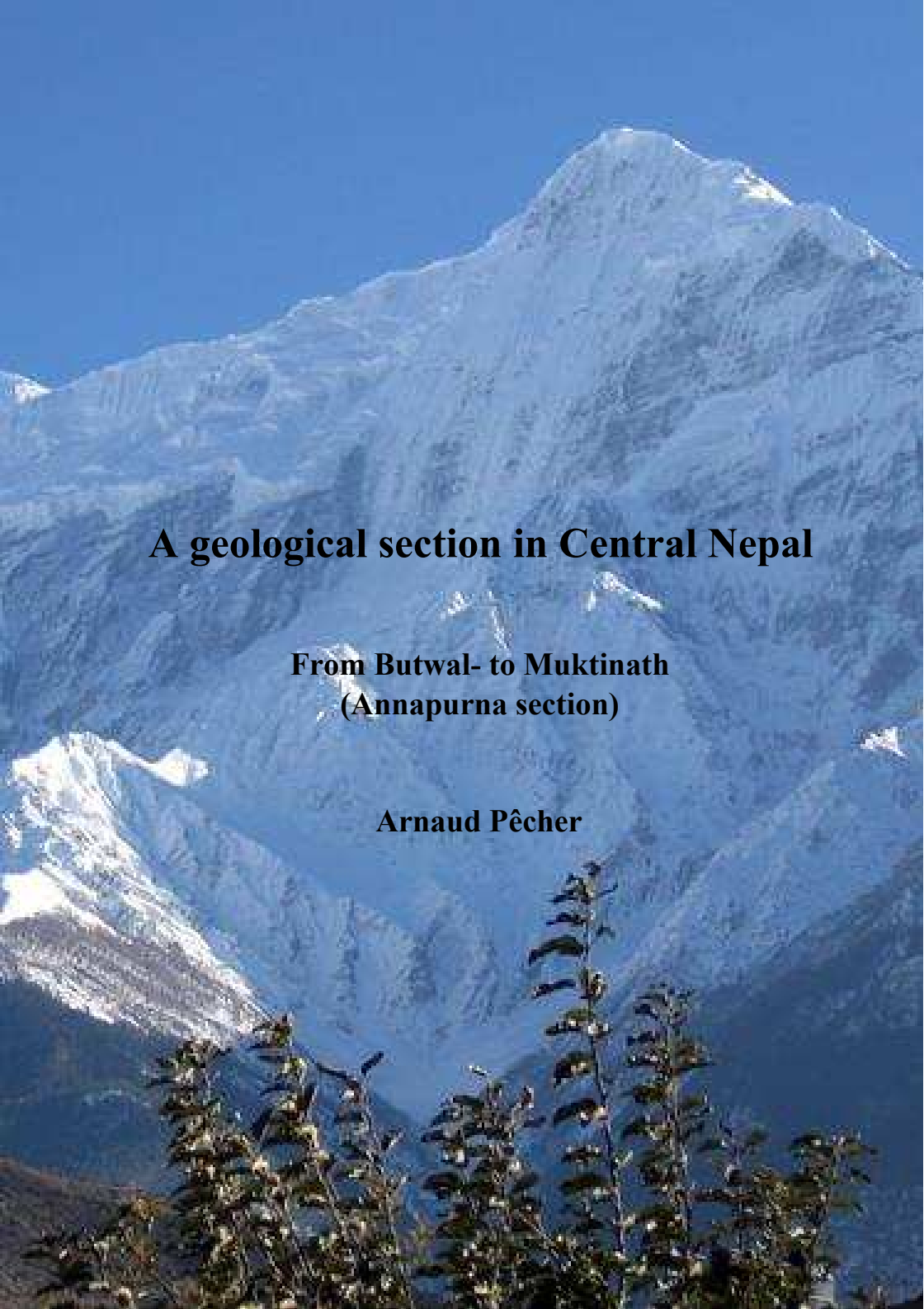




A geological section in Central Nepal

**From Butwal- to Muktinath
(Annapurna section)**

Arnaud Pêcher

A geological section in Central Nepal

From Butwal to Muktinath (Annapurna section)

A field guide by Arnaud Pêcher

This field guide has been written for an European doctoral program (iTECC program, field course, October 2014), with the help of Natalie Voegeli, Yani Najman, Pascale Huyghe, Pieter van der Beek. Some corrections added once back in Europe.

Butwal - Pokhara section: data in the Proterozoic and stops locations from M.R. Dhital and al., 2002

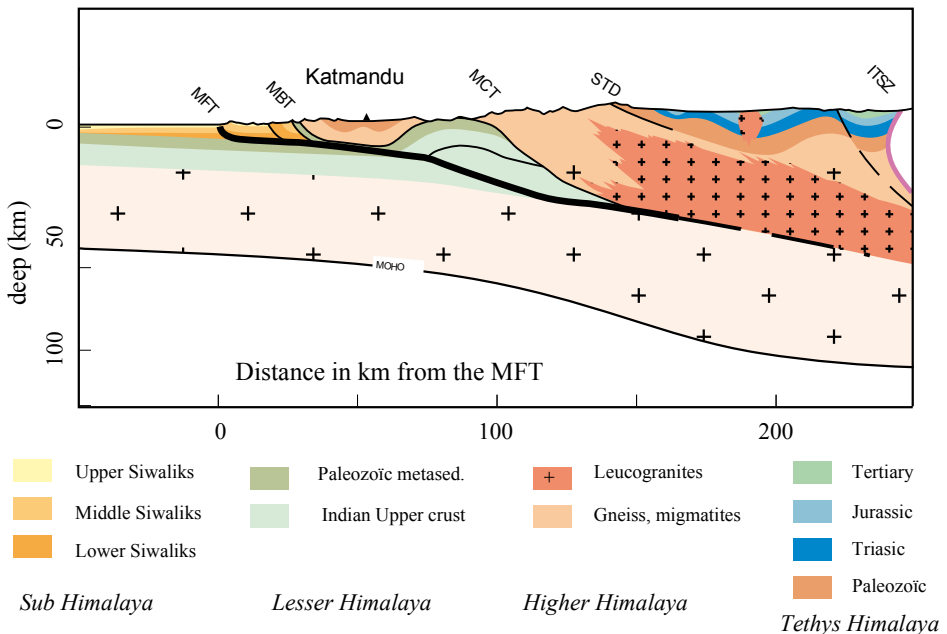
Pokhara to Muktinath: most of the stops - and the related descriptions - from the guidebook by B.N. Upreti and M. Yoshida, Department of Geology of the Tribhuvan University of Kathmandu, 2005. For those stops, labels as in the 2005 guidebook is added in brackets. Example : 4-3 [G68].

Most of the data on the Quaternary are from M. Fort or M. Fort and coworkers (references p. 89).

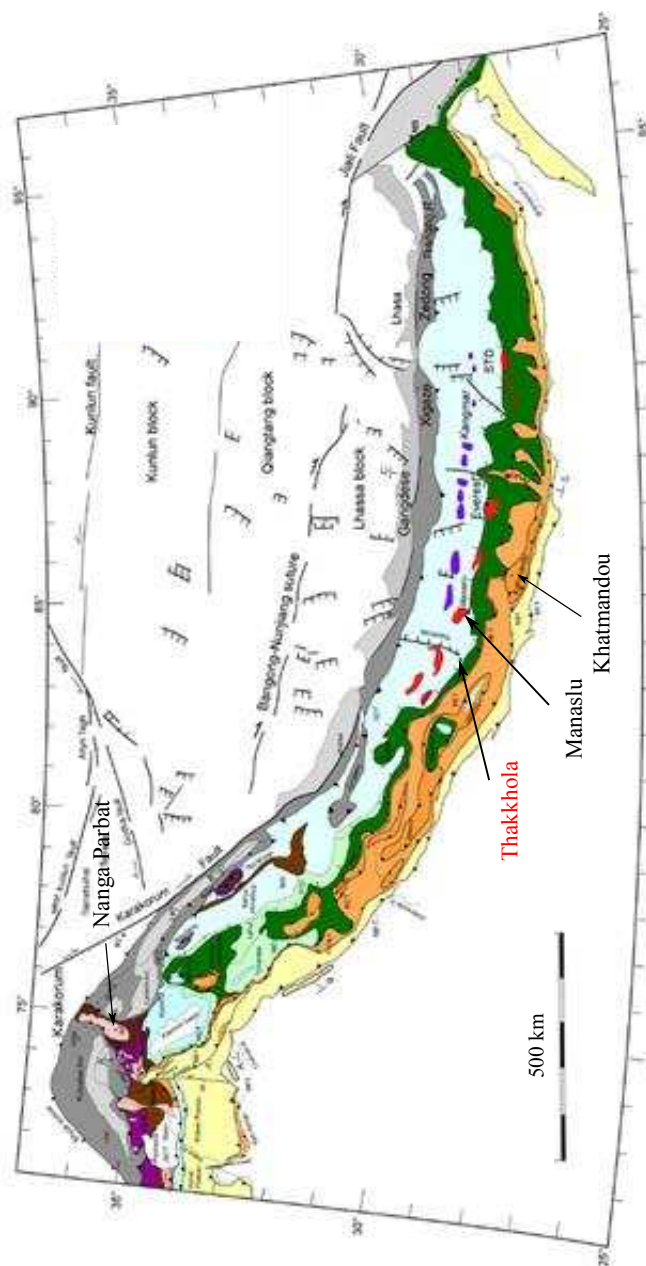




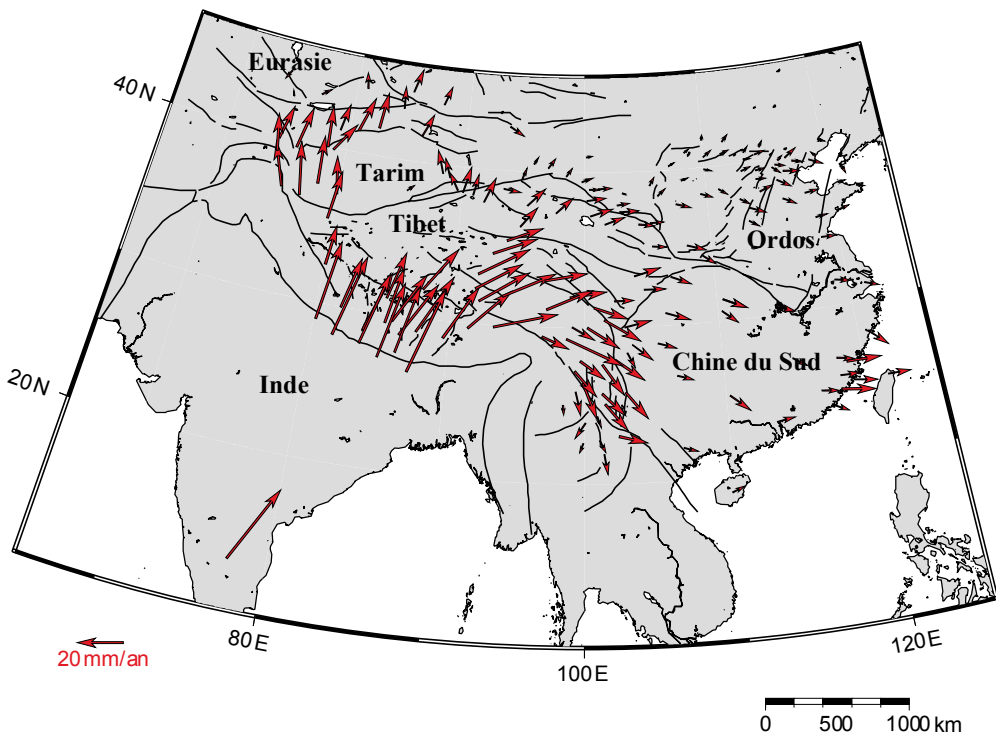
Himalaya and Tibet view from space shuttle. Image taken from over Mount Everest towards west. From left to right the Ganga plain and intra-Siwalik basin (a dun in Hindi), the snow-covered Himalaya, just behind the depression of the Tsangpo suture zone and to the right Tibet with its numerous lakes (often saltlakes). In the red circle, the Kaligandaki gorges and the Thakkhola graben.



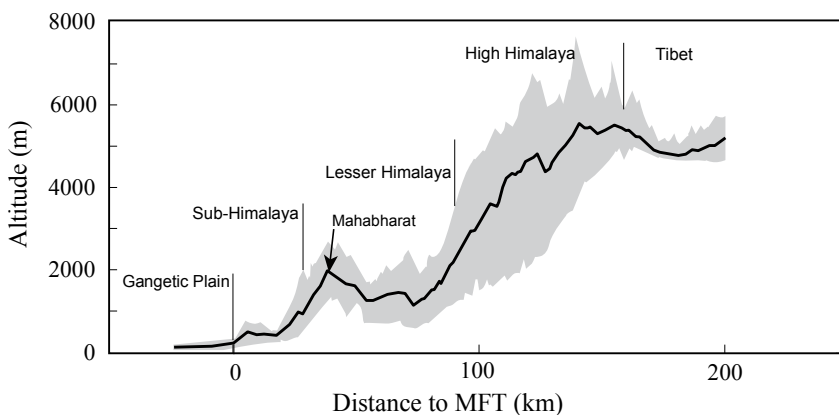
Simplified section across the Himalaya of Central Nepal. Thick line corresponds to the Main Himalaya Thrust (MHT, which terminates in the Main Frontal Thrust), on which the other main thrusts connect (in Bollinger et al., 2006)



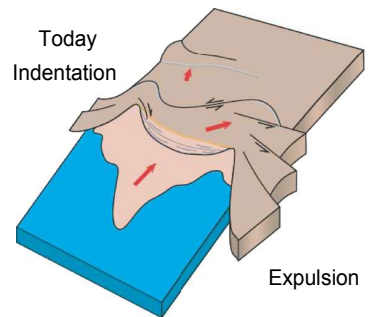
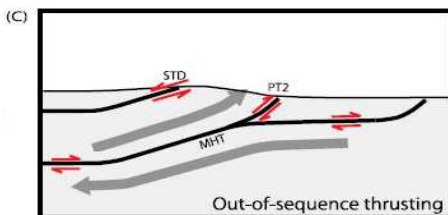
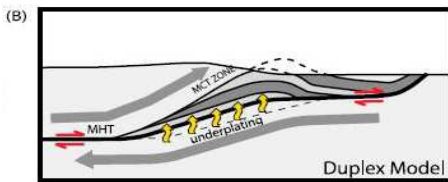
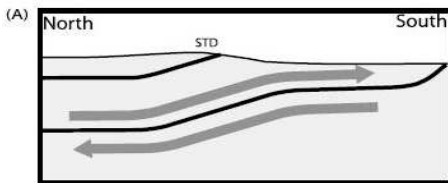
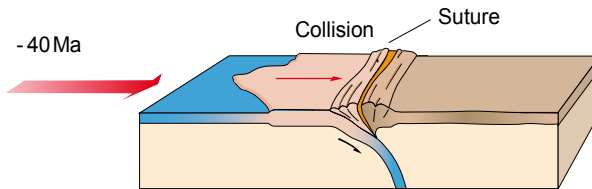
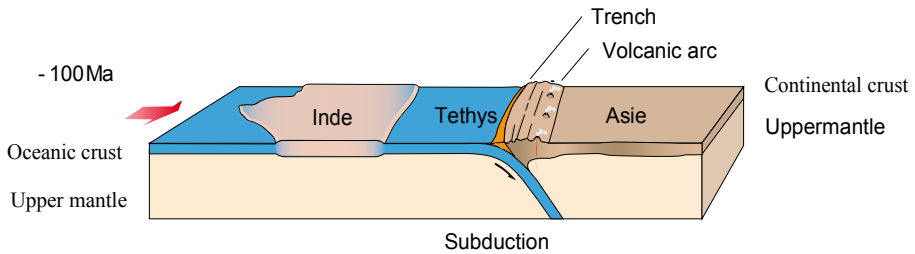
Overview map of the Himalayan Arc, from the western Nanga Parbat syntaxis to the eastern Namche Barwa syntaxis. From South to North : Mio-Pliocene and Quaternary foothills (in Yellow); Lesser Himalaya nappes (brown); the Higher Himalaya Crystalline (green); the Tethyan Sedimentary Series (Cambrian-Late Cretaceous) (blue), cut by the Miocene granites of the Higher Himalaya (red) and domes of gneiss and granite of the Northern Himalaya (purple) ; the Suture zone (flysch, molasses, ophiolites) (grey). In Western Himalaya (Nanga Parbat), there is a Precambrian basement with its metamorphic cover where the Tethyan Sedimentary Series are incorporated (brown and purple).



Velocities, relative to stable Eurasia, measured from GPS over a 10 years period (data from Wang et al., 2001, in Avouac, 2007).



Mean, maximum, and minimum elevation within a 50-km wide swath centered on a section west of Kathmandu. Several geographical domains are distinguished from north to south : Tibet, High Himalaya, Lesser Himalaya, sub-Himalaya, and the Gangetic Plain (Avouac, 2007).

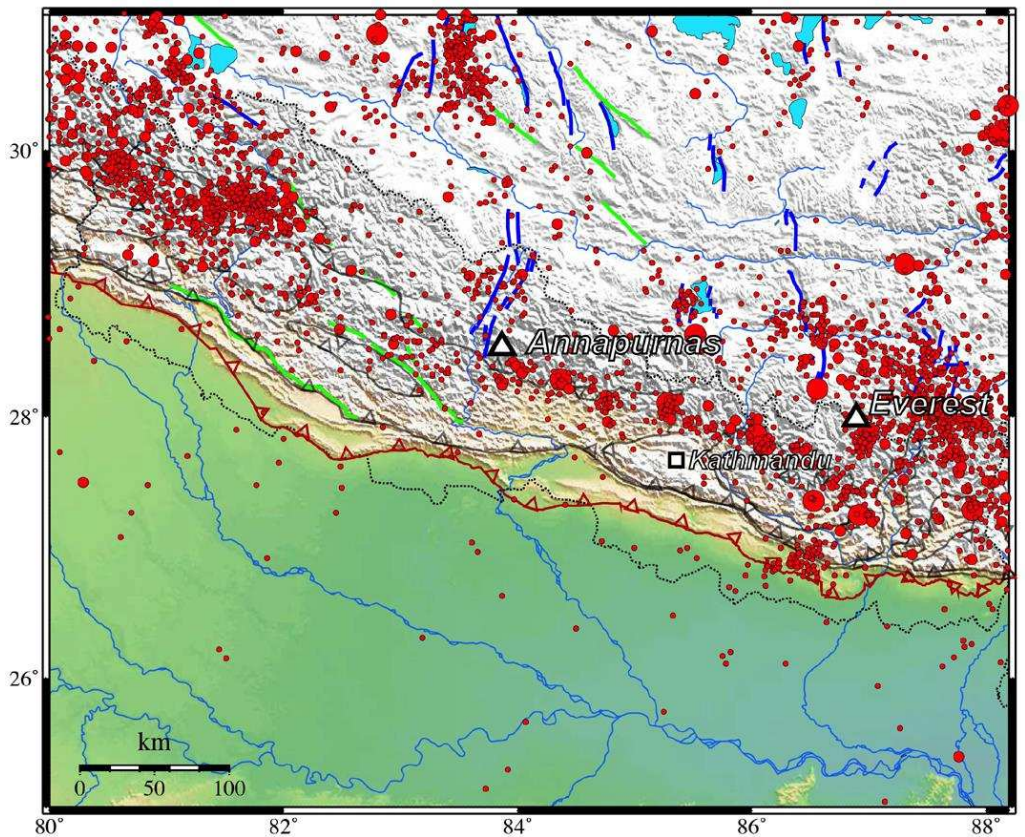


Prior to the collision, an ocean (the Tethys Sea) used to separate the northern margin of India and southern margin of Eurasia. The southern margin of Asia was an active margin with a subduction zone similar, for example, to the Andean subduction zone bordering the western margin of South America. The collision of India and Eurasia occurred around 50 -55 Ma, followed by the indentation of India into Eurasia since the onset of the collision has been absorbed by a combination of crustal thickening and lateral escape (in Avouac, 2007)

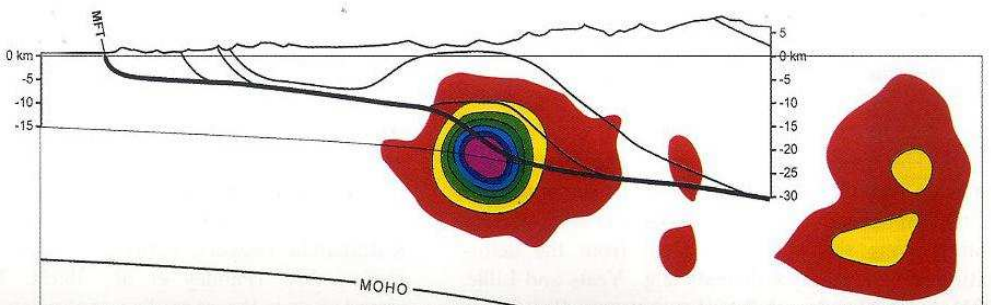
A sketch of the kinematics of the Himalaya, as discussed by Herman et al., 2010.

Stage I (a) : overthrusting and underthrusting along the MHT.

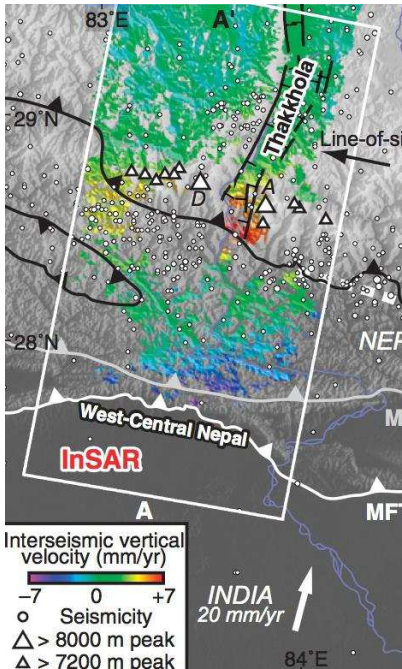
Stage II (b) Duplex formation model, or (c) out-of-sequence thrusting at the physiographic transition



A permanent seismic survey of Nepal, set up in the beginning of the 1980, extends more and more (together with a GPS network). It allows a more precise idea about the current tectonics. This map shows the 1995-2012 seismicity in Nepal: epicenters of earthquakes of magnitude $3.5 < M < 4.5$, $4.5 \leq M < 5.5$ and $M \geq 5.5$. During the same period, thousands of lower magnitude earthquakes have been located by the network (partly unpublished data, Bollinger 2014).



The seismicity is mainly observed below the front of the Higher Himalaya, on a ramp of the Main Himalayan Thrust (thrust-type focus mechanisms) (in Pandey et al., 1999. maximum density : 2.7 events/y)



Movements on the Main Himalayan Thrust

Upper panel: Profiles perpendicular to the mountain range showing the horizontal velocities derived from GPS and the vertical velocities derived from InSAR. Uncertainties on InSAR is 0.7–3.1 mm/yr. Colored curve corresponds to modeled interseismic deformation using a buried-fault model (dip = 6.5°, depth = 24.1 km, slip rate = 20.6 mm/yr).

Middle panel: Stack of six denudation profiles determined from river incision (the average topographic profile is indicated in gray).

Lower panel: Geometry of the inverted dislocation (red line). Blue histogram shows distribution of seismic activity along the profile. Vertical exaggeration in lower panel is 2× (Grandin et al., 2012).

Estimated shortening rate across the range

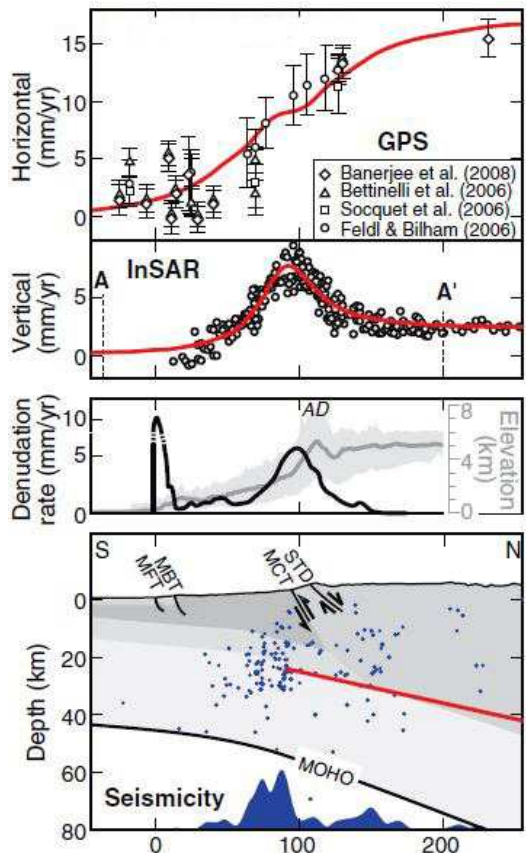
Last 15–20 Myr : 13–19 mm/yr (Mugnier and Huyghe, 2006)

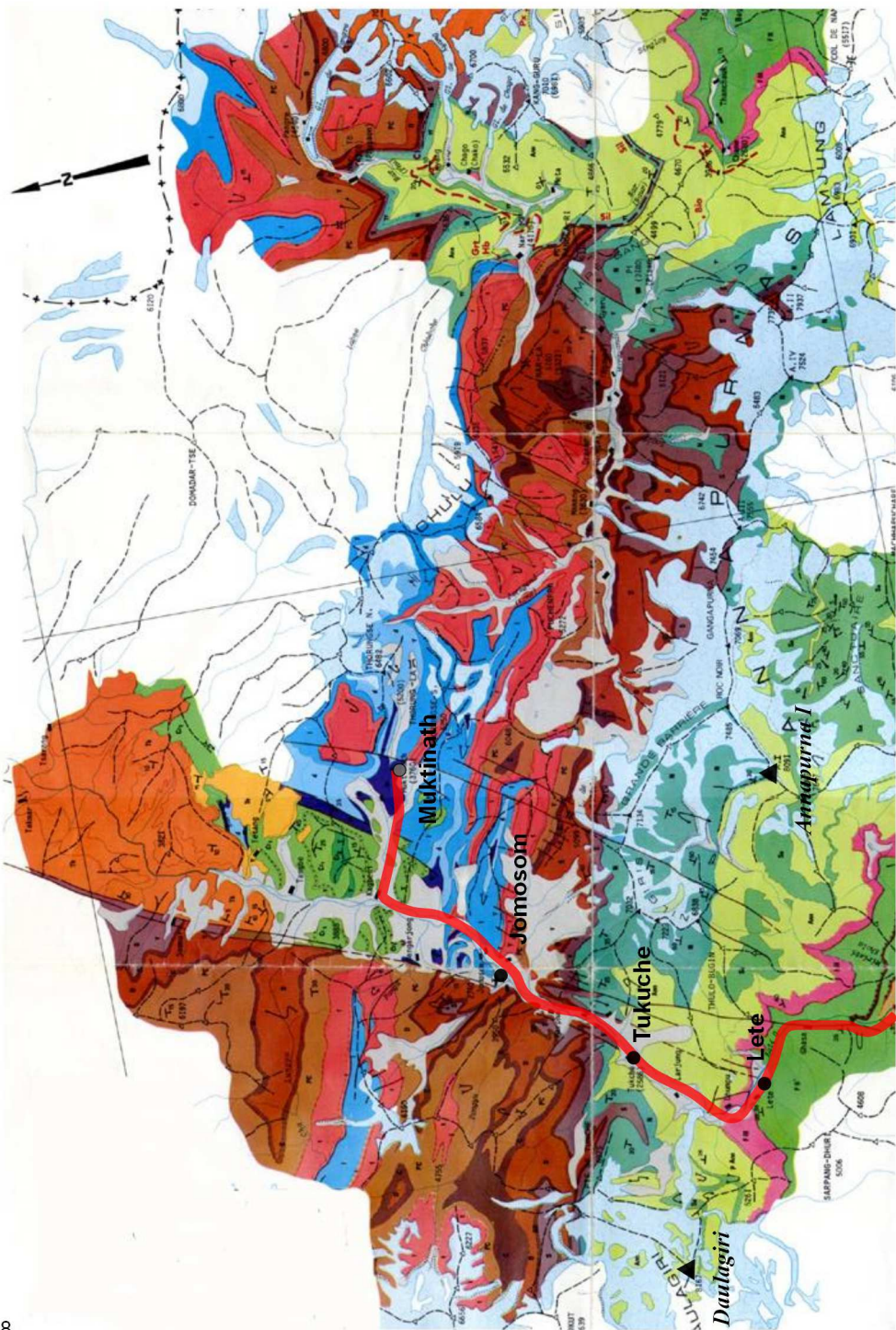
Holocene rate : 21 ± 5 mm/yr (Lavé and Avouac, 2000)

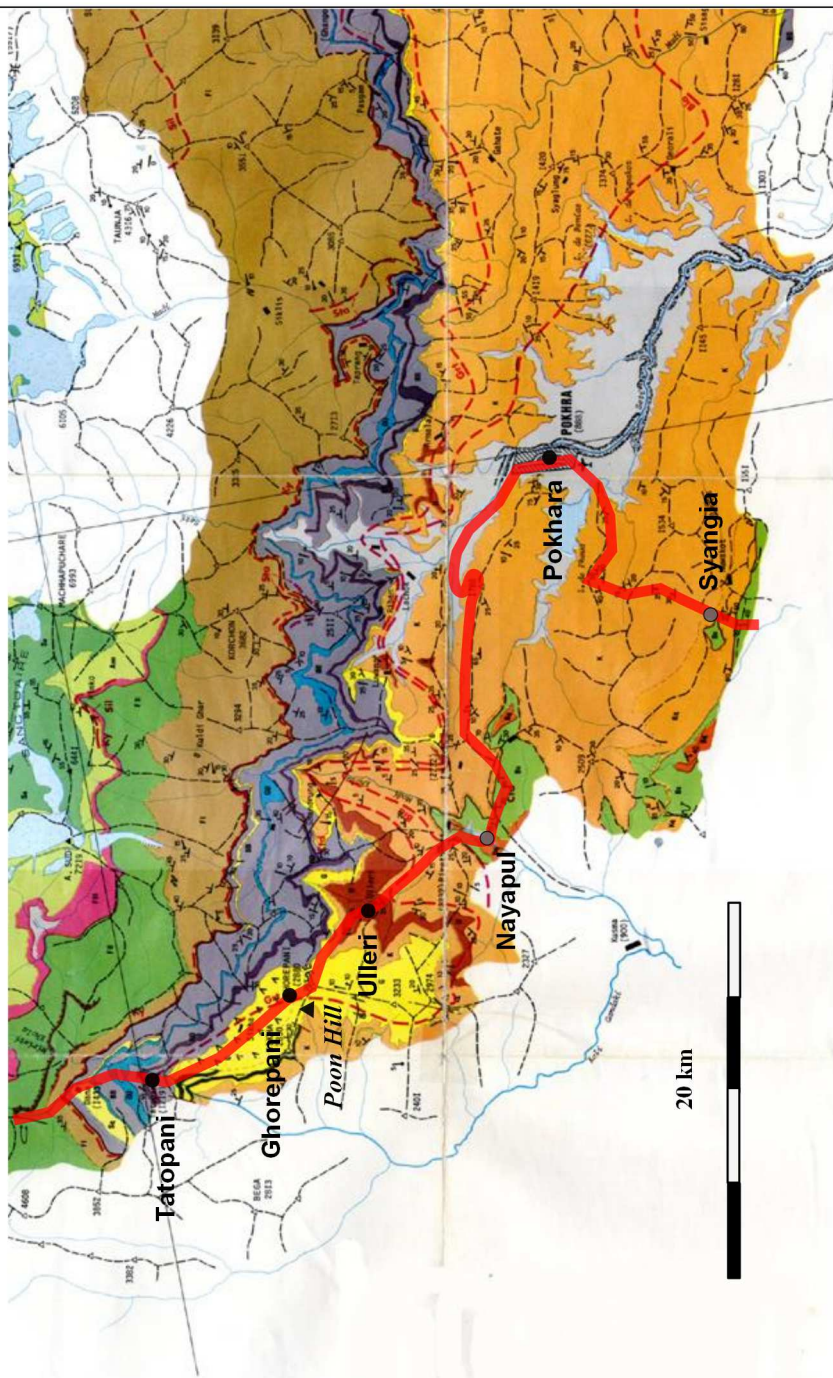
Geodetic rate : 19 ± 2.5 mm/yr (Bettinelli et al., 2006)

Vertical interseismic uplift in Nepal (fig)

Interferometric synthetic aperture radar (InSAR) measurement of the vertical velocity. Velocities are color coded from blue (subsidence) to red (uplift). White circles represent the microseismic activity between 2000 and 2008 recorded by the National Seismological Center of Nepal. Small and large white triangles indicate the locations of the peak with elevation above 7200 m and above 8000 m respectively (Grandin et al., 2012).

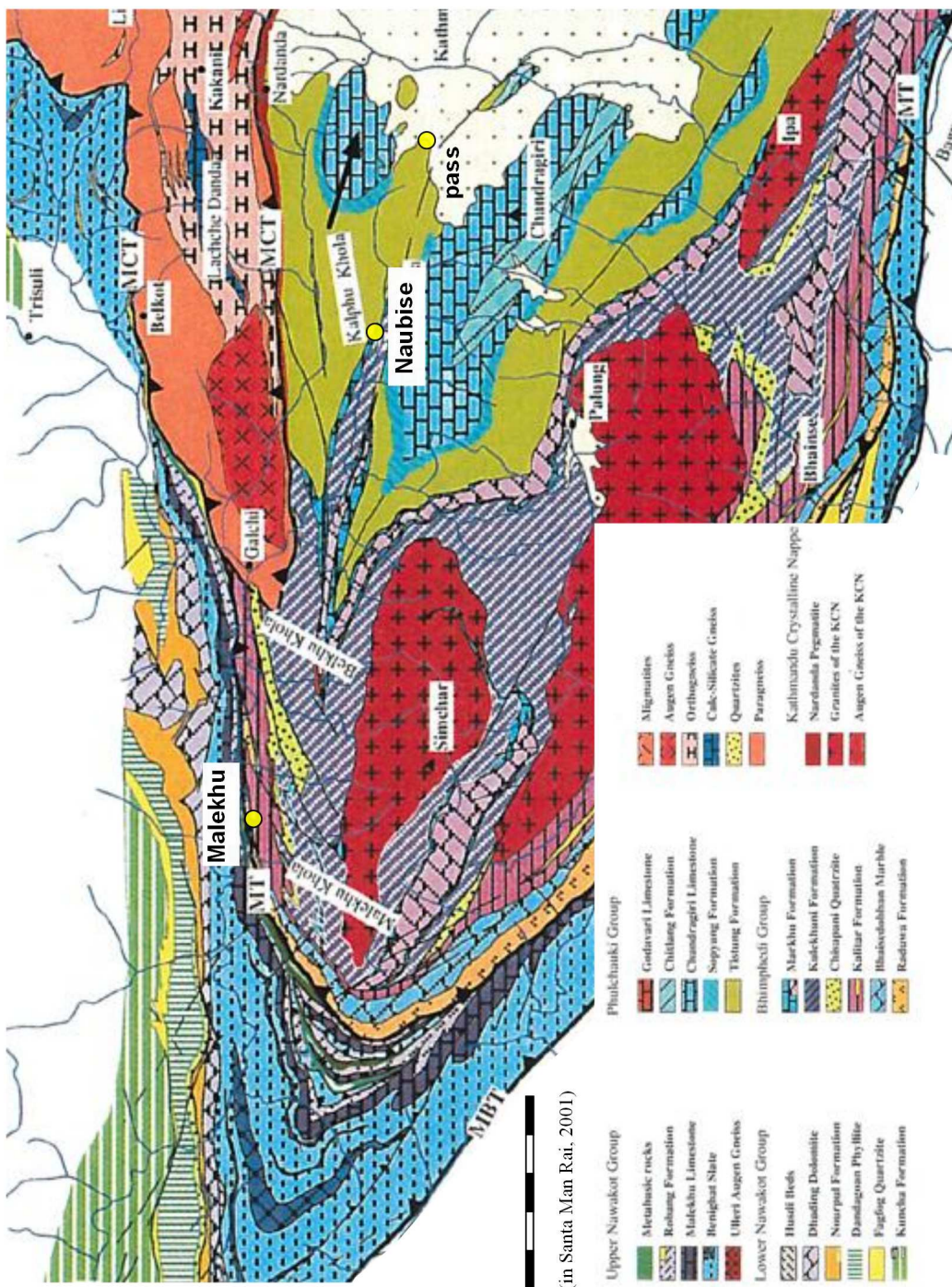






Part of the geological map of Central Nepal (Colehen, Le Fort, Pecher, 1980). Legend at the end of the guidebook. This old map probably remains the most reliable comprehensive map of the Annapurna area. It is lacking some important features. Particularly neither the NHF (over the augengneiss of Formation 3 of HHC, in pink) nor the Munsiri thrust (above the Kunchha Formation, in ochre) are underlined.

Note : the geographical North is 10° left of the top of the page. The maps given in the daily description are turned to the right position.



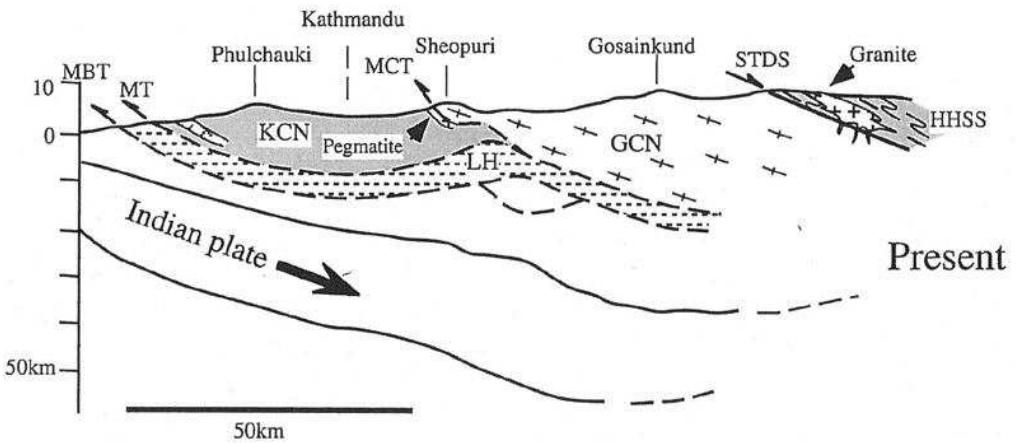
(in Santa Man Rai, 2001)



The heavily urbanized valley of Kathmandu corresponds to lacustrine deposits. From the small pass through which the road exits the Kathmandou valley, we follow a tributary of the Trisuli Gandaki, then the Trisuli itself (one of the main river which cut across all the High Himalaya). During all this way, the road follows a syncline, narrowing eastwards. Mainly gneiss outcrop : they form all the base of the crystalline Kathmandu nape.

Below the Kathmandu nape, the detrital sediments (sandstones, shales and quartzites) and carbonaceous sediments belong to the Proterozoic Nawakot Formations.

The foliation and/or the bedding is nearly vertical. We are in the southern limb of a broad anticline, the Kunchha-Gorka anticlinorium. Down to Mugling, the road runs nearly along the strike, i.e. follows more or less the contact between the Nawakot Formation to the north and the Kathmandu nappe to the south. This contact is quoted as the Main Central Thrust on most of the maps and sections, but actually it better corresponds to the Munsiri thrust.

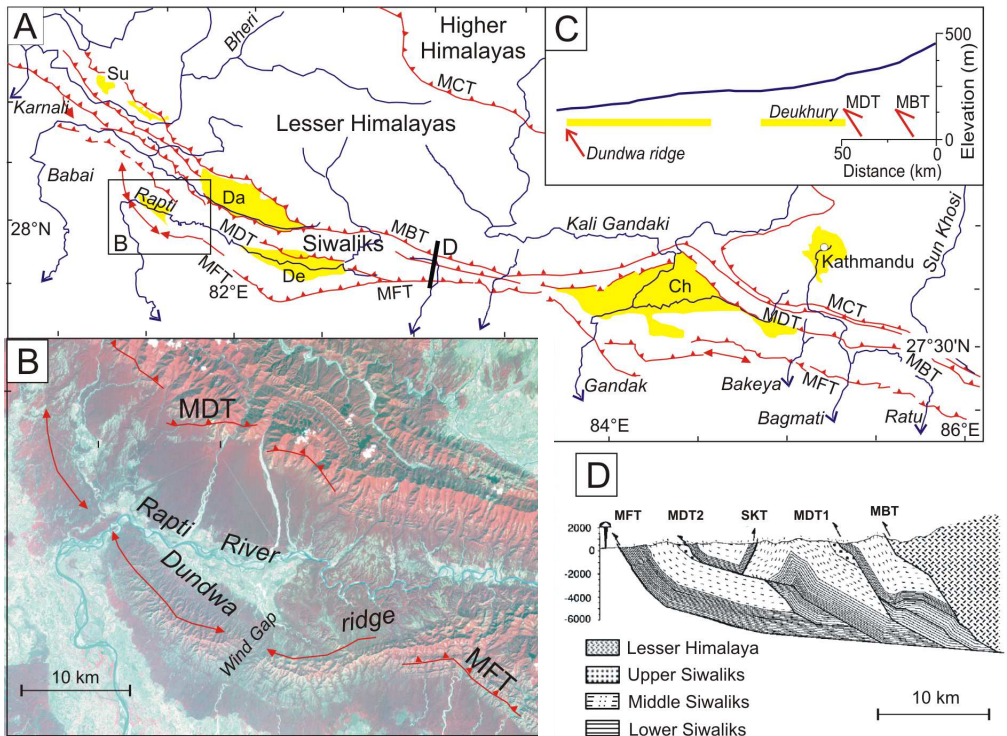


1-1 ($28^{\circ}46.76'$ / $84^{\circ}26.58'$ / 300m, road from Muglin to Narayangadh)

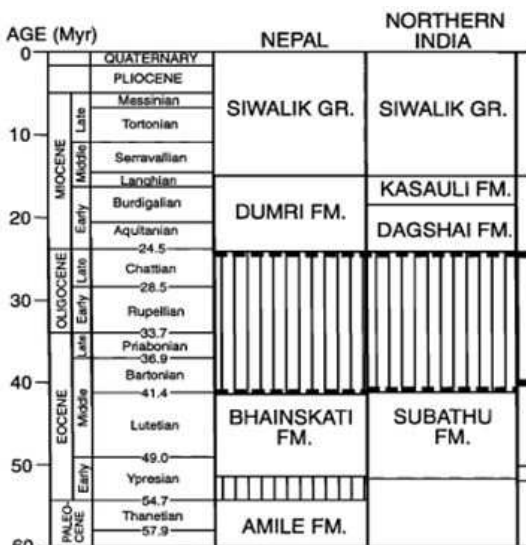
The road cross the Main Boundary Thrust, between the Lesser Himalaya Proterozoic formations and the Siwaliks Miocène formations. A rather poor outcrop, with the dolomites of the Lessert Himalaya overthrust on the Siwaliks sandstones.

1-2 ($27^{\circ}33.11'$ / $83^{\circ}50.53'$ / 540m, road from Narayangadh to Butwal)

At a small pass of the road, a nice view on the Ganga plain and the internal "dun" depressions



Above A : Simplified structural and drainage map of Central and Western Nepal (from van der Beek, et al., 2002) showing major thrusts (MCT - Main Central Thrust, MBT - Main Boundary Thrust, MDT - Main Dun Thrust, MFT - Main Frontal Thrust), fault-propagation folds (arrows), rivers and Quaternary piggy-back basins (Su- Surkhet, Da - Dang, De - Deukhury, Ch - Chitwan). *B* : detail of SPOT image showing termination of Dundwa ridge in two active fault-propagation folds (Rapti area). *C* : Long profil of axial segment of Rapti river. *D* : Balanced cross-section through the Siwalik belt, close to Surai Khola (Mugnier et al., 1999). Location of cross-section indicated in A.



Left The stratigraphy of the foreland basin Sub-Himalaya (from DeCelles et al., 1998)

The foreland basin sediments (fig) are remarkably consistent along strike. Palaeocene-Eocene marine sandstones and mudstones (called the Subathu Formation in India and the Bhainskati Formation in Nepal) overlie the Cretaceous Tethys passive margin sediments (the Amile Formation in Nepal). An unconformity separates the Paleogene marine formations from overlying Late Oligocene-Pliocene rocks of the Dagshai and Kasauli / Dharamsala Fms (India) and Dumre Formation (Nepal) overlain by the Siwalik Group.

In India, both the Paleogene and Neogene parts of the succession are found in the Sub-Himalaya. In Nepal, part of the Paleogene sediments are found in the Lesser Himalaya.

The Paleogene

Provenance : Evidence of Himalayan input is clearly seen in the alluvial sedimentary rocks, since micas and zircons with Cenozoic Ar-Ar and FT cooling ages clearly reflect derivation from the rising Himalaya (e.g. Najman et al 1997, White et al 2002). Evidence of Himalayan input to the unconformably underlying marine sequence is more sparse, but nevertheless recorded by Cenozoic ZFT ages (e.g. Najman et al 2005).

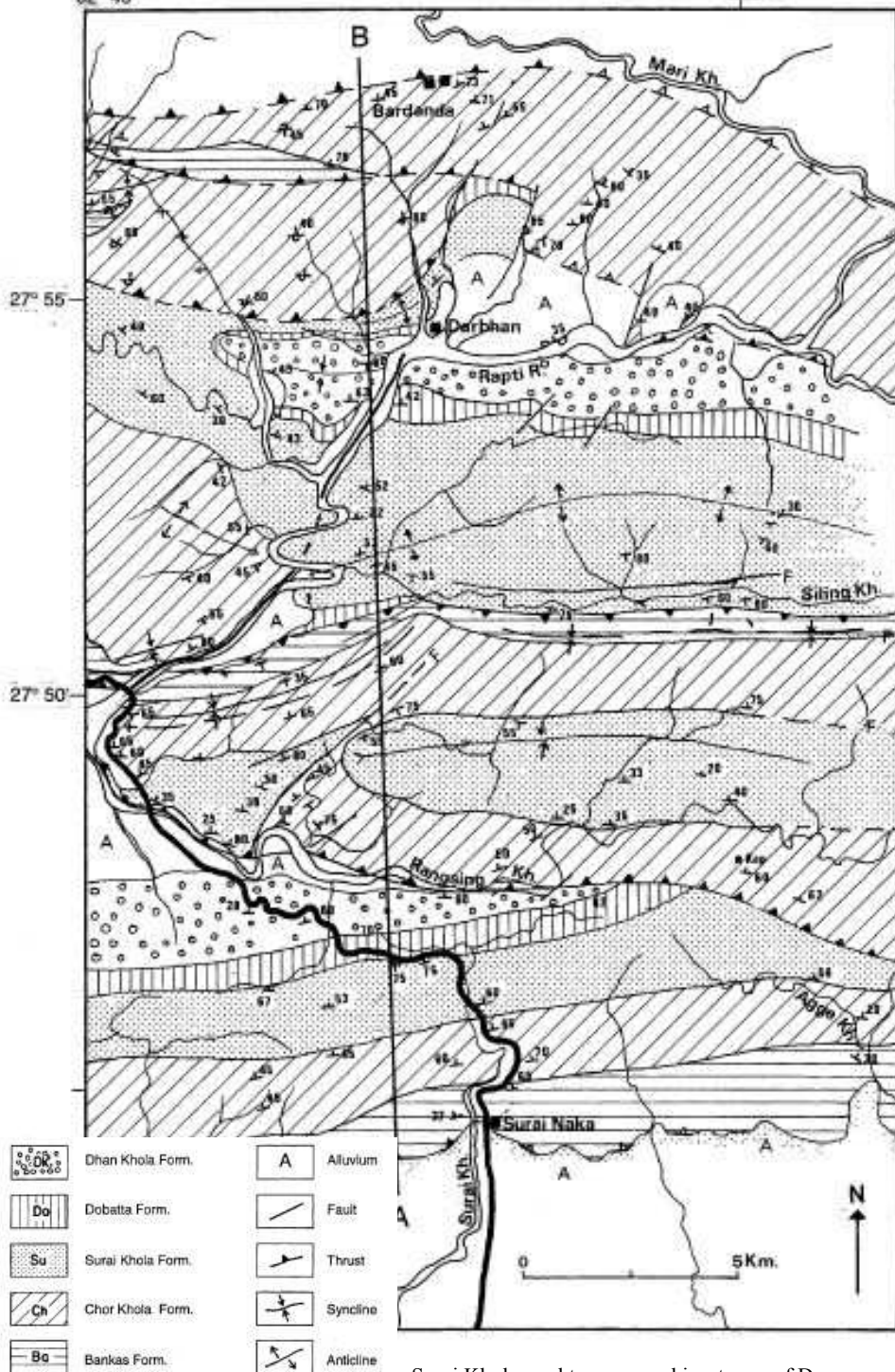
The Neogene

The Siwalik Group of Nepal (15.8 - 1 My) represents a typical fluvial fining-upward succession, with the lower unit (Lower Siw.) consisting of fluvial channel sandstones alternating with oxidized calcareous paleosols, the middle unit (Middle Siw.) consisting of very thick channel sandstones and drab-colored histosols, and the upper unit (Upper Siw.) comprising mainly gravely braided river deposits (De Celles et al., 1998; Nakayama and Ulak, 1999). Such a trend is clearly illustrated along the Surai Khola section (p. 12).

Provenance : Nd-isotope geochemistry demonstrates that the detrital input to the Siwalik foreland basin was predominantly derived from the erosion of formations analogous to the modern Higher Himalaya (France-Lanord et al., 1993). A higher proportion of input of Lesser Himalaya material (about 30 %) started abruptly at 10 My as a response to initiation of the Lesser Himalayan Thrust system at about 12 My (Huyghe et al., 2001).

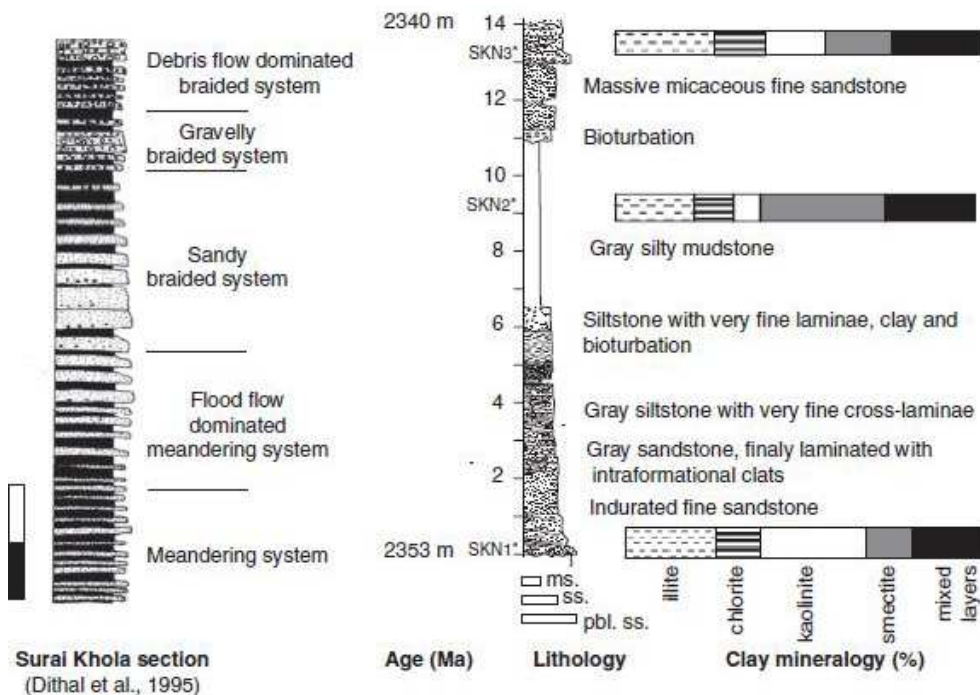
Tectonics and exhumation : The Sub-Himalaya domain is limited by the Main Boundary Thrust to the north and the active Main Frontal Thrust to the south. It is affected by several thrusts that branch off the main décollement, which lies at a depth of 4-5 km (Fig. p.12, top,D). Following the Himalayan forward propagation, the Main Frontal Thrust has been active since 1.8-2.4 Ma (Mugnier et al., 2004) as also evidenced from Apatite Fission Track data (Fig. p. 17, van der Beek et al., 2006) although numerous out-of-sequence reactivations have been reported (Mugnier et al., 2004).

Weathering of silicates : Clay mineralogy shifted from illite-rich to smectite-rich deposits at about 7 My (Huyghe et al., 2005), similar to the trend reported in the Bengal Fan (Bouquillon et al., 1993). It has been shown from the present-day distribution of clay minerals that smectites preferentially formed in paleo-floodplains during early diagenesis because of downward percolating fluids rich in cations from weathering and soil development (Huyghe et al., 2011). Higher proportions of smectite therefore mark increasing weathering of silicates linked to increasing seasonality at about 7 My.

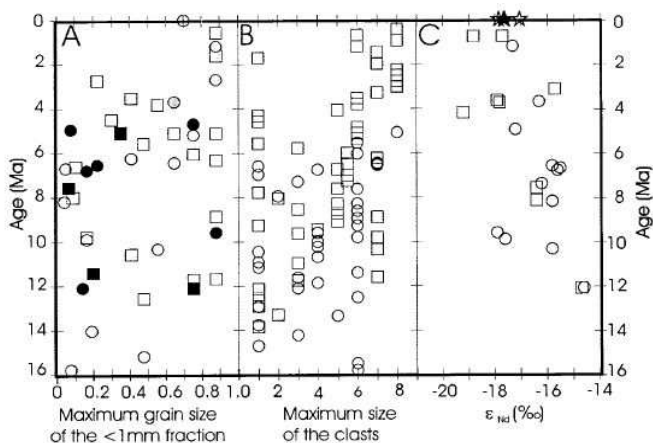


Surai Khola road traverse and inset map of Dang-Dcokhuri Dun valleys (in Corvinus and Rimal, 2001)

Clay minerals and ages in the Siwaliks

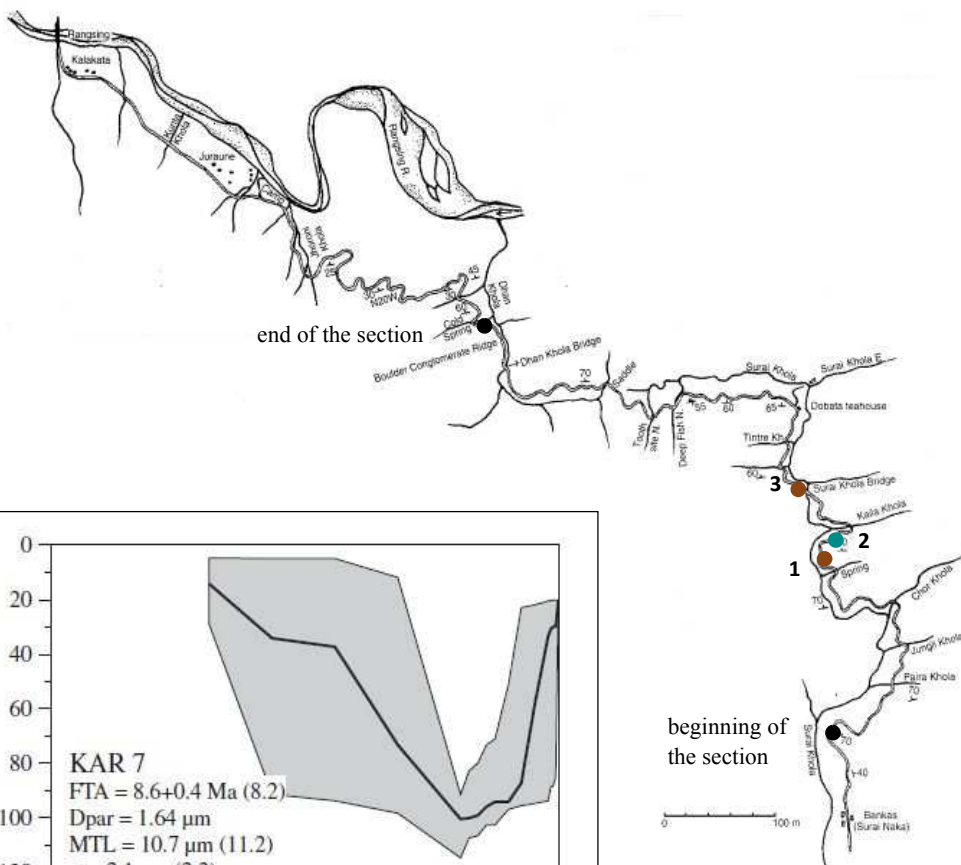


Above : (a) Lithology of the Surai Khola section (Dithal et al., 1995) with depositional environments and fluvial style from Nakayama & Ulak (1999) (vertical scale bar : 1000 m); (b) Stratigraphic log of an individual Siwalik fluvial succession along the Surai Khola section; ms, mudstone; ss, sandstone; phi. ss, coarse pebble sandstone. Clay-mineral proportions are given for basal coarse sandstone and mudstone samples (in Huyghe et al., 2011)



Left Time evolution of Nd isotope composition, maximum grain size, and sedimentary facies of Surai Khola (squares) and Karnali River (circles) sections. A : Maximum grain size of <1mm fraction of mudstones (black symbols), sandstones (open symbols and conglomerates (gray symbols). B : Maximum size of clasts of macroscopic scale. Horizontal scale is (1) clay, (2) silt, (3) fine

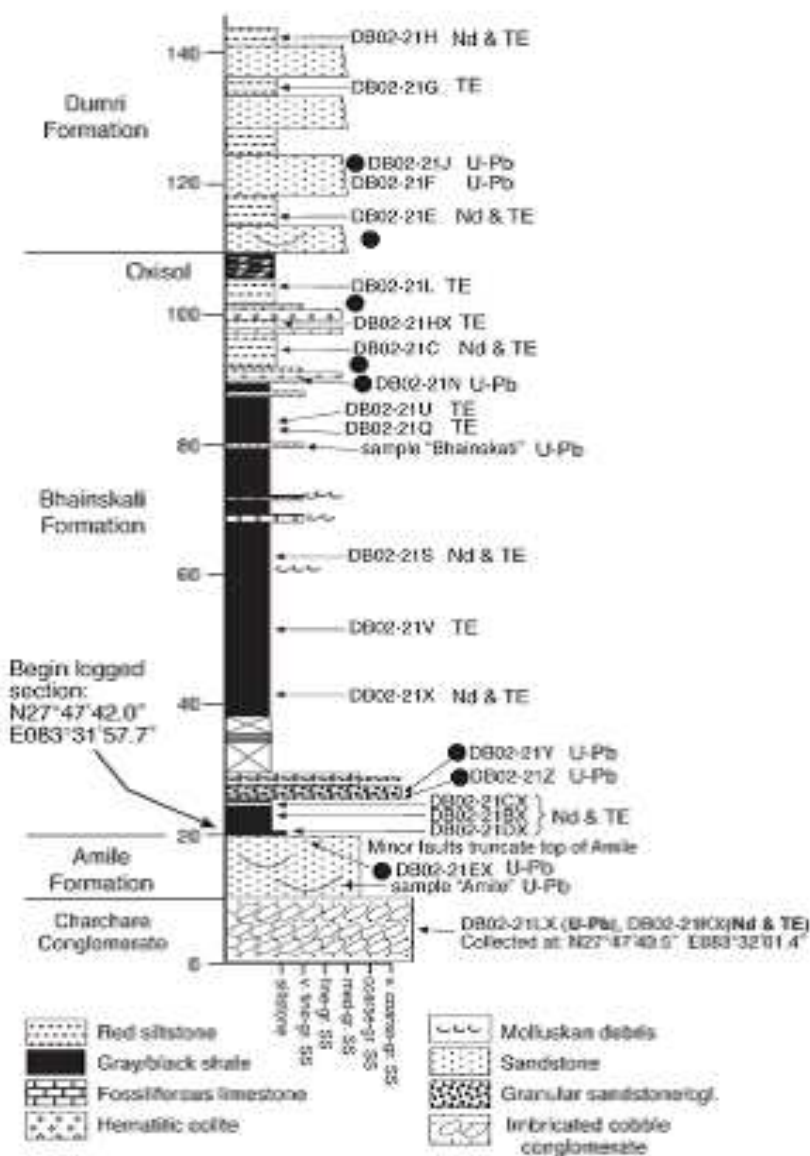
sand, (4) medium sand, (5) coarse sand, (6) gravel, (7) cobble, and (8) large cobble. C: Nd-isotope composition. Stars refer to sediments in modern rivers (open stars for modern Siwalik rivers and black stars for Ganga sampled in Bangladesh) (Huyghe et al., 2001)



Surai Khola road traverse
(Corvinus and Rimal, 2001)

2-1 ($27^{\circ}45.80'N/82^{\circ}50.31'E$)
 2-2 ($27^{\circ}45.91'N/82^{\circ}50.387'E$)
 2-3 ($27^{\circ}46.18'N/82^{\circ}50.20'E$)
 A part of the section with very good exposures. At point 2, a metric level of sandy limestone (53% of CaCO_3), quite surprising in such a series.

Thermal history for a partially reset sample from Karnali river section (west of Surai Khola) (van der Beek et al., 2006). The thick line is the best-fit model, the shaded area corresponds to acceptable model fits. FTA : measured apatite fission-track age, MTL : mean track length, and σ : standard deviation of track length, compared with the best-fit model predictions in parentheses. The thermal history indicates heating from the time of deposition until app. 2 My, followed by a phase of thermal stability or slow cooling, and a final phase of very rapid cooling from app. 0.3 My onward. The strong acceleration of cooling at app. 0.3 My is consistent with the passage of rocks from the basal décollement onto the MFT ramp during exhumation.



Sedimentary log of the Palaeogene section at Dumri bridge (DeCelles et al, 2004)

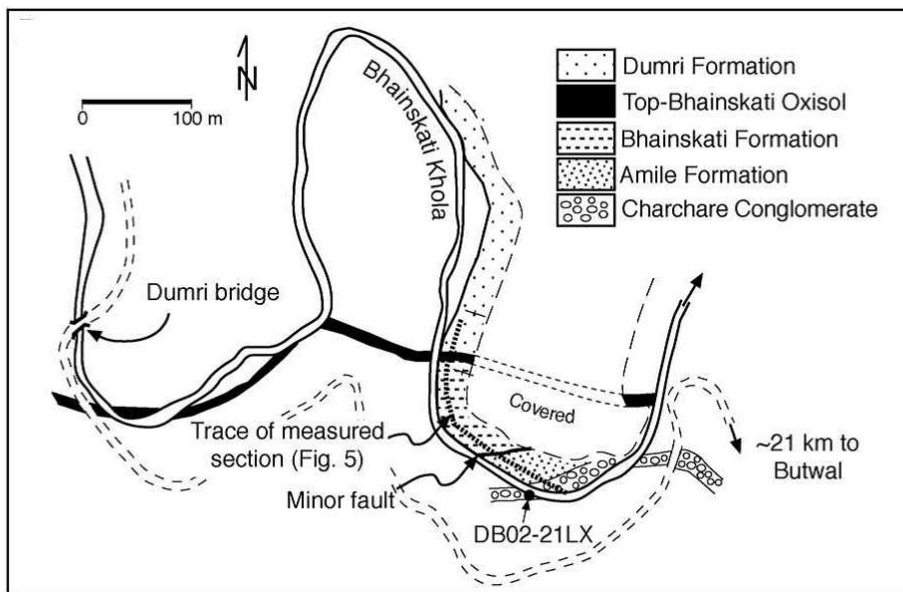
Butwal

(28°41.91N / 83°27.92E / 365 m)

Pokhara

(28°11.97N / 83°58.70E / 835 m)

distance: 157 km



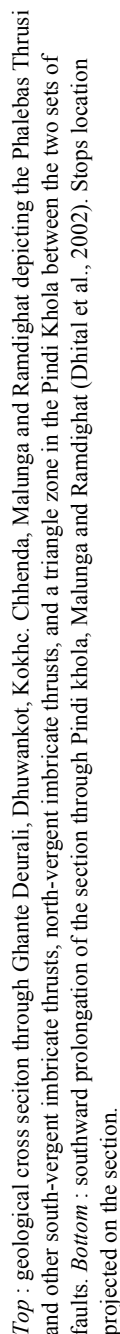
The distinctive oxisol seen at the basin wide unconformity

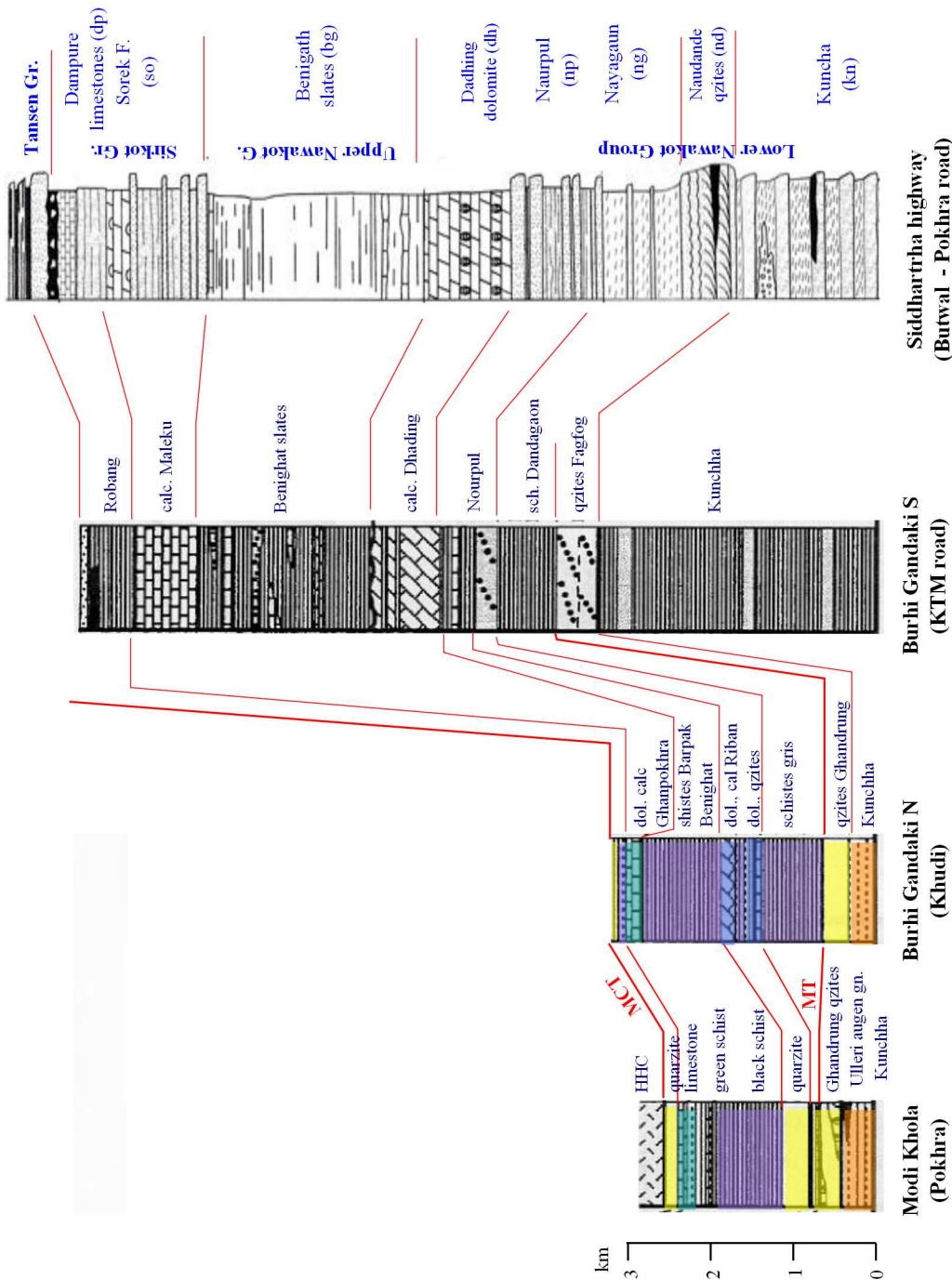
3.1 Section at Dumri bridge (21 km N of Butwal)
 (Parking at 27°47.69'N / 83°31.68'E / 670 m -
 beginning of the path to the section : 27°47.63'N /
 83°31.96'E - section : 27°47.75'N / 83°31.96'E)

This is the classic section, first described by DeCelles et al (1998), with further work published in DeCelles et al (2004) and Najman et al (2005). Above : a sketch map of the location; left page : detailed sedimentary log; left photo : the distinctive oxisol which marks the unconformity.

It is at this location that DeCelles et al (1998) proposed his theory that the basin wide unconformity here clearly marked by an oxisol, is the result of southward passage of a peripheral forebulge over the Eocene sediments that were deposited in a backbulge depozone. It is also here that first evidence was found of Himalayan input in the Eocene marine sediments, as documented by the presence of Cenozoic zircon fission track ages (Najman et al 2005).







The lithostratigraphy of the Lesser Himalaya is quite variable and remains ambiguous. Characteristic and constant key horizons are lacking. There are hardly any fossils present, and they are poorly dated. The variability of the Lesser Himalaya is shown by the rocks found : in the south of the Kunchha anticlinorium, far from the MCT, they are non metamorphic and little deformed, whereas they are deformed and metamorphosed in the northern limb of the anticline. The amount of local nomenclature makes it even more complicated and confusing.

Nevertheless Central Nepal can be divided into two major lithological groups:

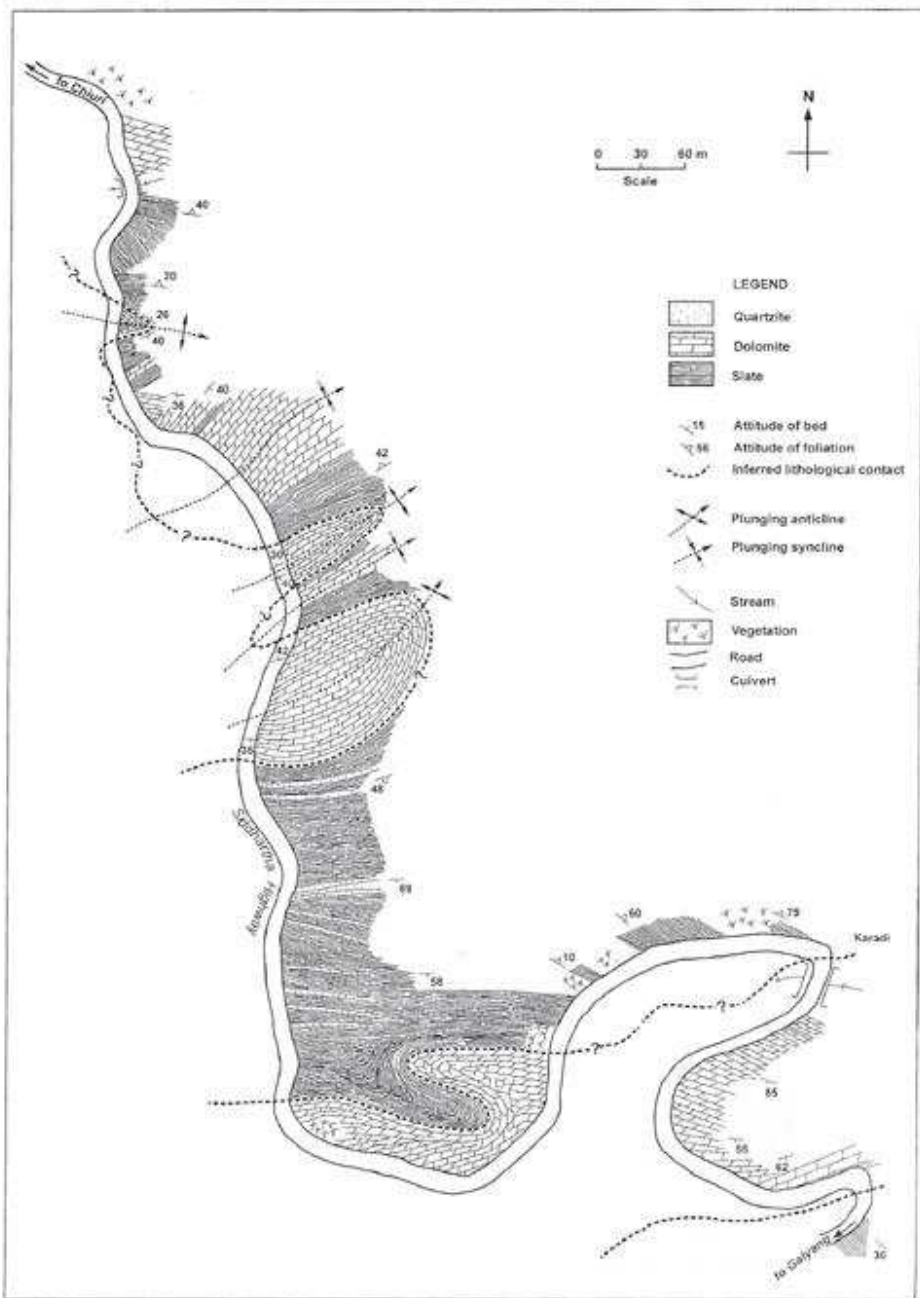
- A lower detrital unit, thick (several km), comprised of 95% of Proterozoic sandstones and reworked felsic volcanogenic sediments, with some amphibolite lenses (tholeiitic basalts) in between. In the northern limb of the anticline of Kunchha, a big sill/laccolith of porphyric granite (ca 1850 Ma) is changed to an orthogneiss (the Ulleri augen gneiss). At the base of Kunchha there is also a small massif of nepheline syenite (not dated) which only outcrops in Arugath area (East of Gorkha).

- A higher, more variable unit with several carbonaceous schist, dolomites and limestones very poorly dated in Nepal, probably mainly Upper Proterozoic to Carboniferous-Permian. Only the limestones of Dhading are dated with Cambrian fossils. There seems to be an important discontinuity between the Upper Cambrian and the Carboniferous.

In Central Nepal, these two units seem to be stratigraphically continuous in the South of the Kunchha anticline, whereas in the North they are probably separated by an important thrust, equivalent to the Munsiri thrust (known in Garwhal, a part of the MCT system).

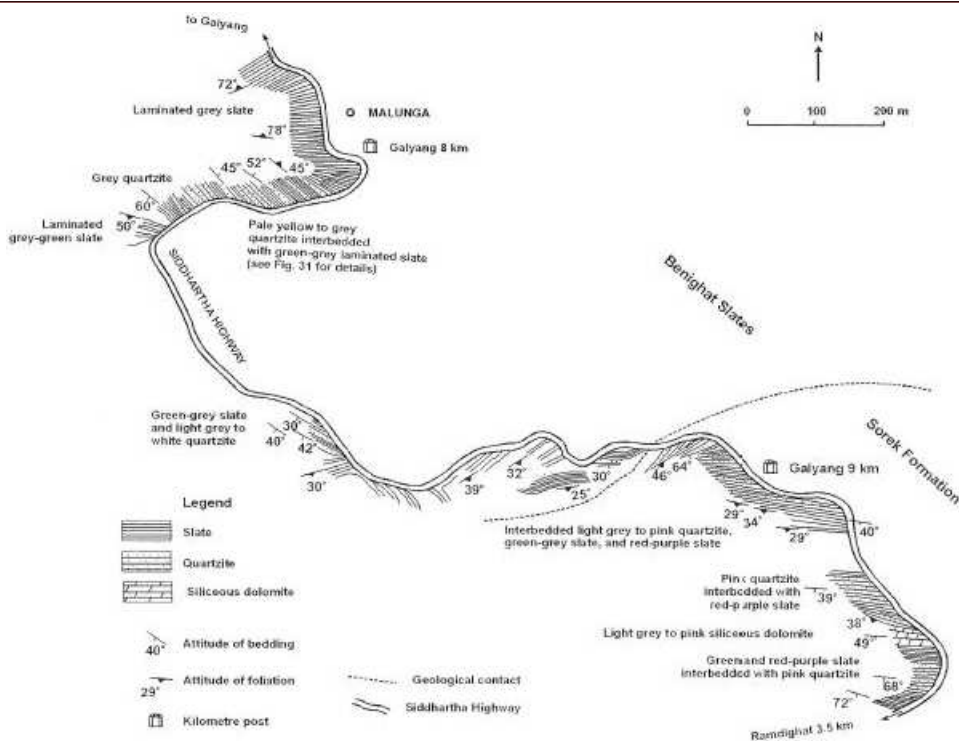
For Kohn et al. (2010), the basal part of the Lesser Himalayan sequence represents the edge of a 1850 +/- 50 Ma continental arc, based on whole-rock chemistry and geochronology. Felsic orthogneisses ("Ulleri", 1780 Ma) within the Lesser Himalayan sequence probably do not represent Indian basement but rather relatively shallow intrusions in an arc edifice and associated sedimentary pile.

The figure here above shows two lithological logs in the northern limb of the Kunchha anticlinorium (following Colchen et al., 1981, colors equivalent to their geological map), and two logs south of it (Kathmandu road, Upreti, 1999 and Butwal road, Dithal et al., 2002). For these last authors, the main contact between Upper and Lower Midlands series (between lower and Upper Nawakot Groups) is not located at the top of the Naudanda (Ghandrung) quartzite, as previously accepted, but higher up.



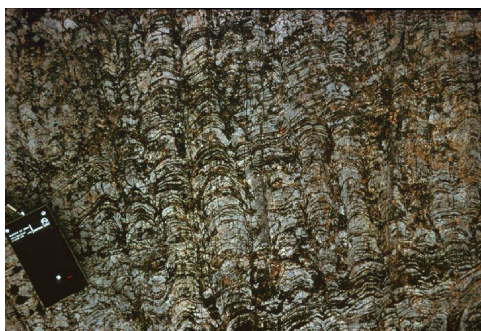
Stop 3.3 - Mesoscopic folds in the Dhading Dolomite and Benighat Slates, on the Siddhartha Highway between Karadi and Chiuri (in Dhital et al., 2002, fig. 27)

3.3 The Proterozoic series (Dhading dolomites and Benighat slates). Road north of Galyang, after Karadi ($27^{\circ}57.31'N$ / $83^{\circ}42.70'E$ / 7855 m, approx. 40 km N of Butwal). The Dhading dolomite and the Benighat slates are highly folded. Divergent axis-directions of the folds.

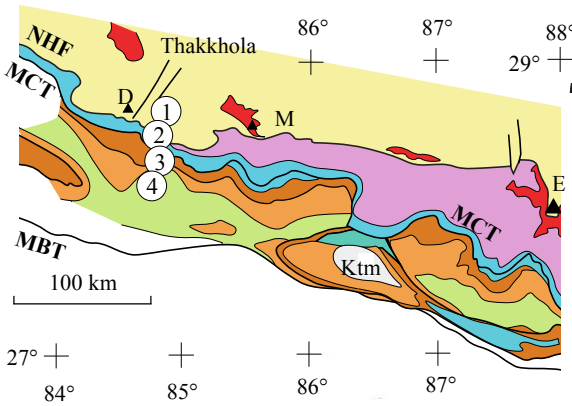


Stop 3.2 - Route map showing a transitional contact between the Benighat Slates (north) and Sorek Formation (south) at Malunga. Notice the appearance of light grey to white quartzite in the upper part of the Benighat Slates at Malunga, and red-purple and green slates and quartzites towards the south in the Sorek Formation. (in Dhital et al., 2002, fig.30)

3.2 The Proterozoic series (Sirkot group and Upper Nawakot group). Road from Ramdighat to Malunga ($27^{\circ}54.90'N$ / $83^{\circ}39.61'E$ / 505 m, approx. 40 km N of Butwal)

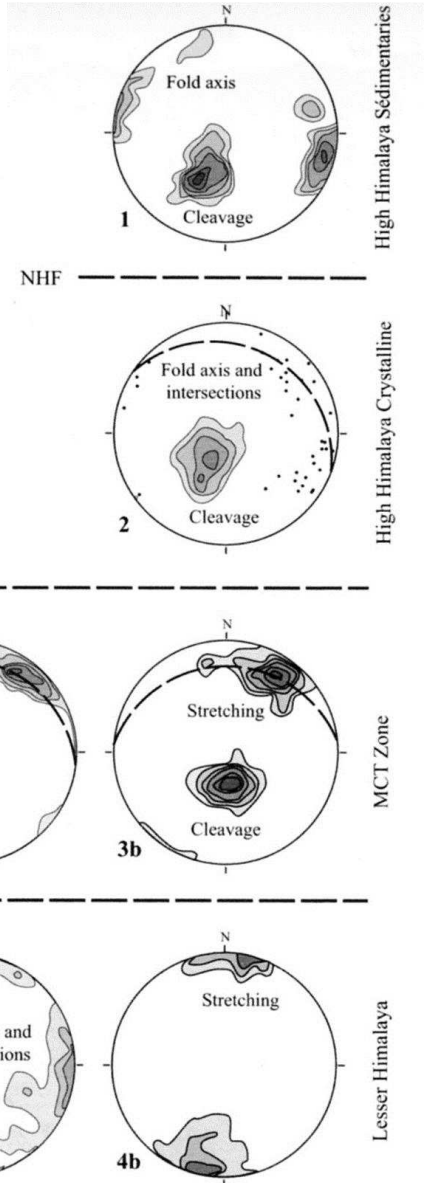


Stromatolites in the Dhading limestones (ph. AP)

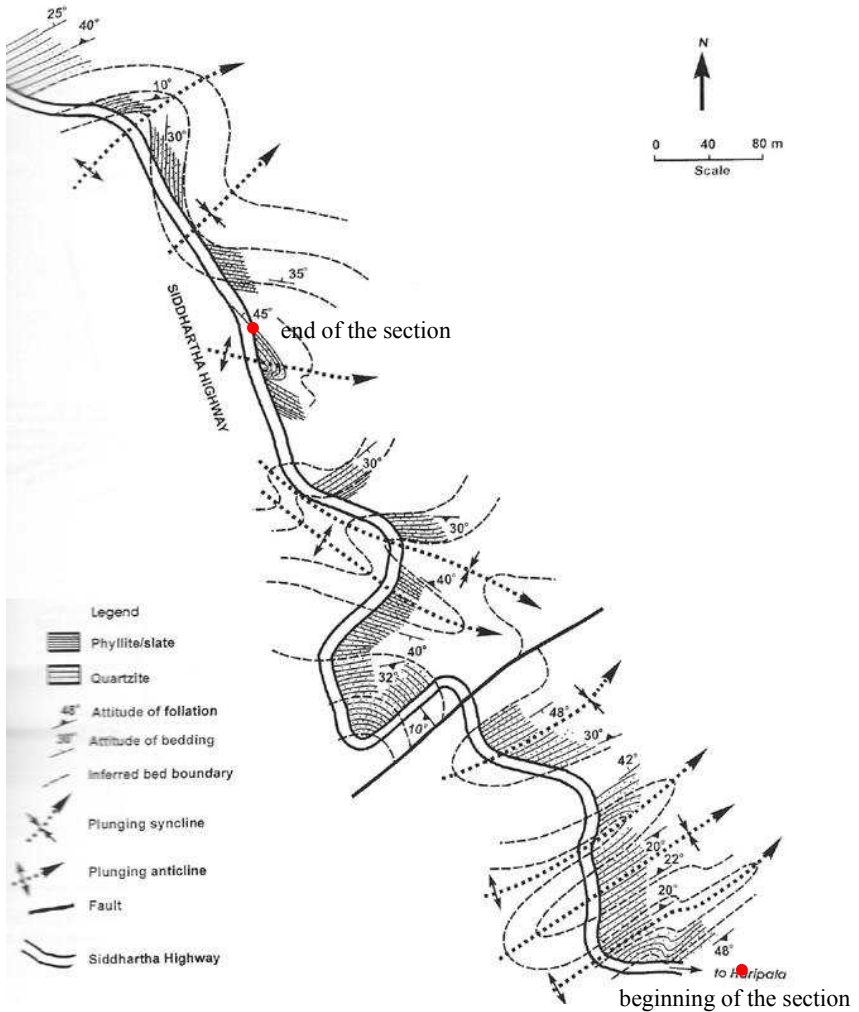


- grenat-staurolite-kyanite
- (chlorite)-biotite-garnet
- chlorite-biotite-(chloritoid)
- chlorite
- very lowgrade metamorphism

Evolution of the structures across the metamorphic Himalayan core

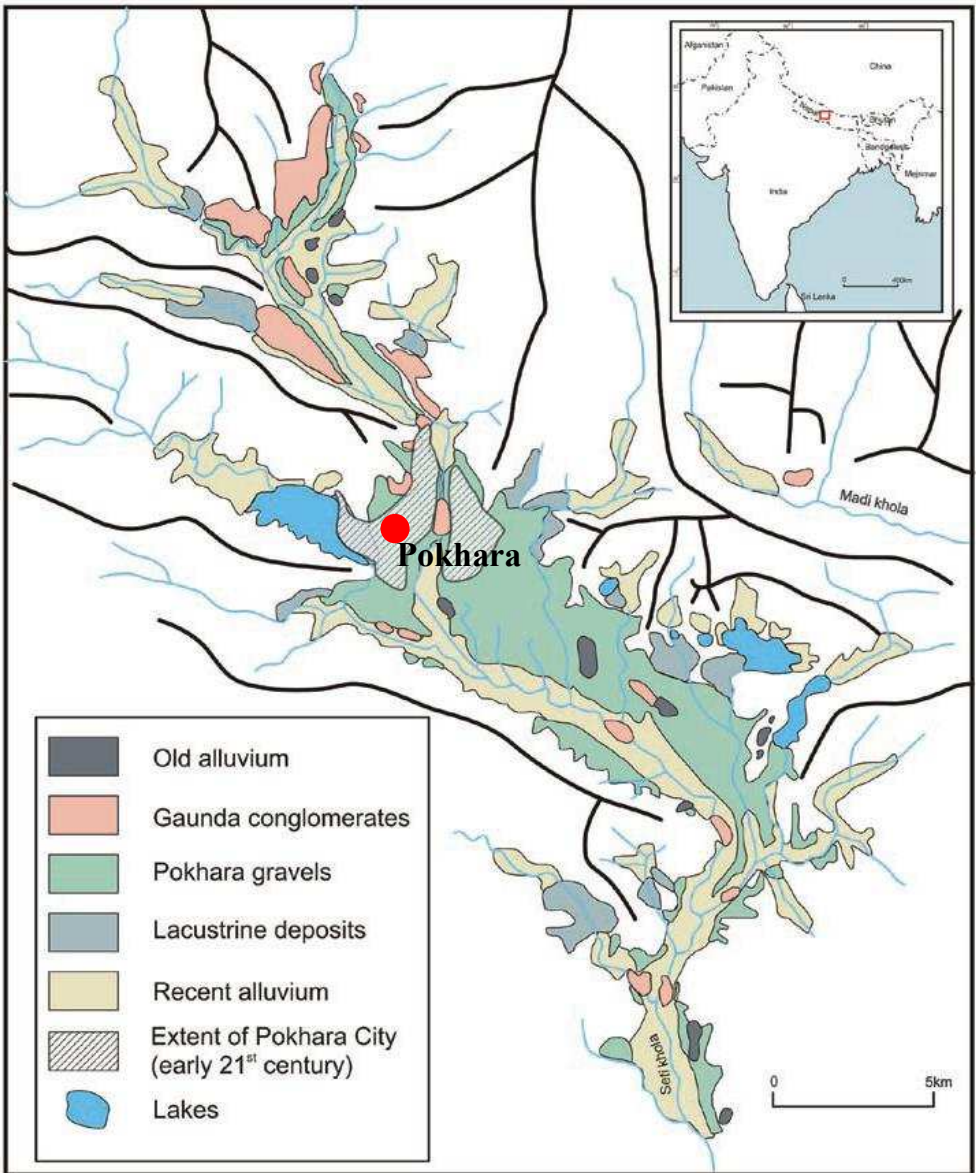


Stereograms of microstructures observed along the Lumbini cross-section (Siddartha Highway) and in Annapurna area (in Mascle et al., 2012)



Geological route map of the Siddhartha Highway between Naudanda and Haripala depicting the contact between the Naudanda quartzite and the Nayagaun Formation. Note that the pelitic band gradually increases from north to south, and there are many mesoscopic plunging folds (in Dhital, 2002)

3.4 Siddhartha highway between Syangja and Naudanda ($28^{\circ}7.71'N / 83^{\circ}52.03'E$ to $28^{\circ}7.82'N / 83^{\circ}51.83'E$ / 1030 m, appr. 35 km to Pokhara). The southern limb of the Pokhara-Gorka anticlinorium. As at stop 1.3, emphasis can be put on the orientation of the numerous folds, and orientation and meaning of the lineation (intersection and/or stretching lineation).



Map of the Pokhara valley deposits (Fort, 2010)

The Pokhara valley is an abnormally broad plain (125 km²), drained by the Seti khola. Its characteristics are those of a large alluvial outwash fan. The present, large-scale morphology of the valley is the result of a complex alternation of aggradation and erosional stages, developed under a tropical, seasonally contrasted climate. In fact, the Pokhara valley has experienced several stages of dissection, separated by brief, yet intense periods of aggradation

The Pokhara basin



Northern part of the Pokhara valley, in front of the Annapurna IV (7524m) (Ph AP). The Seti Khola, in the foreground, is responsible for the accumulation of the indurated Gaunda conglomerates, which underlie the two highest very flat terrace levels, for the catastrophic accumulation of Pokhara gravels, deposited about 500 years ago, and for their recent dissection in several terraces (Fort, 2010).

The youngest aggradation episode is represented by a sudden, widespread, 4 km³ fanglomeratic deposits (the Pokhara gravels) that buried a differentiated, terrace-shaped topography, dammed the adjacent valleys and created lakes behind the filling.

The Pokhara gravels consist of a rapid succession of beds, decimeters or meters in thickness, with predominantly flat basal contacts. The material is mainly composed of layered mostly calcareous gravels, centimeters to decimeters in size, embedded in a muddy calcareous matrix. Blocks of a meter or more in size - mostly gneisses (Higher Himalaya) or quartzites (Lesser Himalaya) - can also be found randomly within the whole accumulation package. The volume of Pokhara gravels (estimated as >4 km³) and their dating between 400 and 1.100 ¹⁴C years suggest the occurrence of a short-lasting, historical event that led to the rapid filling of the Pokhara valley by a giant debris flow and to the damming, and hence flooding of the adjacent valleys.

Ice and rock avalanches and/or dammed lake outbursts, liberating great volumes of water and debris simultaneously, most likely caused the exceptional Pokhara gravel discharge in a catastrophic way. The triggering effect of an event of such magnitude was probably related to an earthquake (the 1505 one is a good candidat), the only mechanism capable of bringing instantaneously a slope into disequilibrium and setting into motion such a huge quantity of ice and rock material.

Older than the Pokhara gravels, the **Gaunda (or Gachok) conglomerates** are the first extensive deposits in the Pokhara valley. They are explained by similar, catastrophic processes. After their deposition and lithification, they were dissected to form a stepped topography of fluvial terraces, well preserved north of the valley, whereas to the center and south of the valley, they disappear under the Pokhara gravels.

The canyons of the Seti khola

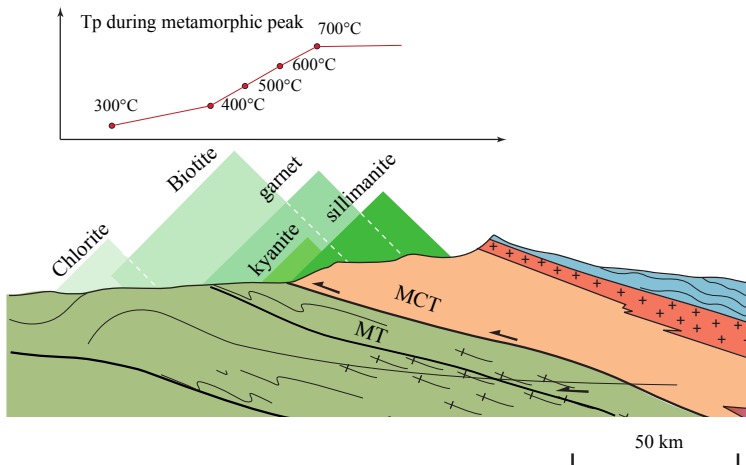
Interrupting the long sections of terraces, they occurred along a few hundred meters to one kilometer reaches and up to 50m deep. They are entrenched into the cemented gravel and boulders of the Gaunda Formation. These gorges are locally so narrow that only the sound of water can be heard: in some cases the stream has even disappeared in underground tunnels.

The Himalaya is characterised by a typical backbone of metamorphic rocks, the Higher Himalayan Crystallines. From top to bottom, the metamorphic pile can be subdivided in 3 main units :

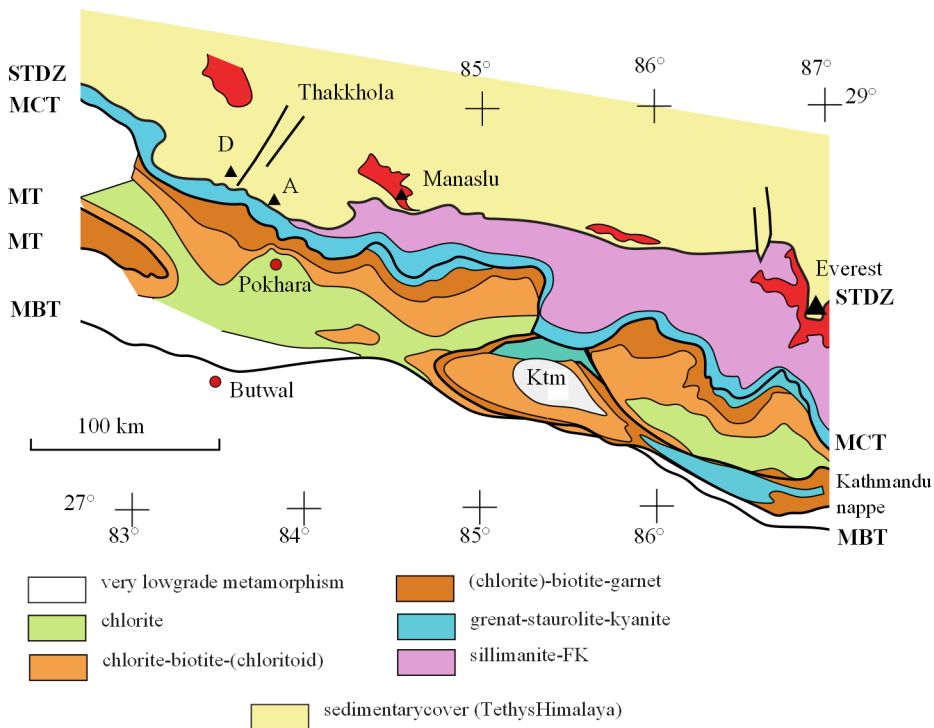
- the metamorphic base of the Tethyan series, above and north of the STDS,
- gneisses and migmatites which outcrop between the STDS and the MCT zone
- below the MCT, the northern part of the Lesser Himalaya (meta-)sedimentary formations, which are much less homogeneous, often carbonaceous and carbonate rich

The "MCT zone" is a heterogeneous shear zone, up to several kilometres thick, affecting mainly the upper series of the Lesser Himalaya. In this zone, two specific thrusts can be recognised. A main thrust, close to the top of the shear-zone, makes a fairly clear lithologic boundary between the Higher Himalayan Crystallines and the Lesser Himalaya metasedimentary formations. This is the MCT, recognised for a long time and now named either MCT 1 or, more often, MCT 2, depending on the authors. A second thrust, not always clearly expressed, follows the footwall of the MCT shear zone. We will speak of the MCT for the upper thrust, and of the Munsiri Thrust (MT) for the lower one.

In the lowermost part of the HHC and below the MCT, the tectono-metamorphic history is characterised by the inverted Himalayan metamorphism, which is observed throughout the Himalaya. Here, the Lesser Himalaya formations of higher metamorphic grade, found in the MCT zone, lie above less and less metamorphic formations southwards, as one moves down across the tectonic pile, down to the hanging wall of the MBT.



The repartition of some main metamorphic index minerals in central Nepal (in Avouac, 2007)



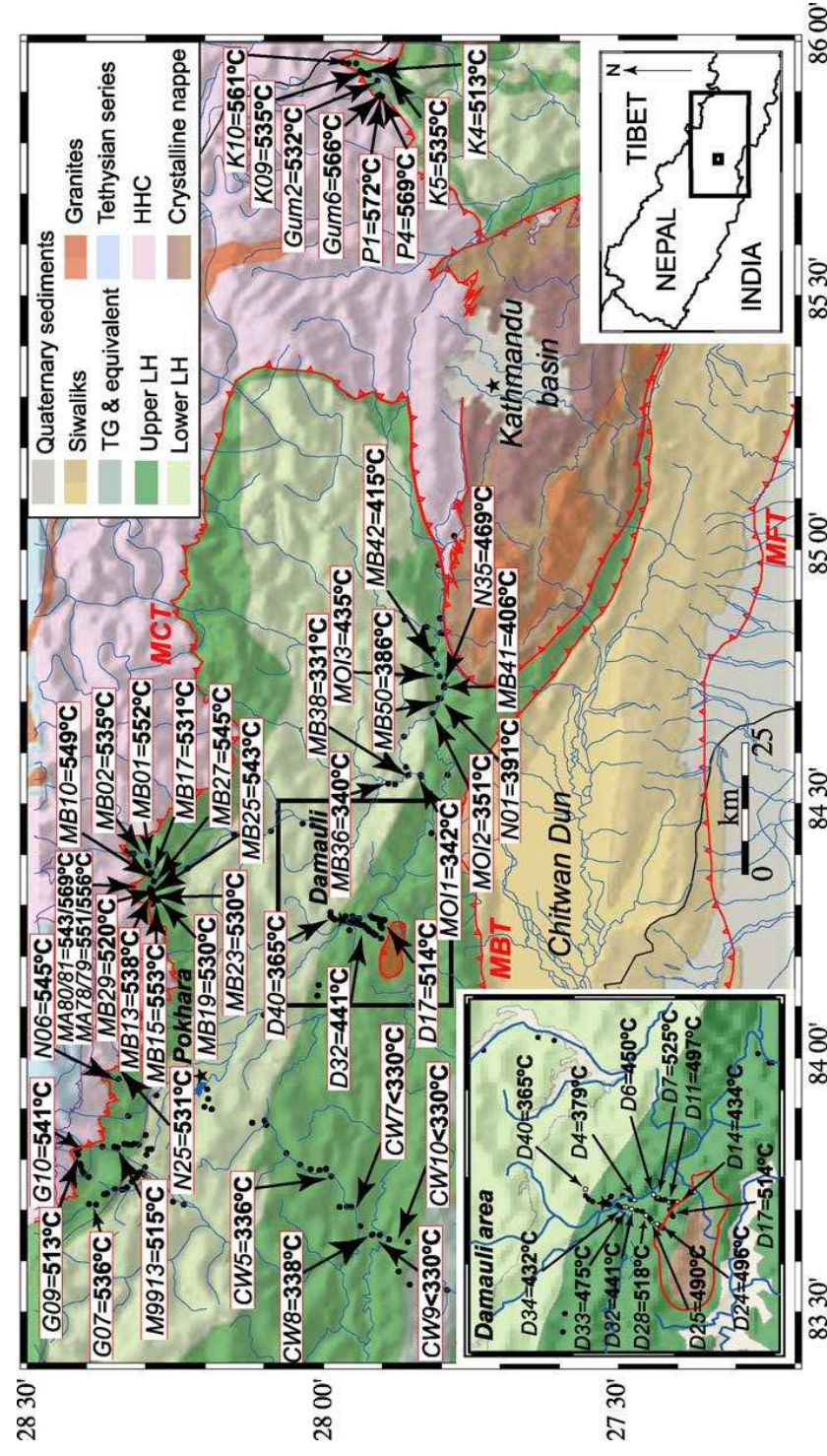
Simplified schematic map of metamorphism in Central Nepal (after Pêcher, 1989). The map clearly illustrates the parallelism between MCT (MCT, and base of the Kathmandu nappe, corresponding to MT) and the metamorphic isograds.

North of the STDZ the "normal" decrease of metamorphism is not detailed within the Tethyan Series. Here, the metamorphism reaches the amphibolite facies (hornblend-diopside) in the basal part of the sequences then strongly decreases northward.

The inverted metamorphism mainly affects the Northern part of Lesser Himalaya, in the footwall of MCT. The dip of the metamorphic foliation is regularly toward NNE. Therefore the relatively high-grade rocks (garnet or garnet-stauroilite-kyanite) are clearly superposed to less metamorphic ones (biotite and/or chlorite).

Above the MCT, one can separate two main metamorphic stages (Pêcher, 1989): Eohimalayan, since app. 35 Ma to 20-23 Ma (time of the thermal maximum), displaying a prograde evolution, followed by a retrograde evolution.

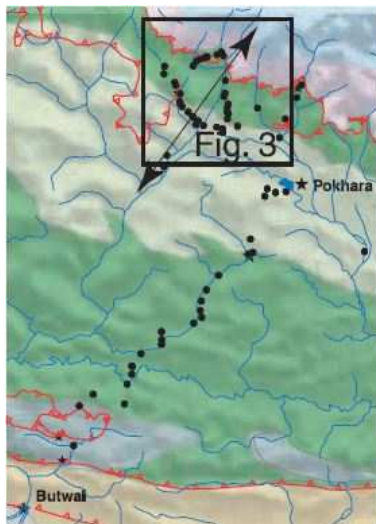
In contrast, in the footwall of the MCT, the evolution (Neohimalayan, peak metamorphism around 15 Ma) is prograde.



Geological map of central Nepal . This map shows the major tectonostratigraphic zones and tectonic contacts. For each sample: label and mean RSCM temperature are given (LH: Lesser Himalaya, HHC: Higher Himalaya Crystalline, TG: Tansen group, MCT: main central thrust, MBT: main boundary thrust, MFT: main frontal thrust). Lower-left inset: temperature data from the Damauli area. The Damauli klippe is considered as an equivalent of the Kathmandu klippe, at least for its thermal evolution (Beyssac et al., 2004)

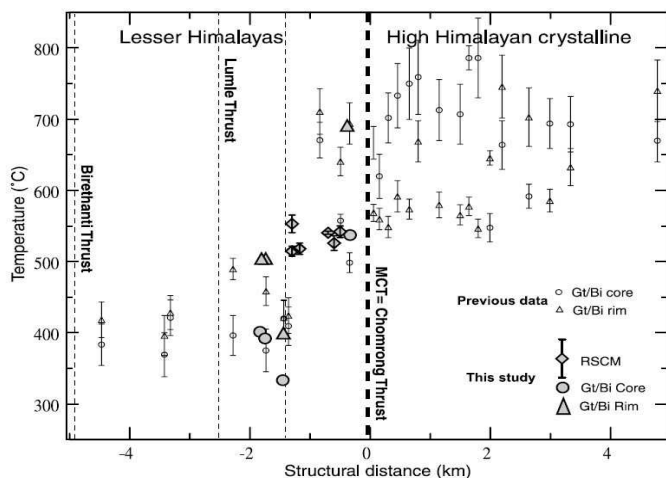
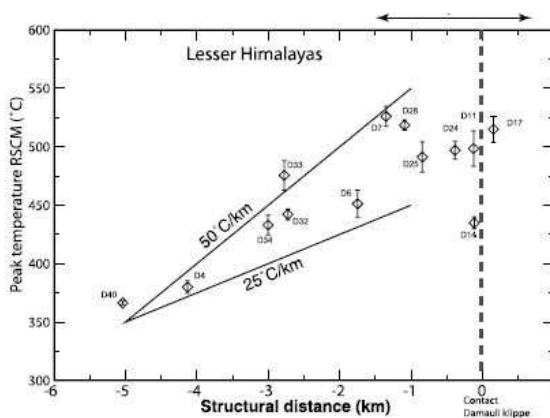
P-Tp metamorphic conditions below the MCT

In the Lesser Himalaya, the metamorphism is low or very low, and good metamorphic index minerals are lacking for conventional petrologic P-Tp determinations (only illite, muscovite and chlorite to the south, appearance of biotite and chloritoid when reaching Pokhara area). Today the best determination of metamorphic Tp conditions are probably still those by Beyssac et al (2004), using Raman spectrometry of carbonaceous material (RSCM method).



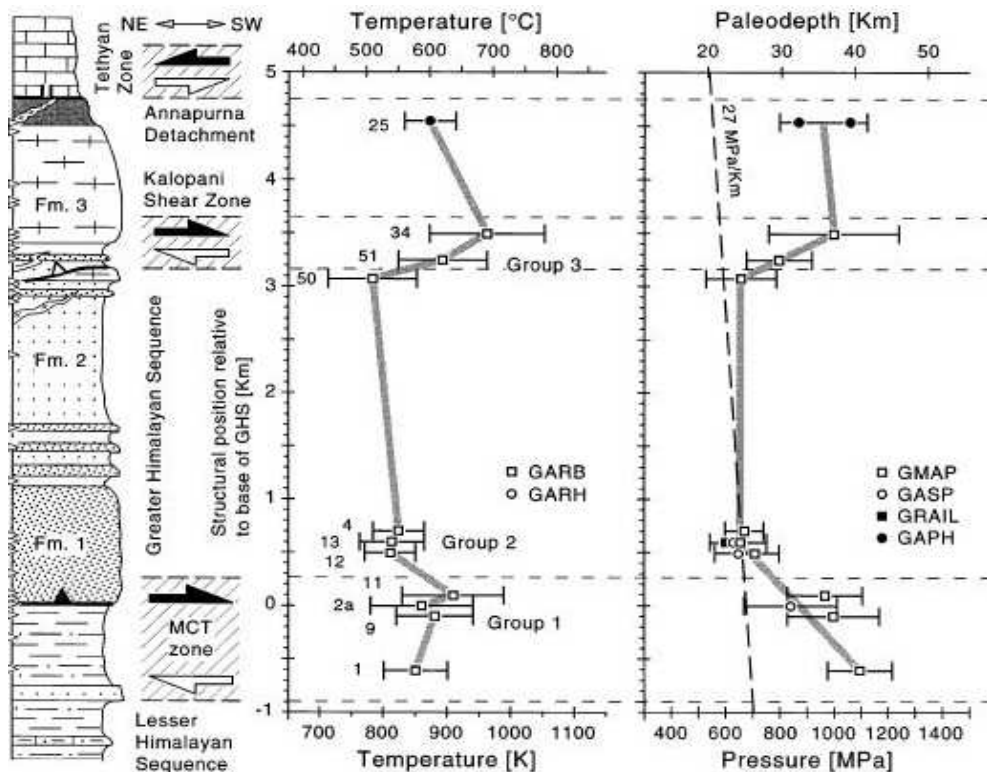
Section Butwal-Pokhara-Tatopani : location of the samples collected for RSCM method on carbonaceous rocks

The data of Bayssac et al (2004) (map p. 32) reveal a large scale thermal metamorphism throughout the Lesser Himalaya, with temperatures decreasing gradually from about 540°C at the top of the LH, close to the MCT, to less than 300°C in the core of the Pokhara-Gorkha anticlinorium. It shows that the metamorphic inverse gradient evidenced by conventional methods close to the MCT, can be traced down throughout the less metamorphosed series of the LH.



Tp peak metamorphic conditions given by RSCM method (in Bollinger et al., 2004)

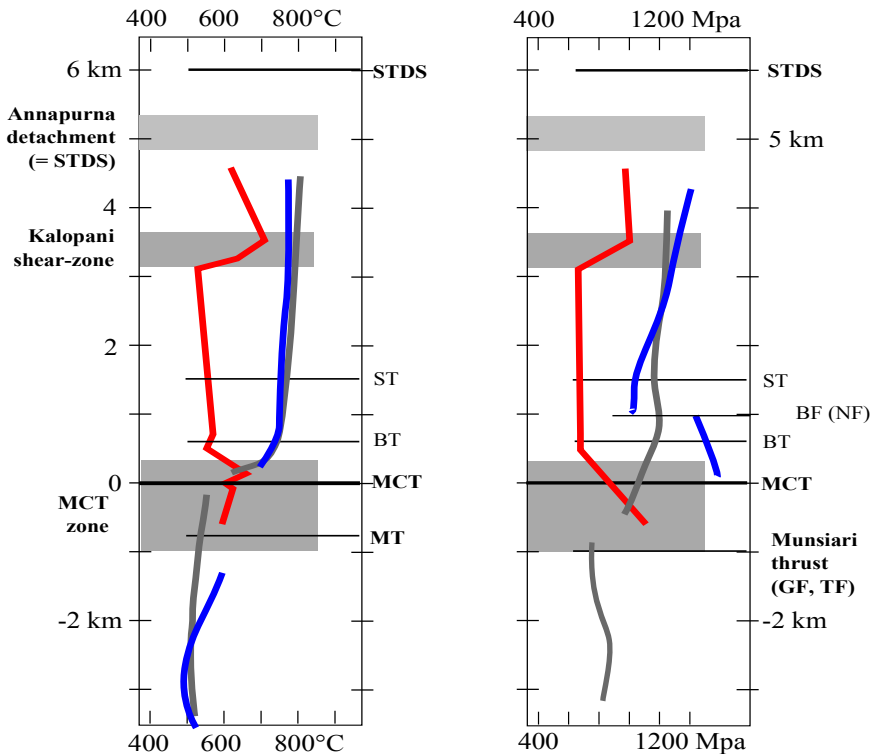
- above: below the Damauli klippe (a piece of the Katmandu nappe, pinched in the MCT zone)
- left: along our itinerary, in Ghorepani area



Temperatures and pressures profiles for the metamorphic sequence in the Kali Gandaki transect (Vannay and Hodges, 1996). Notice :

- the continuous evolution across the MCT shear zone
- the low temperatures calculated for the gneiss and migmatites of the HHC (much lower than what is commonly accepted now in the HHC)
- a metamorphic discontinuity within the Upper HHC (Kalopani shear-zone), may be testifying to late out-of-sequence thrusting.

P-Tp métamorphic conditions in the HHC (Annapurna section)



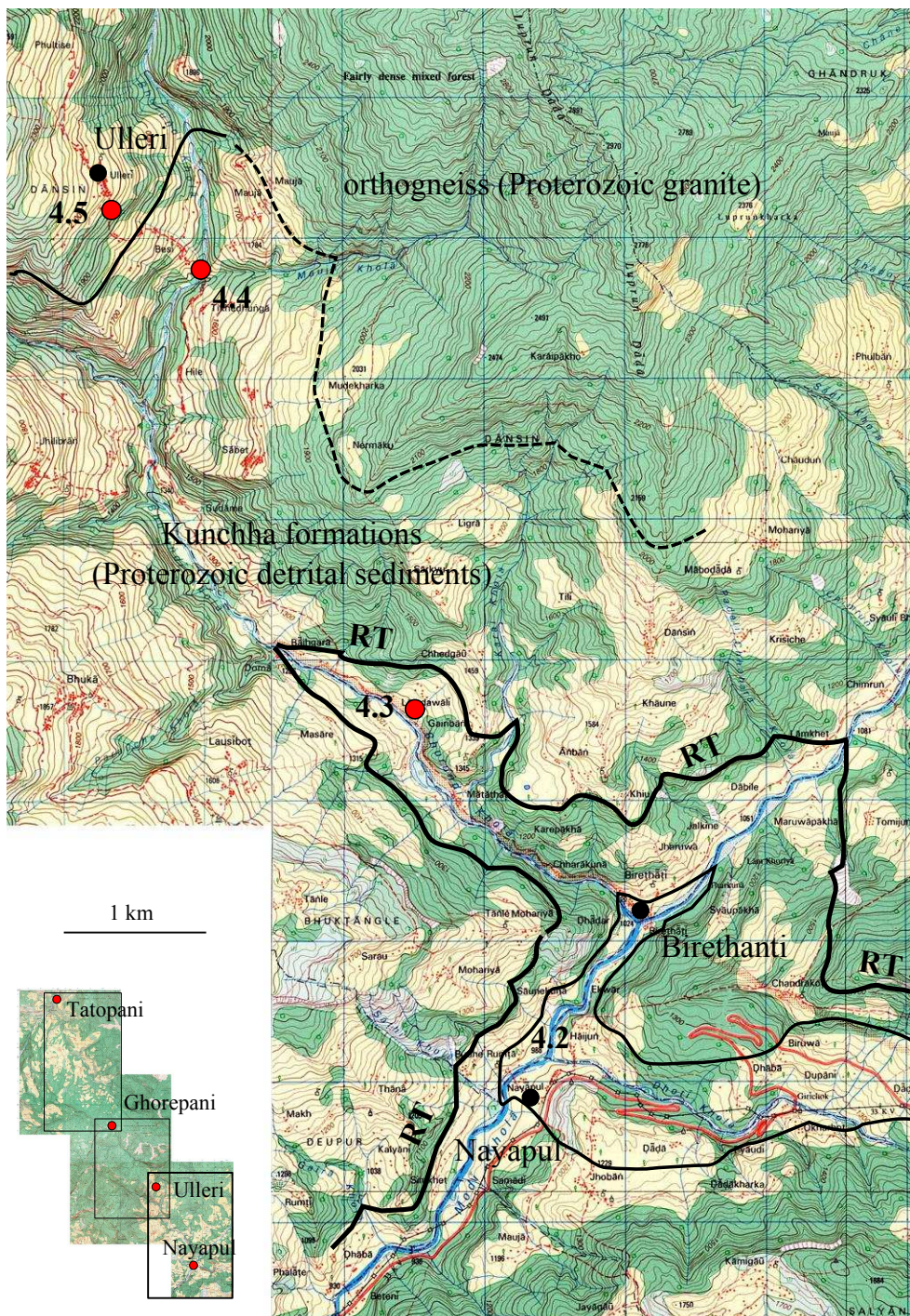
Comparison of 3 P-Tp sections in the HHC, Western Annapurna range

- in red, Kali Gandaki section (data from Vannay and Hodges, 1996, see page 34)

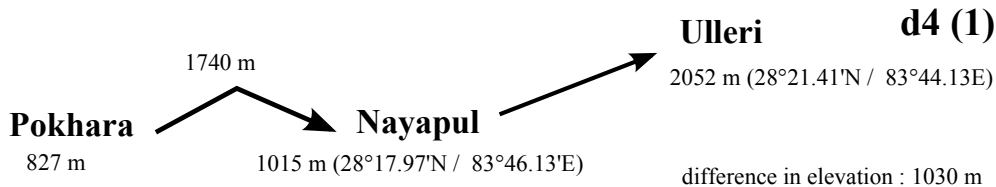
- in blue and gray, data from the Modi Khola section, a little farther to the East (viz. Martin et al., 2010; Corrie and Khon, 2011). Notice the rather good agreement between the two last sets of data.

In Modi Khola, from these data, Corrie and Khon (2011) deduce several additional thrusts, (BT, ST) while Martin et al. (2010) assume several normal fault : above the MCT (BF = Bhanuwa fault), below the MCT (GF = Ghandruk fault, and TF = Tobro fault, at the contact between the Lesser and Higher Midland Formations, i.e. where the Munsiri thrust should be located) . This interpretation is rejected by Corrie and Khon (2011), who retain the Colchen et al. (1980) interpretation.

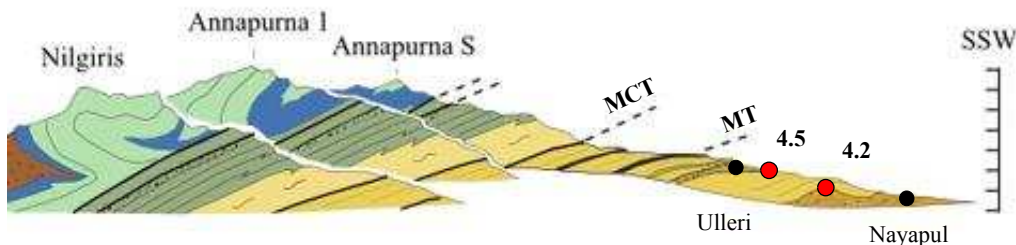
It can be concluded that those data are probably not robust enough to say anything. We will try to analyse the structural shear criteria around NayaPul and Birethanti (Munsiri thrust zone) to make our own opinion.



Our trail from Nayapul to Ulleri. The main geological contacts are from Colchen et al. (1980) and Martin et al. (2010). RT : Ramgirth thrust, at the base of the main Kunchha sheet



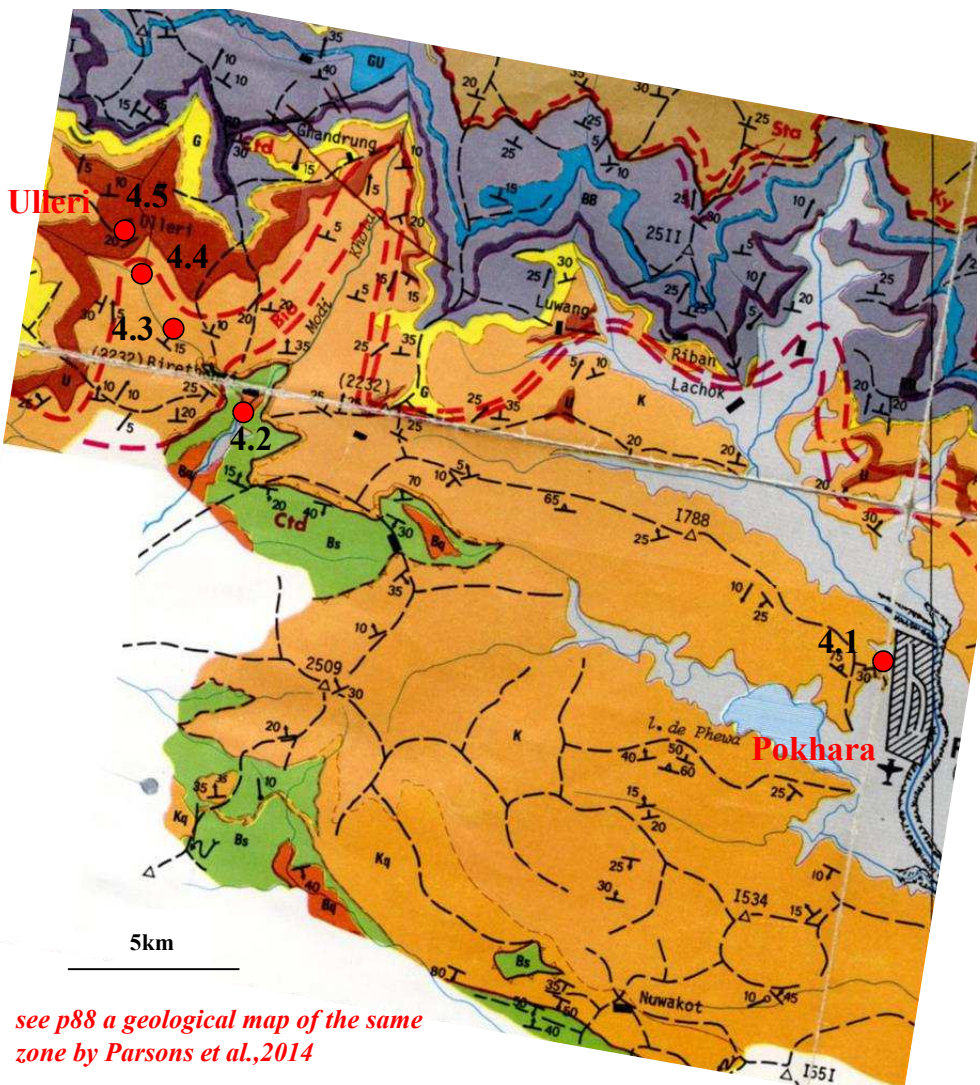
Topics : Midland formations. Munsiri Thrust



From Pokhara to Nayapul (by bus) : the road climbs on the ridge of Naudanda, a structural ridge of Kunchha Formations (predominantly sandstones) dipping about 20° NNE. On the way down to Nayapul, the road enters structurally lower levels, phyllitic (chlorite-rich schist) or quartzitic (Birethanti quartzite)

North of Pokra, cliffs are made by the Kunchha sandstones, gently dipping North (Ph AP)





see p88 a geological map of the same zone by Parsons et al., 2014

Geological map of the Pokhara-Ulleri area (Colchen et al., 1980 and 1986). From bottom (south) to the top (north):

- in green and brown color : the schists and quartzites of Birethanti, possibly belonging to the Kunchha formation, or more probably to a distinct lower tectonic unit, below Kunchha. Between the two units, the Ramgarth thrust is drawn on this map, but unlabelled.
- In yellow color, the Kunchha formation, quartzitic at its basis (Kq), intruded by Ulleri granite close to its top (Ulleri gneiss, U), and ending with the Ghandrung quartzites (G). The Munsiri thrust (not drawn on this map) runs just above (or just below ?) these quartzites.
- In blue and purple color, the Upper Midland Formations, with two main levels of dolomite and limestones.

Thick red dotted lines : southern boundary of some index metamorphic minerals : Bio (biotite) and Grt (garnet), with some sporadic occurrences of Ctd (chloritoid), below the MCT; Ky (kyanite) and Sta (staurolite), only found above the MCT in this area (but also occurring below the MCT further E).

4-1 (along the road, North of Pokhara)

Somme good outcrops in the road cut show the Kunchha Formation (lower Midland Formations), here mainly made of sandstones. Notice the stretching lineation, already quite penetrative, and some S-C shear criteria in the most deformed beds. Sense of movement is top-to-south (as everywhere in the thrusts zone - MT, MCT - between HHC and non-metamorphic and less-sheared Lesser Himalaya).



Ph - Strong stretching lineation in the Kunchha Formation, made of alternations of large sandy beds (in the foreground) and schistose beds rich in muscovite (bank of the river) (Ph. AP taken to the south-east from the right bank of the Midam khola)

4-2 (around Birethanti) (N28°18.21/E83°46.26 to N28° 18.69/E83° 46.30)

We are in the core of the Pokhara anticline, in the lowest structural levels of our section. Green schists and medium to very fine-grained quartzites, with numerous ripple-marks, crop out, below the Quaternary terraces : for some authors (f.i. Colchen et al. 1980, Martin et al. 2010) they are part a lower tectonic unit, below the Kunchha Formation, and separated from them by a thrust (Ramgarh thrust). For others (Upreti and Yoshida 2005) they belong to the Kunchha series. These quartzites can be followed southwards. They increase in thickness in the Nuwakot area (SW of Pokhara).

4-3 [G68] (28°19.21'N 83°45.54'E/1172m, 2 km NW of Birethanti, left bank of the Bhurundi khola)

A good rock exposure shows the alternation of pelitic and psammitic phyllite bedding planes with parallel cleavage dipping 30° N. Sigmoidal S-C fabric in the shists.

4-3b (N 28° 20.04/ E83° 44.55/1284m) Nice sigmoidal S-C fabric in the shists

4-4[G67] (28°21.03'N 83°44.58'E/1516m, bridge on Bhurundi khola)

Amphibolites, interlayered in the Kunchha sandstones. Similar levels crop by place all the way down from Ghorepani to the Kali Gandaki.

4-5 (along the trail, below Ulleri village)

Several outcrops of Ulleri augen gneisses. Ulleri gneisses are actually Lower Proterozoic granites. They form lenses of a few kilometers intruded in the uppermost part of the Kunchha sandstones. We cut the most extensive lens, which can be followed from East of Modi Khola to Kali Gandaki, and reaches 1500 m in thickness.

These gneiss with feldspars of a few centimeters (potash feldspar or occasional albite), showing a highly variable K₂O/Na₂O ratio, have been dated at 1831 Ma (De Celles et al., 2001).

They are highly stretched, with a strong L fabric, and numerous S-C or S-C' tectonic almonds. Actually, we are in the Munsiri - MCT thrust system (see next page)

Between the Higher Himalaya Crystalline made of high grade metamorphic rocks, and the less metamorphic nappes of the Lesser Himalaya, there is not a well-defined single thrust, but a wide and heterogeneous thrust zone. The **Main Central Thrust (MCT)** is the lithological boundary between the Higher and Lesser Himalaya, where also the shearing is maximum. But deformation on both sides is quite heterogeneous, which allows geologists to define several other thrusts, some of them probably of only local importance (see fig. p. 35). Nevertheless, one of them is more conspicuous, between the carbonate-rich and graphit-bearing Midland Upper Formations and the terrigenous Midland Lower Formations (the Kunchha or Nawakot Formation) : it is the **Munsiari thrust** (sometimes named MCT 1). The Upper Midland Formation could be a specific nape, similar to the Almora nappe, pinched below the HHC, between the MCT and the MT. The situation of the Kathmandu nappe and the Damauli klippe, although in a similar position, are unclear.

The MCT zone is characterized by 3 main tectonic markers : the schistosity (flattening plane), often associated to the shear-plane in typical 'C-S' sigmoidal almonds; and the stretching lineation LX, nearly parallel to the transport (movement) direction, and thus often used as a marker of the displacement direction.

Sense of shearing (usually top-to-south) is given by the dissimetry of the tectonic figures, always "monoclinic" (a single symmetry axis perpendicular to the shear direction).

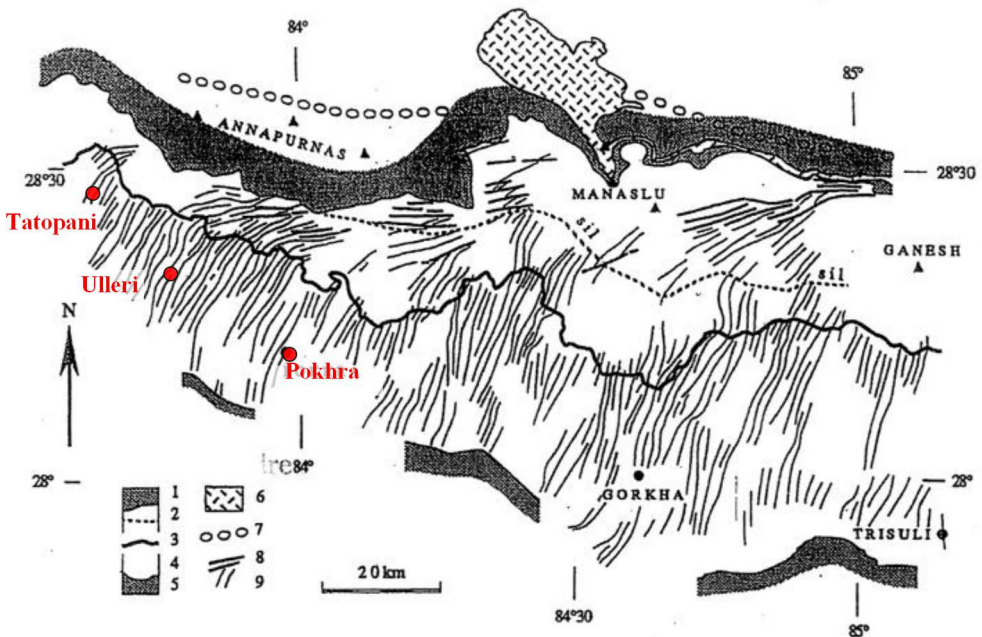
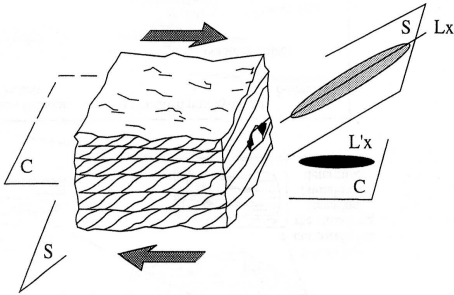


Fig. - The stretching lineation in Central Nepal (Pêcher, 1991; Pêcher et al., 1991)

(1) HHC sedimentary cover, above the STDZ (or NHF) - (2) : Southern boundary for sillimanite - (3) : main HHC-LH contact (MCT) - (4) : Lower Midland formations, Kunchha schist and sandstone - (5) : Carbonate rich Upper Midland formations, southern limb of the Pokhara-Gorkha anticline- (6) : Manaslu granite - (7) : trace of the Annapurnas fold hinge - (8) : LX stretching lineation.

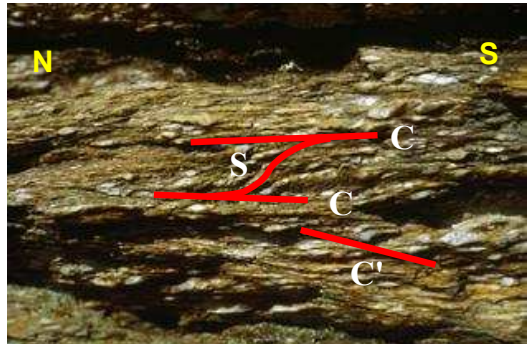
The MCT shearing affects quite a thick zone, marked by well-expressed stretching, of very constant orientation (N20°E) in all the Lesser Himalaya and the base of the HHC.

Structure in the MCT shear-zone



Most of the time, shearing is heterogeneous at all scales. At cm- to m-scale, it is marked by C-S figures, viz. almonds bounded by regular shear planes (C) and sigmoidal flattening plane (S)

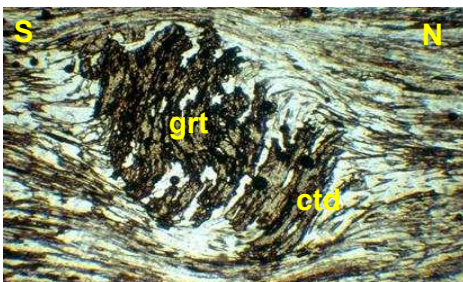
C-S almonds in the Ulleri augen gneiss, an old Proterozoic granite (appr. 1831 Ma), intruded as small laccoliths at the top of the Kunchha Formation, then deformed during Himalayan times in the MCT zone (photo AP from outcrops below Ulleri. Appr. height 1 m, section X-Z).

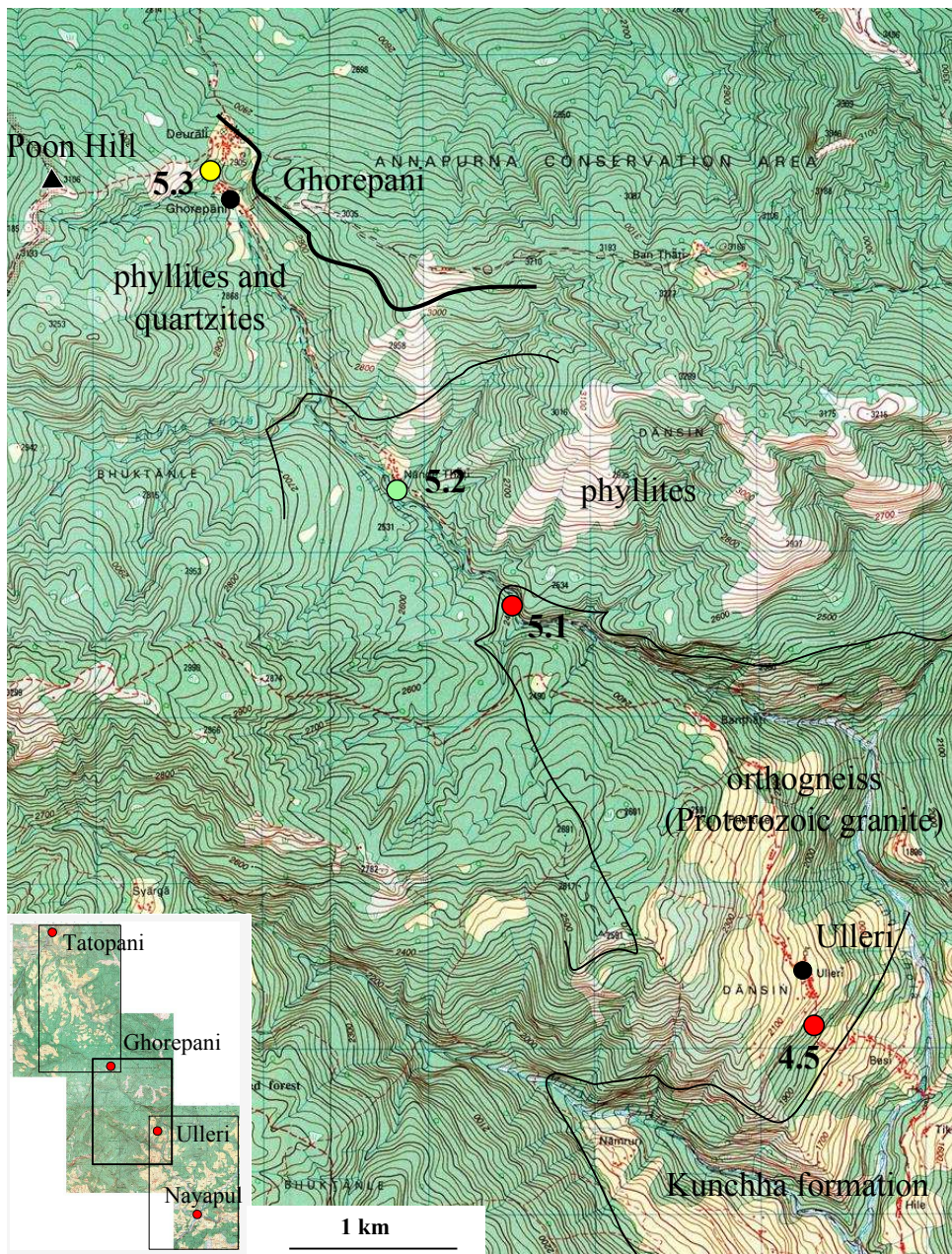


The stretching lineation LX in the Ulleri gneiss, underlined by the stretching of the feldspar and quartzo-felsic tails behind the feldspars (same outcrop as above, section X-Y)



Monoclinic shear fabric can be observed at any scale. Below : thin-sections in samples from the Modi-Khola. Left : schist above the Munsiri thrust, syn-kinematic garnet (grt) and chloritoid (ctd). Right : Gandrung quartzite, typical ribbon fabric; all the extinction bands of the quartz are parallel (strong lattice preferred orientation), tilted to the left, and indicate a top-to-south sense of shearing.





From Ulleri to Ghorepani pass. The main geological contact are from Colchen et al. (1981). Stops points as in Upreti and Yoshida, 2005.

Ghorepani

d5 (1)

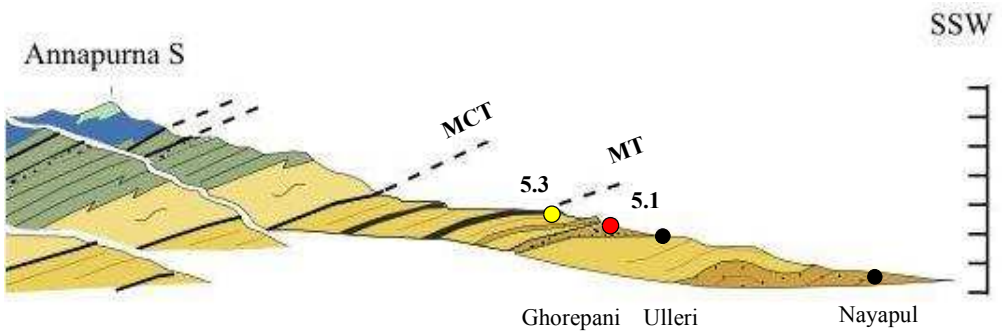
Ulleri

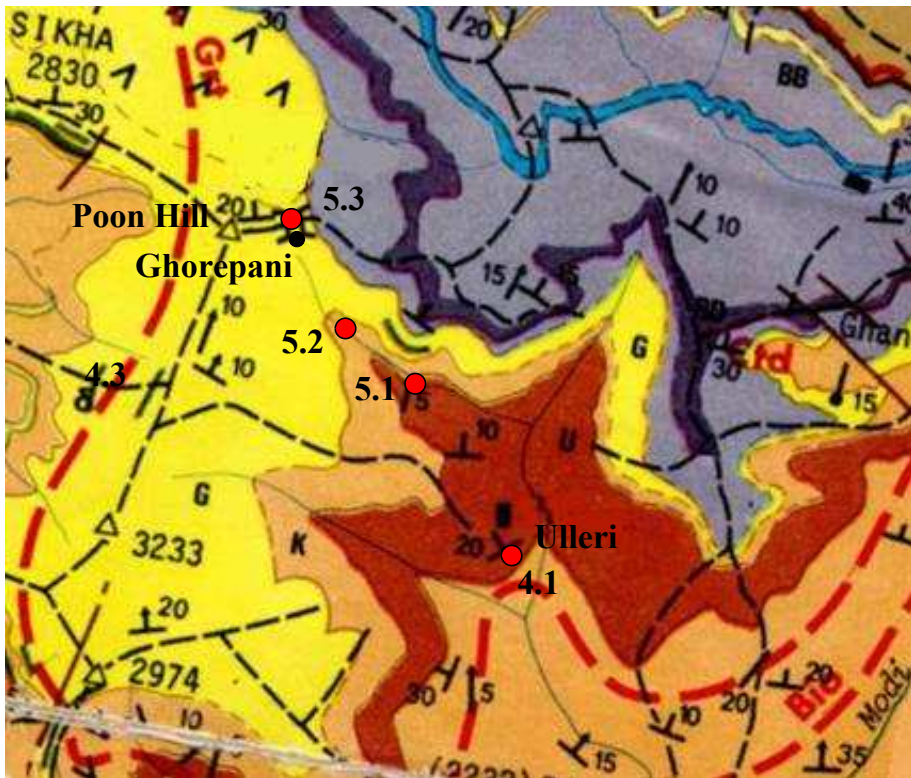
2850 m (28°23.99'N / 83°41.98'E)

2052 m (28°21.41'N / 83°44.13'E)

difference in elevation : 800 m

Topics : Midland formations





From Ulleri to Ghorepani (Colchen et al., 1980)

5-1 [G 66] (28°22.50' / 83°43.07' / 2510m, about 1 km South of Nanga Thati village)

An exposure composed of medium grained biotite quartzite intercalated with very coarse-grained quartz-feldspar-biotite-muscovite-tourmaline augen gneiss. It is the Ulleri augen gneiss. The foliation is gently dipping North-East and is thus parallel to that of the surrounding metasediments.

5-2 [G 65] (28°23.00' / 83°42.625' / 2410m, just South of Nanga Thati, at the confluence of Bhurundi khola and a small valley)

Exposure of chlorite-sericite phyllite, graphite-sericite phyllite with disrupted quartz pods. White quartzite also occurs intercalated with them. The higher grade phyllite along with disrupted quartz veins and pods suggest that some fault related with the MCT movement may run near by these outcrops and affected the rocks.

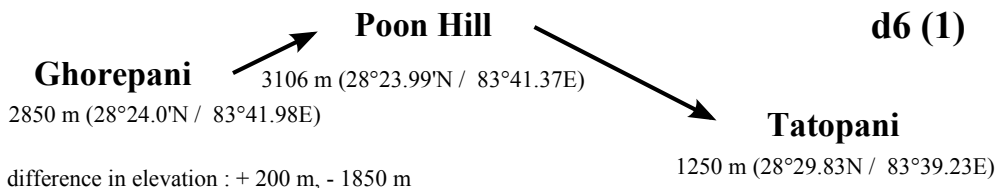
AP- The lithology suggests the Upper Midland Formations, lying above the Ghandrung quartzites, while we are here below these quartzites.

5-2b (28° 23.33' / 83° 42.38' / 2633m) Dark graphitic schists**5-3 [G 64]** (28°24.16' / 83°41.99' / 2840 m, Ghorepani pass)

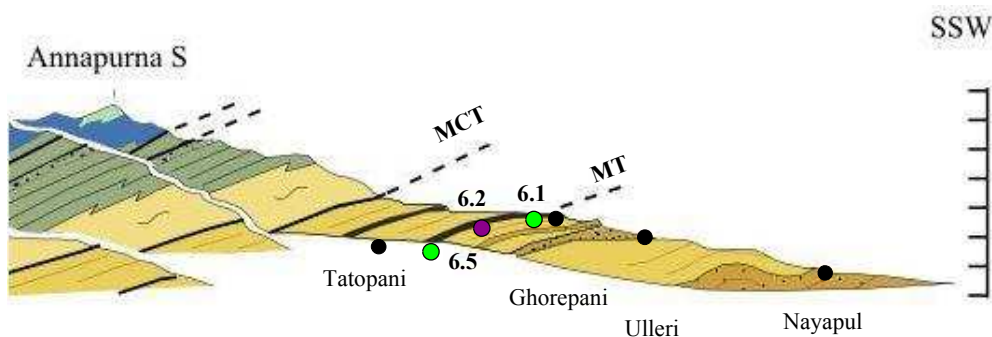
Around the Ghorepani pass, the area is underlain mainly by sericite-chlorite phyllite with quartzite. We are at the top of the Ghandrung quartzite, which make a big structural slab down to the Kali Gandaki.



A boulder of Ulleri augen gneiss (Ph AP)



Topics : from lower Midland to Upper Midlands formations



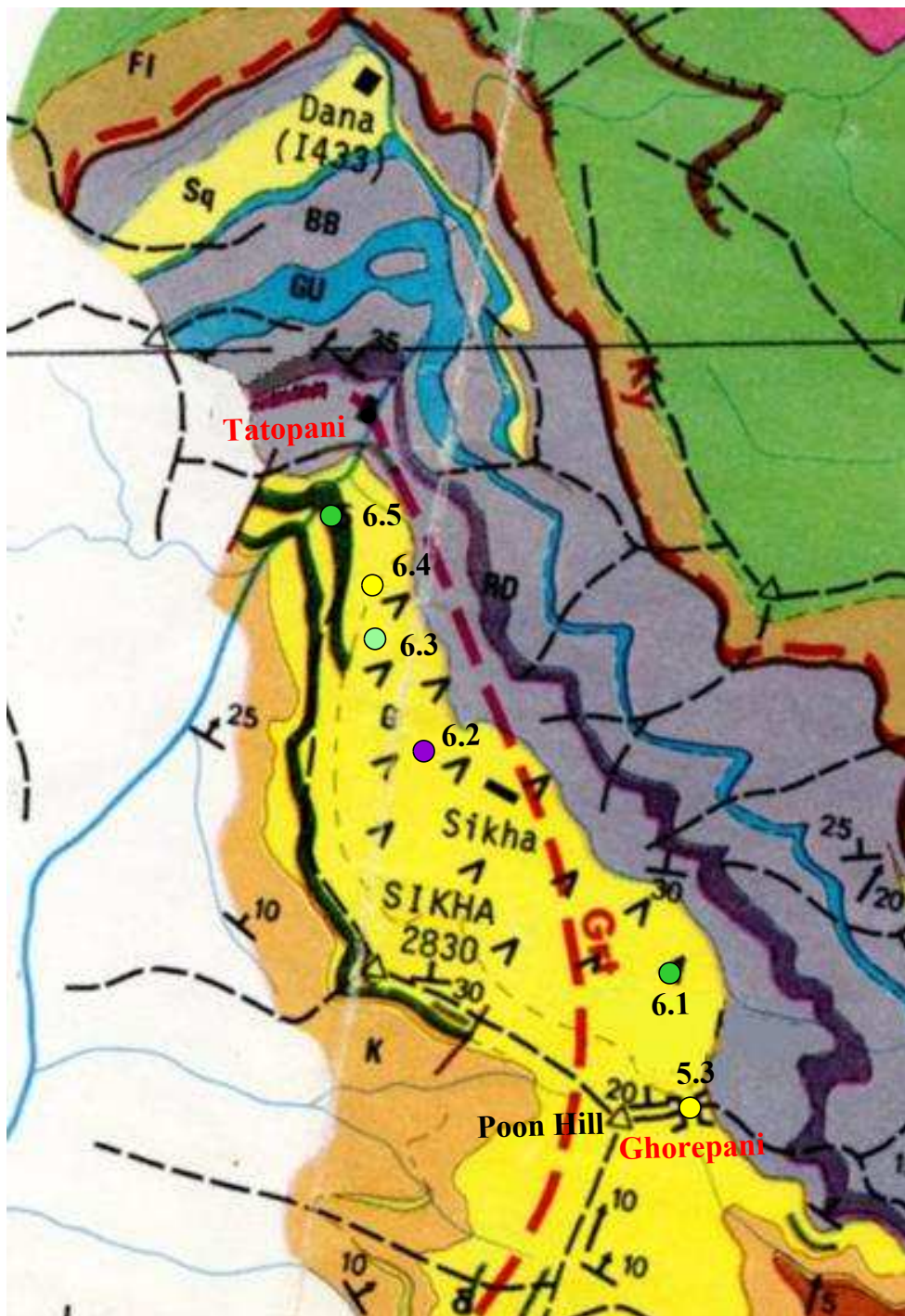
Early in the morning : way up to **Poon Hill**, south of Ghorepani (200 m to climb), to see the very scenic view on the Dhaulagiri and Annapurna high ranges. From here we can observe pretty well in the Dhaulagiri a nearly complete section of the HHC.



Left ; from Ghorepani pass to Khali Gandaki. Stops as in Upreti and Yoshida 2005

Dotted line : approximate upper boundary of the Ghandrung quartzite (Fagfog quartzite, Nawakot complex). The Munsiri thrust is usually drawn at the top of those quartzites.

The quartzites (with some intercalated amphibolitic levels) make the backbone of the ridge from Poon Hill down to Hallikharka (stop 6.4), and all the cliffs south of the ridge.



Note - Most of the slopes from Ghorepani down to the Khali Gandaki are large landslides, there are only a few actual (non-slided) outcrops.

There is a new unmetalled road from Sikha down to the Khali Gandaki. In October 2014, it was ending about 600 m W of stop 6.1, and in very bad shape.

6-1 [G 63] (28°25.09' / 83°41.89' / 2510 m, south of Chitre)

Exposure of green phyllite of basic tuff origin and chlorite schist of possible greywacke (sandstone) origin, mixed with schistose amphibolite of gabbro origin. Further southward for about 1 km, a relatively large gabbro amphibolite mass occurs, its southern margin being partly associated with green phyllite and chlorite schist.

6-2 (28° 26.68' / 83° 40.07'E / 1975m, just after Sikha)

Graphite-sericite-chlorite phyllite, which are probably above the Ghandrung quartzites, i.e. belong to the Upper Midland formation. At this outcrop, the rock is milky coloured, medium grained, and highly jointed quartzite intercalated with fine-grained sericite-chlorite greenish grey phyllite. The schistosity is about 30° towards NE.

About 400 m farther on (28° 26.82' / 83° 39.88' / 1865m), on the other side of a gully, a landslide scratch shows intercalations of quartzites and black schists

6-3 [G 61] (28°28.08' / 83°39.15' / 1600 m, 300 m South of Birauta village)

Sheared phyllite and landslide. At the crossing of a small valley about 300 m before Birauta, a landslide with low-angle sliding planes is observed. Here the basement rock is not hard, but is very phyllitic and relatively soft carrying some clayey matter mixed in.

6-4 [G 60] (28°28.44' / 83°39.23' / 1545 m, small pass between Birauta and Hallekharka villages)

Ghandrung (Fagfog) quartzite. The trail (now a road) cuts through a steep quartzite ridge. A very good outcrop. The steep ridge consists of thinly to thickly well-bedded (>2m), milky colored, medium-grained quartzite.

6-5 [G 59] (28°29.16' / 83°38.89' / 1210 m, bridge on the Khali Gandaki, right bank of the river)

From Hallekharka village, the rock exposure consists of medium-grained, greenish-grey colored amphibolite intercalated with fine-grained greenish-grey phyllite and fine-grained quartzite. The phyllite contains sericite, chlorite, quartz and feldspars.

The main level of Ghandrung quartzites is cut around 600m farther on (28° 29.48' / 83° 38.98' / 1250m)

The amphibolite in Kunchha Formation (Nawakot complex)

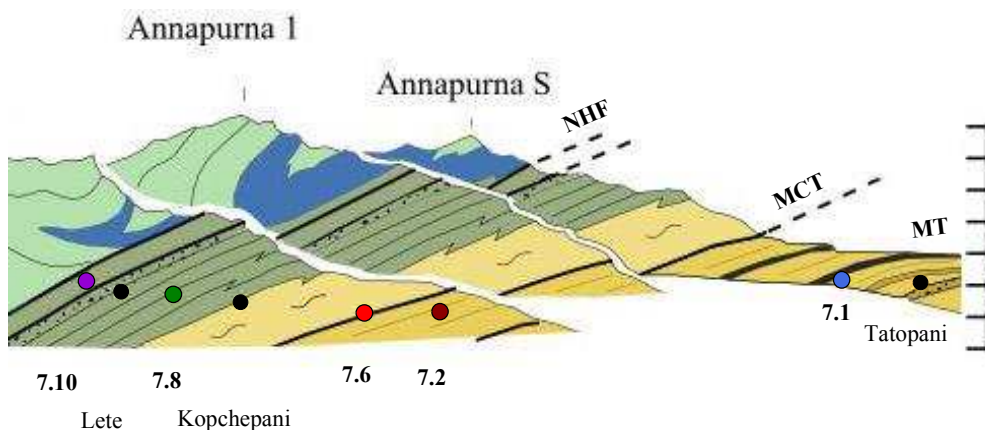
No recent geochemical or geochronological data for amphibolites from Nepal (?), but an old study by Lasserre (1977) : "Amphibolites are mainly developed in the upper part of the Midland Formations, where four main horizons have been studied. Their mineralogy is constant : actinolite, quartz, biotite, clinozoisite, albite, ilmenite, apatite and sphene. Results of chemical analysis of some fifty samples form a fairly homogeneous group showing that they have been derived from differentiated tholeiitic basalts, of island-arc tholeiite type" (in Bordet et al., 1981). Similar interpretation for amphibolites from Western Indian Himalaya (Bhat et al., 1998; Miller et al., 2000, give a zircon age of 1800 +/- 13 Ma; Ahmad, 2008)

2540 m (28°38.48N / 83°35.95E)

Tatopani

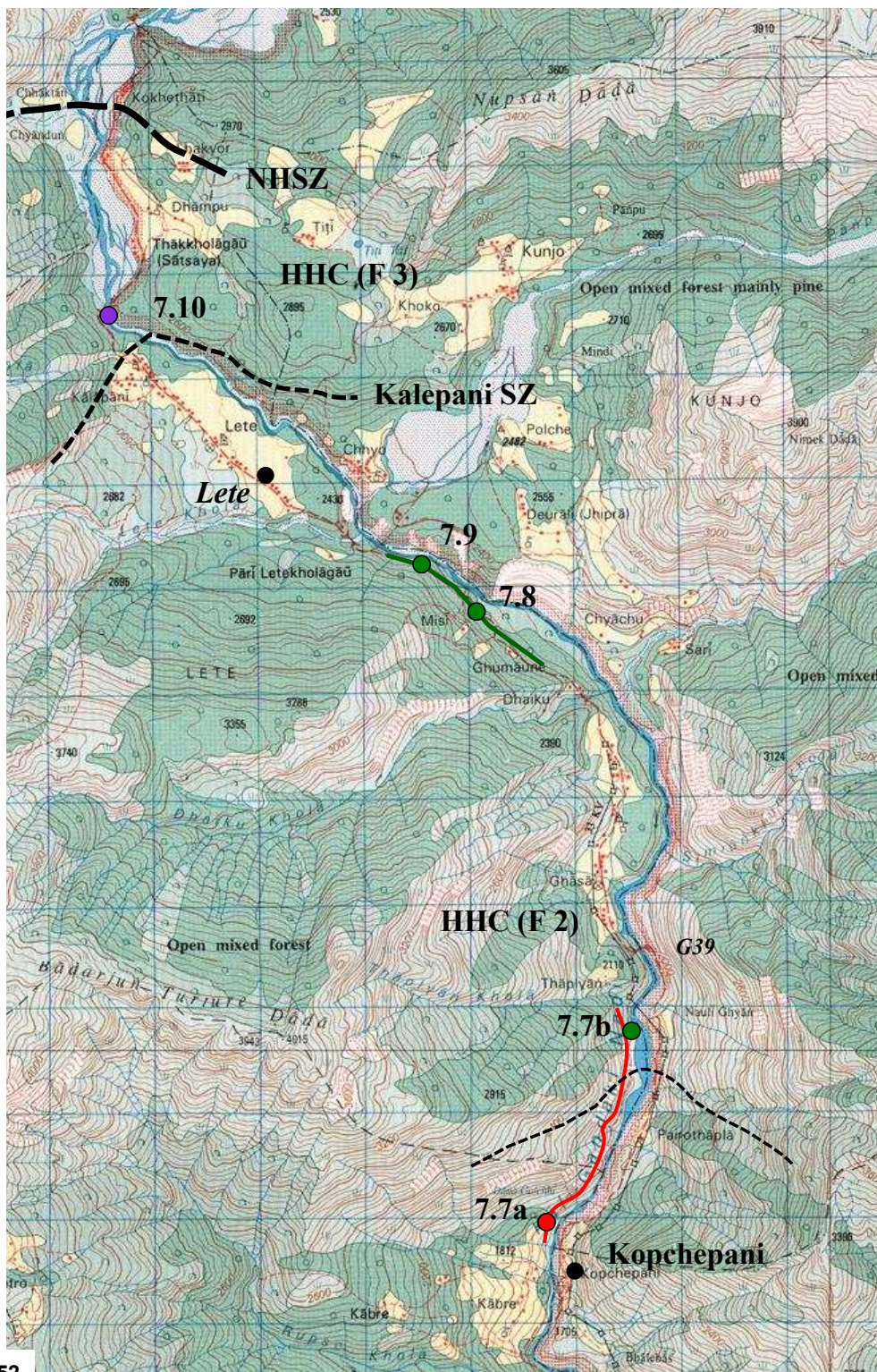
1250 m (28°29.83N / 83°39.23E)

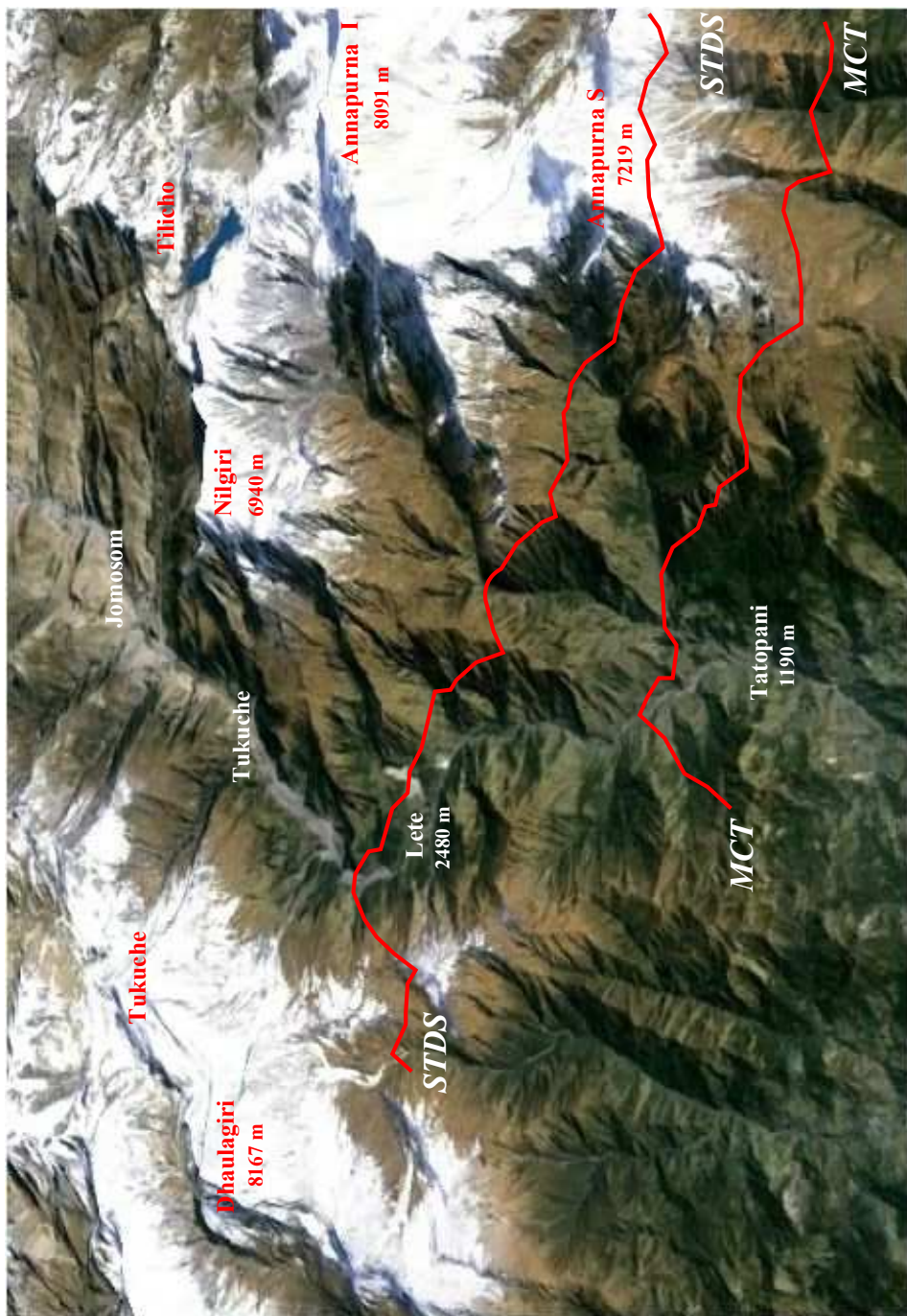
difference in elevation : 1290 m (mainly by car)

Topics : MCT and Higher Himalaya gneiss and migmatites

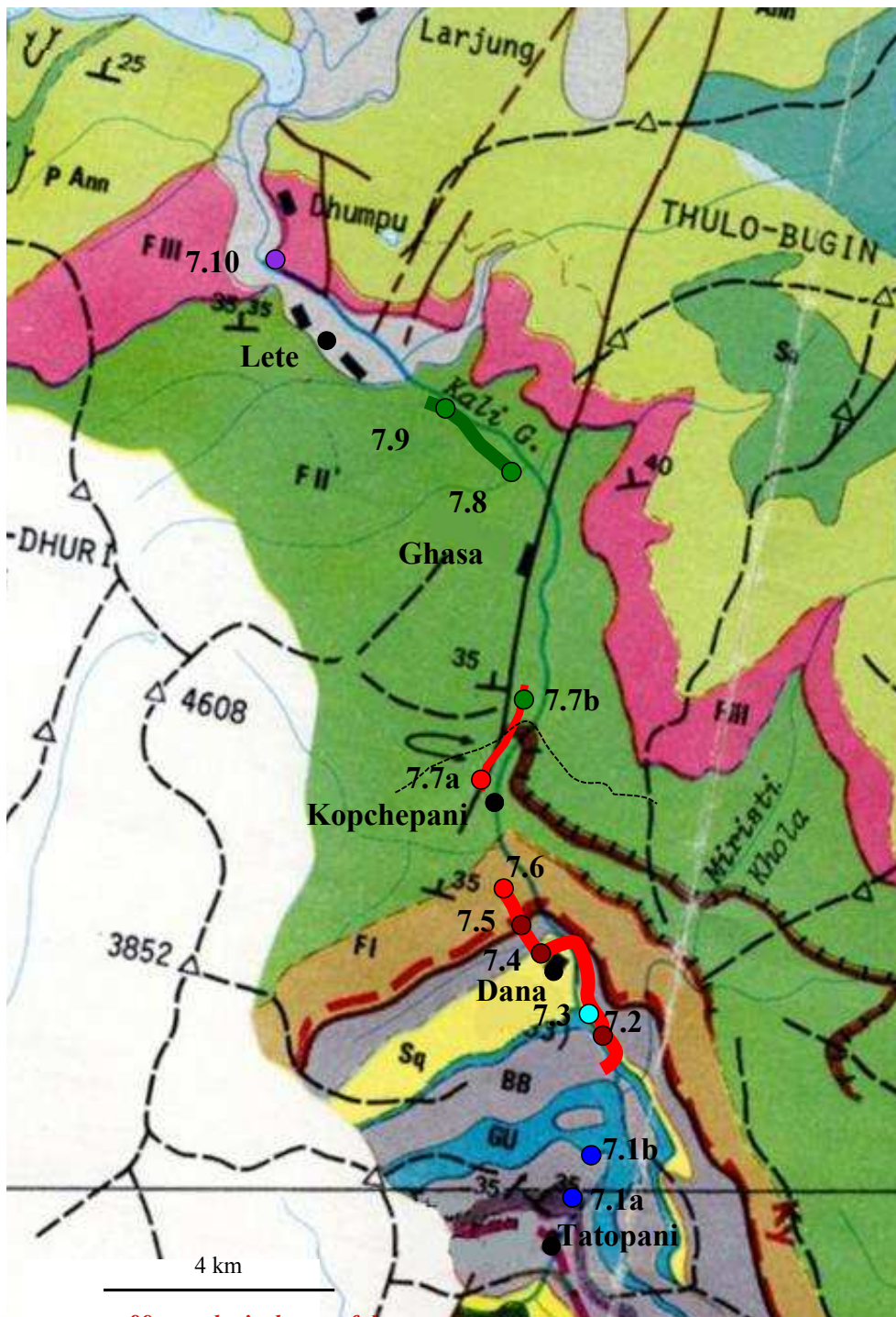
From Tatopani to Lete (left and next page). This part of the sections follows the narrow gorges of the Kali Gandaki river, cutting across the gneisses of the HHC. On several part of the gorges, there is no alternate path to the new road, which roughly follows the old path, on the right (W) bank of the river. Thus for most of the section, we will have to follow the road. Rather than moving from one stop to another by bus - with parking places problems -, we will walk along two parts of the section (the MCT zone - red line figure p. 50 - and the upper part of the HHC -green line, fig. p. 52 -), few km in length each, and stay in the bus in the junction segments.

The stops indicated on the map and described hereafter are the stops given by Upreti and Yoshida (2005), before the road was constructed. Some of the locations are off the road, but we should find similar outcrops in the road cut. The photos given here are not all from the Kali Gandaki section, but also from the Modi khola section, further East.

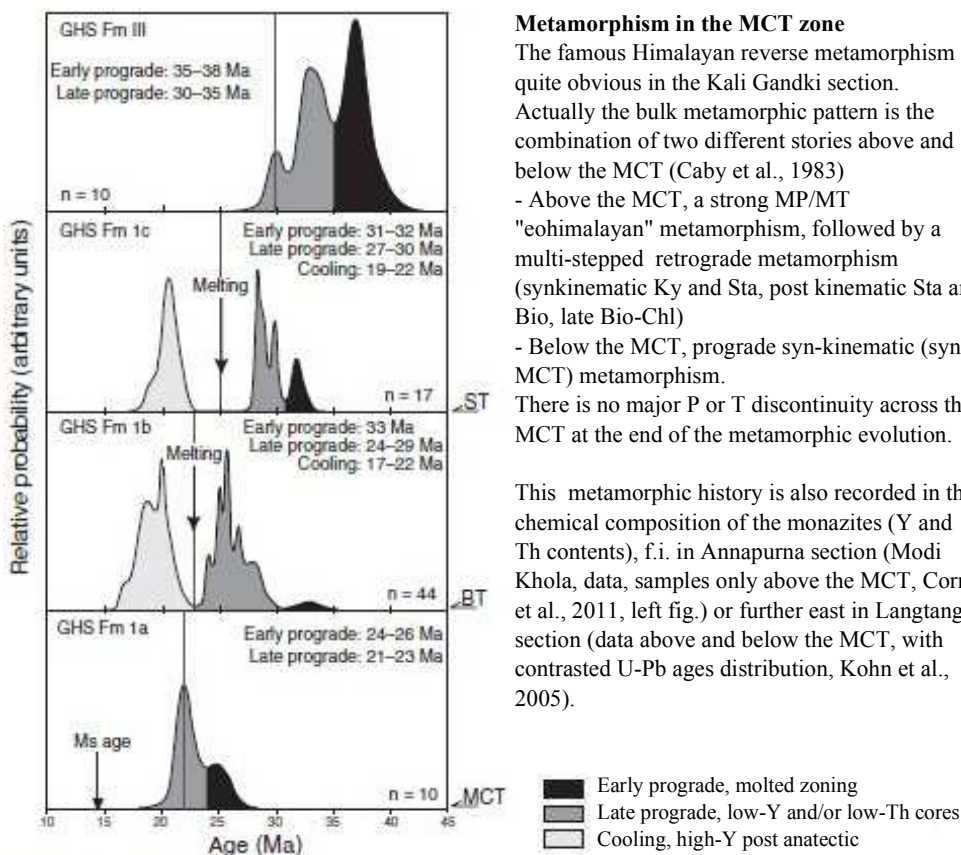




The Kali Gandaki gorges and the High Himalaya from the sky (Google Earth picture)



see p89 a geological map of the same zone by Parson et al., 2014



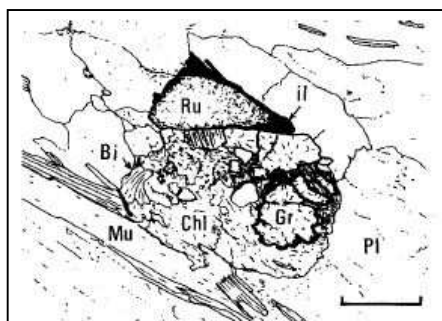
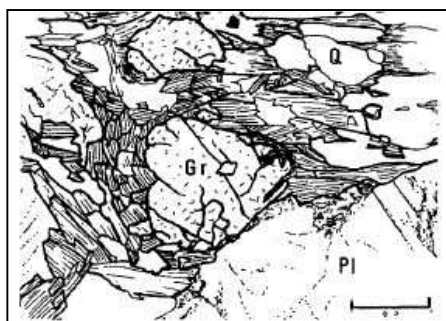
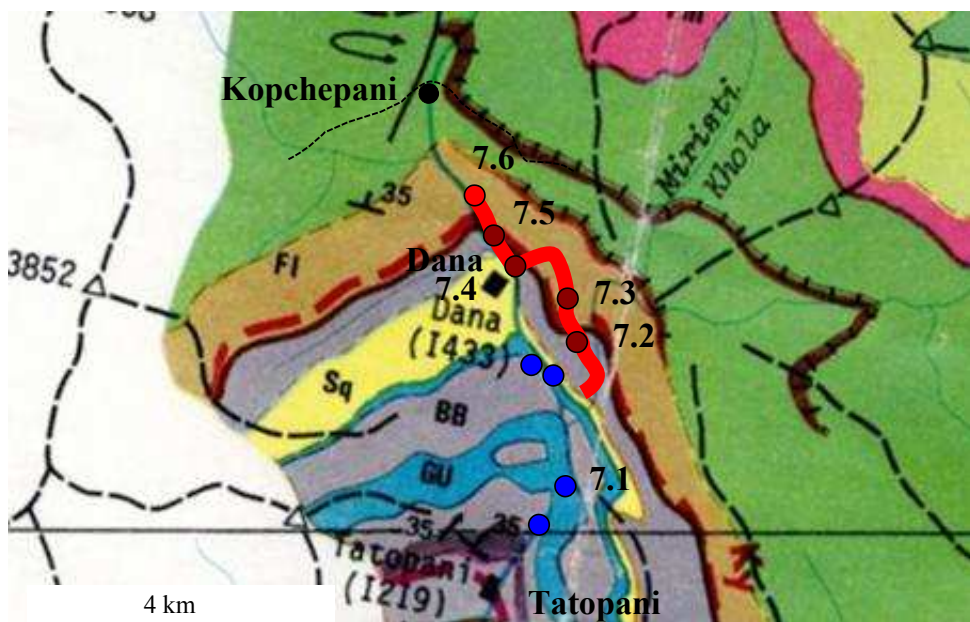
1) First part of the section : between MT and MCT

7-1a [G51] (28°30.33'N / 83°39.45'E / 1280m) (subsidiary thrust zone)

Sericite-phyllite schists with phyllonitic signature; some parts contain garnets.

7-1b [G50] (28°30.54'N / 83°39.45'E / 1295 m) (north of Jalthale)

Black graphite-sericite phyllite of the Benigath slate (Upper Midland Formations, Nawakot Complex. This phyllite is less metamorphosed than the phyllite in the North.



Retrograde metamorphism above the MCT (zone of stops 7-4 and 7-5) (in Caby et al., 1983).

Left : garnet partly destroyed and corroded by microcrystalline biotite.

Right : very near the MCT, chloritized garnet. Notice the oxides at the boundaries of an old rutile grain.

Scale bar : 0.5 mm. Minerals : biotite (Bi), chlorite (Chl), garnet (Gr), ilmenite (il), muscovite (Mu), plagioclase (Pl), quartz (Q), rutile (Ru).

2) The MCT zone (on foot section)

Bridge of Surap (28°31,43'N / 83°39,52'E / 1345 m) *South of Surap, we will cross the Kaligandaki on the bridge to Dharap, and we will continue up to Dana along the former path on the left bank of the Kaligandaki. Then we will continue walking on the road north of Dana*

7-2a (28° 31.67'N /83° 39.46'E/ 1345 m). On the east bank of the Kaligandaki, opposite to Duwarikholagau, the typical carbonaceous black shists of the upper Midlands Formations.

7-2b [G46] (28°31.79'N / 83°39.34'E / 1375 m). About 300m farther North, just northwest of the Dharap village, continuous outcrop of phyllonite, mylonite, ultramylonite and mylonitic granite are observed within about 100-200 m on the wall-like outcrop standing on the lower terrace and also sporadically further above, for about 15 m on the slope along a small trail. The phyllonite develops continuously as if homogeneous in lithology, however in detail they carry even a thin limestone layer, and also sporadically fragments of ultramylonite and granite mylonite occur. About 20-30 m just above the terrace occurs mylonitic granite, and the small trail connecting the lower terrace and the upper main trail from Gadpar to Dharap provides good exposure to examine the relationships between the different lithologies above.

7-3 (28° 31.92' / 83° 39.17'/1380m) The trail cuts a spur of metamorphic limestones. A quite good outcrop to study the upper limestones levels of the Upper Midlands Formations.

Bridge of Dana (28° 32,57'N / 83° 38,90'E) Back to the road, right bank of the Kaligandaki

7-4 [G44] (28°32.56'N / 83°38.89'E / 1455 m) Just N of Dana, small outcrop of mylonitic augen gneiss. The mylonitization reflects the MCT movement. A continuous good outcrop is found about 20-30 m higher than the trail, where various degree of mylonitization of biotite augen gneiss is traced from weakly deformed gneiss. Garnet occurs sporadically. They contain fine to medium grained biotite, muscovite, staurolite, calcite, quartz and plagioclase.

AP - We are now right on the actual main MCT. .

7-5 [G43] (28°32.78'N / 83°38.71'E / 1480 m) To the south of Titar, still in the MCT zone. Prior to coarse grained and migmatized augen gneiss of the HHC, we observe mylonitic biotite-garnet schist associated with quartzite. In the gneiss, the shearing resulted in the occurrence of strongly elongated and coarse quartz-feldspathic augens of the gneiss.

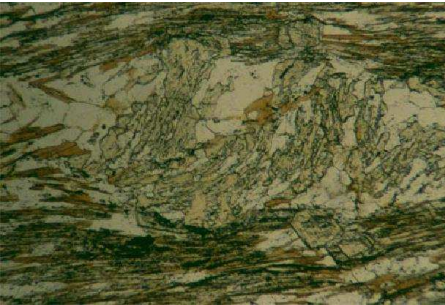


The MCT is best defined as a lithological boundary. But in Formation I of the HHC, we will find several low-dipping bands of sheared gneiss: it is probably possible to define additional "MCT" above the main MCT (as done f.i. by Martin et al., 2010, in Modi Khola section).

Some shear figures in the gneiss of Formation I (ph. AP):

Left - S-C almonds with stretched kyanite crystals.

Right - similar S-C almonds, underlined by quartz-pods



Thin section of a gneiss, base of the Formation I of the HHC (Ph. AP). Staurolite, biotite and small crystals of kyanite. Two generations of staurolite and biotite can be observed



The transition from Formation I (Al rich) to Formation II (Ca rich) is rather gradual, with occurrences of calc-silicate gneiss (calcite, hornblende, scapolite) in the uppermost quartz-feldspar migmatites of the Formation I. *Left* - Migmatized gneiss (partial melting), enriched-in-biotite at some levels, and quartzo-felsic leucosomes developed in the schistosity. Folded levels of calcic gneiss. *Right* - An old hinge still visible in a calc-silicate dislocated level (Ph. AP).

7-6 [G42] (28°33.22'N / 83°38.46'E / 1560 m) To the south of Rupse Chhahara (fall) and to the north of the Titar village, good outcrop of coarse grained biotite-muscovite gneiss. Relatively strong foliation develops throughout the gneiss. This rock belongs to Formation I of the HH gneisses. The gneiss consists of quartz, feldspar, biotite, muscovite and kyanite. Abundant crystals of kyanite are randomly oriented that might have formed later than most minerals that form gneissosity. Micas and some kyanite crystals make a good foliation. In some exposure, migmatization melts can be observed.

Above the MCT, in the HHC

7-7 (a very beautiful 2 km continuous section on the road, from 28° 34.18'N / 83° 38.27'E / 1745 m to 28° 35.10'N/ 83° 38.77'E/1830m)

Aluminous micaceous gneiss and hornblende gneiss of Formation II of the HHC.

Just above the MCT, Formation I gneiss are Al-rich, and often display kyanite and/or staurolite. .

- at the beginning of the section, easily visible obliquity between the dm scale bending of the gneiss (succession of metagrauwackes and metapelites) and the clivage underlined by the biotite orientation, dipping more steeply to the North,

- little farther (28° 34.204'N/ 83° 38.301'E/1759m) syn-kinematic garnets with an internal S-shaped schistosity

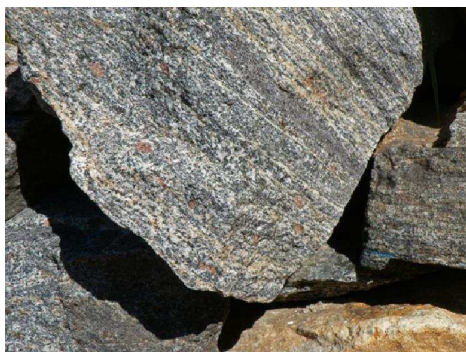
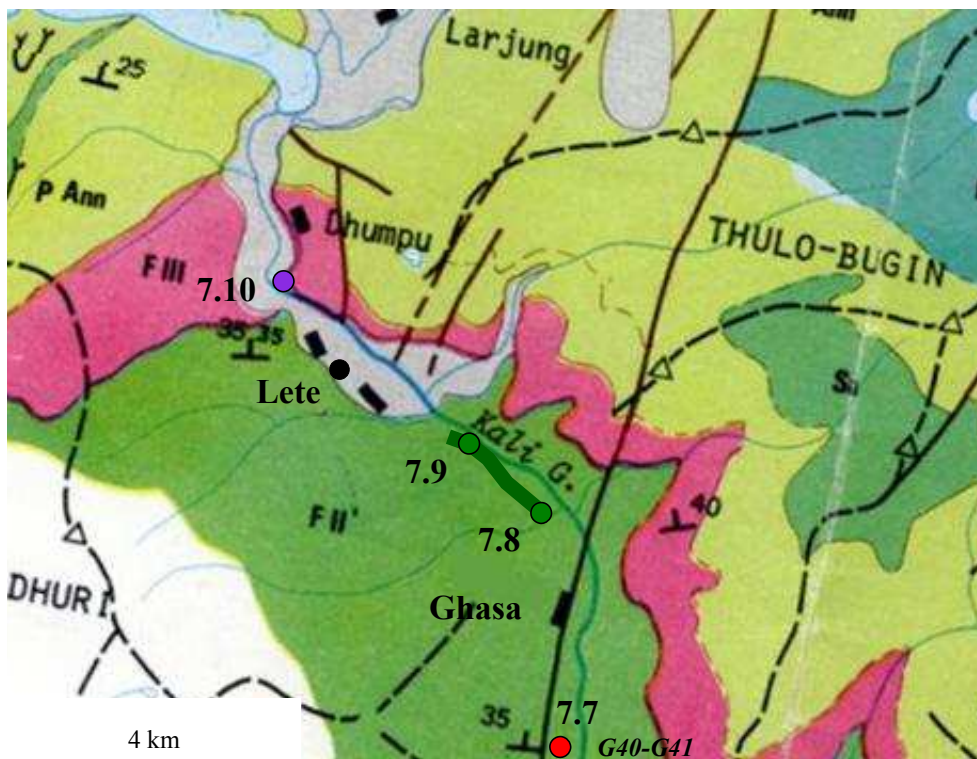
- at the end of the section, Formation II, made of calc-silicates rich gneiss, predominates. In this part of the section, there are intercalations of both type of gneiss. It may be due to all scale recumbent and flattened folds.

End of on foot section



Gneiss of Formation I of the HHC (Ph. AP)

Left : abundant crystals of kyanite randomly oriented in the foliation. *Right* : syn-kinematic large garnet, with an internal schistosity underlined by kyanite crystals (outcrop from Ritirbini, a cattle settlement north of Ghorepani)



Left - Formation II calcsilicate rich gneiss, road before Lete (section 7-8 / 7-9) (Ph AP). The main minerals vary significantly in amount between beds. They are :

- a pale to dark auburn biotite, coating quartz or feldspar
- plagioclase An 30-35 and microcline
- pyroxene (salite) and hornblende
- scapolite (dipyre), sometimes very abundant
- clinozoisite
- calcite, sometimes dolomite.

Right - Tourmaline-feldspar-quartz veins in the upper part of Formation II calc-gneiss. In the Kaligandaki section, large bodies of Himalayan leucogranites (such as the Manaslu granite) are missing. In their place, we will observe many pegmatite veins, with a lot of tourmaline (as also found in the granites), sometimes beryls are also found (occasionally gemstones : aquamarine)



7-8 [G38] (28°37.32'N / 83°37.76'E / 2265 m)

A wide and fresh outcrop of hornblend-biotite gneiss associated with hornblende migmatite of Formation II. Biotite-granitic pods develops sporadically parallel to foliation

7-9 [G37] (28°37.52'N / 83°37.50'E / 2420 m) At about 500 m before the Lete khola suspended bridge, well laminated gneiss with marble bands of Formation II. The green minerals are epidote and diopside, and calcite, quartz, plagioclase and muscovite. Tourmaline-quartz-feldspathic vein are found parallel to the foliation of the gneiss.

AP : in the Kaligandaki section, there is no large body of Himalayan granite, as f.i. in Manaslu area. These tourmaline rich veins are in some way the equivalent of the granite.

North of Lete (by bus)**7.10 [G34]** (28°38.83' / 83°35.67'E / 2530 m)

At the northern end of the Kalapani village on the western side of the suspended bridge over the Kaligandaki, a good exposure of coarse grained, highly foliated granitic gneiss (augen gneiss) of Formation III. It contains biotite, muscovite, garnet, quartz, feldspar and tourmaline. It is comparable with the Chame gneiss (Marsyandi river, east of the Annapurnas), dated at 513 +/- 30 Ma (Le Fort et al., 1986)



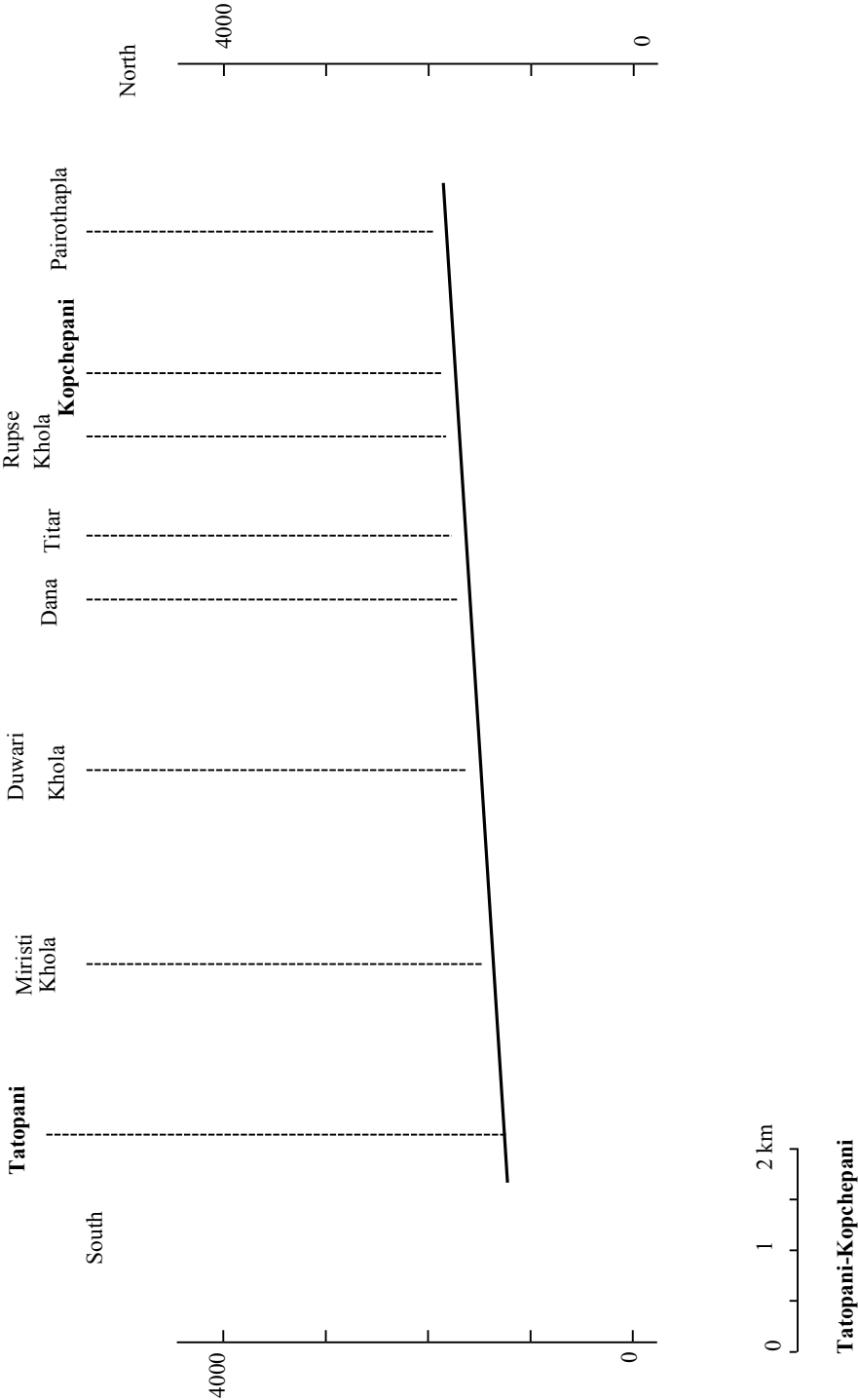
Formation III garnet rich augen gneiss, north of Lete (Ph AP).

Such augen gneiss (a former Caledonian granite) are widespread all over the Himalaya, always in the same structural position, forming thick levels or several thinner levels (old laccoliths) at the top of the HHC. In Kaligandaki, Vannay and Hodges (1996) have identified a P-T hiatus at the base of the gneiss, and inferred from that a thrust zone here (Kalapani shear-zone, see p.35)

East of the Annapurna and in the Manaslu area, the gneiss bears a strong "top-to-east" shear fabric. What about here ?

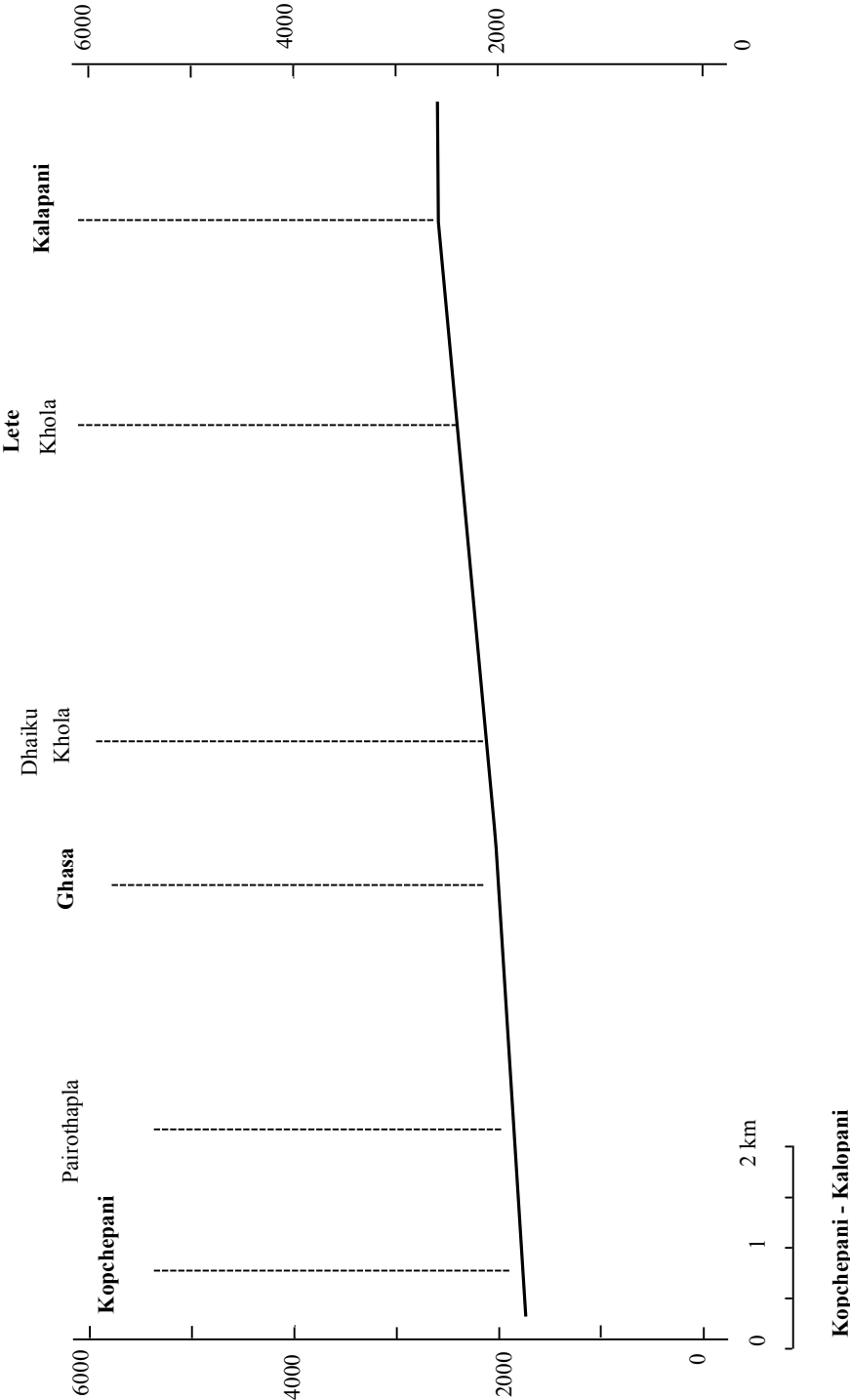
Night in Lete

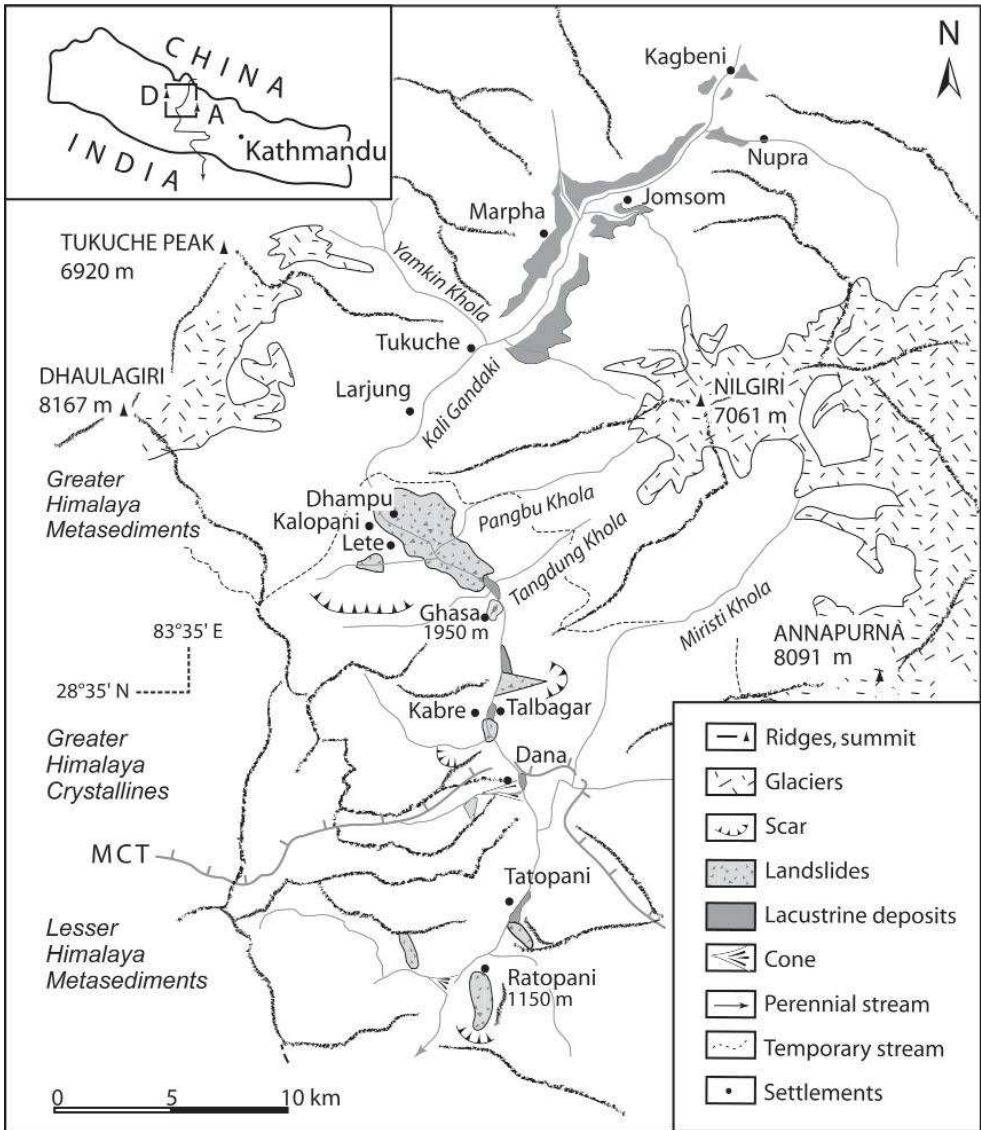
Lete is located on a large alluvio-torrential fan, fed in its upstream part by a rockslide / fall accumulation coming from the south ridge of Dhaulagiri.



(a cross-section along the gorges of the Kaligandaki, to draw by yourself :
main geological boundaries, lithology, minerals, tectonic features)

d7 (7)





Above - Quaternary deposits in the Upper Kaligandaki valley. The valley bottom is formed by a series of flat plains and narrow gorges which are interpreted as the result of mass-wasting features. In several place, they are perched remnants of lacustrine-alluvial deposits, lacustrine sediments derived from upstream and from glaciated tributary valleys, interfingering with retrogressive alluvial fan facies. Lacustrine deposits evidence the large palaeolake of Marpha. Kaligandaki alluvial deposits prograde downstream during and after complete filling of the lake (Fort and Cossart, 2013)

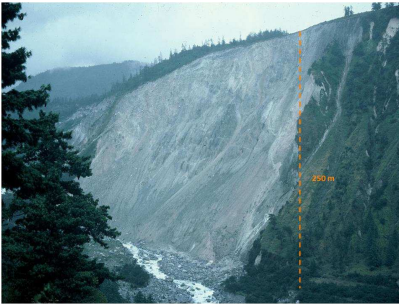
Right - The Palaeolake of Marpha. Jhong khola section, between Muktinath and Kagbeni, showing the fossilisation of a pre-existing topography (Fort, 2000).

The quaternary deposits in Kaligandaki

Large rockslide failures and debris flows are a major process shaping the Himalayas. We will see traces of 2 giant features along our route :

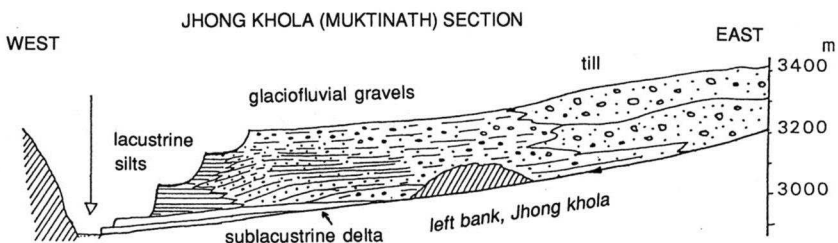
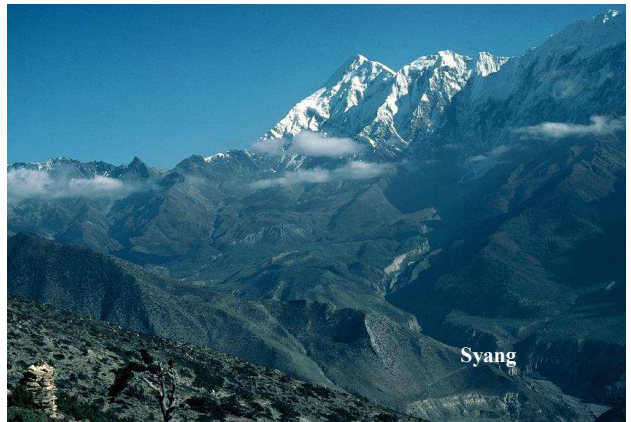
- (i) the large prehistoric Dhampu-Chhoya rock avalanche, coming from the east face of Dhaulagiri, which has blocked the river and induced a lake extending appr. 25 km to north, as far as Kagbeni,
- (ii) the catastrophic debris flow coming from the northern slopes of the Nilgiri and Tilicho peaks, at the origin of the recent Jomosom Formation.

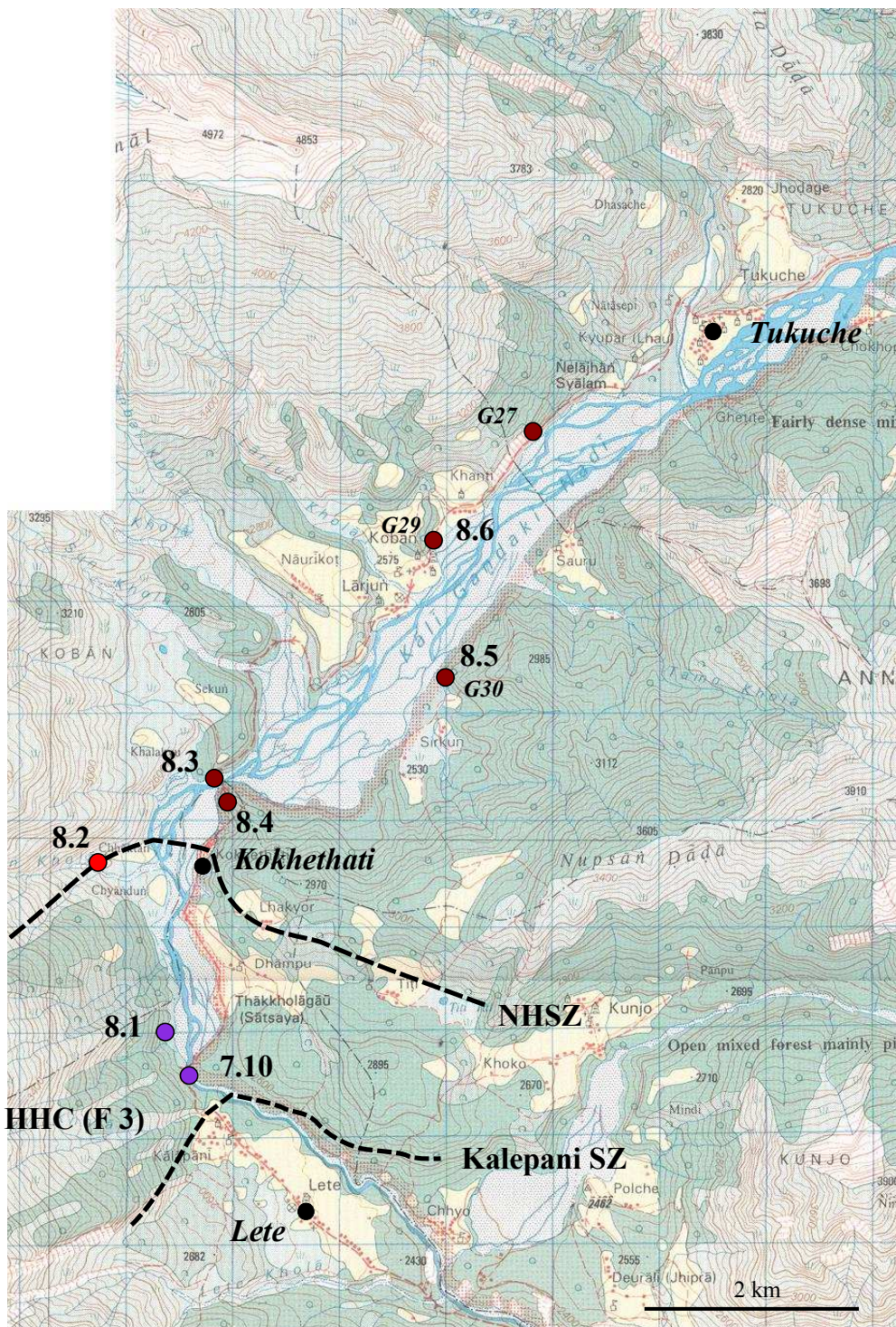
Large-magnitude low-frequency events contribute significantly to the denudation history of the Himalayas, but more frequent medium scale landslides are of daily concern for the Himalayan villagers and geotechnicians. We will see many of them in the gorges of the Kaligandaki, at Tatopani or at Talbagar for instance.



The large Dhampu rock avalanche.
Section of the Kaligandaki left bank exhibiting the fractured rock-avalanche material (Ph M. Fort).

The north face of Tilicho peak (7134 m) with the Tilicho Pass (4900 m) on the left and the Nilgiri North peak (7061 m) on the right (not entirely visible). The wide Thini valley is filled in by a complex 400-metres thick formation made of glacially derived and rockfall products overtopped by morainic ridges and reworked catastrophically by large debris flows (Fort, 2011)





Tukuche

(28°42,58N / 83°38,64E / 2590m)

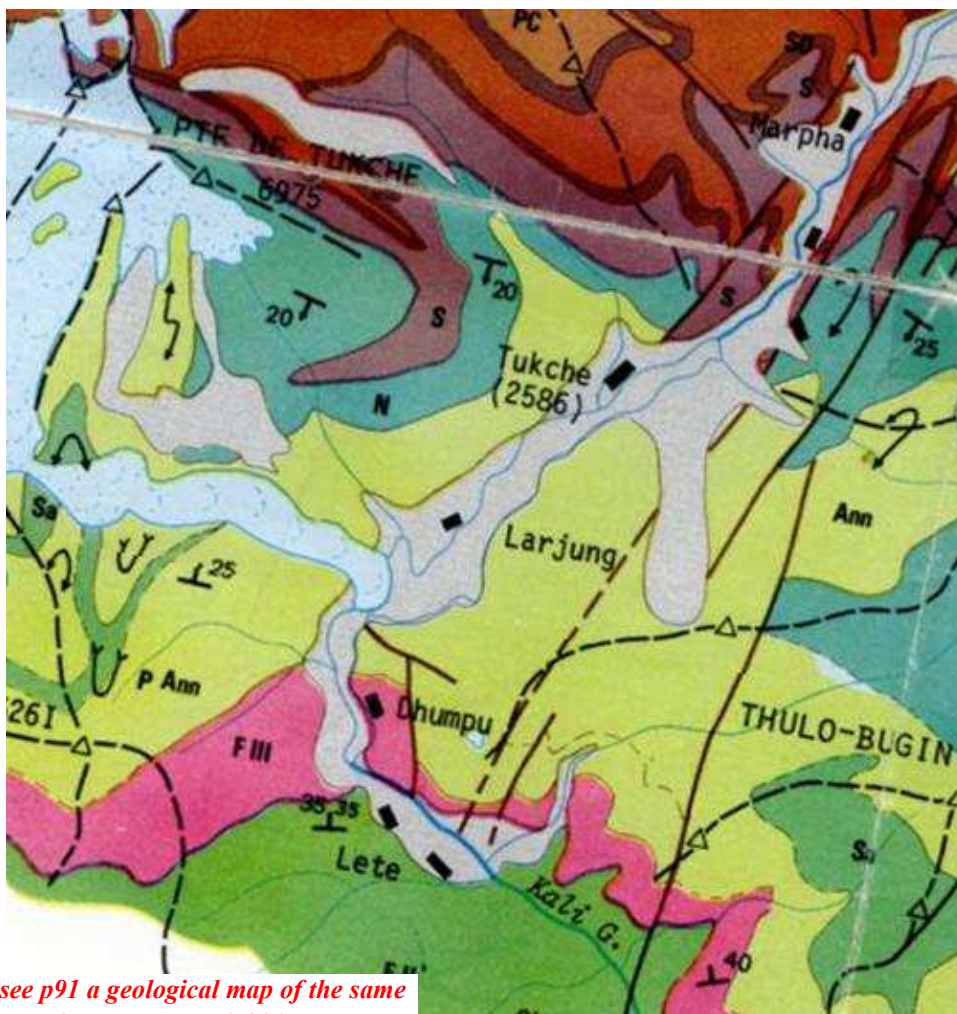
Lete

(28°38.48N / 83°35.95E / 2540m)

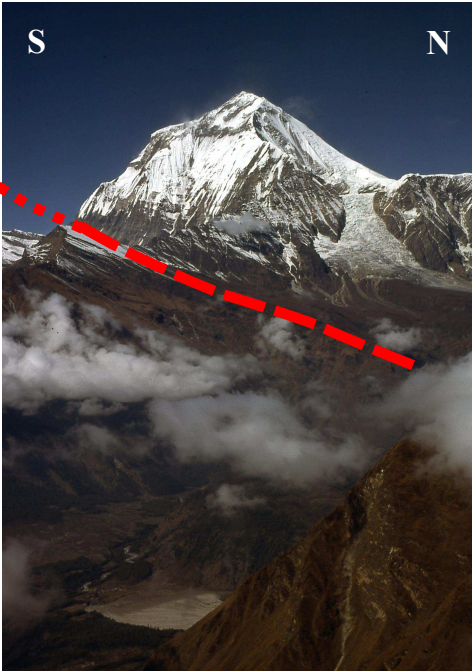
distance: 14 km m (on foot)

Topics : STDS and Paleozoic Series

Up to the bridge north of Kokhethati, we will follow either the road, or the alternate trail, left bank of the Kaligandaki, via Chhyo and Kunjo. Then we will proceed along the trail on the left bank of the Kaligandaki, with a nicer walk and probably better outcrops than along the road, which mainly stays in terraces. We have to come back to the road to join Tukuche for the night, by a temporary bridge south of Tukuche (or backtrack about 2 km from the bridge north-east of Tukuche if the temporary bridge is out).



see p91 a geological map of the same zone by Parsons et al.,2014

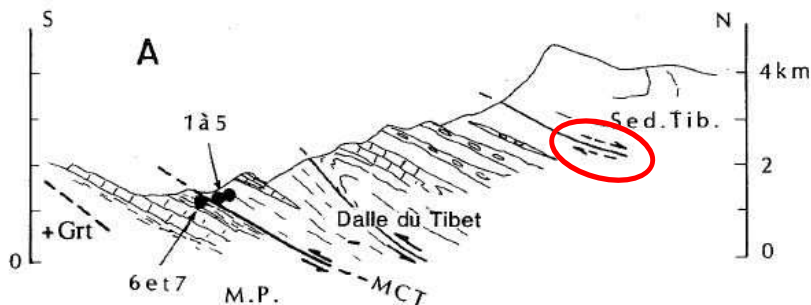


The STD on both sides of the Kaligandaki

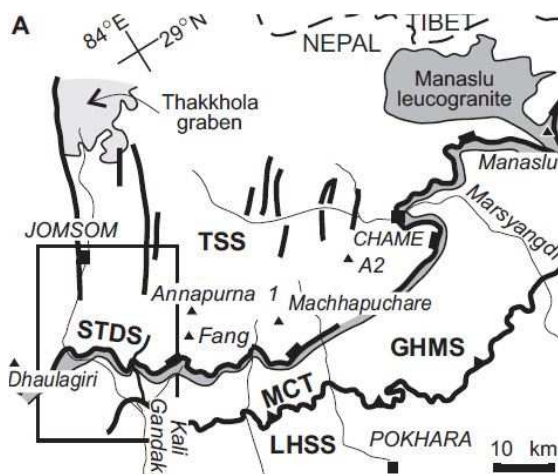
The Dhaulagiri (8167 m) seen from the ridge of Thulo Bugin (right bank of the Miristi, a tributary of the Kaligandaki) (Ph AP). The terrace of Lete (2540 m) is visible in the bottom of the valley. Dotted red line : the STD



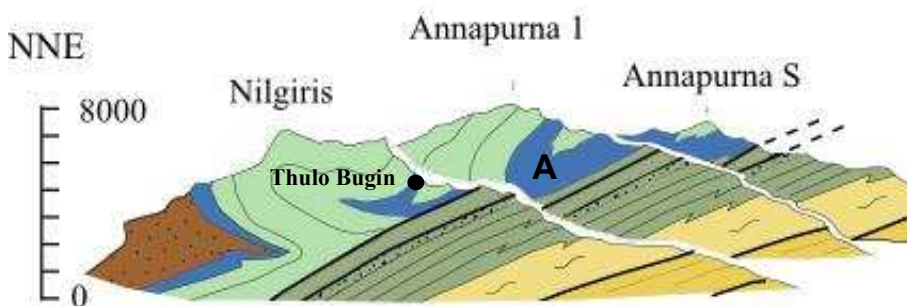
Above the STD, the Annapurna fold (Ph AP)
From Thulo Bugin (around 5000 m), looking eastward, Renaud Caby in front of the western face of Annapurna 1, of lower Paleozoic age.
The dotted line underlines the hinge of the huge Annapurna fold (A on section p. 69 bottom) which can be followed eastward along strike on more than 140 km, as far as the Manaslu area.



Above : The STDS (or rather the North Himalayan fault) was first pointed out (but not named) in Nepal by Caby et al. (1983), as shown on this section.



The North Himalayan Fault is not an discrete fault, but a few tens or hundreds meters thick shear-zone, more often called the STDS (although geologically it doesn't belong to Tibet or bound it !) It can be followed all along the Himalaya (on this map by Gaudin, 1999, it is traced from Dhaulagiri to Manaslu), with sometimes a duplicate fault further north.



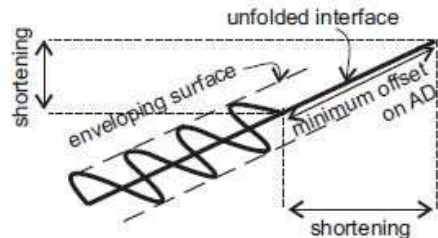
A cross-section passing through the Nilgiri summit (in Mascle et al. 2012). A : Annapurna fold



For Caby et al. 1983 (and many others after them), the Annapurna fold was a collapse structure, a kind of mega drag-fold in the sedimentary pile sliding northward on a north-dipping tectonic contact.

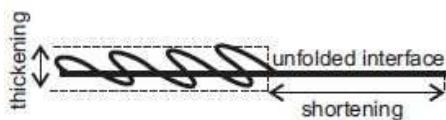
Godin et al. (1999) proposed an alternative model, the north verging Annapurna fold being the trace of eohimalayan north vergent tectonic (as described in western Himalaya in the Chandra fold or the ShikarBeh nappe, cf. Epard et al., 1995)

A Model 1: Drag folding related to extensional faulting

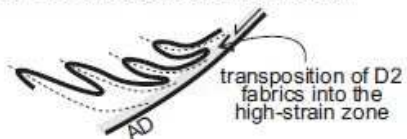


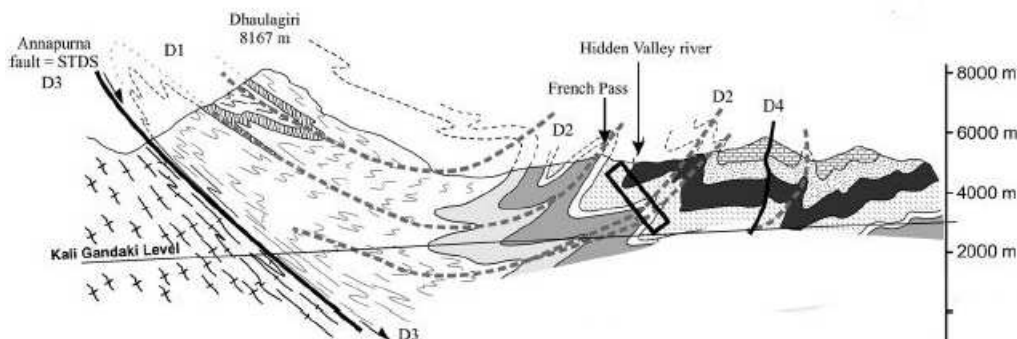
B Model 2: Contraction-generated folding

Part 1 - Northeast-verging contraction

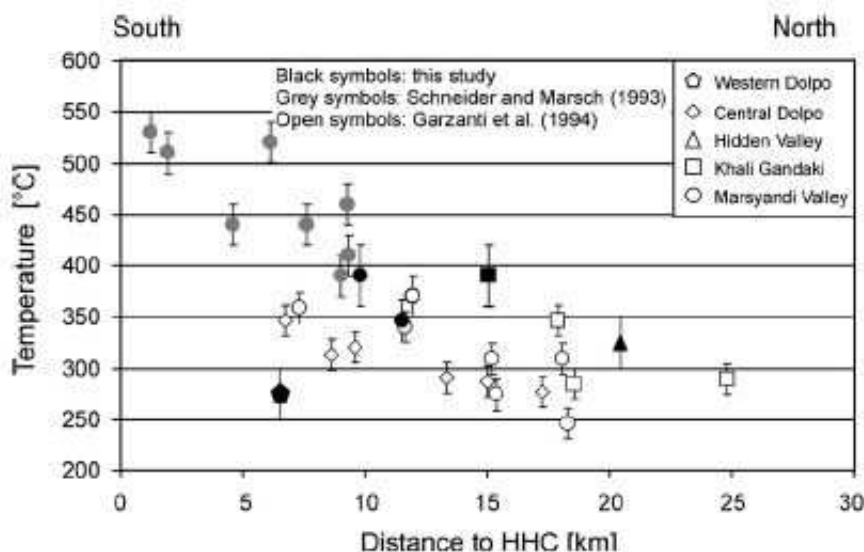


Part 2 - Ductile extensional deformation

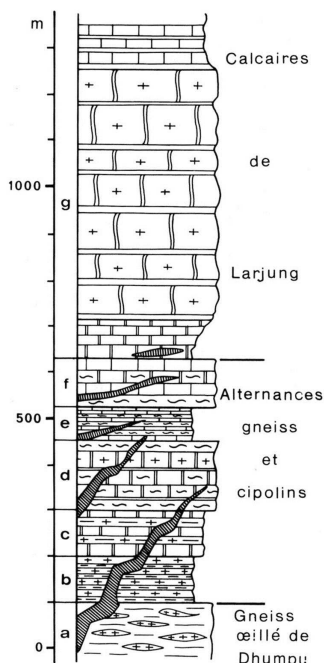




Geological cross-section of the ridge right side of the Kaligandaki river through the Dhaulagiri and Hidden valley area (Hidden valley is just backside of the "French pass" - a name given by the climbers of the first ascent of the Annapurna, in 1950 -) and of the Tukuche Peak. The fold labelling follows Godin's alternate model (Crouzet et al., 2007)



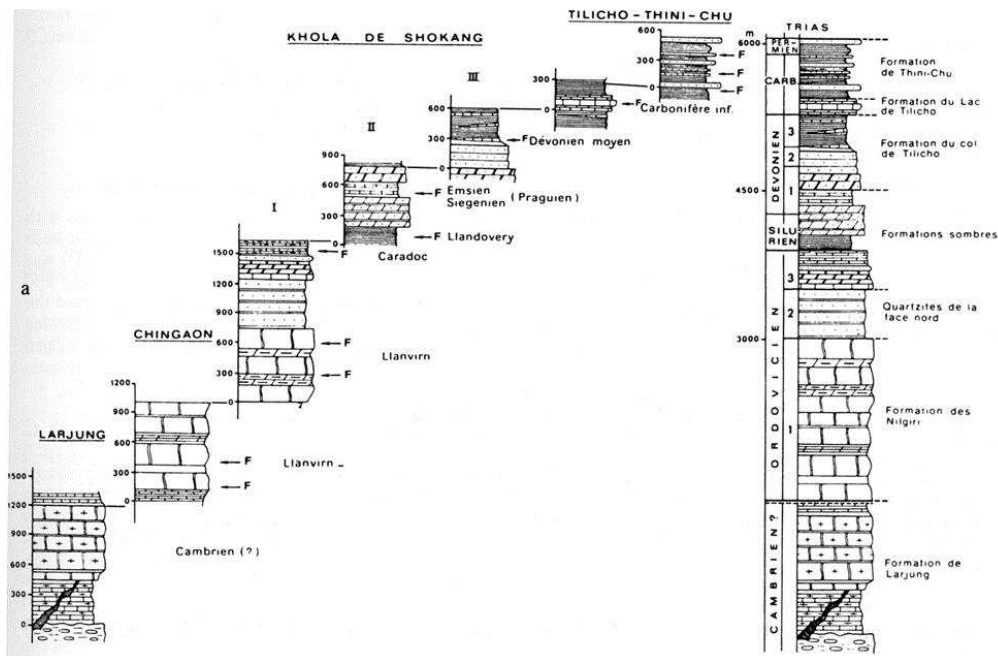
When moving northwards from the STDS, the peak metamorphic temperature quickly decreases in the Paleozoic cover. This figure (Crouzet et al., 2007) shows the shift of temperature versus distance to HHC (or STDS). Temperatures are from illite and chlorite "christallinity", vitrinite reflectance and calcite-dolomite thermometry. In Marpha area, illite K/Ar and zircon FT gives cooling ages of 12-15 Ma.



Above : the contact between the HHC and the sedimentary series in the Chhaktan khola (Ph. AP, stop 8.1)

Left : from the same area, a lithostratigraphy column of the contact zone (Bordet et al., 1971)

Below : Stratigraphy of the Paleozoic in Kaligandaki (Bordet et al., 1971)



8.1 (28°39,06'N / 83°35,58'E / 2505 m, road right bank of the Kali). Augen gneiss of the Formation III. Stretching lineation rather weak, striking N75° to N85°E, sense of shear more often top to West

8.2 [G32] (28°39,90'N / 83°35,02'E / 2670 m). In the Chhaktan khola, a good exposure of STDS marking the boundary between the Tethys sediments (the Annapurna Yellow Formation, also called the Larjung Formation) to the north, and the HHC gneiss to the south. The basal part of the Annapurna Yellow Formation consists of calcareous meta-sandstones with quartz, feldspar, biotite and calcite. The Cenozoic tourmaline-bearing leucogranite intrudes into the marble. The augen gneiss of the HHC also appears to be intrusive in the marble. Thus the STDS is not ascertained at this critical outcrop. *AP - The description from Upreti and Yoshida is interesting, as this outcrop is now classically described and regarded as the STDS. It is in accordance with the description of Bordet et al (1971) (fig. p. 72), who first described this contact (as a non-tectonic contact)*

8.3 [G31] (28°40,32'N / 83°35,84'E / 2505 m, right bank of the Kali, at the bridge). Annapurna Yellow Formation. For Searle 2010 and Parson et al. 2014, we are right on the STDS. Actually, it is not obvious to see indications of a large normal fault here...

8.4 (28°40,14'N / 83°35,82'E / 2515 m) . Lower part of the Annapurna Yellow Formation,. South of the bridge, spur left bank of the Kali. Coarse-grained arenaceous grey marble with the schistosity shown by biotite flakes. Few shear criteria (dissymmetric boudinage, S-C fabric), mixing both normal fault and reverse fault type movements.

8.5 [G30] (28°40,87'N / 83°37,11'E / 2555 m). Cataclasite / breccia zone in the Annapurna Yellow Formation. It develops for about 3 km along the left bank cliff of the Kaligandaki. There is a possibility that this cataclastic zone is correlated with the STDS. From here, it is possible to cross the Kali on a temporary bridge and reach the road on right bank at koban.

8.6 [G29] (28°41,49'N / 83°37,05'E / 2570 m) and **G27]** (28°42,06'N / 83°37,66'E / 2620 m). Road cut on the right bank of the Kaligandaki : good outcrops of the Annapurna Yellow Formation, with still biotite .at the beginning of the section

The Paleozoic

From Kokhethati to Jomsom, the trail stays in the Paleozoic

Two distinct formations can be assigned to the Ordovician :

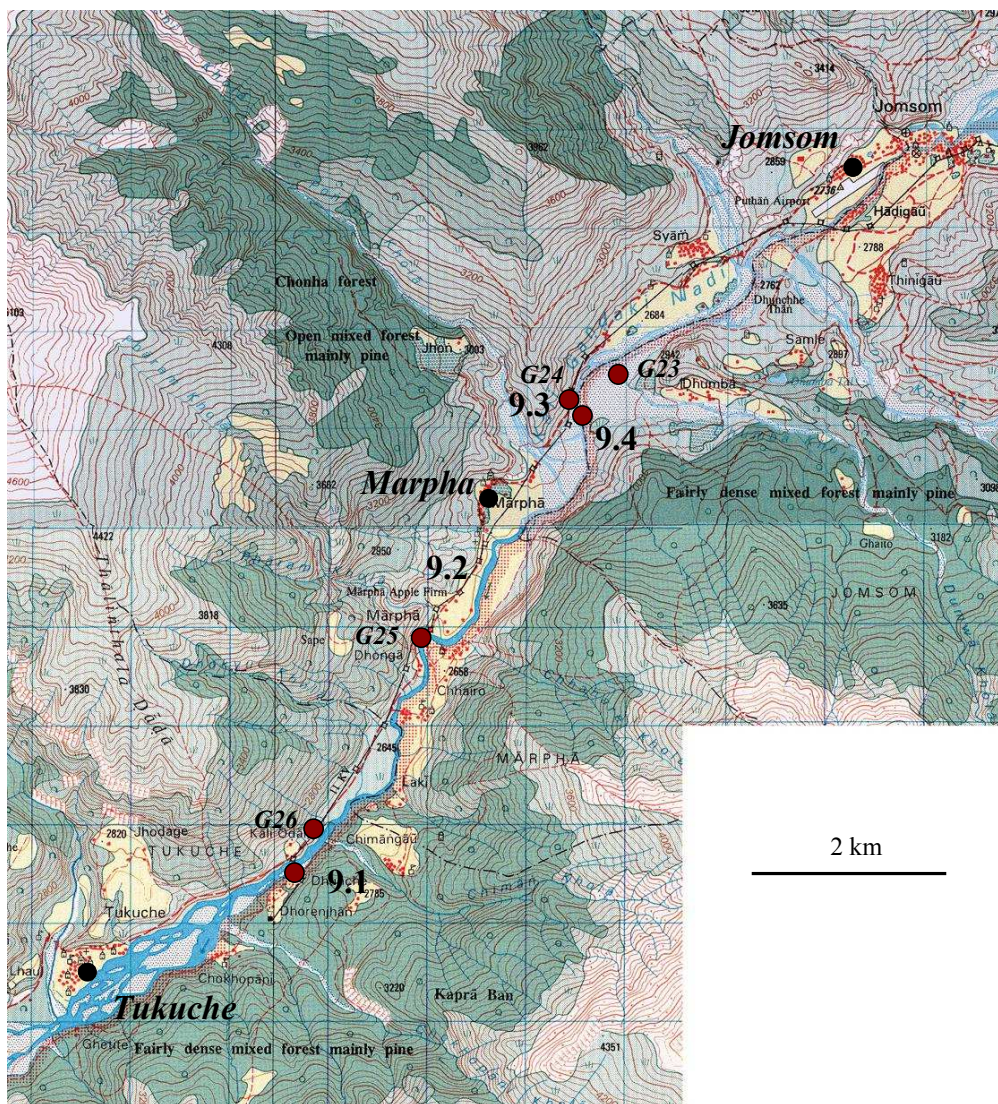
- blue and ochrous limestone of the Nilgiri (1500 m in Nilgiri area) : blue limestone with ochrous veins alternating with predominantly ochrous calcareous schists with oblique stratifications and lumachellic beds with Brachiopods (Llanvirnian),
- quartzite and calcareous schists of the North Face. Detrital sandstone formation (quartzite, 400 m) followed by dolomite and limestone (120 m), sandstone with Brachiopods lumachelles (50 m) and lastly white-pink calcschist with highly fossiliferous levels (230 m).

The Silurian comprises black shale and sandstone with Graptolites (120 m : it is the "dark band" often well visible in the landscape), followed by gritty dolomites (280 m),

The Devonian. Three formations have been identified :

- alternation of black shale and limestone (150 m)
- gritty dolomite, sandstone, lenticular microconglomerates (500 m), followed by some calcareous beds with corals,
- alternations of episodically carbonated shale and sandstones (Tilicho Pass Formation) (about 500 m).

Most of the outcrops from south of Marpha to the Syang khola, south of Jomsom are Devonian.



Jomosom

(28°46,93N / 83°43,37E / 2750m)

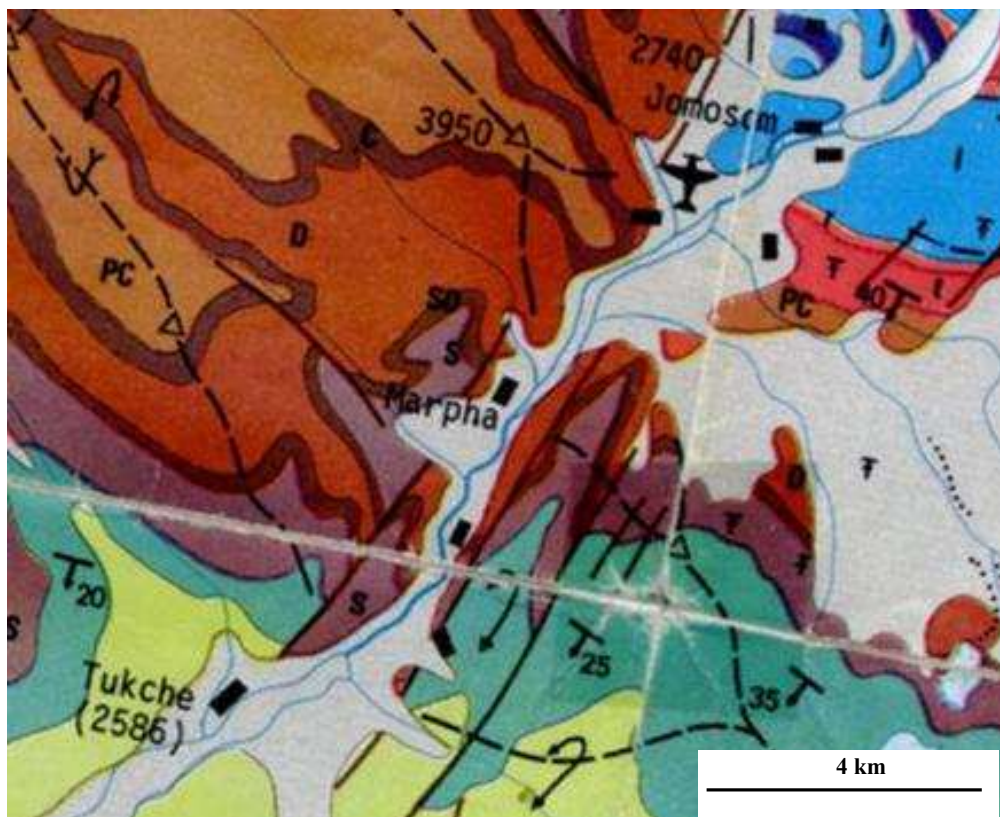
Tukuche

(28°42,58N / 83°38,64E / 2590m)

distance: 13 km m (on foot)

Topics : Paleozoic Series

Given outcrops are those described by Upreti and Yoshida (2005), on the right bank of the river. Several bridges give access to nice footpaths and good outcrops too on the left bank of the Kali.

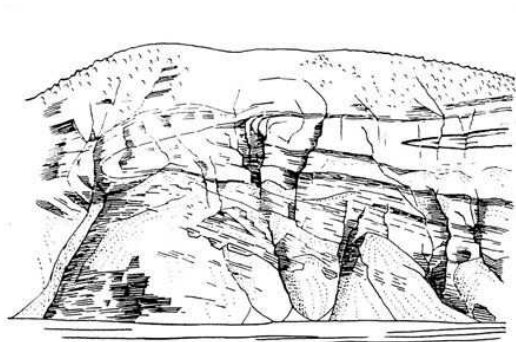


[G26] (28°43,34'N / 83°40,13'E / 2635 m). Just north of the Kali Odar village, calcareous shale/ limestone alternations occur. Limestones carry thin laminated structure. Proportion of the limestone appears to decrease northward. Argillaceous facies contain sericite and biotite and change to "semischist".

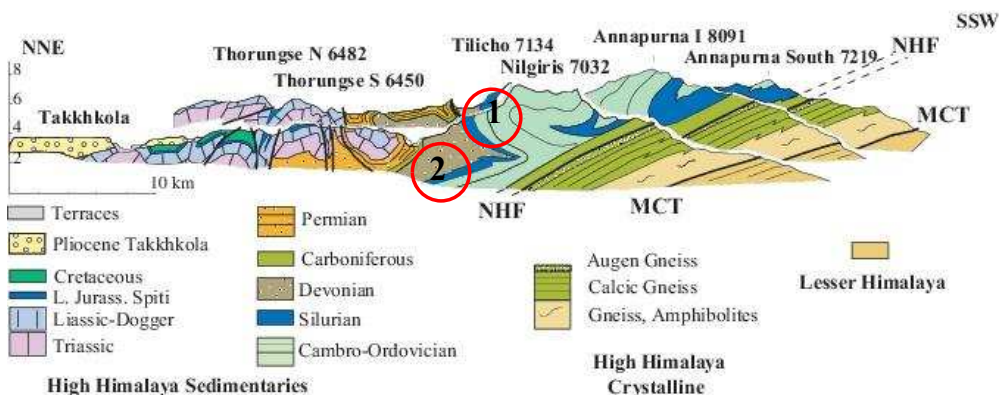
9-1 (28°43,08'N / 83°39,84'E / 2610 m). Little before (South of) G26, left bank of the Kali, at the bridge, a good outcrop of the same limestones. If you stay on the path left bank, possibility to come back to Marpha at the bridge (gompa) 2.5 km to the North.



The back of the Annapurna fold, on the summit of the "Grande Barrière" (Tilicho Peak). Underlined by the red line : the hinge, visible in the Ordovician Nilgiri limestones (label 1 on the section) (Ph. AP)



The large recumbent fold opposite to Marpha (Ph. AP, drawing : Bordet et al. 1971). In the core of the fold, the "dark band" (lower Silurian), surrounded by the Tilicho Pass Formation (Middle Devonian) (label 2 on the section)



Structure of the Tethys Himalaya in the Kaligandaki (Annapurna) section (Colchen et al. 1986 modified, in Mascle et al., 2012)

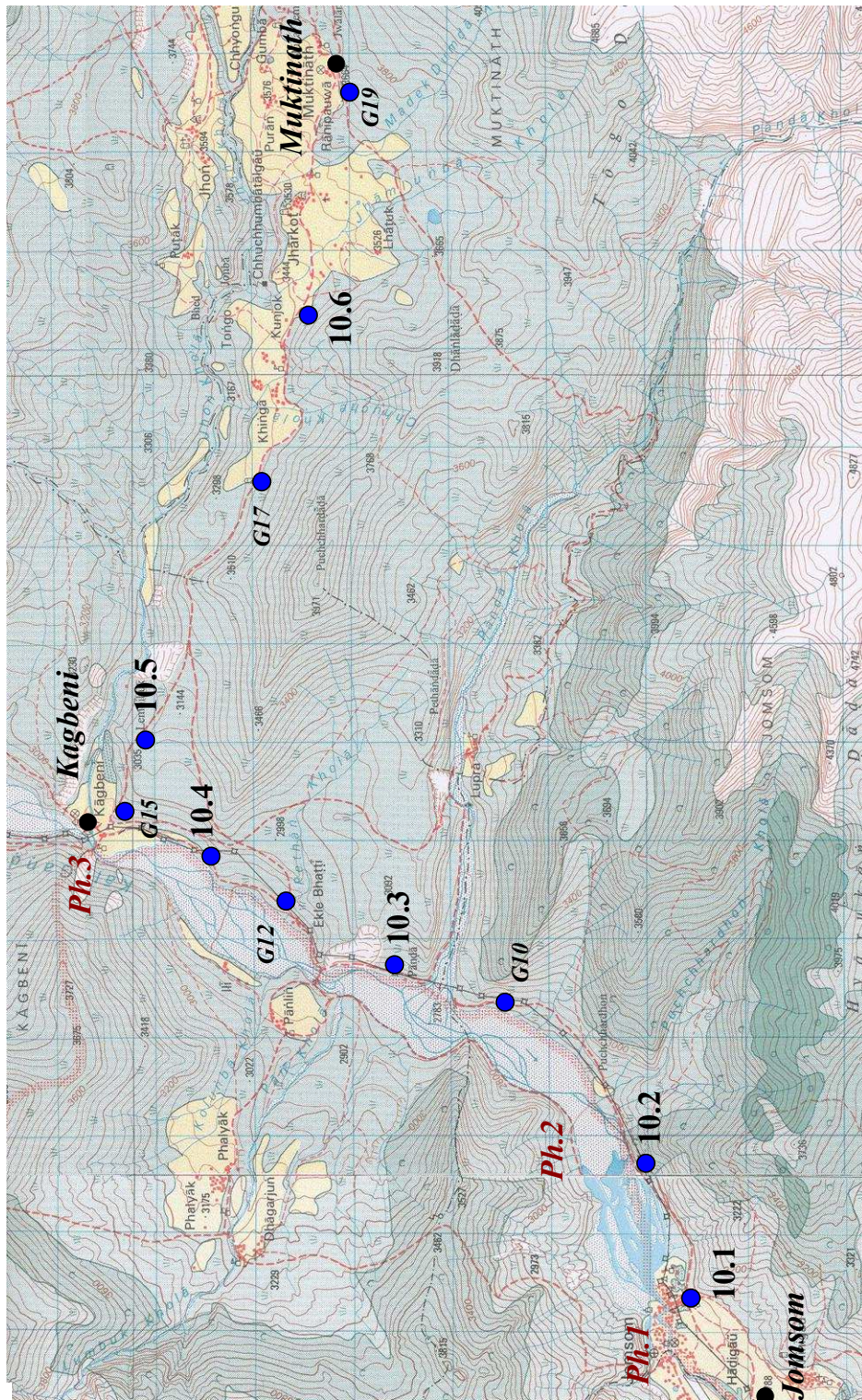
9.2 [G25] ($28^{\circ}44,39'N$ / $83^{\circ}40,83'E$ / 2650 m). Marpha recumbent fold. A possible family of this recumbent fold also develops on the right bank cliff of the river, with an apparent opposite vergence. May be an artefact, as the fold axes are nearly parallel to the Kaligandaki valley (NE-SW), the folds forming a couple of a large antiform and a synform, with a common NW vergence.

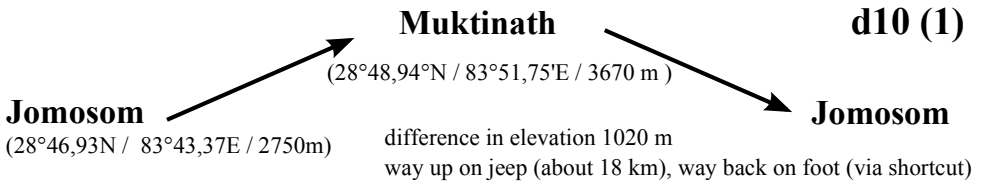
9.3 [G24] ($28^{\circ}45,59'N$ / $83^{\circ}41,66'E$ / 2695 m). Rocks of the Tilicho Pass Formation. Schistosity inclined from the bedding is observed. Some exposures of well laminated (some mm to cm thick), thick bedded (over 1 m) grey limestones with calcareous shale. A beautiful recumbent fold is observed with a marble layer at the core.



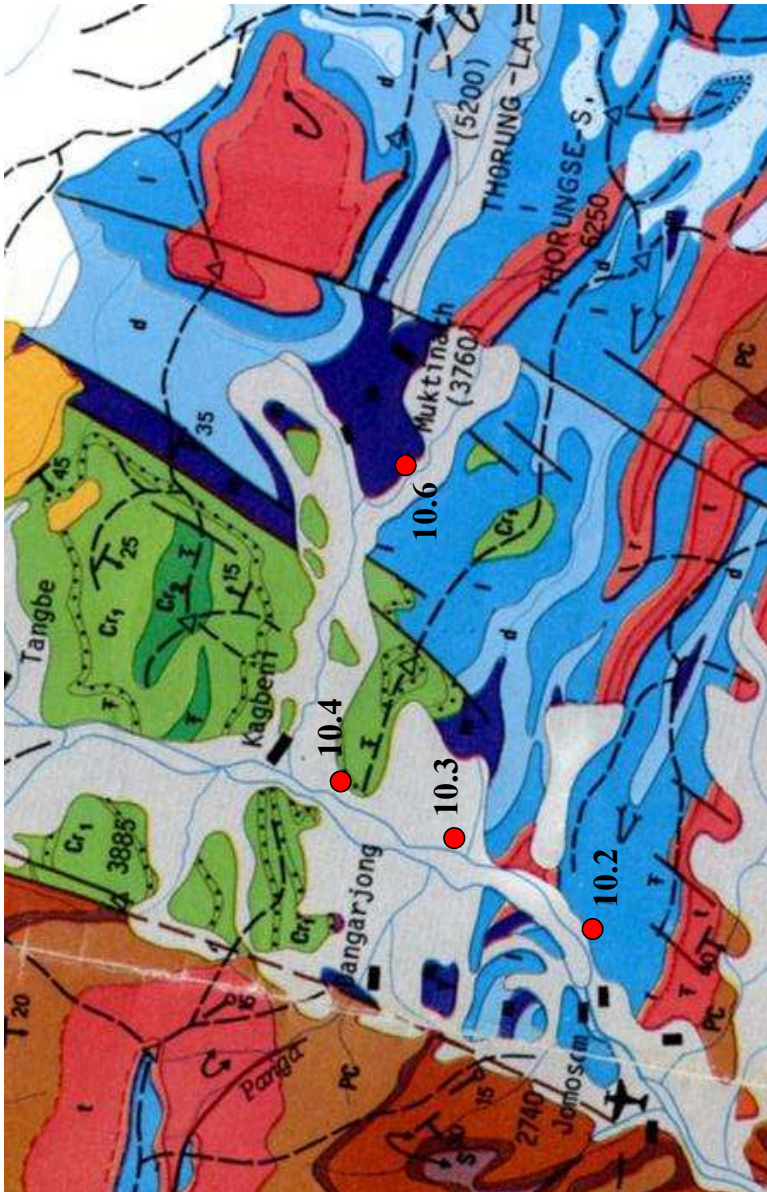
9.4 ($28^{\circ}46.00'N$ / $83^{\circ}42,31'E$ / 2695 m, left bank of the Kali, few 10 meters south of the bridge). Rocks of the Tilicho Pass Formation. A very good outcrop, with metric isoclinal folds cut across by the schistosity, dipping South.

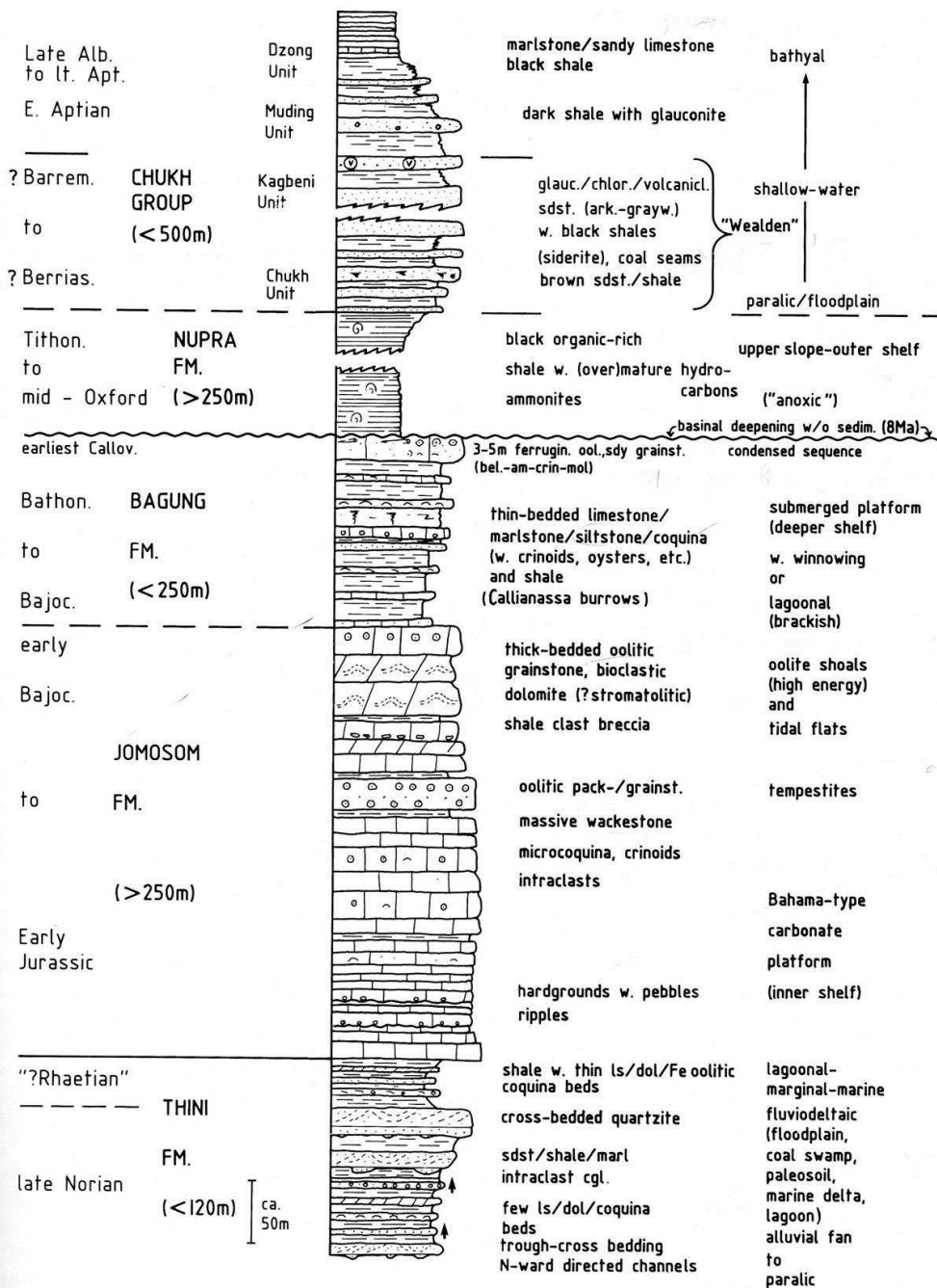
9.5 [G23] ($28^{\circ}45,92'N$ / $83^{\circ}42,19'E$ / 2710 m). To the south of the Syan village and on the left bank of the Kaligandaki, an exposure of well banded greenschist, pelitic schist, psammitic schist and quartzite occurs forming a large, high and steep cliff. These rocks are metamorphosed supracrustal rocks under greenschist facies conditions and contain albite, chlorite, sericite, epidote, and possibly pumpellyite, and belong to the Tilicho Pass Formation. A sudden change of the metamorphic grade compared with rocks to the north is noticeable.





Topics : Mesozoic Series





The Mesozoic stratigraphy in Thakkhola (upper Kaligandaki valley)

Fig. p. 80 and synthesis here below are from Gradstein et al. (1989), a very detailed study of the Mesozoic of Thakkhola. Description of stops are from Upreti and Yoshida (2005)

Mesozoic strata of Thakkhola, Nepal, are grouped into five mappable stratigraphic units that range in age from late Triassic through mid-Cretaceous (latest Albian), and are almost 1.5 km thick. The oldest unit, the **Thini Formation**, is Late Triassic (Norian) in age. The formation consists of well-bedded siliciclastics and carbonates, with carbonates increasing in frequency and thickness upward. The environment was near-shore to locally terrestrial, in the vicinity of an active river system. Sediment transport was from south to north.

There is a gradual and conformable transition from the terrigenous-clastic Thini Formation into the overlying, thick-bedded carbonate unit, the **Jomosom Formation** (Early Jurassic). It consists of well-bedded limestones, with minor marls or shales; it was laid down in a subtidal carbonate-shelf deposits, with evidence of storm-wave action and currents. Grainy sediments, mainly oolitic, are storm-transported and the depositional environment was shallow marine and tropical. Sequences terminate with the development of oolitic shoals. The top of these oolitic bars is sharp and indicates the onset of a new episode of submergence.

A similar depositional style is evident for the conformably overlying unit, the **Bagung Formation** of mid-Early Bajocian through earliest Callovian age (Middle Jurassic). In the Bagung Formation the nature of storm-transported sediment changed to molluscan, oyster-type, lumachelle. This indicates a change from a tropical carbonate platform into a terrigenous-dominated coastline, at a subtropical to temperate latitude.

A hiatus of considerable duration (late Early Callovian through Early Oxfordian, i.e. 6-9 Ma), separates the "ferruginous oolite" of the upper Bagung Formation from overlying dark-colored, fissile shales, the **Nupra Formation**. There is no evidence of emergence during that period, but a marine basin devoid of sedimentation. Climate was probably arid.

The **Nupra shales** (from middle Oxfordian through late Tithonian) are over 250 m thick. Ammonites and belemnites are relatively abundant in this Formation and indicate open-marine conditions in a deep shelf to upper slope basin. The lower Nupra foraminiferal assemblage may have lived under low-oxygen conditions on the outer shelf or upper slope. The upper Nupra shale contains a calcareous benthic species that occurs in deep shelf environments down to deep ocean settings. Shallower, more oxygenated conditions prevailed in Tithonian time.

The transition from Nupra shales to **Chukh Group** is gradual with increasing silt deposition, in a prodelta setting. The Chukh Group (Early Cretaceous) consists of massive to cross-bedded quartzites, silty shale with calcareous cement and plant remains (**Chukh Unit**), followed upwards by terrigenous clastic strata with glauconite and epiclastic volcanoclastic sandstones and conglomerates (graywackes of the **Kagbeni Unit**), in turn overlain by dark shales with glauconite, small concretions and Aptian ammonites (**Muding Unit**). The highest unit of the Chukh Group (Dzong Unit, latest Albian) consists of glauconitic sandstones changing upwards into pelagic marlstone with radiolarians and planktonic foraminifera.

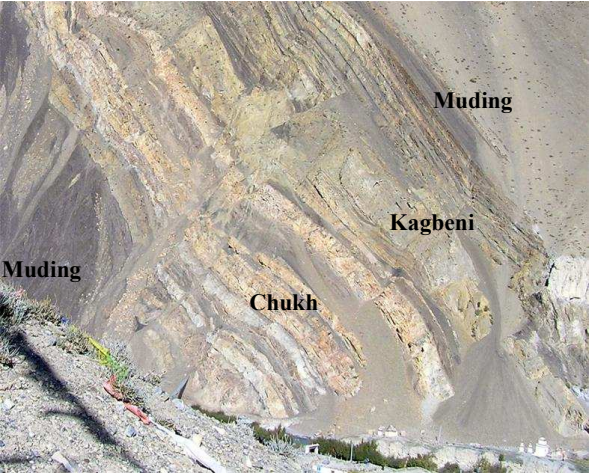
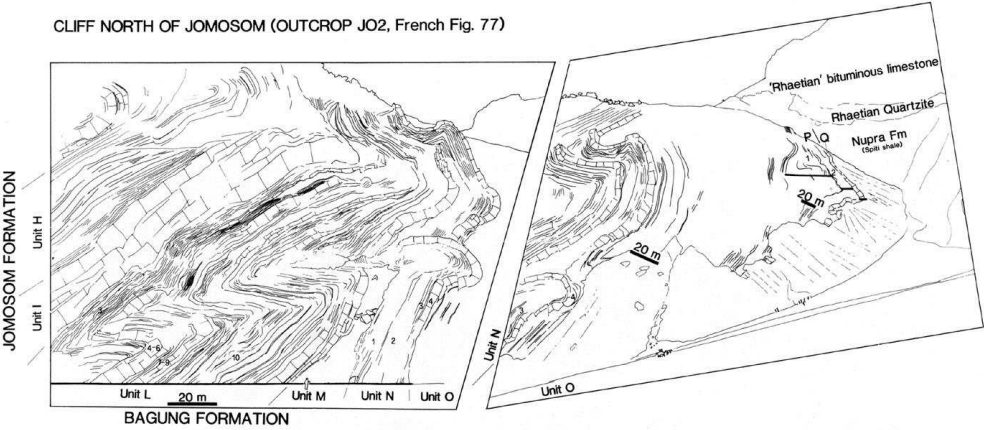
The Neocomian-Aptian volcanoclastic components point to erosion of preexisting outcrops of mafic rocks in subaerial, coastal or submarine environments, during the same interval of time that seafloor spreading started along northwestern Australia and the Ramjahal Traps formed in eastern India.

The Jomosom carbonate platform deposits concur with (sub) tropical conditions in the Early Jurassic, and the siliciclastic sediments of the Nupra Formation and lower Chukh Group concur with a more temperate latitudinal position for Thakkhola in Late Jurassic and Early Cretaceous time. Observations suggest that the Thakkhola Himalayan region was part of a continental margin, facing the Tethys ocean.



Left ph. - The cliff
backside of Jomosom, in
Early and Middle Jurassic
(Gradstein et al., 1989)

CLIFF NORTH OF JOMOSOM (OUTCROP JO2, French Fig. 77)



The cliff facing Kagbeni, right
bank of the Kaligandaki. From
bottom (S) to top (N) : Muding,
Chukh and Kagbeni formations
(Early and Middle Cretaceous)
(Ph. AP).

10.1 [G7 - G8] On the terrace of Jomosom, the west bank of the Kaligandaki displays (fig. p. 82 top, and map 79) (i) thick horizontal deposits of light yellowish brown lake sediments. The Quaternary lake deposit is composed of fine-grained sand and silt. The thickness of the lake deposit is more than 30m. The lake sediments are resting unconformably on the Jomsom Formation. Similar kinds of lake deposits exist lower in the valley, mainly around Marpha and Chimangau village, along the Chiman khola, (ii) a beautiful cliff with the lower Jurassic Jomsom Formation.

10.2[G9] (28°47,20'N / 83°44,90'E / 2775m) Outcrop of the Jomosom Formation : sandstone and shale alternations with a gentle dip crop out, which are unconformably overlain by the Quaternary lake sediment. Dark grey limestones some tens of meters north.

Further northwards along the Kaligandaki valley, steeply to moderately dipping monoclinical or folded rocks (some recumbent folds, see fig. left) of the Jomsom and Baglung Formations is observed extensively on both mountain slopes of the Kaligandaki.

10.3 [G11] (28°48,72'N / 83°46,16'E / 2810 m) South of the Ekkle Bhatti village. On the left bank of the Kaligandaki river, an exposure of dark fine-grained micritic limestone intercalated with shale is observed. This is the type lithology of the Lumachalle Formation. Dark coloured, coarse-grained sandstone is also interbedded. Limestone interbedded with gray shale contains abundant fossils of bivalves and belemnite, giving an age Middle Jurassic (175-161 Ma).



10.4 [G13] (28°49,53'N / 83°46,81'E / 2900 m) (along the river, below the road)

At about half-way between Ekle Bhatti and Kagbeni, there is a good exposure of the Chukh Formation (Lower cretaceous, about 145-100 Ma). Thick beds of pebbly sandstones show a fining upward sequence. They are poorly-sorted, with cross-beddings. Plant fossils and ripple-marks are also preserved in the sandstone!

10.4b [AP] - A similar outcrop will be observed higher in the slope (28°49,58'N / 83°47,06' / 3065 m), along the track, on our way down (Ph. above, in Mascle et al., 2012). Beds are vertical; the stratigraphic top is on the right; the sedimentary sequence begin with calcareous sandstones full of floated shells and vegetation debris which characterize storm deposits; the top is marno-pelitic with varicoloured pipes (M) which represent infilling of halophyte roots (mangrove)

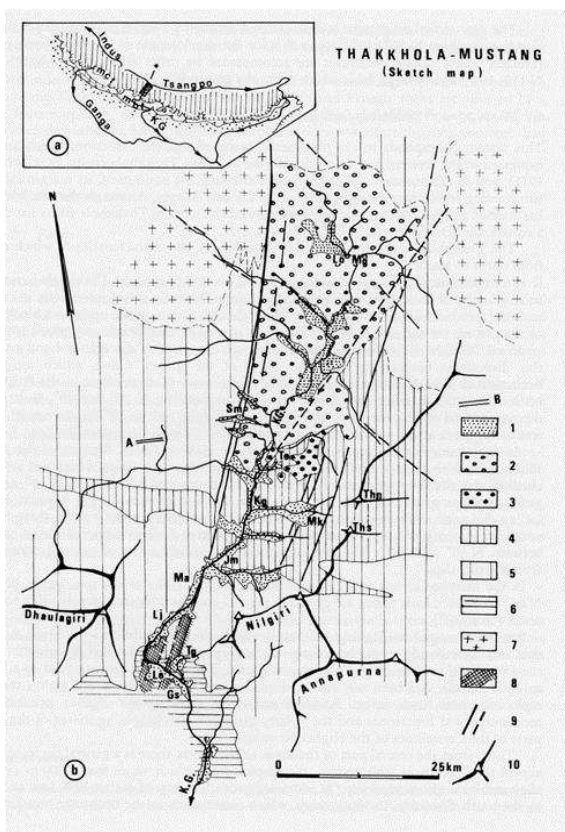
10.5 [G16] (28°49,97'N / 83°47,39'E / 3040 m) (terrace east of Kagbeni)

A beautiful view of the Tibetan Himalayan zone. To the north, upper reaches of the Kaligandaki river, called the Thakkhola, where the upper Mustang district extends, are well exposed, with the Thakkhola graben formations (see next page).

To the west, steep slopes of 6000 m peaks (Sandachhe Himal), west of Thakkhola fault. The large recumbent fold of the Dangmar mountain is in Permo-Triassic series. Lower in the slope, east of Thakkhola fault, the middle to lower Mesozoic sediments can be seen. At the base of the slope, facing the village of Kagbeni, the Chukh Group (Lower Cretaceous) is observed (left ph.)



From the trail joining Kagbeni to Muktinath, looking south, the Dhaulagiri and Tukuche peaks. The peaks are composed of lower Paleozoic rocks. The STDS is below to the left (Ph AP)



Geological map of the Thakkhola-Mustang graben (Fort et al., 1982)
 1- Fluvio-glacial gravels and alluvial deposits, 2 - Thakkhola Formation, 3 - Tetang Formation, 4 - Mesozoic series, 5 - Palaeozoic series, 6 - Crystallines, 7 - Mustang leucogranite, 8 - Mylonites

10.6 [G18] (28°49,18'N / 83°50,07'E / 3415 m) (east of Kunjok village)

The rocks of the Spiti Formation are exposed between Kunjok and Jharkot. Here the pencil-cleaved black shale with thin layers of dark grey limestone is well exposed. Spherical to flattened spherule-shaped light yellow to dark brown calcareous concretions, which sometimes carry good ammonite fossils (saligram in Nepali language), occur sparsely within the layers of shale and limestone. Just about 300 m down from the route along the Jhamiunda khola, a lot of ammonite fossils and concretions up to 2 m in diameter can be found.

Muktinath

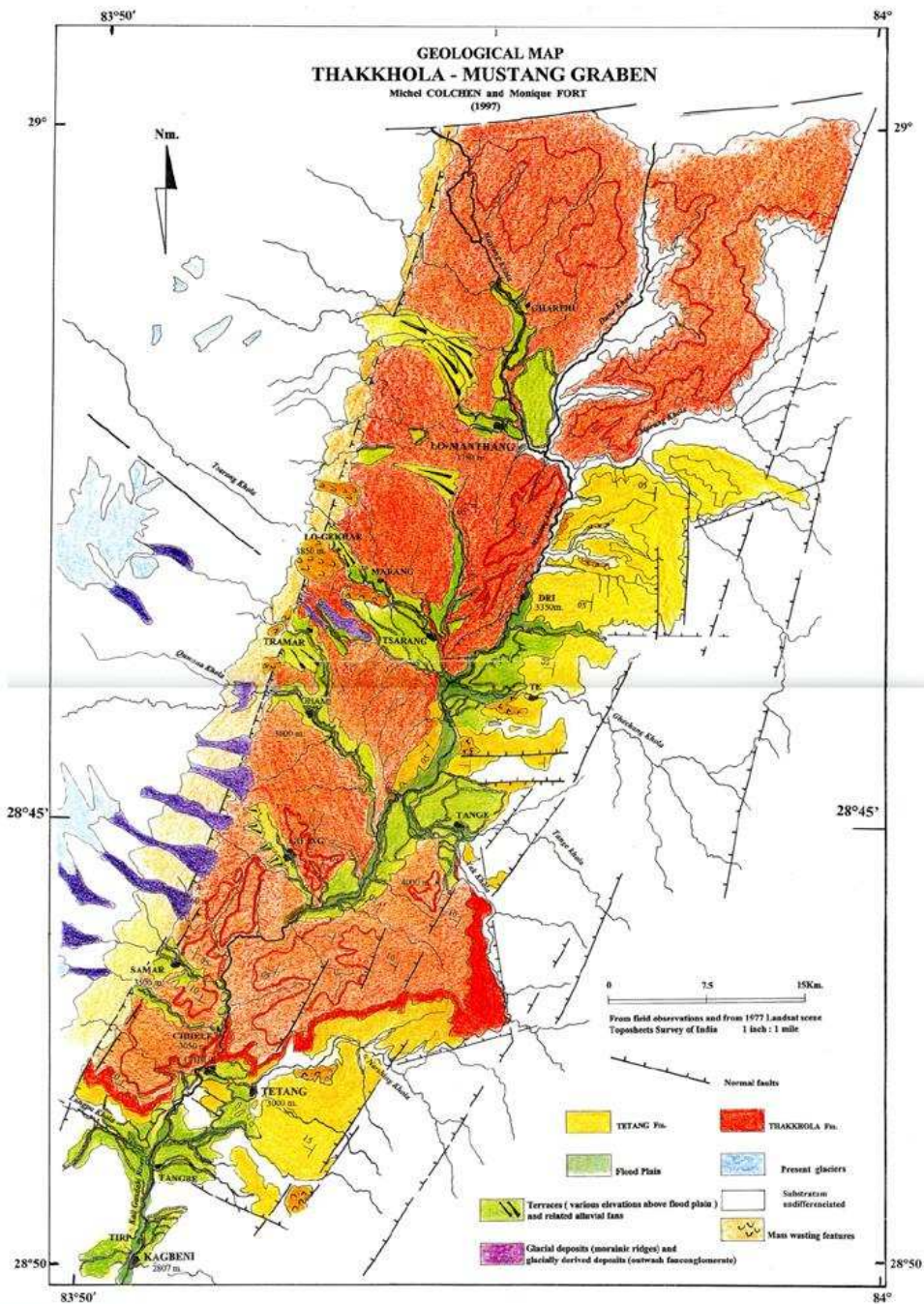
Muktinath village is situated at a height of about 3700 m. The village is named after the holy temple of Muktinath situated on the highest part of the village. One of the most interesting aspect in Muktinath area is the seepage of methane gas from the moraine sediments below the temple, which feeds the flame in Muktinath temple.

The Thakkola-Mustang graben (Fort et al., 1982, Colchen, 1999)

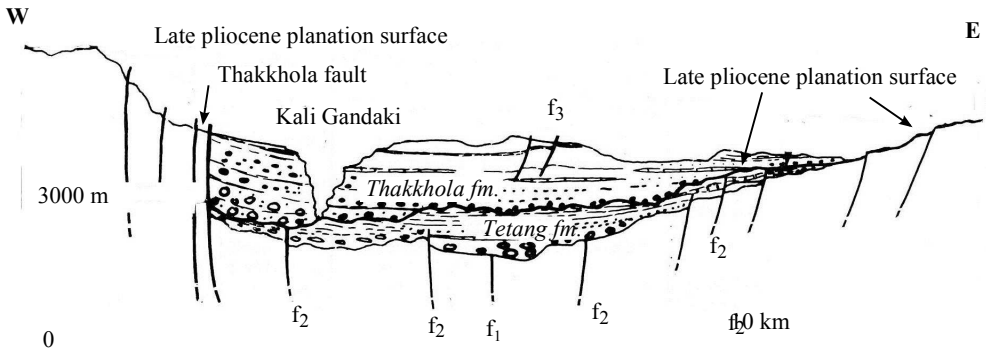
On the way to Muktinath, looking northwards, we will see the thick (800 m) formations of the Thakkhola, poorly dated by polen (probably Plio-Pleistocen, beginning around 3 Ma. First outcrops of these formations are found a few km north of Kagbeni.



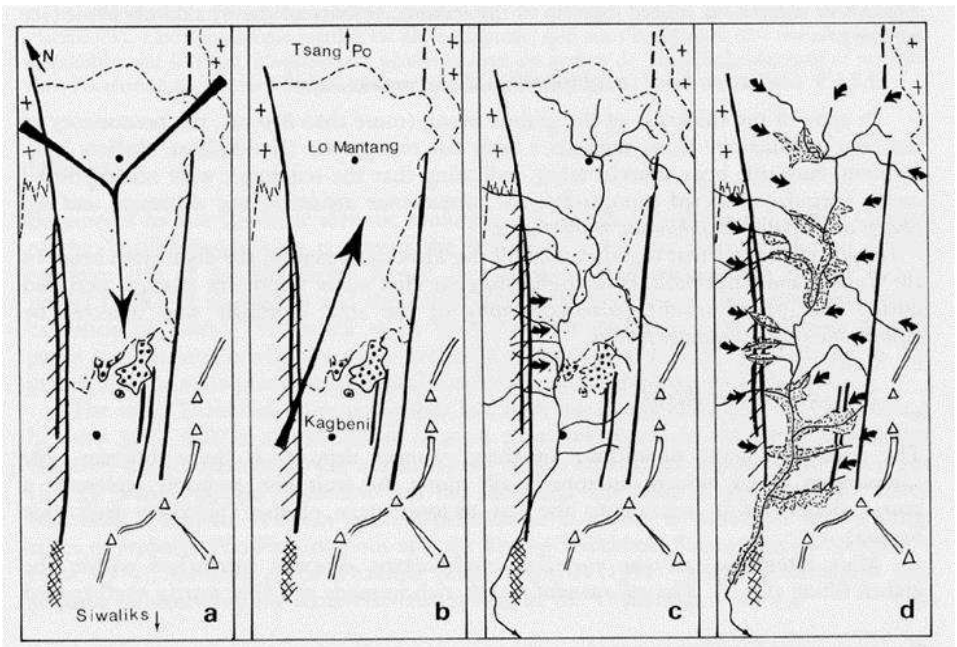
Aerial photograph to the north of the Thakkhola half-graben from above Muktinath. The western limit of the graben forms the slope clearly visible on the left (Ph AP)



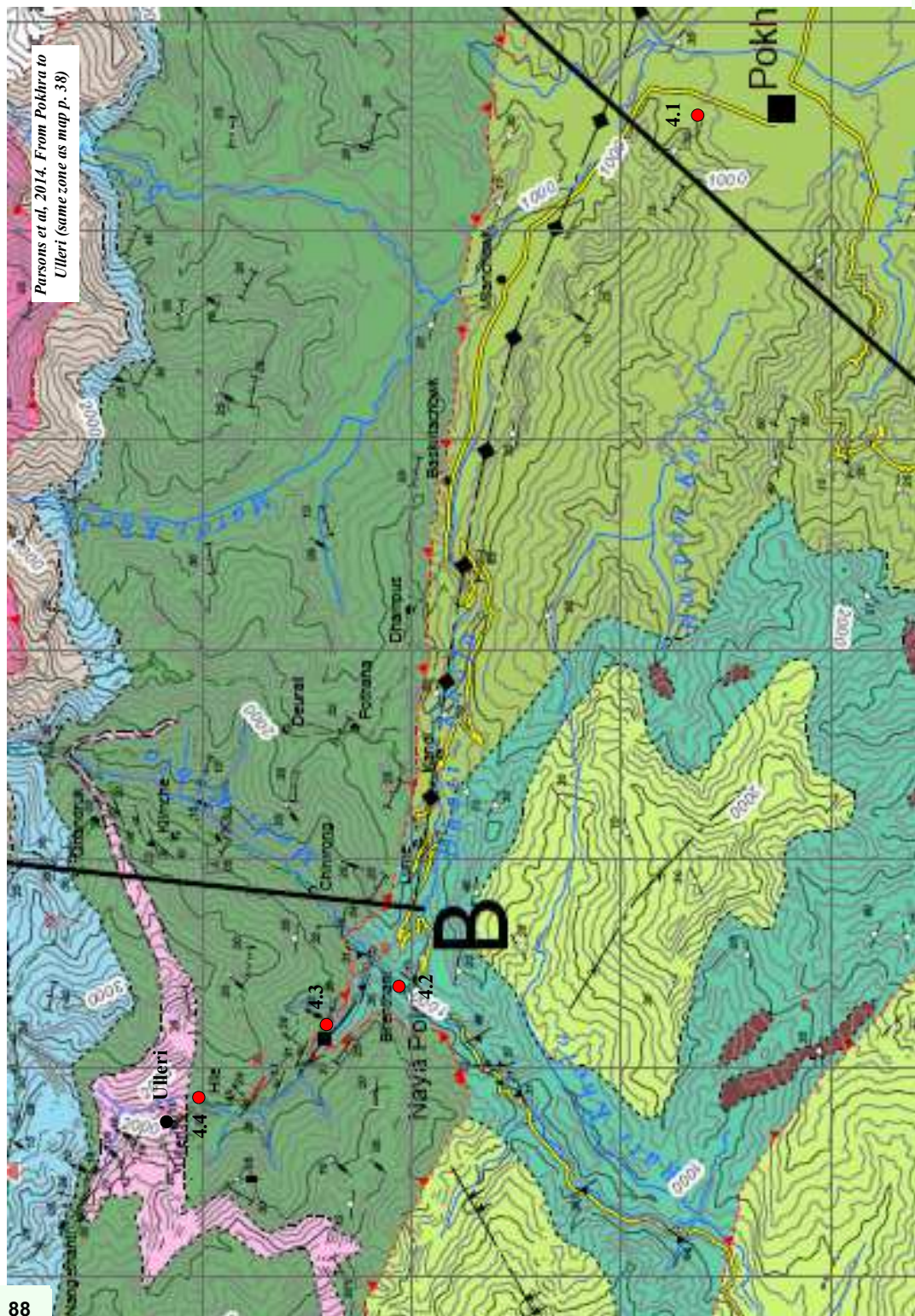
Geological map of the Thakkhola graben, Colchen and Fort (1997) in Colchen (1999). In yellow colour : Tetang Formation. In red : Thakkhola Formation. In green : flood plain



W-E cross-section in the southern part of the Thakkhola-Mustang graben showing the antithetic disposition of the N020-040 normal faults, the discontinuity between the Thakkhola and Tetang Formations and the unconformity with the Mesozoic substrate. f1, f2, f3 : faults of different phases (Colchen et al., 1999)



The successive episodes of the graben evolution. (a) - Tetang period, with granitic pebbles derived from the north (NE and/or NW) (b) - Thakkhola period, with pebbles of mainly Palaeozoic metamorphosed rocks. (c) Sammargaon episode : red breccia coming from the fault escarpment. (d) Kali Gandaki period, dissection and terraces, river flowing to the south (Fort et al., 1982)



Chomrong Thrust (CT) (= MCT)



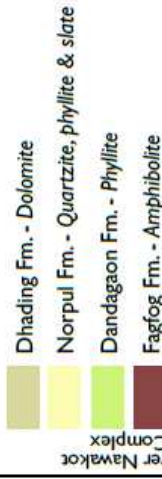
Lower GHS - undiff.

(= Munsiri Thrust)

Main Central Thrust (MCT)

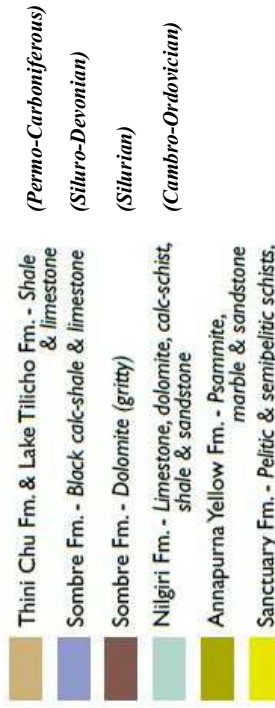
Nawakot Complex (LHS)

Palpa Klippe - (Allochthonous Norpul Fm)



Fagfog Fm. - Quartzite & phyllite, Parsons et al., 2014

Kuncha Fm. - Semipelite & pelite



THS - undiff.

South Tibetan Detachment (STD)

STDS Orthogneiss (Manaslu region)

STDS Metapelite rocks

STDS Metacarbonates - including marble and pelite

Annapurna Detachment (AD) / Deurali Detachment (DD) / Chame Detachment (CD)

Manaslu Leucogranite - Leucogranite pluton (Miocene)

Unit III - Orthogneiss, paragneiss & migmatite

Unit II - Calc-silicate gneiss

Unit I - Pelitic & psammitic gneiss, schist & migmatite

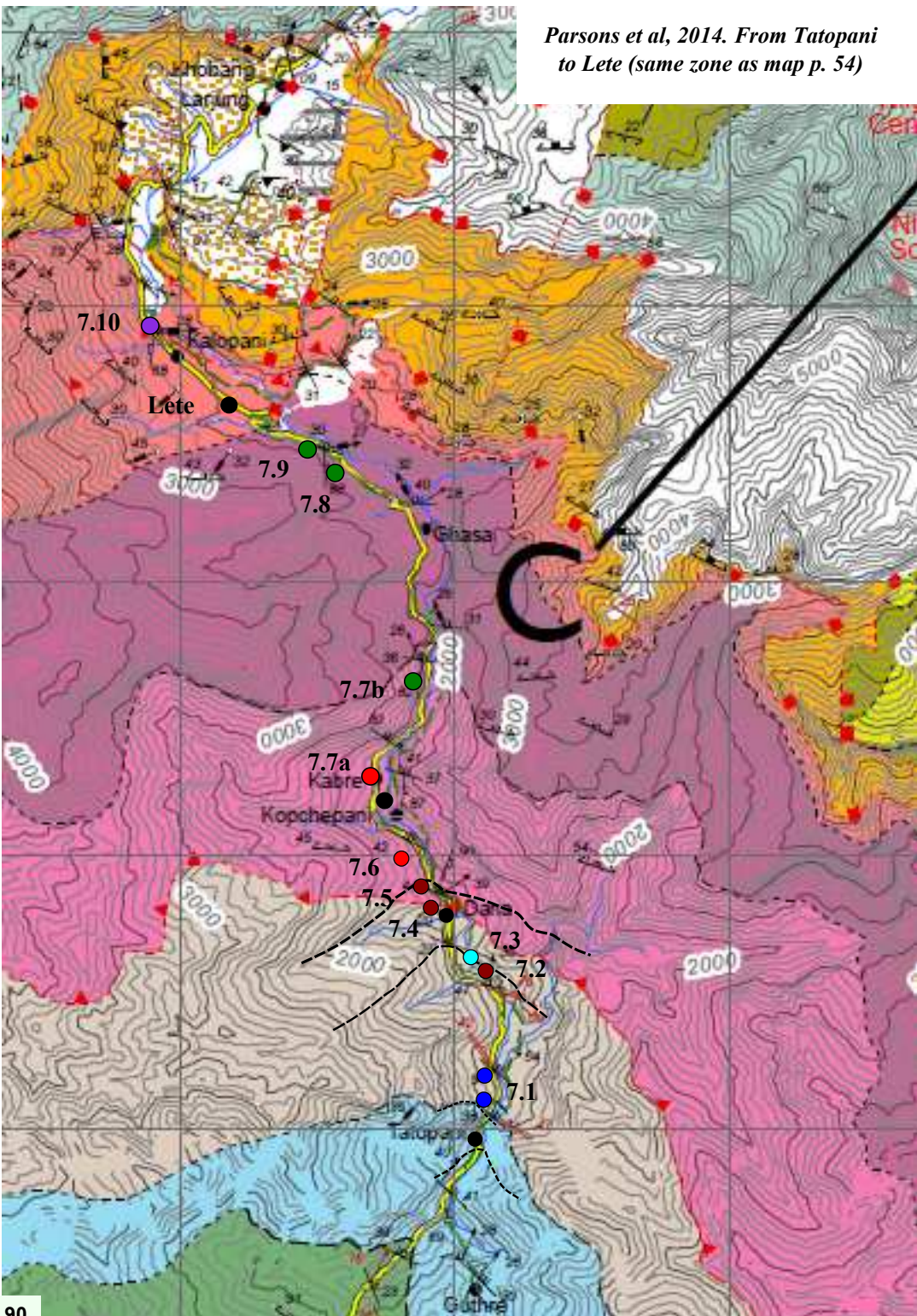
Upper GHS - undiff.

Chomrong Thrust (CT)

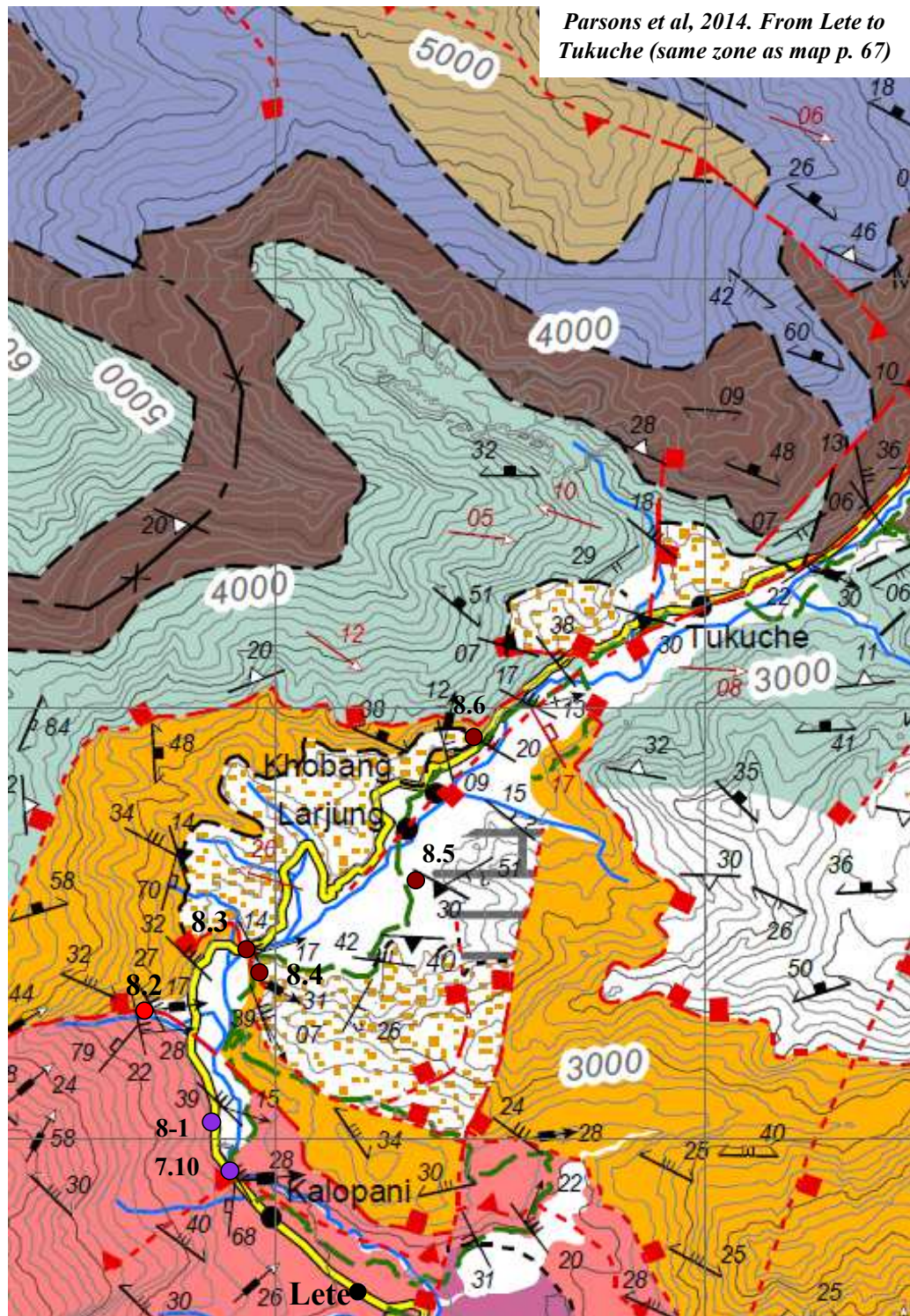
Note - Ages of the formations of the North Himalayan sedimentary series added following Colchen et al., 1981

The MCT - definition and position of the MCT is still debated. Actually, there are several thrusts in the "Main Central Thrust zone", some authors speaking of MCT 1, MCT 2 and even MCT 3. in Parsons et al. map, the original MCT is labelled "Chomrong thrust", while the Munsiri thrust, lower down, is labelled MCT.

Parsons et al, 2014. From Tatopani to Lete (same zone as map p. 54)



Parsons et al, 2014. From Lete to Tukuche (same zone as map p. 67)



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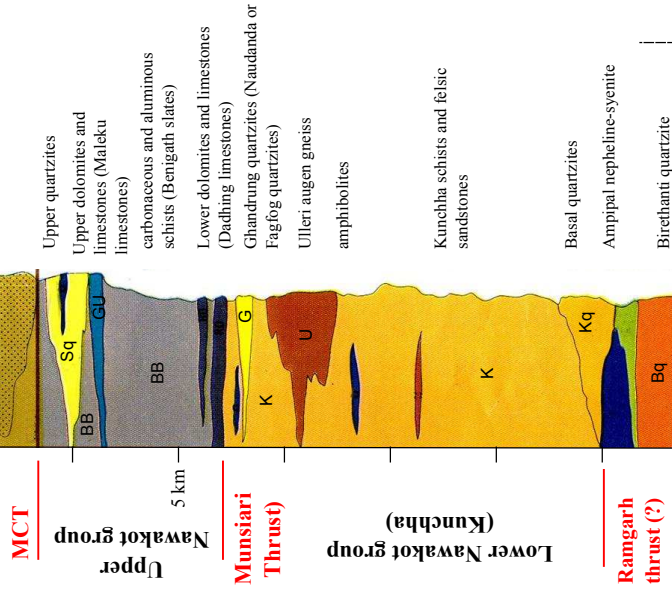
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(1) The North Himalayan Fault (NHF, or STDZ), sometimes duplicated higher up in the sedimentary series,
(2) & (3) The two main thrusts in the wide MCT shear-zone. Nowadays, most of geologists agree to distinguish a thrust at the base of the Higher Himalaya gneiss and migmatites (the main lithological limit) and another thrust lower down, between the Upper and Lesser Midlands Formations (+/- the Upper and Lower Nawakot groups). Nevertheless, names vary. We have kept the term MCT for the upper thrust (sometimes called MCT 2, but also sometimes MCT 1 !), and used the name Munsiri thrust (defined farther west, in Indian Himalayas) for the lower thrust (sometimes called MCT 1, but also MCT 2 !)

(4) At the base of the Nawakot series, the Ramgarh thrust (by analogy with Garhwal Himalaya)

Structure	Metamorphism
Attitude of stratification	Biotite
Vertical dip	Chloritoid
Metamorphic foliation	Kyanite
Post-metamorphic schistosity	Garnet
stretching lineation	Hornblend
Syn-metamorphic fold-axis	Pyroxene
Post-metamorphic fold-axis	Sillimanite
Recumbent anticline	Staurolite
Recumbent syncline	Wollastonite
Series of folds	



A geological section in Central Nepal

From Butwal- to Muktinath (Annapurna section)

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