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.

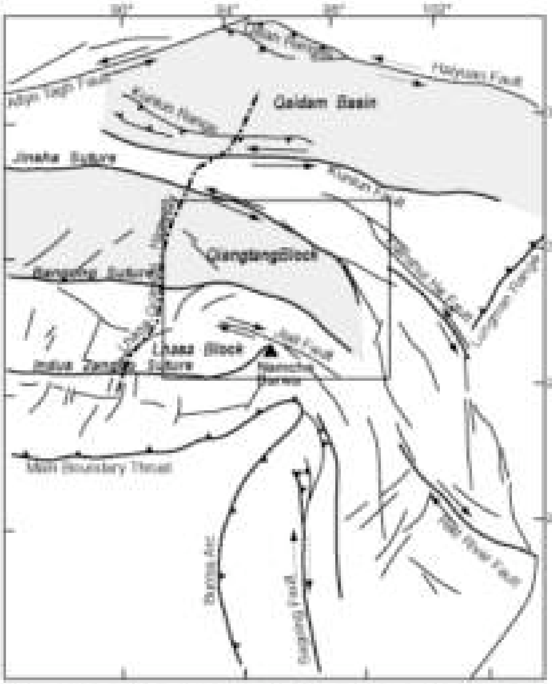
Modeling suggests that the syntaxis is a crustal manifestation of the complex lithospheric dynamics associated with an "indentor corner." Steep lateral velocity gradients mark the eastern margin of the Indian plate, and incoming Indian lithosphere is partitioned into at least two components: deeper Indian 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.

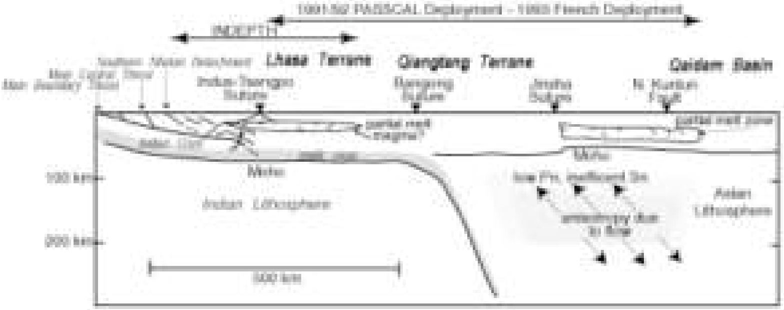
This work will complement and integrate other NSF-supported studies of the diffuse India-Asia collision by examining mass transfer across one of the system’s fundamental yet poorly understood boundaries. Together with these other studies, our proposed project will help provide a coherent image of lithospheric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

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.



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. Approximate area of regional array outlined by box.



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).

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. 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.

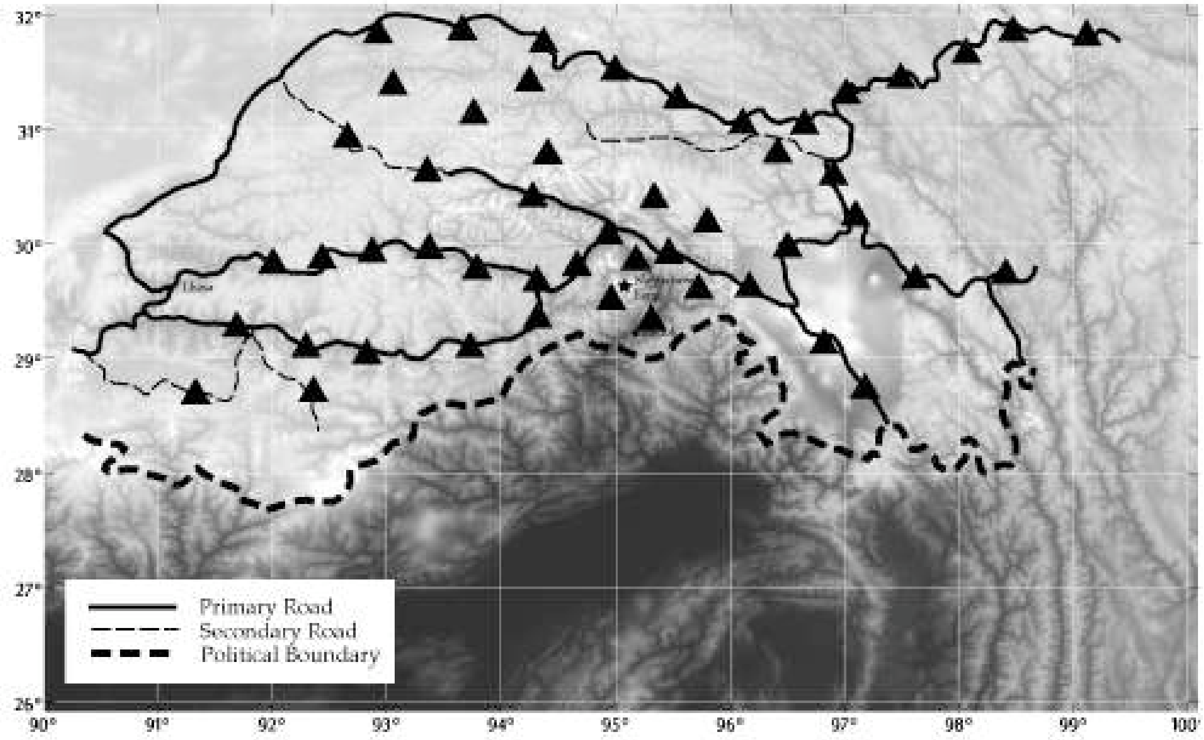
Modern Dynamics: Eastern Syntaxis. Mathematical models and physical experiments both predict that intense deformation should initiate near the original corner of a rigid indentor such as the Indian plate and that through time, this deformation will evolve and propagate, as steep velocity gradients arise 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. 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.

Seismology

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. 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. 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.



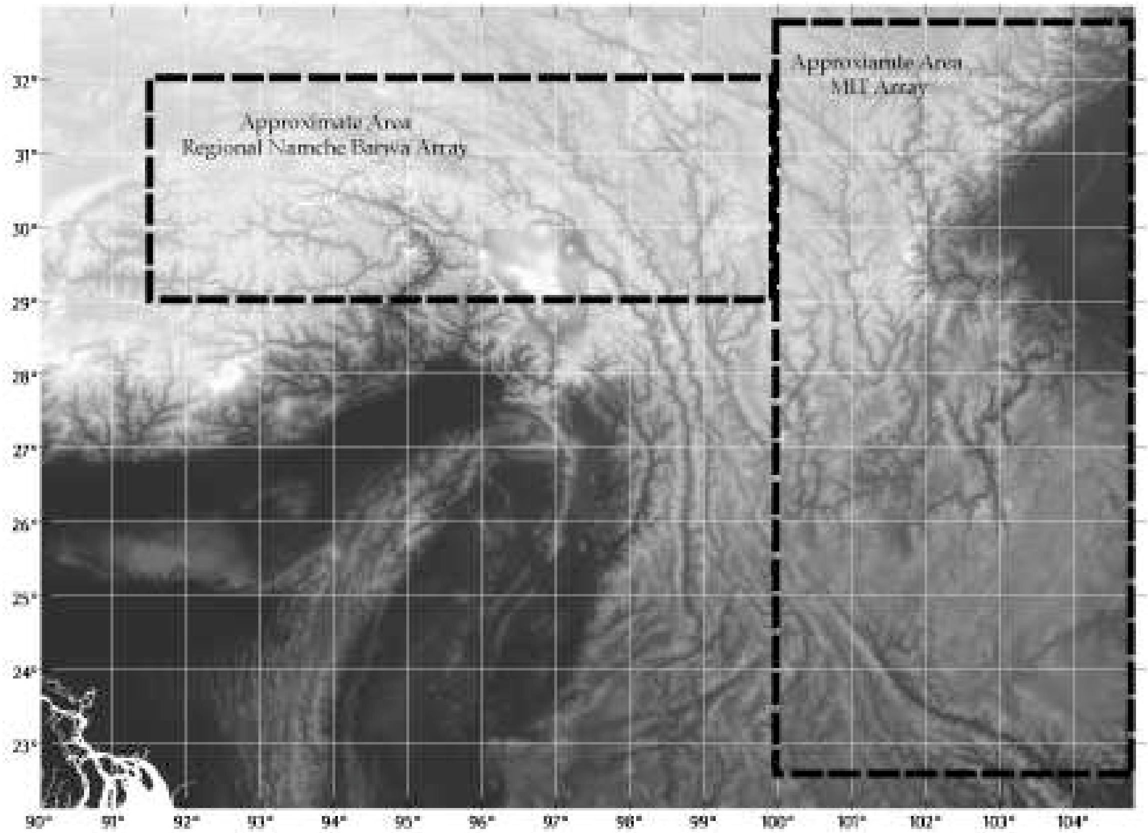
Lithospheric structure: Initial observations constraining the general lithospheric architecture of the Himalaya came largely from studies of moderate to large magnitude (>5.5) seismic events within the Himalayan arc and from surface wave propagation across the Tibetan plateau (Chen and Molnar, 1981; 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) 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.

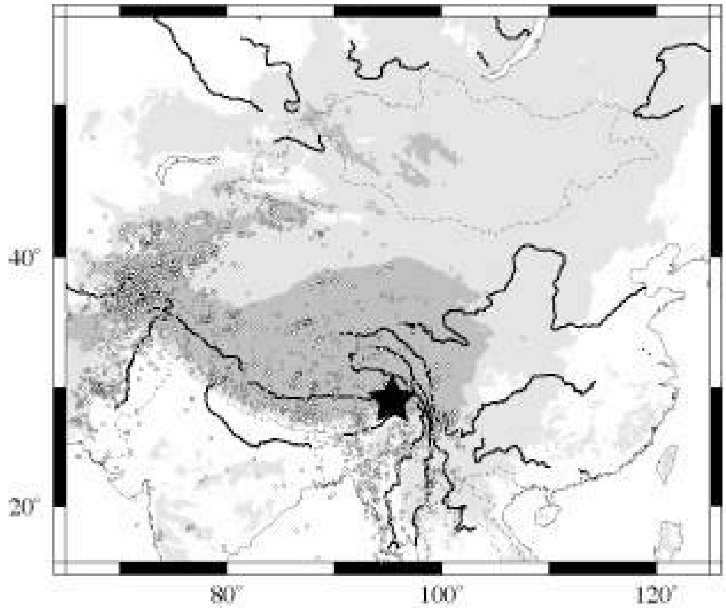
Crustal Dynamics: Source parameters, focal mechanisms and moment release, determined for regional and local events recorded by portable arrays provide a rich data set for analysis of kinematics and style of deformation. While these events may not account for large moment release, they are more frequent 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). 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. 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. The proposed MIT seismic array will nominally be co-located with the current MIT GPS array. 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.

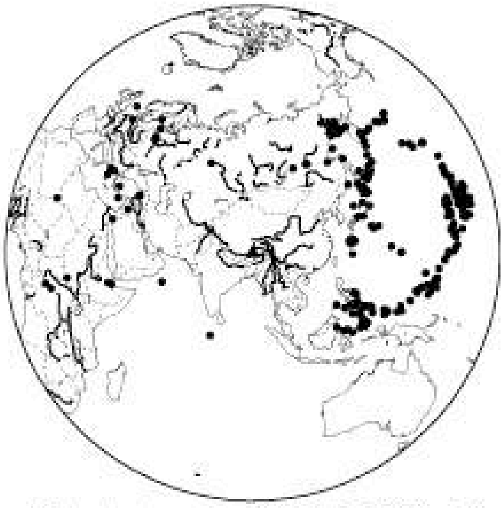


Shaded topography in the eastern syntaxial region. Locations of the proposed regional Namche Barwa and MIT arrays.

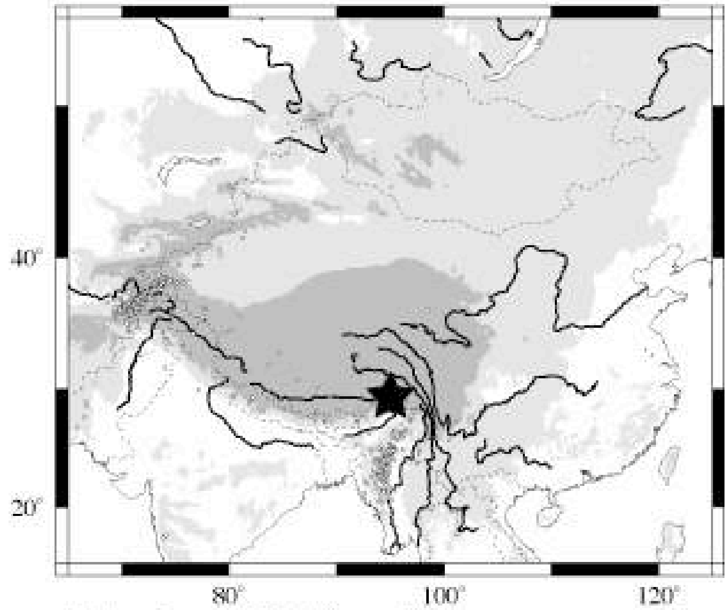
Feasibility: While establishing a dense temporary seismic network in the high Himalayas is logistically challenging, we have successfully carried out a similar campaign at Nanga Parbat in NE Pakistan. Access to the Namche Barwa region is quite good. Adequate bedrock sites exist for deploying sensors so we can avoid station corrections due to low-velocity surface material. Regional seismicity is abundant. 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.



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 Tsangopo. 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 Tsangopo. Topography is shaded: light gray=500-2500 m., dark gray >2500 m.

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. 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 50-element regional broadband array will record for 12 months.

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. 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.