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Research Article

The Benkar Fault Zone: An Orogen-Scale Cross Fault in the Eastern Nepal Himalaya

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The Benkar Fault Zone (BFZ) is a recently recognized, NNE-striking, brittle to ductile, cross fault that cuts across the dominant metamorphic fabric of the Greater Himalayan Sequence (GHS) and the Lesser Himalayan Sequence (LHS) in eastern Nepal. ⁴⁰Ar/³⁹Ar-muscovite cooling ages along a transect across the BFZ in the GHS indicate movement younger than 12 Ma. To understand the mode of genesis, and seismo-tectonic implications of the BFZ, we mapped this fault from the Everest region in the upper Khumbu valley toward the south, across the Main Central Thrust, into the LHS and the Greater Himalayan Nappe. We recognize a series of cross faults segments, which we interpret the BFZ system. The currently mapped section of the BFZ is >100 km long, and its width is up to 4 km in the LHS. The BFZ is semi-ductile in the GHS region but is brittle in the south, where it is expressed as gouge zones, tectonically brecciated zones, sharp fault planes, and segments of nonpenetrative brittle deformation zones. From petrographic and kinematic analysis, we interpret largely a right-lateral, extensional sense of shear. Our work did not continue into the Sub-Himalaya, but the BFZ may continue through this zone into the foreland as documented in other Himalayan cross faults. While several genetic models have been proposed for cross faults in the Himalaya and other convergent orogens, we suggest that the BFZ may be related to extensional structures in Tibet. Understanding cross faults is not only important for the tectonic history of the Himalaya but due to the co-location of cross faults and seismogenic boundaries, there may be a causal relationship. Cross faults also follow many of the north-south river segments of the Himalaya and weakened fault rocks on the valley walls may enhance the landslide hazard in these areas.

1. Introduction

A review of several convergent orogenic belts around the world reveals important lateral heterogeneities along the length of the mountain belts. In different mountain belts, these heterogeneities are expressed as along-strike changes in deformation style, igneous activities, grade of metamorphism, surface processes and geomorphology, and/or seismic activity (see review in Giri and Hubbard [1]). In other cases, abrupt lateral transitions coincide with the spatial occurrence of cross faults/structures (faults/structures that strike at a high angle to the trend of

the orogen). Previous authors have suggested a number of explanations for lateral variations in mountain belts around the world such as changes in (a) continental margin geometry [e.g., 2]; (b) basin geometry and sediment thickness [e.g., 3, 4]; (c) plate kinematics and obliquity of plate convergence [e.g., 5, 6]; (d) lithospheric strength [e.g., 7–9]; and (e) the presence of inherited basement structures [e.g., 10–17].

In the Himalaya, researchers have stressed the significance of cross faults as thrust segment boundaries, sometimes between adjacent zones of contrasting thrust geometries [16, 18–22]. While several cross faults have been

recognized in the Himalayan orogen at multiple structural levels (Figure 1), their extent, mode of genesis, and their impact on the regional seismo-tectonics remain poorly understood. The Himalaya is the planet's most dynamic collisional orogenic system, and researchers have found evidence that links cross faults with regional seismicity [21, 23–27], which makes it imperative to recognize and develop a comprehensive understanding of these structures.

The BFZ was first recognized by Seifert [28] as a NNE-striking, right lateral, normal cross fault that runs along and adjacent to the Dudh Koshi valley in the eastern Nepal Himalaya (Figure 2). Seifert [28] mapped the BFZ in the Greater Himalayan Sequence (GHS, highest part of the range consisting of amphibolite to granulite facies rocks) of the Everest region but its southern continuity, its mode of formation, and timing of movement(s) were beyond the scope of that study. In this article, we summarize the findings of Seifert [28] and present new map data, from regions along the strike of the BFZ toward the south, within the Okhaldhunga Window, and the Greater Himalayan Nappe (GHN). This new field data coupled with $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite cooling ages from the GHS, and petrographic and kinematic analysis for samples collected from multiple levels supports the continuation of the BFZ southward cutting across different litho-tectonic units of the Himalaya. While multiple genetic models can explain the BFZ, extensional fault kinematics in the GHS and possible connection to normal fault systems toward the north point toward the likelihood of the BFZ being genetically linked to the ongoing extension in southern Tibet. Other Himalayan researchers have previously explored similar connections between cross faults and Tibetan extension [13, 15, 19, 29, 30]. The BFZ deformation, especially in the south, could be a surface manifestation of tear(s) or basement faults/structures, such as the West Patna Fault, in the downgoing Indian plate.

2. Tectonic Setting

2.1. Tectono-Stratigraphy of the Himalaya. The onset of continental collision along the Indian and Asian plate margins between 61 and 55 Ma was followed by thickening, shortening, and imbrication of the down-going Indian crustal rocks resulting in the formation of the dynamic Himalayan orogenic belt [31–39]. The Himalaya has been viewed as a composite of four major, laterally continuous litho-tectonic units. From north to south, they are the Tibetan Tethyan Sequence (TTS), the GHS, the LHS, and the Sub-Himalaya. These units are each bounded by north-dipping faults: the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) (Figures 1 and 2) [40–49].

The TTS has largely been defined as a Paleozoic and Mesozoic marine succession of siliciclastic and carbonate rocks deposited in the Tethys Sea [50–54]. The STDS, active during ~28–23 Ma to 16–12 Ma (see Goscombe et al. [48]), juxtaposes these very-low to low-grade (greenschist facies) metamorphic rocks of the TTS against the higher-grade

GHS along a system of low-angle, extensional, top-to-the-north, ductile shear zones, and brittle faults [55–61].

The GHS consists of Neoproterozoic to Ordovician (990 Ma to 520 Ma), high-grade metamorphic rocks of the Indian continent [47, 49, 62–66]. During the Cambrian Bhimphedian Orogeny, rocks of the GHS were deformed, metamorphosed, and intruded by granites with U-Pb ages ranging in between 581 Ma and 453 Ma [64–74]. How these midcrustal rocks were exhumed remains an area of active research in the Himalaya [75–81]. Carosi et al. [82] have stressed the importance of in-sequence and out-of-sequence thrusts and shear zones within the GHS, which in general has been mapped as one continuous tectonic unit.

In the vicinity of the Everest region, the GHS consists of amphibolite to granulite facies, sillimanite-grade, metapelite, orthogneiss, calc-silicate, and amphibolite along with leucogranite intrusions [59, 69, 80, 83–89]. Following the India-Asia collision, these rocks experienced the prograde Barrovian Eohimalayan metamorphism under pressure-temperature conditions of 650°C–680°C, 7–8 kbar (kyanite $\pm$ sillimanite grade) between ~39 Ma and 30 Ma, which was followed by the sillimanite $\pm$ cordierite grade Neohimalayan metamorphism during 28 Ma to 16 Ma at 600°C–750°C, 3–5 kbar [72, 80, 88, 90–93]. Timing of voluminous melt injection and leucogranite crystallization within the GHS has been well constrained between 24 Ma and 15 Ma (see Cottle et al. [94]). In the Everest region, the STDS is represented by the upper, brittle Qomolangma Detachment, with the Ordovician Limestone in the hanging wall, and the lower, ductile Lhotse Shear Zone, with middle-to upper-greenschist facies schist and calc-silicate rock of the Everest Series in its hanging wall (footwall of the Qomolangma Detachment) (Figure 2) [69, 95–97]. Extensional movement along the Lhotse Shear Zone ceased prior to 16 Ma, while the Qomolangma Detachment was active until at least 13 Ma [94, 98]. Cessation of movement along the STDS has been interpreted as the end of tectonic exhumation of the GHS, which was followed by erosional exhumation that likely was accelerated in the Pliocene [80, 98–101].

Apatite fission track ages within the GHS of the Everest and surrounding regions progressively increase with elevation from ~1 Ma near the MCT to ~3 Ma near the STDS [102]. Zircon fission track (ZFT) ages range between ~4 Ma and ~16 Ma and $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite cooling ages range between ~10 Ma and ~17 Ma, and both systems show a systematic increase in ages with elevation [102–104].

The MCT is the lower structural boundary of the GHS and has been variously mapped as (a) a lithological boundary between low- and high-grade metamorphic rocks [40, 84, 105–107]; (b) the kyanite isograd [42, 52, 83]; (c) an abrupt change in U-Pb detrital zircon ages [62, 108] and in Nd isotope compositions [49, 109, 110]; (d) a thick shear zone with or without an upper or lower fault [111, 112]; and (e) the base of a high strain zone [113]. Above or within the MCT zone, the metamorphism is inverted from chlorite- to sillimanite-grade toward the north [40, 42, 111, 112, 114]. The MCT has been interpreted to be coeval with the STDS between 22 and 19 Ma [61, 103, 114–116] along

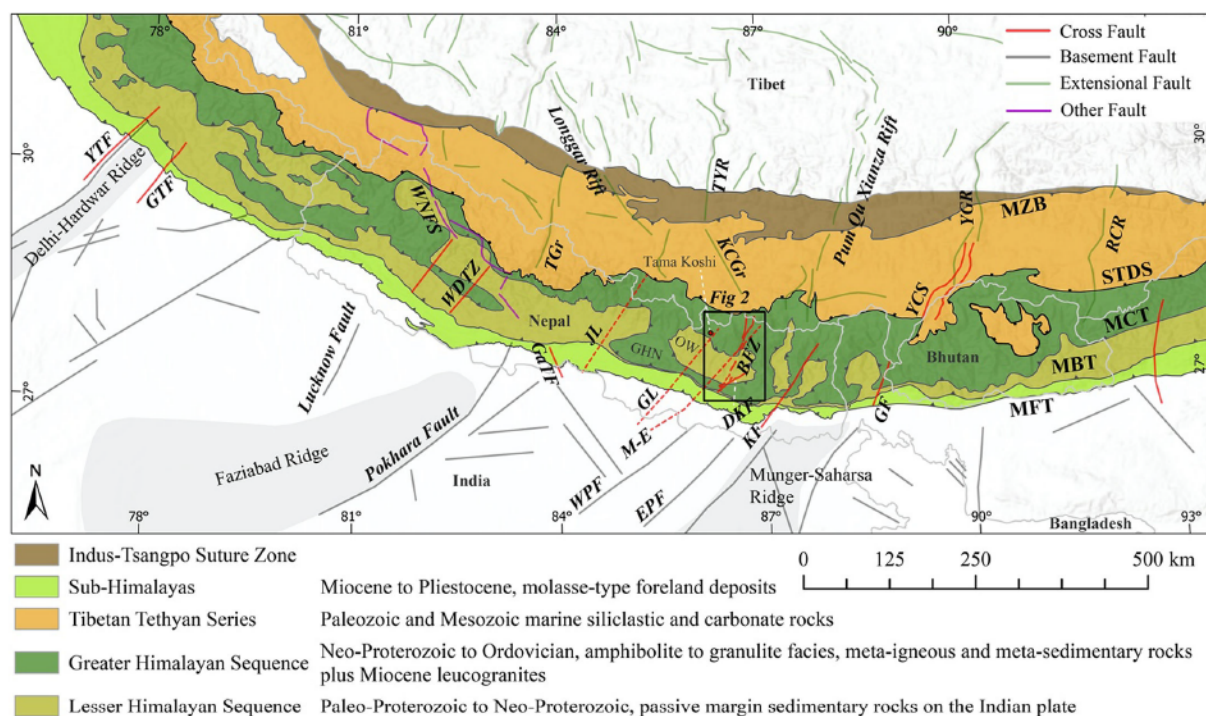


FIGURE 1: Simplified litho-tectonic map of the Himalaya. The red dashed and heavy lines indicate cross faults. Rectangle in the center shows extent of the area shown in Figure 2. Modified from Godin and Harris [13], Goscombe et al. [48], Hubbard et al. [20], and Godin et al. [14]. BFZ: Benkar Fault Zone; DKF: Dudh Koshi Fault; EPF: East Patna Fault; GaTF: Gadi Tear Fault; GF: Gish Fault; GHN: Greater Himalayan Nappe; GL: Gaurishankar Lineament; GTF: Ganga Tear Fault; JL: Judi Lineament; KCGr: Kung Co Half Graben; KF: Kosi Fault; MBT: Main Boundary Thrust; MCT: Main Central Thrust; M-E: Motihari-Everest Lineament; MFT: Main Frontal Thrust; MZB: Main Zaskar Backthrust; OW: Okhaldhunga Window; RCR: Riduo-Cuona rift; STDS: South Tibetan Detachment System; TGr: Thak Khola Graben; WDTZ: Western Dang Transfer Zone; WNFS: Western Nepal Fault System; WPF: West Patna Fault; YCS: Yadong Cross Structure; YGR: Yadong Gulu rift.

with localized Late Miocene to Pliocene movements [117–120].

Several researchers have mapped the MCT in the Dudh Koshi and the adjacent valleys, and they have presented varying spatial locations and definitions of this structure. Ishida [86] and Ishida and Ohta [87] have mapped a system of thrusts that coincide with lithological changes. Hubbard [121] mapped the MCT as a 3- to 5-km-thick, north-dipping, ductile shear zone consisting of augen gneiss, pelitic schist, amphibolite, marble, calc-silicate, slate, and quartzite. Catlos et al. [117] mapped the MCT as a discrete thrust that roughly passes along the top of the MCT zone of Hubbard [121]. The MCT has also been mapped farther toward the south along the base of the Melung-Salleri Augen Gneiss zone [89, 91, 122], which also corresponds to the Phaplu Thrust of Maruo and Kizaki [123]. Several other structural elements have also been mapped in the vicinity of the MCT. The base of the Melung-Salleri Augen Gneiss has been mapped as the MCT-I [111, 117], as a shear zone [124], and as the Midland Thrust [87]. In the adjacent Tama Koshi valley (Figure 1), the contact between the Lesser Himalayan metasediments and the Melung-Salleri Augen Gneiss has been mapped as the Upper Tamakoshi Thrust/Shear Zone [104, 125]. Larson et al. [126] interpreted an out of sequence movement along the Upper Tamakoshi Thrust during 11–8 Ma, which is in agreement with their previous $^{40}\text{Ar}/^{39}\text{Ar}$

cooling ages and quartz fabric work in the region [104, 125, 127].

Like elsewhere in the Himalaya, the basal section of the MCT zone records pressure conditions of 7–8 kbar, which gradually decrease to 4–5 kbar toward the north [80, 121]. Peak temperature, however, sharply increases up section across the MCT from 450°C to 670°C [80, 89, 103, 112, 128, 129].

The LHS, footwall to the MCT, consists of Paleoproterozoic to Neoproterozoic, passive-margin, meta-sedimentary rocks of the Indian plate and associated igneous and meta-igneous rocks [44, 47, 62, 65, 81, 109, 130–134] and Permian to Paleocene, siliclastic, and fossiliferous deposits, known as the Gondwana Sequence, that unconformably overlie the older Precambrian units [49, 81, 135, 136]. The lower stratigraphic levels of the LHS host a gneissic body, which is referred to as the Ulleri Augen Gneiss in western and central Nepal [137, 138] and as the Melung-Salleri Augen Gneiss in eastern Nepal [84, 86]. Throughout the Himalaya, the age of this unit has been well-constrained between 1.75 Ga and 1.90 Ga (see Larson et al. [124], Kohn et al. [132], Larson et al. [139]). Researchers have variously described this gneissic unit as a felsic extrusive rocks [42], a magmatic arc-related rock in a convergent setting [132], a rift-related rock [139, 140], and a “metasomized or tectonized” granitic basement rock [111].

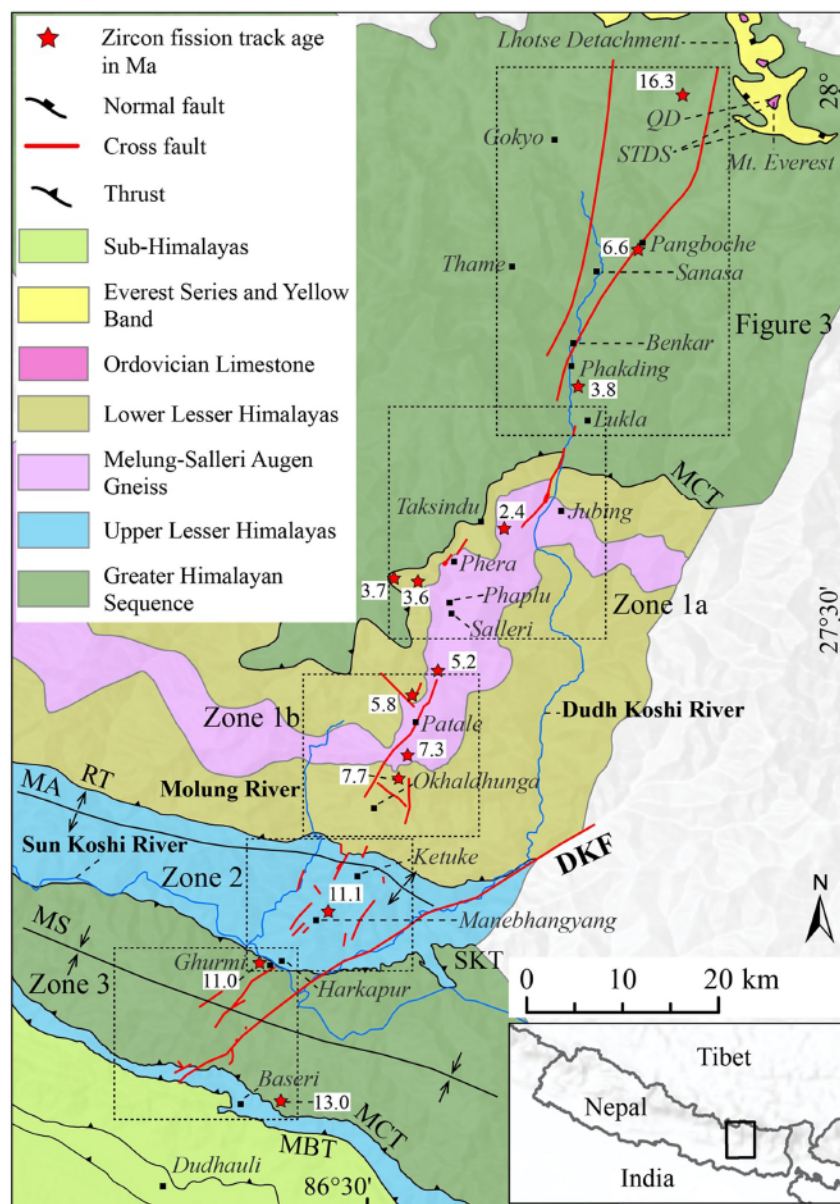


FIGURE 2: Litho-tectonic map of the study area showing the mapped extent of the Benkar Fault Zone (source: [46, 80, 84, 87] Zircon fission track ages south of Lukla are from Nakajima et al. [235] and north of Lukla are from Streule et al. [102]). DKF: Dudh Koshi Fault; MA: Midland Antiform; MBT: Main Boundary Thrust; MCT: Main Central Thrust; MS: Mahabharat Synclinorium; QD: Qomolangma Detachment; RT: Ramghar Thrust; SKT: Sun Koshi Thrust. Grey dotted boxes show the extent of the different litho-stratigraphic zones.

This unit consists of mylonitized, quartz + alkali-feldspar + plagioclase + muscovite + biotite orthogneiss [84, 86, 139], schistose gneiss, and assimilated fragments of the Lesser Himalayan metasedimentary rocks, which generally occur as chloritic schist. Hubbard [121] noted garnets and alkali feldspar augen with myrmekitic texture.

Within the LHS, rocks from the lower stratigraphic levels (Lower LHS) have been thrust over younger rocks (Upper LHS) along the Ramghar or Ramghar-Munsiari Thrust (RT) resulting in the structural culmination known as the Lesser Himalayan Duplex and/or the Midland Antiform/Anticlinorium (Figure 2) [75, 109, 141–148]. In the western Nepal Himalaya, major duplex growth occurred between 11 and

5 Ma before the deformation propagated southward along the MBT [49]. In eastern Nepal, Nakajima [49] suggests that the Midland Anticlinorium developed during and/or after the cessation of the southward transport of the Greater Himalayan thrust sheet at 12–10 Ma.

In our study area, the Lesser Himalayan rocks are well exposed within the Okhaldhunga Window, which toward the south, is bounded by the Sun Koshi Thrust (SKT), the southern continuation of the MCT (Figure 2). Schelling [84] has mapped this thrust as a north-dipping, out-of-sequence thrust. Previous mapping in the LHS of the Okhaldhunga Window and the surrounding region had been done by Ishida [86], Ishida and Ohta [87], Andrews [149], Schelling

[84], Dhital [46], and Baskota and Adhikari [150]. The earlier studies were aimed at building a regional tectonic-stratigraphic framework, and more recent mapping work only covers parts of the Okhaldhunga Window. A detailed lithostratigraphic construction, well established in western Nepal [49] and in central Nepal [151, 152], is still lacking in this region.

South of the SKT, the GHN rocks have been folded into the EW-trending Mahabharat Synclinorium (Figure 2). These rocks are generally interpreted as a nappe of the GHS above the LHS. Larson et al. [126] constructed prograde (515°C and 5.5 kbar to 575°C and 7 kbar; 32.4 ± 0.3 Ma) and subsequent retrograde (480°C–515°C and 6–7 kbar, until 17.5 Ma) metamorphic pathways for these nappe rocks. Equivalent rock units in central Nepal have been mapped as the Kathmandu Complex [151, 152], which underwent an earlier phase of metamorphism, deformation, and granitic and gneissic intrusion during the Bhimpedian Orogeny [46, 67]. The GHN rocks in eastern Nepal were mapped by Ishida and Ohta [87] and Schelling [84] as the Mahabharat Crystallines. Subsequently, Dwivedi [153] constructed a stratigraphic scheme, guided by that of Stöcklin and Bhattarai [151], consisting of seven lithological units namely the Raduwa Formation, the Bhanisedobhan Marble, the Kalitar Formation, the Chisapani Quartzite, the Kulikhani Formation, the Markhu Formation, and the Tistung Formation.

The Sub-Himalaya, footwall to the MBT, consists of Miocene [Eocene; 49] to Pleistocene, molasse-type foreland deposits which display an overall coarsening upward sequence correlating to the southward propagation of the Himalayan deformation front [154–162]. The southern boundary of the Sub-Himalaya is the active and laterally continuous MFT, with a Holocene slip rate of 23 mm/year [163, 164]. The MCT, MBT, and MFT have been interpreted to merge into a basal decollement known as the Main Himalayan Thrust (MHT) [165–169]. Cumulative shortening along these faults varies laterally [e.g.; 144] and accounts for about half of the convergence distance between the Indian and Eurasian plates [49].

2.2. Himalayan Cross Faults and Tibetan Rifts. While the structural geology of the Himalaya is dominated by the major, orogen-parallel thrusts, there is also evidence for structures that cut across the range. Such structures, in places, disrupt the lateral continuity of major thrust structures and litho-tectonic units. Maps produced in the last 40–50 years have noted fault segments orthogonal to the range, but these structures, referred to here as cross faults, have not been the focus of research until lately [e.g., 11, 13, 19, 28, 170–174]. Several explanations have been brought forward to explain cross faults, but the importance in their study lies in their potential link to both seismic and landslide hazards as well as our complete understanding of tectonic processes in collisional orogens [15, 18, 24, 175–177].

One on-going discussion about Himalayan cross faults is a possible link to structures in the Indian cratonic basement. In the Himalayan foreland, several basement ridges

and faults, with high-angled orientation to the Himalayan front, have been recognized and mapped within the Indian plate (Figure 1) [11, 13, 14, 17, 178–183]. In the western Himalaya, introduction of the Delhi-Haridwar basement ridge underneath the evolving wedge spatially coincides with a visible offset of the deformation front, which is bounded by the Ganga and Yamuna Tear Faults [184, 185]. In western Nepal, between 82.5°E and 81°E, Harvey et al. [186] demonstrated a bifurcation of a physiographic transition (east-west trending physiographic transition described by Hodges et al. [187] divides the Himalaya into longitudinal belts of similar topography) and a widening of the regional micro-seismic trend. In the same region, Soucy La Roche and Godin [19] interpret a NNE-striking lateral ramp in the MHT, formed in the Oligocene, to explain along-strike variations in peak temperatures, timing of peak metamorphism, and deformation pathways of two nearby Greater Himalayan thrust sheets. They attribute the genesis of this lateral ramp to the Lucknow basement fault (Figure 1). This lateral ramp interpretation of Soucy La Roche and Godin [19] is in agreement with conclusions of Harvey et al. [186] and van der Beek [188].

Toward the east, the West Dang transfer zone has been described as an orthogonal structure in the Sub-Himalaya to account for abrupt changes in thrust sheet geometry [172, 173] and has also been associated with segmentation of the P-T history within the metamorphic core rocks toward the north [19, 30]. In central Nepal, the north-south trending, >70-km-long, asymmetric Thak Khola graben has been viewed as one of the many structures genetically related to the active east-west extension in Tibet [56, 189–192]. East of Kathmandu, the NE-striking Gaurishankar Lineament spatially coincides with an abrupt, NE-SW termination of the M_w 7.8 2015 Nepal Earthquake aftershocks [[16, 20] and references therein]. In eastern Nepal and India, two cross faults, the Kosi Fault and the Gish Fault, have been mapped as recess-salient boundaries [171, 193, 194]. The Kosi and the Gish Faults also align with the western and the eastern boundaries of the Munger-Saharsa basement ridge, respectively (Figure 1). Clusters of micro-seismicity that follow the Kosi Fault serve to suggest that the Kosi Fault is an active structure [20, 166, 195, 196], which is not surprising given that this fault cuts the active MFT. The Gish Fault is along strike with the Yadong Cross Structure (YCS), which is a NNE-striking, left-lateral fault with apparent offset of the STDS of ~70 km [197]. Wu et al. [197] have interpreted the YCS as the surface manifestation of a lateral ramp in the MHT. In the eastern Himalaya, researchers have reported multiple small to moderate, strike-slip earthquake events that occurred at depths between 13 and 68 km on near-vertical fault planes oriented at high angle to the regional trend suggesting that Himalayan cross faults may pass below the MHT into the Indian plate basement below [15, 21, 25, 27].

The Tibetan Plateau is undergoing syncontractual extension [198, 199], which has been primarily accommodated by several NS-trending rifts and associated normal faults and crustal-scale strike-slip faults [200–206]. Major rift systems in southern Tibet constitute the Longgar rift,

the Tangra Yumco rift, the Pum Qu Xianza rift, the Yadong Gulu rift, and the Riduo-Cuona rift (Figure 1). Geodynamic models proposed to explain these E-W extending rifts include (a) gravitational collapse of Tibet [192, 207], (b) underthrusting of the Indian plate [208–212], and (c) tearing of the downgoing Indian slab [213–218] among others [219–221]. Recent geochemical studies have shown that rifting across Tibet was diachronous and that most rift systems were activated between 16 and 8 Ma [210–212, 222, 223].

2.3. Benkar Fault Zone. In eastern Nepal, the BFZ was recently mapped in GHS rocks in the Everest area [28, 170]. In earlier studies, fault segments and deformation zones, some interpreted as fold limbs in the Everest region, were recognized by Hubbard [85], Carosi et al. [224], and Musumeci [225] and were reinterpreted as cross faults and named the BFZ by Hubbard et al. [170] (Figures 2 and 3). Seifert [28] conducted field mapping, petrographic, structural, and kinematic analysis including electron backscatter diffraction in quartz of the BFZ within the GHS and interpreted the structural and deformation style of this fault by considering existing geochronologic, thermochronologic, thermobarometric, and petrographic data. Hubbard et al. [170] and Seifert [28] interpret the BFZ in the GHS as a NNE-striking, SE-dipping zone of deformation with a dominant normal, right-lateral sense of movement. Within the GHS, the zone of deformation widens northward as it wraps around the increasing volume of leucogranite bodies. Around Gorakshep, the BFZ is ~11 km wide, with mean orientation of foliation $037^{\circ}/43^{\circ}\text{SE}$, while about 30 km south of Gorakshep, the deformation zone narrows to 1–2 km, with a mean foliation orientation of $348^{\circ}/40^{\circ}\text{NE}$. Mineral stretching lineations within the BFZ are represented by dominant SW-plunging orientations, although there are local NE-plunging lineations as well. The BFZ deformation has been concentrated on anastomosing shear zones within sillimanite- and mica-rich domains in nonpenetrative ductile to semi-brittle styles. Seifert [28] has interpreted that the BFZ deformation occurred within upper greenschist to lower amphibolite facies conditions, during the regional retrograde metamorphism of the GHS. The deformation led to syndeformational growth of fibrolite and phyllosilicate within the shear planes. Seifert [28] recognized that the BFZ likely continued to the south, but mapping in that direction was beyond the scope of his work. There is topographic evidence for a continuation of the BFZ southward and tracing it in that direction is important to determine cross cutting relationships with the major thrust fault systems. The goal of this study is to take the mapping and kinematic analysis southward and to collect data that might constrain the timing of movement.

3. Methods

3.1. Geologic Mapping. Our mapping work picks up at the southern limit of the map of Seifert [28] and was conducted along an 80-km-long swath between Jubing and Dudhauri

and included several additional ~E–W transects within that zone (Figure 2). Our final geological maps include partial map data from Ishida and Ohta [87], Hubbard [85], Schelling [84], Dwivedi [153], Dhital [46], and Baskota and Adhikari [150]. We have presented relevant structural data including the orientation of bedding and foliation in lower hemisphere, equal area projection by using “Stereonet 11.5.1” of Rick Allmendinger.

To help guide our mapping, we used Google Earth to locate ~NNE- or ~NE-striking topographic lineament because the BFZ to the north is generally expressed well topographically. During field work, we looked for evidence of shearing and/or faulting such as breccia, fault gouge, mylonitic rock, offset lithologic contacts, and deviations in rock fabric orientation in the vicinity of such lineaments. Upon field investigation, we found out that many of these lineaments do host cross-fault deformation. To develop a comprehensive understanding of cross faults, it is important to also recognize the regional rock fabric, the surrounding lithology, and the major structural elements. Therefore, we mapped rocks units adjacent to and outside of cross fault segments wherever possible. Within the Okhaldunga Window, we have prepared a litho-stratigraphic classification for the LHS. This classification is primarily based on our lithological mapping along with previous work of Dhital [46] and Baskota and Adhikari [150] and has been guided by the classification scheme of DeCelles et al. [49].

The biggest challenge in conducting geological mapping in the LHS, especially for cross faults, is the limited availability of rock exposures due to dense vegetation and human alteration of the landscape for agriculture. This situation limits our ability to precisely map contacts and trace cross-fault segments along strike. We were able to find some excellent outcrops, however along newly cut road sections.

3.2. Kinematic Analysis and Petrography. Oriented and nonoriented petrographic samples were collected from the LHS and the GHN. Standard thin sections were prepared and analyzed with a petrographic microscope. In the field, we measured strike and dip of shear fabric and the trend and plunge of linear features related to deformation such as slickenlines and stretched or aligned mineral lineations indicative of the most recent transport direction. Where possible, we determined shear sense in the field or from thin section. Kinematic data have been presented on stereonet by using the Fault-Kin software package of Allmendinger. Our kinematic and petrographic analyses have largely been guided by Passchier and Trouw [226].

3.3. $^{40}\text{Ar}/^{39}\text{Ar}$ Muscovite Thermochronology. To get a first-order idea of the timing of deformation, we conducted $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of muscovite in the GHS region to see whether cross fault deformation had enough of a vertical component of offset to place constraints on fault timing. Muscovite aliquots were hand separated from pulverized rock samples. Multiple crystals of muscovite were packed in Al foil, loaded into Al discs, and stacked in a flame-sealed glass vial for irradiation. Standards of FC EK (a recollection

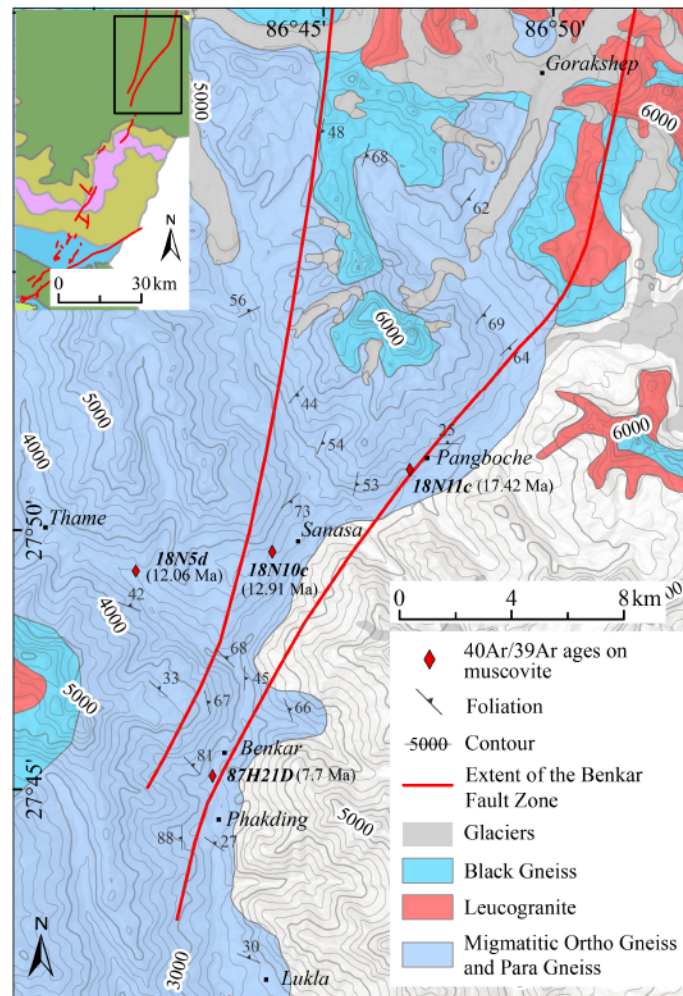


FIGURE 3: Map of the Benkar Fault Zone in the Everest region (source: Seifert [28]). The inset map has been shown in detail in Figure 2. Contour values for all map figures are in meters. Note that the red lines do not represent two discrete fault segments but rather the outer boundary of the cross fault deformation zone. Multiple shear surfaces are present within this deformation zone.

of FC-2; [227]) with an age of 28.294 ± 0.036 Ma [228] were placed within wells adjacent to the samples and throughout the entire stack to permit detailed characterization of the irradiation flux both horizontally and vertically. Samples were irradiated in the Cd-lined (CLICIT) facility of the Oregon State University (USA) TRIGA reactor for 0.33 hour.

Ten to twelve grains samples were step-heated until fused with a Photon Machines 55 W CO₂ laser. Isotope data were collected using a Nu Instrument's Noblesse multi-collector mass spectrometer, run in single collector mode. Samples were heated for 5–10 seconds prior to 120 seconds clean-up. Extracted gases were cleaned using 2 GP50 SAES getters (one operated at 450°C and one at room temperature). The extraction, clean up, and data collection processes were entirely automated. Backgrounds $\pm$ standard deviations from all blank runs were used to correct isotope abundances. Air calibrations were collected after every six analyses to monitor mass discrimination. A $^{40}\text{Ar}/^{36}\text{Ar}$ value of 298.56 ± 0.31 was used to correct the data for mass discrimination [229]. A power law function was

used for the mass discrimination correction [230]. Berkeley Geochronology Centre software “mass spec” was used to regress and reduce age data using the decay constant of $5.5305 \times 10^{-10} \text{ a}^{-1}$ from Renne et al. [228]. The isotope data were corrected for blank, radioactive decay, mass discrimination, and interfering reactions. Age uncertainties are reported to 2σ ; uncertainties on the isotopic measurements are reported to 1σ .

4. Results

To best articulate our results, we have divided our study area into three litho-stratigraphic zones (Figure 2). Our northernmost zone, Zone 1 consists of the Lower LHS between the MCT and the RT. This zone largely coincides with the northern limb of the Midland Anticlinorium. We have subdivided this zone into Zones 1a and 1b to show more detailed maps. We have marked the Upper LHS rocks between the RT and the SKT as Zone 2, which forms the southern limb of the Midland Anticlinorium. The Mahabharat Synclinorium, between the SKT and the MBT,

forms Zone 3 and includes the GHN rocks and slivers of the Upper LHS.

For each zone, we first present brief lithologic and petrographic descriptions of the mapped units and when applicable, associated, major range-parallel structural elements. Subsequently, we present field evidence for the presence of the BFZ within the zone and where possible, augment our field observations with petrographic analysis.

4.1. The Lower LHS (Zone 1)

4.1.1. Litho-Stratigraphy and Petrography. Our litho-stratigraphic scheme of the Lower LHS consists of the Okhaldhunga Formation, the Melung-Salleri Augen Gneiss, the Phera Quartzite, and the Khare Formation (Table 1; Figures 4 and 5). We have further subdivided the Okhaldhunga Formation into the Lower Okhaldhunga Formation, the Barnalu Quartzite, and the Upper Okhaldhunga Formation.

The Lower Okhaldhunga Formation is dominated by gritty/sandy/silty slate and phyllite with frequent beds of metasandstone/metagraywackes. The overlying Barnalu Quartzite consists of micaceous quartzite with thin partings of lustrous phyllite. This unit is overlain by the Upper Okhaldhunga Formation, which is represented by slate, phyllite, metasandstone, quartzite, psammitic schist, schistose phyllite, and graphitic schist. Micaceous quartzite with interbeds of phyllite and schist belonging to the Phera Quartzite rest over the Upper Okhaldhunga Formation. The top-most unit of the Lower LHS is the Khare Formation, which we named after the comparable Khare Phyllite unit of Schelling [84]. The basal section of this unit consists of phyllite and graphitic schist. Laminated silicious carbonate and staurolite-garnet schist in the upper section of this unit have been intruded by amphibolite layers.

Within the Lower LHS, we collected four petrographic samples, one each from the Khare Formation (N312), the Melung-Salleri Augen Gneiss (AC166), the Barnalu Quartzite (AC178), and the Lower Okhaldhunga Formation (F106) (Figures 4, 5, and A1). All of these samples fall outside of the BFZ and reveal the regional, thrust-related, penetrative fabric. The Khare Formation sample (N312) is a garnet-schist (quartz, muscovite, chlorite, biotite, garnet, and plagioclase). This sample displays a strong S/C fabric (thrust sense along $12^{\circ}/342^{\circ}$ [plunge/trend] on $001^{\circ}/34^{\circ}$ NW foliation), spiral inclusion in garnet, deformation lamellae and chess board extinction in quartz, kinking in plagioclase, and retrograde reaction rims of chlorite on garnets online Supplementary Material Fig A1(a). A strong degree of thrust-related shear deformation can also be found in samples from the Melung-Salleri Augen Gneiss (AC 166) and the Lower Okhaldhunga Formation (F106). Sample AC166 comes from an outcrop of granitic schist (quartz, plagioclase, muscovite, orthoclase, biotite, chlorite) online Supplementary Material Figure A1(b). In thin section, we note undulose and sweeping extinction and subgrains in quartz, several bulging grain boundaries, domains with strong grain size reduction, and domains with relatively less intense deformation. Microstructures are consistent with an oblique thrust-sense movement along

a plunge of 20° along an 260° trend on a $055^{\circ}/40^{\circ}$ NW foliation surface. The sample F016 thin section shows a fine-grained matrix of chlorite and muscovite surrounding coarser quartz clasts with tails, which suggests some degree of mylonitization and/or fluid involved deformation online Supplementary Material Figure A1(c). In an outcrop of the Barnalu Quartzite, we saw a small lens (a few centimeters long) of fibrous, lustrous, pale blue mineral, which we interpret to be pyrophyllite (AC178) online Supplementary Material Figure A1(d).

4.1.2. The Main Central Thrust and the BFZ. The MCT is the northern fault boundary of Zone 1. Understanding the cross-cutting relation between the BFZ and the MCT is crucial in defining the genesis of the BFZ because if the BFZ was to terminate at the MCT, then the BFZ would most likely have been a tear fault in the hanging wall of the MCT. In order to determine cross-cutting relations between the BFZ and the MCT, we follow the lithological boundary definition of the MCT, whereby the MCT follows the lithological contact between Khare Formation (Table 1) of the LHS and ortho/para gneissic rocks belonging to the GHS [84, 92, 231]. We do acknowledge that in some parts of the Himalaya, the MCT does not necessarily correspond to the GHS-LHS boundary [134].

The regional fabric orientation in the vicinity of the MCT, west of the Dudh Koshi river, differs from the regional fabric orientation east of the Dudh Koshi river and from farther toward the south online Supplementary Material Figure A2. East of the Dudh Koshi river, fabric related to the MCT dip 30° – 60° toward N or NNE [85]. Toward the west, the MCT makes a counterclockwise bend and assumes a gentle, westward dip online Supplementary Material Figure A2(a) before switching back to a gentle northward dip farther toward the west [84]. East of the Dudh Koshi river, we have marked the MCT along the lithological boundary between the GHS and LHS of Hubbard [121]. West of the Dudh Koshi river, the corresponding lithological contact passes through just north of Taksindu, where garnet-schist, belonging to the Khare Formation, have been overlain by garnet bearing silicate gneiss and mica-schist. Our mapping indicates that the dark, graphitic schist unit, which occurs in the basal levels of the Khare Formation, has been offset by 2 km in an apparent right-lateral sense (Figure 4).

4.1.3. Evidence for the BFZ in Zone 1. Within Zone 1, we were able to recognize and map several exposures of cross fault segments (Figure 6). A ~ 70 -m-wide tectonically brecciated zone is exposed on a road cut section near the Phera village (Figures 4 and 6(a)). Within the breccia zone, strongly deformed graphitic schist is juxtaposed against brecciated quartzite. Foliation orientation in the graphitic schist is $326^{\circ}/35^{\circ}$ NE, which differs from the regional thrust-related rock fabrics that are gently dipping toward the west (Figure 6(a)). Multiple shear planes within this zone display an NNE-strike ($012^{\circ}/63^{\circ}$ SE).

About 2.5 km NNW from the town of Okhaldhunga, a nearly 250-m-wide, distinct topographic depression runs across an EW-trending quartzitic ridge. Within this zone,

TABLE 1: Litho-stratigraphic classification of the Lesser Himalayan Sequence in Nepal.

DeCelles et al. [49] and approximate ages in Ma, Western Nepal	Stöcklin and Bhattarai [151], Central Nepal	This study		Lithologic description from this study
Upper Lesser Himalayan Sequence	Robang Formation	Harkapur Formation		Dolomite and silicious carbonate interbedded with phyllite, calc-phyllite, and quartzite
	Malekhu Limestone			Basic intrusions
	Lakharpata Formation, 1500–1300 (?)	Benighat Slate (with Jhiku Carbonate beds)	Manebhangyang Formation	Dominated by dark/pitch black, carbonaceous slate along with siltstone, silty slate, quartzite, metasandstone, and silicious dolomite
		Dhading Dolomite	Halesi Dolomite	Stromatolitic dolomite with black slate partings
	Syangia Formation, 1760–1728	Nourpoul Formation	Ketuke Formation	Thick to massive beds of arkose quartzite with variegated slaty partings and some granule to pebble-bearing conglomeratic beds
	Galyang Formation, <1760?	Dandagaon Phyllite	Khare Formation	Phyllite, garnet-bearing graphitic schist, silicious carbonate, marble, staurolite-garnet schist, and amphibolite intrusions
Lower Lesser Himalayan Sequence	Fagfog Formation, 1770–1760	Fagfog Quartzite	Phera Quartzite	Medium to coarse grained quartzite with subordinate amount of mica with thin interbeds phyllite/schist
	Lesser Himalayan augen gneiss, 1890–1860		Upper OF	Phyllite, metasandstone, quartzite, psammitic schist, schistose phyllite, and graphitic schist
	Kushma Formation, 1890–1840	Kuncha Formation	Okhaldhunga Formation (OF) and Melung-Salleri Augen Gneiss	Barnalu Quartzite
	Kuncha/Ranimata Formations 1912–1840?		Lower OF	Medium to coarse grained micaceous quartzite with partings of lustrous phyllite
				Gritty/silty slate and phyllite plus metasandstone/metagraywacke
				Granitic intrusions

the north-dipping rocks of the Barnalu Quartzite have been sharply truncated by a >10-m-thick gouge zone (Figure 6(b)). The contact between the gouge zone and the beds has an orientation of $210^{\circ}/70^{\circ}\text{NW}$. Slip-related lineations suggest movement along $19^{\circ}/217^{\circ}$ in a dextral, thrust sense. Due to obscured contacts, we did not observe a noticeable offset along this unit. Along the strike of this fault and toward the north, we document steep, W-dipping fault segments around Patale village (Figure 6(c)). Along an NNE-striking linear valley to the north of Patale, we saw further evidence of fault-related deformation parallel to the strike of the valley.

Toward the west from the aforementioned gouge zone, the Barnalu Quartzite is jointed but remains relatively undeformed. Toward the east, however, this unit has been

sheared and jointed along multiple orientations across a distance of 600 m. The pyrophyllite bearing sample, AC178, was collected from an exposure within this sheared zone. Along the road section from Okhaldhunga to Rumjatar, this quartzite unit abruptly terminates against pelitic rocks belonging to the Lower Okhaldhunga Formation in a left lateral sense of shear with a strike separation of about 700 m along a NW-SW trend (Figure 5). We did not find kinematic indicators related to this fault. However, we noted traces of this fault in the Upper Okhaldhunga Formation, which has been expressed as <1-m-thick, subparallel, steep, brecciated zones ($000^{\circ}/71^{\circ}\text{E}$) that cut into the regional foliation. Just to the north of Rumjatar, we saw multiple exposures of cross faults that run into regional bedding/foliation planes (Figure 6(d)).

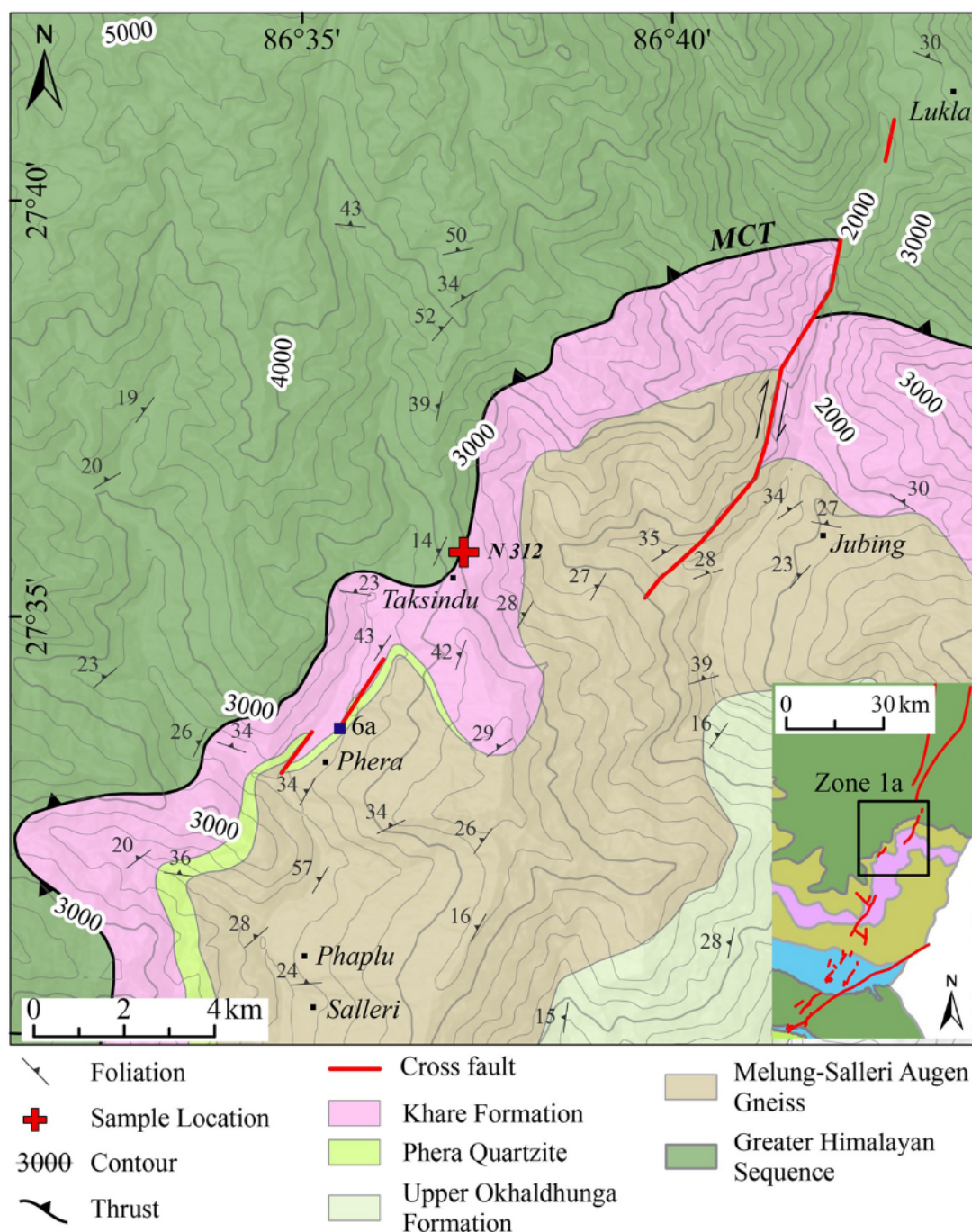


FIGURE 4: Geological map of Zone 1a. Red lines indicate segments of the Benkar Fault Zone. Trace of the MCT between the Jubing-Lukla section from Hubbard [85]. MCT: Main Central Thrust. The inset map has been shown in detail in Figure 2. The blue square shows the location of the photograph shown in Figure 6(a).

4.2. The Upper LHS (Zone 2)

4.2.1. Lithostratigraphy, Major EW-Trending Faults, and Petrography. The Upper LHS consists of the Ketuke Formation, the Manebhangyang Formation, the Halesi Dolomite, and the Harkapur Formation (Table 1; Figure 7). The Ketuke Formation is the oldest unit of the Upper LHS. This unit consists of thick to massive beds of multi-colored arkose quartzite interbedded with variegated slaty partings

and a few granules to pebble-bearing conglomeratic beds. The Manebhangyang Formation overlies the Ketuke Formation along a transitional contact. The basal section of the formation consists of slate, siltstone, silty slate, quartzite, metasandstone, and silicious dolomite. Toward the upper section, the succession is dominated by dark/pitch black, carbonaceous slate interbedded with slate and carbonate. The overlying Harkapur Formation consists of dolomites, silicious carbonate, calc-slate, phyllite, calc-phyllite, and

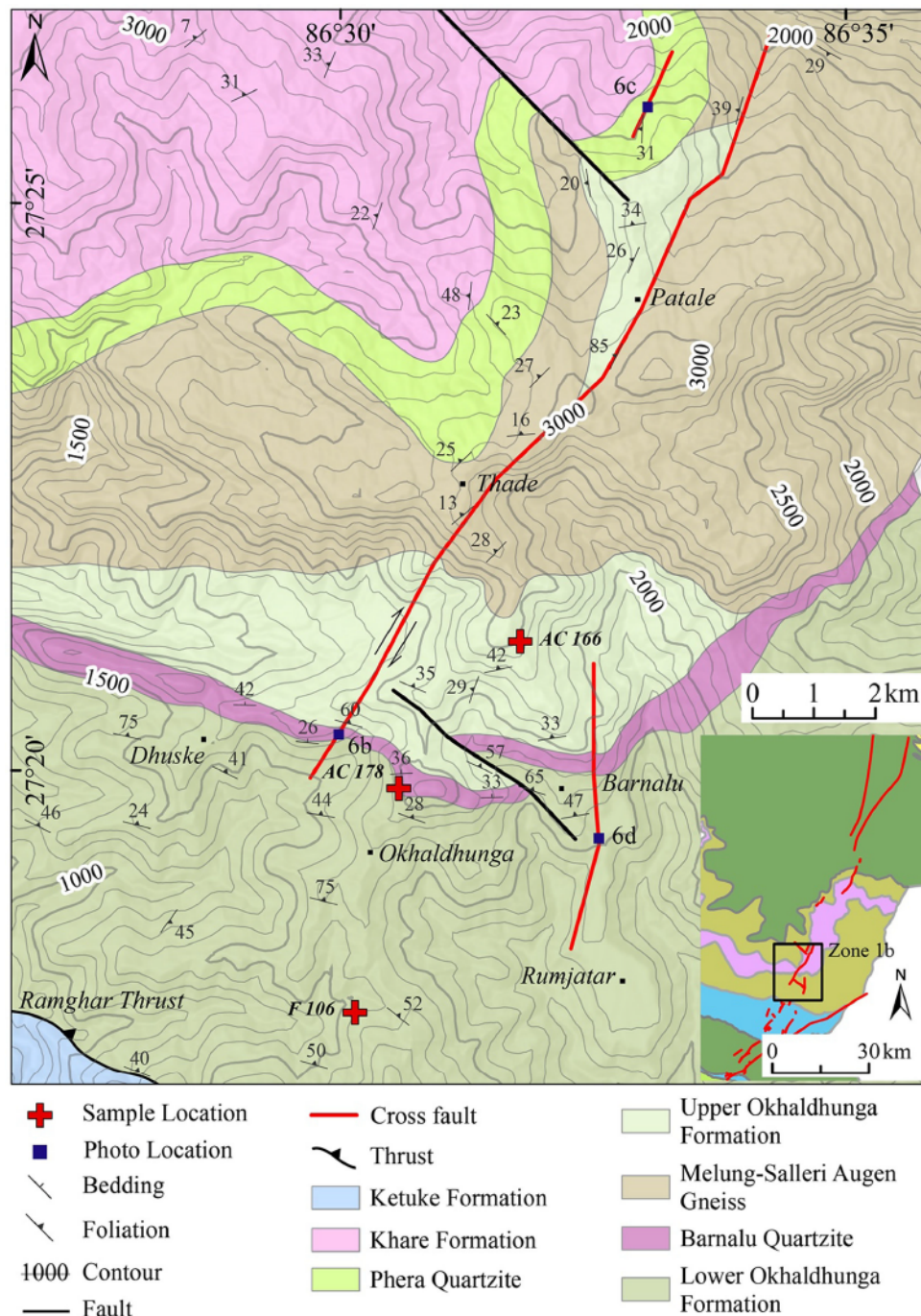


FIGURE 5: Geological map of Zone 1b. Red lines indicate segments of the Benkar Fault Zone. The inset map has been shown in detail in Figure 2. Note that cross fault offsets are <100 m and are not mappable at the current map scale.

quartzite along with frequent basic intrusions. Toward the east of Zone 2, Dhital [46] and Baskota and Adhikari [150] have mapped the stromatolitic Halesi Dolomite between the Harkapur Formation and the Manebhangyang Formation.

Regional rock fabric for Zone 2 is presented in online Supplementary Material Figure A3. Both the Harkapur and Manebhangyang Formations are exposed in the south-dipping limb of the Midland Anticlinorium online Supplementary Material Figure A3(a). The Ketuke Formation forms the core of the anticlinorium and has both north-

and south-dipping limbs, in addition to NS-striking cross fault-related domains online Supplementary Material FigureA 3(b).

The Ramghar Thrust (RT) within the Okhaldhunga window is a north-dipping fault that places the Lower Okhaldhunga Formation over the younger Ketuke Formation (Figure 7). While the RT accommodates the majority of shortening within the Lesser Himalayan fold and thrust belt, as demonstrated throughout the Himalaya, some component of shortening has also been taken up in

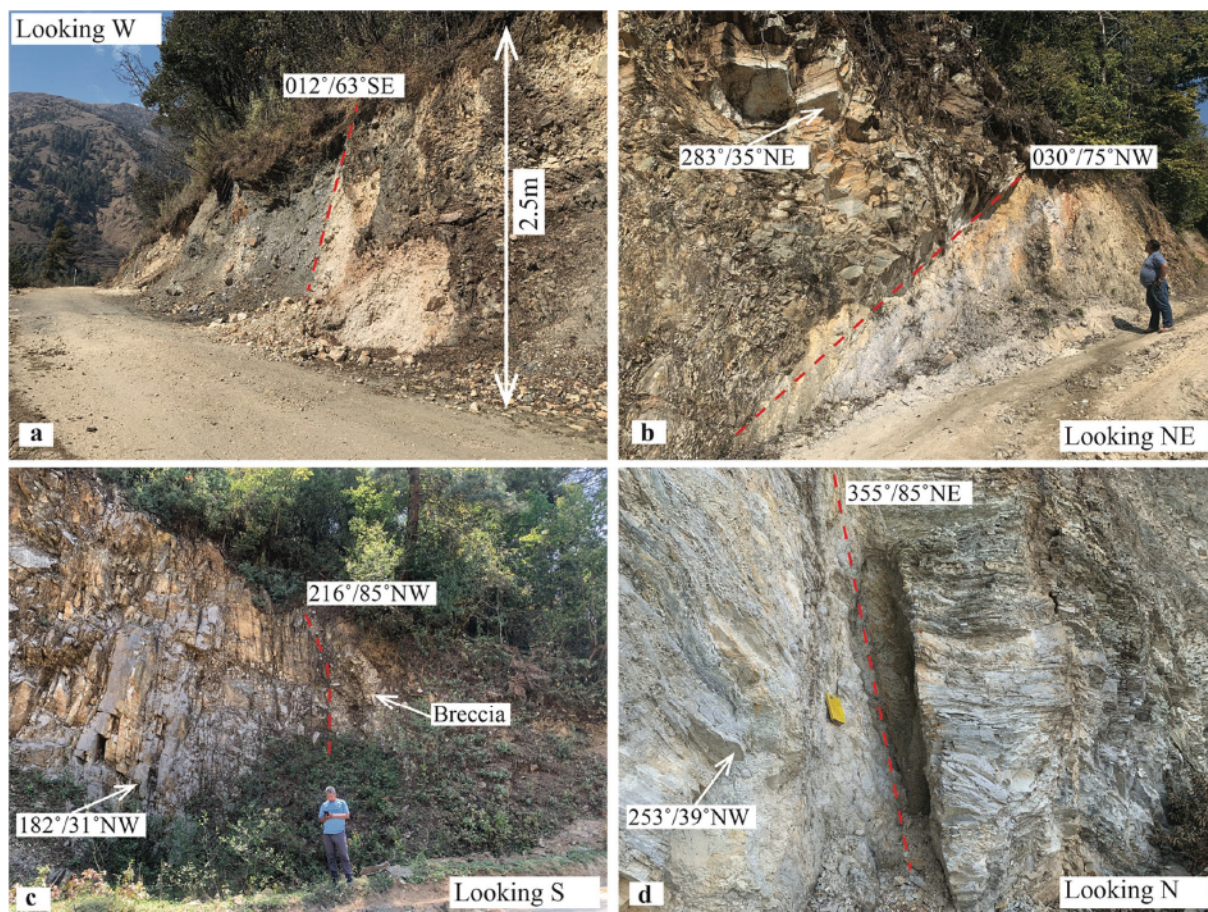


FIGURE 6: Exposures of cross faults in Zone 1. Red dashed lines indicate fault planes. (a) Breccia zone near Phera, (b) Gouge zone in the Barnalu Quartzite, (c) Fault breccia in the Phera Quartzite, and (d) Fault gouge in the Upper Okhaldhunga Formation. Notebook for scale in (d) is 18.5 cm long. Map location for “a” has been shown in Figure 4 and for all others in Figure 5.

shearing and folding at smaller, even microscopic, scales. The RT corresponds to the Taluwa Danda Thrust of Baskota and Adhikari [150]. The Taluwa Danda Thrust has been interpreted to fold over the Ketuke Formation and wedge into the contact between the Ketuke Formation and the Madhavpur Slate. Because of the structural complexity and lack of field evidence related to this interpretation, we have not adapted this idea in our final map.

We have mapped the SKT as the south-dipping, southern continuation of the MCT, that places the GHN rocks over the LHS rocks, and not as an out-of-sequence thrust as suggested by Schelling [84] because our litho-stratigraphic reconstruction for the LHS does not require a presence of an out-of-sequence thrust. Immediately to the north of the SKT, the Harkapur Formation, footwall to the SKT, has been folded into a tight EW-trending synform. Mapping work of Dhital [46] and Baskota and Adhikari [150] indicates a juxtaposition of the Halesi Dolomite with the Harkapur Formation and the GHN rocks along a north-dipping fault.

We also observed multiple exposures of normal faults EW- to WNW-striking, N-dipping within the Okhaldhunga Window (Figure 8). Just to the south of the RT, a beautiful exposure of a normal fault (305°/75° NE) can be seen within the Ketuke Formation. This normal fault has

a dragging effect in the footwall rocks while the hanging wall rocks have been brecciated into pebble-cobble sized fragments (Figure 8(a)). Multiple segments of normal faults can also be seen in other locations within the Ketuke Formation (Figure 8(b)) and in the Lower Okhaldhunga Formation. The sample F106, from the Lower Okhaldhunga Formation, records deformation related to normal faulting. This sample was collected from a slickenside hosted by gritty phyllite, which show a dextral-normal movement along 51°/238° on 085°/70°SE slickenside.

We collected three petrographic samples (E79, E83, and AL239) from the Ketuke Formation and one sample (AJ208) from the Harkapur Formation (Figures 7 and .online Supplementary Material Figure A4. All samples, except E79, were collected from outside the BFZ. Sample AL239 was collected from strongly sheared granule-bearing slate from just to the south of the RT (online Supplementary Material Figure A4(a)). In thin section, this sample reveals multiple sigma clasts, within which grain size has been strongly reduced. These sigma clasts suggest a normal deformation along 17°/105° on 140°/28°NE foliation, which is likely related some of the EW-striking normal faults described in the previous section. Sample E83 was collected near Dhuseni from an exposure of conglomeratic cataclasite

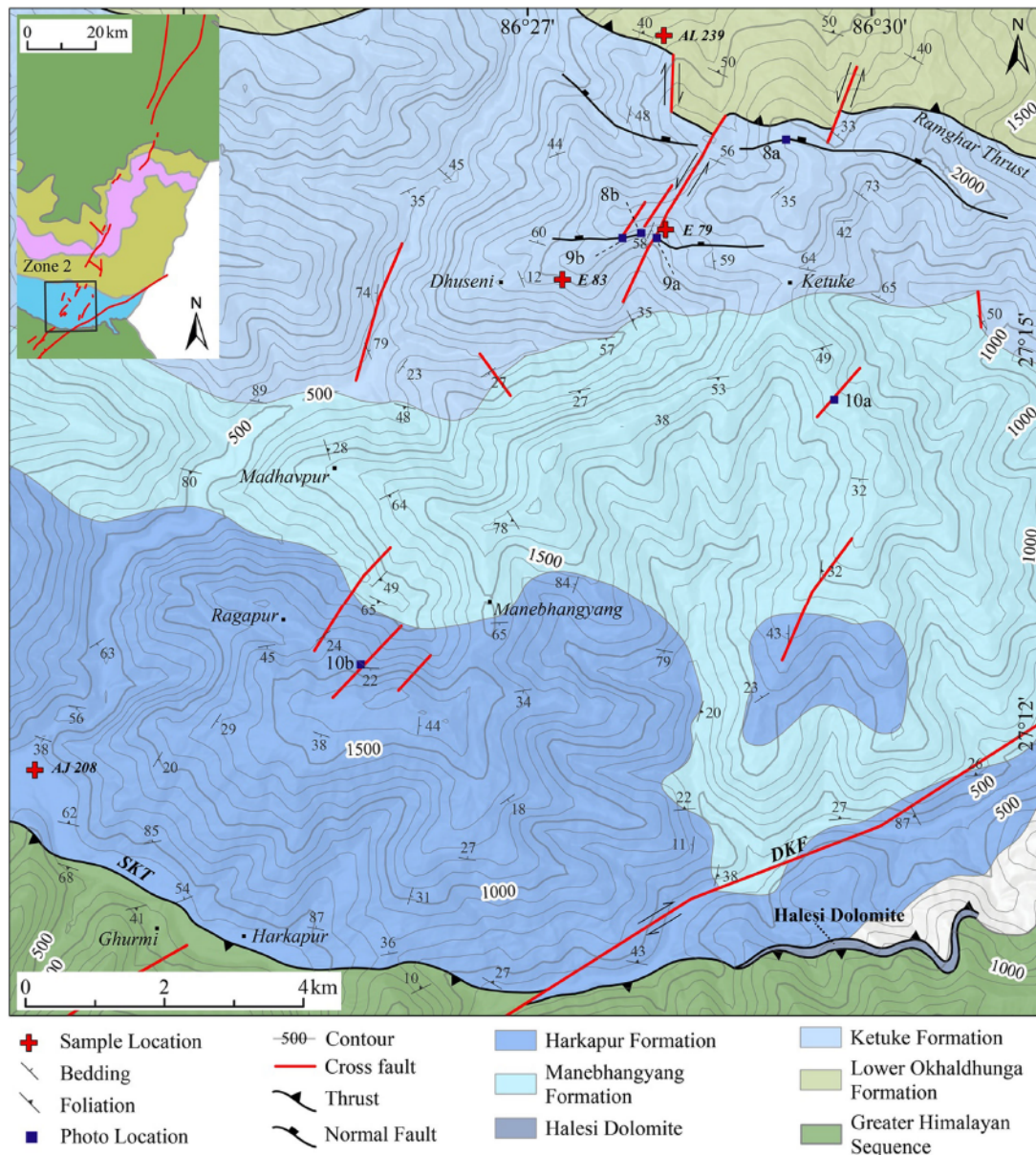


FIGURE 7: Geological map of Zone 2. Red lines indicate segments of the Benkar Fault Zone and the Dudh Koshi Fault. Some map elements adopted from Ishida and Ohta [87], Dhital [46], and Baskota and Adhikari [150]. Note that the strike-slip faults also have dip-slip components. The inset map has been shown in detail in Figure 2. DKF: Dudh Koshi Fault; SKT: Sun Koshi Thrust.

containing an EW-striking slickenside online Supplementary Material Figure A4(b). This sample consists of quartz, plagioclase, and orthoclase in a glassy matrix and quartz fibers make up the slickenlines. In this sample, we interpret an earlier phase of grainsize reduction, pervasive deformation followed by a younger deformation phase. The latter occurred along $75^{\circ}/155^{\circ}$ on $105^{\circ}/78^{\circ}$ SW in a normal sense of movement. The southernmost sample from Zone 2, AJ208, consists of quartz, calcite, and muscovite and displays an excellent fault propagation fold in thin section online Supplementary Material Figure A4(c). Petrography of sample E79 online Supplementary Material Figure A4(d) will be discussed in the next section in relation to cross faults.

4.2.2. Evidence for the BFZ in Zone 2. Zone 2 also hosts numerous exposures of cross fault segments. Within the Ketuke to Dhuseni road cut, cross fault-related deformation has been exposed in a ~500-m-thick, NNE-striking, brittle zone. Within this zone, quartzite beds of the Ketuke Formation have been brecciated and gouged by ~NS- and NNE-striking deformation planes (Figures 9(a) and 9(b)). Several ~W-dipping slickensides indicate a normal, left-lateral motion toward ~SSW, and ~E-dipping slickensides suggest a normal, right-lateral movement toward ~SSE online Supplementary Material Figure A5(a). Dip amount for both groups of slickensides vary between 45° and 70° , and the slickenlines plunge between 05° and 25° toward the south. Slickenlines are made up of quartz and sericite

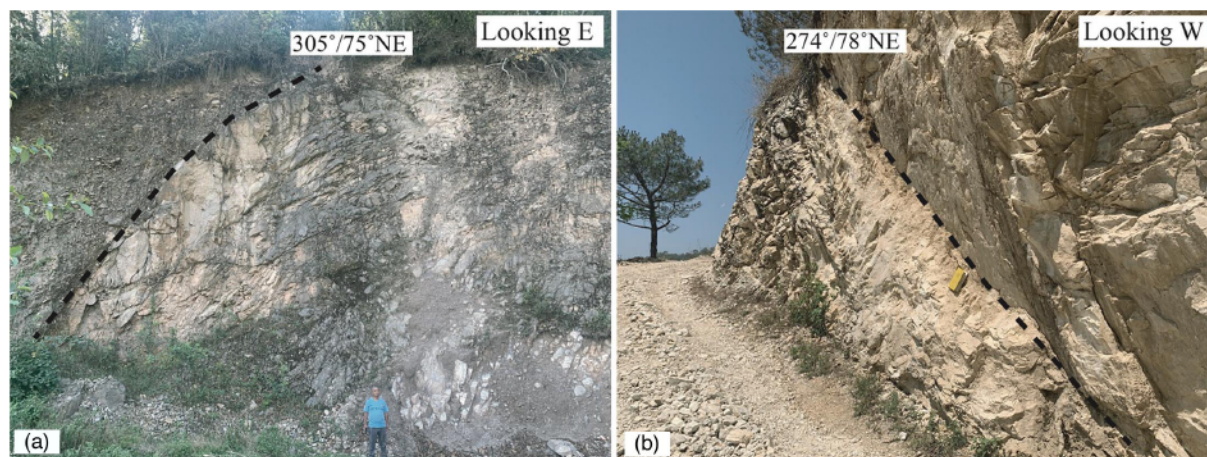


FIGURE 8: Exposure of normal faults within the Ketuke Formation, Zone 2. Location shown in Figure 7. Black dashed lines indicate fault planes. Notebook for scale in (b) is 18.5 cm long.

mineral fibers as seen in the sample E79. A petrographic section of E79 reveals broken and diffused grain boundaries along with wavy and bent deformation lamellae in quartz grains online Supplementary Material Figure A4(d). Anastomosing micro-faults run across quartz grains with a minor reverse-sense offset. The foliation, imparted by quartz grain size, has been cut by fibers of sericite, which in outcrop display a dextral, normal sense of movement along $41^{\circ}/151^{\circ}$ on $034^{\circ}/45^{\circ}$ SE slickenside. Sericite mineralization has largely been localized within the slip surface, but some mineralization can be also noted within the nearby grain boundaries between quartz grains.

While cross fault-related deformation dominates the Ketuke-Dhuseni road section, we also noted a few exposures of EW-trending, steep, outcrop-scale normal faults (Figure 8(b)). Kinematic indicators suggest stronger normal components on some faces and dominant strike-slip component on others online Supplementary Material Figure A5(b).

Toward the north, the cross fault deformation zone continues across the ridge and emerges on the other side, where we mapped ~300 m of left-lateral apparent offset across a NNE-striking cross fault segment along the north-dipping thrust boundary between the Ketuke and the Lower Okhaldhunga Formations (the RT). Similar offsets can also be noted in topography as the east-west-trending quartzitic ridge make abrupt clockwise as well as counter-clockwise bends. In the vicinity of these fault segments, the strike of bedding/foliation in the Ketuke Formation is NS, which is different from an EW-trend elsewhere online Supplementary Material Figure A3(b).

Cross fault-related deformation can also be seen in the Manebhangyang and Harkapur Formations (Figure 10). In a prominent NNE-trending gully toward the south-east from Ketuke, rock units (belonging to the Manebhangyang Formation) have been folded on the western side and abruptly terminate against a NNE-trending fault zone (Figure 10(a)). Toward the southwest from Ketuke, the Manebhangyang Formation shows a higher degree of shear deformation and quartz vein intrusions in the road section

west of Manebhangyang (toward Madhavpur) than we saw to the east. Along this section, rock units show a NNE-striking foliation, while the same unit shows an EW-trend along both the Molung Khola and the Dudh Koshi river transects. Across an EW-trending river valley toward the south, exposures of cross faults cut into the foliation planes of carbonate rocks belonging to the Harkapur Formation along a 1500 m road section between Ragapur and Manebhangyang. These faults appear as ≤ 1 -m-thick gouge zones and can display both normal and reverse sense of shear with up to a meter of offset (Figure 10(b)).

4.3. The GHN (Zone 3)

4.3.1. Lithostratigraphy and Petrography. While we recognize the difficulties in establishing a stratigraphy in a high-grade metamorphic zone, we are adopting the classification scheme of Dwivedi [153] to better visualize possible offsets along cross faults and to outline the structural framework of the GHN (Figure 11). Regional foliation within the GHN has been presented in online Supplementary Material Figures A6. Figures A6a and A6b represent foliation data from the northern and southern limb of the Mahabharat Synclinorium, respectively.

Like in central Nepal, the GHN in our study area consists of the Kathmandu Complex rocks as well as injection gneiss and granite. These gneissic and granitic rocks form distinct mappable units that vary in mineralogy, grain size, and gneissic texture. online Supplementary Material Figure A7 shows representative petrographic sections from Zone 3. Around the town of Ghurmi, a band of augen gneiss (quartz, muscovite, chlorite, orthoclase, plagioclase, and garnet) is seen, which is also exposed in the southern flank of the synclinorium. In petrographic section, this gneissic unit (sample AT333, online Supplementary Material Figure A7(a) shows strong grain size reduction, elongation of quartz grains parallel to foliation, and subgrains formed along boundaries of larger quartz and orthoclase grains. The northern flank of the synclinorium is dominated by banded gneiss, paragneiss, augen gneiss, and silicate

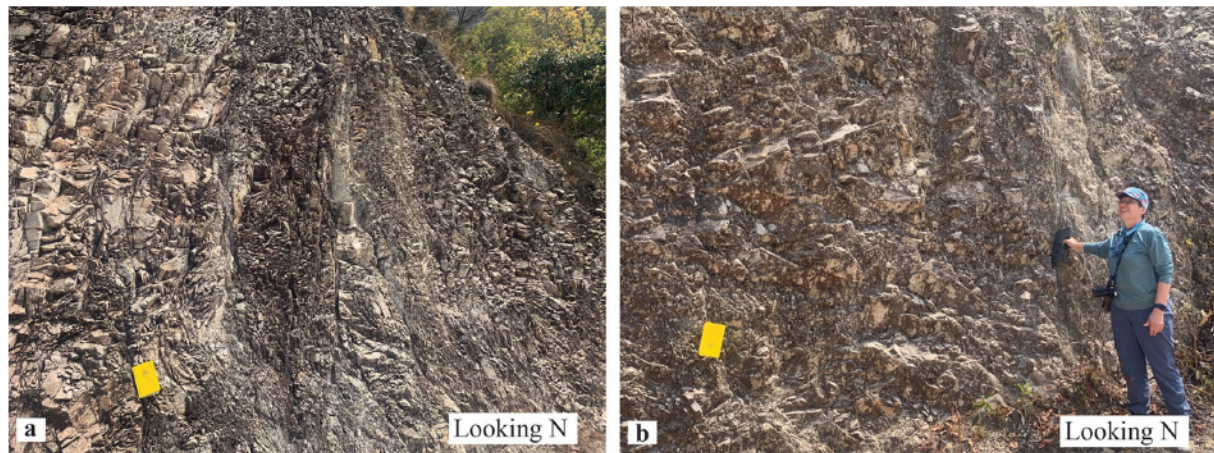


FIGURE 9: Exposures of cross fault zones in the Ketuke Formation. Location shown in Figure 7. The notebook in both photographs is 18.5 cm long.

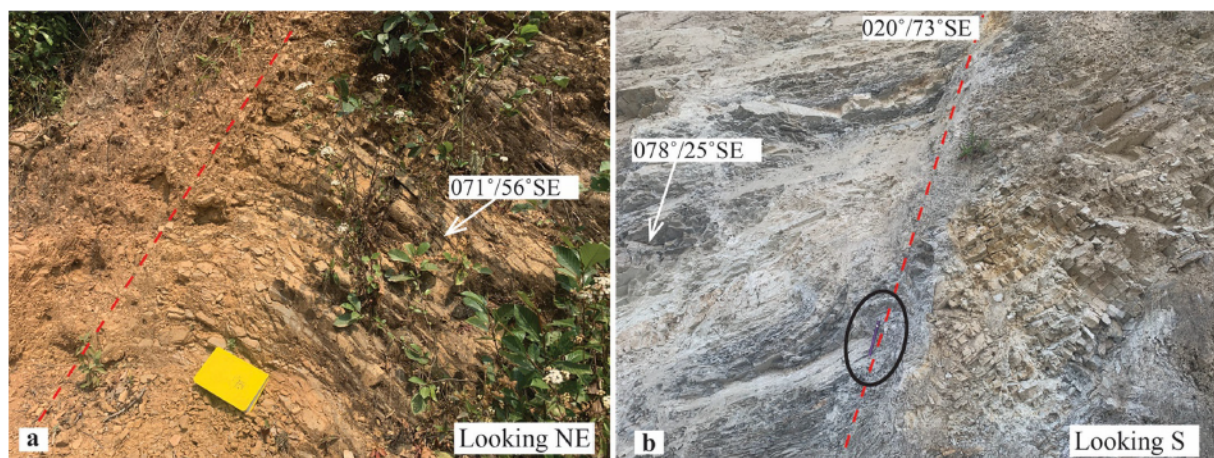


FIGURE 10: Exposures of cross faults in; (a) Manebhangyang Formation and (b) Harkapur Formation. Location shown in Figure 7. Notebook for scale in "a" is 18.5 cm long. Pencil for scale in "b" is enclosed in an ellipse.

gneiss. A sample, C57, collected from just to the south of SKT consists of clinopyroxene (plus quartz, plagioclase, and biotite, online Supplementary Material Figure A7(b), which indicates that there are a few basic layers within these generally felsic rocks. The core of the Mahabharat Synclinorium is dominated by augen gneiss, granite, and granitic gneiss along with minor occurrences of schist and calc-silicate gneiss and pegmatite intrusions and leucocratic lenses. A petrographic sample, AR306, was collected from the Chisapani Quartzite from the southern limb of the synclinorium. Microscopic section of this strongly sheared sample shows grain shape preferred foliation along with some bulging grain boundaries and pinning of quartz grains by muscovite online Supplementary Material Figure A7(c). Garnet-bearing silicate gneiss, biotite-paragneiss, and granite are common in the vicinity of the southern strand of the MCT. A garnet bearing sample from Jinakhu (A26) shows voluminous inclusions of quartz and biotite in garnets indicating a rapid growth online Supplementary Material Figure 7A(d). Delta clast garnets and dominant S/C fabric seen in petrographic section of A26 suggest

an extensional deformation along $55^{\circ}/347^{\circ}$ on $125^{\circ}/65^{\circ}$ NE foliation.

4.3.2. Evidence for the BFZ in Zone 3. Like within the Okhaldhunga Window, we saw several exposures of cross faults toward the south of the SKT (Figure 12). Deformation related to these fault segments can also be noted in petrographic samples online Supplementary Material Figure A8. An excellent exposure of a cross fault can be seen south of Ghurmi, at the confluence between two small drainages. This west-dipping ($214^{\circ}/65^{\circ}$ NW), sharp fault plane places sheared orthogneiss on top of quartzite belonging to the Kulikhani Formation (Figure 12(a)). Petrographic sample AS316 was collected in the vicinity of this fault from a peculiar chloritic augen gneiss. It can be seen, in thin section, that plagioclase grains have been highly altered, and chlorite dominates the mineralogy, which is not a feature that we commonly see in these nappe rocks online Supplementary Material Figure A8(a). Weak shear fabric from this sample indicates left-lateral, reverse sense of deformation along $15^{\circ}/217^{\circ}$ on $050^{\circ}/50^{\circ}$ SE

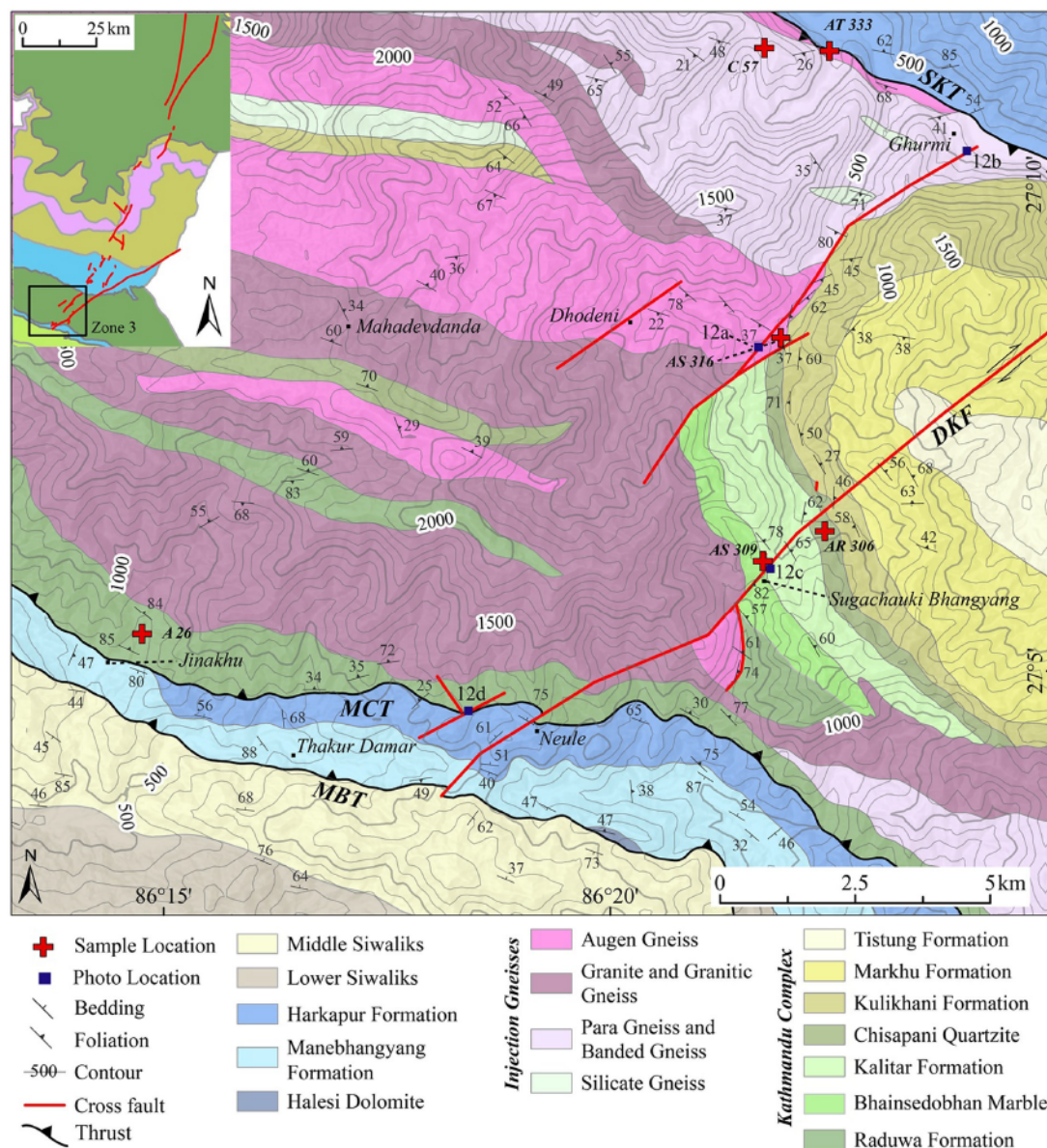


FIGURE 11: Geological map of Zone 3. Red lines indicate segments of the Benkar Fault Zone and the Dudh Koshi Fault (source: [46, 84, 87, 153]). The inset map has been shown in detail in Figure 2. DKF: Dudh Koshi Fault; MBT: Main Boundary Thrust; MCT: Main Central Thrust; SKT: Sun Koshi Thrust.

foliation. This foliation is subparallel to the mapped fault. Several small-scale (cm) shear planes are common along the strike of this fault within the injection gneiss and granites (Figure 12(b)). The Dudh Koshi Fault (DKF) of Ishida and Ohta [87] merges with the BFZ at this point. We found an excellent exposure of the DKF along roadcuts in Sugachauki Bhangyang (Figure 12(c)). At this location, the DKF is a ~100-m-wide, NE-striking, steeply dipping, semi-brittle zone of deformation with a right lateral sense of movement. Rock units on the western side of this fault show prominent drag folds consistent with the right lateral sense of shear. The rocks on the eastern side, however, do not display such folding. A petrographic sample, AS309, from a deformation zone related to the DKF reveals multiple micro-scale faults

that cut the foliation plane ($160^{\circ}/75^{\circ}\text{NE}$; online Supplementary Material FigureA8(b)). These brittle micro-faults run through larger grains and have minor right-lateral offsets. By utilizing the Chisapani Quartzite unit as a marker, we mapped 400 m of right-lateral, strike-separation along this fault.

Toward the south, the DKF can be traced into the thin slivers of the LHS rocks that have been exposed between the MCT and the folded and imbricated MBT. These LHS rocks have been mapped by Adhikari [232], Adhikari [233], and Dhital [46, Chapter 11]. There are several exposures of outcrop-scale cross faults that are cutting the LHS units. One such fault is a >1-m-thick, pitch-black, gouge zone

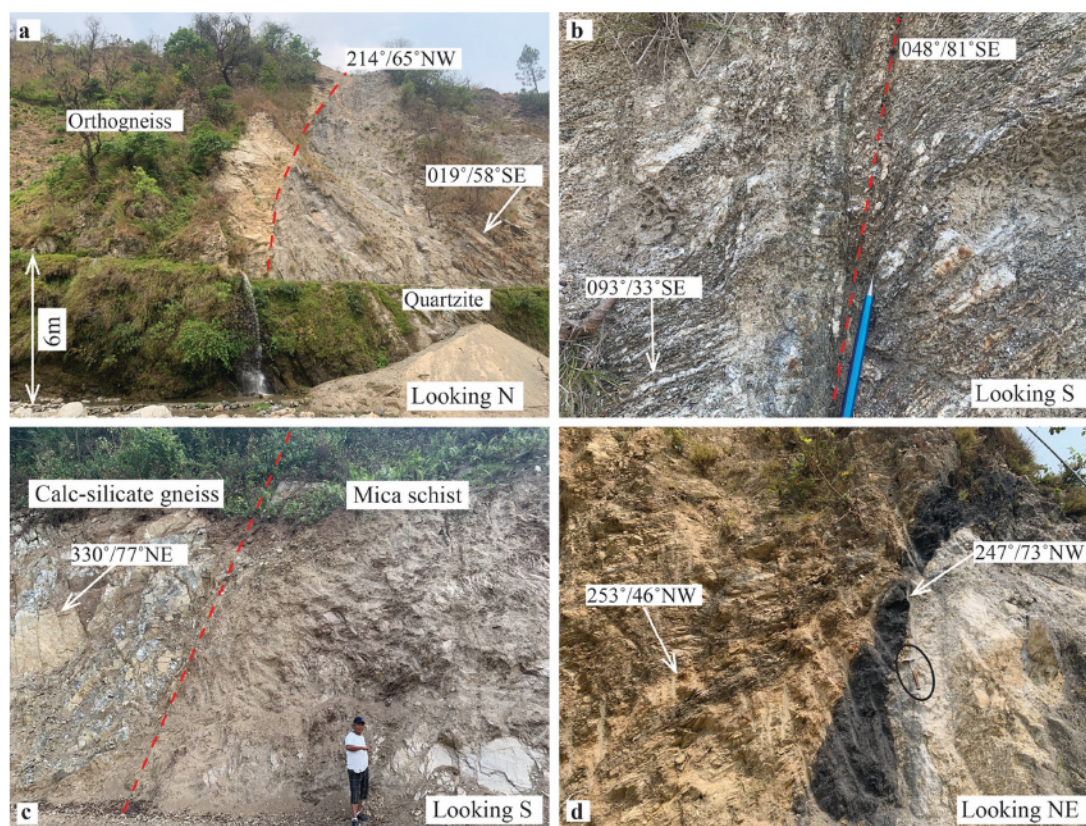


FIGURE 12: Exposures of cross faults in Zone 3. Location shown in Figure 11. Red dashed lines indicate cross faults. (a) Sharp fault plane places orthogneiss against the Kulikhani Formation, (b) Para gneiss near Ghurmi showing a small-scale cross fault. Pencil for scale, (c) An exposure of the Dudh Koshi Fault at Sugachauki Bhangyang, and (d) Gouge zone in the Lesser Himalayan Sequence south of the Main Central Thrust. Hammer for scale in “d” is enclosed in an ellipse.

with an orientation of $247^{\circ}/73^{\circ}\text{NW}$ with a normal sense displacement (Figure 12(d)).

4.4. $^{40}\text{Ar}/^{39}\text{Ar}$ Muscovite Thermochronology in the GHS. In an effort to constrain timing of vertical offset along the BFZ in the GHS, Seifert [28] collected three samples (18N5d, 18N10c, and 18N11c) along a transect across the BFZ in the GHS in the Everest region (Figure 3) and conducted $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite analyses to look for differences in cooling ages. The western most sample, 18N5d (quartz + muscovite + biotite + albite + orthoclase + sillimanite), was collected from the eastern edge of the Thame village (3443 m). The second sample, 18N10c, was collected near Sanasa (3663 m) from an outcrop of quartzofeldspathic gneiss (quartz, biotite, muscovite, orthoclase, sillimanite, garnet). The easternmost sample, 18N11c, is a biotite gneiss (quartz, biotite, muscovite, orthoclase, sillimanite, garnet, hornblende, albite) from near Pangboche (4017 m).

The sample west of the BFZ (18N5d) yielded a plateau age of 12.06 ± 0.42 Ma. Within the fault zone sample, 18N10c yielded an age of 12.91 ± 0.37 Ma, and to the east of the BFZ, sample 18N11c yielded a plateau age of 17.42 ± 0.30 Ma (Figure 13). Because the easternmost sample, which in the absence of the BFZ would be at the same structural level as the other samples, yielded an older age we suggest that this age pattern is consistent with vertical

offset (east side down) that occurred since 12 Ma. We note that we only have a minimum of analyses, which limits our ability to make a definitive interpretation. Because the BFZ deformation wraps around leucogranites, last movement along the BFZ must be younger than those leucogranites ($\sim 24\text{--}15$ Ma). The three cooling ages presented above are consistent with the constraints from the cross-cutting relations with granites, and we present them here so that future work by researchers in the area can build on this preliminary work.

In general, cooling ages increase toward north within the GHS, while they laterally remain comparable [e.g.; 102, 104]. It is noted that there is an elevation difference of ~ 600 m between the youngest and oldest samples. However, at 1 mm/yr exhumation rate [102, 234], this elevation difference can only account for a cooling difference of ~ 1 Ma. Therefore, the juxtaposition of 12 Ma rocks and 17 Ma rocks can represent: (a) a dominant-component of right lateral movement along the BFZ; (b) a dominant-component of normal movement on the BFZ; or (c) oblique right lateral movement. In any scenario, this age pattern suggests movement(s) on the BFZ younger than 12 Ma. The interpretation of oblique right lateral movement is consistent with the field and thin section kinematic interpretation. Just to the south of this transect, Hubbard and Harrison [103] got a rather young $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite

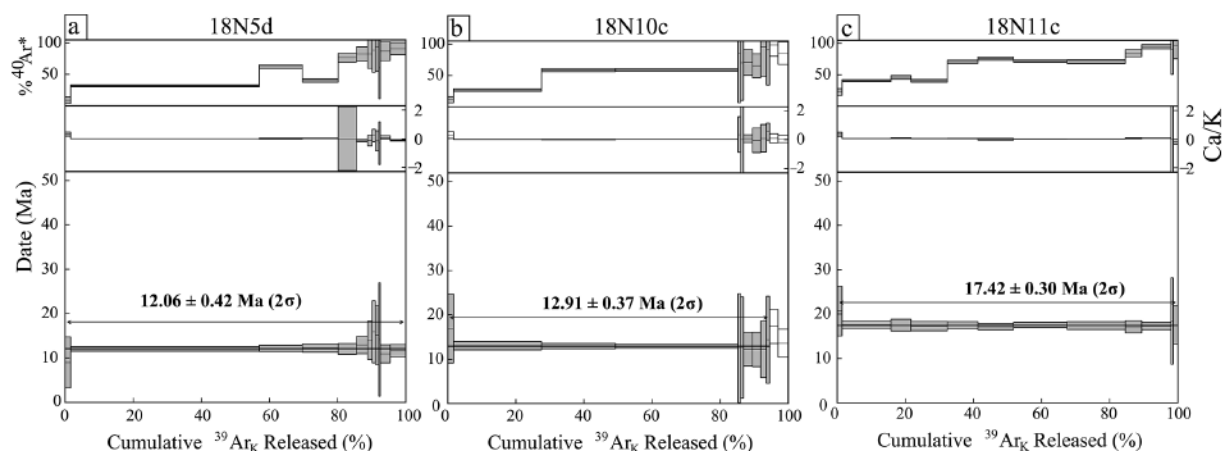


FIGURE 13: $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite cooling ages of three samples from the Greater Himalayan Sequence. Sample locations are shown in Figure 3.

age of 7.7 ± 0.4 Ma from a “sheared pegmatite” near the trace of the BFZ (sample 87H21D, Figure 3). This age could potentially represent mica growth at 7.5 Ma, which could indicate an even younger movement along the BFZ.

5. Discussion and Conclusions

5.1. The BFZ to the South of the Main Central Thrust. We mapped several segments of NNE- to NE-striking brittle deformation zones aligned from Jubing to Dudhauli in the LHS, the GHN, and in the slivers of the LHS just north of the MBT. Based on the dominance of NE-striking zones, we interpret these to be cross-fault segments and to be the southern continuation of the BFZ. The length of the currently mapped BFZ is >100 km and it spans the GHS, LHS, and GHN and cuts across their regional, boundary thrusts. Unlike in the GHS, where the BFZ is ductile to semi-brittle, the BFZ is brittle within both the LHS and the GHN. Within the Okhaldhunga Window, the BFZ has been expressed as gouge zones, brecciated zones, and brittle deformation zones in a nonpenetrative, segmented fashion. In the GHN, the BFZ occurs as sharp fault planes, fractures, and as micro shear zones as seen in Figure 12(b). The width of the BFZ in the Okhaldhunga Window is up to 4 km. Some of these segments within this zone are east dipping while others are dipping toward the west. The sense of movement (dextral vs. sinistral) also varies across segments. We interpret that the BFZ is a culmination of a series of cross faulting events that may have had a changing sense of shear through time. In general, cross-fault segments are more pronounced in more competent units rich in quartz and carbonate such as the Phera quartzite, the Barnalu Quartzite, Ketuke Formation, and the Harkapur Formation. Within pelitic rocks, deformation is most likely accommodated through shearing and folding. We were able to map up to 300 m of strike-separation across some of the fault segments. Poor exposure and laterally variable thickness of the LHS rocks made it challenging to precisely constrain offsets and segment lengths. The BFZ does not have a significant amount of slip compared to the major thrust faults, but this fault might serve as a seismic segment

boundary. The weakened fault zone rocks are often striking parallel to the valley walls on which they are exposed, which also may enhance the landslide hazard in that area.

As shown by Nakajima et al. [235], ZFT ages (closure temperature $205^\circ\text{C} \pm 18^\circ\text{C}$; [236]) within the Okhaldhunga Window gradually decrease toward the north and range between 11 Ma and 2.4 Ma (Figure 2). Similarly, ZFT ages in the GHN range between 13 Ma and 10.8 Ma and also show a general, northward younging trend [235]. Just toward the west of our study area, Larson et al. [104] constrained the $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite cooling ages of the GHN rocks between 27.5 Ma and 17.3 Ma. The brittle nature of cross fault exposures within the Okhaldhunga Window and the GHN suggests that movements along these segments occurred well below $280^\circ\text{C} \pm 30^\circ\text{C}$, at which a transition from mylonite to cataclasite occurs [237]. Thus, it can be inferred that cross fault segments in the Okhaldhunga Window have had movements synchronous to or younger than the ZFT ages. This interpretation is in line with the observation in the GHS, where the BFZ had activity younger than 12 Ma.

It is important to note the contrasting styles of the BFZ deformation observed in the GHS where deformation is semi-ductile as opposed to the LHS and the GHN where the observed deformation is brittle. Such a contrast could be explained through several different models and/or their combinations. It is possible that the BFZ is propagating toward the south, and thus, the cross fault segments are progressively younger toward the foreland and affected the southern regions at shallower crustal levels [182]. It is also possible that the amount of vertical displacement in the BFZ could be greater in the GHS, which would result in the exhumation of deeper sections of the fault zone within the GHS. A higher degree of erosional exhumation in the GHS could also address this disparity. And finally, the GHS could have retained higher temperatures well after its tectonic exhumation, as interpreted in the channel flow model (see Kohn [75]), which would allow for a late ductile deformation.

While our work did not continue into the Sub-Himalaya, we cannot rule out the possibility that the BFZ continues

toward the south into the foreland as seen with other cross faults in the Himalaya [e.g., 171, 184]. We saw multiple exposures of cross faults in the LHS just to the north of the MBT. It is possible that some of these BFZ- and/or the DKF-related segments continue as offset and/or segmented faults across the MFT.

5.2. Genesis of the BFZ and Its Implications. Researchers have interpreted the genesis of Himalayan cross faults through one of the three models [20]. These include the following (a) transport accommodation structures within the orogenic belt [e.g., 222], (b) surface expression of the basement structures in the down-going Indian plate [e.g., 11, 12, 184], and (c) Tibetan extension-related structures [e.g., 197, 238].

Based on local GPS measurement, tectonic transport of the Himalayan belt occurs along a vector perpendicular to the range front [239–241]. Because of the arcuate shape of the Himalaya, this vector gradually changes from SE-directed in the eastern part of Himalaya to SW-directed in the western part of the Himalaya. This changing direction of the transport vector requires range-perpendicular, extensional, accommodation structures as the adjacent thrust sheets diverge away from each other. Bian et al. [222] suggested that pre-13 Ma activity in the Yadong Gulu rift is related to the outward expansion of the Himalayan arc. Such cross fault segments would be confined within the deforming wedge and would have a strong extensional component that gradually decreases away from the deformation front.

Most of the previously mapped Himalayan cross faults have been described at the range front [17, 171, 184, 185]. It has been proposed that these structures may be related to inherited basement structures in the Indian plate include basement ridges and basement faults. Basement ridges obstruct the propagation of thrust-sheets and may create tear-faults such as the Ganga and Yamuna Tear Faults [184]. Basement faults can serve as lateral ramps or can get reactivated and thereby induce cross faults. The Lucknow Basement Fault has been interpreted to be responsible for abrupt lateral changes in metamorphic pathways of thrust sheets and in the topography [19, 186]. This model would require the relative plate motion vector of the Indian plate with respect to the Asian plate to be parallel to the basement ridges/faults, which currently is not the case. This lack of alignment would mean that the ridges are subducting obliquely under the Himalaya. Such oblique subduction of ridges could still be responsible for lateral ramps and other cross structures, but might suggest a lateral migration of cross structures with time [20]. At this point, there is no documentation of such lateral migration of cross fault systems and most of the fault segments within the BFZ are roughly aligned with each other.

The eastward-directed extension in the Tibetan plate has been interpreted as a causal mechanism for most of the extensional cross faults mapped in the TTS such as the Thak Khola graben. The extensional nature of the BFZ, especially in the GHS, points toward its relationship to Tibetan extension like in other places [13, 15, 19, 29, 30]. It is possible that the BFZ connects with the NNW-striking

Kung Co half graben toward the north, which initiated at 4 Ma [242]. Just to the north of the Kung Co half graben is the ~250-km-long, NE-striking, active, Tangra Yumco rift [212]. The southern segment of this rift was activated earlier (19 Ma) than its northern segment (13 Ma) [210, 223]. This northward propagation of the rift system has been cited as supporting evidence for underthrusting of the Indian plate [210, 212, 223]. Another prominent rift system, the Pum Qu Xianza rift (also known as the Xainza-Dinggye rift), is located about 180 km east of the Tangra Yumco rift. The Pum Qu Xianza rift cuts across the suture zone and offsets the STDS [243]. Based on magnetotelluric array data, Sheng et al. [244] “infers” a lithospheric tearing in the downgoing Indian plate (such that the eastern side is deeper and steeper) underneath this rift, which is responsible for rift formation [213, 218]. Farther toward the east, the Yadong Gulu rift, initiated at ~13–11 Ma, also shows a northward younging of rift-related faults [222 and references therein]. Bian et al. [222] hypothesized that slab tearing underneath the Yadong Gulu rift “allowed slab underthrusting to take effect” toward the west. The presence of a slab tear(s) or segmentation in the Indian lithosphere could potentially explain the southern propagation of the BFZ. Deep seated, strike-slip earthquakes as reported in the eastern Nepal Himalaya [21, 25, 27] support the idea of active cross faults [e.g., 17] well below the Himalayan decollement. Geophysical data from the eastern Nepal region could serve to either corroborate or rescind an interpretation of the influence of Tibetan E-W extension on cross fault development including that of the BFZ.

We stress the importance of recognizing and understanding cross faults because of their impacts in regional seismicity and in landslide-related hazards. We note that the West Patna Basement Fault and the Motihari-Everest Lineament are in close proximity of the BFZ (Figure 1). These structures may or may not be genetically related to the BFZ. The West Patna Fault is a NE-striking, active fault within the Indian basement and is roughly on strike with the BFZ [245, 246]. Based on interpretation of satellite images and seismic data, Dasgupta [181] identified the Motihari-Everest Lineament as one of the many cross faults that originate in the Indian basement and span across the Himalayan orogen. Some of these structures are seismically active and most of them display strike-slip fault plane solutions. Tiwari et al. [23] concludes, “the Motihari-Everest fault area is in critical strain (mechanically locked) conditions, as indicated by the stepwise energy release pattern.” Tiwari et al. [23] further suggest that cross faults have an impact on the release of strain energy along regional thrusts during or after a seismic event. To the west, Mendoza et al. [24] reported an abrupt termination of aftershocks of the Gorkha Earthquake along a SE-dipping plane, the surface projection of which coincides with the Gaurishankar Lineament. In parts of eastern Nepal, regional micro-seismic data also show multiple clusters of micro-seismicity concentrated along NNE-trends, some of which have strike-slip sense (see online Supplementary Material Figure A1 of Hubbard et al. [20]). Based on these two observations, we endorse the idea that cross

faults potentially play a role in limiting lateral propagation of thrust rupture, and furthermore, they also have the potential to generate their own seismicity [15, 18, 24, 175–177]. Cross faults also tend to be co-located with major river valleys and dip slopes of fault fabric on valley walls may increase the landslide hazard. Gaining a better understanding of the location and structural nature of cross faults is therefore important to the study of natural hazards in the Himalaya.

6. Conclusions

We continued mapping the BFZ toward the south from Lukla, in the regions between Jubing and Dudhauri, and corroborated our mapping results with kinematic and petrographic analyses. The BFZ is a large-scale cross fault that cuts across the GHS, LHS, GHN, and their regional thrust boundaries. Currently, the mapped length of this fault is at least 100 km, and it is possible that the BFZ continues farther south into the foreland. Within the LHS and the GKS, the BFZ is expressed as brittle, nonpenetrative, offset fault segments with varying sense of shear. In general, these fault segments have a ~NS- or NNE-strike but the dip-direction and sense of movement varies between segments, which might indicate multiple deformational events along this fault. $^{40}\text{Ar}/^{39}\text{Ar}$ -muscovite thermochronology from a transect in the GHS indicates that movement(s) along the BFZ is younger than 12 Ma. Timing of the BFZ is likely to be even younger in the LHS and the GHN as indicated by the brittle nature of this fault toward the south. Cross faults, such as the BFZ, can pose seismic and/or landslide-related hazards and it is, therefore, important to recognize and understand these structures.

Data Availability

Thermochronological data generated in this study are provided in the supplemental files.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Supplementary Materials

Supplementary data have been provided in Excel files labeled with respective sample names.

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