Present-day E-W extension in the NW Himalaya (Himachal Pradesh, India)

Esther Hintersberger[1*], Rasmus Thiede[2], Manfred Strecker[1] and Frank Krüger[1]

[1] *Department of Geosciences, University of Potsdam, GERMANY*
[2] *Department of Geology, ETH Zurich, SWITZERLAND*
[*] *For correspondence, email: estherh@geo.uni-potsdam.de*

During the evolution of most major orogens, both contemporaneously developed compressional and extensional structures have been documented. Thus, localized extension within an overall compressional setting seems to be a fundamental process for the evolution of orogens, however, their kinematic linkage is still debated. Since the Indian-Eurasian collision, the Himalayan mountain belt has formed as the southern termination of the Tibetan Pleteau. While at present day, thrusting at lower elevations within the Lesser Himalaya is observed (Bilham et al. 1997, Lavé and Avouac 2000), several generations of extensional structures have been detected in the high-elevation regions of the Higher Himalaya, both parallel and perpendicular to the strike of the orogen, which are the following: (1) The Southern Tibetan Detachment System (STDS), the most prominent example for orogen-perpendicular extension, was active during the Miocene (around 25 to 19 Ma, Burchfield et al. 1992) and potentially locally reactivated during the Quaternary (Hogdes et al. 2001, Hurtado et al. 2001). (2) Orogen-parallel extension is observed along roughly N-S striking normal faults and graben systems whose onset is mainly constraint to 15-12 Ma (e.g., Fort et al. 1982, Burchfield et al. 1991, Wu et al. 1998, Murphy et al. 2000, Hogdes et al., 2001, Garzione et al. 2003, Thiede et al. 2006). Earthquake information (e.g., Pandey et al. 1999) and fault-plane solutions (Harvard catalog, Molnar and Lyon-Caen 1989) infer that they are recently active. To explain the kinematic linkage between extensional structures in an overall compressional settting, several models have been developed, the most important ones are: (a) radial extension (Molnar and Lyon-Caen 1989), (b) gravitational collapse (Molnar and Chen 1983, Royden and Burchfield 1987), (c) the partitioning of oblique convergence (McCaffrey 1996, McCaffrey and Nabelek 1998), and (d) arc-shaped, convex-southward propagation (Ratschbacher et al. 1994). Alternatively, local extension due to metamorphic dome formation has also been invoked (Aoya et al. 2005). However, the interpolated deformation patterns of these models are not consistent to focal mechanisms of larger earthquakes (Harvard Catalogs) and regional GPS measurements (Banerjee and Bürgmann 2002) in the Sutlej-Spiti River Valleys and the Garhwal in the NW Himalaya (India). These data sets reveal ongoing E-W extension in this area. In contrast to model predictions, however, this direction is neither parallel nor perpendicular to the NW-SE regional shortening direction. Therefore, currently available models of extensional faulting within the Himalaya apparently do not reconcile the observations in this part of the mountain range and alternative, less ambiguous mechanisms have to be involved.

Here we present new geological and geophysical data sets such as newly calculated earthquake fault-plane solutions, new structural geological mapping, fault kinematic analysis of hundreds of brittle faults, and satellite imagery analysis covering the area between the Tso Morari Lake in the Tibetan Himalaya in the north and the mountain front in the Garhwal Himalaya in the south. The data sets that we obtained allow us to get a detailed overview of the extensional deformation history in this area and to try to reveal the underlying driving mechanism. In the following, we describe the data sets in detail.

We observed that globally recorded seismicity data is arranged in a narrow N-S striking swath ranging from the Tso Morari Lake in the Tibetan Himalaya almost to the mountain front in the Garhwal Himalaya (NEIC Catalog). Earthquake fault-plane solutions, however, are only available for the northern part of our study area extending between the Tso Morari Lake and the Spiti River Valley. Therefore, we used several medium-size earthquakes recorded during the last 20 years to determine new earthquake fault-plane solutions using a moment tensor inversion technique. All together, we now have an extended and detailed data set available reaching from the Lesser Himalaya in the south to the suture zone in the north and are able to provide much more detailed view into the recent deformation of the Himalayan wedge. All the new data suggest consistently recently ongoing E-W extension.

Furthermore, in the northern part of the study area, between the Spiti River Valley and the Tso Morari, we found new undescribed large N-S striking normal faults up to 10 km length separating basement rocks from sedimentary deposits. By analyzing high-resolution satellite imagery (LandSat, ASTER, GoogleEarth) we reveal that normal faults have played an integral role during the development of local sedimentary basins. In addition, we have observed structures such as steeply dipping, mainly N-S striking normal faults with displacements in the range of mm deforming fluvial fans and lake deposits in the Spiti River Valley. Inferring the age of these deposits to Quaternary, the normal faults document E-W extension during this time span. By compiling earlier published data (Anand and Jain 1987, Singh and Jain 2006), we were able to extend the record of sedimentary deposits affected by normal faulting further south into the thrust belts in the Garhwal Himalaya.

We have mapped extensional structures in the Garhwal Himalaya and the Sutlej River Valley and compiled them with structures already shown in geological maps (e.g., Steck et al. 1998, Neumayer et al. 2004, Thiede et al. 2006). We found large N-S striking normal faults with gouge zones up to 3 m in width which are observed mainly in a narrow band between 78° and 78.5° E. They are generally associated with steep slickensides indicating dip-slip faulting and E-W extension with limited offset. New-grown micas on the fault plane and within the fault gouge indicate that these faults have their origin in the brittle-ductile transition zone. However, we cannot be absolutely sure whether this limitation on such a small swath is really related to focused concentration of deformation or this is only an artifact due the restricted accessibility in the field area. In addition, small brittle normal fault planes on outcrop scale with displacements up to several cm cover the whole region from Tibetan Himalaya down to the mountain front. These densely spaced, steeply to the W and E dipping structures crosscut all older structures related to the shortening in the mountain belt. To analyze fault kinematic data (strike and dip of the fault, slip direction and sense of slip) for these small fault planes, we determined approx. 30 pseudo fault-plane solutions using the program TectonicsFP (Ortner et al. 2002). The results indicate a regional E-W oriented extension arranged in a diffuse N-S trending swath, overlaying other deformation patterns, e.g., orogen-parallel and orogen-perpendicular extension along the lower-elevation parts of the study area. The consistency with fault-plane solutions derived from seismicity data shows that E-W extension in the area between the Tso Morari and the Garhwal Himalaya seems to be a long-lasting and consistent phenomenon.

Combining all these data sets reveals that there is ongoing extension in the Sutlej-Spiti River Valleys and the Garhwal Himalaya, which is aligned in an overall N-S striking zone. Our compilation of geological and geophysical data sets suggest that E-W extension spreads almost over the entire mountain range from the Tibetan Himalaya in the north to the thrust belt in the south and seems to be a long-lasting phenomenon rather than a localized disturbance in the regional deformation pattern. Crosscutting relationships indicate that this extensional deformation phase here is younger than the extensional deformation phases described at the beginning. Furthermore, this extensional direction is neither parallel nor perpendicular to the regional shortening direction. Therefore, models explaining orogen-parallel or orogen-perpendicular extension are not able to explain the observed extension. We derive a model that proposes a southward propagation of the E-W extension from the Tibetan Plateau into the Himalayan mountain range. In this model, the Karakorum fault, a large strike-slip fault separating the Himalaya and the Tibetan Plateau, would not be able to accommodate the whole E-W extensional deformation in the Tibetan Plateau. Therefore, a part of this extension would be compensated in N-S striking normal faulting in the NW Himalaya, where our study area is located.

References

Ananad A and AK Jain. 1987. Earthquakes and deformational structures (seismites) in Holocene sediments from the Himalayan-Andaman Arc, India. *Tectonophysics* 133: 105-120

Aoya M, S Wallis, K Terada, J Lee, T Kawakami, Y Wang, and M Heizler. 2005. North- South extension in the Tibetan crust triggered by granite emplacement. *Geology* 33(11): 853-856

Banerjee P and R Bürgmann. 2002. Convergence across the Northwest Himalaya from GPS Measurements. *Geophysical Research Letters* 29(13): doi: 10.1029/2002GL015184.

Bilham R, K Larson, J Freymueller and Project Idylhim Members. 1997. GPS measurements of present-day convergence across the Nepal Himalaya. *Nature* 386: 61– 64

Burchfiel BC, Z Chen, LH Royden, Y Liu and C Deng. 1991. Extensional development of Gabo Valley, Southern Tibet. *Tectonophysics* 194: 187-193

Burchfiel BC, Z Chen, K Hodges, Y Liu, LH Royden, C Deng and J Xu. 1992. The South Tibetan Detachment System, Himalayan Orogen: Extension contemporaneous with and parallel to Shortening in a Collisional Mountain Belt. *Geological Society of America Special Paper* 269.

Fort M, P Freytet and M Colchen. 1982. Structural and Sedimentological Evolution of the Thakkhola-Mustang Graben (Nepal Himalayas). *Zeitschrift für Geomorphologie* 42: 75-98

Garzione CN, PG DeCelles, D Hodkinson, R Ojha and B Upreti. 2003. E-W Extension and Miocene Environmental Change in the Southern Tibetan Plateau: Thakkhola graben, Central Nepal. *Geological Society of America Bulletin* 115(1): 3-20

Hogdes KV, Hurtado JM and KX Whipple. 2001. Southward Extrusion of Tibetan Crust and its effect on Himalayan Tectonics. *Tectonics* 20(6): 799-809

Hurtado JM, KV Hodges and KX Whipple. 2001. Neotectonics of the Thakkhola Graben and implications for Recent activity on the South Tibetan Fault System in the central Nepal Himalaya. *Geological Society of America Bulletin* 113(2): 222-240

Lave J and JP Avouac. 2000. Active folding of fluvial terraces across the Siwalik Hills, Himalayas of central Nepal. *Journal of Geophysical Research* 105: 5735-5770

McCaffrey R. 1996. Estimates of modern arc-parallel strain rates in fore-arcs. *Geology* 24(1): 27-30

McCaffrey R and J. Nabelek. 1998. Role of oblique convergence in the active deformation of the Himalayas and Southern Tibet Plateau. *Geology* 26: 691-694

Molnar P and WP Chen. 1983. Focal depths and fault-plane solutions of earthquakes under the Tibetan plateau. *Journal of Geophysical Research* 88: 1180-1196

Molnar P and H Lyon-Caen. 1989. Fault-plane solutions of earthquakes and active tectonics of the Tibetan Plateau and its margins. *Geophysical Journal International* 99: 123- 153

Murphy M, A Yin, P Kapp, TM Harrison, D Lin and G Jinghui. 2000. Southward Propagation of the Karakoram Fault System, Southwest Tibet: Timing and Magnitude of Slip. *Geology* 28(5): 451-454

Neumayer J, G Wiesmayr, C Janda, B Grasemann and E Draganits. 2004. Eohimalayan fold and thrust belt in the NW-Himalaya (Lingti-Pin Valleys): Shortening and depth to detachment calculation. *Austrian Journal of Earth Sciences* 95/96: 28-36

Ortner H, F Reiter and P Acs. 2002. Easy handling of tectonic data: the programs TectonicVB for Mac and TectonicsFP for Windows. *Computers and Geosciences* 28: 1193-1200

Pandey MR, RP Tandukar, JP Avouac, J Vergne and Th Héritier. 1999. Seismotectonics of the Nepal Himalaya from a local seismic network. *Journal of Asian Earth Sciences* 17(5-6): 703-712

Ratschbacher L, W Frisch, GH Liu and CS Chen. 1994. Distributed deformation in Southern and Western Tibet during and after the India-Asia Collision. *Journal of Geophysical Research (Solid Earth)* 99(B10): 19917-19945

Royden L and BC Burchfield. 1987. Thin-skinned N-S extension within the convergent Himalayan Region: Gravitational collapse of a Miocene topographic front. In: Continental Extensional Tectonics, *Blackwell Scientific Publications:* 611-619

Singh S and AK Jain. 2006. Liquefaction and fluidization of lacustrine deposits from Lahaul- Spiti and Ladakh Himalaya: Geological evidences of paleoseismicity along active fault zone. *Sedimentary Geology* 196(1-4): 47-57

Steck A, JL Epard, JC Vannay, J Hunziker, M Girard, A Morard and M Robyr. 1998. Geological transect across the Tso Morari and Spiti areas: the nappe structures of the Tethys Himalaya. *Eclogae geologicae Helvetiae* 91: 103–122

Thiede R, J Arrowsmith, B Bookhagen, M McWilliams, E Sobel and M Strecker. 2006. Dome formation and extension in the Tethyan Himalaya, Leo Pargil, northwest India. *Bulletin of Geological Society of America* 118: 635-650

Wu C, K Nelson, G Wortman, S Samson, Y Yue, J Li, W Kidd and M Edwards. 1998. Yadong Cross Structure and South Tibetan Detachment in the East Central Himalaya (89° - 90° E). *Tectonics* 17: 28-45

Zhang P, Z Shen, M Wang, W Gan, R Bürgmann, P Molnar, Q Wang, Z Niu, J Sun, J Wu, S Hanrong and Y Xinzhao. 2004. Continuous deformation of the Tibetan Plateau from Global Positioning System data. *Geology* 32(9): 809-812