COLLABORATIVE RESEARCH:
U.S. HIMPROBE: GEOLOGY AND GEOPHYSICS IN NW INDIA
TESTING COMPETING MODELS OF HIMALAYAN OROGENESIS

International Cooperative Project

Participation by Institution

United States	
San Francisco State University	Mary Leech
Stanford University	Simon Klemperer
University of Arizona	Peter DeCelles
University of Wyoming	Barbara Carrapa
Canada:	
University of Alberta	Martyn Unsworth*
India	
IIT Roorkee	Sandeep Singh* & A.K. Jain*
National Geophysical Research Institute (NGRI)	S.S. Rai* & Rajendra Prasad*
Wadia Institute of Himalayan Geology (WIHG)	B.R. Arora*
China	
China University of Geosciences, Beijing (CUGB)	Wei Wenbo*

Participation by Methodology

Regional and Structural Geology
Peter DeCelles (UA), Mary Leech (SFSU), A.K. Jain* & Sandeep Singh* (IIT Roorkee)

Geo/thermochronology, Geochemistry, and Petrology
Mary Leech (SFSU), Peter DeCelles (UA), Barbara Carrapa (Wyoming)

Seismology
Simon Klemperer (Stanford), S.S. Rai* & Rajendra Prasad* (NGRI), B.R. Arora* (WIHG)

Magnetotellurics
Martyn Unsworth* (Alberta), B.R. Arora* (WIHG), Wei Wenbo* (CUGB)

Budget summary	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**4-yr total**
San Francisco State**	$126,000	$141,402	$132,761	$112,687	$ 512,850[§]
Stanford University***	$177,724	$236,705	$242,092	$156,867	$ 813,388[§]
University of Arizona	$ 89,665	$117,404	$123,039	$ 95,653	$ 425,761
University of Wyoming	$164,511	$156,747	$ 75,747	$ 68,438	$ 465,443
Totals each year:	$557,900	$652,258	$573,639	$433,645	**$2,217,442**

Start Date: 1 July 2008

* Foreign collaborating investigators for whom no salary support is requested
** Includes participant support for all visiting Indian geologists
*** Includes support for magnetotelluric analysis at University of Alberta, and support for all visiting Indian geophysicists
[§] Totals include REU supplements for undergraduate students ($38,525 SFSU; $16,350 Stanford)

PROJECT SUMMARY

Collaborative Research: US-HIMPROBE: Geology and geophysics in NW India testing competing models of Himalayan orogenesis

Intellectual Merit

Geodynamic models developed for the Himalayan orogenic belt — Earth's archetypal collisional thrust belt — are commonly exported to other collisional orogens. Nevertheless, controversy surrounds Himalayan geodynamics, with two end-member models in need of critical testing before further progress can be realized: the mid-crustal channel flow model and the conventional thrust belt model. In particular, the proposal that structural and metamorphic features of the Himalaya are dominantly controlled by outward flow of middle crust from the core of an actively deforming Tibetan plateau deserves more careful testing. Both models make testable predictions in terms of crustal-scale structural geometry, timing of major faulting events, kinematics, and lithospheric-scale structure. We will test predictions for each model by collecting and integrating detailed structural, petrologic, geo/thermochronologic, seismic, magnetotelluric (MT), and erosional unroofing datasets. Our goal is to produce integrated lithospheric-scale cross sections that honor both geophysical and geological datasets and are incrementally restorable within the constraints imposed by thermochronology, geochronology, and the erosional unroofing record of the Himalayan foreland basin.

In NW India, one can make a complete transect across the Himalayan orogen (away from the complex syntaxial regions) from the Main Frontal Thrust to north of the Indus-Yarlung suture zone within a single country, thereby greatly simplifying the logistical challenges to regional geophysical and geological transects. Moreover, a wealth of geological and thermochronological data already exists in the proposed study area, and will provide a platform for interpreting the detrital record and synthesizing a regional kinematic history. HIMPROBE is the Indian national project, active over the last seven years, to create a NW-Himalayan geotransect from the Sub-Himalaya to the Karakoram Range. Framework broadband seismology, broadband MT, the first phase of seismic reflection, and a comprehensive potential-field transect have been coupled with geological investigations to make this area more data-rich than most regions of the orogen, and to provide the background knowledge on which we can now build with more focused and detailed investigations.

We seek funds in this proposal for a "US-HIMPROBE" effort collaborative with Indian scientists and a Canadian colleague. Two trans-Himalayan geology-geophysics transects are proposed, combined with detailed geo/thermochronology using advanced facilities in the U.S. (U-Pb SHRIMP, MC-LA-ICPMS, ^{40}Ar/^{39}Ar, and fission track labs). We propose an NSF-funded field contribution (personnel and equipment) to joint U.S.-India wide-angle seismic and long-period MT experiments. We will also collaborate with Indian geophysicists on the acquisition, processing and interpretation of new near-vertical seismic reflection profiles, a dense passive broadband seismic transect and 2D array, and broadband MT transects, that will be acquired solely with Indian funding and equipment. The end results of our study will be: (1) a comprehensive cross-section of the lithospheric-scale structure of the NW Himalaya; (2) a temporal reconstruction of the geologic, kinematic, and exhumation histories of the NW Himalaya; and (most important) (3) formal tests and new understanding of the processes involved in the creation of the Himalaya and other collisional orogenic belts.

Broader Impacts

This proposal provides access for scientists from the developing world to modern facilities, methods and ideas in North America, and technology transfer back to India, including research visits to the US for Indian post-doctoral scientists and young faculty. This proposal helps initiate the careers of two untenured women faculty (one minority) at the integrative boundary between geology and geophysics. The project will result in four PhD theses, two MS theses, and multiple undergraduate research projects. Resulting data will include geophysical images of seismogenic faults in densely populated regions of extreme seismic hazard, as well as allowing improved understanding of a region of perennial public interest, the High Himalaya.

PROJECT DESCRIPTION

U.S. HIMPROBE: GEOLOGY AND GEOPHYSICS IN NW INDIA TESTING COMPETING MODELS OF HIMALAYAN OROGENESIS

1. INTRODUCTION

The Himalayan orogen is typically assumed to be uniform along strike, and crustal-scale cross-sections drawn for all parts of the Himalaya are often based on results of the INDEPTH and related experiments in the eastern Himalaya. Recent crustal cross-sections commonly show features predicted by the "channel flow" model (e.g., Jain et al., 2003; Beaumont et al., 2004; Jamieson et al., 2004; Lee et al., 2006; Searle et al., 2006). These features include granitoids derived from a ductile mid-crustal channel formed when anatectic melts in the mid-crust of the Tibetan plateau were driven south gravitationally and by focused erosion at the Himalayan topographic front. The "channel flow" model predicts upwellings of these granitic bodies within the Tethyan Himalaya Sequence as the chain of "North Himalayan gneiss domes" and exposure of the channel at its southern termination in the Greater Himalaya Sequence (GHS) as suggested by widespread migmatites and leucogranite bodies at the top of the GHS in the footwall of the South Tibetan Detachment (STD).

Alternative models for Himalayan crustal structure and geodynamics include the conventional thrust belt model (Boyer & Elliott, 1982), variants of which range between almost exclusively southward verging thrust systems (Srivastava & Mitra, 1994) to orogenic wedge scale back-thrusts (Yin, 2006; Webb et al., 2007). All these models have been applied by different authors to each geographic segment of the Himalaya, but many of the specific predictions made by different models have yet to be tested with geological and geochronological data from regional orogen-transverse transects (Fig. 1).

There are several ways in which the western Himalaya differs from the central and eastern parts of the orogen: there is significantly less precipitation along the topographic front of the western Himalaya, and therefore precipitation-induced erosional exhumation (Wobus et al., 2003; Vannay et al., 2004; Thiede et al., 2004; 2005; Bookhagen et al., 2005a,b) is expected to be less significant than tectonic exhumation; the STD changes from a relatively continuous structure in the east, dying out or merging with the Zanskar shear zone in the NW Himalaya (Yin, 2006; Webb et al., 2007); and high-pressure/low-temperature subduction zone rocks are not seen in the eastern Himalaya but are exposed in the western Himalaya at Tso Morari, India, and Kaghan, Pakistan, suggesting a different subduction geometry in the west (e.g., deSigoyer et al., 2004; Leech et al., 2005, Guillot et al., 2007).

Intriguingly, there is a marked increase in volume and decrease in the age of granitoids from west to east along the Himalaya; this change occurs around the southeastern termination of the Karakoram fault where it merges with the Indus-Yarlung suture zone, near the Gurla Mandhata gneiss dome. If these granitoids are the signature of channel flow, then perhaps the model developed for the eastern Himalaya, strongly influenced by INDEPTH seismic data, is not directly applicable to the western Himalaya. Thus the western Himalaya is an ideal place to look at the thrust-belt architecture of the Himalaya, and to critically test whether channel-flow played any significant role in the development of the Himalaya. On the other hand, the highest heat-flow in the Himalaya is found near Puga (Tso Morari) (>500 $mW.m^{-2}$, Shanker et al., 1976) coupled with seismicity at only 7 km depth. This has been interpreted as being caused by Quaternary intrusions (Gupta et al., 1983). Thus the NW Indian Himalaya also may be the most likely region in the Himalaya to be undergoing channel flow at the present day, and so is the place to test the reality of channel flow as an orogenic process.

We propose a combination of field geology, geo/thermochronology, geochemistry, and geophysics to:
1) create the first crustal-scale cross-section constrained by both geology and geophysics of the western Himalaya and the southwestern Tibetan plateau, tracing the MCT (Main Central Thrust), STD, and MHT (Main Himalayan Thrust) across the suture zone;
2) determine petrogenetic relationships between the granites in the Karakoram shear zone (KSZ), in gneiss domes and the Tethyan Himalaya and Greater Himalaya as a means to test the channel flow model;

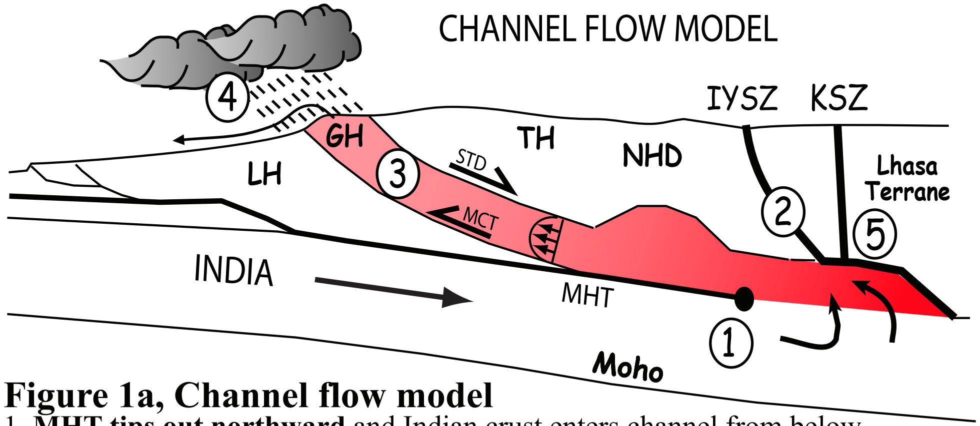


Figure 1a, Channel flow model

1. **MHT tips out northward** and Indian crust enters channel from below.
2. **Indus suture jogs north** beneath southern Lhasa terrane.
3. STD & MCT are coevally active during early Miocene, & facilitate southward & upward transport of GHS rocks **directly to the surface**.
4. Rapid erosion of GHS rocks is driven by monsoonal climate that advects the channel to surface during **early Miocene**.
5. KF extends to middle crust extracting melts of **Indian affinity** from channel.

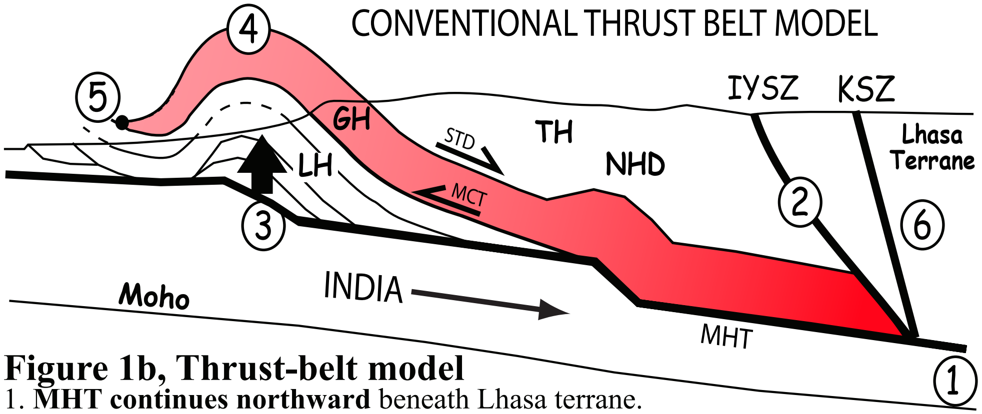


Figure 1b, Thrust-belt model

1. **MHT continues northward** beneath Lhasa terrane.
2. **Indus suture forms backstop** to the thrust belt &merges downward with MHT.
3. Growth of structures in LH during late Miocene **uplifts and tilts STD & MCT** into present steeper dips.
4. GHS rocks not widely exposed until **late Miocene**.
5. Intracutaneous wedge model **requires leading branchline** between MCT & STD
6. KF taps **Asian affinity** mid-crustal melts beneath Tibetan Plateau.

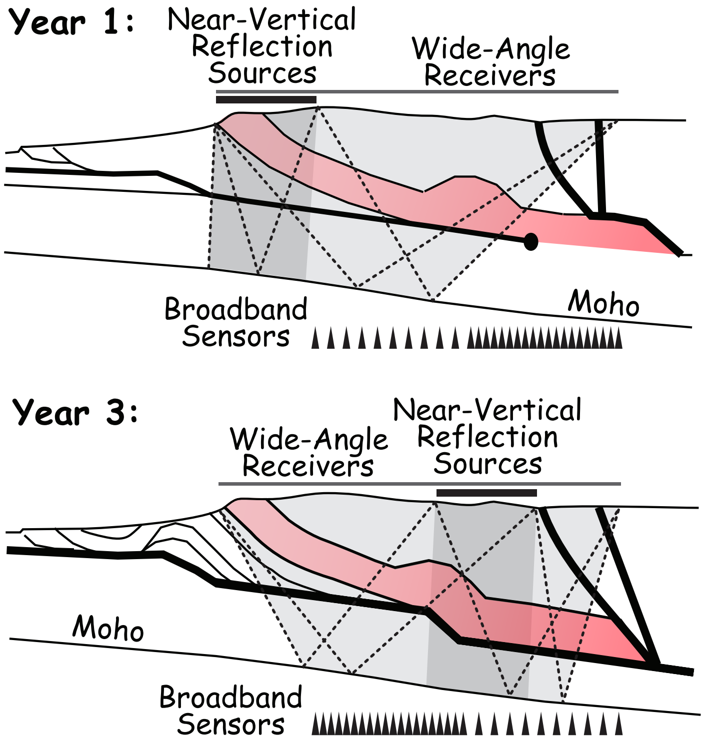


Figure 1c, seismic experiments
top: year 1: near-vertical reflection over GHS and 3-component wide-angle recorders and broadband sensors from MCT to KSZ; superimposed on "channel flow" end-member. *bottom:* year 3: near-vertical reflection over Tso Morari region and wide-angle recorders and broadband sensors again from MCT to KSZ; superimposed on "thrust wedge" model. Dark-shaded region is near-vertical reflection coverage (250 shots of 60 kg spanning 100 km); light-shaded region is wide-angle reflection coverage (60 2 Hz receivers span 300 km). Arrowheads represent 18-month deployments of 30 Guralp 3T sensors at 5- and 10-km intervals to provide dense receiver-functions for CCP migration using the wide-angle 2D velocity field (and will also record the reflection shooting). Combination of receiver-function, wide-angle and near-vertical profiling is intended to distinguish between the two end-member hypotheses shown.

3) establish via geology, magnetotellurics (MT) and controlled-source seismology the amount of melt in the region of the Indus-Yarlung suture zone (IYSZ); and
4) develop a model for the regional structural and kinematic evolution of the western Himalaya and make along-strike comparisons with the eastern Himalaya.

2. WHY THE HIMALAYA OF NORTH-WESTERN INDIA?

We propose to study the Himalaya and southern Tibet Plateau in NW India (Fig. 2), where all the major tectonic features are encompassed within a single country. By regional standards, the infrastructure of the Indian NW Himalaya is well-developed with well-maintained paved roads along our proposed traverses. The area also includes some of the type examples of famous Himalayan tectonic features, including the Tso Morari (where UHP minerals have been documented) and Leo Pargil gneiss domes, the Zanskar shear zone (a likely western extension of the STD), the Kishtwar and Kulu-Larji-Rampur windows (where the structural architecture in the vicinity of the Main Central thrust is exposed at intermediate crustal levels), the Tethyan Himalayan portion of the thrust belt in Zanskar and Lahul (the least understood part of the thrust belt, but also one of its most important elements), and a complete synorogenic unroofing record in the frontal part of the thrust belt (the Paleogene and Neogene foreland basin deposits, Fig. 3a). The northern termination of our transect across the KSZ provides the opportunity to study what may be an important youthful element of the Tibetan lithospheric architecture: it has been suggested that India underthrusts 400 km north of the KSZ (Priestley et al., 2007) though far to the east the Karakorum-Jiali fault is suggested by others to mark the northern limit of underthrusting India in contact with Asian crust (e.g. Jin et al. 1996; Zhang & Klemperer 2005).

The geology of the region is known at an unparalleled level of detail for the Himalaya (Fig. 3a), but deeply entrenched, first-order controversies persist because relatively little geochronology and thermo-

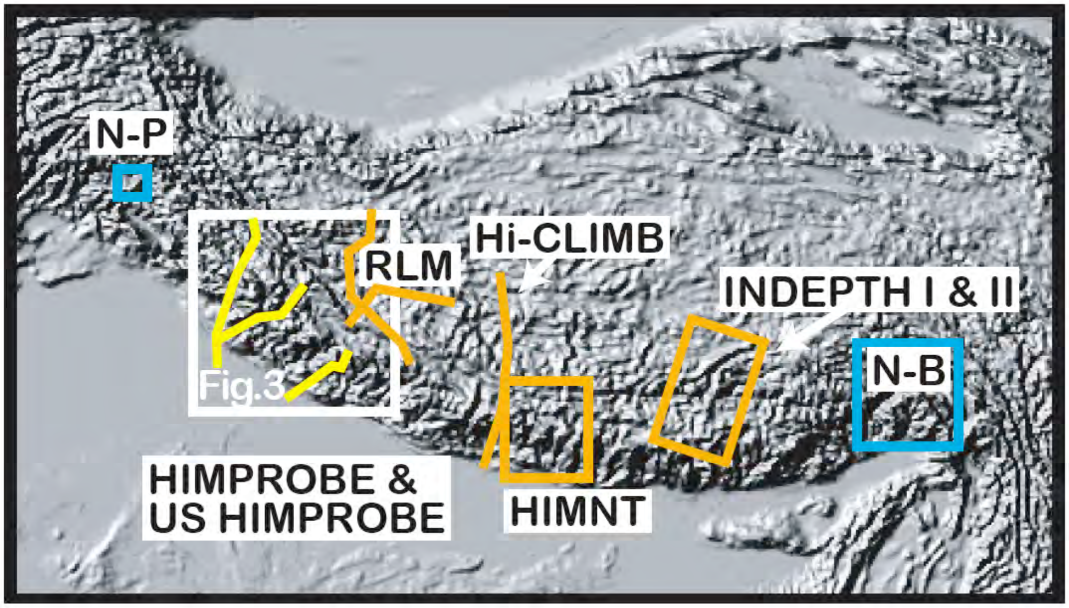


Figure 2. Map of the Himalaya showing the study area for the US-HIMPROBE and Indian HIMPROBE programs (white box, Figure 3 and yellow transect lines), and complementary seismic arrays in Nepal and southern Tibet. Orange boxes and lines: existing seismic arrays (only passive seismology except for INDEPTH) across the Himalaya and southern Tibet (INDEPTH I/II; HIMNT and HiCLIMB: all completed; RLM: Roecker-Levin-Molnar western Tibet broadband deployment funded for 2007-2009 fieldwork by NSF-Geophysics). Blue boxes: Seismic arrays over Himalayan syntaxes (N-P: Nanga Parbat; N-B: Namche Barwar: completed).

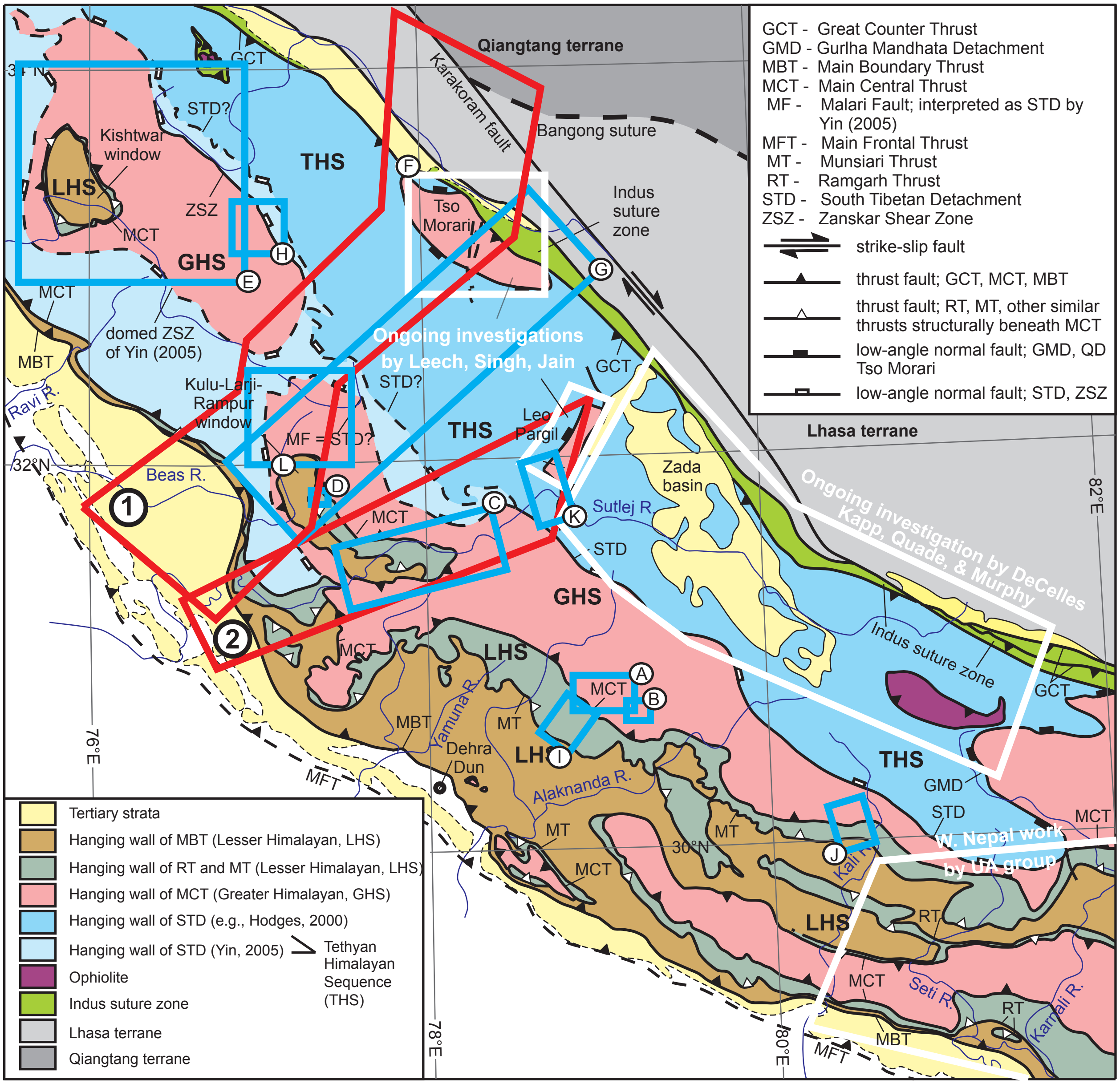


Figure 3a. Geologic map of NW Indian Himalaya and adjacent regions compiled from Valdiya (1980), Srivastava (1992), Steck (2003), Pan et al. (2004), Robinson et al. (2005) and Yin (2005). Political boundaries are omitted for clarity; the border between Nepal and India is located along the Kali river. Transects 1 and 2 to be investigated by US-HIMPROBE are outlined in red boxes. Blue, green and white boxes are recent and ongoing studies providing background and complementary geologic data. The Indian HIMPROBE program was along Transect 1, Beas River to the Indus-Yarlung suture zone.

Ⓐ Sorkhabi et al., 1996
Ⓑ Searle et al., 1992
Ⓒ Jain et al., 2000; Vannay et al., 2004; Thiede et al., 2004; 2005
Ⓓ Lal et al., 1999
Ⓔ Kumar et al., 1995; Sorkhabi et al., 1997
Ⓕ Girard & Bussy, 1999; de Sigoyer el al., 2004; Leech et al., 2005; 2006a,b; 2007a,b, Hassett & Leech, 2007
Ⓖ Schlup et al., 2003; Schlup unpub. Diss., 2003
Ⓗ Dezes et al., 1999; Walker et al., 1999
Ⓘ Metcalfe, 1993; Catlos et al., 2002
Ⓙ Bojar et al., 2005
Ⓚ Thiede et al., 2006
Ⓛ Webb et al., 2007

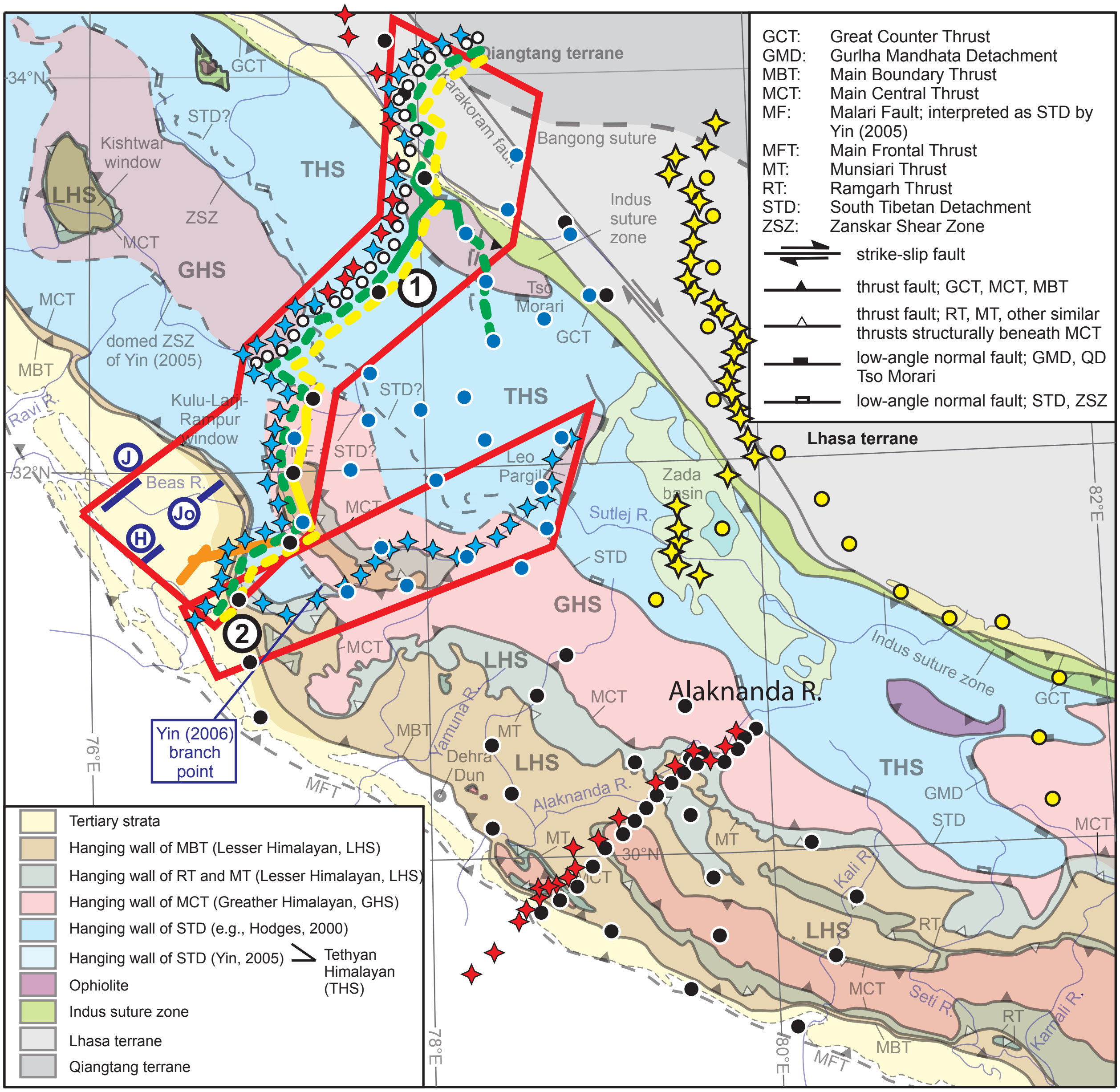


Figure 3b. Geologic map of the HIMPROBE region. Symbols in HIMPROBE transect boxes 1, 2 and along the Alaknanda R. represent existing and planned geophysical measurements. Transects 1 and 2 to be investigated by US-HIMPROBE are outlined in red boxes. Some stations & profiles offset for clarity.

Active-source seismic (Transect 1 only): solid lines: near-vertical reflection; dashed lines: wide-angle refraction. Orange (LHS): 2004 (data at Stanford); yellow (GHS): planned spring 2009; green (Tso Morari): planned spring 2011

- ● Passive seismic: acquired by NGRI (c. 30 km spacing, Transect 1, data at Stanford; c. 15 km spacing, Alaknanda + c. 40 km 2D array), data to be shared 2008
- ○ Passive seismic: NGRI linear array proposed for 2009-2011 (<10 km spacing, Transect 1)
- ● Passive seismic: WIHG 2D seismicity study proposed for 2009-2011 (c. 40 km spacing, Transect 1/2)
- ● Passive seismic: in progress and planned for 2008 (RLM experiment, western Tibet)
- ✦ Magnetotelluric: acquired (Transect 1: WIHG + IIG, data at Alberta; Alaknanda: WIHG)
- ✦ Magnetotelluric: proposed for 2010, WIHG/Alberta T1/T2 (BBMT @ 5km, LMT @ 20 km spacing)
- ✦ Magnetotelluric: acquired BBMT in 2007 & proposed LMT in 2009 (western Tibet, CUGB/Alberta)
- / Locations of Tertiary sections to be measured: H=Haritalyangar; J=Jawalamukhi; Jo=Jogindernagar

chronology has been attempted (in contrast to the state of knowledge in Nepal). Over the last 7 years, the Indian Department of Science and Technology (DST) funded HIMPROBE, a series of separate studies of the NW Himalaya loosely coordinated first by academician Prof. A.K. Jain and latterly by Prof. Sandeep Singh (see letters of support), and based at the Indian Institute of Technology (IIT) at Roorkee, the Wadia Institute of Himalayan Geology (WIHG), and the National Geophysical Research Institute (NGRI). US-HIMPROBE will collaborate with all three institutions. Our objective is to bring experienced Indian and western geologists and geophysicists to work together in this uniquely advantageous part of the Himalaya to develop a solution to the question of how the Himalayan thrust belt operates.

The Indian HIMPROBE project provided framework geological mapping (Jain et al., 2003) and geochronology (in part through an existing IIT-Roorkee - Stanford project, Leech et al., 2005; 2007); and acquired an MT profile (Gokarn et al., 2002; 2003; Arora et al., 2007; Unsworth et al., 2005), well-sampled gravity and magnetic profiles and the first leg of a reflection profile (Rajendra Prasad, unpublished data), and deployed a sparse broadband seismic array (Singh & Rai, 2003; Rai et al., 2006; in review), all along Transect 1 in Fig. 3b. Further north along this transect the remarkably young, coesite- and diamond-bearing Tso Morari eclogites have stimulated numerous specialized studies (e.g., Girard and Bussy, 1999; deSigoyer et al., 2000; Jain et al., 2003; Mukherjee & Sachan, 2003; Schlup et al., 2003; Sachan et al., 2001;2004; Leech et al., 2005; 2007). Excellent exposures along the Sutlej drainage that cuts directly across the main tectonic units (Transect 2, Fig. 3) have yielded several thermochronologic and erosion/uplift studies (Jain et al., 2000; Thiede et al., 2004; Vannay et al., 2004). A complementary geophysics profile along the Alaknanda River has also been selected by the Indian geophysicists to study the setting of the 1999 M6.6 Chamoli earthquake that killed 100 people (Mandal et al., 2000). The south end of Transect 1 crosses the rupture zone of the 1905 M7.8 Kangra earthquake that killed ~19,500 people (Bilham et al., 2001; Bilham, 2007). The entire HIMPROBE study area lies in the Garhwal seismic gap where a $M \geq 8$ earthquake is expected (Gupta et al., 1995), since no great earthquake has occurred since ~1400 (Bilham, 2007), and >100,000 lives are at risk. Crustal-scale geophysical studies help understand the seismic hazard, because knowledge of subsurface fault geometry can help predict the likely nucleation point of future great earthquakes, and because Moho geometry can significantly affect shaking intensities through generation of post-critical reflected waves (Hough et al., 2005).

We have designed US-HIMPROBE to augment, integrate, and systematize geologic mapping of the region, and to take advantage of Indian-led geophysical investigations in the region. We **do not** propose that NSF should fund acquisition of most of the seismic and magnetotelluric datasets required - rather, our Indian collaborators are receiving ongoing funding from the Indian DST to pay for major data acquisition, and we are seeking funding only to participate in project design, field programs, and data analysis, and to participate in fieldwork only where our instrumentation (stand-alone wide-angle seismographs and long-period MT instruments) fills a specific need for the planned science. US-HIMPROBE is **not** intended to be the lead geophysics program, but instead will be an adjunct to the Indian HIMPROBE program, providing additional intellectual and technical resources, and our funding request is correspondingly far lower than the total funding provided by the Indian government to their own scientists.

HIMPROBE vs. INDEPTH

The Indian HIMPROBE project was inspired by the highly successful INDEPTH project but is significantly different from that transect 1600 km to the east. INDEPTH was conceived as the first seismic exploration of the Tibetan Plateau, and helped generate the hypotheses (Nelson et al., 1996) that HIMPROBE will test: because the channel flow hypothesis (Beaumont et al., 2001; Shen et al., 2001) did not exist when INDEPTH studied southern Tibet, INDEPTH did not specifically target features capable of proving or disproving the hypothesis; and INDEPTH, unlike HIMPROBE, never embraced geological methods as co-equal with geophysics in studying the crust.

What can be accomplished with the HIMPROBE transect that was not completed in INDEPTH?

1) *Better imaging of the structure above the MHT, i.e., the MCT and STD.* Because INDEPTH was confined to Chinese Tibet, it never crossed the MCT, and crossed the STD where it is deformed by the

younger Yadong-Gulu rift. The structural relationship of the MCT and STD has the potential to discriminate between the traditional thrust-belt and newer channel-flow models for the structural development of the Himalaya: this is arguably where the "channel" crops out. *INDEPTH focused on plateau formation, whereas HIMPROBE focuses on the Himalayan collisional thrust belt.*

2) In the proposed Transect 1 (Beas River across Tso Morari dome to Shyok), it will be possible to have *fewer geophysical data gaps and denser instrument spacing across the Indus-Yarlung suture zone (IYSZ).* INDEPTH never attempted dense broadband imaging across the IYSZ; INDEPTH reflection imaging had a large data gap at the IYSZ because of extreme topography, and sparse wide-angle under-shooting because of recording limitations now overcome in modern PASSCAL equipment. Hi-CLIMB (NSF-CD funded profile of passive seismic recording only across central Nepal/southern Tibet) has dense broadband spacing but no controlled-source work. *HIMPROBE proposes dense broadband spacing (5-to-10 km) across the IYSZ allowing common-conversion point imaging coupled with selected near-vertical and continuous wide-angle reflection profiling* that will give us the best image of the IYSZ and better Moho location than INDEPTH. The northern extent of the MHT on INDEPTH was strongly debated even within the INDEPTH team (Makovsky et al., 1999, vs. Hauck et al., 1998); but its fate beneath the suture zone is a key test of the channel-flow model (Grasemann et al., 2006).

3) U.S.-HIMPROBE geophysics will complement Indian-funded near-vertical reflection and passive seismology with NSF-funded wide-angle data collection, and Indian-funded "broadband" (i.e., upper-crustal) MT work with NSF-funded "long-period" (i.e., lithospheric) magnetotelluric data collection. *The funded Indian HIMPROBE project provides an inexpensive and convenient vehicle to complete INDEPTH-scale work with better-than-INDEPTH resolution and coverage in the western Himalaya.*

4) HIMPROBE, unlike INDEPTH and Hi-CLIMB, fully integrates geology and geo/thermochronology with the geophysics.

What makes the HIMPROBE profile in the western Himalaya a better location than the INDEPTH profile to distinguish between channel-flow and critical-taper orogenic-wedge end-member models? Rather than return to record denser profiles in the eastern Himalaya south of and within the INDEPTH I and II transects, we propose to collect the data in the western Himalaya to distinguish between these two end-member models (channel flow vs. conventional thrust belt), and simultaneously to address the question of whether orogenic structure is uniform along strike. In NW India there is easy access across the entire orogenic structure from the Main Frontal thrust to the Karakoram Fault allowing uninterrupted seismic instrument deployment. We will also achieve a measure of 3D (along-strike) control with a 2D passive seismic array spanning the region between Transects 1 and 2 (both with MT recording) and a second passive-seismic and MT geophysical transect along the Alaknanda River and into western (Chinese) Tibet, albeit broken with a data gap across the India-China border.

3. GEOLOGICAL BACKGROUND

The geology of the northern Indian Himalaya has been summarized in numerous papers (e.g., Fuchs, 1981; Frank et al., 1995; Vannay & Grasemann, 1998, 2001; Hodges, 2000; Frank et al., 2001; Steck, 2003; DePietro & Pogue, 2004; Yin, 2006) which essentially confirm the work of Gansser (1964) who showed that major Himalayan tectonostratigraphic zones and structures are, to first order, continuous along most of the 2000 km arc. Our summary focuses on regions most relevant to our proposed work; excellent (but in many cases partly contradictory) summaries have been published by Steck (2003), Jain et al. (2002), Valdiya (1984), Hodges (2000), and Yin (2006). Rather than bog down in the complexity of arguments among the many authors involved in these other papers, we provide a simplified summary that attempts to distill the major features of the orogen to introduce tectonostratigraphic terminology that is generally agreed upon and useful for the part of the Himalaya where we propose to work.

The thrust belt is divisible into four major tectonostratigraphic zones separated by major faults/shear zones (Gansser, 1964; Hodges, 2000). From south to north these are the Subhimalayan, Lesser Himalayan, Greater (or Higher) Himalayan, and the Tethyan (or Tibetan) Himalayan zones. In northern India the **Subhimalayan zone** consists of Eocene, late Oligocene to Neogene foreland basin deposits derived from the developing Himalayan thrust belt and later incorporated into the thrust belt as it migrated toward India. The Eocene record is mainly shallow-marine carbonate and fine-grained offshore facies, and the Oligo-Miocene through Pliocene section is entirely fluvial, with an overall upward coarsening trend (Burbank et al., 1996; Najman et al., 1997, 2001). These rocks are in the hanging wall of the **Main Frontal thrust**, which consists of a system of partially overlapping imbricated thrusts and related fault-propagation folds (Burbank et al., 1996; Powers et al., 1998; Wesnousky et al., 1999; Mugnier et al., 1999). The **Main Boundary thrust** marks the northern boundary of the Subhimalayan zone.

In the hanging wall of the Main Boundary thrust are Proterozoic-Cambrian low-grade metasedimentary and meta-igneous rocks of the ~10-15 km thick **Lesser Himalayan Sequence** (Fig. 3; Jain et al., 2002; 2003; Steck, 2003; Myrow et al., 2003; Yin, 2006). The northern or upper structural boundary of the Lesser Himalayan zone is the **Main Central thrust (MCT)**. The MCT carries the 5-20 km thick **Greater Himalayan Sequence (GHS)**, a succession of upper amphibolite-grade paragneisses, calc-silicates, and Ordovician granitic orthogneisses (Fig. 3; Hodges & Silverburg, 1988; Vannay & Hodges, 1996; Vannay & Graseman, 2001; Kohn et al., 2004). In northern India the metamorphic grade in the frontal part of the MCT sheet is considerably lower than it is in Nepal, and the stratigraphic succession is dominated by the siliciclastic Haimanta Formation. Some have suggested that the Haimanta Formation is the lower-grade equivalent of the pelitic lower GHS (Formation I/Unit I in central Nepal; Colchen et al., 1986; Searle & Godin, 2003; Yin, 2006). In the upper part of the GHS sills and dikes of early to mid-Miocene leucogranite are increasingly abundant (e.g., Searle & Godin, 2003; Murphy & Copeland, 2005). According to most authors, the northern or structurally upper boundary of the Greater Himalayan zone is marked by the **South Tibetan detachment (STD)**, a system of north-dipping ductile shear zones and brittle normal faults with top-to-the-north sense of shear/slip (Burg & Chen, 1984; Burchfiel et al., 1992; Hodges et al., 1996; Dèzes et al., 1999; Searle & Godin, 2003). Exact placement of the STD in northern India remains highly controversial. Some workers place it near the contact between Greater and Tethyan Himalayan rocks (the Zanskar shear zone, Dèzes et al., 1999; Steck, 2003); others place the fault down section in the Greater Himalayan sequence (Haimanta Formation) (Yin, 2006; Fig. 3).

The **Tethyan Himalayan Sequence (THS)** consists of folded and thrusted Cambrian-Eocene sedimentary rocks, locally metamorphosed to lower greenschist grade (Gaetani & Garzanti, 1991; Garzanti, 1993; Searle et al., 1997; Murphy & Yin, 2003; Wiesmayr & Grasemann, 2002). Running along the middle of the Tethyan Himalaya is a belt of gneiss domes referred to as the **North Himalayan domes** (e.g., Lee et al., 2000; Thiede et al., 2006). On Transect 2 of our study area, the **Leo Pargil dome** is one of these enigmatic crustal-scale culminations (Fig. 3; e.g., Guillot et al., 2003; Schlup et al., 2003; de Sigoyer et al., 2004; Sachan et al., 2004; Leech et al., 2005; Thiede et al., 2006). Also present in the Tethyan Himalaya are Miocene sedimentary basins, some of which are clearly extensional (Hurtado et al., 2001; Garzione et al., 2003). Directly north of our study area lies the **Zada basin**, where DeCelles has recently completed a project with NSF (Tectonics) funding. The northern boundary of the Tethyan Himalaya is the **Indus-Yarlung suture zone (IYSZ)**, which represents the location of the former subduction zone that existed along the southern margin of Asia. However, the regional structure of the suture zone is very complex and involves several major fault systems, including the **Great Counter thrust**, the **Karakoram strike-slip fault**, and the **Gangdese thrust** (Fig. 3; Yin et al., 1994, 1999; Murphy et al., 2002; Murphy & Yin, 2003). The Oligocene-early Miocene **Kailas Formation** (or Gangrinboche conglomerate) lies in the proximal footwall of the Great Counter thrust, providing age constraints for slip on the thrust. Directly north of the suture zone lies the **Gangdese-Ladakh batholith**, a belt of predominantly Cretaceous to early Tertiary granitic batholiths that represents the former magmatic arc along the southern margin of Asia (Allègre et al., 1984; Yin & Harrison, 2000).

The Karakoram fault zone is a major dextral strike-slip fault system that runs along the northern periphery of our proposed geologic and geophysical transects in India. Although estimates for the initial timing of slip on the Karakoram fault range between early Miocene and Pliocene time (cf. Review in Valli et al., 2007), recent work by Valli et al. (2007) suggests that the fault has been active since at least 21 Ma.

Because this time frame is concurrent with activity on the MCT and STD, it raises the prospect that the Karakoram fault could have been involved in conveying crustal melts to shallow crustal levels.

Because many Himalayan tectonostratigraphic units have been metamorphosed, unit identification can be difficult on the basis of lithological criteria alone. Fortunately, major geochronologic and isotopic differences exist between the Lesser, Greater, and Tethyan Himalayan units (Parrish & Hodges, 1996; Ahmad et al., 2000; Miller et al., 2000, 2001; Whittington et al., 2000; Argles et al., 2003; DeCelles et al., 2000, 2004; Robinson et al., 2001; Richards et al., 2005; Martin et al., 2005; Murphy, 2007). Lesser Himalayan units are characterized by Paleoproterozoic Nd model ages and very negative values of εNd (average –23), and contain detrital zircons that cluster at ~1.86 Ga and 2.4 Ga, as well as distinctive ~1.83 Ga granitic orthogneisses (Fig. 4). Greater Himalayan units are much younger, with mean εNd values of –16 and detrital zircon clusters at ca. 1.1 Ga and 2.4 Ga, and 470-510 Ma orthogneisses. Tethyan rocks are similar to Greater Himalayan rocks but also contain a telltale population of 470-510 Ma detrital zircons derived from the underlying GHS orthogneisses, as well as a more juvenile component of Nd.

4. GEOPHYSICAL BACKGROUND

Teleseismic observations provided the most fundamental early understanding of the Himalaya and southern Tibet, particularly the twin discoveries of a cold upper mantle (Barazangi & Ni, 1982) and an aseismic, presumably ductile, lower crust (Chen & Molnar, 1983). Geophysics has contributed to our knowledge of structure and rheology (gravity: Lyon-Caen & Molnar, 1983; refraction profiling: Hirn et al., 1984; teleseismic receiver functions: Schulte-Pelkum et al., 2005; tomography: McNamara et al., 1997; improved hypocentral depths: Chen et al., 2004; Monsalve et al., 2006; Priestley et al., 2007; magnetotelluric: Unsworth et al., 2005; see recent comprehensive review: Klemperer, 2006).

Despite the growing database, it is still hotly argued whether Tibetan lithosphere is better described as deforming homogeneously by vertical coherent deformation (England & Houseman, 1986; England & Molnar, 1997; Flesch et al., 2005), or by ductile flow in the middle and/or lower crust ('channel flow') (e.g., Bird, 1991; Clark & Royden, 2000; Shen et al., 2001; Beaumont et al., 2004), or by both in different areas (e.g. Bendick & Flesch, 2007). Even if ductile flow characterizes the Tibetan lower crust, can a flowing channel extrude outwards beneath the Himalaya? The currently popular channel-flow model is in large part defined by the INDEPTH Continental Dynamics project and also built upon many previous studies (see review, Klemperer, 2006). The INDEPTH transect (see Fig. 2), produced several important findings: (1) imaged for the first time the **Main Himalayan Thrust (MHT)** (CMP reflection: Zhao et al., 1993, Alsdorf et al., 1998a (Fig. 5a); wide-angle reflection: Makovsky et al., 1996a, 1999) which is the modern subduction thrust between India and Asia; (2) discovered a zone of partially molten crust in southern Tibet (electrical conductivity anomalies: Chen et al., 1996, Fig. 6; wide-angle converted waves: Makovsky et al., 1996a, Makovsky & Klemperer, 1999 (Fig. 5b); CMP reflection: Brown et al., 1996; teleseismic surface wave and receiver function studies: Kind et al., 1996); (3) synthesized the structure of southern Tibet in a fundamentally new way emphasizing the extrusion of partially molten crust into a ductile channel that reaches the surface as the Greater Himalayan Sequence between the MCT and the STD (Nelson et al., 1996), and is also related to the North Himalayan gneiss domes (e.g., the Kangmar and Mabja domes) and their formation above a ramp on the MHT (Lee et al., 2000; 2004) or triggered purely by superjacent extension (Beaumont et al., 2004). The INDEPTH synthesis (Fig. 5c) stimulated the thermo-mechanical numerical modeling of Beaumont et al. (2001, 2004, 2006) who sought to duplicate the geometries seen on the INDEPTH transect. These models make predictions about uplift/exhumation histories, P-T-t metamorphic histories and age profiles across the Himalaya (Jamieson et al., 2004, 2006).

The controversy as to whether channel-flow is a real geologic phenomenon, or merely an internally-consistent thermal-mechanical numerical model with no real application to the Himalaya, has recently been conflated with another geophysically-driven controversy about continental rheology. Conventional wisdom is that the continents represent a jelly-sandwich (strong upper crust – weak lower crust – strong upper mantle), based largely on the perceived absence of earthquakes from the lower crust and their rare

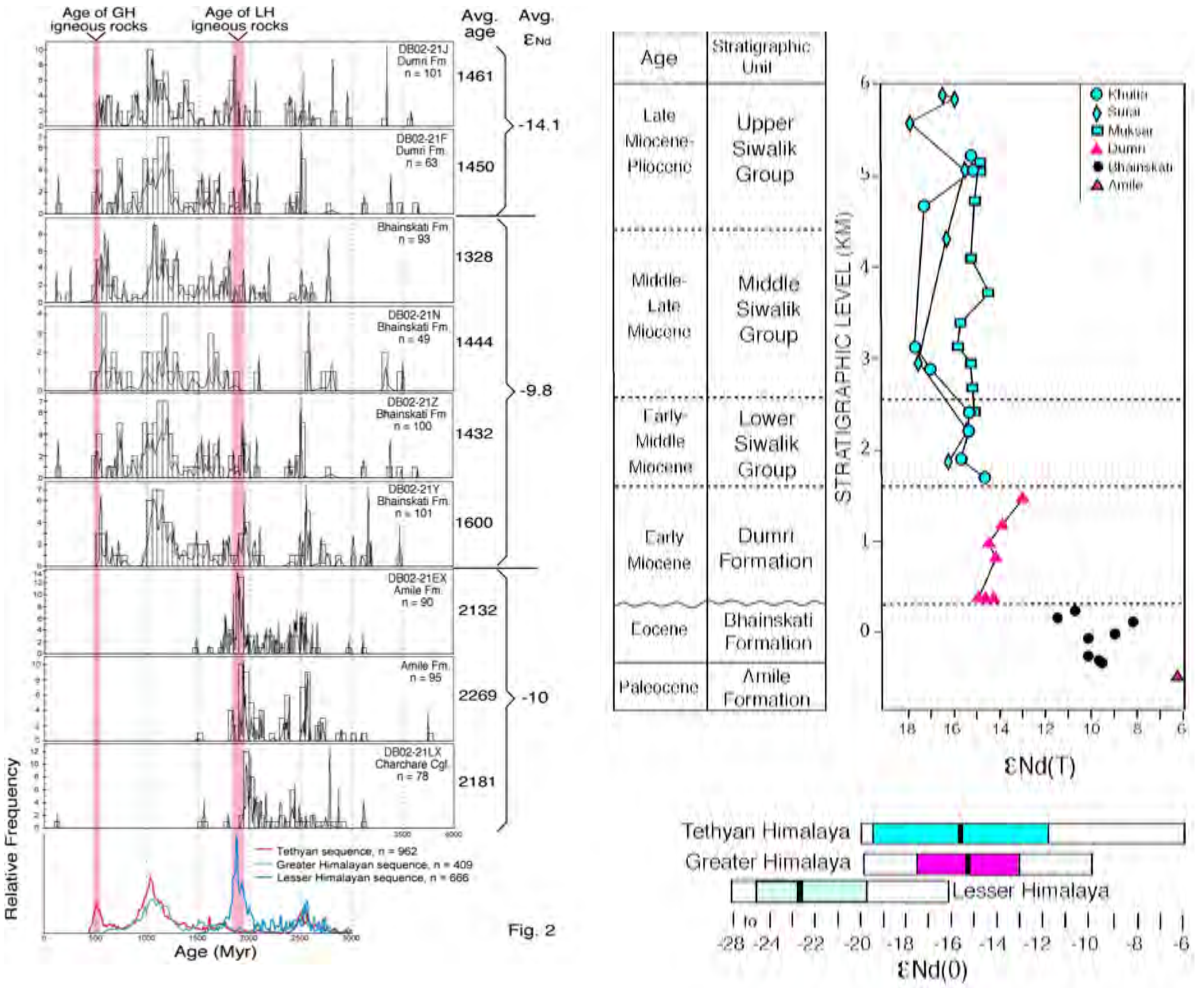


Fig. 4. Isotopic data from Cretaceous-Paleocene pre-orogenic and Eocene-Miocene synorogenic foreland basin deposits in Nepal (DeCelles et al., 2004). (A) U-Pb ages of detrital zircons. Lower panel shows data from Himalayan source terranes. Note that each of the three source terranes (LHS, GHS, THS) has a distinctive detrital zircon age spectrum. Pink bars represent intrusive ages (ca. 1.8 Ga in LHS, ca. 500 Ma in GHS). The data from the Amile and Charchare Formations (Cretaceous-Paleocene) show typical patterns of LHS zircons, indicating continued derivation from the Indian subcontinent. Beginning with the basal Bhainskati Formation (Eocene) the zircon patterns mimic THS fingerprints, with strong early Paleozoic and Grenville age components. (B) Nd-isotopic data from fine-grained overbank deposits in the same section, compared to data from Himalayan source terranes (lower panel, after Robinson et al., 2001). In lower panel the mean values (black bars) and ranges (colored strips) are shown. The overall upsection shift to more negative values in all sections was interpreted to indicate increasing contributions from LHS rocks. However, GHS and THS rocks also continued to dominate the signal into Pliocene time.

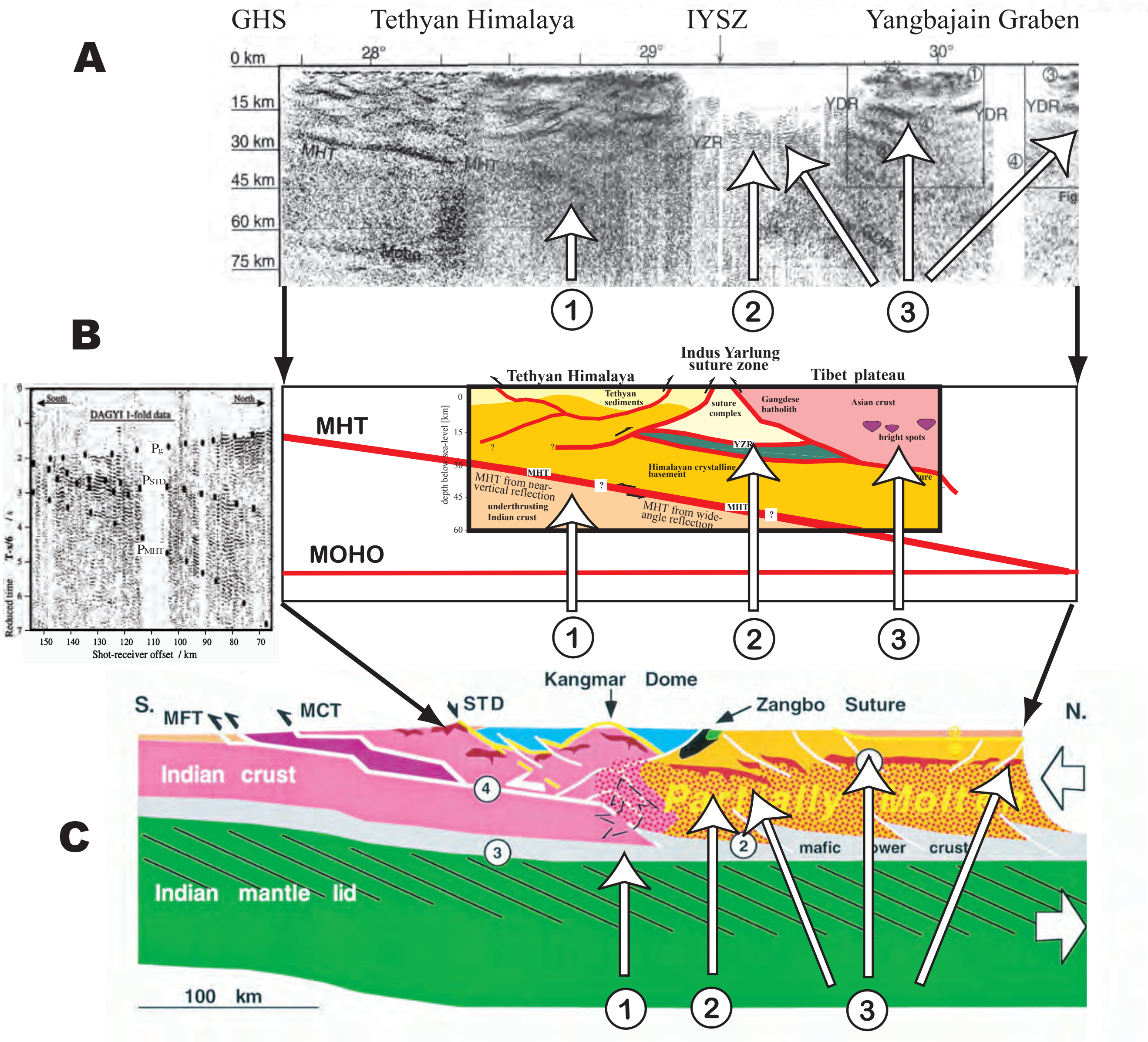


Figure 5. Active-source profiling results and resultant channel-flow model from INDEPTH.
A: Migrated reflection profile from Project INDEPTH (Alsdorf et al., 1998).
B: Wide-angle reflections from MHT (and STD) - single 50-kg shots recorded on a single 4.5 Hz geophone at offsets to >150 km (Makovsky et al., 1996a) - and interpretation of MHT continuous beneath IYSZ (Makovsky et al., 1999).
C: (note smaller scale) Interpretive cross-section (Nelson et al., 1996), with proposed channel flow between MCT and STD fed by both Indian crust (purple) and Lhasa block crust (orange).
Circled (1): northward termination of Main Himalayan Thrust (MHT) reflections in A, interpreted in C as a structural ramp causing uplift of Kangmar dome; but in B no termination was seen.
Circled (2): YZR reflection parallel to MHT but beneath Indus-Yarlung suture, interpreted as thrust slices in B and hence as evidence for a lack of a ramp in MHT. Our combined active- and passive-source acquisition is intended to resolve the uncertainty over the northern extent of the MHT.
Circled (3): inferred active magma chambers. In A, B and C melts are in the Lhasa Block (YDR reflector); C implies Lhasa Block material should be seen in GHS (none has yet been found); B suggests these melts are unrelated to a channel (removes a primary motivation for the Channel Flow model).
These different models highlight important controversies generated but not resolved by INDEPTH data.

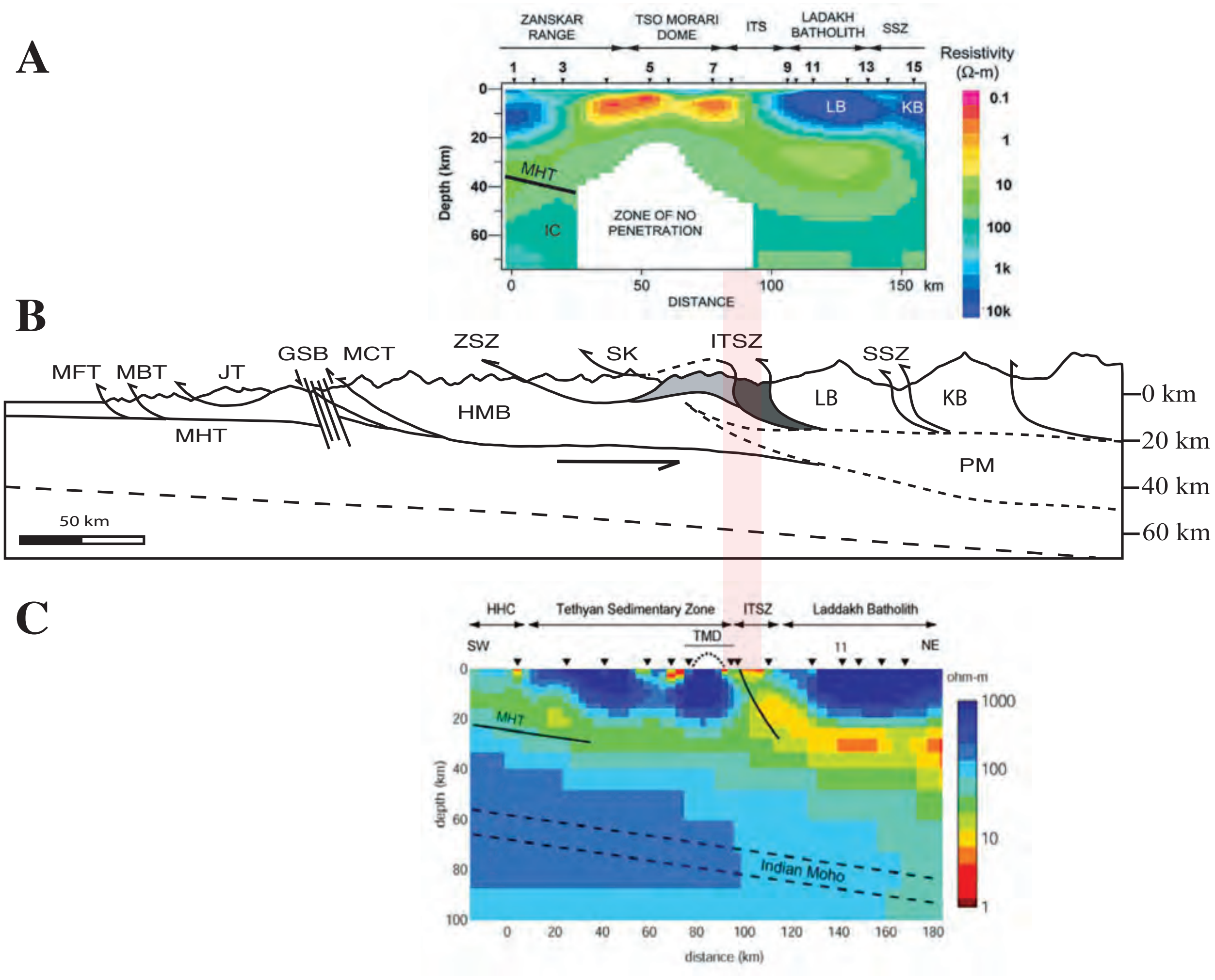


Figure 6. Zone of high conductivity and possible partial melt beneath the NW Himalaya; figures all true scale and aligned on the Indus-Yarlung suture zone (ITS).
A: Geoelectrical structure across the Indus-Yarlung suture zone (Gokarn et al., 2002) showing high conductivity beneath the Tso Morari complex analagous to that seen by INDEPTH in Tibet (Chen et al., 1996) and following the general structure of the channel flow model in Beaumont et al. (2004).
B: Tectonic cross-section (topography is exaggerated) (from Jain et al., 2003) across the Indus-Yarlung suture zone (dark gray) and Tso Morari Complex (light gray) showing the inferred partial melt zone (PM). The line of cross-section B is approximately along Transect 1 in Fig. 3. Cross-section is adapted from INDEPTH (Nelson et al., 1996) (Figure 5c), and is not yet well-constrained by surface mapping.
C: Conductivity structure from Arora et al. (2007) showing higher peak conductivities in the mid-crust (~20-40 km) and a continuous conductive channel north beneath the suture zone. Unsworth is the only scientist to have worked with both the Gokarn et al. (2002) and Arora et al. (2007) datasets, and has applied more modern processing methods to achieve this inversion.
Abbreviations: GSB, Garhwal seismic belt; HMB, Himalayan metamorphic belt (HHC and TMC); JT, Jutogh thrust; KB, Karakorum batholith; LB, Ladakh batholith complex; MFT, MBT, MCT, MHT, Main Frontal, Boundary, Central, and Himalayan thrusts; PM, partially molten crust; SK, Spongtang klippe; SSZ, Shyok suture zone; TMD, Tso Morari dome/complex; ZSZ, Zanskar shear zone.

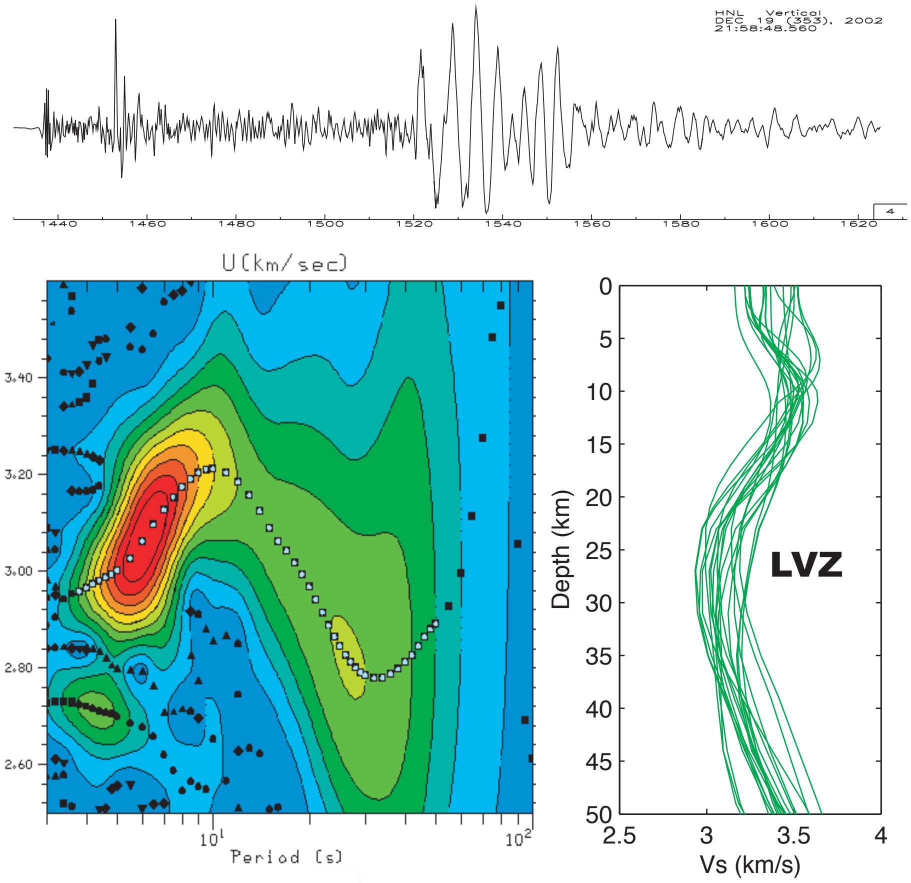
occurrence, including in southern Tibet, in the upper mantle (Chen & Molnar, 1983). A strength minimum in the middle-lower crust facilitates channel flow and complete decoupling of the upper crust and upper mantle, but does not require it. Recently those who believe that the "upper-mantle" earthquakes in southern Tibet are at crustal, not mantle depths (Maggi et al., 2000; Jackson, 2003) suggest that the lower crust is stronger than the upper mantle (Jackson, 2002, 2003). If so, the lack of a broad strength minimum throughout the lower crust must greatly inhibit or even prevent channel flow, except where the crust is locally weakened by magmatic intrusion (McKenzie & Jackson, 2002). Recent papers arguing that the teleseismically-recorded earthquakes are below (Chen & Yang, 2004), close to (Priestley et al., 2007) or above (Mitra et al., 2005) the Moho depend critically on estimates of crustal thickness, which varies locally and requires local seismic experiments to determine (e.g., Yuan et al., 1997; Zhang & Klemperer, 2005). At least some small Himalayan earthquakes now seem clearly to be in the mantle (Schulte-Pelkum et al., 2005; Monsalve et al., 2006). We require detailed seismic (crustal thickness) and magnetotelluric (fluid content) observations in the HIMPROBE area to understand crustal rheology and permissible deformation styles. Also critical to understanding lithospheric strength north of the Indus-Yarlung suture is the location of the "Indian mantle suture" (the point at which the top of subducting Indian crust intersects Tibetan Moho) and the "Indian mantle front" (northern extent of Indian lithosphere beneath Tibet). Datasets that bear on this are gravity (cf. Jin et al., 1996; Sastry et al., 2003; 2005 [on Transect 1]) as well as local seismicity and teleseismic recordings (e.g. Priestley et al., 2007 along Transect 1).

The HIMPROBE geophysical transects from the Subhimalaya to the Tibetan Plateau, in conjunction with INDEPTH and other experiments, will also provide important evidence as to whether orogenic structure and style are similar along the entire collisional belt. Following the INDEPTH successes, important NSF-funded geophysical studies have taken place across the Himalaya at the western Himalayan syntaxis, Nanga Parbat (Zeitler et al. 2001a;b) and in central Nepal 500 km east (HIMNT: Schulte-Pelkum et al., 2005, and Hi-CLIMB: J. Nabelek, W.P. Chen, pers. comm.) (Fig. 2). In the HIMPROBE area, our Indian collaborators had already deployed a temporary, sparse broadband seismic array along our proposed Transect 1 (Fig. 7; Rai et al., 2006; Caldwell et al., 2007; all data now at Stanford), and were encouraged by our collaboration on an earlier version of this proposal to deploy more-densely spaced broadband stations along the Alaknanda River and across the Chamoli hypocenter for seismic-hazard studies (Fig 3b; Rai & Singh, 2005). Moho conversions from the passive array are interpreted as representing an unbroken Moho from the Subhimalaya to the Indus-Yarlung suture, and conversions from the MCT are also observed (Singh & Rai, 2003; Suryaprakasam et al., 2003, Rai et al., 2006). Although the existing Transect 1 data are too sparse for common-conversion point (CCP) imaging and teleseismic migrations to be successfully applied to crustal interfaces, the observation of clear intra-crustal converters encourages us that we may identify and image the MCT and STD, key to geophysical tests of Himalayan geodynamic models, including channel flow. Our NGRI colleagues have also recorded the first leg of a reflection profile along Transect 1 (Fig. 8; Rajendra Prasad, pers. comm.) that shows reflections from the MHT and occasionally from the Moho; these data are currently being re-processed at Stanford prior to publication.

Our WIHG colleagues have collected sparse magnetotelluric data along Transect 1 (Fig. 3b & 6a; Gokarn et al., 2002; Unsworth et al., 2005; Arora et al., 2007), and along the Alaknanda River (B. Arora, pers. comm.). The initial HIMPROBE magnetotelluric data have already been published by our Indian collaborators, and data from both existing broadband MT data for crustal sounding (Gokarn et al., 2002) (Fig. 6a) and long-period MT data for imaging the upper mantle (Arora et al., 2007) (Fig. 6c) have been made available for re-processing (Unsworth et al., 2005). The newer processing methods available in North America are resulting in significant model changes compared to the earlier published results from India, and make clear the necessity for denser data acquisition. Nonetheless, MT data collected to date support a substantial uniformity along the Himalaya, notably high conductivities interpreted as indicating melts beneath the North Himalayan gneiss domes (e.g., Kangmar dome on the INDEPTH transect, Leo Pargil dome in the HIMPROBE area) (Unsworth et al., 2005). These melts may be important for the crust to deform in channel flow and are therefore an important target. NW India is perhaps the only place where we can collect a continuous MT profile across the orogen – the only continuous profile thus far

Figure 7.
Seismogram (a) and surface-wave velocity analysis (b) for a single M=5 earthquake; velocity inversions shown for 16 events (c) (code of Herrmann & Ammon, 2002) with ray-paths along Indus-Yarlung Suture Zone. Low-velocity zone (LVZ, 15 to 30 km depth) in upper crust likely corresponds to zone of high-conductivity and high heat-flow beneath Tso Morari (Figure 5). Knowledge of 2D velocity field is important for accurate receiver-function migration for CCP imaging.

Analysis at Stanford by Ph.D. student Warren Caldwell (Caldwell et al., 2007) of data provided from existing HIMPROBE transect 1 by S.S. Rai, NGRI.



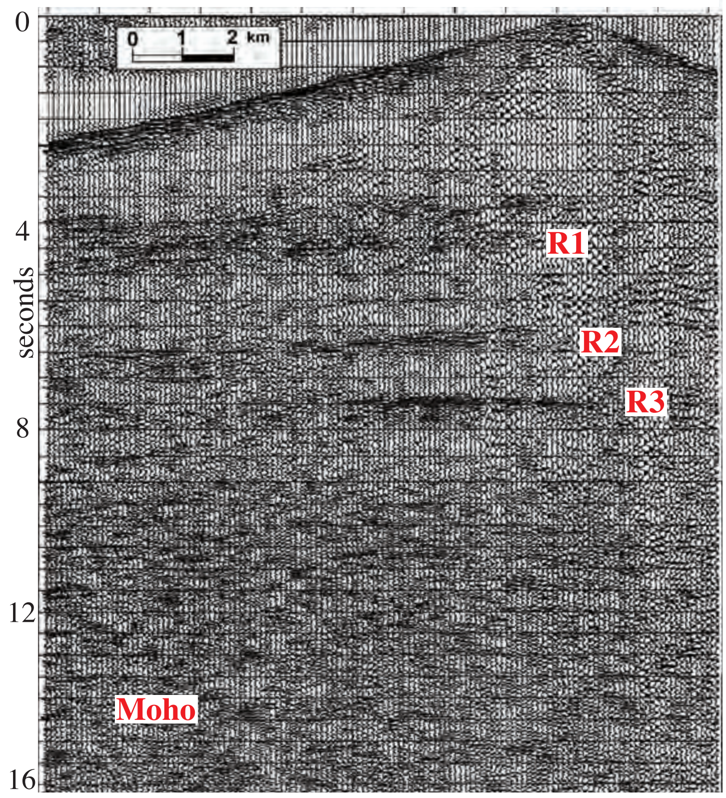


Figure 8.
Single shot-gather from 2004 Lesser Himalaya seismic profile, extracted from data-set provided to Stanford by Rajendra Prasad, NGRI, in October 2007, now the focus of re-processing efforts at Stanford by Ph.D. student Indrajit Das.

R1, possibly R2: prominent sedimentary reflections from within thrust duplexes; R2 or R3: Main Himalayan Thrust (MHT); R3: possibly MHT; or Vindhyan or Aravalli (Precambrian) below decollement.

Data collected using 60 kg charges in 25 m holes and the NGRI EAGLE-88 RF telemetry system to collect 18-fold 24 second data.
Prominent reflectivity is encouraging; statics corrections (topographic corrections) that are a major problem for stacking this profile will be far less severe in potential future profiling further north (More Plains; Tso Morari region).

published is merged INDEPTH (China) and French (Nepal) data with a substantial, 70-km, data gap leading to poor resolution in a critical region of the profile (Unsworth et al., 2005).

In western Tibet, our Chinese colleagues from CUGB have collected broadband MT (crustal sounding) data in 2007 across the border from the Alaknanda profile, which will together provide along-strike control to our Transect 1 but with a significant data gap. Along the same road in western Tibet, a new passive seismic array was installed north of the HIMPROBE area in 2007 and will be densified in 2008 (S. Roecker, pers, comm., RLM in Fig. 2). Collaboration and data exchange between NGRI and the Roecker-Levin-Molnar group (EAR-Geophysics project "Imaging the Upper Mantle Beneath the Western Tibetan Plateau") would be facilitated within the framework of an NSF-funded HIMPROBE project, but this Alaknanda-west Tibet transect will always suffer from a c. 80 km gap across the international border, and coarser spacing (>20 km) in Tibet: their primary targets are in the mantle, not in the crust.

Although the Indian projects along the Alaknanda are excellent examples of modern integrated data collection, they are simply in the wrong place for our academic objectives of studying channel-flow vs. thrust-belt models, because the India-China border prevents detailed study in the crucial areas from the STD to the IYSZ where the fundamental tests are possible (Figs. 1, 3).

5. TESTING MODELS FOR HIMALAYAN GEODYNAMICS

As discussed above, myriad geophysical datasets and sparse petrological samples from Tibetan lower/middle crust indicate that Tibetan middle crust (below about 20 km depth) is partially molten, and therefore susceptible to southward flow in response to the gravitational potential energy gradient between high Tibet and low India (cf. summaries in Klemperer, 2006; Hodges, 2006). Building on earlier ideas expressed by Burchfiel & Royden (1985) and Bird (1991), Nelson et al. (1996) made the conceptual connection between this modern situation and its possible ancient counterpart in the high Himalaya, where Early Miocene leucogranites in the upper part of the Greater Himalayan sequence suggest partial melting (LeFort, 1975; Castelli & Lombardo, 1983; Ferrara et al. 1991; Davidson et al., 1997; Kohn & Parkinson, 2003). Coupled with abundant evidence for ductile flow in Greater Himalayan sequence rocks (e.g., Grujic et al., 1996; 2002; Carosi et al., 1999; 2006; Grasemann et al., 1999; Grasemann and Vannay, 1999; Vannay & Grasemann, 2001; Law et al., 2004; Jones et al., 2006), the argument was made that the GHS is the early Miocene equivalent of the modern partially molten middle crust of Tibet and that the two are contiguous in the subsurface beneath the northern Himalayan thrust belt and the Gangdese magmatic arc along the southern half of the Lhasa terrane. Nelson et al. (1996) further speculated that the process of getting the Tibetan middle crust to daylight in the Himalaya involved rapid, monsoonally-driven erosion along the south flank of the Himalaya. Thus was born the controversial but extremely fertile concept of channel flow in the Himalayan-Tibetan orogenic system. One of the most attractive aspects of the model is that it explicitly links climate-driven surface processes with deep crustal processes in the context of topographic gradients set up by continental collision (Beaumont et al., 2004; Jamieson et al., 2006). The channel flow model has been enthusiastically embraced by many Himalayan workers (cf. Searle & Szulc, 2005; Searle et al., 2006; and numerous other papers in the volume edited by Law et al., 2006) and exported worldwide (e.g., Applachians: Hatcher & Merschat, 2006; Canadian Cordillera: Brown & Gibson, 2006; Hellenides: Xypolias & Kokkalas, 2006); but not always critically.

On the other hand, many objections to the channel flow model have been raised (e.g., Harrison, 2006), and virtually all features in the Himalaya have been 'successfully', if perhaps not unerringly, interpreted in terms of the alternative orogenic wedge model, involving ductile thrusting in the mid crust in the northern hinterland and brittle ramp-flat thrusts and duplexes in the frontal thrust belt (e.g., Coward and Butler, 1988; Schelling, 1992; Srivastava & Mitra, 1994; Ratschbacher et al., 1994; Powers et al., 1998; Powers et al., 1998; DeCelles et al., 2001; Johnson, 2002; Avouac, 2003; Murphy & Yin, 2003; Mugnier et al., 2004; Robinson et al., 2006; Robinson & Pearson, 2006; Yin, 2006; Murphy, 2007). This traditional thrust belt model for the Himalaya is based mainly on regional-scale, restorable cross-sections, with only a few first-order constraints on the structural architecture in the subsurface, particularly in the northern half of the thrust belt. The advantage of a restorable cross section is that real geological structures can be integrated into an interpretation that is indeed feasible, if not necessarily correct (Boyer and Elliott, 1982). An objection to published applications of the channel flow concept to the Himalaya is the difficulty to reproduce documented structures and kinematic sequences throughout the entire thrust belt, except at the coarsest scale (STD, MCT and the North Himalayan domes). The difficulty of arriving at a consensus is illustrated by comparing the Nelson et al. (1996) INDEPTH paper, which is credited with originating the channel flow model, with the Hauck et al., (1998) INDEPTH paper, which adopted a more conventional thrust belt interpretation: same data set, same authors, and two radically different interpretations.

One reason for the continuing debate is that few if any published papers contain unambiguous ‘tests’ of the channel flow model. It remains to be seen if the model is in fact disprovable, and therefore truly scientific (Hodges, 2006). A major problem in assessing the applicability of the channel flow model to any orogenic belt is that channel flow is strictly a fluid dynamic process that requires knowledge of parameters that are not measurable with geological and geophysical data (e.g., Reynolds number, viscosity, boundary conditions), and it is inherently difficult to specify the geodynamic causes of what should be generically referred to as “crustal extrusion” or “ductile extrusion” (Grasemann et al., 2006; Jones et al., 2006). Many geological features in the rocks (e.g., structures and textures) can only inform us about whether or not ductile deformation occurred, not whether or not this deformation was caused by gravity-driven flow in a mid-crustal channel. Strain type and distribution are ambiguous with regard to 'channel flow'; they cannot differentiate between simple ductile extrusion (i.e., some form of ductile thrusting) and true channel flow (e.g., Grasemann et al., 2006). Channel flow is a fluid dynamical process, which can only be inferred to have produced observable features in the rocks. Features that are explicitly required (Beaumont et al., 2001, 2004; Jamieson et al., 2006) for the channel flow model in the Himalaya include: (1) a high Tibetan plateau in order to provide the gravitational pressure gradient that drives the southward flow; (2) coevally active shear zones above (the STD) and below (the MCT) the flowing channel, which do not merge in the up-current (down-dip, northward) direction; (3) displacements along these bounding shear zones should also decrease northward, theoretically to zero along shear zone ‘tips’ (Grasemann et al., 2006); (4) flow in the channel cannot reach the surface unless rapid erosion or upper crustal extension provides the pathway to the surface (Beaumont et al., 2006; Hodges, 2006). These four sets of “observables” can therefore provide a test of the channel flow model for the Himalaya as follows:

Test 1: <u>Channel flow requires</u> coeval slip along the MCT and STD. Documented coeval, early Miocene slip on these two fault systems (Hodges et al., 1996; Godin et al., 2006) is one of the facts that gave rise to the original idea of channel flow. Therefore, we know that this aspect of the model stands up.

Test 2: <u>Channel flow requires</u> high elevation in the Tibetan Plateau and gravitationally driven southward flow. We need to know when the plateau rose to high elevations. Several recent stable isotope paleoaltimetry studies in central and southern Tibet provide enough information to allow us to state that the Plateau had risen to its modern elevation at least as early as late Oligocene (26 Ma) (Garzione et al., 2000; Currie et al., 2005; Rowley and Currie, 2006; DeCelles et al., 2007). This predates slip on the MCT and STD, and therefore we may assume the gravitational driver was in place. However, it <u>remains unknown</u> whether partial melts extended north beneath the plateau, in a position to be driven south. Therefore we must study the age and location of the northernmost melts of Indian affinity; such melts are potentially exposed along the Karakoram fault, and more certainly in the Leo Pargil gneiss dome.

Test 3: <u>Channel flow requires</u> a link between rapid exhumation (either tectonically- or climatically-driven sensu England and Molnar, 1990) on the south flank of the Himalaya and southward/upward advection of the material in the channel (Jamieson et al., 2006; Hodges, 2006). The existence and timing of this required rapid erosion <u>remain unknown</u>, at least in detail sufficient to determine whether or not it was contemporaneous with activity on the STD and MCT. If rapid exhumation did not occur coevally with slip on the STD and MCT, then the link between exhumation and channel flow fails.

Test 4: Channel flow requires that the MHT tip out in a down-dip (northward) direction, so that inflowing Indian crust can access the channel (Nelson et al., 1996; Grasemann et al., 2006). The down-dip extent of the MHT remains unknown. We hope to image this northward termination (or continuation) of the MHT because INDEPTH-style profiling was very informative on the location and shape of the MHT—in fact the MHT was one of the major deliverables provided by INDEPTH 1 – but gaps in the INDEPTH profiles leave us uncertain whether the MHT ends at, or continues north beneath, the IYSZ.

Test 5: Channel flow makes predictions for regional scale kinematics of the Himalayan thrust belt. Published versions of the model make diverse predictions about kinematics, some versions requiring only early Miocene channel flow, others requiring present-day channel flow (e.g., compare Hodges, 2006 with Jamieson et al., 2006). However, regardless of timing, the only truly required features of channel flow are listed above. Thus far, no regional-scale cross section has been constructed that is both restorable and inclusive of the kinematics predicted by channel flow. Existing cross sections for northern India either do not extend deep enough to interpret regional structural relationships in the subsurface (e.g., Steck, 2003) or they exhibit gross imbalances and nonrestorable geometries (e.g., Jain et al., 2000; Vannay et al., 2004). At best, existing cross sections provide only a conceptual framework for the regional structure and leave the open the question of kinematic history. Therefore, we propose to reconstruct a straightforward kinematic history of the entire thrust belt. This in turn requires an incrementally restorable cross section, constrained by geochronological, thermochronological, and erosional unroofing data, that spans the entire thrust belt and extends at least as deep as the MHT. So far, only a single version of a geometrically restorable cross section across the entire Himalaya exists, in western Nepal and adjacent Tibet (Murphy, 2007), but this has no timing indicators in its northern half and has not been incrementally restored except in the southern half, and lacks geophysical control. Once we have a restorable cross section, built from geological and geophysical data, we can begin to assess kinematic details with regard to channel flow.

This analysis leaves us with four tasks:
1. Seismically image the down-dip termination of the MHT (if it exists) or its northern continuation);
2. Determine the location of mid-crustal melts and determine their petrogenetic affinity;
3. Build a restorable cross section (using geophysics and geology), and restore it incrementally under constraints provided by real data; and
4. Determine when rapid exhumation began along the south flank of the Greater Himalaya — it must have been coeval with slip on the MCT and STD in order for channel flow to work.

Task 1: Imaging the MHT

Crustal reflection, crustal refraction and passive-seismic receiver functions offer the potential to image the key intra-crustal horizons (MCT, STD, Great Counter Thrust, and MHT) that provide critical tests of the two models. Channel flow requires parallel STD and MCT, and a downdip termination of the MHT. Conventional thrust belt models require northward merging STD and MCT; and the intra-cutaneous wedge (Yin et al., 2006; Webb et al., 2007) variant requires parallel STD and MCT in the north, southward merging of the two faults, and contiguity of the STD and the Great Counter Thrust. Wedge models suggest major ramps on the MCT/MHT beneath the North Himalayan gneiss domes (including Leo Pargil) but channel flow does not. Indeed, all of these seismic methods have already provided partial and hence controversial images of these structures in different places along the Himalaya (near-vertical reflection: Zhao et al., 1993; Nelson et al., 1996; Rajendra Prasad in prep.; wide-angle refraction: Makovsky et al. 1996a, 1999; receiver functions: Schulte-Pelkum 2005, Rai et al., 2006, Rai & Singh, 2005). The northern limit of the MHT, south of or at the mantle suture, should be interpretable from broadband seismic profiles – even if our Transect 1 that reaches just north of the KSZ does not extend far enough north, combining existing seismic and MT data from along the Alaknanda River with the ongoing seismic work of Roecker et al. and our proposed MT work in western Tibet will certainly cover any possible location of this mantle suture (Fig. 2 and 3b).

Task 2: Finding the location of mid-crustal melts and their petrogenetic affinity

The geometry of modern melt distributions will be tested by our seismic and MT experiments; those will together relate the distribution of melts to specific structures (MHT, IYSZ, KSZ). If a modern channel reaches no further than the KSZ it will be imaged by Transect 1 data; whereas if a modern channel extends further north, it will be seen on the combined HIMPROBE-Alaknanda and Chinese western Tibet data sets. MT data will provide limits on the possible percentage of melt (Unsworth et al., 2005) hence viscosity (Rosenberg & Handy, 2005) above and below the major structures to be imaged by the seismic data (MHT, IYSZ, KSZ).

The existence of a Miocene channel will be tested by geochemically measuring Asian or Indian affinity of possible channel material using Nd isotopes and U-Pb age constraints. The Leo Pargil gneiss dome (on Transect 2) is the westernmost in a chain of domes formed within the Tethyan Himalaya Sequence that extends east 1600 km through the North Himalayan gneiss domes (including the better known Kangmar dome on the INDEPTH transect). These gneiss domes (usually cored by granites) and the leucogranites found in the Greater Himalayan Sequence are likely surface exposures of the channel. If the IYSZ indeed acts as a backstop for Indian crust (Fig. 1) and is the source of partially molten material feeding channel flow, Nd isotopes should confirm an Indian affinity in gneiss dome granites and GHS leucogranites (Fig. 4; e.g., Murphy, 2007). The Leo Pargil dome, like its eastward neighbor the Gurla Mandhata dome (Murphy, 2007), contains granitoids that will indicate not only indicate an Indian or Asian affinity for the melts but their petrogenetic relationship to the LHS, GHS or THS. Our proposed sampling of granites exposed in the Karakoram shear zone (KSZ), coupled with seismic and MT imaging, provides another opportunity to test the location and source rock for channel flow melts. Because the Karakoram fault arguably penetrates the whole crust (Rai et al., 2006) and initiated during putative active channel flow in the Early Miocene (Valli et al., 2007), the c. 20-15 Ma granites in the KSZ may sample Indian crustal melts thereby supporting a channel flow model (Fig. 1a) or they may only show Tibetan affinity, thereby strongly limiting a channel flow model and confirming the northerly reach of Indian crust (Fig. 1b).

Task 3: Creating a restorable cross-section of the western Himalaya

The first-order aspects of the conventional thrust belt model are testable by documenting the timing of slip on major thrust faults, the subsurface geometric relationships between the various faults, and the degree to which the kinematic history of the thrust belt resembles a southward propagating orogenic wedge responding to short-term changes in taper. Regional mapping of shear zones and sampling for geochronology, thermochronology, and isotope geochemistry (Sm-Nd) will help to identify major structures (Fig. 4), resolve problems in regional tectonostratigraphy that have clouded understanding of the kinematic history of northern India, and establish thermal and temporal constraints on regional uplift and exhumation. These data sets will allow us to determine the crustal-scale geometry of the Himalayan thrust belt in northern India and construct regional balanced cross sections that can be retrodeformed in a temporal sequence provided by thermochronologic and sedimentary provenance data.

The South Tibetan detachment poses a serious challenge to the conventional thrust-belt model. Normal faults in conventional thrust belts are usually relatively minor features that make slope-reducing adjustments in the trailing part of the thrust belt (Hodges et al., 1996) or facilitate collapse when the regional stress field relaxes (Constenius, 1996). The apparently large displacement on the STD (at least ~30-40 km, Burchfiel et al., 1992; but perhaps much greater, Grujic et al., 2002; Searle et al., 2003) may simply reflect the great size of the Himalayan orogenic wedge. To accommodate collapse, normal faults in thrust belts usually sole into and partially reactivate pre-existing thrusts, and regional extension is ultimately accommodated along the basal detachment. An important prediction of the critical taper model for the STD is that it should *merge* with the basal detachment in the subsurface beneath the Tethyan Himalaya, and its kinematic history should be compensatory in the sense of Hodges et al. (1996).

In a conventional thrust belt model, the Leo Pargil gneiss dome should form above a major ramp in the basal detachment (Fig. 1b) (or alternatively would require a complex backthrust geometry); the MCT sheet and all other major thrust sheets in the Himalaya should have detached from the basal Himalayan detachment, and the underlying 'basement' should have continued to underthrust beneath southern Tibet; the kinematics of thrust stacking should be relatively simple, resulting in generally upright panels of rock with consistent facing directions; and the present steep northward dip of Greater Himalayan rocks directly above the MCT was caused by tilting above younger growing structures in the footwall. Geophysical imaging will be particularly important in testing the subsurface geometry of the MCT, STD and MHT. Although some cross-sections based only on INDEPTH reflection data draw a ramp beneath the Kangmar Dome (analogous to Leo Pargil on Transect 2) (Nelson et al., 1996, Fig. 5c; Lee et al., 2000), INDEPTH wide-angle reflection data argue against a ramp (Makovsky et al., 1999, Fig. 5b), as do recent HIMPROBE gravity models for Transect 1 (Sastry et al., 2003, 2005). The channel flow model is consistent with either a ramp or no ramp; but for the conventional thrust belt models the thrust sequence and mappable surface geometry will differ if a ramp exists. Our proposed geophysical profiling seeks to image the STD and MHT to establish whether they merge, and whether a major ramp structure exists.

A variation on conventional thrust belt development was proposed by Yin (2006) in which Greater Himalayan rocks were inserted between overlying Tethyan rocks and underlying Lesser Himalayan rocks as a southward verging intra-cutaneous wedge (ICW). The kinematics are similar to passive roof duplexes and triangle zones that form at the fronts of many thrust belts (Vann et al., 1986), but the scale of Yin's (2006) wedge is an order of magnitude larger than typical passive roof duplexes and triangle zones. Unlike the channel flow model, the ICW model requires a branch line between the STD and MCT at the southern tip of the wedge. Yin (2006) shows a branch point between the MCT and STD on his regional compilation (Fig. 3a), requiring that the STD be located considerably farther down-section, well within rocks that others have mapped as the Greater Himalayan sequence (Fig. 3). We will attempt to replicate Yin's (2006) branch point by mapping in detail the area around the Kulu-Larji-Rampur window (Fig. 3), and we will search for other potential branch points along the frontal trace of the MCT.

Task 4: Determining the initiation of rapid exhumation along the south flank of the Greater Himalaya

The exhumation driving advection that is required to convey channel flow to the surface (Fig. 1a) can be tested for by documenting the detrital unroofing record in foreland basin deposits as well as the exhumation history along the southern Himalayan front since the Miocene. Specifically, Beaumont et al. (2004) predicted that Greater Himalayan detritus should appear in the record as the channel surfaces, which should have occurred during the Early Miocene. In addition, the present steep dip of the MCT and STD (as well as the intervening GHS rocks) should have been acquired during emplacement of the MCT sheet (Fig. 1a), rather than as an artifact of later tilting by growth of underlying Lesser Himalayan structures (Fig. 1b). This can be determined by combining bedrock thermochronology and detrital unroofing data: if the GHS was advected toward the surface during MCT emplacement, then the unroofing record should match the timing of MCT/STD slip, whereas if the MCT/GHS/STD were tilted and uplifted after MCT emplacement, then the unroofing record should lag behind the kinematic record.

Activity on the STD and the MCT should be matched in time to accommodate ductile channel flow; timing of slip on the MCT and STD can be determined by the same methods that were used in Nepal: thermochronology and geochronology (Hodges et al., 1996; Catlos et al., 2002; Kohn et al., 2004; Murphy and Copeland, 2005; Robinson et al., 2005), detailed mapping and dating of variably deformed leucogranite bodies (e.g., Murphy and Harrison, 1999; Grujic et al., 2002; Murphy and Copeland, 2005), and documenting the detrital unroofing history (DeCelles et al., 1998a, b, 2004; Najman et al., 2004; Robinson et al., 2001; Bernet et al., 2006; van der Beek et al., 2006). Previous work in the study region (Vannay et al., 2004; Thiede et al., 2005) suggests that the timing of slip on the STD and MCT in this area is similar to timing in Nepal. The detrital record of erosion during the growth of the thrust belt will be assessed by conventional petrography and detrital geo- and thermochronometers (U-Pb zircon, ^{40}Ar/^{39}Ar white mica, apatite and zircon fission tracks) in well-dated Tertiary foreland basin deposits preserved along the south flank of the Himalaya. In particular, the detrital thermochronological record preserved in Neogene sediments should be key for determining if early Miocene rapid exhumation was contemporaneous with, and therefore capable of driving, slip on the STD and MCT. Previoius studies of the erosional history of the Himalaya based on Oligo-Miocene sediments in this region demonstrated a prominent peak in muscovite ^{40}Ar/^{39}Ar ages at 16-17 Ma (Najman et al., 1997, 2000, 2001, 2004; White et al., 2002). Similarly, Bernet et al. (2006) noted a ~16 Ma static peak in zircon fission track (ZFT) ages from the Siwalik Group in eastern Nepal. At first glance these data give credence to the idea that rapid exhumation during the early Miocene could have helped to drive channel flow to the surface, however these ages post-date the best-dated parts of the STD and MCT in central Nepal (Hodges et al., 1996). A strong argument can be made that the 16-17 Ma cooling ages reported in these studies reflect the fact that white mica is predominantly derived from the MCT sheet, and that the detrital ^{40}Ar/^{39}Ar signal is insensitive to rapid cooling on more southward Lesser Himalayan thrust sheets. Bernet's (2006) data were surprising because double-dating by the U-Pb method showed that the bulk of the early Miocene ZFT ages were from grains that have a Lessser Himalayan affinity with less, but significant, contributions from the Greater and Tethyan Himalaya. All of these studies suggest that a concerted effort combining middle- and low-temperature thermochronometers is needed to fully assess the meaning of the detrital signal.

6. WORK PROGRAM

Geologic studies

We propose to study the Indian Himalayan thrust belt along two regional transects that cross the entire thrust belt, and the synorogenic foreland basin deposits in three stratigraphic sections in the southern part of the study area (Fig. 3a). Transects are planned along the Beas River (Transect 1) across the Kulu-Larji-Rampur window up to the Karakoram (geophysics on this transect will continue as far across the KSZ as border concerns permit), and along the Sutlej River north to the Leo Pargil dome (Transect 2) (Fig. 3a). In general all PIs expect to work on aspects of both transects. (The timing of proposed field seasons is shown on the timeline in Fig. 10.) The first joint field trip for all PIs will be across the IYSZ, and in the Tso Morari Complex and KSZ as part of the post-2008 Himalaya-Karakoram-Tibet (HKT) workshop in Leh, India. In Year 2, Singh and Jain (IIT Roorkee) will join all PIs to complete a cross-section through the Himalaya along the Beas River (Transect 1); this will be a good starting transect for students, who will need to develop a working knowledge of Himalayan stratigraphy and structure before they can begin to work independently. We anticipate that the combined Arizona, San Francisco, Stanford and Wyoming groups will be involved on this Year 2 transect in order to establish field sampling protocols, a consistent stratigraphic basis for further mapping, and, for the geophysicists, an appreciation of the large-scale structural elements of the thrust belt. Fieldwork will involve Indian colleagues and local guides, using rental vehicles along the available roads, and extended porter-supported foot traverses in regions where roads are not available. Major roads and a well-established network of trails are present along parts of each planned transect. Accommodation in lodges is available along roads, and we will camp on long foot traverses. We expect a typical field season to last ~6 weeks for Leech, DeCelles, Carrapa, and SFSU graduate students, and ~10 weeks for UA and UWyo graduate students. Our efforts will be seasonally divided in order to take advantage of summer working conditions at high elevations and dry winter conditions in the frontal lower elevation regions (Fig.11).

Regional geologic mapping and structural analysis

Leech (SFSU) will work within the KSZ and along Transects 1 and 2, all areas of previous field work in 2004-2006 (Leech et al., 2005; 2007), and in which the syn-deformation granitoids, gneiss domes and exhumation of the GHS will be primary targets of study. The Arizona and Wyoming teams will work along portions of Transects 1 and 2. All teams will map the large-scale structures, measure bedding, foliation, cleavage, and kinematic indicators, and collect samples for U-Pb zircon, ^{40}Ar/^{39}Ar, and zircon and apatite fission track dating. We will also collect selected samples of key pelitic lithologies for Nd isotopic analysis (see below for explanation).

DeCelles and one PhD student will focus on the Tethyan and Lesser Himalayan rocks and the frontal Subhimalayan part of the thrust belt. The latter work will naturally merge with work in the Tertiary synorogenic sedimentary rocks (see below). Geologic maps will be compiled in ArcGIS. Balanced regional cross-sections will be constructed using 2Dmove and retrodeformed according to kinematic constraints provided by structural data and chronological constraints provided by the proposed thermochronology and analysis of foreland basin sediments (see below). Clearly, these cross sections will underestimate total shortening in the thrust belt because they will not sufficiently incorporate intense ductile strain that is characteristic of rocks in the structurally higher parts of the Lesser Himalayan sequence and in the Greater Himalayan sequence. In addition, hanging-wall cutoffs are commonly not preserved owing to the great depths of erosion and footwall cutoffs can only be fixed by conservative adherence to the template constraint (Woodward et al., 1987). Nevertheless, such cross sections are useful because they provide at least first-order constraints on shortening and regional kinematic sequencing.

Leech and one MS student will target the KSZ in Year 1; Transect 1 in Year 2; and Transect 2 in Year 3. Field parties will work from the MCT to the STD (in Year 2 and 3) and into the Leo Pargil gneiss dome (Year 3). Oriented samples will be collected for microstructural and strain analysis at SFSU (e.g., C'-type shear band cleavage, mica fish, sigma clasts, strain shadows, microboudinage, foliations recorded by mineral inclusions, and quartz fabrics/recrystallization textures). Leech will focus on the relatively high-grade, ductilely deformed rocks, particularly in the Munsiari and Main Central thrust sheets, and on the STD. Major objectives include determining the extent to which the ductile shear zones have been modified or reactivated by later brittle faulting and testing the Yin (2006) model showing a branch point between the STD and MCT along the Sutlej and a domed STD bounding the Kulu-Laruji-Rampur and Kishtwar windows along Transects 1 and 2 (Fig. 3a). Samples will be collected for ^{40}Ar/^{39}Ar thermochronology to constrain the timing of shear within the KSZ, and the MCT and STD zones. Petrology and geochemical analyses will be jointly performed at SFSU and Stanford. Singh (IIT Roorkee) will coordinate all aspects of the geologic collaboration in India, critically including field logistics, while the entire program will benefit from the intellectual direction of AK Jain (IIT Roorkee) as head of the original HIMPROBE program.

Synorogenic foreland basin deposits

The synorogenic foreland basin deposits will be studied by DeCelles, Carrapa, Krugh (UWyo post doc) and students in three sections (two in the Siwalik Group and one in the Paleogene succession) indicated in Figure 3b. Magnetostratigraphically-dated sections of Neogene Siwalik Group strata at Haritalyangar and Jawalamukhi (Sections "H" and "J" in Fig. 3b; Johnson et al., 1983; Meigs et al., 1995) will be sampled by DeCelles, Carrapa, Krugh, and a Wyoming PhD student, for modal sandstone petrographic analysis, detrital zircon U-Pb dating, detrital apatite and zircon fission track (AFT; ZFT) dating, and detrital white mica ^{40}Ar/^{39}Ar dating. The samples will be collected in the context of measured section logs to be provided by the workers who performed the original magnetostratigraphic studies (see letter of support from A.J. Meigs) and our own logs. The Paleogene record of Himalayan unroofing will be studied in Eocene and Oligo-Miocene strata exposed near the village of Jogindernagar (Section "Jo" in Fig. 3b), where White et al. (2001, 2002) documented the magnetostratigraphy (see letter of support from Y. Najman). Paleogene rocks in northern India were sampled for detrital ^{40}Ar/^{39}Ar muscovite analyses by White et al. (2001) and Najman et al. (2000). However, no detrital zircon, apatite fission track nor U-Pb data have been reported from these rocks in India, and we anticipate that this type of data will be definitive regarding the timing of initial Himalayan unroofing (e.g., DeCelles et al., 2004). The detrital thermochronology and geochronology studies will form the basis of one PhD dissertation (University of Wyoming student co-directed by Carrapa and DeCelles) and post-doctoral research, which we foresee will result in several papers. Analysis of petrographic thin sections will be conducted at both the University of Wyoming and the University of Arizona. U-Pb detrital zircon dating will be done at Arizona. We plan to double date the same zircons analyzed for fission track to be able to discriminate the source of the investigated samples (e.g., Bernet et al., 2006). This will be combined with petrographic work will follow established practices (Gazzi-Dickinson method, standard thin sections stained for Ca-plagioclase and K-feldspar, 500 grains per slide).

U-Pb geochronologic and Nd-isotopic studies

The purpose of the U-Pb detrital and bedrock zircon dating and the Nd isotopic analyses will be to help distinguish between Lesser, Greater, and Tethyan Himalayan lithologies (and potentially Tibetan material). Recent work in India (Ahmad et al., 2000; Miller et al., 2000, 2001; Whittington et al., 2000; Argles et al., 2003; Myrow et al., 2003; Richards et al., 2005), Nepal (Parrish & Hodges, 1996; DeCelles et al., 2000; Robinson et al., 2001; Martin et al., 2005), and Tibet (Murphy, 2007) shows that GHS and LHS rocks can be distinguished from each other by detrital zircon ages and ε-Nd values, and the association of early Proterozoic vs. Cambro-Ordovician granitoids; indeed, in many cases it is impossible to distinguish LHS from GHS rocks without these data (Martin et al., 2005; Richards et al., 2005). Although Tethyan Himalayan rocks are isotopically similar to GHS rocks, they contain a telltale ca. 450-500 Ma detrital zircon population (probably reworked from the underlying GHS Cambro-Ordovician orthogneisses) that is absent from the LHS and GHS, and a slightly more juvenile component of Nd. ε-Nd values for leucogranites from the GHS, granitoids in the Leo Pargil gneiss dome, and granites in the Karakoram shear zones will distinguish between melt sources (e.g., Murphy, 2007). Coupled with careful field mapping of major shear zones, these data will help us assess the along-strike pattern of (tectono)stratigraphic separation on major thrust faults, which is key to identifying where the MCT and STD are located (e.g., Steck, 2003; Searle et al., 2003; Webb et al., 2007). Detrital U-Pb zircon dating will be done in the MC-LA-ICPMS laboratory at the Arizona LaserChron Center (see letter of support from George Gehrels) and bedrock U-Pb zircon dating will be done in the Stanford-USGS SHRIMP laboratory (see support letter from Joe Wooden). One hundred zircon grains per sample will be dated in detrital samples and 25 grains will be dated in igneous samples. The Stanford-USGS SHRIMP is ideal for dating complexly-zoned zircons that often display relict Proterozoic protolith cores, Pan-African (450-500 Ma) magmatic zircon growth, and Tertiary metamorphic and/or igneous zircon growth (e.g., Leech et al., 2005; 2007). The whole-rock Nd-isotopic work on pelitic samples will be done by a student researcher at Arizona under the supervision of Jonathan Patchett (see letter of support from J. Patchett).

Thermochronologic studies

Most basement thermochronology will be done at Stanford and detrital thermochronology will be divided between Wyoming (AFT and ZFT) and Stanford (^{40}Ar/^{39}Ar) (see support letter from Marty Grove).

Detrital apatite and zircon fission track in conjunction with ^{40}Ar/^{39}Ar thermochronology will be conducted on ~30 samples distributed along three stratigraphic sections for 10 samples per section. Analyses will be mainly done at the University of Wyoming under the direction of Carrapa. The detrital ^{40}Ar/^{39}Ar thermochronological work will be done at Stanford. Detrital thermochronology at Stanford and UWyo will follow established protocols; 100 grains per sample for AFT, ZFT and ^{40}Ar/^{39}Ar dating (e.g., Hodges et al., 2005, and references therein; Sobel & Dumitru, 1997; Carrapa et al., 2006; Carrapa & DeCelles, 2007). ^{40}Ar/^{39}Ar thermochronology of detrital minerals will be used to constrain sediment sources, paleodrainage evolution in response to tectonics, source cooling rates and pattern of orogenic exhumation (e.g., Carrapa et al., 2003; 2004a,b). Apatite fission track-length thermal modeling (using AFTsolve; Ketcham, 2005) will be conducted on bedrock and detrital samples to constrain the thermal history of the source-sink couplet and to check on the degree of annealing of the detrital samples (e.g., Carrapa et al., 2006). We foresee post-burial annealing to have played a role on the deepest detrital samples (e.g., Van der Beek et al., 2006). For those samples zircon fission track ages will be used for provenance and source cooling interpretations (e.g., Bernet et al., 2006) while the AFT signals will be used to gain information on maximum burial temperatures and subsequent cooling. Detrital thermochronology is extremely labor intensive; for example, sample FT preparation will require several months each year and a single detrital sample requires roughly a week to analyze for AFT and a week for ZFT. Furthermore, thermal modeling of detrital and bedrock samples will follow counting and will require significant additional time. For those reasons, Carrapa proposes to hire a postdoctoral scholar as well as a PhD student for this work. The postdoc will focus on detrital ZFT while the PhD student will work on detrital AFT. Carrapa will be involved in all aspects of detrital (^{40}Ar/^{39}Ar and FT) and bedrock thermochronology.

Additionally, we plan to collect 40 bedrock samples along the two main transects indicated in Figure 3. We will apply a strategy involving sampling across short and long wavelength topography in order to constrain both paleotopography and representative exhumation rates, and to constrain the timing of shear in the MCT and STD zones (Stock & Montgomery, 1996; Braun, 2002, 2005). We plan to apply AFT, ZFT, white mica ^{40}Ar/^{39}Ar (step heating experiments) to all bedrock samples and feldspar ^{40}Ar/^{39}Ar (multi diffusion domain modeling; Lovera et al., 1997) to a select subset of 20 bedrock samples. Our new multidisciplinary thermochronological dataset will complement existing studies (Najman et al., 1997; 2000; 2001; 2004; 2005; White et al., 2002; Vannay et al., 2004; Thiede et al., 2005; Szulc et al., 2006). Basement thermochronology work will begin in Year 1 using samples and data collected from Transects 1 and 2 by Leech in 2004 and 2006. An additional 10 white mica ^{40}Ar/^{39}Ar samples will be dated from mylonites and/or syn-deformation granitoids in the Karakoram shear zone (e.g., Valli et al., 2007).

Following the field plan outlined above, Leech will target variably deformed gneisses, migmatites, and leucogranites to sample for thermochronology, relating geochronology to deformation, and focus on the Tertiary history of bedrock samples. These high-grade metamorphic rocks have the advantage of providing a full suite of minerals for geo/thermochronology used for both low- and high-temperature systems within the same sample. This work will integrate major and trace element geochemistry and thermobarometry using the electron microprobe and SHRIMP at Stanford; collection of zircon trace element data is now routinely done during U-Pb analysis (see Wooden support letter).

Geophysical and crustal-scale studies

Indian scientists have carried out initial seismic and MT studies along Transect 1 as a part of the Indian HIMPROBE study, but with sampling that is sparse by standards of recently funded NSF proposals. Limited MT investigations have continued in the Tso Morari region (Transect 1) for geothermal exploration (Harinaryana et al., 2004), and seismic imaging and MT experiments have continued along the Alaknanda River for earthquake-hazard studies, now with denser station spacing at the instigation of our collaboration (S.S. Rai & B. Arora, pers. comm.). Two new seismic reflection profiles are planned by NGRI along Transect 1, but in order to generate Indian support for the additional densely sampled passive-seismic and MT experiments that we believe are necessary to tightly constrain the geologic models in this area, despite these being focused on academic objectives, our Indian counterparts need evidence of international collaboration and support. Although the NGRI and WIHG groups each own their own equipment and receive funding allowing acquisition of a significant new dataset each year, the evidence of international approval provided by a successful NSF proposal is needed if we are to have meaningful input on experiment design and detailed targets. Data will be made available equally at Indian and North American sites, with the expectation that analyses will be carried out jointly, and authorship assigned in accordance with the work done – note the track record of generosity of the Indian side, already providing data access and opportunities for first-authorship (e.g., Leech et al., 2005; 2006a; 2007a; Unsworth et al., 2005; Caldwell et al., 2007). All data collected with Indian equipment and funds will continue to be automatically available to us as collaborators, and although US investigators cannot promise Indian data to a US archive, our experience suggests other scientists will be given access in the future. All data collected with PASSCAL equipment through this proposal will be archived at IRIS-DMC, and data collected with Unsworth's long-period MT equipment will also be freely available.

Active-source seismic data: Indian near-vertical and US wide-angle reflection

India has a 30-year tradition of collecting Deep Seismic Sounding data, and has collected more crustal-scale reflection data than all but a handful of other countries (e.g. Tewari & Kumari, 2003; Reddy, 2001). NGRI Hyderabad has begun a series of profiles in the Himalaya along HIMPROBE Transect 1 (Fig. 3b). In 2004 Klemperer consulted with NGRI on acquisition parameters based on the successful INDEPTH recording program, and the first 100-km-long profile was completed by Rajendra Prasad's group in summer 2004 across the Sub-Himalaya and Lesser Himalaya (Fig. 8), thereby extending into the orogen excellent oil-industry reflection images (Powers et al., 1998) of the complex thrust duplexes above the basal décollement (MHT) (note that more recent geodetic results (Banerjee & Bürgmann, 2002) cast doubt on the larger-scale décollement geometry inferred by Powers et al.). Preliminary processing has been completed at NGRI, and the raw field data have now been provided to Stanford (October 2007) for additional processing prior to publication (Fig. 8).

The second phase of HIMPROBE reflection work in the Greater Himalaya will be funded for 100-km data acquisition prior to the monsoon in late spring 2009 (Fig. 3b). The third and final reflection recording along Transect 1 is planned for late spring 2011, in the More Plain region of the Tethyan Himalaya (Fig. 3b), using flat valleys equivalent to the valleys crucial to INDEPTH 1 and 2 reflection-profiling success. Funding of this last phase will be through the national Lithospheric Transect project (see letter of support from Rajendra Prasad). Acquisition of all these reflection profiles would be funded entirely by NGRI, and primary responsibility for processing will lie with NGRI, though Stanford will receive copies of the raw data, as we have been for the Lesser Himalaya data already recorded with no US involvement.

We propose to complement the near-vertical acquisition in both 2009 and 2011 by recording the c. 250 60-kg explosive charges to be drilled and detonated (at Indian expense) along each reflection profile at offsets of up to 200 km (schematic experiment layout in Fig. 1c). In both years we will use 60 PASSCAL RT-130 units at c. 5 km receiver spacing with 3-component L-22 2 Hz seismometers to record continuous records for the c. 2 months planned for the Indian near-vertical acquisition with nominal 400-m shot-spacing. (PASSCAL Texans are not useful for the long field season planned by NGRI; use of L-22s with RT-130s offers the potential bonus of augmenting recordings of local and teleseismic earthquakes e.g. Gashawbeza et al., in review). NGRI will handle import/export of PASSCAL equipment in conjunction with India's DST, though shipping and field deployment costs will be at US expense (this proposal). This wide-angle recording is analogous to data that were vital in INDEPTH studies to extrapolate reflector continuity beyond and between the reflection profiles (Makovsky et al., 1996a, 1999) as well as making physical-property measurements of reflection bright-spots representing subsurface fluids (Makovsky et al., 1996b, Makovsky & Klemperer, 1999). Experience from INDEPTH (Makovsky et al., 1996a, 1999) shows that the explosive sources should be recorded at offsets of up to 200 km on the fixed "refraction" recorders (Fig. 5b), thereby building up a densely sampled reversed profile over two field seasons (Fig. 1c). Analysis of these wide-angle reflections/refractions will allow imaging of major structures (e.g., MCT, MHT, STD, cf. Makovsky et al., 1996a, 1999) beneath (undershooting) areas of topography too rugged for vertical reflection profiling for direct comparison with the transmission-wavefield broadband images; will allow direct measurements of crustal velocities important in estimating lithology and metamorphic grade. Our analysis will allow observation of possible P-S converted phases from the fluid bodies that are inferred from existing MT data (Gokarn et al., 2002, Harinaryana et al., 2004, Unsworth et al., 2005, Arora et al., 2007) (Fig. 6a & c), and possibly from existing teleseismic data (Rai et al., 2006; Caldwell et al., 2007) (Fig. 7) to exist in this region. Combination of near-vertical reflections, wide-angle conversions and MT observations was a powerful tool in the INDEPTH surveys for estimating types (magmatic or aqueous) and quantities of fluid in the crust (Makovsky & Klemperer, 1999; Li et al., 2003), and is therefore vital for estimating the thermal and mechanical properties of the putative flow channel in the mid-upper crust. Finally, the wide-angle survey will be important in providing the 2D velocity model for migration of the receiver functions from our proposed passive seismic experiment.

Passive seismic recording: Structural imaging

Data acquisition will be the responsibility of NGRI Hyderabad, led by S.S. Rai (see attached letter of support), who have both the equipment (broadband CMG 3T/ESP sensor (flat from 30 s to 50 Hz) and REFTEK RT130 data logger (4 Gb recording capacity); currently 30 available units) and the logistical experience to do this, as shown by the preliminary results of their existing sparsely sampled profile (Figs. 3b, 6; Singh & Rai, 2003; Rai et al., 2006). Since we began working with NGRI, deployment of 25 stations has taken place along the Alaknanda River first as a linear array at ≤15-km station spacing from the MCT to the STD orthogonal to the Greater Himalaya, and currently as a c. 40-km-spaced 2D array for seismicity studies (Fig. 3b) (Rai & Singh, 2005). Preliminary results show a clear signal from the MHT beneath the LHS and GHS, and clear negative amplitude (phase reversal) in the mid-crust (S.S. Rai, pers.

comm.). A Stanford student will spend summer 2008 at NGRI to work on CCP imaging of the Alaknanda profile, following which the data-set will be made available to Stanford.

The new broadband seismic acquisition proposed here is a dense profile (5-to-10-km station spacing - required to stack an migrate crustal converters) along Transect 1 from the Greater Himalaya to the KSZ, with no data gaps (we cross no political borders) (Fig. 3), acquired with the NGRI instruments in two deployments from 2009 to 2011. This dense profile is proposed as part of the NGRI-Stanford collaboration, and is unlikely to be acquired unless US-HIMPROBE is funded. Klemperer will participate in experiment planning, and a Stanford student will participate in deployment of the profile in order to become familiar with station siting with respect to local geology, topography, etc., but all deployment costs will be borne by NGRI. Following the experiment, an NGRI scientist will visit Stanford (end of year 2) to work on the data (culminating in participation in the San Francisco HKT meeting). All data will be made available equally at NGRI and Stanford. When combined, the results of the older sparse data-set and the proposed new transects will provide a complete image from the MCT to the KSZ, significantly denser than the INDEPTH passive seismic profile in southern Tibet (Nelson et al., 1996), or the HIMNT experiment in Nepal (Schulte-Pelkum et al., 2005), and of similar density to the Hi-CLIMB data, though unlike Hi-CLIMB augmented by controlled-source images and geologic mapping. We expect to form clear images of the MCT, STD and MHT as they deepen beneath the Tethyan Himalaya and either terminate south of or undercut the Indus-Yarlung suture.

Our broadband deployments should record adequate earthquake coverage to allow processing to stack and migrate common image gathers. Current algorithms in use at NGRI include basic receiver-function imaging, but at Stanford we will apply more advanced imaging methods under continuing development at Stanford (e.g., Sava et al., 2004; Shragge et al., 2004, 2006; Wilson et al., 2004) (Fig. 9). Fig. 9b shows an example of our current abilities to migrate a densely sampled passive-seismic wavefield, using wave-equation migration in a methodology that allows incorporation of 2D velocity models, surface topography, and formation of separate P and S images for separate estimation of physical parameters. Note that the Cascadia dataset (Fig. 9a,b) is a good analog in scale to the features we hope to image in HIMPROBE: the Moho varying from positive to negative impedance contrast is a good analog to a possible STD reflector above variably frozen and partially molten Greater Himalayan channel; and the dipping subduction zone is a good analog to a deeper, more steeply dipping, MHT reflector.

The intended outcome of this experiment is the geometry and northern limit of the MHT (see "Testing Models" section). Additionally it may be possible and would be useful to estimate anisotropy in different crustal layers, because of our expectation that any flow channel (whether active or fossil) should be anisotropic. Gneisses in the exhuming zone of Nanga Parbat are ubiquitously anisotropic, averaging 12% in S-velocity leading to predictions of nearly half-a-second splitting delays across a 10-km thick channel (Meltzer & Christensen, 2001; Meltzer et al., 2001). Mid-crustal anisotropy has now been measured in Tibet using receiver-function (Sherrington et al., 2004) and surface-wave (Shapiro et al., 2004) techniques, and Schulte-Pelkum et al. (2005) (Fig. 9c) has shown that individual stations in the Nepal Himalaya show strong azimuthal variation in receiver-function polarity and amplitude, best interpreted as anisotropy above the MCT and MHT. Effects of dip and anisotropy can be separated because the azimuthal variation of anisotropy is a "2-q pattern" (two cycles over the full range of backazimuths), whereas a converted arrival from a dipping interface shows a "1-q pattern" (Bank & Bostock, 2003; Bostock, 2003; Savage, 1998). Seismic velocity anisotropy can also be recognized from three-component controlled-source data (e.g., Satarugsa & Johnson, 2000), and with our proposed active and passive station spacings denser than previously achieved in either INDEPTH or HIMNT, HIMPROBE should be better able to localize the depth, thickness and degree of anisotropy of the highly strained layer. Klemperer's research group already has experience in shear-wave splitting (Gashawbeza et al., 2004; Walker et al., 2001, 2004b, 2005), and is working with a suite of programs for analyzing single-layer, multi-layer and dipping-layer anisotropy, and in receiver function analysis, including anisotropic RF analysis (Wilson et al., 2003, Gashawbeza et al., in review).

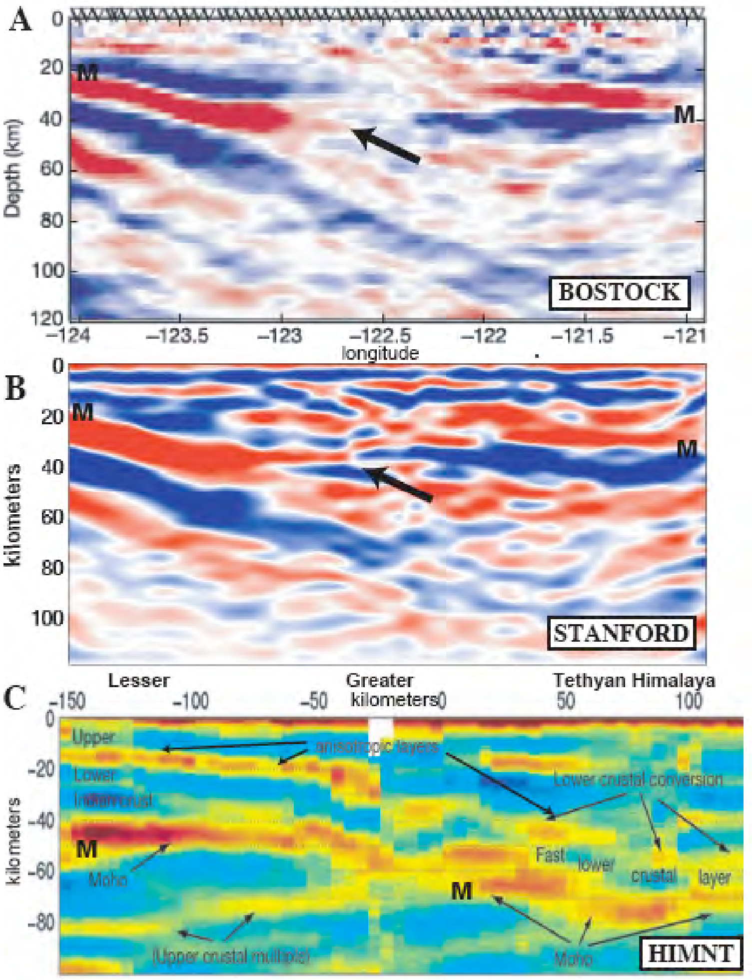


Figure 9. A, B: True-scale images of the Cascadia subduction zone from teleseismic data of Nabelek et al. (1993). **A:** calculated velocity perturbations using a Kirchhoff-based inversion technique (Bostock et al., 2002). **B:** Stanford image (Shragge et al., 2005) uses shot-profile wave-equation migration (downward continuation) in a 2D velocity model (Wilson et al., 2004; Sava et al., 2004). At Stanford we include free-surface multiples and forward-scattered and back-scattered P-P, P-Sv, Sv-P, Sv-to-Sh and Sh-to-Sv, and we do a better job at resolving the Moho (M) and crustal features in the center of the profile (arrow) where Bostock loses amplitude. Our wave-equation migration allows straightforward calculation of angle gathers (common image-point gathers) hence simultaneous velocity-model estimation and image formation; and also allows us to properly account for surface topography (Shragge & Sava, 2004). **C:** Migrated common-conversion point image of Himalaya at same scale (Schulte-Pelkum et al., 2005). Great thickness of Himalayan crust allows internal crustal structure to be resolved in principal but station spacing >50 km in Greater & Tethyan Himalaya reduces image quality and makes correlation of intra-crustal structures speculative.

Passive seismic recording: Local seismicity studies

Data acquisition will be the responsibility of the seismology group at WIHG (see support letter from B.R. Arora), who have recently purchased 30 Nanometrics Taurus data-loggers and Trillium-240 broadband sensors (flat response from 240 s to 35 Hz). WIHG has historically operated temporary short-period networks in the NW Himalaya (e.g. Thakur et al., 2000) but the new equipment will allow significant improvements in quality and density of recordings. The new broadband seismic acquisition proposed here is an areal array spanning the Sutlej and the Beas drainages (Transects 1 & 2) and extending across the orogen from the Main Central Thrust to the Karakoram Shear Zone. This c. 200-km x 200-km areal array can be instrumented at c. 40-km spacing, and will be anchored on its NW margin by the dense linear NGRI array (above). Existing seismicity and seismotectonic studies in this region are not yet far advanced (e.g. Kumar & Mahajan, 2001; Thakur et al., 2000; Kayal et al., 2003) though local seismicity is abundant – the Thakur et al., study reported 267 local M2 to M4 events in a 16-month period, mostly in the MCT region. In addition, the Leo Pargil and Tso Morari domes are characterized by active normal faulting (Thiede et al., 2006), most notably the 1975 M=5.8 Kinnaur earthquake and its aftershocks (Singh et al., 1975; Khattri et al., 1978; Molnar & Chen, 1983).

As with the 1D array proposed by NGRI, US-HIMPROBE PIs will participate in experiment planning, one U.S. student will participate in deployment. Following the experiment, an Indian scientist will visit Stanford (beginning of year 4) to work on the data (culminating in participation in the San Francisco AGU meeting and HIMPROBE workshop). All data will be made available equally at WIHG and Stanford, where we have access to the ANTELOPE software (through IRIS) for automatic detection of first arrivals and preliminary earthquake locations. We expect to have a good 2D velocity model for the NW Himalaya from our wide-angle studies, for earthquake re-locations.

In addition to Indian objectives to advance understanding of seismic hazard, this seismicity study offers the potential to examine the relationship of the extensional domes to the orogenic thrust architecture to aid in constructing our crustal structural cross-sections, as well as studying the depth distribution of seismicity to test the existence of mantle earthquakes in this region (as recently reported from eastern Nepal: Schulte-Pelkum et al., 2005; Monsalve et al., 2006) and evaluate whether the NW Himalaya is best represented by a single strong seismogenic lithosphere with no weak lower-crustal layer (Priestley et al., 2007), in contrast to the bimodal earthquake-depth distribution claimed by Monsalve et al. (2006).

Magnetotelluric data

Data acquisition will be the responsibility of the MT groups at Wadia Institute of Himalayan Geology, led by B. Arora (Institute Director), and at China University of Geosciences, Beijing (Wei Wenbo (Chinese PI on INDEPTH MT team); broadband data already acquired in western Tibet), with assistance from Unsworth (Alberta). The participation of Unsworth will continue the excellent rapport developed between seismic and MT team members during INDEPTH in which high-quality MT data were acquired and jointly interpreted with seismic results (e.g. Nelson et al., 1996; Li et al., 2003; Unsworth et al., 2004, 2005; Mechie et al., 2004). Unsworth's new collaborations with Arora, and Wei Wenbo in China, means that he is the only MT scientist with access to all the relevant data-sets, and therefore we have requested that he participate in US-HIMPROBE, despite his non-US affiliation. Although we request NSF funds for his travel to the field, Unsworth brings Canadian funds for his salary and for PhD studentships. Together, these groups (Alberta, Wadia, and CUGB) have both the available equipment (Phoenix broadband and Narod long-period systems) and the logistical experience to do this work, as shown for the Indian side by the results of their existing sparsely sampled profile along HIMPROBE Transect 1 (Fig. 6a) (Gokarn et al., 2002; Arora et al., 2007), and for the Chinese by their INDEPTH datasets (e.g. Wei et al., 2001). Note that the only existing MT section yet published from the frontal Himalayan thrusts across the IYSZ (Unsworth et al., 2005) is a merged combination of INDEPTH data from southern Tibet (China) and French data in Nepal (Lemmonnier et al., 1999), in which the 70 km data gap across the international border shows almost no resolution. The HIMPROBE MT along Transect 1 will be the first continuous profile across the entire orogen with a uniform dense sampling of data.

The HIMPROBE broadband MT data sampled to mid-crustal depths (Gokarn et al., 2002). These data have been re-processed by Unsworth et al. (2005) to give quite different models compared to Gokarn et al, (2002). Long-period MT data give deeper penetration and were collected on the HIMPROBE transect by Arora et al. (2007). The model derived from the long-period data reveals a pervasive conductor at mid-crustal depths, but significant differences exist in the shallow portion. To address these model differences, additional MT data is needed. We will join our Indian MT collaborators to record additional MT data, with a smaller inter-station spacing, and coverage that continues south of the STD along broadband Transects 1 and the Alaknanda River section (Fig. 3b). Ongoing Indian fieldwork will likely take place in the 2008-9 and the joint field campaign is planned for 2010 with both long-period and broadband systems. Our goal will be to collect broadband MT data with 5 km spacing and long-period MT data at 20 km spacing. With acquisition on Transect 1 (300 km) and along the Alaknanda River (150 km) this will require 90 broadband stations and 20+ long-period stations. The rugged terrain in this area is similar to that encountered in Southern Tibet during INDEPTH and there will be places in narrow gorges where it is not possible to measure electric fields. At these locations we will collect 3-component magnetic field data. We will derive not only the vertical magnetic-field transfer function at each site, but also the inter-station horizontal magnetic-field transfer functions following the approach of Soyer et al. (2001). These data can be included in 2-D and 3-D inversions and are essential in filling in gaps where conventional MT data are not available. They also have the advantage that they are unaffected by galvanic distortion effects, which can complicate MT data in regions with deep valleys. With 6-10 broadband MT systems in the field (both from Indian and North American institutions), and 2-3 days of recording at each station, these data can be collected in approximately 70 days. Long-period MT data require one month per station and 2 deployments of North American or other LMT instruments will be made during the field season. As with the passive seismic acquisition, all field costs will be borne by the Indian teams (apart from minor shipping expenses for Alberta equipment to supplement the Indian equipment), though Alberta scientists will participate in acquisition in the 2010 field season, and one WIHG scientist will travel to Alberta to work with Unsworth following that field season (visit culminating in attendance at HIMPROBE project meeting in San Francisco and Fall AGU).

The transects in India will be integrated with new data in China collected by the China University of Geosciences, Beijing (CUGB). The combined HIMPROBE and Chinese data will give transects extending across the Western Tibetan Plateau (Fig 3b). Because the CUGB data are only broadband (upper-crustal to crustal penetration) we will take advantage of Unsworth's existing planned fieldwork in Tibet in 2009 to collect long-period (lithosphere-penetrating) MT along the CUGB profile (also coincident with the RLM passive seismic profile, Figure 3b). Only local travel is shown for this experiment-of-opportunity, no international airfares or equipment shipping; though we request funds for one Chinese scientist to travel to the San Francisco HIMPROBE project meeting and HKT in 2010.

MT data will be available for modeling by all participants, and we expect the joint effort to result in significant technology transfer of advanced modeling methods to the Indian scientists. MT data time series will be converted to frequency domain using standard, statistically robust, processing algorithms (Egbert, 1997; Chave & Thompson, 2004), including the use of remote reference technique at all stations. To determine the dimensionality of the MT data, the tensor decomposition algorithm of McNeice and Jones (2001) will be used, and then the data components that are consistent with a 2D analysis will be inverted using the algorithm of Rodi & Mackie (2001). Three-dimensional forward modeling and inversions will be used to validate the two-dimensional interpretations.

Expected products of seismology and magnetotellurics

Geophysical data acquisition will yield the densest combined seismic and MT image across the Himalaya, from the frontal thrusts not accessible to purely Chinese programs such as INDEPTH, to the interior-Tibetan sutures (Indus-Yarlung and Shyok sutures) not accessible to purely Nepali programs. The combination of structural, velocity and conductivity information allows the best possible estimation of thermal and mechanical parameters of the Indian crust, for direct comparison with channel-flow and thrust-wedging models. Our seismic images will identify the northern limit of the MHT, and the relationship of the MCT to the STD. Our MT images will locate the southern limit of high impedance-contrast/high conductivity bodies interpretable as crustal melts or their associated waters will allow a direct test of the viability of the channel-flow model in extruding the Greater Himalayan sequence in the western part of the Himalayan orogen at the present day. The MT images of Gokarn et al. (2002) (Fig. 6a) suggest that partial melt may be present beneath the Tso Morari Complex, but an alternate inversion (Fig. 6c, Arora et al., 2007) argues for caution until more data are obtained. Dense MT measurements can be sensitive to fluid concentrations around 1%, and the addition of seismic images provides a powerful constraint on tradeoffs between conductivity and thickness (e.g. Li et al., 2003). Where partially molten, a channel less than 1 km thick should be visible to our combined techniques; where frozen, it must probably be >5 km thick to be confidently recognized. The structural image beneath the Tso Morari dome will directly reveal whether this body is connected with and part of the GHS, thereby shedding light on the thrust sequence or flow channels in this area. The combined seismic images at and north of the suture zone will provide a formal test of whether India is gently underthrust beneath Tibet in the western Himalaya (as suggested by preliminary interpretations of the sparse Transect 1 data: Rai et al., 2006), or whether the Indian continent is abruptly truncated at either the Indus-Yarlung or Karakoram faults. Fig. 9c shows that it is possible to seismically image numerous structural boundaries within the crust (note the Himalayan crust is 60 to 70 km thick here, twice the thickness of the example in Fig. 9b), and so it should also be possible to image thrust ramps in the MHT e.g., beneath the Greater Himalaya (of great importance to earthquake hazard) and beneath the Tso Morari dome, bearing on the relation of the

Himalayan gneiss domes to the GHS. As always, combining MT will add additional constraints.

Other methodologies: gravity models, geodetic surveys, numerical modeling

Potential-field data – especially gravity anomalies – provide an important means of testing the validity of our final crustal models derived from a combination of the seismic and magnetotelluric data. The pioneering flexural models of the NW Himalaya by Lyon-Caen and Molnar (1983, 1985) that showed the northward dip of the Moho increases from 3° beneath the Lesser Himalaya to ~15° beneath the Greater Himalaya were based on the Das (1979) data set with c. 10 to 30 km station spacing. An important new data-set of nearly 400 new stations with spacing of only 1.5 to 2 km (and collocated magnetic data) (Banerjee and Satyaprakash, 2003) has been acquired by HIMPROBE, together with surface sampling for density measurements, to allow far more detailed modeling (e.g., Sastry et al., 2003, 2005). Currently all models (Lyon-Caen and Molnar, 1983, 1985; Sastry et al., 2003, 2005) are dominated by inferred Moho topography; but if we have independent measurements of Moho depth from our seismic measurements, we can use the new, precise gravity measurements to infer crustal density changes as might be expected from partial melt zones. Both Banerjee and Sastry, who are working with these data, are at collaborating institutions (WIHG and IIT-Roorkee, respectively), and Klemperer has already co-operated with Sastry in his interpretations. The magnetic data should also be available to us.

If channel flow or thrust wedging is continuing to extrude the Greater Himalayan sequence, then in principle repeated high-resolution geodetic surveys could detect these motions, and distinguish velocity fields due to different flow or thrust models. In practice however, it is very difficult to see beyond the elastic strain accumulation-and-release cycle to resolve longer-term tectonic processes and deformation styles (R. Bürgmann, pers. comm.), and probably impossible to resolve the different types of models which we hope to test geologically, so that we see no compelling reason to incorporate geodetic studies in this proposal. A regional GPS data-set exists in our area which shows the Main Frontal Thrust building up a slip deficit at 14 mm/yr, and the Karakoram fault slipping at 11 mm/yr (Banerjee & Bürgmann, 2002). A somewhat more extensive and more precise dataset is now being analyzed (Banerjee, 2003) but does not seem to materially change our understanding.

Ultimately we expect to generate the geological and geophysical data that will not only test between existing end-member mechanical models, but – if our results favor channel flow – may also justify more detailed numerical models tuned to match our western Himalayan results. Because the outcome of the observational part of our program cannot be known until later in the project, we have chosen not to seek funds for any one individual to carry out detailed modeling. However, our discussions with Chris Beaumont (Dalhousie) about which predictions of his models are testable suggest that his group could be logical collaborators in the future, after our project has returned useful data. We will invite his group to attend our HIMPROBE workshops (though we request no funding here).

7. RATIONALE FOR A COLLABORATIVE INTERNATIONAL, MULTI-DISCIPLINARY APPROACH

Development of the large, multidisciplinary datasets needed to establish the internal structure and kinematic and exhumation histories of the rugged Himalayan thrust belt in NW India requires the expertise of a sizeable group of experienced scientists, working together with shared goals and objectives. INDEPTH showed the value of integrated multi-disciplinary geophysical and geological studies in southern Tibet and the Himalaya (e.g., Nelson et al., 1996). To successfully test geodynamic models in the NW Himalaya we need a similarly integrated approach. We need to collect the seismic and MT data that can search for partial melts beneath the IYSZ, and map the mid-crustal thrust structure beneath gneiss domes. We need to collect the structural, thermochronological, and provenance data to establish a regional geometric and kinematic basis for testing specific predictions of the three main geodynamic models. But since HIMPROBE is a successful national project in India, why US-HIMPROBE?

The first, completed phase of HIMPROBE was a success in India because of the dearth of pre-existing regional data in the NW Himalaya (though there are many prior smaller-scale geologic studies, both Indian and international, Fig. 3a). The Indian DST funding allowed Indian scientists to make a first-order contribution to knowledge of the NW Himalaya, and enabled both young and senior scientists to develop new projects. Thus far the different groups have tended to work in relative isolation, important synergies were not developed, and there was no strong pressure for renewed DST funding for collaborative studies in the NW Himalaya. For example the broadband and long-period MT data were separately acquired by two different institutions, published separately, and were only compiled and jointly interpreted through the involvement of Martyn Unsworth. Similarly, the existing broadband seismic transect and the preliminary seismic reflection profile along the southern part of Transect 1 were collected by separate groups working separately. The possibility of recording controlled seismic sources on broadband stations and thereby simultaneously collect near-vertical, wide-angle and broadband data is an opportunity that seemed unlikely to be exploited until discussions about a joint India-US-HIMPROBE project motivated the separate groups in India to plan for future work together.

Beyond our experience in the US of organizing large collaborative projects, there are available facilities (U-Pb SHRIMP and MC-LA-ICPMS, ^{40}Ar/^{39}Ar, and fission-track) and geophysical modeling methods (e.g., MT tensor decomposition algorithms and broadband CCP imaging codes, see previous sections) not yet in use in India, so that a US-HIMPROBE collaboration will result in technology transfer to the Indian scientists, and access to exciting new data for western scientists.

8. PERSONNEL

We have assembled a PI team of scientists who have all previously worked in the Himalaya and/or Tibet, and have all previously worked with other members of the team. We have strengths in structural mapping (DeCelles, Leech), geo/thermochronology and petrology (Leech, Carrapa, Krugh), sedimentology (DeCelles, Carrapa), active-seismic and passive-seismic (Klemperer) and magnetotelluric (Unsworth) components of this project. Leech has mapped in numerous high-grade terranes and used a wide variety of geo/thermochronometers to decipher orogenic evolution (e.g., Leech and Stockli, 2000; Leech et al., 2006b; 2007a; Webb et al., 2006). Klemperer has worked with Project INDEPTH since its successful recording of the first deep reflection profile in Tibet (Zhao et al., 1993), and in addition to leading numerous active-source experiments has recently supervised PhD students in passive seismology for lithospheric structure (shear-wave splitting and receiver functions); two new PhD students have begun theses on existing HIMPROBE active and passive datasets (Figs. 7 & 8). DeCelles has worked on the regional structure and tectonic history of the Nepalese portion of the Himalayan thrust belt and foreland basin system for more than 10 years, supervised four PhD dissertations in the Nepalese Himalaya, and been author or co-author on more than 20 papers on this part of the thrust belt.

Carrapa has a broad base of thermochronology expertise crucial for generating the large bedrock and detrital datasets needed for this project. Carrapa has worked extensively in the Alps, Andes, and western U.S. Cordillera, applying her expertise in ^{40}Ar/^{39}Ar and fission-track thermochronology to bedrock and detrital studies. She is also an expert in clastic sedimentology. William Krugh is currently finishing his PhD project at ETH in Zurich (Switzerland) in low-T-thermochronology. He will start a post-doctoral research with Carrapa at the University of Wyoming in January 2008. His expertise is in apatite and zircon fission track and (U-Th)/He thermochronology and structural geology.

Our choice of Martyn Unsworth (Alberta) as the lead MT investigator in North America is because he has established unique working relationships with both Baldev Arora (WIHG) and Wei Wenbo (CUGB) who control access to the Indian and Chinese MT data-sets. Unsworth brings his expertise, students, technicians and instruments to this project at no cost except travel funds (he has a 12-month salary at his home institution). None of the foreign collaborators will draw salary or student support from NSF sources; hence by involving these scientists we take advantage of ongoing efforts in our target area while expanding the scope of our project at little cost.

9. MANAGEMENT PLAN & DURATION OF PROJECT

Leech has an established project with IIT-Roorkee in the Tso Morari and Leo Pargil gneiss domes, and following field work with HIMPROBE coordinator A.K. Jain and HIMPROBE member Sandeep Singh in 2004, began to plan the US-HIMPROBE collaboration proposed here. Klemperer has visited Hyderabad to establish a joint project on existing NGRI data, and has scouted all the roads now proposed for use in Transect 1. Unsworth has similarly been given access to IIG-Mumbai and Wadia Institute data. Our visits, seminars and collaborative fieldwork, and the collaborative data analyses we have initiated, have motivated a large group of the HIMPROBE PIs to develop with us the plans outlined here for a third phase of HIMPROBE. Some aspects were already funded (Alaknanda geophysics transect) by the Indian DST following an earlier submission of this proposal. The proposed 2009 reflection profile is already essentially approved; within the Indian system applications will not be made for funding other field seasons until closer to the time, but we have strong assurances that the international validation provided by NSF approval of a HIMPROBE counterpart program will all but guarantee funding of the additional geology, seismic, and MT acquisition and analysis projected here.

Leech will organize HIMPROBE workshops at SFSU prior to the Fall AGU meeting (annually for NSF-funded HIMPROBE members, and in Year 4 also for Indian participants) and in conjunction with the Himalaya-Karakoram-Tibet workshops in Years 1 and 2 (with full participation by Indian geophysicists and geologists). Leech is co-organizing the HKT workshop in Leh, India, in 2008 and will arrange an initial meeting of Indian collaborators before Year 1 field work begins. Leech and Klemperer will co-chair the 2010 HKT meeting in San Francisco (end of Year 2) with significant HIMPROBE participation.Indian counterparts are essential in each discipline, and are identified as: overall leadership: academician A.K. Jain, IIT Roorkee; project management and regional & structural geology: Sandeep Singh and A.K. Jain (IIT Roorkee – Singh, 2003; Jain et al., 2002); petrology & geochemistry: Sandeep Singh; active-source seismology: Rajendra Prasad (NGRI); broadband seismology: SS Rai (NGRI); long-period MT: Baldev Arora (Wadia Institute).

We plan a four-year project (Fig. 10; note this figure also shows current, unfunded activities). Year 1 includes analysis and dating of samples collected opportunistically in previous field seasons (by Leech) for which there is no current funding, and ongoing analysis of the Alaknanda broadband array. Major geological fieldwork will take place in the foreland during fall/winters from 2008-2010 and is scheduled for summers along both Transects 1 and 2 from 2008-2011, simultaneously with controlled-source seismic acquisition late in Years 1 and 3, and broadband acquisition, in years 1, 2 and 3. MT acquisition will occupy two summers, 2009 and 2010. This plan allows time to work up and write up the results of each field season and lab work, including visits of Indian geophysicists to Stanford and Alberta.

10. SYNTHESIS AND PUBLICATION OF RESULTS

This project brings together PIs with very different ideas for the development of the Himalaya: in previous publications DeCelles has favored a conventional thrust belt model (approaching the problem from the foreland side), whereas Klemperer favors a channel flow solution (with a perspective informed by work mainly in the southern Tibetan Plateau). The primary challenge of the HIMPROBE project will be to converge on a single solution for the western Himalaya. Although numerous previous studies have approached the northern Indian Himalaya with some of the same objectives, we believe ours is the first integrated attempt to merge regional-scale geophysical and geological datasets. As in other areas of geoscience, true breakthroughs are to be found at the interfaces of different disciplines. The final product of at the end of this 4-year project will be a synthesis paper co-authored by all PIs integrating the geology and geophysics to build a crustal-scale cross-section for the western Himalaya. If all the PIs can agree on a single synthesis, we will have understood whether channel flow or a thrust belt model is a better description of the Himalaya, our archetypal collision orogen.

11. EDUCATION, HUMAN RESOURCES & BROADER IMPACTS

This project will support two untenured, early-career female faculty members: Leech (a Native American) at SFSU and Carrapa at UWyo. The project will include one post-doctoral researcher (UWyo), four PhD students (one at UA, one at UWyo, two at Stanford), two Masters students (SFSU), and several undergraduate researchers (SFSU, Stanford, UWyo); plus unfunded PhD students in India and Canada.

Undergraduates in the Geosciences BS program at SFSU (a federally-recognized minority-serving institution) complete a senior research thesis as part of their undergraduate training. Since 1989, ~75 students have completed research projects which require a written thesis, and a public oral defense; many students have presented papers at national meetings, co-authored published papers, received funding, and gone to graduate school. Members of the SFSU Geosciences Department have been involved with the Council for Undergraduate Research and helped bring special sessions on undergraduate research to the Fall AGU meeting and developed workshops for faculty on how to develop an undergraduate research program. Leech is currently working with an undergraduate to do U-Pb dating of the Leo Pargil gneiss dome in the Stanford-USGS SHRIMP lab and funds are requested through NSF's REU program to involve three more undergraduates in field and lab-based research over the 4-year grant. Klemperer leads his department's initiative for summer undergraduate research and will apply for funding through Stanford's Undergraduate Research Program to support 2 undergraduate geosciences or physics majors to complete research projects based on data collected during fieldwork. Leech and Klemperer have advised several undergraduates (including minority and female students) in research projects through this program — students have participated in field and laboratory work, presented their research at national meetings, and published first-authored papers on their research.

The proposed budget also includes substantial stipend requests for graduate student researchers. SFSU is not a PhD-granting institution, so Leech will recruit one MS student to start work in Year 1 and one MS student to start in Year 2 or 3. DeCelles will recruit a new PhD student to work on this project. Klemperer requests funding for two geophysics PhD students, one (Warren Caldwell) in passive seismology (teleseismic migrations) and one (Indrajit Das) who will work on the active-source data, and will include two undergraduates in geophysics field work and subsequent data analysis (e.g. earthquake locations). Carrapa has trained several undergraduate students to work in the lab and two graduate students at the University of Potsdam. She in presently advising two graduate students at UWyo. Carrapa will hire a postdoctoral scholar (Krugh) for two years, recruit a PhD student for four years and several undergraduates (one each year) to work on the detrital thermochronology (see work program). For all of these individuals the research experience in the Himalaya and in the application of low-T-thermochronology would represent an outstanding training experience

Earthquake hazard estimation

An important outcome of the seismic work will be better images of the seismogenic thrust beneath the Lesser Himalaya, and its deeper crustal configuration. Knowledge of the thrust-fault geometry and crustal structure will allow more detailed understanding of likely seismic hazard, including enhanced shaking at significant distance due to Moho reflections. Although our work cannot mitigate the hazard, it can raise public awareness and encourage governmental planning and stricter application of building codes, lack of which contributed to the ~80,000 deaths from the M=7.6 Kashmir earthquake on 10/8/05.

Technology transfer

We have requested 16 months of training/collaborative research visits by Indian post-doctoral scientists over the 4-year period. Because the bulk of the geophysical data are being acquired with Indian funds, we have a major commitment to training and collaborative research, and our plans include three-month visits by Indian geophysicists, one in passive seismology, one in active seismology, and one in MT. Additionally, two geologists will make two one-month visits. Training will center around the use and development of existing geophysical inversion and processing software and geochemical and geochronologic techniques. Visits will in general be timed to follow field seasons and culminate with presentations at AGU and participation in HIMPROBE group meetings held at the same time.

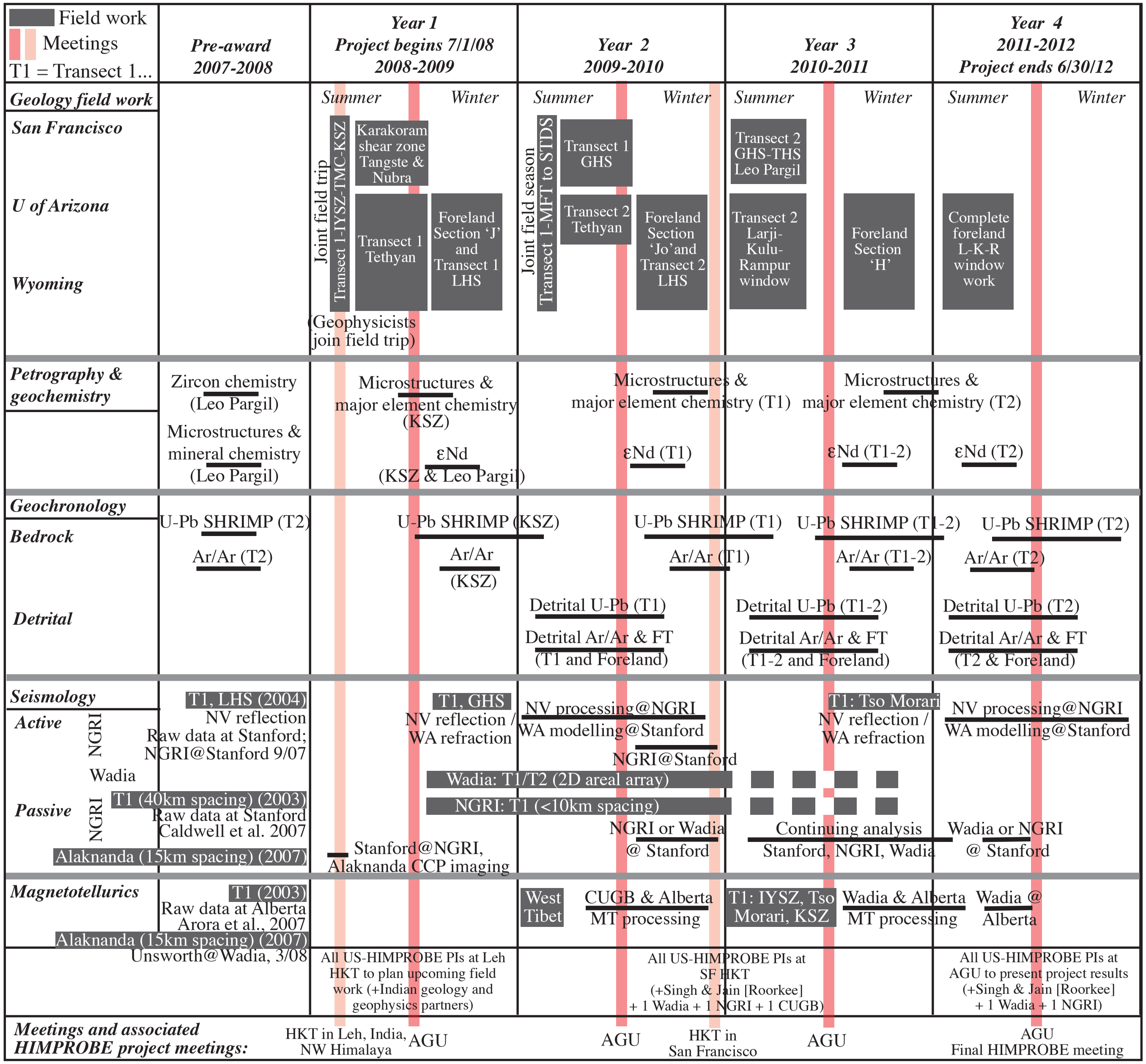


Figure 10. HIMPROBE timeline and work schedule from pre-award to project end in June 2012.

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Leech, M.L., 2001, Arrested orogenic development: eclogitization, delamination, and tectonic collapse, Earth and Planetary Science Letters, 185, p. 149-159.

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Webb, L.E., Leech, M.L., and Yang, T., 2006, ^{40}Ar/^{39}Ar thermochronology of the Sulu terrane: Late Triassic exhumation of high and ultrahigh-pressure rocks and other implications for Mesozoic tectonics in East Asia: In, Ultrahigh-pressure metamorphism: Deep continental subduction (B.R. Hacker, W.C. McClelland, and J.G. Liou, eds.), Geological Society of America Special Paper 403, doi: 10/1130/2006.2403(01).

SYNERGISTIC ACTIVITIES

Several undergraduate education resources adopted by DLESE (Digital Library for Earth System Education): For my natural hazards, California geology, and geology of the National Parks courses. All three can be found at: http://www.dlese.org/dds/query.do?q=leech&s=0

Geoscience education journal publication: Leech, M.L., Howell, D.G., and Egger, A.E., 2004, A guided inquiry approach to learning the geology of the U.S., *Journal of Geoscience Education*, 52, 368-373.

Toward increasing diversity in the geosciences: Co-organizer, NSF-NASA-NOAA-USGS "Joint Society Conference on Diversity in the Earth and Space Sciences", June 2003; and Member-at-Large, GSA Committee on Minorities and Women in the Geosciences, 2001-2004.

NSF Graduate Research Fellowship Program panelist: One of a twenty-member panel which reviews c. 400 applications annually to select c. 30 NSF graduate research fellows in Earth Sciences, 2003-present.

MARC (Minority Access to Research Careers) Honors Program Faculty Mentor, SFSU, 2006-present. MARC provides academic support and research experience to prepare participants for entrance into competitive graduate programs and successful completion of a Ph.D. in the sciences.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators (in the last 48 months)
Rachel Beane (Bowdoin), Benjamin Bostick & Cynthia Chen (Dartmouth), Barbara Carrapa & Rasmus Thiede (Potsdam, Germany), Peter DeCelles & Paul Kapp (University of Arizona), Johannes Glodny (ETH, Zurich), David Howell & Joseph Wooden (USGS), A.K. Jain, R.M. Manickavasagam & Sandeep Sing (IIT Roorkee), Alan Jones (Dublin), Simon Klemperer & Chris Mattinson (Stanford), Ellen Metzger (San Jose State University), Martin Unsworth (Alberta), Laura Webb (Syracuse University), Ernst Willingshofer (Vrije University), Xu Zhiqin & Yang Tiannan (Chinese Academy of Geological Sciences)

Graduate and Postdoctoral Advisors
Gary Ernst and J.G. Liou (Stanford), Bradley Hacker (UC Santa Barbara), Martin Menzies & David Mattey (University of London)

Students advised/co-advised
James Metcalf [PhD], Katherine Keranen [PhD], Nathan Fitzgerald [BS] (Stanford); Christina Spanoghe [BS] (San Jose State); Christina Polito [BS], Molly Cornell [BS], William Hassett [BS], Brian Fuller [BS/MS], Lisa Garman [BS], Yuko Mamiya [BA], Jonathan Boxerman [M.S.], Johnathan Brown [M.S.], Chris Baldassari [MS], Erika Amir [MS], Matthew DeHart [MS], James Kirwin [MS], Andrew Matthew [MS], Robert Sas [MS], Beth Ziegelbaum [MS] (SFSU)

HONORS AND AWARDS

2003-2004	NSF/AAAS Women's International Science Collaboration grant
2001-2003	University of California President's Postdoctoral Fellowship
1999-2001	National Science Foundation International Research Fellowship Award
1999	National Science Foundation Earth Sciences postdoctoral fellowship (Declined)
	National Science Foundation-NATO postdoctoral fellowship (Declined)
1998-1999	Lieberman Fellowship, Stanford (for leadership and teaching skills)
1995-1998	National Science Foundation Minority Graduate Fellowship

SIMON L. KLEMPERER

Geophysics Dept, Stanford University, Stanford, CA 94305-2215.

EDUCATION

1980	B.A.	Natural Sciences (Mineralogy & Petrology), Cambridge University
1985	Ph.D.	Geophysics, Cornell University (advisors: Jack Oliver, L. Brown, D. Karig)

PROFESSIONAL EXPERIENCE

1985	Research Associate, Consortium for Continental Reflection Profiling (COCORP), Cornell University (advisor: Jack Oliver)
1985-87	Research Associate, British Institutions' Reflection Profiling Syndicate (BIRPS), Cambridge University (mentor: Drum Matthews)
1987-90	Royal Society University Research Fellow, Cambridge University
1990 on	Professor, formerly Associate Professor, of Geophysics, Stanford University Professor, formerly Associate Professor, (by courtesy) of Geological and Environmental Sciences Director, IRIS-PASSCAL Instrument Center at Stanford, 1992-1998 Director, Stanford Earth Sciences GIS Laboratory, 1994-1999

PUBLICATIONS MOST RELEVANT TO THIS PROJECT (5)

Caldwell, W.B.*, S.L. KLEMPERER, and S.S. Rai, 2007. Testing the Presence of Fluids/Crustal Melts in the India-Asia Collision Zone Using Rayleigh Wave Dispersion Analysis, *EOS, Trans. Am. Geophys. Un.,* Fall Mtng. 2007, Abstract T31B-0464.

KLEMPERER, S.L., 2006. Crustal flow in Tibet: geophysical evidence for the physical state of Tibetan lithosphere, and inferred patterns of crustal flow. *In:* "Channel flow, ductile extrusion and exhumation in continental collision zones, eds. R.D. Law, M.P. Searle & L. Godin, Geological Society of London Special Publication v. 268, 39-70.

Leech, M.L., S. Singh, A.K. Jain, S.L. KLEMPERER, and R.M. Manickavasagam. 2005. The onset of India-Asia continental collision: early, steep subduction required by the timing of UHP metamorphism in the western Himalaya, *Earth Planet. Sci. Letts*, v. 234, 83-97.

Makovsky, Y.*, S.L. KLEMPERER, L. Ratschbacher, and D. Alsdorf. 1999. Midcrustal reflector on INDEPTH wide angle profiles; an ophiolitic slab beneath the India-Asia suture in southern Tibet? *Tectonics,* v. 18, pp. 793-808.

Makovsky, Y.*, S.L. KLEMPERER, L.-Y. Huang, D.-Y. Lu, and Project INDEPTH Team. 1996. Structural elements of the southern Tethyan Himalaya crust from wide-angle seismic data. *Tectonics*, v. 15, pp. 997-1005.

OTHER PUBLICATIONS (5)

Haines, S.S.*, KLEMPERER, S.L., Brown, L., Guo J., Mechie, J., Meissner, R., Ross, A., and Zhao, W. 2003. INDEPTH III seismic data: from surface observations to deep crustal processes in Tibet. *Tectonics,* v. 22 (1), 1001, doi:10.1029/2001TC001305.

KLEMPERER, S.L., and W.G. Ernst, eds. 2003. The George Thompson Volume: The Lithosphere of Western North America and its Geophysical Characterization. Geological Society of America International Book Series #7, 544 p.

Gashawbeza, E.M.*, KLEMPERER, S.L., Wilson, C.K., and Miller, E.L. Crustal thickness and composition of the northwest Basin and Range Province from teleseismic receiver functions. *J. Geophys. Res.,* in review.

Makovsky, Y.* & S.L. KLEMPERER. 1999. Measuring the seismic properties of Tibetan bright-spots: free aqueous fluids in the Tibetan middle crust. *J. Geophys. Res.,* v. 104, 10,795-10,825.

Zhang, Z.J., and KLEMPERER, S.L. 2005. West-east variation in crustal thickness in northern Lhasa block, central Tibet, from deep seismic sounding data. *J. Geophys. Res.*, v. 110, B09403, doi:10.1029/2004JB003139, pp.14.

***advisee of Klemperer.** **Over 100 additional publications.**

HONORS AND AWARDS

1982-84	Milton Dobrin Scholar, Society of Exploration Geophysicists
1987-90	Royal Society University Research Fellowship
1988	President's Award of the Geological Society of London
1995	Fellow of the Geological Society of America

POST-DOCTORAL ADVISEES AT STANFORD UNIVERSITY:

Former: Eiji Kurashimo, Charlie Wilson, Caitlin O'Connell-Rodwell, Jason Wood, Tanni Abramowitz, Andrew Long, John Hole, Bruce Beaudoin, Ginger Barth

GRADUATE STUDENTS AT STANFORD UNIVERSITY:

Current:

5 PhD: Warren Caldwell, Indrajit Das, Ewenet Gashawbeza, Marianne Karplus, Katie Keranen.

Former:

Ph.D. degrees: Moritz Fliedner, Nicola Godfrey, Seth Haines, Darcy Karakelian, Derek Lerch, Yizhaq Makovsky, Kris Walker

M.S. degrees: Kathleen Burnham, Emily Chetwin, Frances Cole, Brian Hicks, Jeff Johnson, Brian Galloway, Bryan Kerr

M.S. (Exploration & Development) degrees: Reynaldo Cardona, Miguel Diaz, Abdulaziz Al-Buali, Jesse Lomask, Osman Khan, Azer Mustaqeem, Saleh Al-Dossary, Agus Djamil, Francisco Maldonado, George Viegas, Yacob Tesfaye, Maureen Jacoby, Gwendolyn Hofler, Thomas Finkbeiner, Lindy Phillip, Anthony Stell, Michael Milan, Sandor Talas, Wade Skelton, Jennifer Crisi, Paul Peterman, Kristine Fraser.

RECENT COLLABORATORS

INDEPTH Deep Profiling of Tibet and the Himalaya: co-PIs: Larry Brown (Cornell), Jim Ni, Tom Hearn (NMSU), Eric Sandvol (MSU), Jim Mechie, Rainer Kind (GFZ-Potsdam), and Chinese colleagues.

Ethiopia-Afar Geoscientific Lithospheric Experiment (EAGLE): co-PIs are Randy Keller (Oklahoma), Steve Harder (UT El Paso), Tanya Furman (Penn State), and Kevin Mickus (SWMSU). Additional co-authors are Becky Bendick (Montana), Andy Nyblade (Penn State), Peter Maguire (Leicester), Cindy Ebinger (Rochester), Mary Fowler (RHUL), Graham Stuart (Leeds), Kathy Whaler (Edinburgh) and scientists from Ethiopia.

EARTHSCOPE USArray Basin-and-Range transition zone, Northwest Nevada: Jon Glen, David Ponce, Joe Colgan (USGS), Tony Lowry (Utah State), Ken Stokoe & F-Y Menq (UT Austin)

EARTHSCOPE PBO Ultra-low frequency electromagnetic observatory: Darcy McPhee, Jonathan Glen (USGS); Barbara Romanowicz & Dave Alumbaugh (Berkeley)

Other recent co-authors outside Stanford: Andy Calvert (Simon Fraser University), Andy Goodliffe (Alabama), Mary Leech (SFSU), Steve Pride (Lawrence Berkeley Labs), Bob Stern (UT Dallas), Götz Bokelmann (Montpellier), Tom Owens (South Carolina)

SYNERGISTIC ACTIVITIES (5)

Broadening the participation of under-represented groups, and enhancing undergraduate education:

In last 5 years have supported 11 undergraduates (5 female) on REU projects, including field-based research; 4 (3 female) have continued to grad. school; 3 peer-reviewed undergraduate-authored publications resulted (Geophys. Res. Letts., Tectonophysics, J. African Earth Sci.).

Director of Undergraduate Studies for Geophysics, and Faculty Director, School of Earth Sciences Undergraduate Summer Research Program, Stanford.

Service to the scientific community:

Member, NSF EAR Continental Dynamics Review Panel (1998-2005)

Convenor and volume editor, "The Lithosphere of Western North America and its Geophysical Characterization", Stanford University, CA (2001)

Development and dissemination of databases to support research:

Compilation of GIS database of geologic and tectonic data for the Bering Shelf, Chukchi Sea, Arctic Margin and adjacent landmasses, published by GSA and USGS

MARTYN J. UNSWORTH

Institute for Geophysical Research, University of Alberta, Edmonton, Alberta, Canada

EDUCATION

1986	B.A.	Natural Sciences, Cambridge University (Class I)
1991	Ph.D.	Earth Sciences, Cambridge University. (Advisor: Martin Sinha)

PROFESSIONAL EXPERIENCE

1989-1991	Research Assistant, Los Alamos National Laboratory
1992-1993	Post-doctoral Research Fellow, Department of Astronomy and Geophysics, University of British Columbia, Vancouver, B.C. (Advisor: Doug Oldenburg)
1993-2000	Research Associate Professor (formerly Research Assistant Professor), Geophysics Program, University of Washington, Seattle
2000-present	Professor (formerly Associate Professor), Department of Physics, University of Alberta

PUBLICATIONS MOST RELEVANT TO THIS PROJECT

Arora, B., M.J. UNSWORTH, G. Rawat, Deep resistivity structure of the Northwest Indian Himalaya and its tectonic implications, *Geophys. Res. Lett.*, 34, L04307, doi:10.1029/2006GL029165, 2007.

UNSWORTH, M.J. A.G. Jones, W. Wei, G Marquis, S. Gokarn, J. Spratt, and the INDEPTH MT Team. Crustal rheology of the Himalaya and Southern Tibet inferred from magnetotelluric data, *Nature,* **438,** doi:10.1038/nature04154, 78-81, 2005.

UNSWORTH, M.J., W. Wei, A.G. Jones, S. Li, P.A. Bedrosian, J.R. Booker, S. Jin, and M. Deng, Crustal and upper mantle structure of Northern Tibet imaged with magnetotelluric data, *J. Geophys. Res.*, **109**, doi:10.1029/2002JB002305, 2004.

Wei, W., M.J. UNSWORTH, A.G. Jones, J.R. Booker, H. Tan, K. D. Nelson, L. Chen, S. Li, K. Solon, P.A. Bedrosian, S. Jin, M. Deng, J. Ledo, D. Kay and B. Roberts, Detection of widespread fluids in the Tibetan crust by magnetotelluric studies, *Science*, **292**, 716-718, 2001.

Li, S., M.J. UNSWORTH, J.R. Booker, W. Wei, H. Tan and A.G. Jones, Partial melt or aqueous fluids in the Tibetan crust: constraints from INDETH magnetotelluric data, *Geophys. J. Int.*, **153**, 289-304, 2003.

PROFESSIONAL ACTIVITIES

Editor, *Geophysical Journal International*, April 1998 to present
Editorial Board, *Physics of the Earth and Planetary Interiors*, April 2001 to present
Department of Energy proposal review panel, Environmental Management Science Plan, 1997.
USGS review panel, Earthquake Hazard Reduction Program, 1999.
Member Electromagnetic Working Group, Earthscope project, IRIS, 2006-present
Guest Professor, China University of Geosciences, Beijing, 2004-present

GRADUATE STUDENTS SUPERVISED IN PAST FIVE YEARS

Shenghui Li, Paul Bedrosian, Wen Xiao, Ersan Turkoglu, Volkan Tuncer, Ted Bertrand, Dennis Rippe, Anna Forstrumm

COLLABORATORS IN PAST TWO YEARS

Larry Brown (Cornell University), Phil Wannamaker (University of Utah), Alan Jones (Dublin), Wei Wenbo (China University of Geoscience), Bai Denghai (Chinese Academy of Sciences), Francis Wu (SUNY Binghampton), Ian Ferguson (Univ. of Manitoba), Bai Denghai (Chinese Academy of Sciences), Baldev Arora (WIHG), David Wiltschko (Texas A and M University)

BIOGRAPHICAL SKETCH: Peter G. DeCelles

Department of Geosciences
University of Arizona
Tucson, Arizona 85721
(520) 621-4910 (e-mail: decelles@geo.arizona.edu)

Professional Preparation:
B.S. in Geology: University of Notre Dame, 1980
M.S. and Ph.D. in Geology, Indiana University, 1984
Postdoctoral Scholar, Stanford University, 1984-1986

Appointments:
Cox Visiting Professor, Stanford University, 2007-08
Associate and Full Professor, University of Arizona, 1993–present.
Visiting Professor, University of Rome, 1996
Visiting Professor, University of Bologna, 1990–1991, 2007
Assistant Professor, University of Rochester, 1986–1993

Publications Closely Related to Proposed Project:

DeCelles, P.G., Kapp, P., Ding, L., and Gehrels, G.E., 2007, Cretaceous-mid Tertiary basin development in the central Tibetan Plateau: Changing environments in response to changing climate, tectonic partitioning, and elevation gain: Geological Society of America Bulletin, v. 119, p. 654-680, doi: 10.1130/B26074.1.

DeCelles, P.G., Gehrels, G.E., Najman, Y., Martin, A.J., Carter, A., and Garzanti, E., 2004, Detrital geochronology and geochemistry of Cretaceous—Early Miocene strata of Nepal: Implications for timing and diachroneity of initial Himalayan orogenesis, Earth and Planetary Science Letters, v. 227, p. 313-330, doi:10.1016/j.epsl.2004.08.019.

DeCelles, P.G., Robinson, D.M., and Zandt, G., 2002, Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau, Tectonics, v. 21, no. 6, 1062, doi:10.1029/2001TC001322.

DeCelles, P. G., Robinson, D. M., Quade, J., Ojha, T.P., Garzione, C.N., Copeland, P., and Upreti, B. N., 2001, Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal: Tectonics, v. 20, p. 487-509.

DeCelles, P.G., Gehrels, G.E., Quade, J., Lareau, B., and Spurlin, M., 2000, Tectonic implications of U-Pb zircon ages of the Himalayan orogenic belt in Nepal: Science, v. 288, p. 497-499.

Five Other Significant Publications:

DeCelles, P.G., Kapp, P., Fan, M., Quade, J., Dettman, D., and Ding, L., 2007, High and dry in the central Tibetan Plateau during the Oligocene: Earth and Planetary Science Letters, v. 253, p. 389-401.

DeCelles, P.G., and Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-thrust belt, central Utah: Implications for the Cordilleran magmatic arc and foreland basin system, Geological Society of America Bulletin, v. 118; no. 7/8; p. 841–864; doi: 10.1130/B25759.1, p. 841-864.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105-168.

DeCelles, P. G., and Horton, B. K., 2003, Implications of early-middle Tertiary foreland basin development for the history of Andean crustal shortening in Bolivia: Geological Society of America Bulletin, in press, January, 2003.

DeCelles, P.G., Gehrels, G.E., Quade, J., and Ojha, T.P., 1998, Eocene-early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal: Tectonics, v. 17, p. 741-765.

Synergistic Activities:

Associate Editor and Co-Editor, Basin Research, 1997-present
Co-Editor, Journal of the Nepal Geological Society, 2002
Associate Editor, Geology 2004-05
College of Science Outstanding Teaching Award, University of Arizona, 2000
Director, University of Arizona Geologic Field School, 1996-present
The Explorers Club (Fellow)
Education and training: 10 of my 11 Ph.D. students hold tenured or tenure-track appointments, and two of them have been awarded the Donath Medal of the Geological Society of America

Collaborators: (not including former students and current Arizona faculty)

B.N. Upreti (Tribuvan University)
Gautam Mitra (University of Rochester)
William Cavazza (University of Bologna)
Gian Paolo Cavinato (University of Rome)
Peter Copeland (University of Houston)
Mark Harrison (ANU, UCLA)
Yani Najman (Lancaster University)
Eduardo Garzanti (University of Milan)
Barbara Carrapa (University of Wyoming)
Ricardo Alonso (University of Salta, Argentina)
Brad Hacker (UC Santa Barbara)

Advisors:

M.S. and Ph.D. advisor = Lee J. Suttner, Indiana University
Postdoctoral advisor= Stephan A. Graham, Stanford University

Advisees During Past 5 Years:

Ofori N. Pearson (Ph.D.) – 2002 (USGS, Denver)
David Barbeau (M.S., Ph.D.) – 2003 (Assistant Professor, University of South Carolina)
Aaron Martin (Ph.D.) – 2005 (Assistant Professor, University of Maryland)
Andrew Leier (Ph.D.) – 2005 (Assistant Professor, University of Calgary)
Facundo Fuentes (M.S.) – 2005 (Ph.D. expected 2008)
Matt Fabijanic (M.S.) – 2005 (ExxonMobil)
Joel Saylor (Ph.D.) – expected 2008
Lynn Peyton (Ph.D.) – expected 2008
Scott McBride (M.S.) – expected 2008
Total graduate advisees – 20

BARBARA CARRAPA

Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071

EDUCATION & PROFESSIONAL EXPERIENCE

University of Pavia (Italy)	Geology	M. Sc.: 1998
Vrije University, Amsterdam (The Netherlands)	Geology	Ph.D.: 2002
Vrije University, Amsterdam (The Netherlands)	Geology	Post-doc:2003
University of Potsdam (Germany)	Geology	Post-doc: 2003-2006
University of Wyoming (Laramie, U.S.A)	Geology	Assistant Professor: June 2007-present

---

MOST RELEVANT PUBLICATIONS

Carrapa, B. and DeCelles, P.G., (in press) Eocene exhumation and basin development in the Puna of Northwestern Argentina, **Tectonics**.

DeCelles, P.G., Carrapa, B. and Gehrels, G.E. (2007) Detrital Zircon U-Pb Ages Provide New Provenance and Chronostratigraphic Information from Eocene Synorogenic Deposits in Northwestern Argentina. P.G. **Geology**, v.35, issue 4.

Mortimer, E., Carrapa, B., Coutand, I., Schoenbohm, Sobel, E., Jose Sosa Gomez, Strecker, M.R., (2006) Compartmentalization of a foreland basin in response to plateau growth and diachronous thrusting: El Cajon-Campo Arenal basin, NW Argentina. **GSA Bull.**, v. 119, 637-653.

Carrapa, B., Strecker, M., Sobel, E.R. (2006) Cenozoic orogenic growth in the Central Andes: Evidence from sedimentary rock provenance and apatite fission track thermochronology in the Fiambalá Basin, southernmost Puna Plateau margin (NW Argentina). **EPSL**, 247, 82-100.

Carrapa, B. Adelmann, D., Hilley, G., Mortimer, E., Sobel, E.R. & Strecker, M. (2005) Oligocene uplift, establishment of internal drainage and development of plateau morphology in the southern Central Andes. **Tectonics**, v.14, doi: 10.1029/2004TC001762.

OTHER SELECTED PUBLICATIONS

Mortimer, E. and Carrapa, B. (2007) Footwall drainage evolution in response to increasing fault displacement: Loreto fault, Baja California Sur, Mexico, **Geology**, v. 35, 651-654.

Strecker, M.R., Alonso, R.N, Bookhagen, B., Carrapa, B., Hilley, G.E., Sobel, E.R., Trauth, M.H. (2007) Tectonics and Climate of the Southern Central Andes, **Ann. Rev. Earth Planet. Sci.,** 35, 747-787.

Coutand, I., Carrapa, B., Deeken, A., Schmitt, A.K., Sobel. E.R., Strecker, M.R., (2006) Orogenic plateau formation and lateral growth of compressional basins and ranges: insights from sandstone petrography and detrital apatite fission-track thermochronology in the Angastaco Basin, NW Argentina. **Basin Research**, 18, 1–26.

Carrapa, B., Wijbrans, J., Bertotti, G. (2004) Detecting differences in cooling/exhumation patterns within the Western Alpine arc through ^{40}Ar/^{39}Ar thermochronology on detrital minerals (Tertiary Piedmont Basin, NW Italy), **GSA Bull.**, Paper 378, chapter 5.

Carrapa, B., Wijbrans, J. & Bertotti, G. (2003) Episodic exhumation in the Western Alps, **Geology**, 31, 601-604

SYNERGISTIC ACTIVITIES

-2004-2005: undergraduate and graduate general education; organizer of the meeting on *Andean Geology* for undergraduate students at Potsdam University;

-2005: organizer of the Distinguished Lecture series (Graduate School of Earth Surface Processes) for graduates, post graduates and faculty members at Potsdam University.

-September 2006: high level general education (graduate-post to graduate level); organizer of the workshop '*From source to sink. The detrital record of orogenic evolution; quantitative techniques in provenance studies';*

at the International conference: ‘Shaping the Earth’s surface, Dynamics and changing environments’. September, 25-28, 2006, University of Potsdam, Germany.
-September 2008: convener of the session *“Detrital thermochronology”* at the 11th International Conference on Thermochronometry; Anchorage (Alaska).

COLLABORATORS & OTHER AFFILIATIONS

Collaborators in the last 48 months
Prof. Manfred Strecker (University of Potsdam, Germany)
Dr. Edward Sobel (University of Potsdam, Germany)
Prof. Peter DeCelles (University of Arizona, Tucson, USA)
Prof. Brian Horton (UCLA; USA)
Prof. Paul Kapp (University of Arizona, Tucson, USA)
Prof. Eric Ferré (Southern Illinois University, Carbondale, USA)
Prof. Lindsay Schoenbohm (Ohio State University, Columbus, USA)
Prof. Andrea Di Giulio (University of Pavia, Italy)
Dr. Sanjeev Gupta (Imperial College of London, UK)
Dr. Ricardo Alonso (University of Salta, Argentina)
Prof. George Hilley (Stanford University)

Graduate and postgraduate advisors
Jan Wijbrans, Giovanni Bertotti, Sierd Cloetingh, Paul Andriessen (Vrije University, Amsterdam, The Netherlands); Manfred Strecker (University of Potsdam, Germany).

Students advised
Jan Arndt (University of Potsdam); Jörn Hauer (University of Potsdam); Chiara Barbieri (University of Pavia)
Current students
Sharon Bywater (University of Wyoming)
John Trimble (University of Wyoming)

AWARDS

July 2006: **Sofja Kovalevskaja Award** (four years of independent research funds: 750,000euro, for the PI Dr. Carrapa and her students from the Alexander von Humboldt Foundation). The PI could not accept this award due to other commitments.
January 2004-December 2005: **Research Fellowship** from the Alexander von Humboldt Foundation;
November 1998: **Master Thesis Fellowship** from the Academy of Sciences and Letters of Milano (Italy) for the best thesis of the year in sedimentology.

Sandeep Singh

Department of Earth Sciences, Indian Institute of Technology Roorkee,
Roorkee – 247 667, INDIA

EDUCATION

Lucknow University, Luknow	Geology	B.Sc., 1984
University of Roorkee, Roorkee	Applied Geology (six semester)	M.Tech., 1987
University of Roorkee, Roorkee	Applied Geology	Ph.D., 1994

PROFESSIONAL EXPERIENCE

March 89-April 96	Research Scientific "B", University of Roorkee, Roorkee
April 96-Jan 07	Assistant Professor in Geology, University of Roorkee (till Sep 2001) now it is Indian Institute of Technology Roorkee, Roorkee
Jan 07-present	Associate Professor

PUBLICATIONS MOST RELEVANT TO THIS PROJECT (5)

A.K. Jain**,** Sandeep Singh and R.M. Manickavasagam (2002). Himalayan Collision Tectonics. Gondwana Research Group Memoir No. 7, 114 pp.

A. K. Jain, Sandeep Singh, RM. Manickavasagam, M. Joshi and P. K. Verma (2003) HIMPROBE Programme: Integrated studies on geology, petrology, geochronology and geophysics of the Trans-Himalaya and Karakoram. Geological Society of India Memoir no. 53, pp. 1-56.

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., and Manickavasagam, R.M., 2005, Early, steep subduction of India beneath Asia, Earth and Planetary Science Letters, v. 234, pp. 83-97.

Sandeep Singh, Rajeev Kumar, Mark E. Barley and A.K. Jain, 2007, SHRIMP U-Pb ages and depth of emplacement of Ladakh Batholith, eastern Ladakh India. Journal of Asian Earth Sciences, 30 (3-4), 490-503.

Mary L. Leech, Sandeep Singh and A.K. Jain (2007) Zircon reveals complex history in the UHP Tso Morari Complex, western Himalaya. International Geological Review, 49, 313-328.

OTHER PUBLICATIONS (5)

A. K. Jain, Kumar, D., Sandeep Singh, Kumar, A. and Lal, N (2000): Timing, quantification and tectonic modelling of Pliocene Quaternary movements in the NW Himalaya: evidences from fission track dating. Earth and Planet. Sci. Letters, 179, 437-451.

Singh, Sandeep (2003) Conventional and SHRIMP U-Pb zircon dating of the Chor Granitoid, Himachal Himalaya. Journal of Geological Society of India. V. 62 (5), pp. 614-626.

Singh, Sandeep, M.E. Barley, S.J. Brown, A.K. Jain and RM. Manickavasagam (2002) SHRIMP U-Pb in zircon geochronology of the Chor Granitoid: evidence for Neoproterozoic magmatism in the Lesser Himalayan granite belt of NW India. Precambrian Research, 118, pp. 285-292.

Singh, Sandeep and A. K. Jain (2003) Himalayan Granitoids. *In:* Singh, S. (ed.) *Granitoids of the Himalayan Collisional Belt,* Journal of the Virtual Explorer, v. 11, 1-20.

Sandeep Singh, Stefan Claesson, A.K. Jain, David G. Gee, P.G. Andreasson and RM. Manickavasagam (2006). 2.0 Ga granite of the lower package of the Higher Himalayan Crystallines (HHC), MagladKhad, Sutlej Valley, Himachal Pradesh, India. Journal of Geological Society of India, 67 (3), 295-300.

SYNERGISTIC ACTIVITIES

Member, *Development Research Committee* of Research Council for culture and Society of Academy of Finland.

Secretary, ***Commission on Granite***, *International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)*, An Association of the International Union of Geodesy and Geophysics, 2001-2004.

Member of Editorial Board, *Virtual Explorer,* Electronic Journal published from Monash University Australia, ISSN numbers: 1441-8126 (for the printed journal), 1441-8142 (for the online journal) and 1441 8134 (for the CD-ROM's journal).

Guest Editor, *19th Himalayan-Karakoram Workshop volume* **Journal of Asian Earth Sciences** Published by **Elsevier Publication,** Volume 29 issue 2-3

Regional Editor, *Himalayan Notes,* published from Department of Geology, Box 871404, Arizona State University, Tempe, AZ 85287-1404, USA.

Involved in running and maintaining of National Facility on Geochronology/Isotope Geology at Indian Institute of Technology

Involved in Himalayan Geotransect Programme (HIMPROBE) and also in HIMPROBE-East.

Organized a workshop on Himalayan Tectonics (the HIMPROBE Result) in October 2003

Member of the core team Establishing a National Facility for ^{40}Ar-^{39}Ar Geo-thermochronology at the Indian Institute of Technology (IIT) Bombay

Convenor, National Conference on Geochemical and Isotopic Evolution of Continental Crust, IITRoorkee, November 2005.

Organizing Secretary, 23rd Himalayan-Karakoram-Tibet Workshop, Leh, India in 2008.

Member, School Management Committee, Adarsh Bal Niketan, IIT Roorkee.

Member, Core-group, Intellectual Property Right (IPR) Cell, IIT Roorkee.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators

Prof. D.G. Gee, Prof. S. Claesson and Dr. P.G. Andreasson, Lund University and National Museum of natural history, Stockholm, Sweden 1987-91

Prof. Mark E. Barley, Centre for Global Metalogeny, School of Earth and Geographical Science, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

Dr. Jan Koslar, Department of Geochemistry and Mineralogy, Charles University, Albertovn 6, Prague, 2, 128 43, Czeck Republic

Prof. Ernst Hegner, Professor of Geochemistry and Geochronology, Head Isotope Laboratory, Department of earth Sciences, Geochemistry Section, Ludwig-Maximlans-Universitat, Munchen, Germany

Students supervised for Ph.D.

Rajeev Kumar (2005), Th. Nikunj Bihari Singha (2007), James Pabem (on going), M. Rogibala (on going), Ramesh Lasiram (on going)

Students supervised for Post graduate dissertation

Sanjeev Bhoi (2000), Arnindam Chakraborty (2000), Biswajayee A. Patra (2002), Rajnish Ranjan (2002), Iswar Chand Das (2003), Ajay Kumar Arya (2004), Manish Bisht (2004), Satya Prakash Mohanty (2004), Dibya Prakash Dahl (2006), Swagata Dey (2006), Vipin Paliwal (2007), Kaushal Singh Barfal (2007), Rahul R. (2007), Jaganath Mukherjee (2007)

HONORS AND AWARDS

1990-1991	Doctoral Fellowship to Sweden
1994	Khosala Annual Research Award (silver medal)
2000-2001	BOYSCAST Fellow
2002-2003	INSA-DFG Exchange Fellowship to Germany
2005	Fellowship to visit Swedish Museum of Natural History for U-Pb work

Arvind K. Jain

Department of Earth Sciences,
Indian Institute of Technology Roorkee,
Roorkee – 247 667, INDIA

EDUCATION

Lucknow University, Luknow	Geology	M.Sc., 1964
University of Roorkee, Roorkee	Geology	Ph.D., 1970

PROFESSIONAL EXPERIENCE

Aug 71-Sept. 74	Scientific Officer, Wadia Institute of Himalayan Geology, Delhi (now in Dehradun)
Oct. 74-July 76	Lecturer in Geology, University of Roorkee, Roorkee
Aug. 76-Dec. 85	Reader in Geology, University of Roorkee, Roorkee
Jan. 86-June 2007	Professor in Geology, University of Roorkee (till Sep 2001) now it is Indian Institute of Technology Roorkee, Roorkee
July 2007-onwards	Emeritus Fellow, IIT Roorkee

PUBLICATIONS MOST RELEVANT TO THIS PROJECT (5)

A. K. Jain, Rm. Manickavasagam, Sandeep Singh, and S. Mukherjee (2005). Himalayan collision zone: new perspectives - its tectonic evolution in a combined ductile shear zone and channel flow model. Journal of Himalayan Geology, 26 (1), 1-18.

A.K. Jain, Sandeep Singh and R.M. Manickavasagam (2002). Himalayan Collision Tectonics. Gondwana Research Group Memoir No. 7, 114 pp.

A. K. Jain, Sandeep Singh, RM. Manickavasagam, M. Joshi and P. K. Verma (2003) HIMPROBE Programme: Integrated studies on geology, petrology, geochronology and geophysics of the Trans-Himalaya and Karakoram. Geological Society of India Memoir no. 53, pp. 1-56.

Mary L. Leech, Sandeep Singh and **A.K. Jain** (2007) Zircon reveals complex history in the UHP Tso Morari Complex, western Himalaya. International Geological Review, 49, 313-328.

M.L. Leech, Sandeep Singh, **A.K Jain,** S.L. Klemperer, and R.M. Manickavasagam (2005) Early, steep subduction of India beneath Asia, Earth and Planetary Science Letters, v. 234, pp. 83-97.

OTHER PUBLICATIONS (5)

A. K. Jain, D., Kumar, Sandeep Singh, A. Kumar, and N Lal (2000) Timing, quantification and tectonic modelling of Pliocene Quaternary movements in the NW Himalaya: evidences from fission track dating. Earth and Planet. Sci. Letters, 179, 437-451.

A. K. Jain, Sandeep Singh and RM. Manickavasagam (2003) Intracontinental Shear Zone in the Southern Granulite Terrain: Their Kinematics and Evolution. In: Ramakrishna, M. (ed.) Tectonics of Southern Graulite Terrain Kuppam-Palni Geotransect, Geological Society of India Memoir 50, pp. 225-253.

Rajeev Kumar, Nand Lal, Sandeep Singh, and **A.K. Jain** (2007) Cooling and exhumation of the Trans-Himalayan Ladakh Batholith, as constrained by Fission track apatite and zircon ages. Current Science, 92(4), 490-496.

Singh, Sandeep and **A.K. Jain** (2003) Himalayan Granitoids. *In:* Singh, S. (ed.) *Granitoids of the Himalayan Collisional Belt,* Journal of the Virtual Explorer, v. 11, 1-20.

Singh, Sandeep, Mukherjee, P. K., **Jain, A. K**., Khanna, P. P., Saini, N. K. and Kumar, R. (2003) Source characterization and possible emplacement mechanism of collision-related Gangotri Leucogranite along Bhagirathi Valley, NW-Himalaya. *In:* Singh, S. (ed.) *Granitoids of the Himalayan Collisional Belt,* Journal of the Virtual Explorer, v. 11, 60-73.

SYNERGISTIC ACTIVITIES

Co-ordinatated a multidisciplinary – multitutional geotransect programme (HIMPROBE) in the NW Himalaya

Co-ordinating 17 institution for the HIMPROBE-East Programme in NE-Himalaya

Established a National Facility on Geochronology/Isotope Geology at Indian Institute of Technology Roorkee, Roorkee

Member of:

National Committee on Paleoseismicity by DST
National Committee on IGCP 276
International Association of Structure and Tectonics
Joint Secretary, Indian Geological Congress
Subgroup on "Structure and Tectonics", WIHG, Dehradun
Council, Geological Society of India
Governing Body, WIHG, Dehradun

COLLABORATORS & OTHER AFFILIATIONS

Collaborators

Prof. D.G. Gee, Prof. S. Claesson and Dr. P.G. Andreasson, Lund University and National Museum of natural history, Stockholm, sweden 1987-91

Prof. S. Nishimura, Kyoto University, Japan 1987-1990

Prof. E. Stump and Dr. R.B. Sorkhabi, Arizona State University, Tempe, USA, 1993-96.

Prof. K. Arita, Hokkaido University, Japan, 2003-onward

Students supervised for Ph.D.

S.K. Gupta (1983), P.K. Sharma (1985), A. Anand (1986), R.C. Patel (1992), M. Karamati Moezabade (1992), Ashok Kumar (1992), A. Asokan (1993), Sandeep Singh (1994), A.H. Tizro (1995), Yash Paul (1995), J. Das (1995), Devender Kumar (1999), Bahman Soleimani (1999), Rajeev Kumar (2005), Soumyajit Mukherjee (2007)

HONORS AND AWARDS

1965-1969: Junior Research Fellowship (U.G.C.)
1969-1971: Senior research Fellowship (U.G.C.)
1979: Young Scientist: Exchange Programme- Government of India and United Kingdom
1979-1981: Post-doctoral Fellowship: *Alexander von Humboldt Foundation*, Germany
1991: Visiting Scientist: Institute of Petrology and Mineralogy, Lund University, Lund, Sweden
1994 Khosla Research Award: University of Roorkee, Roorkee,
2003 Invitation Fellowship, JSPS, Japan
2004 Fellow of the Indian National Science Academy (FNA), New Delhi

PROF. BALDEV ARORA

Director, Wadia Institute of Himalayan Geology (WIHG), Dehradun 248 001, India

EDUCATION

M.Sc. (Geophysics)	1968	Banaras Hindu University
Ph.D. (Geophysics)	1977	Bombay University

AWARDS AND HONOURS

National Mineral Award – 2002
Fellow: Indian Geophysical Union
Fellow: National Academy of Sciences, Allahabad
Fellow: Geological Society of India
Convener, 17th International Workshop on Electromagnetic Induction in the Earth,
NGRI, Hyderabad, India Oct 18-23, 2004
Member, IAGA Executive Committee

PROFESSIONAL EXPERIENCE

Indian Institute of Geomagnetism, Mumbai	1971	Research Associate to Associate Professor
	1992	Professor & Head, Solid Earth Geomagnetism
WIHG, Dehra Dun	2003	Director
Visiting Fellow	1981	Australian National Univ., Canberra
Visting Professor	1991	Univ. of Oulu
Visiting Professor	1995-97	National Inst. Space Research, SJC, Brazil

MOST RELEVANT PUBLICATIONS (5)

B.R. Arora and C.D. Reddy, The deep conductive structures of the Garhwal Himalaya and their seismotectonic significance, In: Uttarkashi Earthquake, Eds. H.K. Gupta and G.D. Gupta, Mem. Geol. Soc. India, **30**, 109-124, 1994.

Arora, B., M.J. Unsworth, G. Rawat, Deep resistivity structure of the Northwest Indian Himalaya and its tectonic implications, Geophys. Res. Lett., 34, L04307, doi:10.1029/2006GL029165, 2007.

B.R. Arora, W.H. Campbell, E.R. Schiffmacher, Upper mantle electrical conductivity in the Himalayan region, J. Geomagn. Geoelectr., **47**, 653-665, 1995.

B.R. Arora, Seismotectonics of the Frontal Himalaya through the electrical conductivity imaging, In: Seismotectonics in Convergent Plate Boundaries, Eds. Y. Fujinawa and A. Yoshida, Terra Scientific Publishing Company, Tokyo, pp261-272, 2002.

C.D. Reddy and **B.R. Arora,** Quantitative interpretation of geomagnetic induction response across the thrust zones of the Himalaya along the Ganga-Yamuna valley, J. Geomagn. Geoelectr, **45**, 775-785, 1993.

OTHER SIGNIFICANT PUBLICATIONS (5)

B.R. Arora and M.V. Mahashabde, A tranverse conductive structure in the northwest Himalaya, Phys. Earth Planet Inter., **45**, 119-127, 1987.

B.R. Arora, F.E.M. Lilley, M.N. Sloane, B.P. Singh, B.J. Srivastava and S.N. Prasad,, Geomagnetic induction and conductive structures in northwest India,, Geophys. J. R. Astro. Soc., **69**, 459-475, 1982.

B.R. Arora and Sri Niwas, eds., , "**Natural Source Electromagnetic Induction in the Earth**", New Age International (P) Ltd. Publishers, New Delhi, 1997.

B.R. Arora, P.B.V.Subba Rao and Vipul Nagar, Electrical conductivity signatures of plume-lithosphere interactions in the Indian Ocean, In: Indian Continental Lithosphere: Emerging Trends, Eds. T.M. Mahadevan, **B.R. Arora**, K.R.Gupta, Mem. Geol. Soc.of India, **53**, 393-418, 2003.

F.E.M. Lilley and **B.R. Arora,** The sign convection for quadrature arrows in geomagnetic induction studies, Rev. Geophys. Space Phys., **20**, 513-518, 1982.

SHYAM SUNDAR RAI

National Geophysical Research Institute, Uppal Rd., Hyderabad 500 007, India

EDUCATION

B.Sc. (Hons.)	1973	Banaras Hindu University	Phys. (Hons), Maths, Geology
M.Tech.	1977	University of Roorkee	Geophysics
Ph.D.	1988	Indian School of Mines	Geophysics

EMPLOYMENT

Scientist G (Group Leader, Seismic Tomography) National Geophysical Research Institute
Visiting Professor, Indian Institute of Science Education and Research - Kolkata

HONORS AND AWARDS

Fellow, National Academy of Sciences, India	2005
Fellow, Indian Academy of Sciences	1996
Krishnan Medal, Indian Geophysical Union	1991
CSIR Young Scientist Award	1988

GRADUATE STUDENTS

PhD awarded: G. Mohan, ISM, Dhanbad, 1995; Suryaprakasam, Osmania Univ., Hyderabad, 2001; S.K. Singh, Osmania Univ., Hyderabad, 2003; S.K. Gupta, Osmania Univ., Hyderabad, 2004

PUBLICATIONS MOST RELEVANT TO THIS PROJECT (5)

Rai, S.S., Padhi, A., Ashish, and Rajgopala Sarma, P. High crustal seismic attenuation in Ladakh-Karakoram. *Bull. Seismolog. Soc. Am.,* in review.

Prakasam, K.S.**, Rai, S.S.**, Chandra, S. Gaur, V. K., and Priestley, K., 2008, Complex mantle transition zone discontinuities beneath western Himalaya, Ladakh-Karakoram, *Geophys. J. Int., in press.*

Jagadeesh, S. and **Rai, S. S.**, 2007, Thickness, composition and evolution of the Indian Precambrian crust, *Precambrian Research*, doi: 10.1016/j.precamres.2007.07.009

Mukhopadhyay, S., Tyagi, C., and **Rai S.S.**, 2006. The attenuation mechanism of seismic waves in northwestern Himalayas, *Geophysical J. International,* **167**, 354-360

Rai, S.S., Priestley, K., Gaur, V.K., Singh, M. P., and Searle, M., 2006, Configuration of the Indian Moho beneath the NW Himalaya and Ladakh, *Geophys. Res. Lett.,* **33**, no.15, 5 pp., L15308.

OTHER PUBLICATIONS (5)

Mitra, S., Priestley, K., Gaur, V.K., and **Rai S.S.**, 2006. Frequency-dependent Lg attenuation in the Indian Platform. *Bull. Seismolog. Soc. Am.,* **96**, 2449-2456.

Mitra, S., Priestley, K., Gaur, V.K., **Rai S.S.**, and Haines, J., 2006. Variation of Rayleigh wave group velocity dispersion & seismic heterogeneity of the Indian crust & uppermost mantle. *Geophysical J. International,* **164,** 88-98.

Rai S.S., Priestley K.F., Prakasam K. S., Srinagesh D., Gaur V.K. and Du Z. 2003, Crustal shear velocity structure of the south Indian shield, *J. Geophys. Res*., **108**(B2), 2088, doi:1029/2002JB001776.

Rai, S.S., Prakasam K.S. and Agrawal N., 1999, Pn wave velocity and Moho geometry in North Eastern India, *Proc. Ind. Acad. Sci.,* **108**, 297-304.

Rai, S.S., Gupta, S., Priestley, K., and Gaur, V.K., 2004, On the efficacy of the recent crustal images of the Indian shield from receiver functions, *Current Science,* **87,** 582-583.

MEMBERSHIP OF SCIENTIFIC COMMITTEES

Member, Research Advisory Committee (Earth and Environment Science), CSIR, 2001 - present
Member, PAMC, Seismology (1998 – 2001), SERC (2003 - present), DST, New Delhi,
Member, Sectional Committee, Indian Academy of Sciences (1999 – 2002).

B. RAJENDRA PRASAD

National Geophysical Research Institute, Uppal Rd., Hyderabad 500 007, India

EDUCATION

B.Sc. (Hons.)	Osmania University (Class I)
M.Sc (Tech.) (Exploration Geophysics)	Osmania University (Class I, First rank)
Ph.D.	Osmania University

EMPLOYMENT

Scientist F, Grade IV (Deputy Director), NGRI Hyderabad	1998 to present
Scientist A through E, National Geophysical Research Institute	1978 - 1998

PUBLICATIONS MOST RELEVANT TO THIS PROJECT (5)

RAJENDRA PRASAD, B., & Vijaya Rao, V., 2005. Seismic imaging of Indian continental crust. Journal of Himalayan Geology, 26,125-138.

RAJENDRA PRASAD, B., Kesava Rao, G., Mall, D.M., Koteswara Rao, P., Raju, S., Reddy, M.S., Rao, G.S.P., Sridher, V., Prasad, A.S., 2007. Tectonic implications of seismic reflectivity pattern observed over the Precambrian Southern Granulite Terrain, India. *Precambrian Research*, **153**, 1-10.

RAJENDRA PRASAD, B., G. Kesava Rao, D.M.Mall, P.KoteswaraRao, S. Raju, , M.S.Reddy, G.S.P.Rao, V.Sridher and ASSRS Prasad, 2006, Deep Seismic Reflection Study over the Southern Granulite Terrain along Vattalkundu-Kalugumalai segment: Some preliminary results, *Gondwana Research, 10,* 29-40.

RAJENDRA PRASAD, B., Vijaya Rao, V. and Reddy, P.R.,1999, Seismic and magnetotelluric studies over a crustal scale fault zone for imaging a metallogenic province of Aravalli Delhi Fold Belt region, *Current Science*, V.76 No.7,pp1027-1031.

RAJENDRA PRASAD, B., Tewari, H.C., Vijaya Rao, V., Dixit, M.M. and Reddy, P.R., 1998. Structure and tectonics of the Proterozoic Aravalli Delhi Fold Belts in the NW India from deep seismic reflection studies. *Tectonophysics*, 288, pp.31-41

OTHER PUBLICATIONS (5)

RAJENDRA PRASAD, B., Behera, L., and P. Koteswara Rao, P. 2006. A tomographic image of upper crustal structure using P and S wave seismic refraction data in the southern granulite terrain (SGT), India, Geophys. Res. Letts., 33, L14301. doi:10.1029/2006GL026307.

Reddy, P.R., RAJENDRA PRASAD, B., Vijaya Rao, V., Prakash Khare, Keshav Rao, G., Murty, A.S.N., Sarkar, D., Raju, S., Rao, G.S.P., and Sridhar, V., 1995. Deep seismic reflection profiling along Nandsi-Kunjer section of Nagaur-Kunjer transect, preliminary results, In: Sinha Roy, S. and Gupta, K.R. (Eds.), Continental crust of NW and Central India, *Geo.Soc.India, Mem. 31*, pp. 353-372

Reddy, P.R., B.RAJENDRA PRASAD, V.V.Rao, K.Sain, P.P.Rao, P.Khare and M.S.Reddy, 2003. Deep Seismic Reflection and Refraction / Wide-angle Reflection studies along Kuppam-Palani Transect in Southern Granulite Terrain, *Memoir, Geological Society of India*, 50, pp.70-106.

Tewari, H.C., RAJENDRA PRASAD, B., Vijaya Rao, V., Reddy, P.R, Dixit, M.M, and Madhava Rao, N., 1997. Crustal reflectivity paramater for deciphering the evolutionary processes across the Proterozoic Aravalli Delhi Fold Belt. *Jour.Geol.Soc.India,* V.50, pp.779-785.

Vijaya Rao, V., RAJENDRA PRASAD, B., Reddy, P.R and Tewari, H.C., 2000. Evolution of of the Proterozoic Aravalli Delhi Fold Belt in the NW India from deep seismic reflection studies. *Tectonophysics*, v.327, pp.109-130.

PROF. WEI WENBO

Professor, School of Geophysics and Information Technology, China University of Geosciences, Beijing
and
Geo-detection Laboratory, State Key Laboratory of Geological Processes and Mineral Resources,
Ministry of Education, Beijing

EDUCATION

Ph.D. (Geophysics)	China University of Geosciences, Beijing

PROFESSIONAL EXPERIENCE

China University of Geosciences, Wuhan	1970-1975	Faculty member
China University of Geosciences, Beijing	1975-2007	Associate to Full Professor

MOST RELEVANT PUBLICATIONS

Chen, L., J.R. Booker, A.G. Jones, N. Wu, M.J. Unsworth, **W. Wei,** and H. Tan, Electrically Conductive Crust in Southern Tibet from INDEPTH magnetotelluric surveying, Science, **274**, 1694-1696, 1996.

Wei, W., M.J. Unsworth, A.G. Jones, J.R. Booker, H. Tan, K. D. Nelson, L. Chen, S. Li, K. Solon, P.A. Bedrosian, S. Jin, M. Deng, J. Ledo, D. Kay, B. Roberts, Detection of widespread fluids in the Tibetan crust by magnetotelluric studies, Science, **292**, 716-718, 2001.

Unsworth, M.J., **W. Wei**, A.G. Jones, S. Li, P.A. Bedrosian, J.R. Booker, S. Jin, and M. Deng, Crustal and upper mantle structure of Northern Tibet imaged with magnetotelluric data, J. Geophys. Res., **109**, doi:10.1029/2002JB002305, 2004.

Unsworth, M.J. A.G. Jones, **W. Wei**, G Marquis, S. Gokarn, J. Spratt, Crustal rheology of the Himalaya and Southern Tibet inferred from magnetotelluric data, Nature, **438**, 78-81, doi:10.1038/nature04154, 2005.

Wei, W., S. Jin, G. Ye, M. Deng, H. Tan, M.J. Unsworth, J. Booker, A.G. Jones, S. Li, Features of faults in the central and northern Tibetan plateau based on results of INDEPTH (III)-MT, Earth Science Journal of China University of Geosciences,**31**(2), 257-265, 2006.

OTHER SIGNIFICANT PUBLICATIONS

Nelson, K.D., Zhao, W., Brown, L.D., Kuo, J., Che, J., Liu, X., Klemperer, S.L., Makovsky, Y., Meissner, R., Mechie, J., Kind, R., Wenzel, F., Ni, J., Nablek, J., Leshou, C., Tan, H., **Wei, W.**, Jones, A.G., Booker, J.R., Unsworth, M., Kidd, W.S.F., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Wu, C. Sandvol, E., Edwards, M., Partially molten Middle Crust Beneath Southern Tibet : Synthesis of Project INDEPTH results*,* Science, **274**, 1684-1686, 1996.

Li, S., M.J. Unsworth, J.R. Booker, **W. Wei**, H. Tan and A.G. Jones, Partial melt or aqueous fluids in the Tibetan crust: constraints from INDETH magnetotelluric data, Geophys. J. Int., **153**, 289-304, 2003.

Spratt, J.E., A.G. Jones, K.D. Nelson, M.J. Unsworth and the INDEPTH MT team, Crustal structure of the India-Asia collision zone, southern Tibet, from INDEPTH MT investigations, Physics of the Earth and Planetary Interiors*,* **150**, 227-237, 2005.

Solon, K., A.G. Jones, K.D. Nelson, M.J. Unsworth, **W. Wei**, H. Tan, H., S. Jin, M.Deng, J.R. Booker, S. Li, P. Bedrosian, 2005. Structure of the crust in the vicinity of the Banggong-Nujiang suture central Tibet from INDEPTH magnetotelluric data, Journal of Geophysical Research, **110**, B10102, doi: 10.1029/2003JB002405, 2005.

UNIVERSITY OF ALBERTA

Prof. Mary Leech
Department of Geosciences
San Francisco State University
San Francisco
CA 94132
USA

November 8th 2007

Dear Mary,

I am writing to express my continued enthusiasm to participate in the Himprobe project. I was disappointed that the previous NSF submission was declined, but remain convinced that the proposed research in the Indian Himalaya is important and will capitalize on the recent geophysical work by Indian and Chinese scientists.

Since 2002 I have collaborated with both the Indian MT groups that are working in the Himalaya. I have worked with Dr. Gokarn at the Indian Institute of Geomagnetism and reprocessed his broadband MT data from the Northwest Himalaya. These data were compared to the INDEPTH data in Southern Tibet in a joint paper in *Nature* in 2005. I have also worked with Prof. Arora at the Wadia Institute of Himalayan Geology and have hosted one of his research group, Mr. Gautam Rawat, for a visit to my department. We have recently published the results of this collaboration on long-period MT data in *Geophysical Research Letters*.

These two MT datasets have impressed upon me the importance of additional geophysical studies in the NW Himalaya. From a logistical perspective this region has the advantage that a traverse can be made from the Indian Craton to the Tibetan Plateau, without crossing political boundaries. However, the scientific reasons for working here, as eloquently described in your proposal, are more compelling. Since the previous Himprobe submission there has been a significant amount of Chinese geophysical work in Western Tibet. My colleagues at the China University of Geoscience in Beijing, led by Professor Wei Wenbo, have recently collected a major broadband MT transect at 80°E. While we will need to negotiate the details, I am confident that we will be able to integrate this Chinese work with new MT data that is being collected in India. This includes both the existing Himprobe data and new work that would be supported by this proposal.

My updated plans for Himprobe MT research take into account the continued Indian MT work in the Northwest Indian Himalaya and the new Chinese studies in Western Tibet. This will require (a) reduced MT field effort in India focused on the two profiles, (b) the inclusion of existing Chinese data and (c) collection of long-period MT data collection in Western Tibet.

In terms of practical details, I have Canadian funds to support graduate students from NSERC. I won't require salary support, as I receive 12 months salary from the University of Alberta. I will continue to host Indian visitors for MT data analysis and will be able to reciprocate with visits to work with Dr. Arora and his group at the Wadia Institute. I and my graduate students will be available to play a major role in Indian-led MT fieldwork over the next 4 years. However, it is clear that my Indian colleagues are quite capable of collecting the MT data on their own, and the most important aspect of this proposal will be to work together on MT data analysis and synthesis with other geological and geophysical data from the region. If long-period data collection goes ahead in western Tibet in 2009, then this will be very cost effective as our MT instruments will already be in China as part of the INDEPTH-4 program
.
I am aware of the potential issues surrounding the financial support of non-US based scientists in collaborative projects such as this. Previous research support to my group from the Continental Dynamics Panel has been greatly appreciated, and is most certainly not taken for granted. However, as we have previously discussed, projects such as Himprobe depend critically on having the right local contacts in both India and China. I believe that my work in Tibet and the Himalaya since 1995 gives me a unique position to be able to co-ordinate the research efforts of scientists in both India and China.

Please let me know if additional details are required to define my role in this project. I believe this proposal will generate significant new results with a very modest budget. It will effectively build on some exciting research that is developing on both sides of the Himalaya in both India and China.

Sincerely

Martyn Unsworth

Martyn Unsworth
Professor
University of Alberta

Indian Institute of Technology, Roorkee

DEPARTMENT OF EARTH SCIENCES

Dr. Sandeep Singh
Assoc. Professor

ROORKEE-247 667,UTTARANCHAL, INDIA
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Dated: October 21, 2007

Dear Dr. Mary Leech

I am glad to inform you that the Department of Science and Technology, Government of India has funded us a research proposal to work out the Himalayan Collision Tectonics with special emphasis on migmatites and leucogranite generation, we have 2.1 million rupees for this project. I also got funding from Ministry of Human Resource Development (MHRD), New Delhi supporting this project and to establish Cathodoluminicence (CL) Facility at IIT Roorkee, 1.0 million rupees have been allocated for this project. Apart from that I have submitted a project “Migmatite, decompression and exhumation of the Higher Himalayan Crystalline (HHC), Sikkim Himalaya”.

I am very happy to know, when you visited us, and came to know that you are planning to file a project to NSF to work on the Beas and Sutlej Valley Areas. I take this opportunity to invite you and your group to collaborate with our group at the Indian Institute of Technology Roorkee. We will be very happy to carry out lab work (Rb-Sr WR-mineral dating and Geochemistry) as well as active participation in the field. In this collaborative project we will provide complete access to our Ultra-clean lab as well as geochemical facility including our LA-ICP-MS lab (at Institute Instrumentation Centre), EPMA and TRITON T1 Mass Spectrometer (at National Facility on Geochronology/Isotope Geology).

Your research work is an important research that fits well with our multidisciplinary HIMPROBE programme which we conducted under the coordinatorship of Prof. A.K. Jain, who is also an active member of our team. We have extended the HIMPROBE programme to eastern sector under the coordinatorship of Prof. A.K. Jain. For this next phase of HIMPROBE project we have received funding from DST for 1.6 million rupees as a Roorkee component which includes fieldwork only.

I am positive that once you get this project we will come out with exciting results.

Sandeep Singh

(Dr. Sandeep Singh)
Electronically Signed
Head P.I. in India

Indian Institute of Technology, Roorkee

Prof. A.K. Jain, FNA

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November 14, 2007

Dear Dr. Leech

It was extremely nice to have interacted with you during the field work in Ladakh Himalaya. During the discussions it was known that you are interested to file a NSF project on the Ladakh and Kinnaur Himalaya. The components you intend to take up in your project tenure are complementary to our multidisciplinary HIMPROBE program which was conducted under the DST sponsored coordinated program. I had coordinated this program at the national level, hence I fully realize the importance of your program in filling in the gaps in our existing knowledge of the western sector in the Himalaya.

To augment the same geotransect program, we are of the opinion that we should extend the same type multidisciplinary-multi-institutional program in other sectors of the Himalaya. In this regard, the DST has started another geotransect program as HIMPROBE – East. In this project we undertaken crucial project in the Subansiri region of Arunachal Pradesh, adjoining to the Eastern Himalayan Syntaxis.

To augment the Ar-Ar geochronology in the country, the DST is actively considering our proposal on the NW Himalaya, wherein we will be collaborating with the Indian Institute of Technology Bombay for research along the HIMPROBE corridor. It is likely that funds would be made available soon.

I am sure that we will be able to solve some of the basic problems of the Himalayan Tectonics with your collaboration wherein new scientific inputs will provide new thinking.

AK Jain

(Dr. A.K. Jain)

राष्ट्रीय भूभौतिकीय अनुसंधान संस्थान
NATIONAL GEOPHYSICAL RESEARCH INSTITUTE
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(COUNCIL OF SCIENTIFIC & INDUSTRIAL RESEARCH)
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Dr. Shyam S. Rai
Scientist G and Group Head
Visiting Professor, Indian Institute of Science, Education & Research, Kolkata

13.11.07

Subject: Participation in INDO-US research program in Himalaya

Dear Simon
Greetings!
I reconfirm my commitment to work on the joint Indo-US research program related to modeling of the internal structure of western Himalaya using broadband seismological observations. As you know we have been working in western and central Himalaya since 2002. During 2002-2003 we made a broadband seismic profile from Delhi to Karakoram. Some of the results from profile are published (GRL and GJI), accepted for publication in GJI and others are submitted for publication in EPSL and BSSA. Most of the waveform data from this experiment is available with you as a part of our joint research co-operation to model the crustal structure from surface wave and also the study of crustal anisotropy. The initial results from this cooperative program have been submitted for presentation in the AGU 2007 meeting.
During May 2005- June 2007, we made an experiment in Kumaon Himalaya with a linear profile with ~20 broadband seismographs with inter-station spacing of 7 km from Lesser Himalaya to STD. The data is being analyzed. Initial results clearly bring out the signature of MHT and also discontinuous Indian Moho. Further a well defined shallow LVZ is imaged beneath Badrinath leucogranite. As we discussed earlier, I hope one of your students would be visiting NGRI next year for working on CCP imaging.
During 2007-2009 we would be acquiring data in Kumaon Himalaya with 30 broadband seismographs spread all over the region to investigate the seismicity pattern, earthquake mechanics and 3-D velocity, attenuation imaging. Most of our seismographs have Guralp CMG-3T 120 secs period seismometer and REFTEK data logger.
All our experiments have been funded by Deptt. Of Science and Technology and I hope the support would be available to me in future programs also. I would be most willing to participate in the Indo-US program to study the deep structural framework of western Himalaya. I would also welcome participation of US scientist in the field. It would be very appropriate that NGRI scientists visit your institute for data modelling and interpretation.
I look forward to working with you in deep exploration of Himalaya.
Regards

Srai
(Shyam S Rai)

Prof. Simon Klemperer
Deptt. Of Geophysics, Stanford University, USA

डा॰ बी॰आर॰ अरोड़ा
निदेशक
Dr. B.R. Arora
Director

वाडिया हिमालय भूविज्ञान संस्थान
(भारत सरकार के विज्ञान एवं प्रौद्योगिकी विभाग का एक स्वायत्तशासी संस्थान)
33, जनरल महादेव सिंह मार्ग, देहरादून – 248001 (उत्तराखण्ड)
WADIA INSTITUTE OF HIMALAYAN GEOLOGY
(An Autonomous Institution of
Deptt. of Science & Technology, Govt. of India)
33, General Mahadeo Singh Road
DEHRA DUN - 248001 (Uttarakhand)

Date: 15th November, 2007

Prof. Simon Klemperer,
Department of Geophysics,
Stanford University,
Mitchell Building 353,
Stanford CA 94305-2215, USA

Prof. Martyn Unsworth
Department of Physics and Institute for
Geophysical Research,
University of Alberta, Edmonton,
Alberta, T6G 2J1, CANADA.

Dear Prof. Simon Klemperer / Prof. Martyn Unsworth,

Wadia Institute of Himalayan Geology, an autonomous research institute of Department of Science and Technology, Government of India, confirms its participation in the multidisciplinary project "HIMPROBE: geology and geophysics in NW India testing competing models of Himalayan orogenesis" being submitted for NSF funding. The participation of the Wadia Institute in the above project will involve two major components.

MT surveys along the selected transects in collaboration with University of Alberta. The measurements on these profiles form part of the Institute's on-going activity to map the deep crustal structures for constraining the evolutionary models of the Himalaya. Further, using resistivity imaging as a proxy to rheological behaviour of the medium attempt would be to map the geometry of brittle ductile transition that control space-depth distribution of seismicity. For this work, WIHG will utilize the available 2 units of broadband MT units (Metronix - Germany) as well as 4 units of long period MT being procured from Livov Institute of Ukraine. Additional measurements required to achieve the projected objectives NSF project will be taken jointly. However, the main area of collaboration would be joint analysis and interpretation. Institute shall also welcome extension of these profiles to Nepal, Tibet and China to provide adequate coverage across the Indus-Suture Zone and Trans Himalayan sector. The teams have already established a strong collaborative program on the interpretation of MT data. Under this collaboration one paper is already published (Arora et al. GRL, 2007) as well as one young scientist Mr. Gautam Rawat was trained in the processing of MT data at the University of Alberta by Prof. Martyn Unsworth.

Second involvement of WIHG will be in the area of passive seismology. Here the primary responsibility of WIHG would be to deploy an areal array aimed at detecting and understanding the on-going seismicity in the TsoMorari-LeoPargil-Kinnaur Sector of the NW Himalaya. This sector located outside the concentrated Himalayan seismic belt has remained continuously active where the sources and nature of seismicity remains largely unquantified. Such a project would assist in understanding the structure but also have a clear hazards objective. For this objective, WIHG also proposes to fill-up the vital gaps in the proposed array to generate adequate data-base for detailed mapping of deep structures using principles of receiver functions. Additional attempts would be made to examine SKS phase splitting to quantify anisotropic properties of the Indian lithospheres.

Contd/- 2.

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Dr. B.R. Arora
Director

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For these studies, WIHG will bank upon its recently acquired broadband systems from M/s Nanometrics (Trillium 240 equipped by Taurus DAS). About 20 such instruments would be available for such experiments. It is expected that 10 more instruments presently employed in the NE syntaxial zone of India will also be shifted to provide dense coverage to provide regional coverage of the study area. Principal responsibility of collaborator headed by Prof. Klemperer of Stanford University would be in the design and plan of the experiment as well as providing training to young students of WIHG in joint processing and analysis.

Since both these activities form part of the projects sponsored by Ministry of Earth Sciences, Government of India, we will mobilize our own resources for operation of field work. Policy guidelines associated with this sponsored projects would permit sharing of processed data after initial period of 18 months and the first publication of results emerging from these data sets, Indian collaborator would be the first author. In subsequent publications authorship would be rotated. It is implied that the data set generated by joint efforts will be freely available to both the groups but would not be passed on to other users without the consent of each other.

From the Wadia Institute, Drs. V.M. Choubey, Naresh Kumar, Gautam Rawat, D. Hazarika and the undersigned shall participate in the joint project.

Institute welcomes and wishes both the team a great success in their endeavour.

BRArora

(B.R. Arora)

Dr. B.Rajendra Prasad
Scientist-F &Project Leader,
Controlled Source Seismology Project
National Geophysical Research Institute
Uppal Road, Hyderabad 500007

Date: November 15th, 2007

Dear Prof . Simon Klemperer

We really had good interactive meeting with you and your team at Stanford University during my visit. I am sorry for the delay in replying you. I was on lecture/examination tour of Andhra University, Vizag for a couple of days.

As I mentioned to you at Stanford, we have already recorded the Bhota- Barsar-Chail Chouk-Ner Chouk, two lines each measuring 35 and 65 km long across the Jwalamukhi Thrust , Main Boundary Thrust. It was an unexpectedly very successful experiment, given the logistics and topography using explosive as source. The final output was a good 30-fold reflection data set with reflections from the sedimentary column, Main Himalayan Thrust and from the Moho noticeable even on raw shot gathers. I did give you a portion the data set for our joint processing and interpretation efforts with an aim to ascertain that we did it right.

I may also state that we submitted a project to DST for funding for the Larji-Khoksar profile, from the Main Central Trust to the South Tibet Detachment to be recorded as an explosive source profile, with a source 60-kg in each hole with foldage of 30 over a line length of 100 km. I am expecting that it may be favorably received by DST and may materialize around the first quarter of 2009.

As discussed US-Stanford will provide as many 3-component seismic sensors and data-loggers as possible to record these shots at wide-angle, to complement our near-vertical experiment. We at NGRI will try our best in assisting with arranging import and export permits for this equipment though the shipping and deployment will be at US expense. We may also embark upon a joint NGRI-STANFORD project for processing and interpretation of the data sets acquired (both near-vertical and wide-angle). I understand that the first paper will be first-authored by an Indian scientist followed by others.

In fact NGRI is planning to carry out under its In house R& D effort a Lithospheric scale N-S transect to characterize the Indian continental Lithosphere. This huge campaign, though in formative stage, has a priority to cover Tso-Morari and Indus Suture Zone in the immediate future probably in early 2010/2011. If permissions comes by I am plan to involve Stanford University researchers as per their availability/schedule

Best regards,

(Dr.B.Rajendra Prasad)

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To: Professor Simon Klemperer
Department of Geophysics
Stanford University
U.S.A.

November 16th 2007

Dear Prof. Klemperer,

We have been interested to learn from Martyn Unsworth about your proposed HIMBROBE research project in India. As you know, China University of Geosciences in Beijing has been working in Western Tibet in the last couple of years and we have just collected a new MT profile across the Banggong Suture Zone at 80 degrees east.

I would be interested to discussing a plan to combine our data with those already collected in India, as well as those that you may collect in the coming years of the HIMPROBE project.

Obviously we would need to make a formal contract to discuss the important details of finances, permission and publications. However, I would like to state our interest to work in this project with you. It will very important to make long-period MT measurements on the transect in Western Tibet.

Sincerely,

Wei Wenbo Wei Wenbo
Professor
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Dr. Mary Leech
Department of Geosciences
San Francisco State University
San Francisco, CA 94132

November 6, 2007

Dear Mary,

There will no problem providing time on the SHRIMP-RG for your proposed work on your HIMPROBE project. We are charging $600 per day for use of the ion probe for Stanford collaborations, and a day of analytical time is usually 22-24 hours. Our facility has excellent imaging capabilities which include digital reflected and transmitted light photographs plus CL, SE, and BSE pictures on our dedicated SEM. As you well know images are critical to aid the interpretation of the analytical data and are included in the analytical use fee. Significant modifications were made to the ion microprobe in Feb.-March, 2003 that improved both its transmission and mass resolution. These modifications allow even better quality data to be acquired in a shorter period of time for geochronology studies.

The SUMAC facility and staff have a great deal of experience with U-Th-Pb age studies of zircons, monazites, and sphenes for geochronology and detrital provenance studies using the SHRIMP-RG. The minerals we use for age standards are all well tested and the procedures for data acquisition and reduction are fully established and tested. We continue to work with Ken Ludwig on the development of SQUID II which will provide a much for flexible data reduction system for ion microprobe analysis.

We have been doing various trace element studies in a wide variety of minerals for many years. Recently we have begun more detailed trace element studies in zircon combined with using Ti concentrations for evaluation of temperatures of crystal growth based on the studies by Bruce Watson's group. These studies are proving to be very informative about zircon formation and magma and metamorphic histories. We have been concerned about a robust standard for trace elements in zircons and were uncomfortable with using glass standards that did not match the zircon bulk composition. As a result Frank Mazdab has grown synthetic zircons doped with trace element concentrations high enough to be measured accurately with the electron microprobe. CZ3, the gem quality zircon we have used for U and Th concentration calibration has been calibrated on the ion probe against these synthetic zircons and has proven to be homogeneous for most elements we measure. CZ3 and many of the other gem zircons used for U concentration and/or U-Pb age calibration (i.e. 91500, SL13) have low trace element abundances. We are testing other zircons to find one that is homogeneous and has much higher trace element concentrations and have one new standard (MAD) fully calibrated and in use in conjunction with CZ3.

We have expanded our U-Th-Pb analysis routines for zircon to include a variable number of trace elements at the same time. Hf is always included and anywhere from a few heavy rare earth elements to a set of 9 elements from La to Yb can be included. Very little extra time is required for the trace element analyses and the contribution to data interpretation is significantly aided, especially for studies involving zircons grown or overgrown during metamorphism. We prefer to do the analysis for Ti concentration as a part of a package separate from U-Th-Pb analysis. Mass resolution of 10,000-12,000 is used to analyze approximately 30 elements from Li to U and requires about 15 minutes for 2 scans through the entire mass range. However, we have developed a U-Pb package that does Ti, Si P, Y (and Al, Ca, Fe for quality control) plus 9 REE and Hf. This routine takes about 20 minutes. We have found it particularly useful for work with metamorphic rim – igneous core pairs and zircon grown and/or recrystallized in metamorphic events.

We are expanding trace element studies to other minerals of interest for U-Th-Pb geochronology (titanite, monazite, rutite, apatite) and for temperature control (quartz, titanite, rutile - continuing work by Watson's group). We have an excellent titanite standard for trace elements now (BLR, our U-Th-Pb standard) and have begun detailed trace element studies on titanites. Early results indicate that trace element concentrations and REE patterns in titanites are more responsive to the conditions of formation than those in zircons. These studies are proving to be very complimentary to our traditional work in U-Th-Pb geochronology and should provide significant help with interpretation of U-Th-Pb age data in addition to helping to better understand mineral growth and petrologic processes. Please see abstracts by Wooden and others and Mazdab and others (2006 Goldschmidt, 2006 Fall AGU), Wooden and Mazdab and Mazdab and Wooden (2007 GSA Annual Meeting) and papers by Lowery-Claiborne (2006 Min. Mag.) and Grimes and others (2007 Geology) for early progress on the techniques, applications, and interpretations of trace element studies.

I am enthusiastic about the potential of the proposed work to contribute to several major problems and about the opportunity to work with you on this project.

With best regards,

Joe

J.L. Wooden, USGS Director and SUMAC Facility Manager
U.S. Geological Survey
Stanford University & Menlo Park, California

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Dr. Mary Leech
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Dr. Barbara Carrapa
Assistant Professor
Department of Geology & Geophysics
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Laramie, WY 82071

To NSF Reviewers and Panel members:

This letter documents my strong interest in collaborating with PI's Mary Leech and Barbara Carrapa as well as their students and colleagues to generate and interpret ^{40}Ar/^{39}Ar detrital and thermal history data in support of their proposed Continental Dynamics research:

Collaborative Research: US-HIMPROBE: Geology and geophysics in NW India testing competing models of Himalayan orogenesis

I have been involved in study of the Himalayan orogenic belt for more than a decade and agree that the careful integration of new detailed structural, petrologic, geo/thermochronologic, seismic, magnetotelluric (MT), and erosional unroofing datasets from the planned transects from the western Himalaya should permit rigorous evaluation of existing geodynamic models and in particular address issues related to crustal-scale structural geometry, timing of major faulting events, kinematics, and lithospheric-scale structure. In particular, I can certify that the thermochronologic measurements outlined in the proposal are feasible and can be performed in the Stanford noble gas laboratory as described in the proposal text (see Facilities and Instrumentation for description of analytical capabilities of the Stanford ^{40}Ar/^{39}Ar laboratory). After consulting with PI's Leech and Carrapa, I have determined that $43,000 over 4 years will allow the laboratory to recover its cost to perform the extensive array of proposed ^{40}Ar/^{39}Ar measurements. These include extensive analysis of muscovite and potentially other detrital phases from ~30 basin samples plus ~50 step-heating sequences of basement samples (including ~20 detailed K-feldspar runs). By my estimate, approximately 2 month of laboratory time per year will need to be allocated per year over this 4 year interval to complete the collection of this basement and detrital thermal history data set. I look forward to working closely with the PI's and their students in all aspects of the ^{40}Ar/^{39}Ar analysis (sample preparation, data acquisition, and interpretation). This effort will include extensive modeling of K-feldspar using the multi-diffusion domain approach and integrated basin-basement thermo-kinetic analysis. This is a major commitment that I look forward to fulfilling.

Sincerely,

Marty Grove
Professor of Research & Director of Stanford's Geo/thermochronology Facilities

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Dr. Peter DeCelles
Dept. of Geosciences
University of Arizona

7 November 2007

Dear Pete:

This letter expresses my strong support for your CD project on dynamics of the Himalaya. We have previously collaborated with two of your PhD students (Delores Robinson and Aaron Martin) on applying Nd isotopes to the origins of rocks in Himalayan thrust units, and these studies resulted in papers published in *EPSL and GSA Bulletin* respectively. I would like to continue to support your efforts.

For the present proposal, we envisage approximately 20 Sm-Nd analyses of critically-located metapelites, with a view to documenting Greater or Lesser Himalayan affinity. The new work would most probably be conducted as a senior undergraduate thesis or capstone experience, or as a component of a graduate thesis. We have experience of training several senior undergraduates for Nd and/or Sr isotopic work, and this mode works well for limited-scope projects because the analyses can be done in an efficient and economical manner, while at the same time offering a quality research experience for the student.

In the present case, there is a factor that causes difficulty and raises the cost, namely that we no longer have our hard-money technician to perform student training. This means that either I or (if available) an already-trained student or postdoc will need to spend a total of ~120 hours to train the undergraduate or graduate student to conduct Sm-Nd analysis. Including training period, a student will need about 16 weeks at 20 hours per week to follow through all aspects of Sm-Nd analysis for 20 samples. These aspects include rock powder preparation, dissolution, spiking, chemistry, filament preparation, mass spectrometry, and processing of results. The student's educational experience will be valuable largely because he or she will learn the process thoroughly, with some in-depth understanding of isotopes applied to tectonics.

Please budget a per-sample fee of $620. For 20 samples, this would amount to $12,400. This cost will include:

My summer time, or postdoc's time (hours totaling approx 3 weeks), to train your student;
Student wages + benefits ($12.60/hour);
Basic analytical costs (supplies, maintenance) of $100/sample.

Good luck with your proposal!

P. Jonathan Patchett

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4 November, 2007

Dr. Peter DeCelles
Department of Geosciences
University of Arizona
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Re: NSF Proposal "US Himprobe: Geology and Geophysics in NW India…"

Dear Pete:

We would be pleased to collaborate with you on your HIMPROBE proposal to study the geodynamics of the Himalaya of northern India. Given the large data set that we have recently generated from similar rocks in Nepal, your project will provide a fabulous tool for investigating along-strike variations in provenance and kinematic evolution of the thrust belt.

The U-Th-Pb geochronologic analyses would be conducted at the University of Arizona LaserChron Center (www.geo.arizona.edu/alc), which is designed to help NSF-supported researchers acquire geochronologic data. The analyses would be conducted by laser-ablation ICPMS utilizing a 193 nm Excimer laser (from New Wave Research) coupled to a multicollector ICP mass spectrometer (GVI Isoprobe). We are presently able to determine U-Th-Pb ages of detrital zircon grains with a precision of 2-3% (2-sigma), and a throughput of ~30 unknowns per hour. Most analyses are conducted with a laser beam diameter of 25 to 50 microns and a pit depth of 15 microns. We generally analyze 100 grains per sample for a detrital zircon provenance study.

We strongly encourage the involvement of students in your geochronologic research because the spatial resolution of laser ablation coupled with the real-time age display of our ICPMS provide an excellent tool for learning the theory and methodology of U-Th-Pb geochronology. If students or other members of your research group are able to visit the facility and conduct the analyses, the cost of each U-Th-Pb analysis is $4, and we are also able to cover travel costs for students (up to $200 per day). If members of your research group are unable to conduct the analyses, we can do the lab work and provide publication-ready figures and tables for a cost of $8 per analysis. The above costs assume that you are able to provide reasonably pure zircon separates – if not, we would charge $300 to process each sample.

Good luck with your proposal, and please let me know if I can provide additional information!

Sincerely,

George Gehrels
Professor of Geosciences

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Dear Pete,

I am pleased to hear of your proposal to work in the Indian sector of the Himalaya. The area you propose to work has a lot of promise for working out the structural history from the foreland basin sequence. I have worked in the Jawalmukhi reentrant on two occasions. I would be happy to provide you with any of the data and other resources I have from the reentrant and the Jawalmukhi stratigraphic section including field notes, detailed log of my measured section, sample location map, raw paleomagentic data, paleomagentic correlations, and anything else i've got. The sample location maps are good; Doug Burbank was able to go back to the section on his own a year after I measured the section and collected samples. He was able to locate all the sample locations for resampling. Thus I think you could probably know where you are stratigraphically and magnetically down to the chron level (or subchron). As I recall the Haritalyangar section of Johnson is pretty short and could be extended. I did a reconnaissance of the section, which is in my notes. Nick Brozovic has a number of additional measured sections from the reentrant that he also dated with magnetostratigraphy. Some of his sections are longer and cover more of the section, which could be useful. The area is pretty accessible as there are a lot of roads and outcrop. One limitation is the maps of the area. I can loan you a nearly complete set of topographic maps of the reentrant from the Indian Survey. Whereas some of the roads are not on those maps, there are different names for villages on the maps, and other shortcomings, the drainage system and topography are good and they can be used effectively for orienteering and mapping. I also did a 10-day reconnaissance trip up the Sutlej River (which is a transverse river that flows from Tibet across the thrust belt, through the reentrant to the foreland) to the India-Tibet border to collect data and assess the feasibility of drawing regional, crustal scale cross-sections. The proposal I wrote never flew, but the exposures are really good and you can see a cross-section with 1 or more kilometers of relief all the way from Tibet to the undeformed foreland on the south. Good luck with your proposal and I will assemble everything I've got when you give me the word.

Dr. Andrew Meigs
Associate Professor

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7 November, 2007

Professor Peter DeCelles
Department of Geosciences
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Tucson, Arizona 85721 USA

Dear Peter,

I am writing to support your proposal to National Science Foundation for new work on the Siwaliks and the Eocene-early Miocene sections in India. I have recently done a significant amount of work in the Indian Siwaliks, but we have neither U-Pb zircon data nor fission track data. There is still a need for additional Ar-Ar work and conventional petrographic work as well. We have already published all of our results from the Paleogene sections, and I have no current plans to continue with these rocks. However, lots of work needs to be done in the Paleogene sections as well, particularly in terms of U-Pb zircon.

Your set-up at Arizona places you in an ideal position to tackle the zircon analyses. I would be happy to make available the magnetic stratigraphic data (part of Nikki White's thesis work) and all of our measured section notes. The sections are easy to get to and the logistics of working in the Indian Subhimalaya are relatively simple compared to working in Nepal. I would also be happy to advise you and your students on key locations and logistical matters.

Good luck with the proposal.

Sincerely,

Yani Najman