ABSTRACT

Explaining the presence of normal faults in overall compressive settings is a challenging problem in understanding the tectonics of active mountain belts. The Himalayan-Tibetan orogenic system is an excellent setting to approach this problem because it preserves one of the most dramatic records of long-term, contemporaneous shortening and extension. Over the past decades, several studies have described extensional features, not only in the Tibetan Plateau, but also in the Himalaya. For a long time, the favored model explained the function of the Southern Tibetan detachment system, a major fault zone in the Himalaya, as a decoupling horizon between the regime of crustal shortening forming the Himalayan wedge to the south and the extensional regime of the Tibetan Plateau to the north. However, in recent years, increasing evidence has shown that N-S-trending normal faults in the Central Himalaya crosscut not only the Southern Tibetan detachment system, but also the Main Central thrust.

Here, we present new structural data and geologic evidence collected within the NW Indian Himalaya and combine them with previously published seismicity data sets in order to document pervasive E-W extension accommodated along N-S-trending faults extending as far south as the footwall of the Main Central thrust. We conducted a kinematic analysis of fault striations on brittle faults, documented and mapped fault scarps in Quaternary sedimentary deposits using satellite imagery, and made field observations in the Greater Sutlej region (Spiti, Lahul, Kinnaur) and the Garhwal Himalaya. Studies of extensional features within the regionally NW-SE-trending NW Indian Himalaya provide the advantage that arc-parallel and E-W extension can be separated, in contrast to the Central Himalaya. Therefore, our observations of E-W extension in the Indian NW Himalaya are well suited to test the applicability of current tectonic models for the whole Himalaya. We favor the interpretation of E-W extension in the NW Indian Himalaya as a propagation of extension driven by collapse of the Tibetan Plateau.

INTRODUCTION

The mechanistic principle governing the spatial-temporal evolution of normal fault systems in active mountain belts is still a matter of dispute (e.g., Kapp and Guynn, 2004; Selverstone, 2005; Murphy et al., 2009). Observations in Cenozoic orogens related to continent-continent collision like the Himalaya-Tibet region (e.g., Armiço et al., 1986; Molnar, 1992; Chen and Yang, 2004; Zhang et al., 2004), the Pamir (e.g., Burtman and Molnar, 1993; Strecker et al., 1995), or the Alps (e.g., Michard et al., 1993; Wheeler and Butler, 1993; Seward and Mancktelow, 1993; Selverstone, 2005; Sue et al., 2007) document extension and normal faulting occurring contemporaneously at higher elevations, with shortening and thrusting occurring at lower elevations.

Various mechanisms attempting to explain this high-elevation normal faulting have been proposed. In the transition between the Himalaya and Tibet region, the generation of normal faults parallel to the trend of the orogen, e.g., the Southern Tibetan detachment system (Burg et al., 1984; Burchfiel et al., 1992), has been explained by processes associated with channel flow or extrusion of the orogenic wedge (e.g., Grujic et al., 1996; Nelson et al., 1996; Beaumont et al., 2001; Vannay and Geissmann, 2001). Other explanations include the increase of potential gravitational energy, followed by collapse due to excess elevation (e.g., Royden and Burchfiel, 1987; Buck and Sokoutis, 1994; Hodges et al., 2001), basal shear produced by southward crustal flow below the Himalaya (Yin, 1989), and, more recently, a passive roof-thrust model (Yin, 2006; Webb et al., 2007).

Models that have been invoked to explain orogen-perpendicular grabens of the Himalaya and the southern Tibetan Plateau include an additional variety of mechanisms. The most prominent ones include (1) radial thrusting (e.g., Seeger and Armbruster, 1984; Armijo et al., 1986; Molnar and Lyon-Caen, 1989); (2) oroclinal bending (e.g., Ratschbacher et al., 1994; Kapp and Yin, 2001; Robinson et al., 2007); (3) partitioning of oblique convergence into thrusting and normal faulting components (e.g., McCaffrey, 1996; McCaffrey and Nabelek, 1998); (4) southward propagation of the subduction front (Murphy and Copeland, 2005); (5) concentrated compression at the Central Himalayan front (Kapp and Guynn, 2004); (6) change of boundary conditions along the eastern margin of Asia (Yin, 2000; Yin and Harrison, 2000); (7) convective removal of the mantle lithosphere (England and Houseman, 1989); and finally, (8) those models linked with escape tectonics in the course of the continental collision process (e.g., Molnar and Tapponnier, 1978; Tapponnier et al., 1982; Molnar and Chen, 1983; Royden and Burchfiel, 1987). In general, these models can be combined into two major groups; the first one contains all models where extension is related to processes within the Himalaya and the arcuate shape of the orogen, such as oroclinal bending, and radial thrusting. The second group relates extension to deeper-seated processes, mainly within the Tibetan Plateau.

The Himalayan collision zone, which is characterized by ongoing shortening due to the convergence of India and Eurasia, hosts major active normal fault systems that strike approximately perpendicular to the trend of the orogen (Armijo et al., 1986; Royden and Burchfiel, 1987; Molnar and Lyon-Caen, 1989; Burchfiel et al., 1991; Ratschbacher et al., 1994; McCaffrey and Nabelek, 1998; Hodges et al., 2001; Murphy et al., 2002; Aoya et al., 2005; Thiede et al., 2006). Global positioning system (GPS) measurements
and fault-plane solutions of earthquakes indicate approximately radial shortening in the Himalaya and E-W extension in the Tibetan Plateau (Zhang et al., 2004; Molnar and Lyon-Caen, 1989). However, in the central part of the Himalaya between 84°E and 92°E longitude, tectonism does not conform to this first-order kinematic differentiation. In this high-relief region, with mean elevations of ~3000 m, numerous N-S–striking extensional fractures, closely spaced normal faults, and linked graben systems document extensional processes that are not limited to the Tibetan Plateau and the internal parts of Himalaya, but that also affect the high Himalayan realm farther south. Crosscutting relationships indicate that these extensional structures cut all preexisting deformation fabrics and structures, including older, orogen-parallel normal faults. This is documented by observations in the vicinity of the Gurma Mandhata gneiss dome and around the Ama Drime Massif (e.g., Murphy and Copeland, 2005; Jessup et al., 2008). The driving forces for their generation, whether they are rooted in the geometry of the Himalaya or in the eastward motion of the Tibetan Plateau, are still an open question, mainly because in the Central Himalaya, both extensional directions are oriented approximately E-W.

In this paper, we take advantage of the regionally NW-SE–oriented strike of the orogen in the NW Indian Himalaya to differentiate between extension triggered within the Himalaya and extensional processes triggered by deformation of the Tibetan Plateau. We present new field evidence from structural mapping, analysis of satellite imagery (ASTER, GoogleEarth, Landsat), and new fault kinematic data from brittle faults from the NW Indian Himalaya. We document normal faulting that is not simply localized in close vicinity to major structures, but rather is a ubiquitous, pervasive phenomenon affecting the NW India Himalaya as a whole. Our new data help define the spatial-temporal character of the extensional deformation and provide valuable information on the causal mechanisms of active normal faulting of the studied region. Our data set shows that extension is not limited to the higher parts of the Himalaya, but it is also found in the lower-elevation regions, with 20% elevations of around 1500 m, in the foreland of the Main Central thrust.

Because previous models explaining the origin of extension in the Himalaya have been generally based on data from the Central Himalaya, we used our new observations from the NW sector of the orogen to evaluate those models. Based on this evaluation, we favor a scenario where E-W–oriented extension in the NW Indian Himalaya is triggered by extension in the Tibetan Plateau.

**GEOLOGICAL SETTING OF THE NW HIMALAYA**

**Principal Structures Related to Shortening**

In the NW Himalaya, the curved orogen trends dominantly NW-SE and can be separated into five principal lithologic-tectonic provinces, including the Sub-Himalaya, the Lesser Himalaya, the Higher Himalaya, and the Tethyan Himalaya (Gansser, 1964). These tectonic provinces are fault bounded and accommodate ~30%–50% of India-Eurasia plate convergence (Banerjee and Burgmann, 2002; Zhang et al., 2004). The NW Himalaya has accommodated SSW-directed shortening and thrusting caused by the underthrusting of India beneath Eurasia since the collision at around 55 Ma (Kloutukwijk et al., 1985). This process has been associated with a stepwise southward migration of thrust systems, from the Main Central thrust (since 23–20 Ma; Hodges et al., 1996) to the Main Boundary thrust (since 11–9 Ma; Meigs et al., 1995) to the Main Frontal thrust (since 5 Ma; Schneeberger et al., 1999). In addition to these structures, in the NW Himalaya, the ductile, north-dipping Mnsiari thrust (MT) between the Main Central thrust and the Main Boundary thrust separates the Lesser Himalayan crystalline sequence from the Lesser Himalayan para-gneisses (Fig. 1B; Vannay et al., 2004).

**Extensional Structures in the Himalaya**

Contemporaneous with crustal shortening along the southern mountain front, large regions of the Himalaya are characterized by activity along orogen-parallel and orogen-perpendicular normal faults (e.g., Le Fort et al., 1982; Burchfiel et al., 1992; Wu et al., 1998). One of the extensional hallmarks of the Himalaya is the system of orogen-parallel, linked normal faults associated with the Southern Tibetan detachment system. The Southern Tibetan detachment system strikes parallel to major thrusts and separates the lower-grade metamorphic rocks of the Tethyan Himalaya in the hanging wall from the high-grade metamorphic footwall of the Higher Himalaya (Burg et al., 1984; Burchfiel and Royden, 1985; Burchfiel et al., 1992). During the Miocene, the Higher Himalaya was exhumed during coeval extension along the Southern Tibetan detachment system and thrusting along the Main Central thrust. Some studies have proposed that the Southern Tibetan detachment system has been reactivated as recently as the Quaternary (Hodges et al., 2001; Hurtado et al., 2001).

In the NW Indian Himalaya, the Sangla detachment is the local expression of the Southern Tibetan detachment system in the Greater Sutlej region (Vannay and Grasemann, 1998; Wiesmayer and Grasemann, 2002). This structure is well recognized in the field; however, evidence for neotectonic activity has not been observed by us or by several earlier investigations (e.g., Vannay and Grasemann, 1998). Recent studies in the vicinity of the Kulu Valley (Fig. 1B) suggest that the Southern Tibetan detachment system and the Main Central thrust merge in map view, which the authors explain with a passive roof-thrust model for the development of the Southern Tibetan detachment system (Yin, 2006; Webb et al., 2007). In the Sutlej Valley, the brittle Karcham normal fault crosses the Main Central thrust mylonites, showing a top-to-the-east displacement, and it is assumed to have been the counterpart of the Munsari thrust during the exhumation of the Lesser Himalayan crystalline sequence (Janda et al., 2002; Vannay et al., 2004). Other extensional detachments, including the Leo Pargil detachment zone (Thiede et al., 2006) farther north and the Gurma Mandhata detachment zone (Murphy et al., 2000, 2002) farther east (Fig. 1), which form the low-angle ductile normal faults of two major domes exhumed during the Miocene in the Tethyan Himalaya.

A second group of extensional structures are made up of N-S–striking normal faults. In the NW Himalaya, several N-S–striking, high-angle brittle normal faults are documented in the vicinity of the Gurma Mandhata dome (Murphy et al., 2000, 2002), the Kaurik-Chango normal fault at the western flank of the Leo Pargil dome (Hayden, 1904; Thiede et al., 2006), and the Tso Kar and Tso Morari normal faults north of the Spiti Valley (e.g., Steck et al., 1993; Fuchs and Linner, 1996; Epard and Steck, 2008). Also in the Central Himalaya, between 83°E and 90°E, several large-scale, Neogene normal faults strike perpendicular to the orogen (Fig. 1A). These include structures bounding the Thakola graben (Le Fort et al., 1982; Garzione et al., 2000; Hurtado et al., 2001; Garzione et al., 2003), structures close to the Ama Drime Massif (Jessup et al., 2008; Cottle et al., 2009) in Tibet, and the southern end of the Yadong graben in Bhutan (Wu et al., 1998; Guo et al., 2008). Several of these offset the Southern Tibetan detachment system, especially the N-S–striking normal faults bounding the Ama Drime Massif in the Central Himalaya, which displace the Southern Tibetan detachment system for several kilometers and thus represent the youngest deformation phase (Jessup et al., 2008). However, the southern and the northern terminations of those normal faults are not yet fully documented. This raises the question of
Figure 1. (A) Geological map and structural provinces of the entire Himalaya, modified after Yin (2006) and references therein. For the western Himalaya, the structures as mapped by DiPietro and Pogue (2004) are used. (B) Structural map of the NW Indian Himalaya, modified after Thiede et al. (2005), and references therein. Earthquakes, shown as dark-gray dots, are taken from the National Earthquake Information Center (NEIC) catalog; fault-plane solutions for the larger earthquakes are from the Harvard Centroid Moment Tensor (CMT) catalog. The fault-plane solution for the Kinnaul earthquake (KEQ) is labeled explicitly. Dotted rectangles represent the locations of figures shown later in the text. Locations of Figures 3 and 4 are too close to each other to be separated on this map scale; therefore, they are represented by one box. The base map shows elevations taken from a Shuttle Radar Topography Mission (SRTM) image. Abbreviations: AD—Ama Drime Massif, BR—Brahmaputra River, GM—Gurla Mandhata gneiss dome, IR—Indus River, ITSZ—Indus-Tsangpo suture zone, KEQ—Kinnaul earthquake, KF—Karakorum fault, KNF—Karcham normal fault, LPDZ—Leo Pargil detachment zone, MBT—Main Boundary thrust, MCT—Main Central thrust, MFT—Main Frontal thrust, MT—Munsirhi thrust, SD—Sangla detachment, STD—Southern Tibetan detachment system, TM—Tso Morari, TG—Thakholia graben, YG—Yadong graben, ZB—Zada Basin.

whether the N-S–striking grabens in the central and southern Tibetan Plateau are linked to the extensional processes observed within the Himalaya, or if they represent an entirely different, but possibly coeval process that generates very similar structures and geomorphic features that have their origin in the Tibetan Plateau.

Seismicity in the NW Indian Himalaya

Fault-plane solutions derived from seismicity in the Himalaya-Tibet region reflect first-order deformation patterns and provide insight into the characteristics of the present-day regional stress field (Fig. 1B). In the southern Tibetan Plateau, fault-plane solutions document pure normal faulting, indicating E-W extension, both at shallow crustal levels (<15 km) and at greater depths of 80–95 km (Molnar and Chen, 1983; Molnar and Lyon-Caen, 1989). In contrast, earthquakes in the Himalaya with radially oriented thrusting
focal mechanisms and magnitudes of up to 8.0 are located at depths between 20 and 40 km and are primarily related to the underthrusting of India beneath Eurasia (e.g., Seber and Armbruster, 1981; Ni and Barazangi, 1984).

We extracted all seismic events of magnitude >3.2 recorded between 77.5°E and 79°E within the NW Indian Himalaya from the global seismicity catalogs (National Earthquake Information Center Catalog [NEIC], 2009; Harvard Global Centroid Moment Tensor [CMT] Catalog, 2009). This subset of seismic events can be separated into two groups. The southern Himalayan front is characterized by a group of large earthquakes with magnitudes up to M = 8.6 and dominant NE-SW shortening (Fig. 1B). Some of the most prominent examples are the Kangra (4 April 1905, M[estimated] = 8.6; Middlemiss, 1910), Uttarkashi (20 October 1991, Mw = 6.8; Kayal et al., 1992), and Chamoli earthquakes (29 March 1999, Mw = 6.6; Rastogi, 2000). The second group is characterized by shallow earthquakes with depths <15 km occupying a narrow swath between 78°E and 78.5°E, stretching from the Tso Morari dome in the north to close to the Main Central thrust in the south (Fig. 1B). The Kinnaur earthquake (19 January 1975, M = 6.8), with its epicentral zone close to the Leo Pargil gneiss dome, was the most prominent event of this group (fault-plane solution KEQ, see Fig. 1B). Fault-plane solutions for this event and other major earthquakes in the Sutlej region provide additional evidence for ongoing E-W extension (e.g., Molnar and Chen, 1983). The degree of activity in the Sutlej region is much higher than that recorded along other N-S–striking structures in the Himalaya, such as the Thakkola graben in Nepal, where only microseismicity with magnitudes <4 is observed (Pandey et al., 1999).

**METHODOLOGY**

**Field Mapping and Analysis of Satellite Imagery**

Previously, structures related to E-W extension have been only described around prominent morphologic features such as graben or dome systems. We were interested to see whether these extensional structures are restricted to these features, or if normal faulting is more pervasively distributed across the orogen. To explore this question, we collected structural field data on recent normal faults and interpreted satellite images from the Lesser and Higher Himalaya of NW India. We focused on an area extending from the Tso Morari dome in the north to the Garhwal Himalaya in the south, covering the region shown in Figure 1B.

We determined the kinematics of brittle faults in basement rocks and sedimentary strata, such as lake deposits and fluvial-terrace conglomerates. To better understand recent fault displacement, we analyzed fluvial terraces and paleosurfaces affected by Quaternary faulting (section: Macroscale Normal Faults from Satellite Imagery and Field Observations; Figs. 2–5). We used satellite imagery (LandSat, ASTER, and GoogleEarth) where the border region between India and China did not permit direct field access. Detailed investigations of the fault inventory in river terraces were undertaken, such as in the immediate vicinity of the Leo Pargil gneiss dome and in the Spiti Valley (section: Normal Faults in Sediments and Soft-Sediment Deformation).

**Kinematic Analysis of Brittle Fault Data**

To obtain a better image of the distribution of paleo-strain axes in the study area, we collected fault kinematic data. We measured the strike and dip, slip direction, and sense of slip for...
In addition, we took samples from Quaternary sedimentary deposits affected by normal faulting or layers subjected to soft-sediment deformation that may have been caused by coseismic activity along nearby faults. These samples, collected in 20-cm-long, opaque tubes, were dated with the OSL technique. The analysis of the OSL samples was carried out by the Sheffield Centre for International Drylands Research (UK). The samples were prepared under subdued red lighting to extract and clean quartz following the procedure outlined in Bateman and Catt (1996). The remaining pure quartz, with grain sizes between 90 and 250 μm, was mounted as 4-mm-diameter aliquots and checked with infrared stimulated luminescence for feldspar contamination, which was not given. All OSL measurements were carried out using an upgraded DA-15 Riso luminescence reader system, equipped with a calibrated 87Sr/86Sr beta source and blue Light Emitting Diodes (LEDs) for stimulation. The OSL signal was measured through a Hoya-340 filter. All samples were analyzed using the single aliquot regenerative (SAR) approach (Murray and Wintle, 2000), where the last measurement replicated the first one. Aliquots were excluded from further analysis if the ratio of first and last dose point exceeded ±10% of unity. To remove unstable signals, the samples were preheated prior to OSL measurements using a preheat temperature of 180 °C for 10 s.

EXTENSION STRUCTURES IN THE NW HIMALAYA

Here, we report on different phenomena related to normal faulting in the NW Indian Himalaya, where the deeply incised Sutlej and Spiti Rivers provide an excellent and easily accessible natural transect through the entire mountain range. Apart from the structures already mentioned here and described in literature, we documented pervasively distributed young normal faults related to EW extension at the kilometerscale based on the analysis of satellite imagery and field work, and at the outcrop-scale between the southern Himalayan mountain front and the Indian-Chinese border. Additionally, we assessed normal faulting in fluviolacustrine sediments, including soft-sediment deformation. In the following sections, we use the term “macroscale” to describe faults traced over distances of hundreds of meters up to several kilometers, “mesoscale” for faults with several meters of fault zone observed in outcrops that can be traced over several meters, and “outcrop-scale” for faults and fault planes visible at a scale of a few centimeters up to a few meters.
Macroscopic Normal Faults from Satellite Imagery and Field Observations

**Area Southeast of Tso Morari**

In addition to the 40-km-long Tso Morari normal fault (see Fig. 1B), there is a second en echelon set of parallel east-dipping normal faults to the southeast, which we term the eastern Tso Morari fault system (see Fig. 2). The two fault strands are exposed for 20 and 10 km, respectively, and are spaced ~2 km apart. In the central sector of the eastern fault, the fault diverges into a lozenge-shaped segment, which converges with the main fault ~5 km south. The eastern Tso Morari fault system separates sedimentary rocks of Neoproterozoic and Cambrian age and Ordovician granites in the foothills from fan gravels of inferred Quaternary age that constitute a large, contiguous bajada adjusted to the Pare Chu River. The alluvial fans in the hanging wall of the easternmost fault, as well as fluvial terraces parallel to the Pare Chu River, which crosses the fault, are apparently not displaced by the fault (Fig. 2).

Approximately 6 km east, the landscape is dissected by numerous W- to WNW-dipping normal faults (Fig. 2). The fault scarps are less pronounced compared to the eastern Tso Morari fault system, but they strike N-S. These faults clearly show evidence for top-to-the-west normal faulting. Similar to the larger, east-dipping faults on the west, the fluvial deposits of the Pare Chu River and its tributaries are not displaced by these west-dipping faults, and therefore they postdate faulting in this region (Fig. 2). However, the normal faults offset gently inclined erosion surfaces that were sculpted into the Proterozoic to Paleozoic basement rocks (see eastern part of Fig. 2). These surfaces are interpreted to represent a pediment surface that was formerly adjusted to a higher base level of the Pare Chu River, but that became subsequently abandoned due to base-level lowering.

**Normal Faulting North of Leo Pargil**

One of the most striking preserved young features affected by normal faulting is an extensive, originally contiguous gravel-covered paleo-surface with ubiquitous erosional remnants in a formerly closed sedimentary basin northwest of the Leo Pargil gneiss dome (for location, see Fig. 1B). The basin is bounded by E- and W-dipping normal faults. In the center, the paleosurface consists of large, gently NE-tiled segments that are incised by small streams. The geomorphic character of the surface remnants and their lower eroded sectors is similar to features observed in the Zada Basin of the upper Sutlej River, southeast of the Leo Pargil gneiss dome. Based on similar outcrop and geomorphic characteristics, we infer that this surface constitutes the remnant of extensive gravel-covered lacustrine marls that once filled the basin before the current rivers started incising and eroding the basin fill due to headward erosion.

Based on the degree of preservation of the fault scarps, what we infer to be the oldest normal faults occur at the eastern and western margins of the basin. Movement along these structures created accommodation space for the sedimentary fill, which is now being incised and evacuated. Farther basinward toward the east, there are also morphologically younger N-S-striking faults that offset fluvial-terrace and alluvial-fan surfaces that have prograded into the basin fill in the course of down-cutting. These surfaces thus postdate the extensive basin fill and are located at a lower elevation than the top of the surface that forms the youngest part of the basin-fill unit. However, the youngest alluvial-fan deposits in this area cover the faults and clearly postdate tectonic activity along these older normal faults (Fig. 3).

The western margin of the basin is delimited by east-dipping normal faults, which are readily identified on satellite imagery. The normal faults constitute a sharp boundary between the basement rocks in the footwall and the sedimentary cover in the hanging wall. Several terrace levels in the northern part of the basin indicate that the
paleosurface was displaced by normal faulting. In contrast, multiple extensive terraces observed along most of the larger rivers in the southern part of the basin are not displaced and thus also postdate activity along the border faults.

More recent normal faulting affecting an alluvial fan of inferred Quaternary age and sub-recent fluvial terrace deposits is observed within the basin center (see Fig. 4). This has resulted in a horst-and-graben morphology, which indicates that normal faulting is still active.

**Lingti Valley**

In the Lingti Valley, between the Tso Morari Lake in the north and the Spiti Valley in the south, prominent N-S–striking normal faults can be identified on satellite imagery (Fig. 5A). The most prominent normal fault is exposed east of the Lingti River and can be traced for ~8 km. Our field observations confirm that this fault dips to the west and has a vertical displacement of several hundred meters (Fig. 5C). An undated erosional paleosurface sculpted into Jurassic carbonates and preserved at an average elevation of 4700 m within the hanging wall is displaced by this fault and subsidiary structures. Furthermore, there are brittle normal faults arranged in bookshelf manner on the western border of the Lingti River that affect the same erosional paleosurface (Fig. 5B). These latter structures dip ENE. A minimum vertical displacement on each fault strand of ~20 m can be inferred from correlation of the layers across the fault planes (Fig. 5B). In the lower parts of the valley, steeply dipping brittle faults striking N-S are observed. Limited striations on these fault planes plunge downdip and, therefore, fit into an overall E-W extensional regime.

Our observations in this area are consistent with mapping of normal faults by Neumayer et al. (2004) at different length and displacement scales, ranging from mesoscale features to several-kilometer-long structures in the southeastern part of the valley. Similarly, these authors related the normal faults to E-W extension and interpreted them as representing the youngest tectonic movements in the region.

**Mesoscale and Outcrop-Scale Faults Observed in the Field**

Mesoscale and outcrop-scale brittle normal faults are ubiquitous in the area surrounding the Tso Morari–Leo Pargil seismic zone and document the extent of active normal faulting in the Higher Himalaya and also south of the Southern Tibetan detachment system (Fig. 6). Our field observations reveal a network of small-scale normal faults that cannot be detected on satellite imagery. Between the Spiti River in the north and the Main Boundary thrust in the south, numerous steeply dipping N-S–striking normal faults and extensional fracture zones form a dense network, with surface disruptions virtually every 15–20 m (Fig. 7A). Identical to the large-scale structures described previously, these faults result from E-W extension and crosscut all older structures. Taken together with all other sites visited in the field, these structures thus represent the most recent phase of deformation in this part of the Himalaya.

In addition, prominent N-S–striking normal faults with gouge zones up to 3 m wide dominate a diffuse band between 78°E and 78.5°E. They are typically associated with steeply plunging striations indicating dip-slip faulting and E-W extension. In most cases, smaller, parallel, brittle fault planes are observed in their vicinity. Because none of these faults is overprinted by any other structure, we infer that they also reflect the youngest phase of deformation in the region. Synkinematic micas on fault planes and within fault gouges indicate that these faults were associated with deeper-seated processes and originated in the brittle-ductile transition zone but have been exhumed since. Consequently, the faulted basement rocks exposed at the surface today were initially deformed by E-W extension at greater depths, suggesting that this style of deformation has been sustained over long time scales. In the exhumed orthogonalism of the footwall of the southernmost sector of the Leo Pargil detachment zone, we found synkinematically grown
muscovites on a west-dipping fault (strike/dip 178/83°W, see marked location in Fig. 7B) associated with a steeply dipping lineation (trend/plunge: 280/82°W). The 40Ar/39Ar dating of these micas provides ages of 16.3 ± 0.04 Ma and 16.9 ± 0.04 Ma (see Table 1; Fig. 8). This age coincides with the onset of exhumation of the Leo Pargil gneiss dome at 16–14 Ma, also derived from 40Ar/39Ar mica cooling ages farther north (Thiede et al., 2006). Therefore, it is possible that normal faulting in the hanging wall of the Leo Pargil detachment zone had already started before this time. However, the 40Ar/39Ar age presented here can be considered as a lower boundary for the onset of E-W extension in the NW Indian Himalaya.

Normal Faults in Sediments and Soft-Sediment Deformation

With the exception of the spatially limited Quaternary basin fills described previously herein, mostly Paleozoic basement rocks are affected by normal faults in the Higher and Tethyan Himalaya due to the virtual absence of Cenozoic deposits at these high elevations. Hence, it is difficult to unambiguously constrain onset and duration of extensional processes in this region. In places, weathered conglomeratic gravel of unknown age overlying basement rocks is affected by extensional fractures and normal faults. In particular, at the junction of the Spiti River and its tributary, the Lingi River, 2 m of fine-grained, gray, alluvial-fan sediments are overlain by 1.5 m of laminated sandy-silt lake sediments (Fig. 9). Both units are displaced by several N-S–striking normal faults. A slightly older generation of NW-SE–striking normal faults is systematically displaced by the N-S–striking faults, supporting our inference that N-S–striking normal faulting reflects the youngest phase of deformation in the NW Indian Himalaya. However, because the NW-SE–striking normal faults are approximately parallel to the trend of the regional slope, it may be possible that this fault set is not tectonic in origin but instead results from gravity sliding. In contrast, the N-S–striking faults are oblique to the regional slope; a gravitational origin can thus be excluded. Interestingly, some fault planes end in layers that have flame structures, typically associated with deformation during earthquakes (Fig. 9). This observation suggests a possible seismogenic origin of these faults. OSL dating of these deposits provides a burial age of 39.9 ± 2.2 ka for the interface between the alluvial-fan sediments and the lake sediments, illustrating the recent nature of seismogenic processes in the Tethyan Himalaya, which is in line with the instrumentally recorded seismicity in this region (e.g., Molnar and Chen, 1983).

Evidence for soft-sediment deformation of lacustrine sediments is also observed farther east, along the lower Spiti River near the western flanks of the Leo Pargil gneiss dome, where lake deposits reach a thickness of up to 100 m. They extend along the valley for ~8 km and are located between 10 and 100 m above the recent river bed (Fig. 10). The sediments are mainly composed of clay with intercalated thin sandy or silt layers, which are between 0.5 and 10 cm thick. In several locations within the lacustrine sediments, we identified soft-sediment deformation phenomena, such as flame structures, neptunian dikes, and intruded lenses of conglomerate (Fig. 10). All these phenomena can be traced laterally up to 50 m. OSL dating of the sandy layers above the strata affected by soft-sediment deformation provides ages of 29.2 ± 1.6 ka at point B and 31.7 ± 3.9 ka at point D, indicating that the sedimentary deposits at these outcrops are related to the same lake. The OSL ages at points A and C are given as 5.61 ± 0.48 ka and 21.3 ± 1.1 ka, respectively, showing that there are several generations of lake deposits in this region. Details of the OSL dating results are given in Table 2.

Interestingly, soft-sediment deformation within different lacustrine sedimentary bodies is found mainly in the vicinity of the Kaurik-Chango normal fault. Given the proximity to the regional active tectonic structures, the soft-sediment deformational structures could be seismogenic. The last large earthquake on this fault (Kinnair earthquake, 19 January 1975, M = 6.5, fault-plane solution labeled with KEQ in Fig. 1B) produced surface ruptures on the order of 0.5 m (Singh et al., 1975; Bhargava et al., 1978). Due to the absence of a present-day lake in the source area of the 1975 Kinnair earthquake, a comparison between recently produced seismogenic features and our inferred older, possibly earthquake-induced soft-sediment deformation...
Figure 7. (A) Combined kinematic information of brittle deformation (fault planes and striations) in the NW Indian Himalaya. Data close to the Leo Pargil dome were previously published by Thiede et al. (2006). (B) Synopsis of the pseudo–fault-plane solutions shown in different gray colors based on the data shown in A. For details for obtaining the pseudo–fault-plane solutions, see text. For details about the "Ar/Ar" Ar ages, see text, Table 1, and DR1 (GSA Data Repository [see text footnote 1]). Structural map and base map showing elevation are the same as in Figure 1B.
Figure 8. \(^{40}\)Ar/\(^{39}\)Ar ages in inverse isochron and spectra diagrams measured on white mica from rocks within the footwall of the Leo Pargil detachment zone. Increments indicate number of temperature steps considered for the age termination with the isochron plot. Both samples yield well-constrained plateau ages of 16.3 and 16.9 Ma. TFA—total fusion age; WMPA—weighted mean plateau age; IA—isochrone age. Detailed information is available in GSA Data Repository DR1 (see text footnote 1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight (mg)</th>
<th>TFA (Ma)</th>
<th>WMPA (Ma, ±2σ)</th>
<th>IA (Ma, ±2σ)</th>
<th>Steps used (total steps)</th>
<th>% (^{39})Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>B270901-3</td>
<td>3.2</td>
<td>16.4</td>
<td>16.3 ± 0.04</td>
<td>16.3 ± 0.04</td>
<td>8–23 (23)</td>
<td>87</td>
</tr>
<tr>
<td>B270902-4</td>
<td>3.3</td>
<td>17</td>
<td>16.9 ± 0.06</td>
<td>16.9 ± 0.14</td>
<td>8–16 (21)</td>
<td>39</td>
</tr>
</tbody>
</table>

Note: TFA—total fusion age; WMPA—weighted mean plateau age; IA—isochrone age.

Figure 9. Fluvio-lacustrine sediments in the upper Spiti Valley, at the junction to the Lingti Valley. The sediments are affected by normal faulting. The two fault populations strike N-S and 105–285. Some of them terminate in layers with soft-sediment deformation typically associated with deformation during earthquakes (lower-right inset). See Figure 1B for location.
features is not possible. However, although other mechanisms could be invoked locally, the close relationship between normal faults and various types of soft-sediment deformation features in lake sediments in the immediate vicinity of the seismically active belt between the Tso Morari Lake and the Leo Pargil gneiss dome suggests a co-genetic origin.

**PALEOSTRAIN RESULTS**

We collected fault kinematic information at ~100 outcrops between the Tso Morari dome in the north and the Lesser Himalaya in the south. We focused on the southern continuation of the Tso Morari–Leo Pargil seismicity zone and the area between the Leo Pargil gneiss dome in the east and the Kullu Valley in the west. We only considered brittle faults that could be clearly assigned to the youngest deformation phase in the area. The striations on the mainly N-S-striking normal faults related to this deformation phase are typically steeply dipping. However, there are several instances where older fault planes have been reactivated.
as oblique normal faults. In total, we selected ~30 outcrops where we had sufficient data related to the youngest deformation phase in the local context. For these measurements, we calculated pseudo–fault-plane solutions (Fig. 7B).

The majority of the pseudo–fault-plane solutions shows chiefly E-W extension. In the vicinity of the Leo Pargil gneiss dome, the extension direction is NW-SE. In the southwest of the study area, the extension direction is NE-SW, and thus perpendicular to the strike of the orogen (light-gray pseudo–fault-plane solutions in Fig. 7B). Clear crosscutting relationships between fault planes associated with these different extension directions are rare. Observations at a single outcrop indicate that fault planes related to the NE-SW extension have been locally overprinted by faulting during E-W extension.

Diffuse E-W–oriented extension is observed in virtually the entire study area. However, the density of fault planes dipping steeply W or E in the region associated with the N-S seismicity belt is much greater, and enhanced seismicity between the Tsomoriri Lake and the Leo Pargil gneiss dome is much more pronounced compared to other regions of the study area. Nevertheless, at present, we have no data to test if this zone of focused seismicity is a temporary, short-lived feature, or if it is important over longer geologic time scales.

DISCUSSION AND CONCLUSIONS

The new data we present here, including map-scale normal faults identified on satellite imagery and in the field, mesoscale faults, outcrop-scale fault-kinematic data, and fault-cut Quaternary sediments, document ongoing normal faulting extending from the Greater Sutlej River region to the Garhwal Himalaya. The different observations record E-W–oriented extension over a diffuse, approximately N-S–striking swath between 77.5°E and 79°E. Next, we first address the possible onset and/or ages of the different evidences for deformation, and secondly discuss their origin and possible underlying driving mechanisms.

Possible Onset of E-W Extension in the Higher Himalaya

A comparison of our own newly derived 40Ar/39Ar and OSL ages with already published studies in the NW Himalaya allows us to estimate the possible ages of the onset of normal faulting and its continuation to the present day. The following sections discuss the possible timing for the different types of extensional features, where available.

Brittle Faulting on Mesoscale and Outcrop Scale

Synkinematic micas on fault planes and within fault gouge and quartz-filled tension gashes suggest that at least part of the brittle faulting related to E-W extension has its origin in the brittle-ductile transition zone. This zone broadly coincides with depths where temperatures are around 350 °C. The 40Ar/39Ar cooling ages of micas recording a closure temperature of ~350 °C have age ranges between 14 and 19 Ma for the Higher Himalaya, and 4.3–6.7 Ma for the Lesser Himalayan crystalline sequence between the Munsari thrust and Main Central thrust, respectively (Vannay et al., 2004; Thiede et al., 2005, 2006). These ages can be thus considered as the older limit of brittle deformation behavior of the rocks. The age obtained for synkinematic muscovites on a fault plane in the footwall of the Leo Pargil gneiss dome in our study provides a similar age constraint of ca. 16 Ma (see Figs. 7 and 8). Because those micas are synkinematically grown on a fault that is compatible with the E-W tension, we infer that E-W extension was already active in the Higher and Tethyan Himalayas at that time. In addition, ductile mineral stretching lineations observed in the footwall of the Leo Pargil detachment zone along the western flank of the Leo Pargil also indicate E-W extension at lower structural levels between 14 and 16 Ma (Thiede et al., 2006). Combining all of these observations, we suggest that E-W extension was initiated at least around 4 Ma in the Lesser Himalaya and between 14 and 16 Ma in the Higher and Tethyan Himalayas.

Large-Scale Normal Faults on Satellite Imagery

Age constraints on the large-scale normal faults that we evaluated mainly from satellite imagery are essentially nonexistent. The age of the faulted paleosurface in the Tsomoriri area and in the Lingtik Valley is unknown, but based on regional relationships, it can be estimated with reasonable certainty to be of Quaternary age. In the sedimentary basin NW of the Leo Pargil gneiss dome, however, a rough age estimate can be made. The sedimentary fill is clearly related to transient basin isolation, and we infer that normal faulting caused hydrologic isolation and the generation of accommodation space for sediments. The onset of basin filling, therefore, must have been simultaneous with the beginning of normal faulting, and the partially preserved paleosurface provides a minimum timing for the onset of normal faulting in this basin.

Despite a lack of radiometric ages to further decipher these processes, the age of the sedimentary basin fill may be comparable to the fill units of the much larger Zada Basin on the SE side of the Leo Pargil dome, and a crude age estimate may be possible based on observations there. Saylor et al. (2009) suggested that the oldest sedimentary deposits in the Zada Basin are late Miocene. Normal faults along the eastern flank of the Leo Pargil gneiss dome constitute the western border of this basin. Hence, if these normal faults are mechanically linked and are an integral part of the extensional structures that characterize this dome, the structures on the western flank of the dome and the sedimentary fills are coeval.

Soft-Sediment Deformation

Soft-sediment deformation features along the western flank of the Leo Pargil gneiss dome occur in lacustrine sediments that were deposited in a landslide-dammed lake (Booikhagen et al., 2005). The 39Ar ages at the lowest part of these sediments show a consistent calibrated age of 28.5 ± 0.9 ka (Booikhagen et al., 2005). Our OSL ages of sandy layers immediately above those strata affected by soft-sediment deformation provide similar ages within error, attesting to the recent nature of seismogenic movements in this region and to protracted activity along the Kaurik-Chango normal fault. Mohindra and Bagati (1996) and Banerjee et al. (1997) reported similar features in the Pare Chu Valley directly north of the area shown in Figure 10. Based on OSL dating and sedimentary analysis, these authors inferred at least nine separate earthquakes with magnitudes large enough to produce soft-sediment deformation within the last 29 k.y. Because the soft-sediment deformation features that we observed are only a few kilometers away from these lacustrine sediments, they all likely underwent soft-sediment deformation in the same tectonic environment. Thus, there is widespread evidence for seismic activity along the Kaurik-Chango normal fault indicating E-W extension since at least the Pleistocene.

Possible Mechanisms for E-W Extension in the Tethyan and Higher Himalaya

Models and interpretations of orogen-perpendicular grabens in the Central Himalaya can be separated into three major groups: (1) models linking the graben systems to escape tectonics in the course of the India-Eurasia collision process (e.g., Tapponnier and Molnar, 1976; Tapponnier et al., 1982); (2) models that relate the arc-perpendicular structures to the arcuate geometry of the Himalaya and/or the Indian subduction zone (e.g., Ratschbacher et al., 1994); and (3) models invoking processes such as slip partitioning resulting from oblique convergence.
<table>
<thead>
<tr>
<th>Model</th>
<th>Observations from the NW Indian Himalaya:</th>
<th>E-W extension oblique to the regional trend of the orogen</th>
<th>Extent of E-W extension</th>
<th>E-W extension not limited to larger structures</th>
<th>Role of the KF</th>
<th>Normal faulting south of the South Tibetan Detachment System</th>
<th>Migration of extensional structures from the TP into the Himalaya</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horse-tail</td>
<td>(1) Local extension due to dome formation of the Leo Pargl dome (e.g., Acaya et al., 2005)</td>
<td>Yes</td>
<td>Limited to the vicinity of the Leo Pargl gneiss dome</td>
<td>No, mainly focused to dome structures</td>
<td>Not predicted</td>
<td>Not predicted</td>
<td>No</td>
</tr>
<tr>
<td>Horse-tail</td>
<td>(2) Horse-tail termination of the KF (adapted after Kim et al., 2004)</td>
<td>Yes</td>
<td>SE of the KF</td>
<td>No, normal faults should be arranged in single splays originating at the KF</td>
<td>Large slip rate, greater impact</td>
<td>Not specified, but possible</td>
<td>No</td>
</tr>
<tr>
<td>Oblique convergence</td>
<td>(3) Oblique convergence between India and Asia (e.g., McCallum and Nabelek, 1988)</td>
<td>No</td>
<td>Southern Tibet and Himalaya above the subducting plate</td>
<td>No, slip is mainly concentrated on KF</td>
<td>Large slip rate, taking up all shear</td>
<td>Not specified, but possible</td>
<td>No</td>
</tr>
<tr>
<td>Change of boundary conditions</td>
<td>(4) Change of boundary conditions along the eastern margin of Asia (Yin, 2000; Yin and Harrison, 2000)</td>
<td>Yes</td>
<td>Whole Asia, including the Tibetan Plateau (TP) and Himalaya</td>
<td>Yes</td>
<td>Not specified</td>
<td>Not specified, but possible</td>
<td>Yes</td>
</tr>
<tr>
<td>Gravitational collapse of the TP including continuous deformation and coupled crust and mantle</td>
<td>(5) Gravitational collapse of the TP including continuous deformation and coupled crust and mantle (e.g., Zhang et al., 2004)</td>
<td>Yes</td>
<td>Entire TP and Himalaya</td>
<td>Yes</td>
<td>Not a major feature</td>
<td>Not specified, but possible</td>
<td>Yes</td>
</tr>
<tr>
<td>Extrusion of the TP along large strike-slip faults; no mantle flow involved; Tibet behaves as rigid blocks</td>
<td>(6) Extrusion of the TP along large strike-slip faults; no mantle flow involved; Tibet behaves as rigid blocks (e.g., Tapponnier et al., 1982)</td>
<td>Yes</td>
<td>Entire TP and Himalaya</td>
<td>Yes</td>
<td>Large slip rate, major feature</td>
<td>Not specified, but not likely</td>
<td>Yes</td>
</tr>
<tr>
<td>Convective removal of the lower mantle lithosphere</td>
<td>(7) Convective removal of the lower mantle lithosphere (England and Houseman, 1989)</td>
<td>Yes</td>
<td>Entire TP and Himalaya</td>
<td>Yes</td>
<td>Not a major feature</td>
<td>Not specified</td>
<td>Yes</td>
</tr>
<tr>
<td>Gravitational collapse of the TP including decoupled crust and mantle by a weak lower crust</td>
<td>(8) Gravitational collapse of the TP including decoupled crust and mantle by a weak lower crust (e.g., Nelson et al., 1986)</td>
<td>Yes</td>
<td>Entire TP and Himalaya</td>
<td>Yes</td>
<td>Not a major feature</td>
<td>Not specified, but not likely</td>
<td>Possible</td>
</tr>
</tbody>
</table>
the greater Sutlej region could be an integral part of such a horsetail termination of this large strike-slip fault system (see Kim et al., 2004; Fig. 11A). Accordingly, the areas of localized normal faulting between the Tso Morari dome in the north and the Zada Basin in the south could be interpreted as single branches of a horsetail structure.

The third and final alternative explanation links normal faulting in the NW Indian Himalaya to southward propagation of active extensional processes on the Tibetan Plateau (Fig. 11B). For example, fault-plane solutions of earthquakes in this region show dominant E-W extension (Molnar and Chen, 1983; Molnar and Lyon-Caen, 1989). If the observed E-W extension in the NW Indian Himalaya is related to extension in the plateau, then the role of the Karakorum fault as a first-order boundary between the tectonic stress regime in the Tibetan Plateau and compression in the Himalaya would be of secondary importance. The ongoing controversy concerning the displacement rate of the Karakorum fault (e.g., Lacassin et al., 2004; Chevalier et al., 2005; Searle and Phillips, 2007) underscores its ambiguous role in the recent deformation history of the Himalaya-Tibet region. If displacement rates are low (e.g., Searle et al., 1998; Murphy et al., 2000; Phillips et al., 2004) normal faulting in the Greater Sutlej region could indicate that the Karakorum fault has not been able to fully accommodate the E-W extension generated in the Tibetan Plateau. In this scenario, the Karakorum fault does not decouple the extensional processes in Tibet from the shortening regime in the Himalaya. Thus, extensional features in the NW Indian Himalaya would be linked to southward propagation of normal faulting and graben formation that is currently observed in Tibet and the transition with the Central Himalaya.

Whereas the first hypothesis has only local significance relevant for the immediate surroundings of the Leo Pargil gneiss dome, the other two hypotheses could explain normal faulting affecting much more extensive regions. Both hypotheses represent regional-scale end-member scenarios. One of the crucial issues in correctly assessing the different factors producing normal faulting is the importance of the Karakorum fault for recent deformation processes in the NW Himalaya. If the observed structures are indeed part of a horsetail termination of the Karakorum fault, this structure would represent a first-order decoupling zone between the Tibetan Plateau and the Himalaya. Conversely, if normal faulting were related to the propagation of extensional faulting originating on the Tibetan Plateau, then the Karakorum fault would be of secondary importance.

The three scenarios presented here may not be mutually exclusive. All present viable explanations for ongoing E-W–oriented extension in the Higher Himalaya of NW India. However, the overall distribution and orientation of normal faults is inconsistent with the hypothesis of doming and tectonic exhumation of the Leo Pargil gneiss dome. If doming were the primary driver for extension, normal faults should be concentrated close to the flanks of the gneiss dome and not in a N-S–striking swath of active faulting and seismicity that affects all preexisting contractional structures. Furthermore, the normal faults should be oriented radially around the outline of the gneiss dome; however, this is not the case. The processes responsible for doming at the Leo Pargil gneiss dome may still contribute to the evolution of local normal faults. In particular, the rotation of the extensional axis from E-W to NW-SE in the vicinity of the gneiss dome could be a result of doming. Nonetheless, doming does not appear to be a viable mechanism to explain the regional extent of E-W extension observed in the NW Indian Himalaya.

The two remaining end-member models that involve the Karakorum fault may better reconcile the observed structural evolution of the NW Indian Himalaya. In the model that relates the observed E-W extension with the horsetail termination of the Karakorum fault, single splays of normal faults perpendicular and south of this major structure would be expected. Our observations, however, did not reveal such single splays. Furthermore, the strike of such splay faults should rotate toward the Karakorum fault into a NW-SE direction, i.e., parallel to the strike of the Karakorum fault, as indicated by the gray lines in Figure 11A. This should be particularly true for smaller-scale structures. This is not the case, as was clearly shown by Epard and Steck (2008), who mapped Quaternary normal faults in the area between the Tso Morari and the Karakorum fault, immediately north of our study area. These faults do not show any change in strike direction close to the Karakorum fault. In addition, if there were a kinematic linkage between the long-lived Karakorum fault and E-W extension described here, the normal faults should have accrued higher total strain. This would imply that such faults would be more or at least equally pronounced as those normal faults observed around the Gur light Mandhata dome at the southernmost end of the Karakorum fault and south of our study area.
We thus conclude that predominant, pervasive, and active E-W extension in the NW Indian Himalaya is a regional phenomenon and not restricted to the well-known regions of focused extension (e.g. Leo Pargil dome, the Gurja Mandhata dome, the Thakhkola graben, the Ama Drime Massif, and the Yadong graben). Our observations demonstrate that E-W extension affects the entire mountain belt from the Indian-Eurasian suture zone to the footwall of the Main Central Thrust in the Garwhal Himalaya. Importantly, extensional processes are not limited to regions north of the Southern Tibetan detachment system, as previously thought. Although geochronologic data documenting the onset of normal faulting are still sparse, E-W extension has apparently been a protracted process that started at around 16 Ma and has continued until the present day. Based on the regional relationships documented in our study, we propose that E-W extension in the NW Indian Himalaya is transferred from the Tibetan Plateau due to the inability of the Karakorum fault to accommodate all of the ongoing E-W extension on the Tibetan Plateau.

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