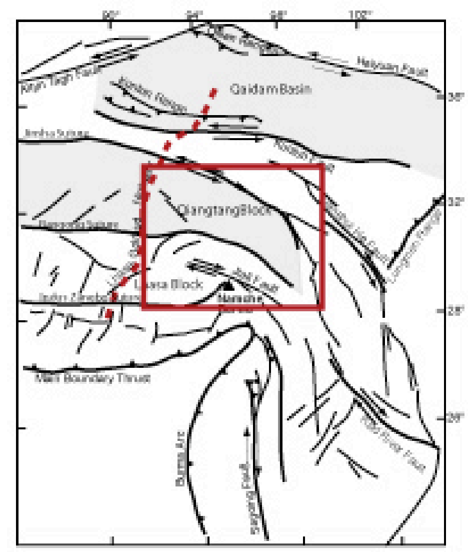


Figure 3a. General structural setting of eastern Tibet and the syntaxial region (after Holt et al., 1991 and Wittlinger et al., 1996). Lhasa-Golmud Highway through central Tibet (shown by dashed line) is corridor along which most recent studies of Tibetan lithosphere have been carried out. Approximate area of proposed regional array outlined by box.

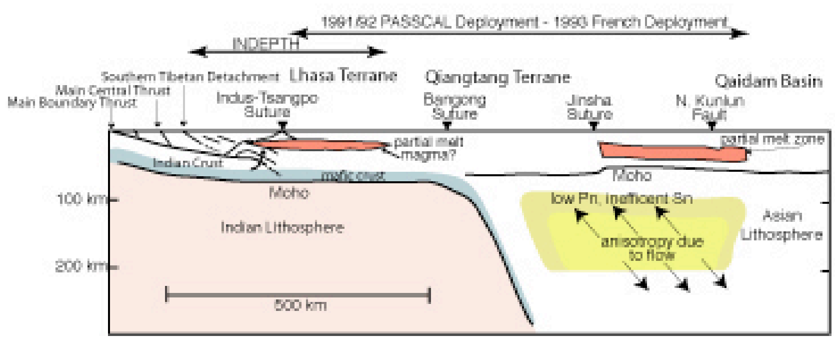


Figure 3b. Cross section across central Tibet (modified from Owens and Zandt, 1997; and Nelson et al., 1996). Line of section corresponds roughly with location of Lhasa-Golmud Highway (above).

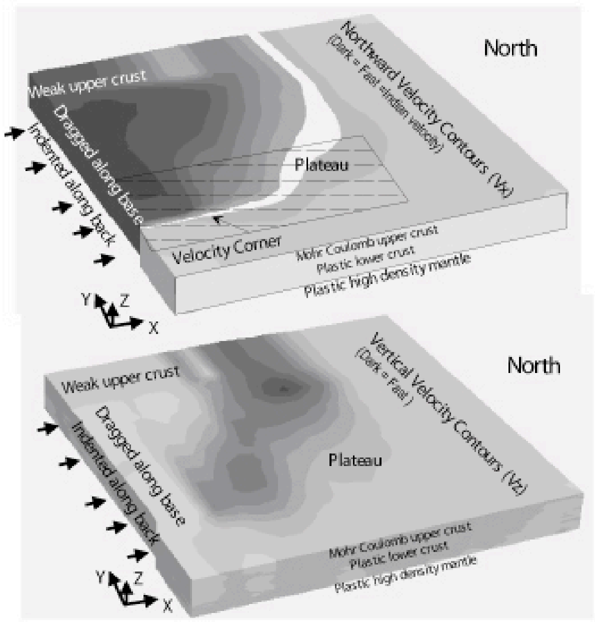


Figure 4a. Preliminary numerical model of the Indian/Eurasian collision. (a) Boundary conditions, initial rheologies and velocity contours are shown for the entire collision zone.

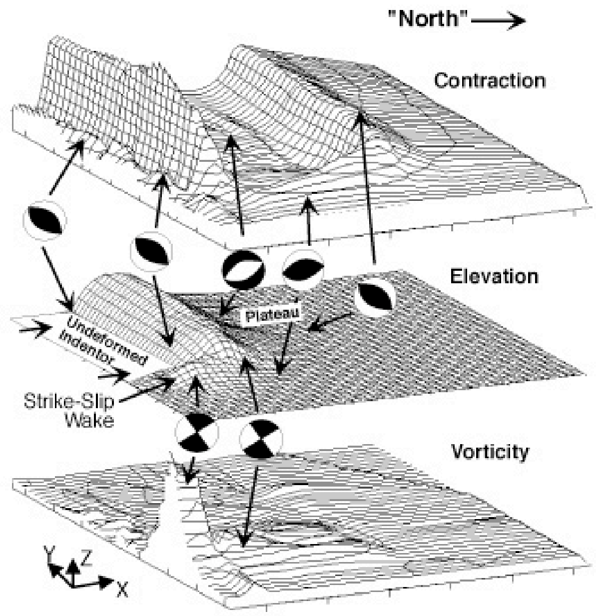


Figure 4b. Deformation and topographic growth for the indentor corner only (dashed box of 2a). Deformation in the velocity-corner region is represented by the grids for *contraction* [= -0.5(eu / ex + ev /ey); positive values represent areal reduction] and *vorticity* [= 0.5(eu /ey - ev / ex) positive values represent clockwise rotation]. Elevations along the eastern edge of the orogen are reflected in the central figure by the plateau and the inboard and outboard topographic slopes. The eastern strike-slip ranges, oriented parallel to the relative convergence vector, are left in the wake of the indentor. Stereographic projections illustrate sense of deformation at several specific sites.

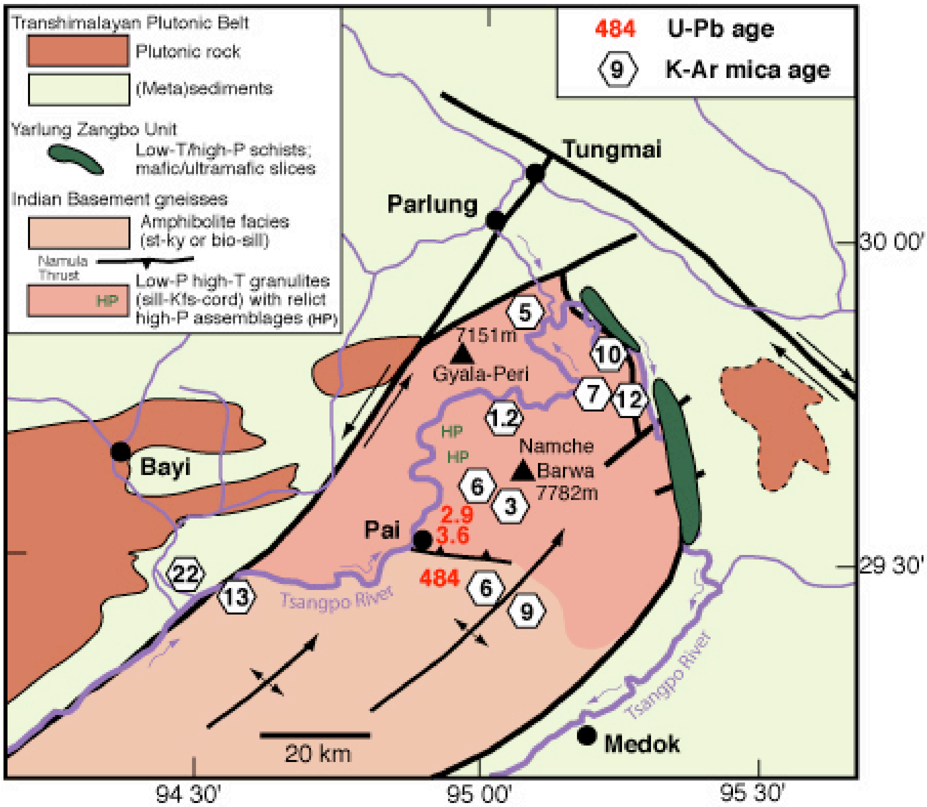


Figure 5. Geological sketch map of the Namche Barwa metamorphic massif (see Figure 1 for location of massif in India-Asia collision zone). Compiled from Burg et al. (1997), Liu and Zhong (1997), and observations made during our reconnaissance visit in May, 1998. Metamorphic zonation within the massif is only approximate; also, metamorphic grade continues to decrease considerably towards the southeast. Note the remarkable 180° bend made by the Tsangpo, and the stream capture which has occurred at the apex of this bend. Figures 6 and 7 describe the nature of the Tsangpo's gorge through the region. For reference, to the west of Pai, the river's grade is virtually nil; downcutting begins several kilometers downstream (northeast) of Pai.

Comparison of this sketch map to Figure 19 (Section III) underscores the great, visible similarities between the Namche Barwa and Nanga Parbat massifs: the manner in which their bounding structures and sutures wrap around each massif, the active faulting superimposed on massif boundaries; their overall structure (~north-plunging antiform), and the co-location of each massif and a major river (which cuts across the massif to form a deep gorge). Like Nanga Parbat, Namche Barwa exposes Indian-plate Proterozoic basement gneiss that has experienced a low-pressure, high-temperature granulites-facies metamorphism within the past several million years; preliminary geochronological data (Burg et al, 1997) suggest very rapid exhumation took place following this metamorphism.

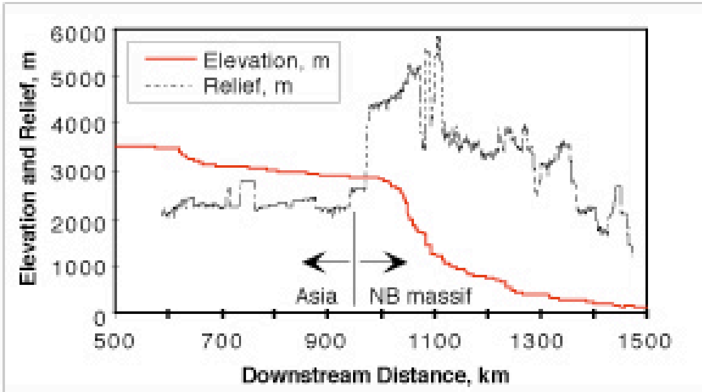


Figure 6. Elevation and relief profile along the Tsangpo river as it traverses SE Tibet, the Namche Barwa massif, and the Bid Bend gorge. Data from GTOPO30 DEM. Also shown is approximate position of massif's western boundary. Note that the Tsangpo follows a complex course in the Big Bend gorge (see Figure 5). The relief (black line; maximum elevation difference within 20 km of river) jumps up where the river starts to slice its deep gorge through the high peaks of the easternmost Himalaya.

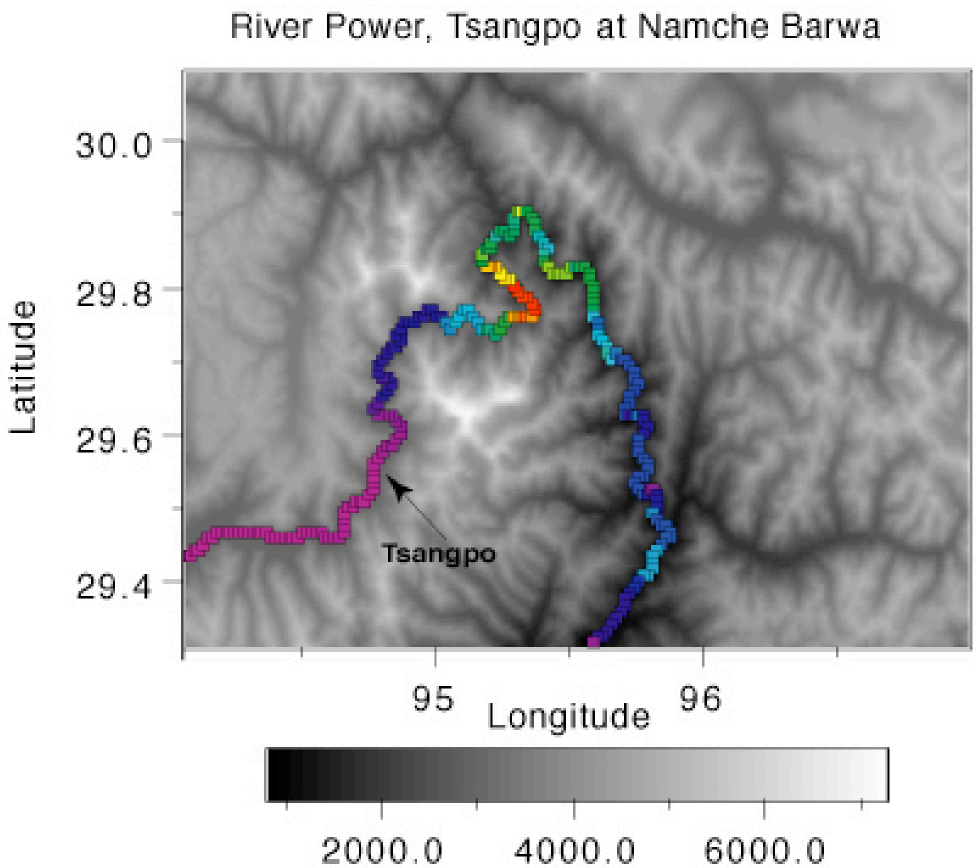


Figure 7. Variation of river power (one form of the erosion index developed in Section II-4) along the length of the Tsangpo through the Namche Barwa area (gray shading reflects elevation, light being high), showing local area of rapid energy expenditure (shown by red area) where the river makes its steepest descent. Perhaps the tight hairpin turn of the Tsangpo, just where erosion is likely to be most rapid, is a plan-view manifestation of the localized crustal deformation at a "tectonic aneurysm" due to the erosional driven thermal-weakening of the crust.

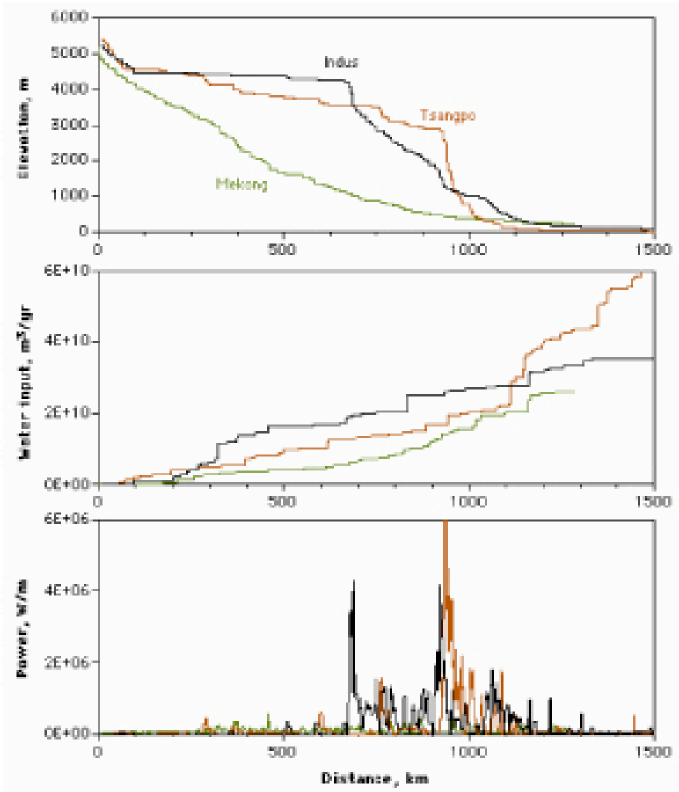


Figure 8. From top to bottom, downstream variation in channel elevation (river profile) computed from DEM, cumulative water input into basins from DEM and digital precipitation data, and river power per unit length of channel for three rivers: Tsangpo (Red), Indus (black) and Mekong (green). River power, one form of the erosion index, enables us to calculate how erosion rates and bedrock incision rates vary spatially where the bedrock's inherent resistance to erosion is relatively uniform.

Note exceptionally large knickpoint on the Tsangpo. Independent measures of discharge and erosion can provide region-specific calibration for river power-based erosion maps. For example, the peak in power at ~900 km on the Indus is precisely where incision rate in bedrock attains 12 mm/yr, and is suggestive of similar rates at the Tsangpo knickpoint; and the relatively modest power at the Mekong corresponds to a basin-averaged erosion rate of 0.19 mm/yr. Discharge can be calculated from water input taking into account evaporation with guidance from direct discharge measurement from gauging stations.

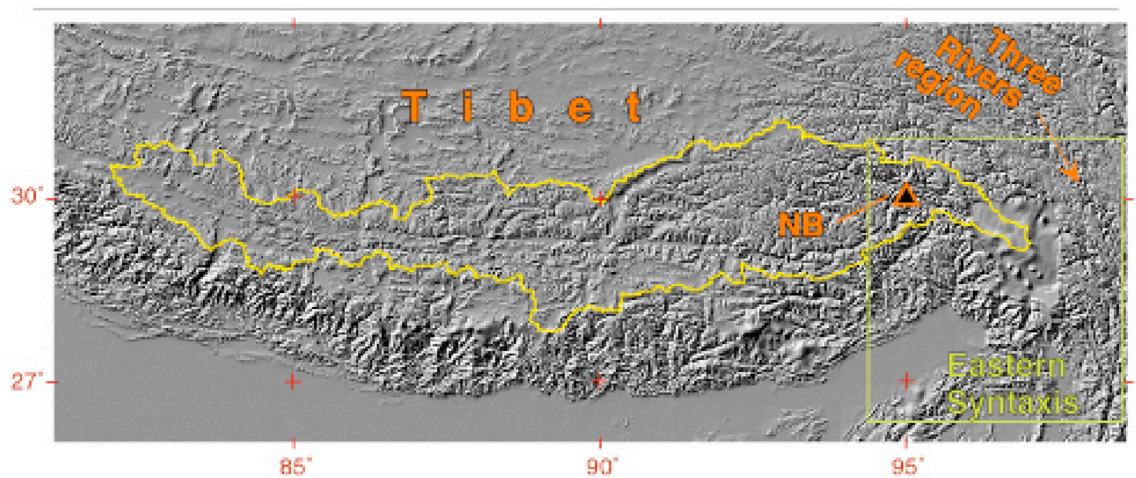
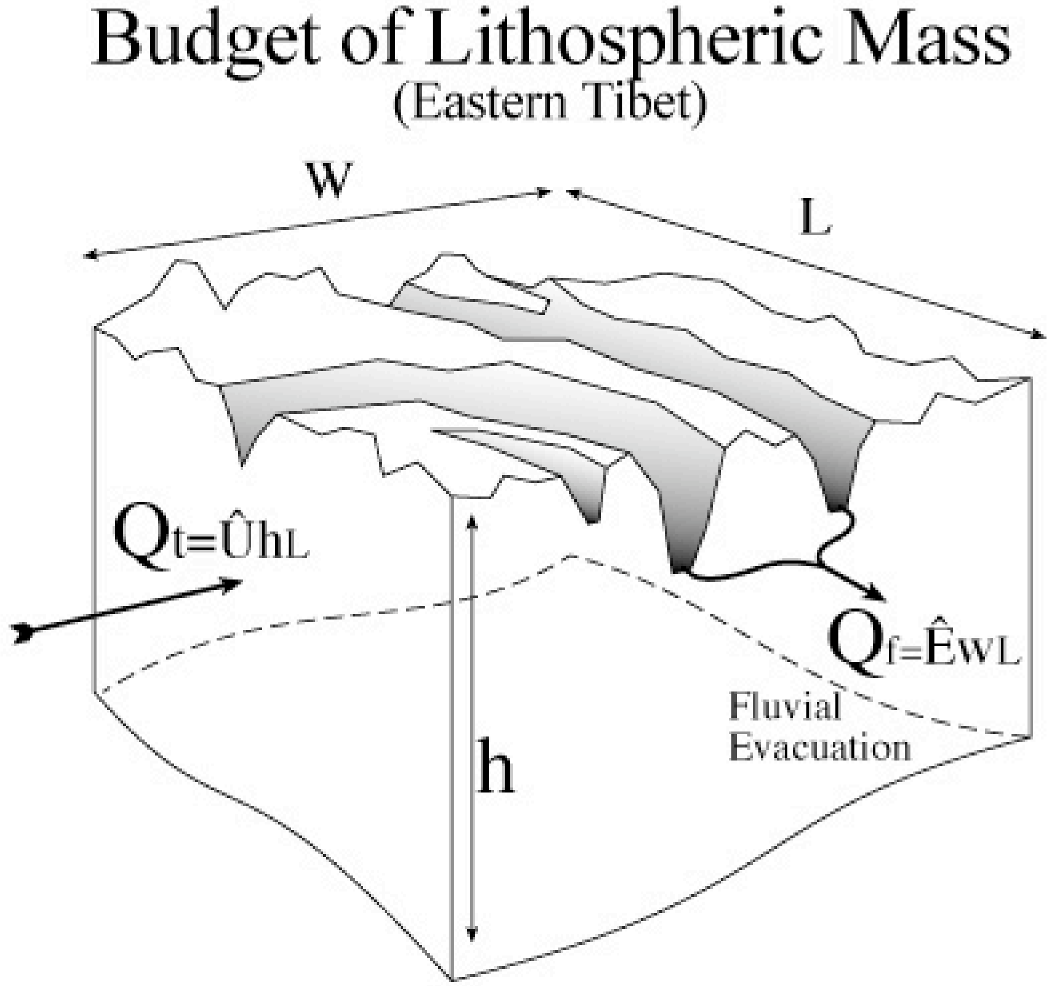


Figure 9. Regional topography, southern Tibet, showing drainage basin of Yarlung-Tsangpo River above Namche Barwa knickpoint (yellow line).Approximate location of eastern Himalayan syntaxis and deeply incised Three Rivers region is also shown. NB - Namche Barwa massif.



$$f = \frac{Q_f}{Q_t} = \frac{\hat{E}W}{\hat{U}h}$$

Fluvial Evacuation is significant if $f >> 0.01$

Typical values:

$E \approx 0.1 - 1.0$mm/yr
$U \approx 10$mm/yr
$W \approx 300$km
$h \approx 60$km
$\therefore f \approx 0.5$ to 0.05

Figure 10a. Comparison of tectonic advection, Q and fluvial evacuation, Q_f, of lithospheric mass. The ratio, f, of these mass fluxes is a function of mean erosion rate, E; width, W, of highly incised domain in eastern Tibet; mean rate of eastward lithospheric displacement, U; and representative lithoshperic thickness, h.

Figure 10b. Drainage basins derived from the GTOPO30 data set for which erosion indices (see section II-4) where calculated for the entire Himalayan chain. Basins were cut-off at an elevation of 200 m.

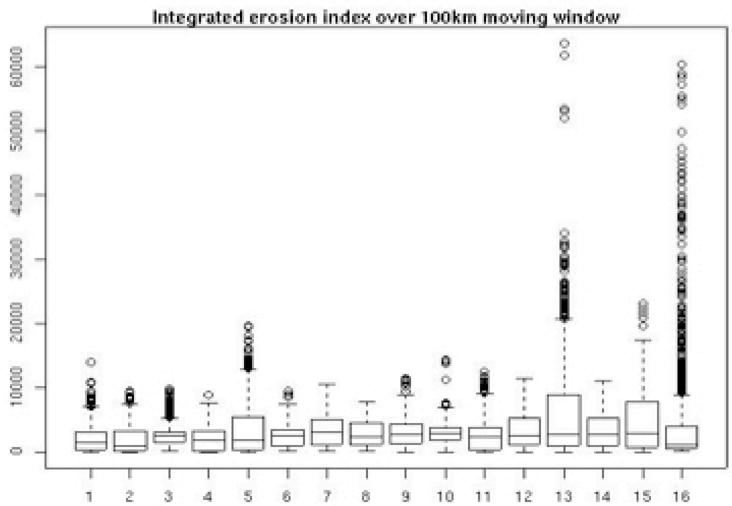


Figure 10c. Integrated index of erosion rates (IIER) for the rivers draining those Himalayan basins shown in Figure 10b. IIER is the erosion index, e (e.g. lower curves in Figure 8, discussed in Section II-4), averaged over 100 km reaches of the main drainage; this 100 km-window was moved continuously along the river at 1 km intervals and the local river slope used for calculating e, is a 3 km-average. The rivers are labeled by number from west to east, ranging from the Indus (#1) to the Tsangpo River (#16). For each river, a box represents the 25th and 75th percentiles of the IIER values respectively, and the bisecting line shows the median value. The whiskers represent all values within 1.5 times the interquartile range (IQR). Values above 1.5 IQR, plotted individually as circles, are of particular interest as they reflect the extreme erosion rates where the rivers drop steeply from their knick points. These data suggest that maximum erosion rates generally increase eastward due largely to increasing precipitation. The most rapid erosion in the Himalayas is expected along the Tsangpo (#16) and the Arun (#13), where integrated erosion indices are up to 3-4 times those along the Indus, underscoring that fluvial evacuation could be a potent means of removing lithospheric mass from the eastern indentor corner (Figure 10a).

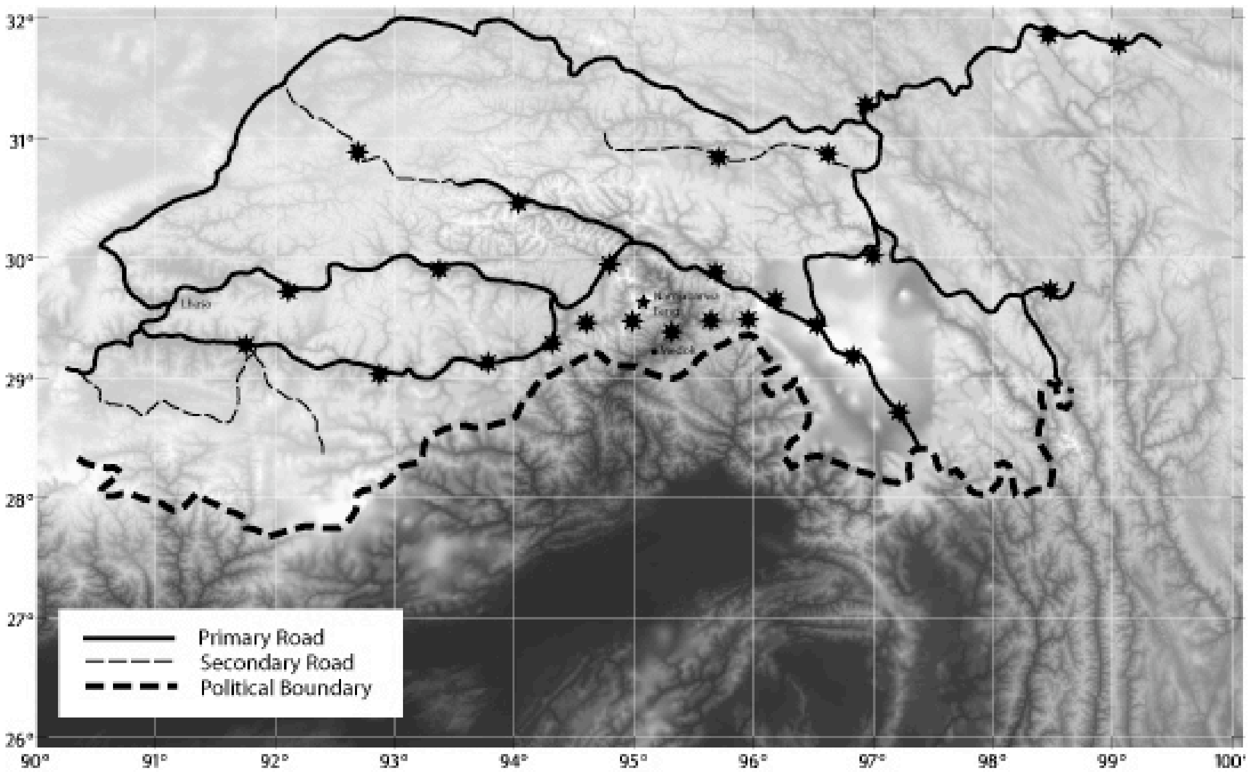


Figure 11. Proposed GPS station locations. Political boundaries, primary and secondary roads shown. Tertiary roads not shown.

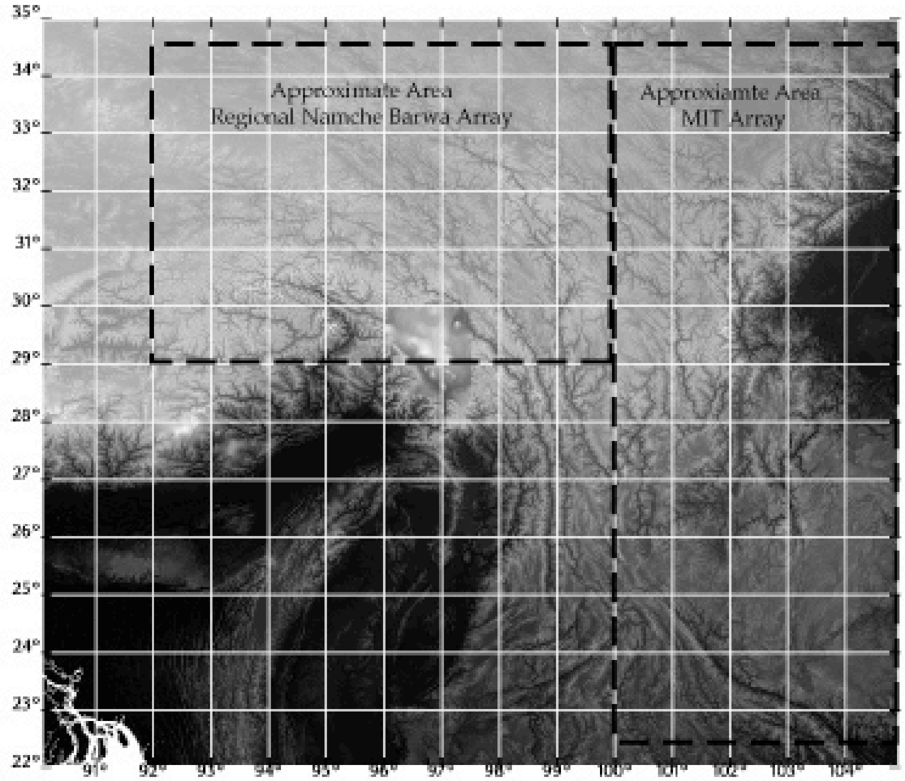


Figure 12a. Shaded topography in the eastern syntaxial region. Locations of the proposed regional Namche Barwa and MIT arrays.

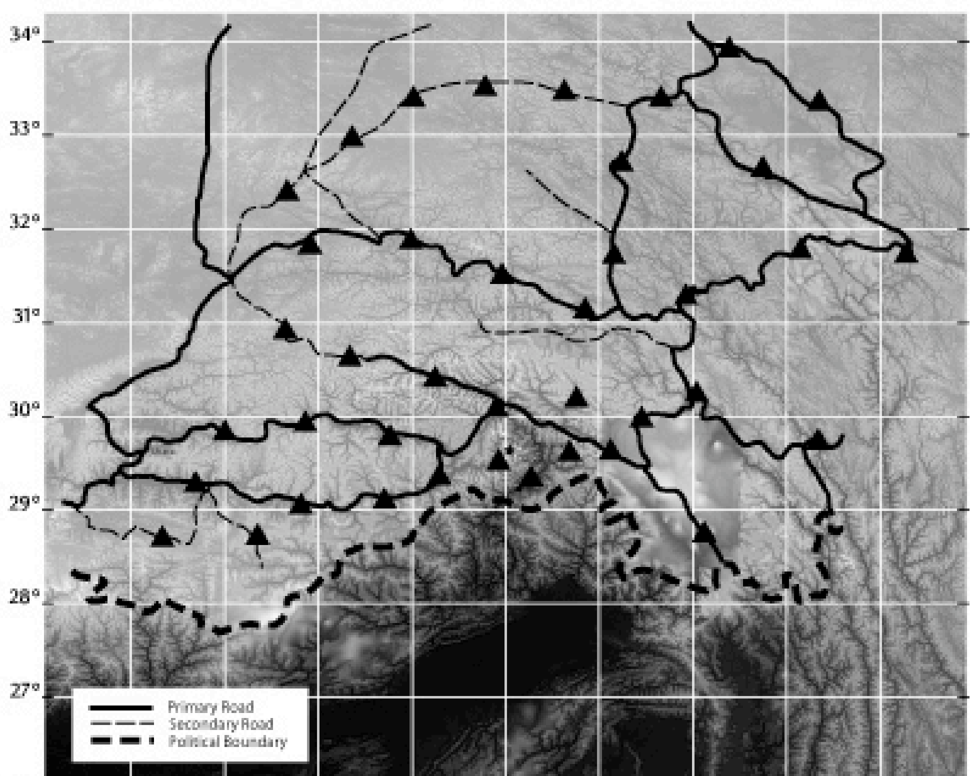


Figure 12b. Proposed seismic broadband station locations. Political boundaries, primary and secondary roads shown. Tertiary roads not shown.

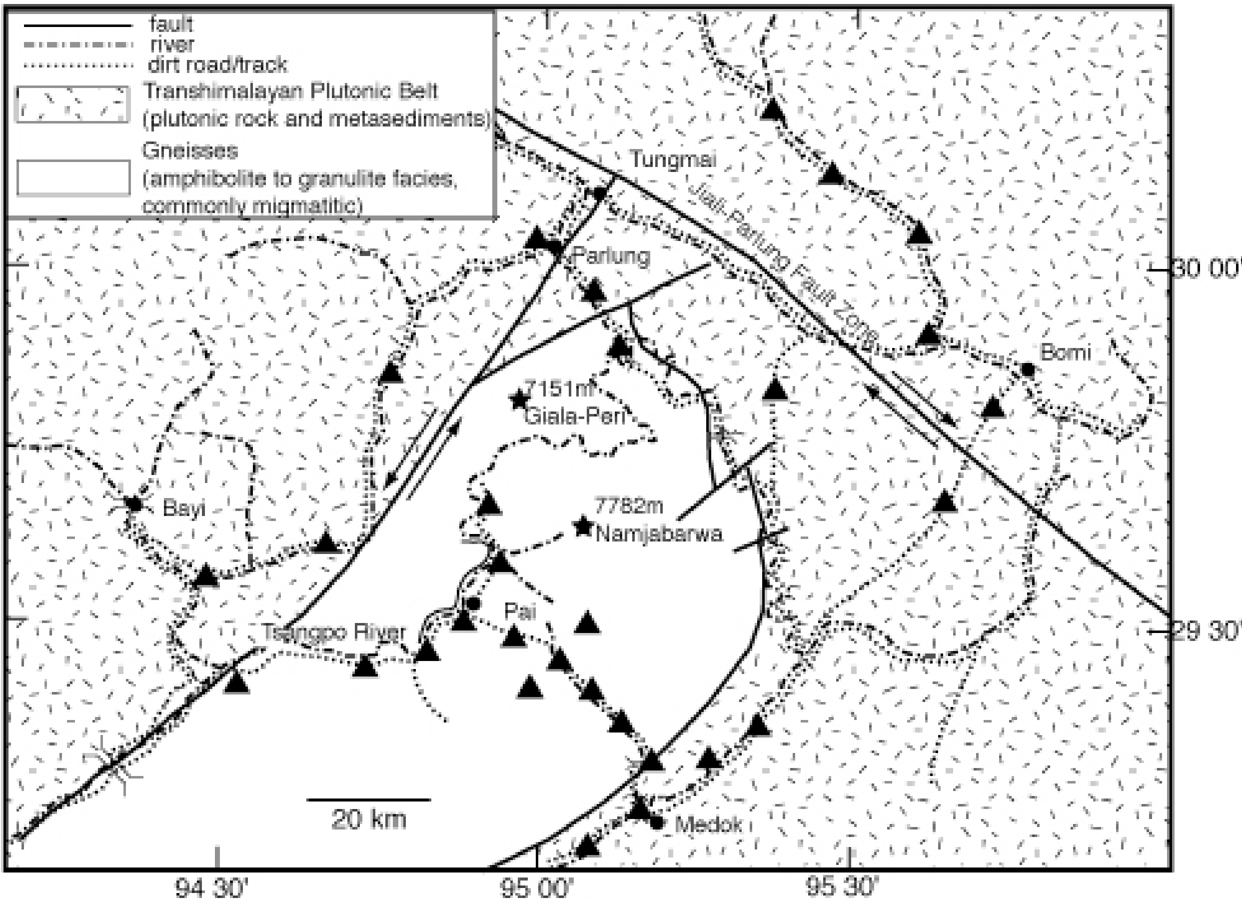
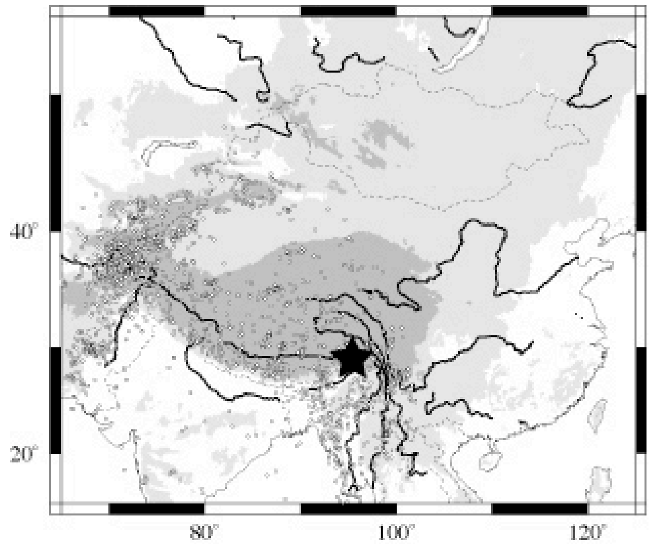
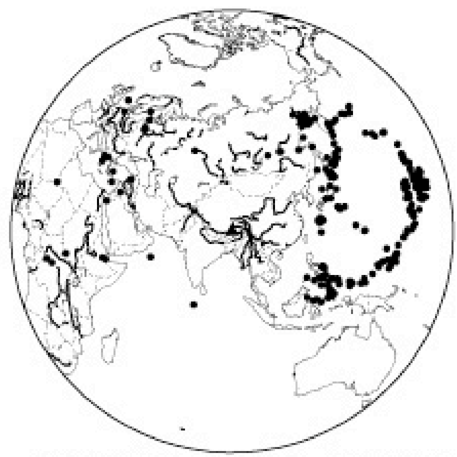


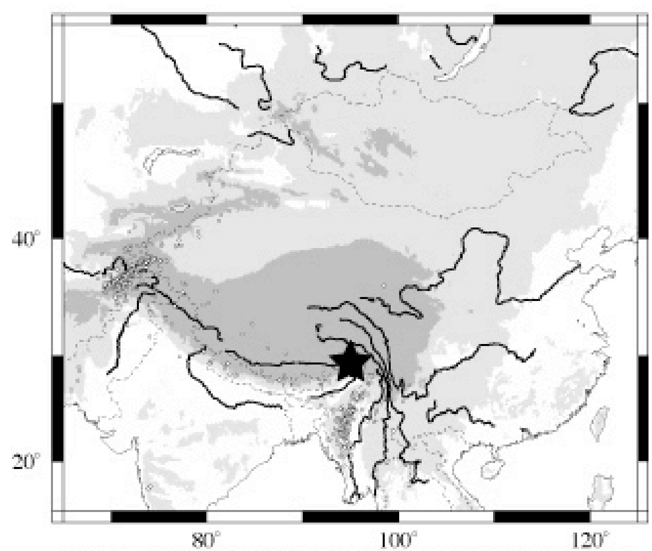
Figure 13. Proposed 30 element local short period array. Station locations marked by triangles. Geology and structure after Burg et al., 1998.



Regional events (Mb>4.5) recorded in a seven year period. Hypocenters <50 km depth. N=3868. (Data from IRIS DMC). Star sits astride the 180° bend in the Tsangpo. Topography is shaded: light gray=500-2500 m., dark gray >2500 m.



Teleseismic events (Mb>5.5, 30-90 deg) recorded at GSN station LSA (Lhasa) in a 12 month period (1995). N=365. (Data from IRIS DMC.



Regional events (Mb>4.5) recorded in a seven year period. Hypocenters >50 km depth. N=985. (Data from IRIS DMC). Star sits astride the 180° bend in the Tsangpo. Topography is shaded: light gray=500-2500 m., dark gray >2500 m.

Figure 14. Regional and teleseismic events.

Figure 16. TOP:Regional events Mw>4.5 recorded in a seven year period. N= x. Star sits astride the 180° bend in the Tsangpo. Top left: hypocenters <50 km depth. Top right:hypocenters >50 km depth. Bottom: Teleseismic eventsMw>5.5 recorded within a single year.

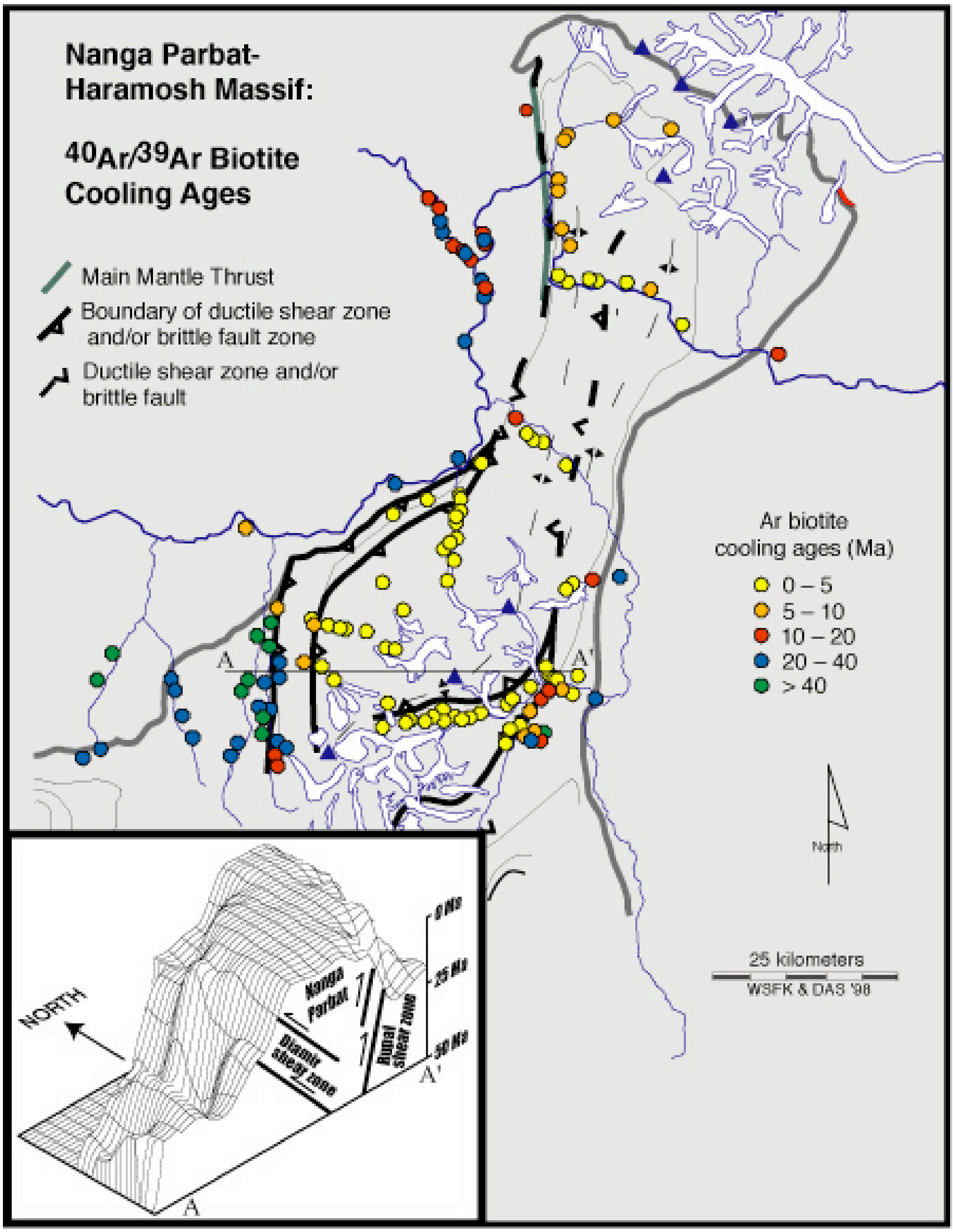


Figure 15. Ar-Ar biotite cooling ages, Nanga Parbat massif (most ages determined by total-fusion Ar-Ar analysis). Some data from Zeitler, 1985; Treloar et al., 1989; Zeitler et al., 1989; George et al., 1995; Winslow et al., 1996; Whittington, 1996; and Reddy et al., 1997; bulk of data from Schneider et al., 1997 and D.A. Schneider, Ph.D. dissertation in progress. Biotite cooling ages (T_C 300°C) define major structural breaks around Nanga Parbat massif, and mimic the pattern seen in metamorphic grade (Figure 18b) and microseismicity (Figure 19). Inset shows "thermochronometric morphology" of massif taken approximately along swath A-A'.

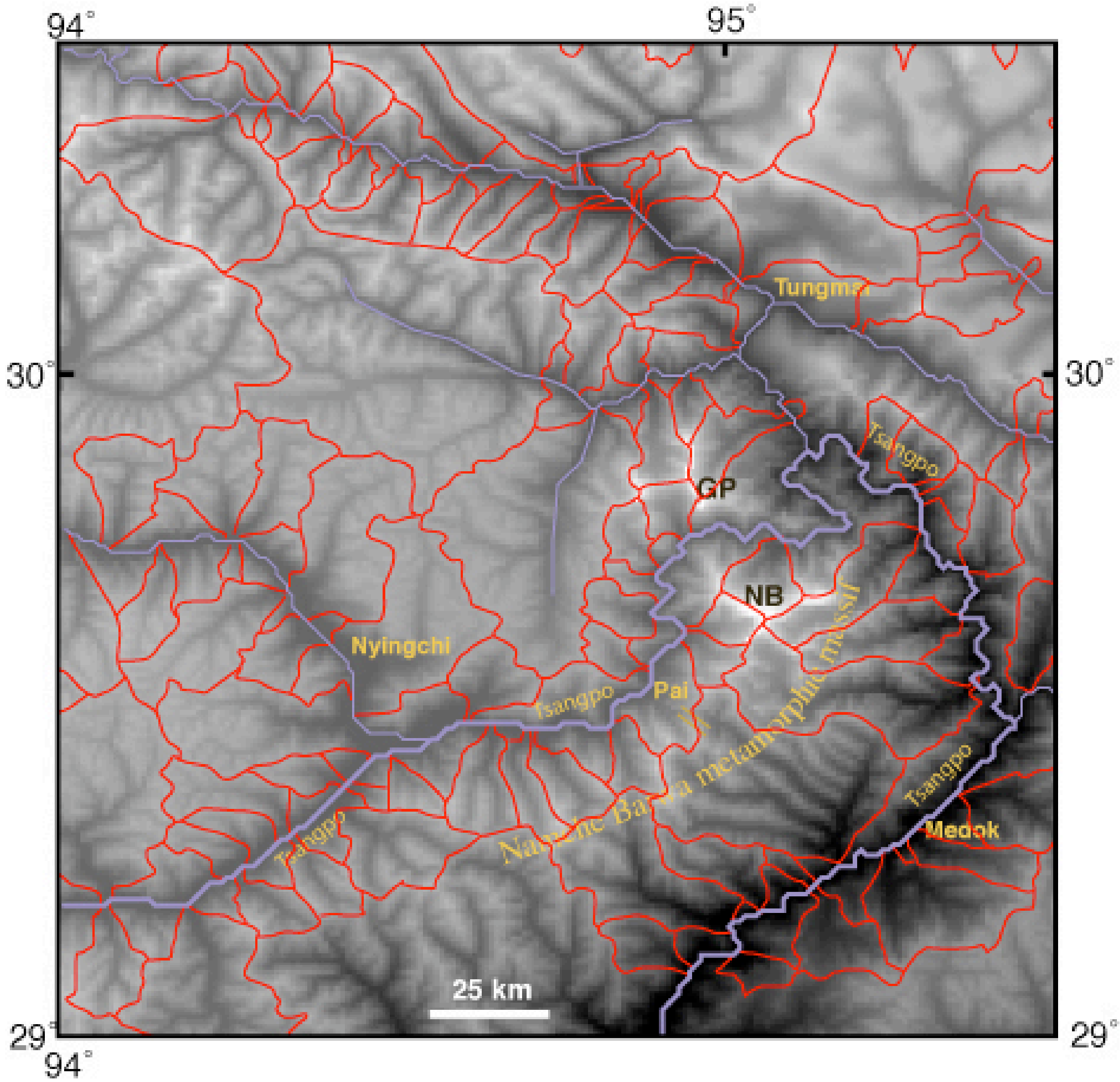


Figure 16. Major drainage sub-basins around the Namche Barwa metamorphic massif. NB - Namche Barwa peak; GP - Gyala Peri peak. A convenient consequence of the elongate nature of the massif, encircled by the Tsangpo River and its Big Bend, is that sampling sediment from the mouths of ~40 basins will make it possible to use detrital mica ages to make an efficient reconnaissance of the cooling-age distribution of the bulk of the massif, despite the presence of rugged topography and inaccessible higher elevations.

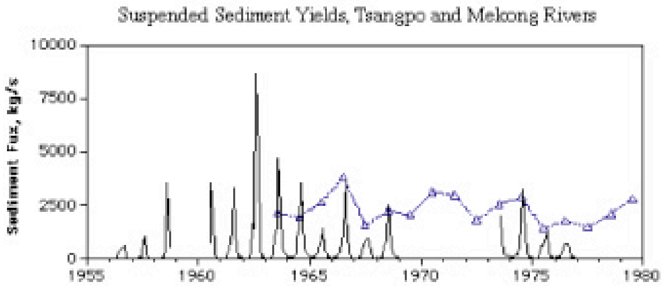


Figure 17a. Monthly values of suspended sediment flux for the Tsangpo and annual values for the Mekong (triangles) during the 1956-79 period (Hydrologic Bureau, 1982).

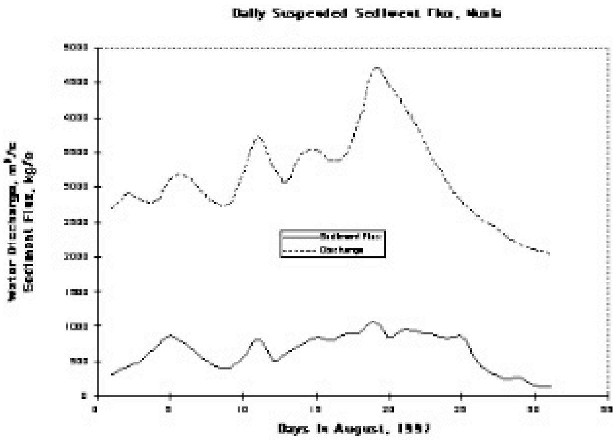


Figure 17b. Unpublished daily values for August 1997 obtained from the Hydrology Institute in Lhasa, Tibet. Similar data are available starting in 1955.

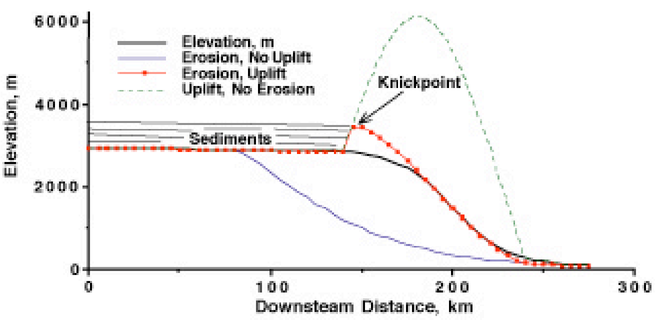


Figure 18. Model of 0.4 m.y. of river-profile development across the Namche Barwa massif, assuming bedrock incision rate is proportional to river power (eqn. 1 with n=1.5, K such that maximum incision rates are 10 mm/yr). With no uplift, the initial profile (heavy line) retreats quickly (70 km) and becomes more gentle (blue curve). With antiformal uplift at 10 mm a-1, as prescribed (dashed line), uplift exceeds incision; the knickpoint rises but its upstream propagation is halted (red line with symbols), and sediments would accumulate upstream of the knickpoint.

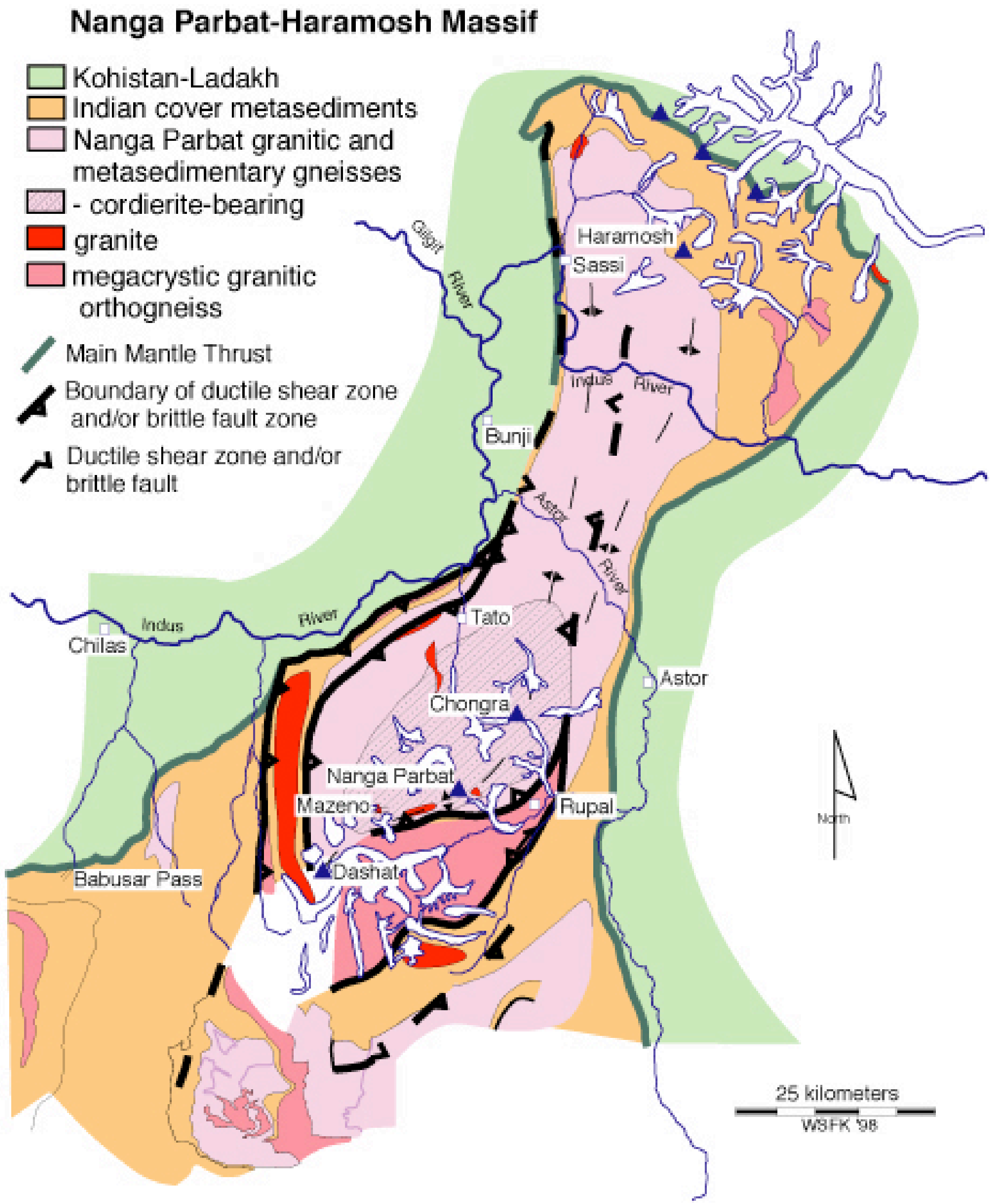


Figure 19a. Geological sketch map of the Nanga Parbat-Haramosh Massif. Compiled from Butler et al., 1992; Greco and Spencer, 1993; Fontan and Schouppe, 1995; Lemenncier et al., 1996; and unpublished mapping by M. Edwards, W.S.F. Kidd, M. Asif Khan, and D.A. Schneider.

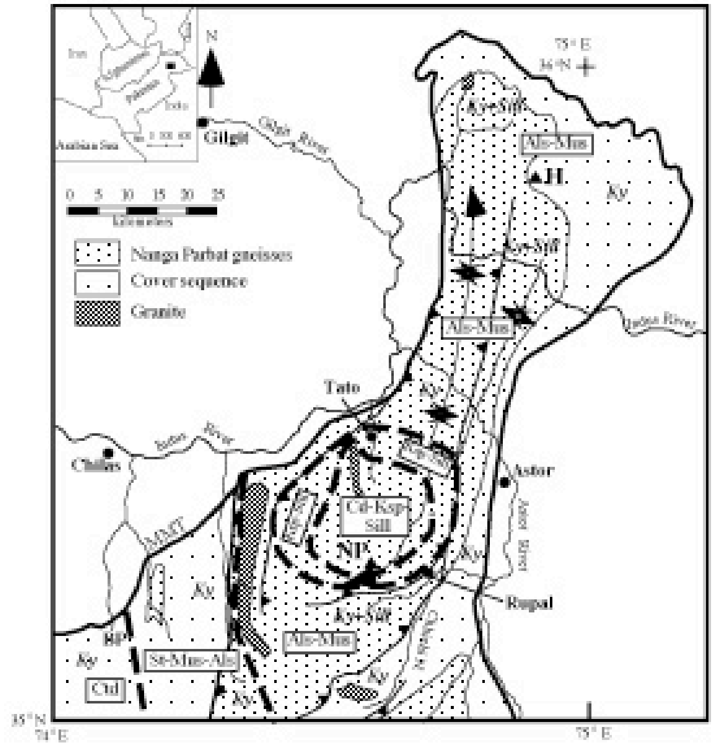


Figure 19b. Metamorphic field-gradient map for the Nanga Parbat Haramosh Massif, showing the approximate positions of major metamorphic reactions in metapelites. Diagnostic mineral assemblages are shown in boxes; dominant aluminosilicate shown in italics. The position of the chloritoid breakdown reaction line is particularly uncertain due to low sample density, while the concentric isograds in the vicinity of the Nanga Parbat summit are better constrained. NP=Nanga Parbat summit; H=Haramosh summit; BP=Babusar Pass; Ctd=chloritoid; St=Staurolite; Mus=muscovite; Als=aluminosilicate; Ksp=alkali feldspar; Cd=cordierite; Ky=kyanite; Sill=sillimanite.

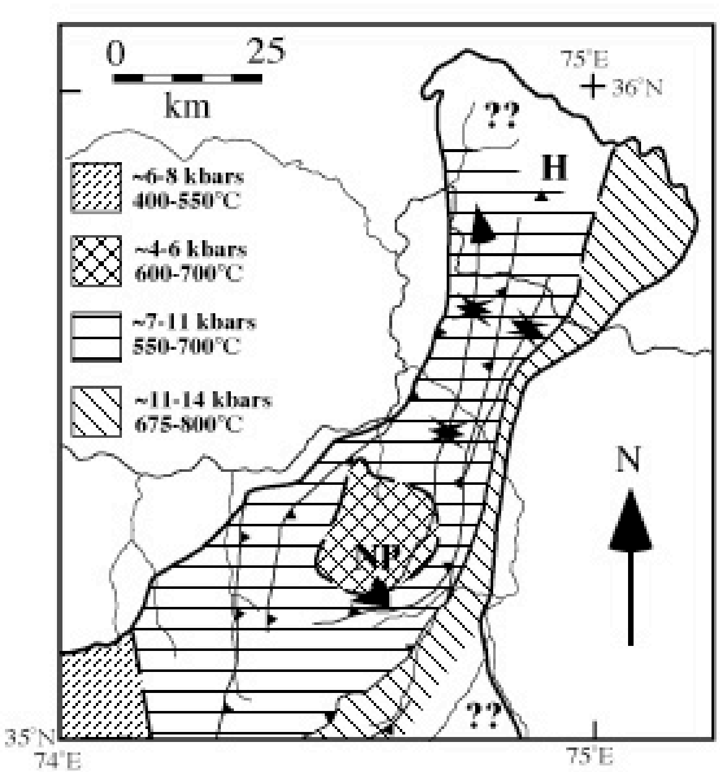


Figure 19c. Pressure-temperature map broadly outlining four metamorphic zones within the NPHM, based on populations of thermobarometric estimates of final equilibration from both this study and previous work. Dashed lines indicate less certain demarcations between zones. There are presently no data for northwest and southeast sections of the massif. Abbreviations as in Figure 19b.

FIGURE 20 is missing in action at the moment: it represents the geophysical and overall project results from Nanga Parbat reported in papers by Meltzer and by Zeitler et al.

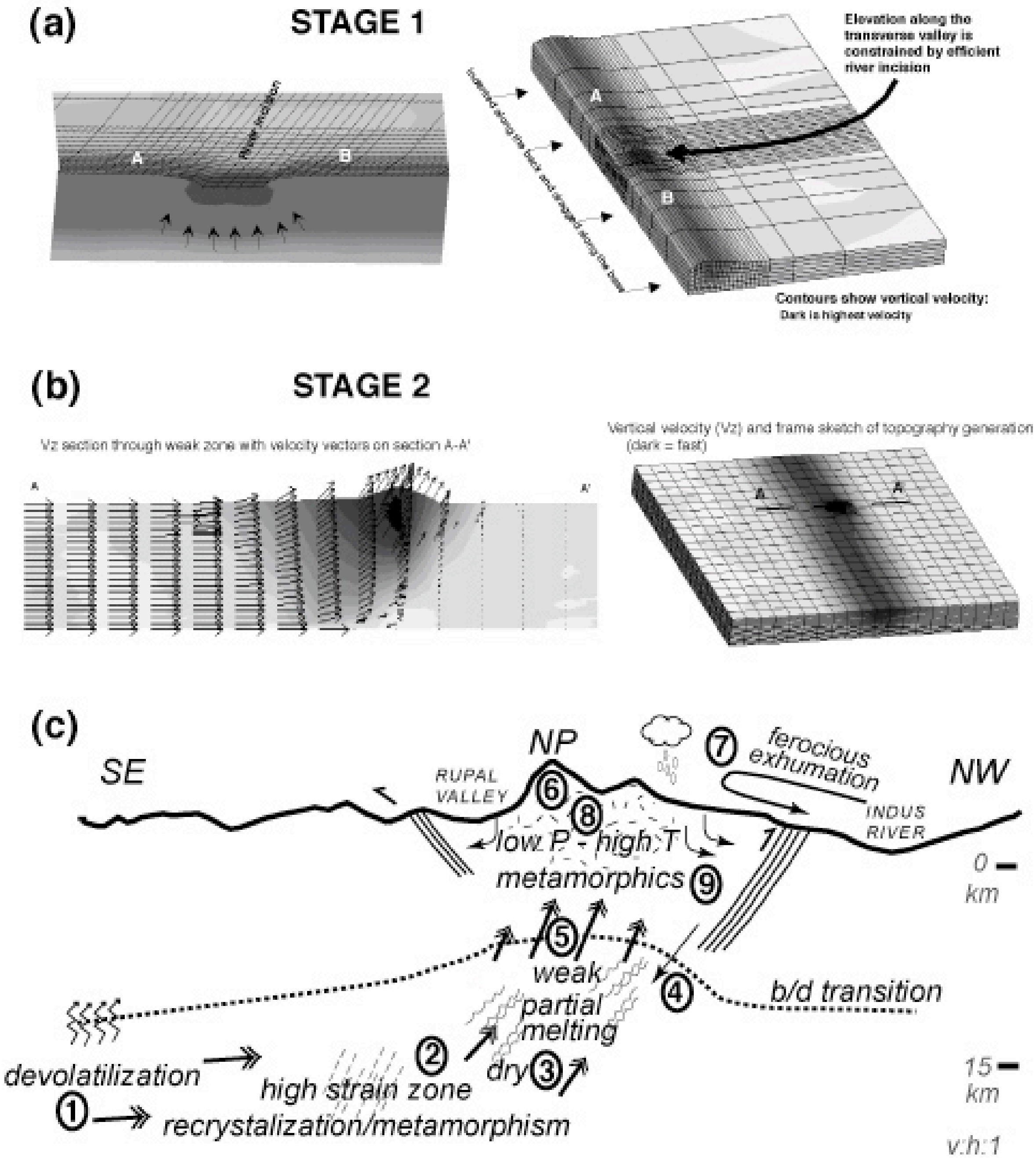


Figure 21. Numerical example of the influence of transverse erosion on the uplift pattern of an orogen. (a) *Stage 1*. Weakening of crust by first-order river incision across thickening orogenic welt. (b) *Stage 2*. Positive feedback develops, in which additional crust flows into weak zone; rapid advection of material here builds mountain over weak crust, at point of maximum exhumation rate. (c) Cartoon illustrating phenomena associated with the tectonic aneurysm predicted by this model: (1) devolatilized material enters (2) a high-strain zone where melting and recrystallization can occur before (3) the now-dry material enters the zone of rapid exhumation where it can undergo decompression melting, and later, water-saturated melting should it encounter any fluid (e.g., kneaded into the massif along shear zones (4)). The rapid advection leads to: elevation of isotherms and the brittle-ductile transition (5) (as well as localization of microseismicity above this zone); weakening of the upper crust (potentially a positive feedback); counter-intuitive localization of high topography (6) over the weak zone, aided by efficient erosion (7); exposure of migmatites (8) showing a strong decompression path; and development (9) of strong meteoric circulation systems. At Nanga Parbat, these are all documented phenomena based on the work of the Nanga Parbat Continental Dynamics project and earlier studies. An important next step will be study of the inception and early stages of such a system, particularly the role of surface processes.