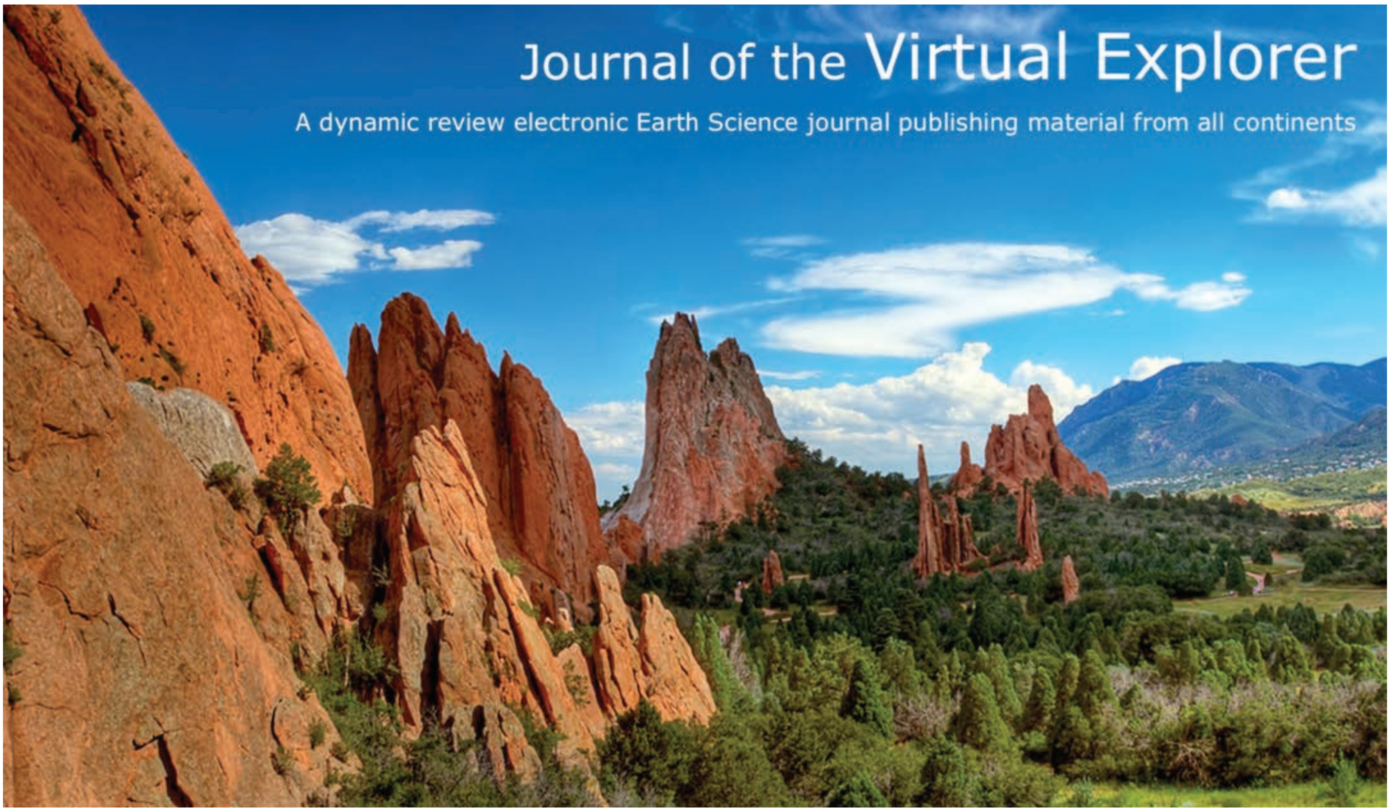

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The geology between Khimti Khola and Likhu Khola valleys: a field trip along the Numbur Cheese Circuit (central-eastern Nepal Himalaya)

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IN THIS GUIDE

This paper describes a 11-days field trip along the Numbur Cheese Circuit (NCC), running along the Khimti Khola and Likhu Khola valleys in central-eastern Nepal Himalaya. The purpose of this guide is to introduce the most interesting geological aspects of this sector of the Himalaya through observations of selected outcrops, samples and view-points along the NCC.

The NCC trek crosses a thick portion of the Greater Himalayan Sequence (GHS), divided into a lower (GHS-L) and an upper (GHS-U) portion. Along this path, the GHS-L consists of Grt ± St ± Ky -bearing two-micas micaschist, associated to metric to decametric -thick levels of two-micas quartzitic gneiss, Grt + Zo granofels and small lenses of impure marble. In its lower structural levels, the GHS-L shows intercalations of phylladic Ank-bearing micaschist (+ greenish Bt), whereas in the uppermost structural levels evidence of partial melting are locally observed.

Upwards, the GHS-U (corresponding to the Higher Himalayan Crystallines) consists of Grt + Bt + Kfs + Ky/Sil anatectic paragneiss (i.e. Barun Gneiss) and Kfs + Bt + Sil ± Grt paragneiss (i.e. Black Gneiss) characterized by Qtz + Sil nodules. Metric to plurimetric -thick layers of calc-silicate granofels and impure marble are locally intercalated. Networks of leucogranitic and pegmatitic dikes occur in the upper structural levels of the GHS-U, and are spectacularly exposed in the highest peaks.

From a structural point of view, in the NCC area, the GHS is dominated by lithological boundaries and foliations dipping towards the north. The Main Central Thrust Zone, namely the shear zone related to the exhumation of the high-grade GHS on the lower Lesser Himalayan Sequence (LHS), is roughly centered on the intensively top-to-the-S sheared GHS-L. Locally, evidences of late top-to-the-NE extension has been observed in the GHS-L.

INTRODUCTION

This paper describes a geological field trip along the Numbur Cheese Circuit (NCC) in the central-eastern Nepal Himalaya (Fig. 1A); the guide is intended not only for geologists but also for trekkers interested in the geological and natural aspects of the area. The NCC, located ca. 200 km east of Kathmandu in the Ramechap district, has been only recently promoted and developed as a trekking route in Nepal and is therefore quite unknown to both trekkers and geologists. It is named in honor of the Numbur Chuli peak (6959 m) and of the famous yak-cheese produced in the local workshops. The NCC is at the south-east termination of the Rolwaling region and connects two major valleys: the Khimti Khola to the west and the Likhu Khola to the east. These two valleys are also crossed by the Jiri to Lukla trekking route at

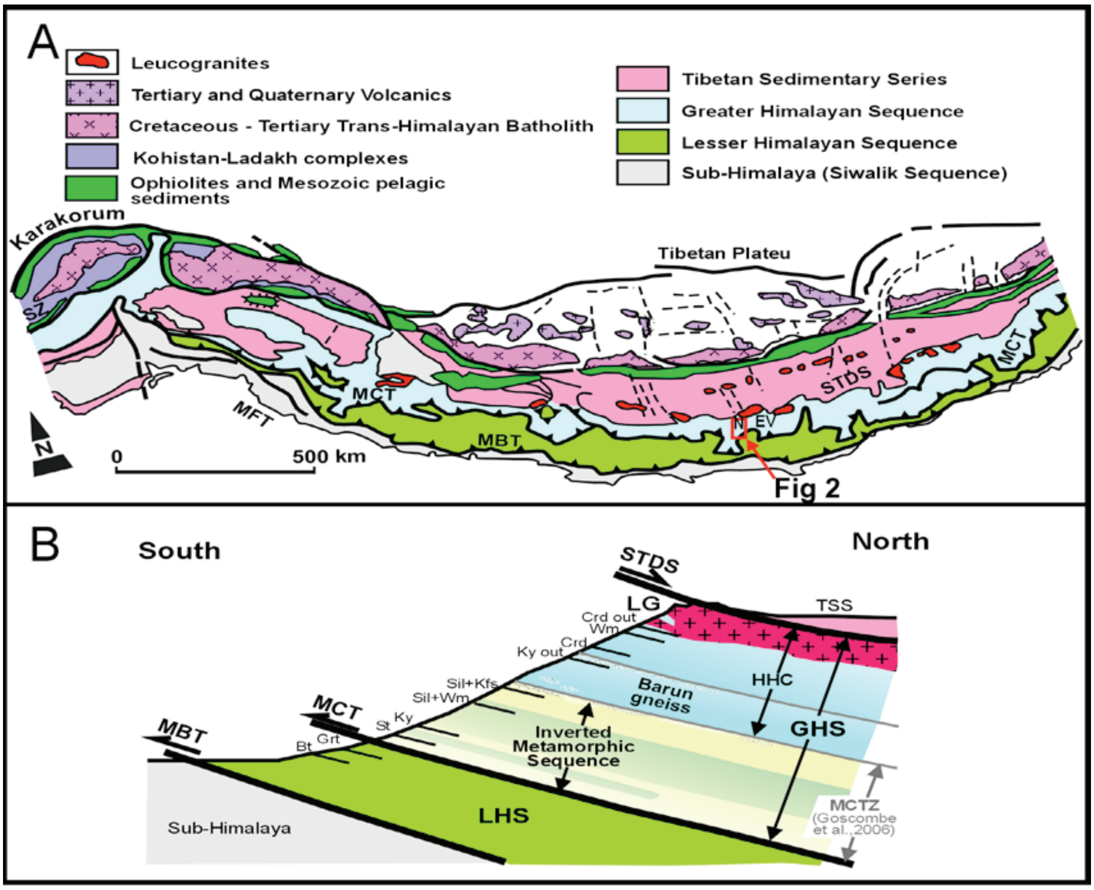

Figure 1
(A) Simplified tectonic sketch map of the Himalaya (redrawn after Dietrich and Gansser, 1981). The location of Fig 2 is reported. (B) Schematic cross-section across the central-eastern Himalaya (modified from Goscombe et al., 2006 and Searle et al., 2008). EV, Everest; LG, leucogranites; LHS, Lesser Himalayan Sequence; MBT, Main Boundary Thrust; MCT, Main Central Thrust; MCTZ, Main Central Thrust Zone; MFT, Main Frontal Thrust; N, Numbur; STDS, South Tibetan Detachment System; SZ, Indus/YarlungTsangpo Suture Zone. Mineral abbreviations are after Whitney and Evans (2010).

Shivalaya and Kinja, respectively (Fig. 2).

The area of the NCC has been investigated by the authors of this paper in the framework of extensive geological field studies across the east-central Himalayan orogen (e.g. Groppo et al., 2013; Mosca et al., 2013). A 11-days geological field trip along the NCC is proposed on the basis of personal experience of the authors. The itinerary runs clockwise, beginning and concluding at Shivalaya, a village located in the Khimti Khola valley. This village can be reached after a 8 hour drive from Kathmandu and its tourist information-point and market allow also to ultimate trek logistics.

Following a general description of the Himalayan chain, this paper introduces the NCC at a regional scale describing main geological features of the area extending from the Khimti Khola to the west to the Dudh Kosi to the east; for this scope, a few representative images are illustrated along classical Jiri to Lukla and Dudh Kund trekking-routes.

Then, in the second part of the paper, the most peculiar geological aspects of the area between the Khimti Khola and the Likhu Khola valleys are introduced through observations of selected outcrops, samples and view-points along the NCC.

REGIONAL GEOLOGICAL SETTING

The Himalayan orogen, resulting from the continent-continent collision between the Indian and Eurasian plates began approximately around 55-50 million years ago (e. g. Le Fort, 1975, 1996; Rowley, 1996; Leech et al., 2005), is commonly subdivided into four longitudinal tectonostratigraphic domains, separated by major north-dipping tectonic contacts (Fig. 1). From south to north, and from lower to upper structural levels, these domains are the Sub-Himalaya, the Lesser Himalayan Sequence (LHS), the Greater Himalayan Sequence (GHS) and the Tibetan Sedimentary Series (TSS). The Sub-Himalaya domain, or Siwalik Sequence, consists of un-metamorphosed foreland deposits dated as Neogene. To the north, these deposits are bounded by the Main Boundary Thrust (MBT), along which they are thrusted by the LHS. The LHS consists of low-grade metasediments (metapelitic schists, carbonates and quartzites) associated with granitic orthogneiss (e.g. Upreti, 1999; Goscombe et al., 2006; McQuarrie et al., 2008, Khon et al., 2010 and references therein). The GHS consists of medium-grade to anatectic rocks resting between the Main Central Thrust

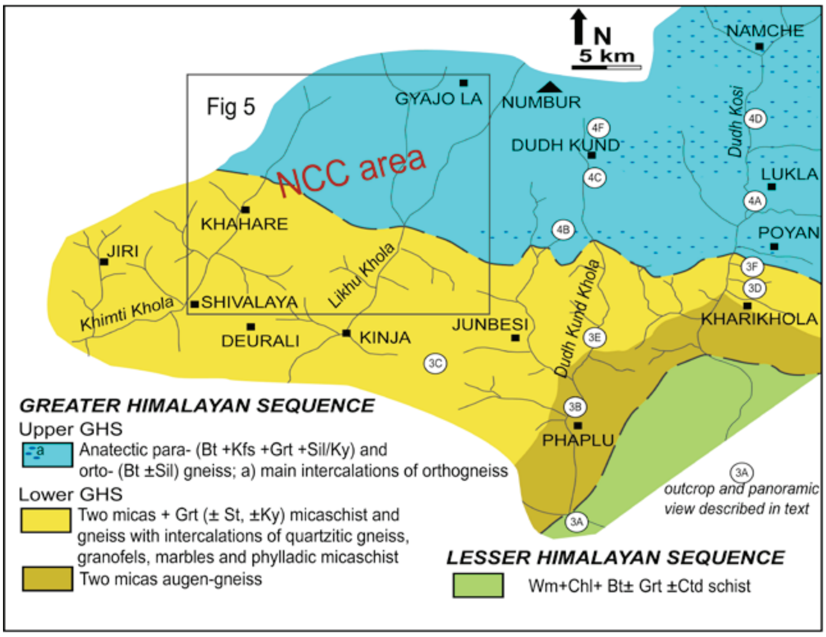

Figure 2

Tectonic sketch map of the area between the Khimti Khola valley to the west and the Dudh Kosi valley to the east. Location of the representative outcrops shown in Fig. 3 and Fig. 4 is reported. The area crossed by the NCC (located between the Khimti Khola and the Likhu Khola valleys) is detailed and illustrated in the proposed itinerary (Fig. 5).

(as originally defined by Gansser, 1964) and the extensional South Tibetan Detachment System (STDS; Burchfield et al., 1992; Carosi et al., 1998; Kellet et al., 2010). The GHS consists of two main portions characterized by different rocks, here reported as lower and upper GHS (Fig. 2).

The lower structural levels of the GHS, namely the lower GHS (GHS-L), are composed of medium- to high grade metasediments and granitic orthogneisses, recording a metamorphic grade increasing structurally upward from the staurolite zone to the sillimanite zone and, locally, to anatexis (e.g. Goscombe et al., 2006; Groppo et al., 2009; Mosca et al., 2012). These rocks define an inverted metamorphic sequence, roughly centered on the Main Central Thrust Zone (MCTZ; Goscombe et al., 2006, Mosca et al. 2012, 2013): this is the shear zone driving the juxtaposition of the high grade upper GHS over the LHS metasediments (see Searle et al. 2008 for an exhaustive discussion about the MCTZ). The upper GHS (GHS-U) consists of high-grade para- and orthogneiss, typically anatectic, also known as Higher Himalayan Crystallines (HHC). These rocks host networks and lens-shaped bodies of two-micas and tourmaline-bearing leucogranites, and are characterized by a progressive decrease in peak-pressure structurally upward (Pognante and Benna, 1993; Lombardo et al., 1993; Davidson et al., 1997; Guillot, 1999; Hodges, 2000; Groppo et al., 2012, 2013).

The Tibetan Sedimentary Series overlie the GHS along the STDS and consist of Upper Precambrian to Eocene sediments originally deposited onto the Indian continental margin (e.g. Gaetani and Garzanti, 1991).

THE NCC AND ITS ADJACENT AREAS

The NCC crosses a thick portion of the GHS exposed in the central-eastern sector of the Himalayan chain (Figs. 1 and 2). A tectonic sketch map of the area between the Khimti Khola and the Dudh Khosi valleys, investigated during several field campaigns, is reported in Fig. 2. A selection of the most representative meso-structures and of the main rock-types cropping out in this area is reported in Figs. 3 and 4.

The general geologic setting of the area extending from the Khimti Khola to the west to the Dudh Kund Khola to the east (Fig. 2) has been described mainly by Ishida (1969), Maruo and Kizaki (1981) and Schelling (1992). Opposite to the relatively poor geological knowledge of the Khimti Khola and Dudh Kund area, the Dudh Kosi valley - immediately eastward of Dudh Kunda - has been the object of extensive geological studies since long time (e.g. Carosi et al. 1999; Searle et al., 2003 and therein reference), because it represents the principal trekking-route to the Everest region. To the west of the area shown in Fig. 2, recent papers (Larson, 2012; 2013; Larson and Kellett 2014- field guide submitted for this JVE volume) describe the geology of Tama Kosi region.

As shown in Fig. 2, the LHS is exposed in the south-eastern sectors of the considered area, along the Dudh Kosi and Dudh Kund Khola valleys, downstream of Kharikhola and Phaplu villages respectively (Fig. 2). The LHS typically consists of grey to pale-green fine-grained quartz-sericite schists, slates and graphitic phyllites, locally intercalated with metric-scale layers of both massive Grt ± Ctd -bearing quartzites and Chl-sericite schists (Fig. 3A).

The GHS-L starts with two micas augen-gneiss (Fig. 2 and 3B), often with a well-developed mylonitic structure. This gneiss is considered as the lateral equivalent of the granitic orthogneiss known as the Ulleri formation in different sectors of the Himalayan chain (e.g. Upreti, 1999). Metric to plurimetric levels of Phl ± Ky -bearing phyllonite and Chl-bearing schist are intercalated within this gneiss and they are interpreted as the product of a metasomatic transformation of the granit-

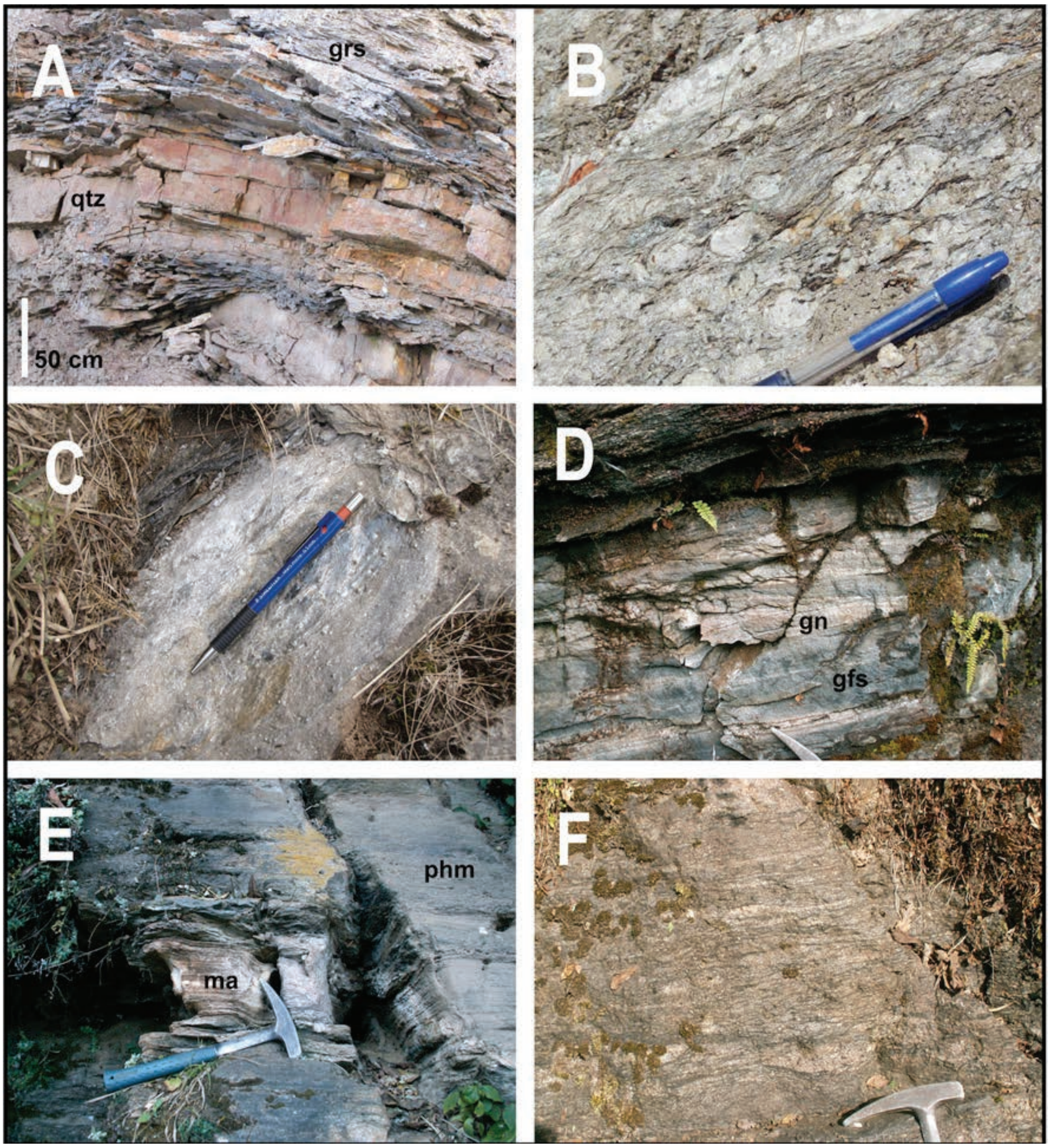

Figure 3
Representative meso-structures and lithologies of the Lesser Himalayan (A) and of the lower portion of the Greater Himalayan Sequence (GHS-L) (B-F). See Fig. 2 for their locations. (A) Pale-green fine-grained graphitic slates (grs) intercalated with levels of quartzite (qtz). (B) Typical outcrop appearance of two-micas mylonitic augen gneiss exposed in the area between Phaplu and Nunthala villages: the large K-feldspar porphyroclasts are enveloped by the main foliation defined by muscovite and biotite. (C) Grt-bearing two-micas gneiss exposed in the lower portion of the GHS-L. (D) Garnet-bearing two-micas mylonitic gneiss (gn) intercalated with Grt + Zo calc-silicate granofels (gfs). (E) Impure Phl -bearing marble intercalated to phylladic micaschist (+ greenish Bt) and to Ky-bearing two-micas micaschist (phm). (F) Grt + Sil -bearing two-micas mylonitic gneiss with evidences of partial melting

ic protolith along shear zones (Dalla Fontana et al., 2012). Up section, Grt ± St ± Ky -bearing two-micas coarse-grained micaschist and gneiss (Fig. 3C) are exposed. These rocks are associated to metric to decametric thick levels of two-micas quartzitic gneiss, Grt + Zo granofels (Fig. 3D) as well as to small lenses of impure marbles (± Phl, ± Wm) intercalated with metric levels of phylladic Ank-bearing micaschist (+ greenish Bt) (Fig. 3E). The uppermost GHS-L consists of Bt ± Grt ± Sil gneiss showing local evidence of partial melting (Fig. 3F) and characterized by a pervasive growth of late coarse-grained Wm flakes.

Upwards, the lower structural levels of the GHS-U (or HHC) consist of Grt + Bt + Kfs + Ky/Sil anatectic paragneiss, reported in the literature as Barun Gneiss (Lombardo et al., 1993; Groppo et al., 2012) (Fig. 4A). The Barun Gneiss is overlaid by Kfs + Bt + Sil ± Crd ± Grt anatectic paragneiss (i.e. Black Gneiss: Lombardo et al., 1993): the locally well-developed Crd-bearing assemblages record a progressive decrease of peak-pressure conditions structurally upward (Groppo et al., 2013). The GHS-U also contains bodies of Bt ± Sil ± Grt anatectic augen-gneiss (Fig. 4B), whose abundance significantly increases toward the upper structural levels (Fig. 2). Metric to plurimetric thick layers of calc-silicate granofels and impure marbles (Di + Pl + Qtz + Kfs ± Scp) are also present in the GHS-U (Fig. 4C). Networks of

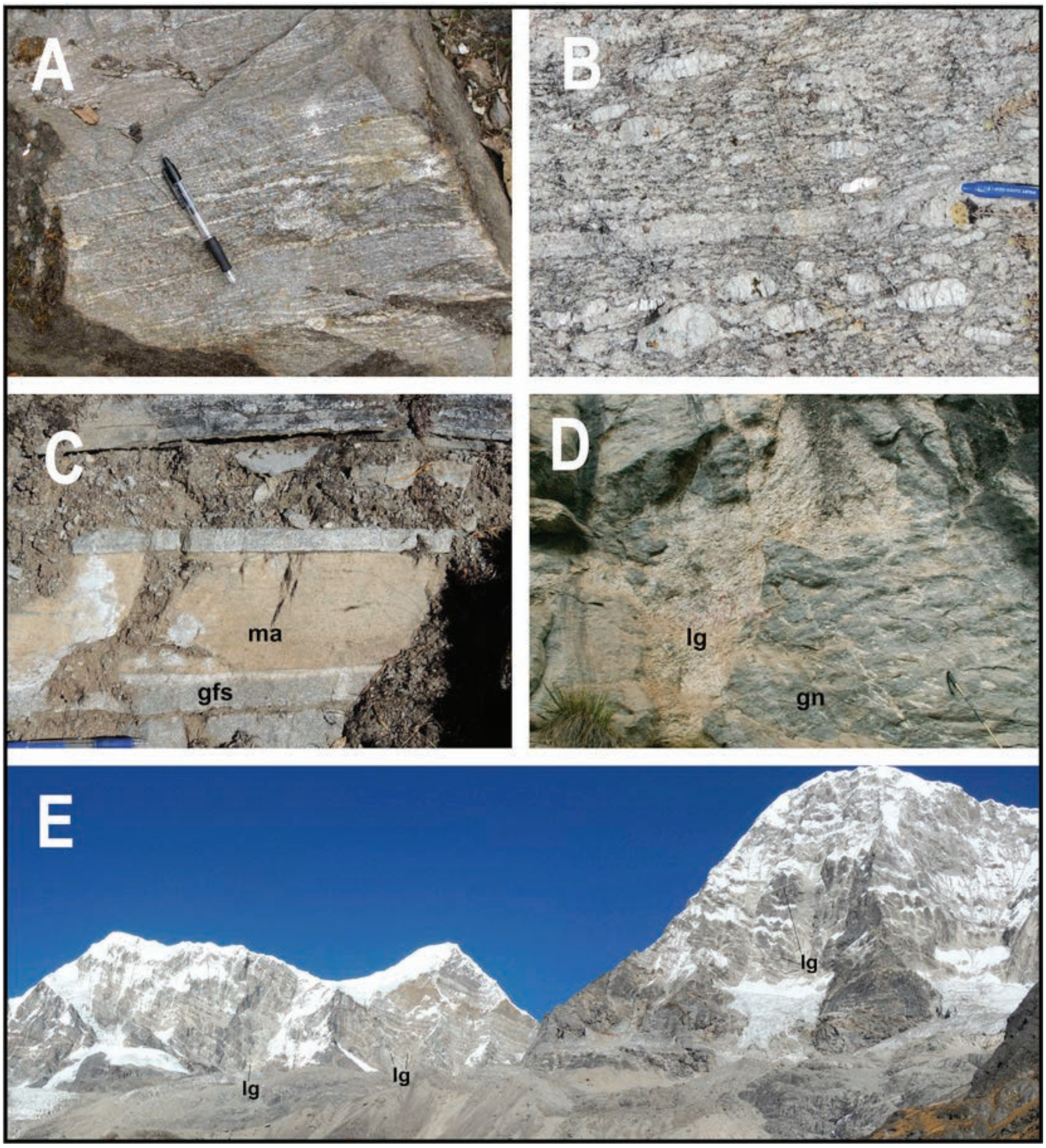

Figure 4
Representative meso-structures and lithologies of the upper portion of the Greater Himalayan Sequence (GHS-U or Higher Himalayan Crystalline). See Fig. 2 for their locations. (A) Grt + Kfs + Ky + Sil anatectic paragneiss ("Barun Gneiss-type"). The main foliation is defined by a peculiar compositional layering, consisting of Qtz + Kfs ± Sil layers alternated with Qtz + Pl + Bt + Grt + Sil layers. (B) Sillimanite-bearing anatectic orthogneiss. (C) Impure marble (ma) and calc-silicate granofels (gfs) (D) Leucogranite dyke (lg) cross-cutting the main foliation of the Bt + Grt -bearing gneiss (gn). (E) Panoramic view of mountain system to the north of the Dudh Kund lake. Leucogranite and pegmatitic dykes (lg) are variably oriented with respect to the main foliation of the gneiss.

leucogranitic and pegmatitic dikes are intruded in the middle-upper levels of the GHS-U (Fig. 4D), such as those spectacularly exposed in the highest peaks (Fig. 4E).

From a structural point of view, this sector of the Himalaya is typically dominated by tectonic contacts and composite foliations dipping toward the north at a regional scale. A pervasive lineation, marked by the preferred orientation of minerals such as kyanite, sillimanite and micas, shows often a dip-slip feature. The main foliation is deformed by crenulations and folds, most of them with NE-SW trending axes and axial planes dipping toward the NW. Open folds with N-S trending axes are also recognizable.

The Main Central Thrust Zone (MCTZ), namely the shear zone related to the tectonic juxtaposition of the high-grade GHS-U over the lower grade LHS, is roughly centered on the intensively sheared GHS-L (Mosca et al., 2013). Meso- and microstructural kinematic indicators across the GHS-L mark a consistent top-to-the-S sense of shear at a regional scale. The MCTZ boundaries are not easy to be identified because they do not coincide with sharp ductile tectonic contacts; on the opposite, shearing related to the MCTZ activity variably affects also the adjacent portions of LHS and GHS-U.

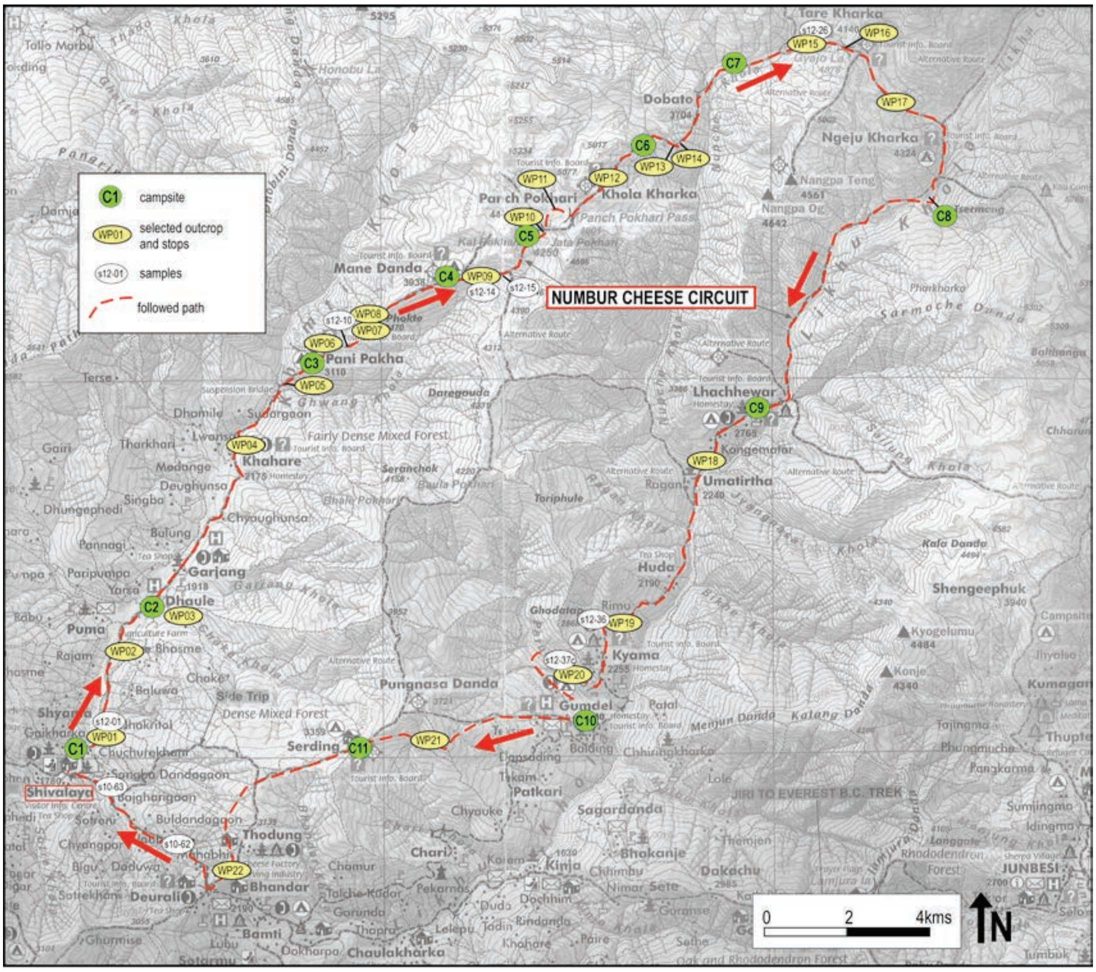

Figure 5
Location of campsites, selected outcrop and stop, and samples described in the text.List of campsite: C1, Shivalaya; C2, Garjang-Dhaule; C3, Pani Pakha; C4, Mane Danda; C5, Jata Pokhari; C6, campsite West Dobato; C7, Tare Kharka; C8, Ngeju Kharka; C9, Lhachhewar; C10, Gumdel; C11, Serding. Coordinates of outcrops and samples are reported in the text.

FIELD TRIP ALONG THE NCC

Location of campsites, selected outcrops and samples described along the NCC field trip are reported in Fig. 5.

Day 1 - Trek from Shivalaya to Garjang-Dhaule (2-2.5 hours)

The proposed itinerary along the NCC starts at Shivalaya (campsite C1 in Fig. 5, N 27°36'32.24" E 86°17'43.17", at 1800 m a.s.l.), a nice village along the Khimti Khola river where the motorable road ends (Figs. 6A and 6B). From the geological point of view, the village is located in the lower part of GHS (GHS-L), mainly characterized by Grt-bearing two-micas coarse-grained micaschist and gneiss (Fig. 2).

From Shivalaya, the NCC goes up easily following upstream the left bank of the Khimti Khola. Just outside the village, phylladic micaschist associated to layers of impure marble (Figs. 6C and 6D) are exposed along the road (WP01 - N27°36'33.91" E86°17'56.89"). The phylladic micaschist consists of greenish Bt + Pl ± Wm and contains variable amounts of calcite and ankerite (Fig. 6E-sample12-01, N27°36'33.38" E86°17'54.55"). The main foliation is defined by the preferred orientation of biotite and white mica and locally envelops pluri-mm carbonate-bearing lenses. It dips on average 20-30° to the NE. Impure marble contains variable amounts of quartz, phlogopite and white mica These rocks are deformed along a pluri-metric fault zone, showing normal movements of top down to the NE.

Going up, the trail crosses glacial deposits (lodgment till) involved by shallow landslides (Fig. 7A).

Outcrops of coarse-grained Grt-bearing two-micas gneissic micaschist are exposed in several places along the trail (WP02 - N27°37'27.80" E86°18'20.89"; Figs. 7B and 7C). The gneiss shows a pervasive mylonitic foliation defined by biotite and white mica, enveloping pluri-mm porphyroclasts of garnet. This foliation generally dips to the

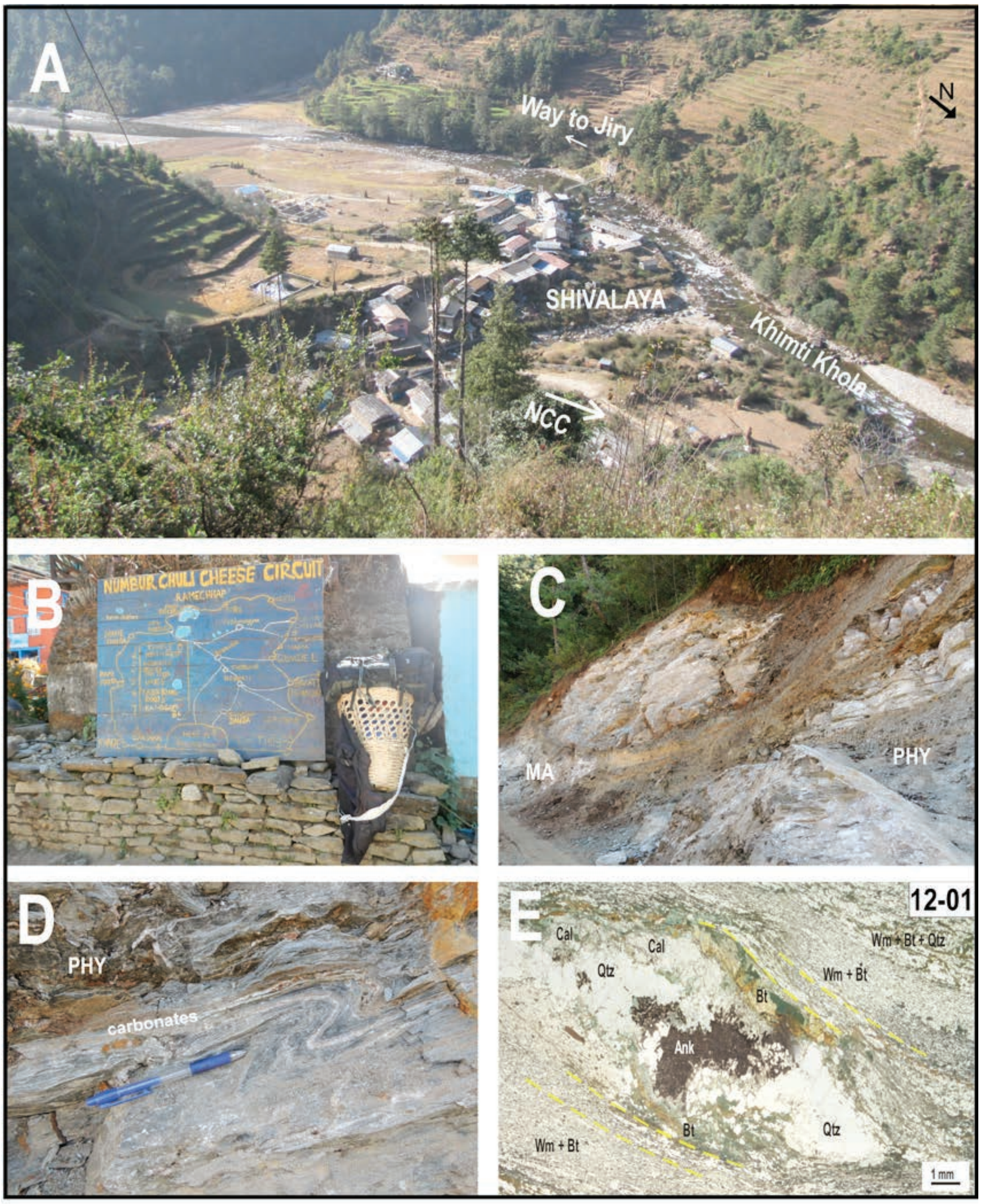

Figure 6

Trek from Shivalaya to Garjang-Dhaule(A) The village of Shivalaya on the left side of the Khimti Khola river: this is the starting and the arrival point of the proposed field trip along the NCC. (B) Sketch of the Numbur Cheese Circuit described at the Shivalaya information-point. (C) Intercalation of phylladic micaschist (PHY) and impure marble layers. (D) Detail of the outcrop of Fig. 6C, showing decimetric folds defined by the phylladic micaschists (PHY) and by carbonate-rich levels. (E) Microstructure of the phylladic micaschist shown in Fig. 6D. The main foliation, defined by white mica and biotite, envelops lens-shaped domains containing quartz, calcite and ankerite (sample12-01a) (Plane Polarized Light: PPL).

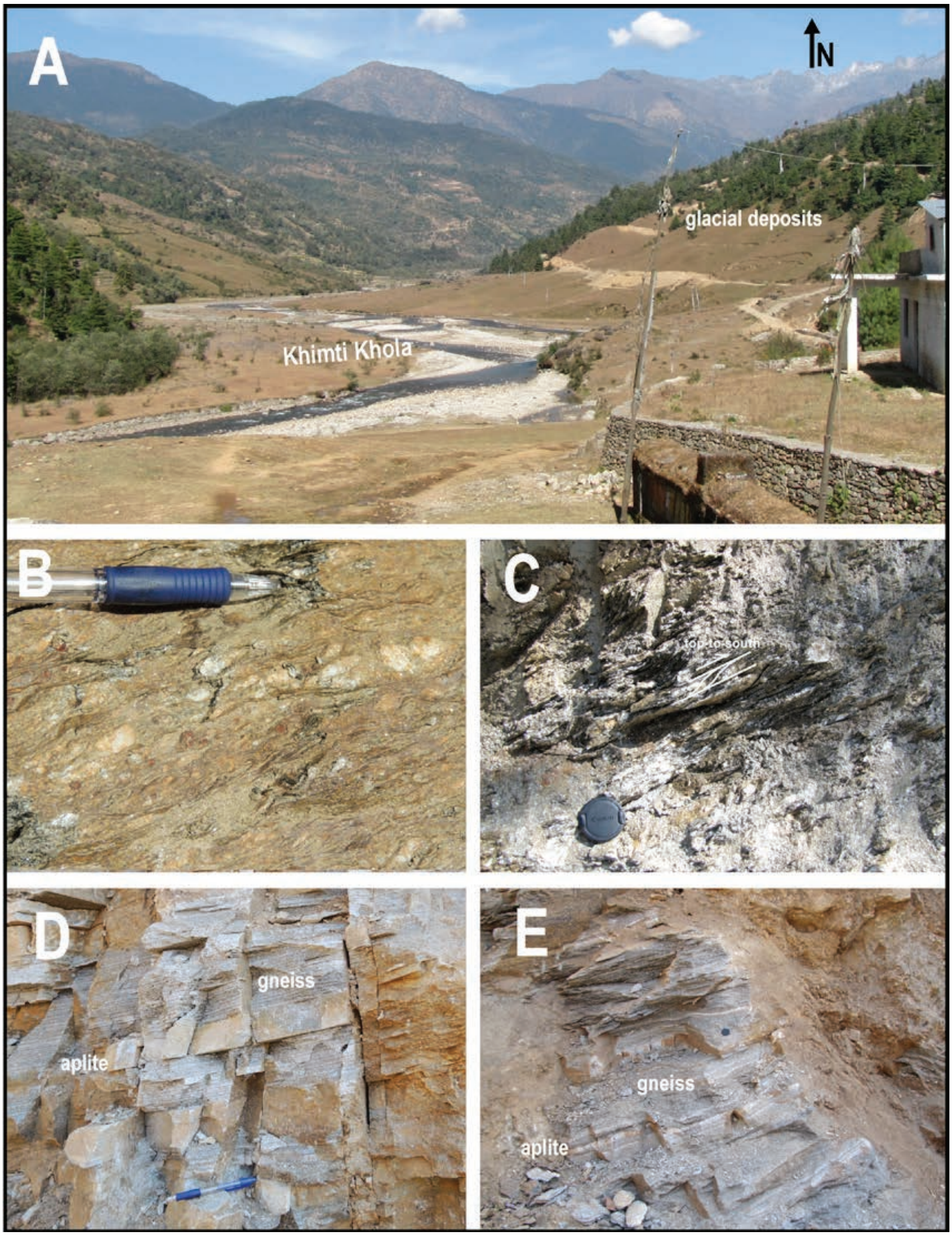

Figure 7
Trek from Shivalaya to Garjang(A) The path toward Garjang crosses glacial deposits with shallow landslides. (B) Mylonitic Grt-bearing two-micas gneissic micaschists. The main foliation, defined by phyllosilicates, envelops lens-shaped Qtz-rich domains and red garnet crystals up to a few mm in size. (C) S-C fabric in the Grt-bearing two-micas gneiss, suggesting top-to-the-S sense of shear. (D) and (E) Grt-bearing two-micas gneiss exposed near Garjang, showing aplitic levels ranging in thickness from cm to few dm.

contains a locally pervasive stretching lineation defined by the preferred orientation of kyanite and/or biotite. Fig. 9C shows microstructural details of the gneiss (sample 12-10, N27°42'18.86" E86°22'25.26"): a mm-sized garnet has inclusions of quartz, biotite, kyanite and plagioclase, partially replaced by Sil + Bt, and muscovite forms late flakes overgrowing the main foliation. Cm-scale intrafolial folds can be recognized, and stretched and deformed Turm + Grt -bearing pegmatites are locally observed parallel to the compositional layering (WP07 -N27°42'24.48" E86°22'32.00"; Fig. 9D).

At an altitude of ca. 3800 m (WP08 - N27°42'27.53" E86°22'34.29"), an outcrop located on the right side of the path offers the possi-

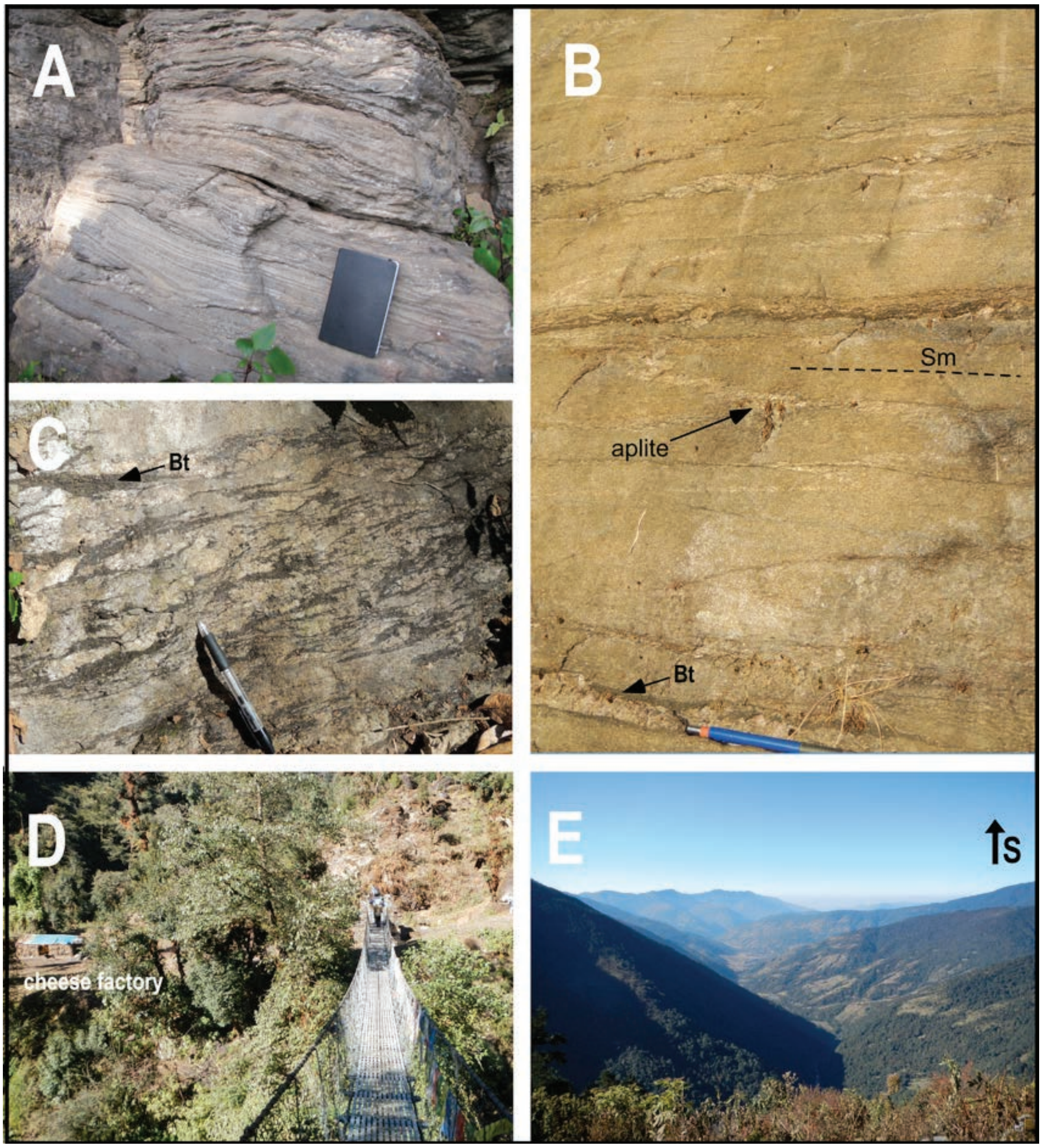

Figure 8
Trek from Garjang to Pani Pakha. (A) Grt-bearing two-micas banded gneiss cropping out in the rock walls above the Garjang campsite (sample 12-03, N27°38'43.48" E86°19'21.38"). (B) Detail of the outcrop reported in Fig. 8A, showing folded aplitic layers within two-micas gneisses. The aplitic layers show mm-thick Bt-rich selvedges. (C) Banded gneiss characterized by quartz-feldspatic domains rimmed by Bt-rich selvedges, suggesting an incipient partial melting. (D) The suspension bridge crossing the Gwang Khola and the cheese factory at the base of the climbing path to Pani Pakha campsite. (E) Panoramic view of the middle Khimti Khola valley from the Pani Pakha campsite.

bility to observe interesting meso-structures of the GHS-U. In the upper part of the rock wall, calc-silicate granofels (Di + Pl + Ep + Kfs + Scp assemblage) and anatectic orthogneiss define a m-scale fold (Fig. 9E). In turn, they are separated from the anatectic orthogneisses of the lower part of the outcrop by a geometrical ductile discordance.

Further on, the path reaches the top of the crest divide, from where the Numbur massif appears behind multicolor prayer-flags. The path continues relatively flat up to the summer pasture of Mane Danda (Fig. 9G) where the campsite is located (campsite C4 in Fig. 5, N27°42'56.59" E86°23'16.32", at 3970 m). This final part of the path offers magnificent panoramic views of the mountains extending to the north (Fig 9G-F). The thick gneiss sequence encircling the upper Khimti Khola results variably folded and deformed by large faults (Fig. 9F).

Day 4 - Trek from Mane Danda to Jata Pokhari (2.5-3 hours)

From the Mane Danda campsite the path runs along the right flank of the Gwang Khola, moving towards the upper part of this valley, characterized by a progressive series of glacial cirques hosting lakes at different elevations (see next days).

Outcrops and blocks observed along this trail

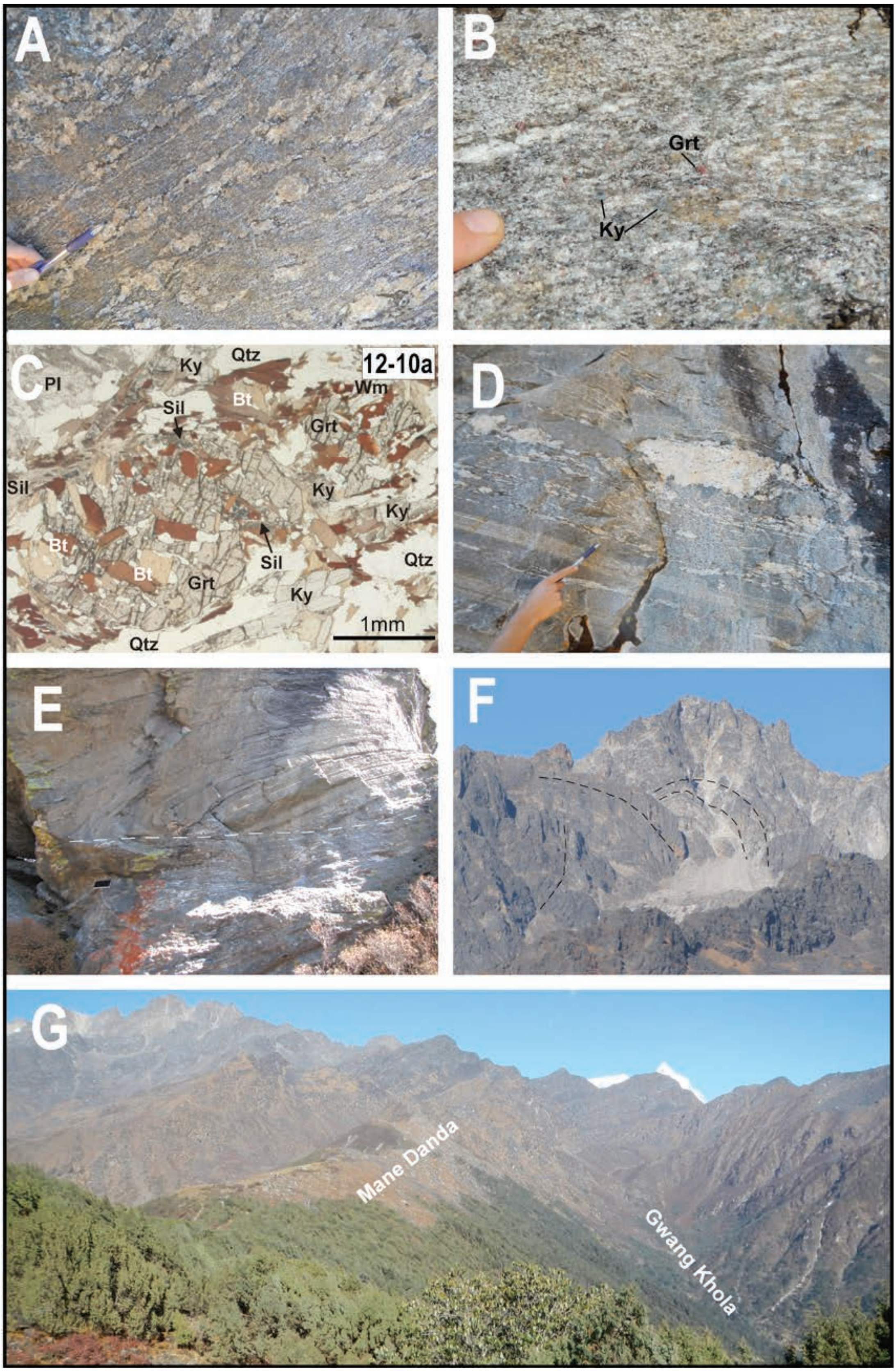

Figure 9

Trek from Pani Pakha to Mane Danda. (A) Grt-bearing two-micas gneiss showing mesoscopic evidence of incipient anatexis (sample 12-09). (B) Field appearance Grt + Bt + Kfs + Ky ± Sil anatectic paragneiss exposed on the way up to Mane Danda. These gneisses are characterized by the occurrence of mm-sized red garnet and blue kyanite crystals. (C) Microstructure of sample 12-10 showing a mm-sized garnet with inclusions of quartz, biotite, kyanite and plagioclase, partially replaced by Sil + Bt. Muscovite forms late flakes overgrowing the main foliation (PPL). (D) Sheared and boudinated pegmatitic dykes occurring in the anatectic Grt-bearing paragneiss. (E) Outcrop showing a pluri-m scale fold involving calc-silicate granofels and anatectic gneiss. (F) GHS-U gneissic sequence deformed by folds, as identifiable in panoramic view. (G) The Mane Danda pasture along the watershed between the Khimti Khola and the Gwang Khola. The snow-capped peak of the Numbur appears in the back-ground.

are anatectic gneiss characterized by the assemblage Grt + Bt + Kfs + Sil (Barun Gneiss-type). Field appearance of this gneiss along the path (WP09 - N27°43'2.17" E86°23'52.25") is shown in Figs. 10 A-D. They are characterized by an evident compositional layering, defined by mesocratic layers (Bt + Grt + Pl + Sil) alternating with leucocratic layers (Qtz + Kfs ± Pl ± Grt), cut by discordant pegmatitic and aplitic dykes. The main foliation, parallel to the compositional layering, is defined by the preferred orientation of biotite and sillimanite and envelops porphyroclastic garnet up to a few mm in size (Fig. 10E: sample 12-14, N27°43'2.80" E86°23'52.05"; Fig. 10F: sample12-15, N27°43'6.84" E 86°24'17.48"). White mica typically occurs as coarse-grained late flakes overgrowing the main foliation and replacing sillimanite. The main foliation generally dips to the NE and E and has a down-dip mineral aggregate lineation, but it is variably deformed by close to open folds and crenulations. The Jata Pokhari campsite (campsite C5 in Fig. 5, N27°43'33.33" E86°24'54.09", at 4225 m) is located in a glacial cirque with a lake (Figs. 10G and 10H).

Day 5 - Trek from Jata Pokhari to campsite West Dobato (6-7 hours)

A short climb from the Jata Pokhari campsite allows to reach the sacred Panch Pokhari lakes (4508 m), spectacularly located within a large glacial cirque (Fig. 11A). Every year many Hindu and Buddhist devotees visit this place in August during the Janai Purnima festival.

Along the climbing path (WP10 - N27°43'47.20" E86°24'56.11"), the anatectic Grt + Bt + Sill gneiss (Barun Gneiss-type) shows a main foliation usually dipping 20-40° to NW and NNE. This foliation is folded by tight folds with hinge lines plunging shallowly NE and locally associated to the development of an axial plane cleavage. At the outcrop scale, the "Barun Gneiss" often contains cm-thick sheared and boudinated quartz-feldspathic layers (Fig. 11B; WP11 - N27°43'57.30" E86°25'21.18"). From the Panch Pokhari lakes, the path climbs up to the Panch Pokhari pass (4610 m), allowing spectacular panoramic views of the Numbur massif (Fig. 11C). Then it continues towards the Nupche Khola, a tributary of the Likhu Khola valley.

After trekking along the descending path for roughly 200 m, the summer settlement of Khola Kharka is reached (N27°43'54.63" E86°26'13.64", at 4400 m). From there, the path continues to descent: most outcrops and blocks along the trail consist of fine-grained Kfs + Bt + Sil ± Grt paragneiss characterized by aligned Sil + Qtz nodules up to few cm in size (Figs. 11D and 11E; WP12 - N 27°44'10.52" E86°26'29.59"). These rocks are considered as the lateral equivalent of the Black Gneiss defined in the Everest region by Lombardo et al. (1993). The campsite, here informally called campsite West Dobato (campsite C6 in Fig. 5, N27°44'33.46" E86°26'52.18"), is located at an altitude of ca. 4000 m within a large circle partially filled by significant amounts of heterometric blocks (most of them consisting of Black Gneiss-type rocks) from the surrounding steep walls.

Day 6 - Trek from campsite West Dobato to Tare Kharka (4-5 hours)

From the campsite West Dobato, the path steeply descends alongside the valley flank towards the Nupche Khola river. Exposures of Bt + Grt + Sil gneiss can be observed at several places. The main pervasive foliation, always parallel to the compositional layering (WP13 - N27°44'24.53" E86°27'15.09"; Fig. 12A), dips on average 30° towards NNW and NE, and a mineral lineation, defined by biotite and/or sillimanite, plunges in the same directions. Along the path, at an altitude of ca. 3800 m (WP14 - N27°44'27.65"N E86°27'22.65"; Fig. 12B) the gneissic sequence is deformed by a m-scale fault zone, characterized by late top-to-the-NE extensional displacements. From there, the path turns northward and moves upstream along the right side of the Nupche Khola valley (Fig. 12C), reaching its bottom at the small summer settlement of Dobato. A little upstream, outcrops of gneiss with Sil + Qtz nodules (Black Gneiss -type) occur, and a number of sub-angular blocks of calc-silicate granofels are found along the mountainside.

Moving on, the path passes from the right to the left side of the Nupche Khola (bridge at N27°45'42.71" E86°27'35.33"); then it climbs up to the Tare Kharka campsite (campsite C7 in Fig. 5, N27°45'43.52" E86°28'2.94", at 4140 m). The campsite is spectacularly located on a flat alluvial plain bounded by modeled glacial moraines and resting a few hundreds of meters above the Nupche Khola (Figs. 12D and 12E). Looking to the north, the campsite offers impressive views of thick gneissic sequence spectacularly intruded by networks of leucogranitic dykes (Fig. 12D).

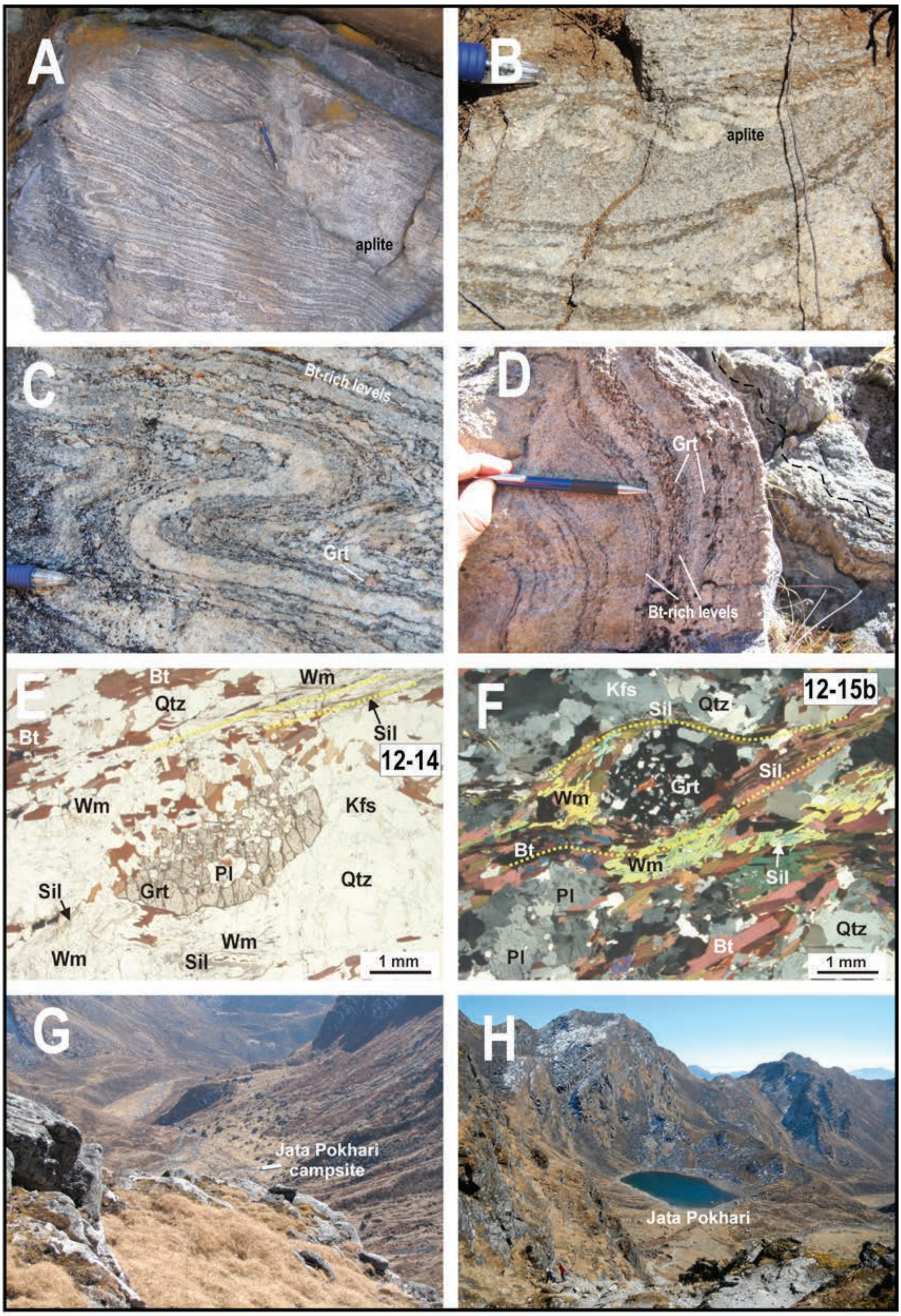

Figure 10
Trek from Mane Danda to Jata Pokhari. (A) Folded anatectic Grt + Bt + Kfs + Sil paragneiss (Barun-type) cut by an aplitic dyke. (B, C) Detail of thin folded aplitic dykes from the same outcrop of Fig. 10A. (D) Anatectic Grt + Bt + Kfs + Sil paragneiss characterized by a compositional layering defined by mesocratic layers alternating to leucocratic layers. A gentle open fold deforms the compositional layering. (E) and (F) Microstructure of samples 12-14 and 12-15, respectively. The main foliation, parallel to the compositional layering, is defined by Bt and Sil, this last partially replaced by coarse-grained late Wm flakes. Pluri-mm Grt includes Pl, Qtz and Bt (PPL). (G) and (H) Panoramic view of the Jata Pokhari campsite from the trail climbing to the Panch Pokhari lakes.

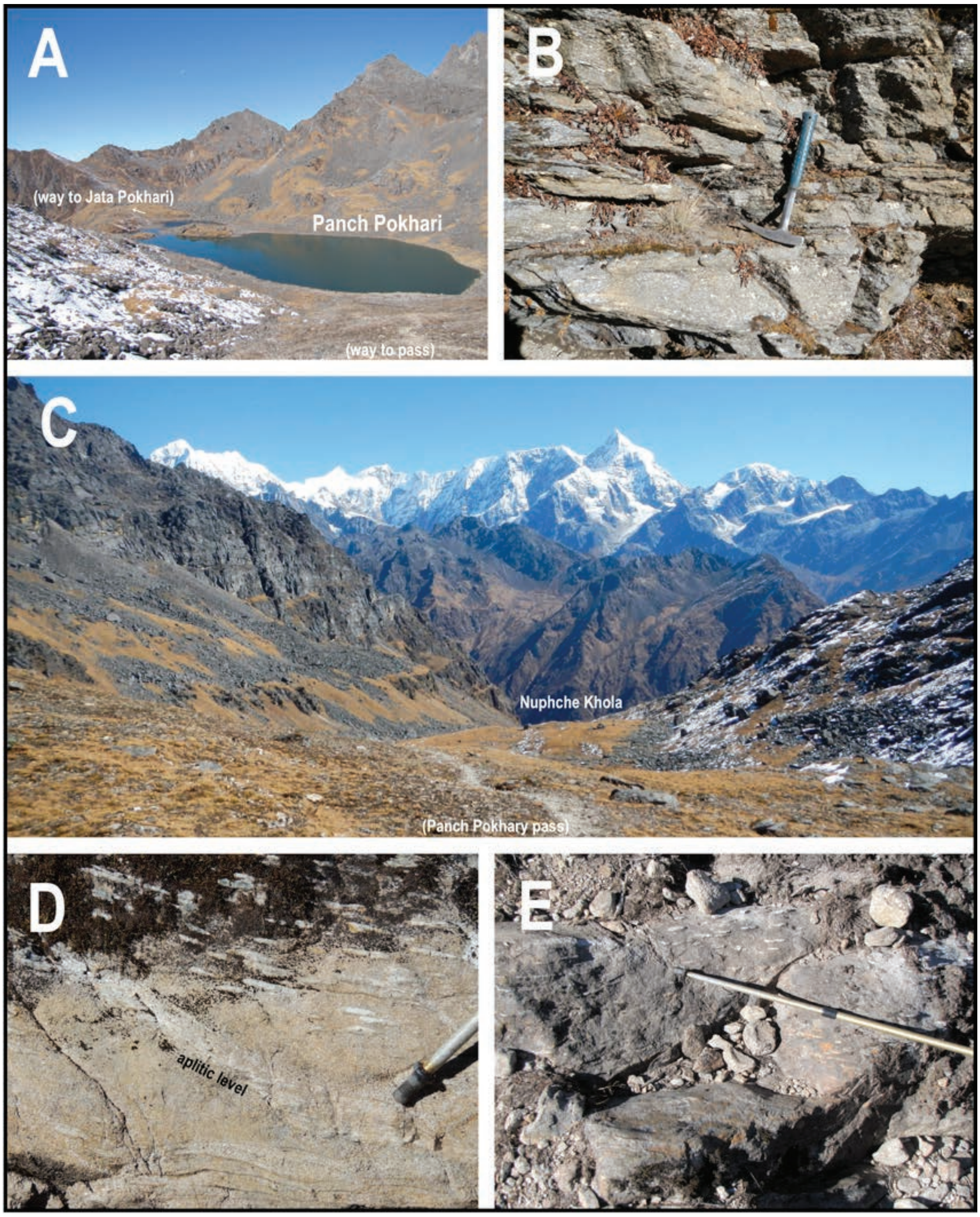

Figure 11
Trek from Jata Pokhari to campsite West Dobato. (A) View of the Panch Pokhari lakes from the path climbing to Panch Pokhari pass. (B) Anatectic gneiss showing boudinated quartzo-feldspathic layers. (C) Panoramic view of the Numbur Massif from the Panch Pokhari pass. Looking to the east. (D) and (E) Outcrop of fine-grained Kfs + Bt + Sil ± Grt paragneiss (Black Gneiss-type) characterized by peculiar Sil + Qtz nodules up to few cm in size, aligned along the main foliation.(PHY) and by carbonate-rich levels. (E) Microstructure of the phylladic micaschist shown in Fig. 6D. The main foliation, defined by white mica and biotite, envelops lens-shaped domains containing quartz, calcite and ankerite (sample12-01a) (Plane Polarized Light: PPL).

Day 7 - Trek from Tare Kharka to Ngeju Kharka (6-7 hours)

This is probably one of the most spectacular day of the proposed itinerary. From the Tare Kharka campsite, the path is quite flat and follows upstream the river for about an hour; then it starts to climb steeply and it finally reaches the Gyajo La pass (also reported as Thulo Lapcha, 4877 m), traditionally used by local Sherpas to move the yaks across the mountains.

Along the climbing trail to the pass, fine-grained Bt + Grt + Sil gneiss crops out extensively, showing Sil + Qtz nodules up to few cm in size (WP15 - N27°46’3.23” E86°29’5.10”; Fig 13A and 13B, sample 12-26, same coordinates of WP15). The pervasive foliation dips 30-40° to the NE. Calc-silicate granofels (Fig. 13C) occurs as dm-thick layers in this gneissic sequence.

The Gyajo La pass (WP16 - N27°46’3.46”

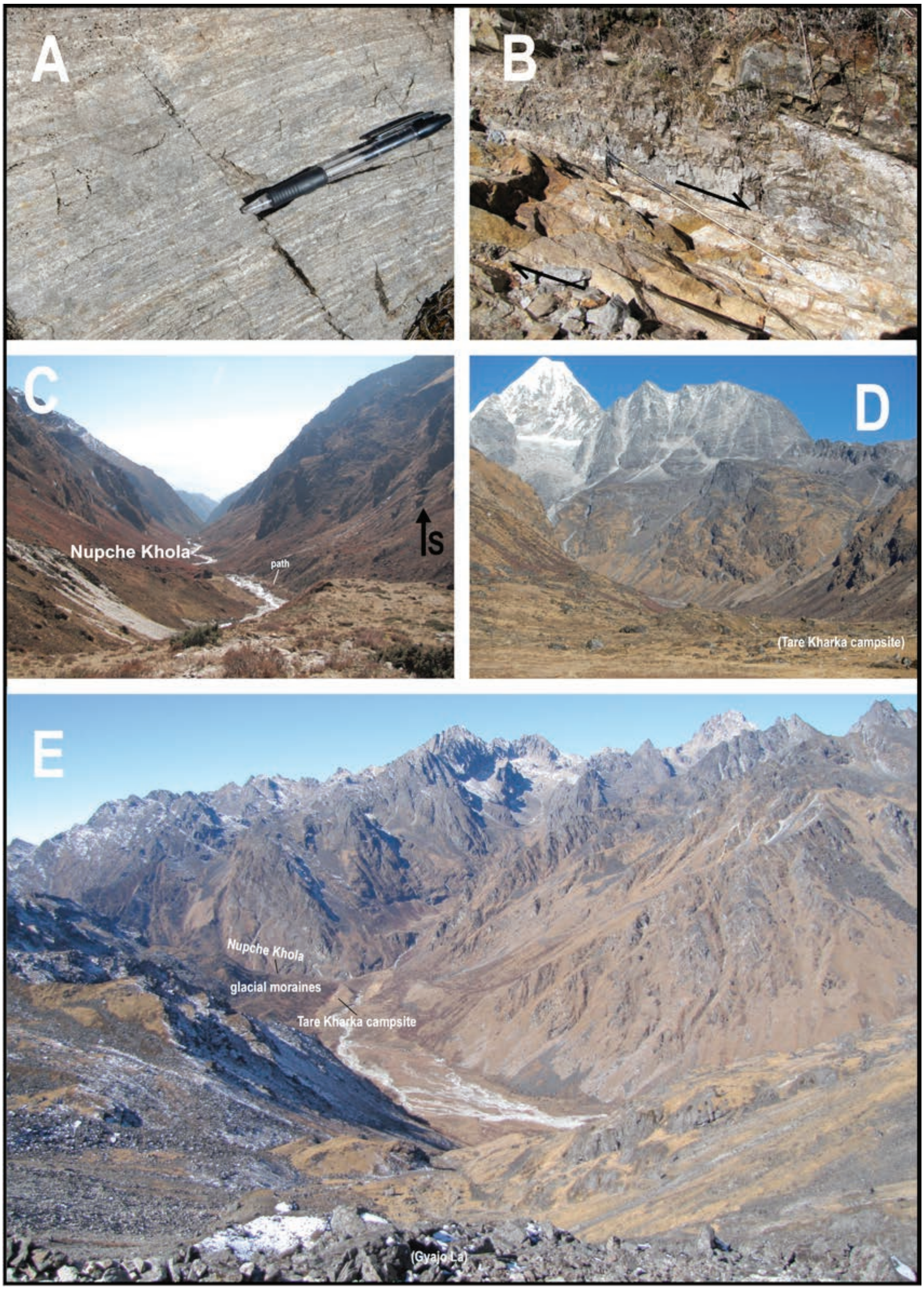

Figure 12
Trek from campsite West Dobato to Tare Kharka. (A) Kfs + Bt + Grt + Sil gneiss cropping out along the path descending from campsite West Dobato toward the Nupche Khola river. (B) Late top-to-the-NE extensional fault zone within the anatectic paragneiss. (C) View of the Nupche Khola bottom valley as seen from the path climbing up to the Tare Kharka campsite. (D) Panoramic view of the Numbur Massif looking to the north from the Tare Kharka campsite: the exposed section of GHS-U gneiss is intruded by a network of leucrogranitic dykes. (E) View of the Thare Kharka campsite from the path climbing to Gyajo La Pass.

E86°29'40.30") offers spectacular panoramic views of the mountains encircling the upper Nupche Khola valley to the north-west (Figs. 13D and 13E) and of the Likhu Khola valley and the Numbur Massif to the north-east (Fig. 14A). A number of glaciers are present in the uppermost part of the valleys, and their more recent history is spectacularly documented by thick and continuous lateral and frontal moraines (Figs. 13E and 14A).

From the pass, the path goes down following

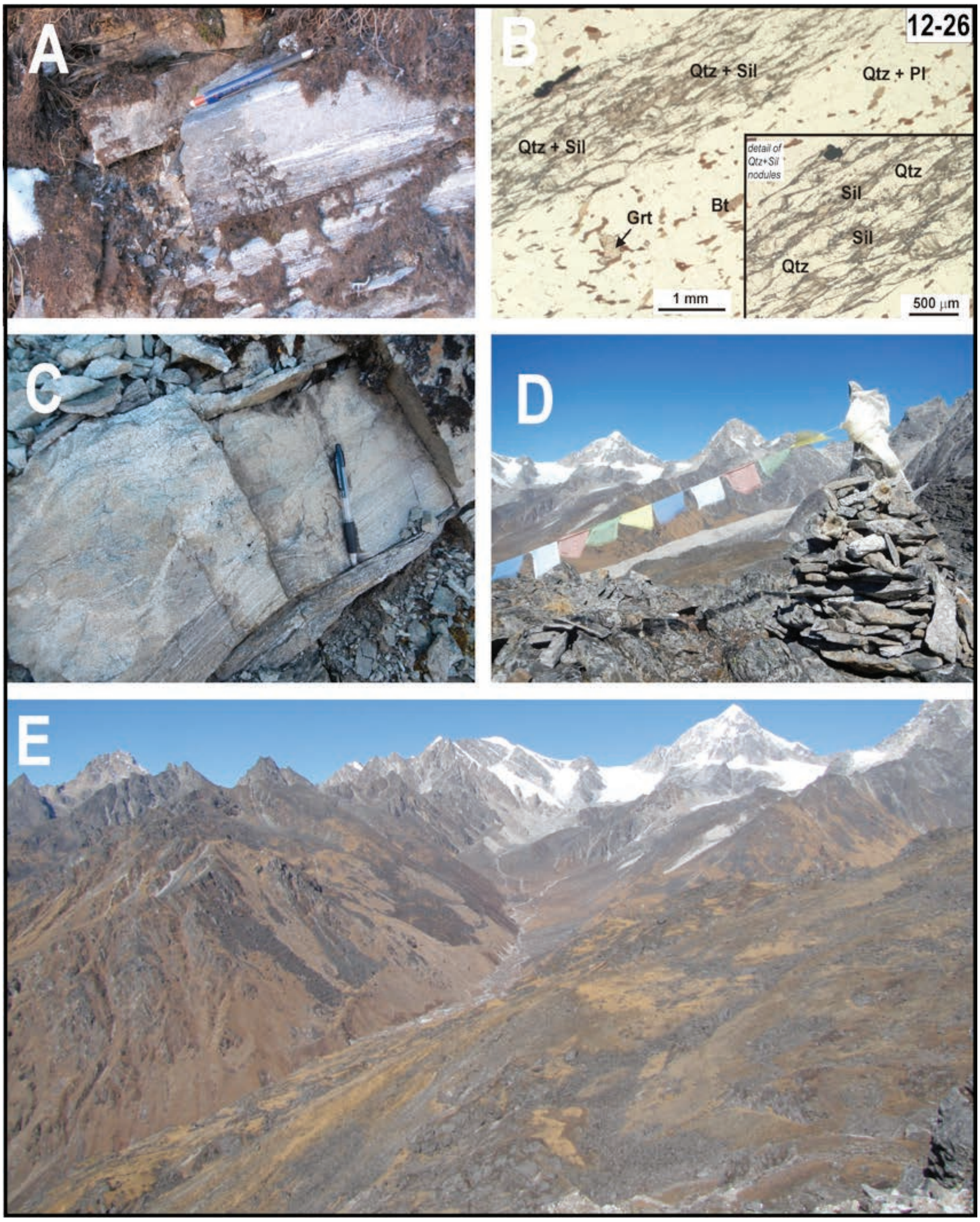

Figure 13
Trek from Tare Kharka to Ngeju Kharka. (A, B) Outcrop (A) and microstructure (B: PPL) of fine-grained Bt + Kfs + Sil gneiss with Qtz + Sil nodules (sample 12-26) cropping out along the path climbing to the Gyajo La Pass. (C) Fine-grained Bt + Sil + Grt gneiss associated to levels of calc-silicate granofels. (D) Prayer flags at the Gyajo La pass (4880 m). (E) Panoramic view of the upper Nupche Khola valley looking toward north from the Gyajo La pass. Note in the distance the frontal glacial moraine cut by the spillway.

the right lateral moraine of a tributary glacier of the main Likhu Glacier (Fig. 14A). An impressive supraglacial landslide is shown in Fig. 14B. Exposed rocks are anatectic gneiss (Barun Gneiss-type), crosscut by leucogranitic intrusions and dikes of different sizes (Figs. 14B and 14C). The outcropping gneiss is characterized by a foliation usually dipping to the NE and by sillimanite and/or biotite marking pervasive stretching lineation plunging towards the same direction. This foliation is deformed by tight folds and crenulations plunging NNE (WP17 - N27°45'11.29" E86°30'37.47").

The panoramic view of the Numbur Massif is superb all along the descending path towards the Likhu Khola, and the main Likhu glacier has spectacular glacial moraines, bounding a glacial lake and cut by the spillway (Fig. 15). Several minor glacial moraines are also present along the left side of the valley (Fig. 15).

Once reached the Likhu Khola valley bottom, the path progressively descends downstream along the river. A bridge allows to cross the river (bridge at N27°44'10.01" E86°30'58.83"), thus finally reaching the Ngeju Kharka campsite (campsite C8 in Fig. 5, N27°44'0.81" E86°31'1.66", at 3680 m) located in an flat wooded area on the left bank of the valley.

Few cheese factories are encountered along the path, which is mainly set in the alluvial deposits of the Likhu Khola, consisting of coarse-grained, poorly sorted sediments and large blocks made up of GHS-U lithologies.

The Lhachhewar campsite (campsite C9 in Fig. 5, N27°41'4.44" E86°28'4.61", at ca 2750 m,) is located on a terraced area before the confluence of the Lihku Khola with the Nupche Khola. Lhachhewar is the last village in the upper Likhu Khola valley: this is a nice village, with several stone houses surrounded by cultivated fields.

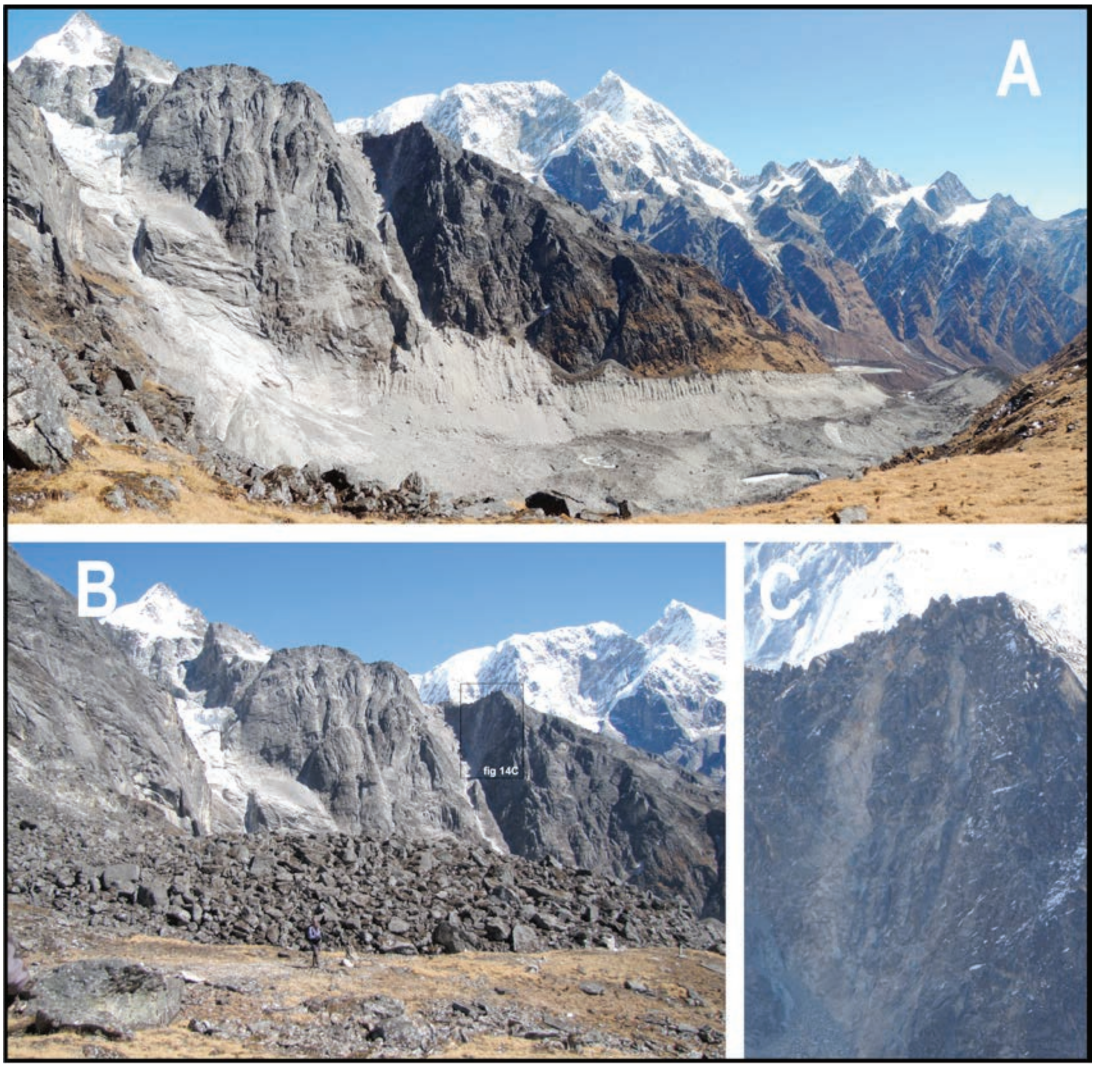

Figure 14
Trek from Ngeju Kharka to Lhachhewar. (A) Spectacular lateral glacial moraines of a tributary glacier of the main Likhu glacier, seen from the path descending from the Gyajo La pass towards the Likhu Khola. (B) Detail of a supraglacial landlside. (C) Detail of a leucogranite dyke intruded in the GHS-U gneiss.

Day 8 - Trek from Ngeju Kharka to Lhachhewar (4-5 hours)

Once left the Negju Kharka campsite and crossed again the river, the path descends gently along the right side of the Lihku Khola valley through a suggestive rhododendron and coniferous forest, spotted by reddish barberry bushes. The Numbur Massif remains still visible for a while behind us.

Day 9 - Trek from Lhachhewar to Gumdel (7-8 hours)

From Lhachhewar campsite the path runs 2 km up and down alongside the valley flank: sub-angular blocks coming down from the near mountain sides consist of anatectic Bt + Grt gneiss (Barun Gneiss -type). Then, the path descends quickly through the forest towards the confluence of the Likhu Khola with its tributary Nupche Khola (Umartina area). Rock faces exposed in the forest (WP18 - N27°40'22.89" E86°27'19.88"; Fig. 16A) consist of anatectic Bt + Grt gneiss with abundant late muscovite flakes. The main foliation is moderately dipping on average towards NE.

along the left flank of the Perung Khola valley. A number of outcrops exposed along the road (WP20 -N27°37'46.58" E86°25'27.58") consist of intensively deformed Grt-bearing two-micas gneiss and micaschist (Fig. 16D), with dm-thick layers of quartzite and calc-silicate granofels (Grt + Zo + Pl + Amp assemblage: Figs. 16E and 16F; sample 12-37c, N27°37'46.58" E 86°25'27.58") stretched along a pervasive mylonitic foliation. The foliation dips on average 20-30° towards ENE and NE, and contains a mineral aggregate lineation plunging NE. S-C fabrics indicate a top-to-the-SW sense of shear. A suspension bridge allows to cross the Perung Khola river and the road finally reaches the village of Gumdel (campsite C10 in Fig. 5, N27°37'10.22" E86°25'27.07", at 2250 m), with a lodge and small shops.

Figure 15
Trek from Ngeju Kharka to Lhachhewar. Glacial moraines of the main Likhu glacier, bounding a glacial lake and cut by the spillway. The panoramic view of the Numbur Massif is superb all along the descending path towards the Likhu Khola

A suspension bridge allows to cross the Nupche Khola river, and then the path continues downstream along the right bank of the Likhu Khola, crossing a rhododendron forest. The lithology is now changed, and Grt + Ky -bearing two-micas gneiss and micaschist mark the entrance in the GHS-L sequence (see outcrop at WP19 - N27°38'24.54" E36 86°25'57.51"; Fig. 16B and 16C; sample 12-36, same coordinates of WP19). The main foliation defined by the isorientation of white mica and biotite, on average dips to NNE; numerous stretched quartz lenses also occur between the foliation planes. Garnet forms pre- to syn-kinematic pluri-mm grains with inclusion of plagioclase and quartz, and post-kinematic kyanite crystals overgrow the main foliation (Fig. 16C).

After the forest, the path reaches the rural village of Kyama (N27°37'47.60" E86°25'43.09", at 2550 m), located on the terraced right side of the Likhu Khola valley. There is a small Gompa (monastery) just outside the village. From the village, the path becomes a dusty road which descends

Day 10 - Trek from Gumdel to Serding (5-6 hours)

In the morning, the view from the village of Gumdel is very nice, extending from the upper Likhu Khola valley to the Numbur Massif (Fig. 17A). From the village, the path progressively starts to ascend along the right flank of the Likhu Khola valley. The outcrops exposed along the dusty road consist of mylonitic Grt-bearing two-micas gneiss and micaschist, showing variably folded and stretched veins of quartz. Examples of this rocks can be observed in the outcrops exposed along the road on the eastern side of the Chari Khola (WP21 - N27°36'40.41" E 86°23'1.23"; Figs. 17B-D). The mylonitic foliation generally dips 20-30°

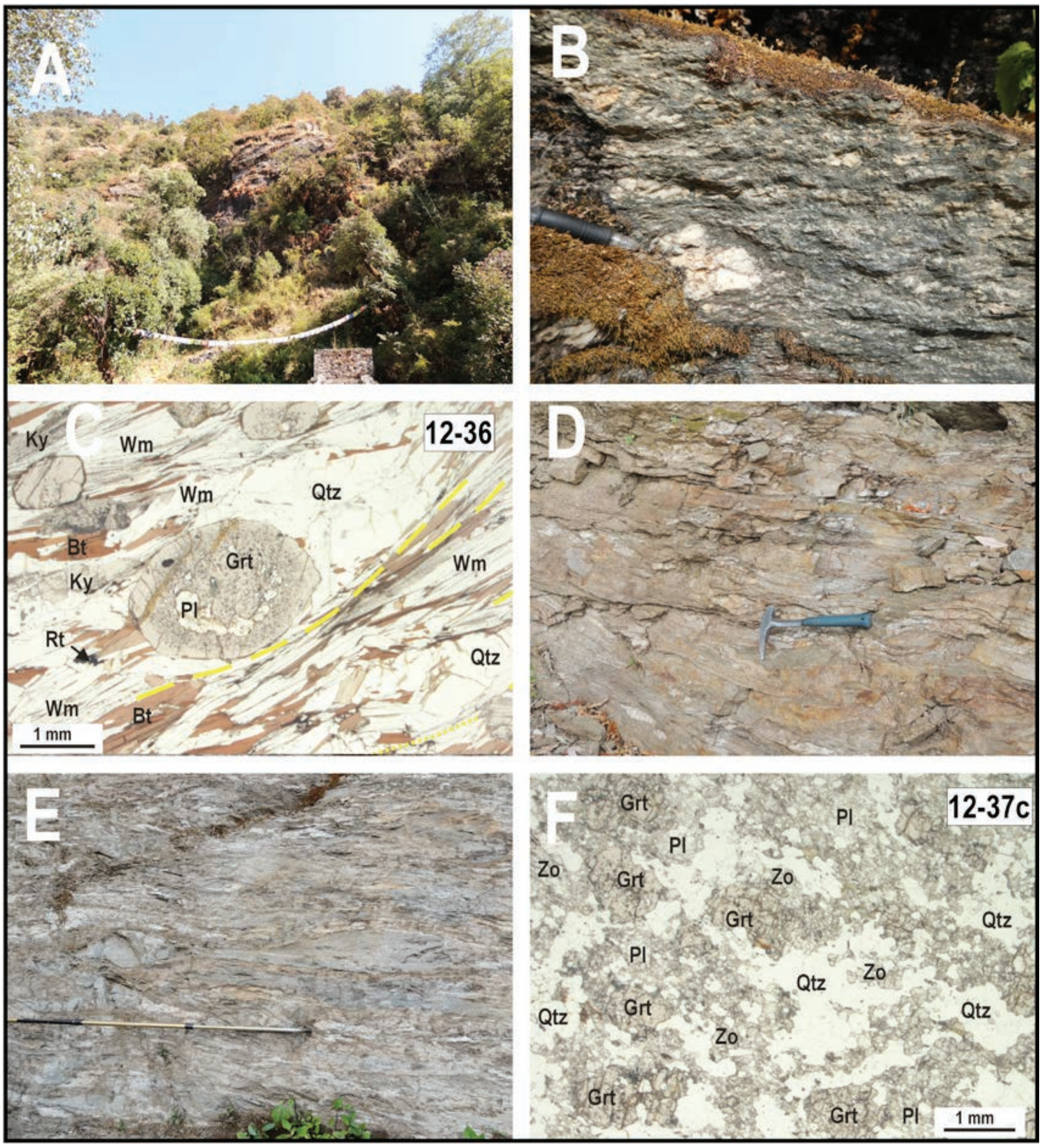

Figure 16

Trek from Lahaksewar to Gumdel. (A) Outcrop of Bt gneiss at the junction between the Nupche Khola and the Likhu Khola valleys (Umartina area). These rocks represent the lowermost structural levels of the GHS-U sequence. The main foliation is dipping on average toward the north. (B) Grt + Ky gneissic micaschist with the main foliation enveloping Qtz-rich lensoidal domains up to a few cm in size (sample 12-36). (C) Microstructure of Grt + Ky -bearing two-micas micaschist (sample 12-36, PPL). The main foliation is defined by white mica and biotite; garnet forms pre- to syn-kinematic grains with inclusion of plagioclase and quartz. (D) Intensive shearing of Grt-bearing two-micas micaschist cropping out along the road toward Gumdel. (E) Layers of calc-silicate granofels (sample 12-37c) intercalated to Grt-bearing two-micas micaschist and gneiss. The outcrop records an intensive shearing along the main foliation. (F) Microstructure of Grt + Zo -bearing calc-silicate granofels (sample 12-37c, PPL).

to the NNW and N, and aligned biotite marks a pervasive down-slip lineation. Kinematic indicators (S-C fabrics) suggest top-to-the-S sense of shear. Evidences of top-to-the-E/NE late extensional deformations (meso-scale faults and associated fractures) are also present in these outcrops. A steep stairway through a dense virgin forest leads to Serding campsite (campsite C11 in Fig. 5,

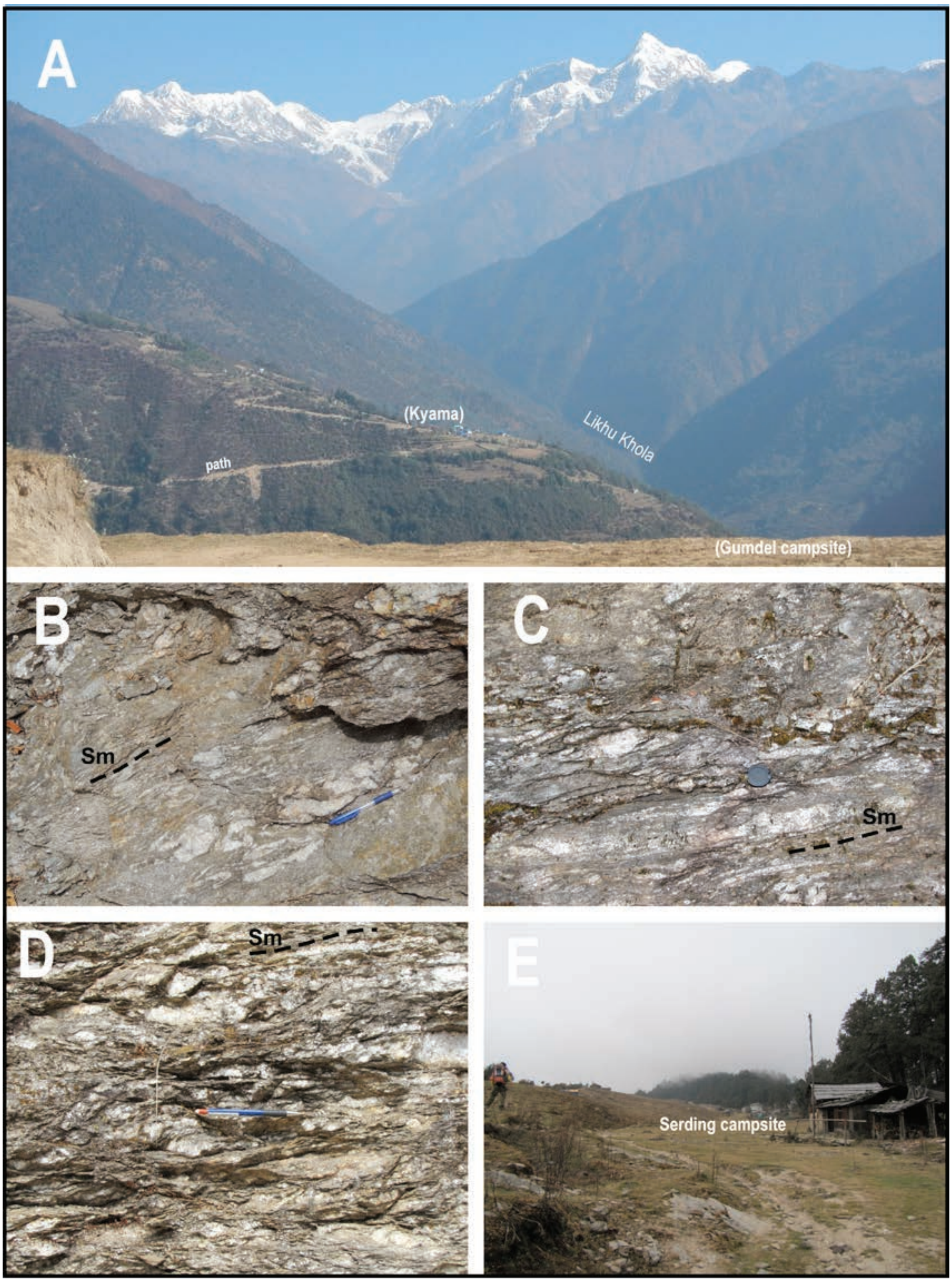

Figure 17
Trek from Gumdel to Serding. (A) Panoramic view of the Likhu Khola valley and of the Numbur Massif from the village of Gumdel. (B, C, D) Mylonitic Grt-bearing two-micas micaschist, showing folded and stretched quartz veins. (E) The Serding campsite.

N27°36'45.04" E86°22'1.05", at 3300 m), located in a nice flat area on the top of a crest between the main Likhu Khola and Khimti Khola valleys.

Day 11 - Trek from Serding to Shivalaya (5-6 hours)

From the Serding campsite, the path steeply descends through a dense forest towards the Deurali pass, offering good panoramic view of the icy mountains to the west (Fig. 18A) Along the descending path, Grt-bearing two-micas gneiss and micaschist are exposed in scattered outcrops

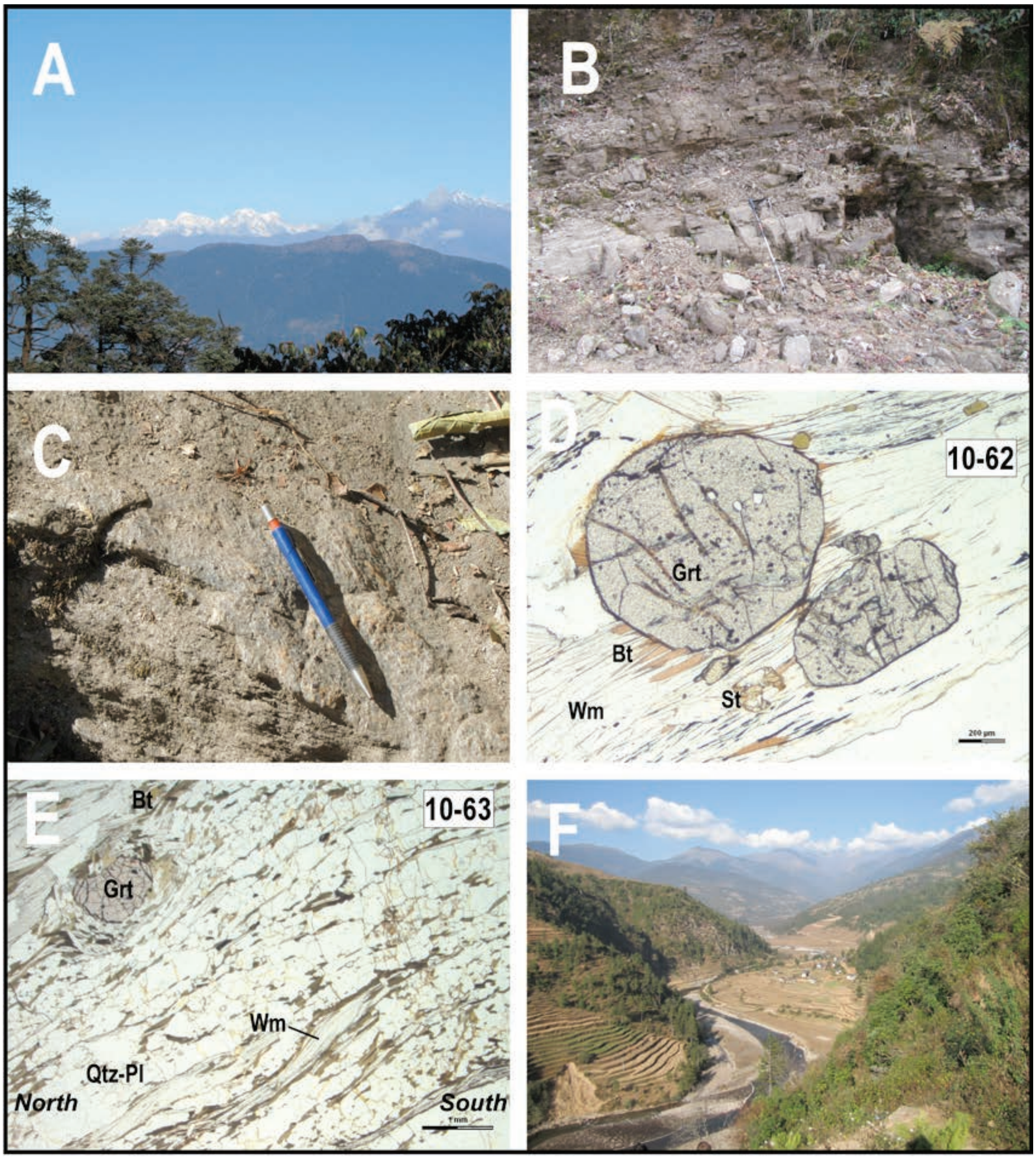

Figure 18
Trek from Serding to Shivalaya. (A) Panoramic view of Himalaya looking to the west from the descending path from the Serding campsite toward the Deurali pass. (B) Grt-bearing two-micas micaschist cropping out along the path toward Deurali pass. (C) Grt+St -bearing two-micas micaschists with a well developed mineralogical stretching lineation (evidenced by the pen). (D, E) Microstructure of Grt ± St -bearing two-micas micaschist (D: sample 12-62; E: sample 12-63; PPL). Note mica-fish in (E) indicating top-to-the-S sense of shear. (F) The arrival in Shivalaya and the last view of the Khimti Khola valley.

(WP22 - N27°35'15.50" E86°20'11.77"; Fig. 18B). They show a main foliation dipping 10-30° towards NW and N, and a pervasive stretching lineation defined by aligned biotite plunging in the same directions. Mesoscopic S-C fabrics suggest a top-to-the-S/SE sense of shear.

Immediately before the Deurali pass the path becomes a dusty road again. At the Deurali pass (2710 m), the NCC reaches the main Jiri to Lukhla trekking-route. To close the NCC loop, one may follow the main road toward the west, quickly descending to Shivalaya. Along the road, the exposed Grt-bearing two-micas schist shows a pervasive foliation dipping to the NNW (Fig. 18C). The main foliation is defined by the isorientation of muscovite and biotite. Pluri-mm garnet grains and small staurolite crystals partially overgrow the main foliation (Figs. 18D: sample 10-62, N27°39'46.84 E86°35'11.28; and Fig. 18E: sample10-63, N27°39'54.17" E86°35'7.07"). The general top-to-the- S/SE sense of shear is also revealed by microstructures (mica-fishes in Fig. 18E).

After a final steep descent in the forest, the village of Shivalaya appears along the Khimti Khola river. The descending path offers the opportunity of a last view of the valley with its cultivated fields, and of the sinuous trend of the Khimti Khola river (Fig. 18F).

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