Thrust Sheets, Tectonic Windows, and Intermontane Basins in the Nepal Himalaya

Megh Raj Dhital and Basanta Raj Adhikari

Abstract The Himalayan Range is generally classified into a number of broad longitudinal tectonic belts. Despite a long history of investigation, some fundamental issues of their stratigraphy and structure are still unresolved. Especially, there has been considerable controversy over delineating the Greater Himalayan and Lesser Himalayan belts of Nepal. The Greater Himalayan thrust sheet represents the hanging wall of the Main Central Thrust. In Nepal, the thrust sheet forms two large open folds: the Great Midland Antiform in the inner zone and the Great Mahabharat Synform in the outer part. The Main Himalayan Thrust and Main Central Thrust constitute respectively the floor and roof of a mega duplex where some detached Lesser Himalayan horses are exposed in various tectonic windows. The Main Himalayan Thrust plays a role of sole thrust in the imbricate stack developed within the foreland fold-and-thrust belt. The key structural and stratigraphic aspects of thrust sheets, tectonic windows, klippen, and intermontane basins are discussed together with the neotectonic activity in the Nepal Himalaya.

Keywords Nepal himalaya · Tectonic window · Thrust sheet · Mega duplex · Active fault · Thakkhola graben

1 Introduction

Although it was almost a century ago that Argand (1924) had proposed a collision of India with Eurasia and the creation of Himalaya, its tectonic features are still not clear. Continental tectonics is complex and mountain ranges differ significantly from one another in their internal structure (Molnar 2015). Continent-continent collision

---

M. R. Dhital
Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kirtipur, Nepal

B. R. Adhikari (✉)
Institute for Disaster Management and Reconstruction, Sichuan University-Hong Kong Polytechnic University, Chengdu, China
e-mail: bradhikari@ioe.edu.np

Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal

© Springer Nature Switzerland AG 2020

T. K. Biswal et al. (eds.), *Structural Geometry of Mobile Belts of the Indian Subcontinent*,
Society of Earth Scientists Series,
https://doi.org/10.1007/978-3-030-40593-9_11

in the Alps developed a number of north-vergent nappes (Heim 1922; Schmid et al. 1996; Ballévre et al. 2018; Manzotti and Zucali 2013; Dal Piaz et al. 2003; Malusá et al. 2011). Detailed field mapping supported by abundant fossils and radiometric age determinations in the Alps made it possible to delineate accurately the geological structures and prepare a comprehensive geological map. Unfortunately, it was not the case with the Himalaya, except for the Tethyan sedimentary sequence, where the fossils abound. Hence, there have been utterly diverse views on Himalayan tectonics.

Since Nepal is centrally located within the Himalayan arc, geological investigations in this segment play a pivotal role in understanding this quintessential collided orogen and consequently deciphering continental plate tectonics. Hagen (1969) published the first tectonic map of Nepal where he proposed about 20 nappes. But Hashimoto et al. (1973) and Talalov (1972) denied almost all of Hagen's nappes, and advocated vertical block faulting. Heim and Gansser (1939), Lombard (1958), Bordet (1961), Gansser (1964), and Stöcklin (1980) drew a single and continuous thrust sheet (the Tibetan Slab or the Greater Himalayan Crystallines) and they consolidated the concept of Main Central Thrust (MCT).

Most of the contemporary geological maps of Nepal result essentially from the amalgamation of previous maps and some new observations with an appealing tectonic model. Such hybrid geological maps differ from author to author. For example, Schelling and Arita (1991) made a geological map of East Nepal and drew a 'balanced' cross-section by incorporating a huge north-dipping fictitious ramp and reckoned 185–245 km of crustal shortening. This model was utilised subsequently by Pandey et al. (1995) in Central Nepal to depict the distribution of earthquake hypocentres and prepare a seismotectonic model for the Nepal Himalaya. Several other researchers (e.g., Upreti and Le Fort 1999; DeCelles et al. 2001; Robinson et al. 2006; Goscombe et al. 2006; Searle et al. 2008) have published different hybrid geological maps to estimate either crustal shortening or deformation mechanism in the Himalaya.

During post-collisional underthrusting of the Indian lithosphere, the overlying crystallines were subjected to partial subduction as well as a complex cycle of prograde and retrograde metamorphism (Bhargava 2000; Webb et al. 2007; Carosi et al. 2018a, b). Owing to continued convergence, the crystallines were ultimately detached from the subducting Indian Plate and propagated to the south in the form of a thrust sheet that dragged through the incompetent sediments composing the Lesser Himalaya. This process resulted into a south-verging mega duplex where the Lesser Himalayan sequence is sandwiched between the Main Himalayan Thrust (MHT), supposed to represent the floor, and the MCT, corresponding to the roof (Figs. 1 and 2). The very thick (more than 15 km) Greater Himalayan Crystallines constitute the hanging wall of the MCT. The thrust sheet is stiff and competent enough not to yield to significant deformation. Since various researchers have defined the MCT (e.g., Heim and Gansser 1939; Gansser 1964; Valdiya 1980; Arita 1983; Amatya and Jnawali, 1994; DeCelles et al. 1998, Searle et al. 2008; Carosi et al. 2018b), here the thrust is taken as the dislocation separating the rocks of Nawakot Complex from the overlying Kathmandu Complex or their counterparts (Stöcklin 1980). The

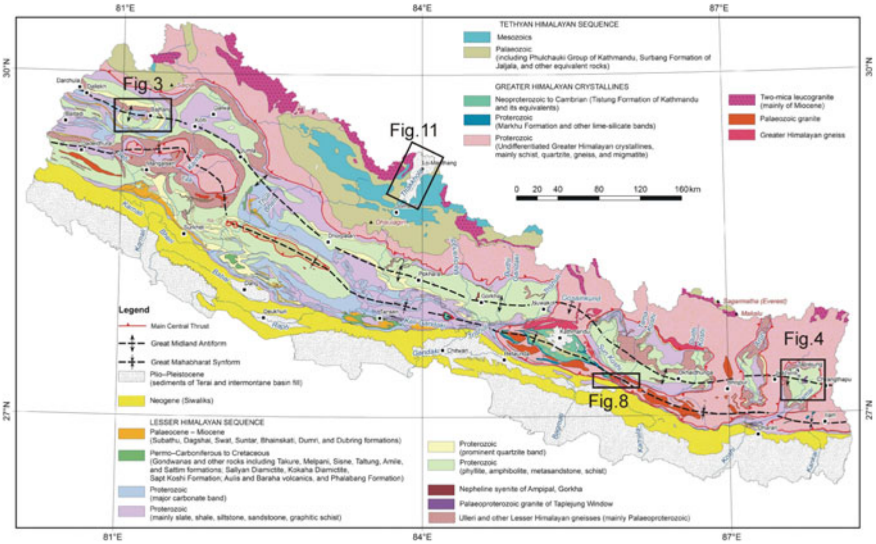

Fig. 1 Generalised geological map of Nepal depicting main litho-tectonic units. *Source* Modified from Dhital (2015)

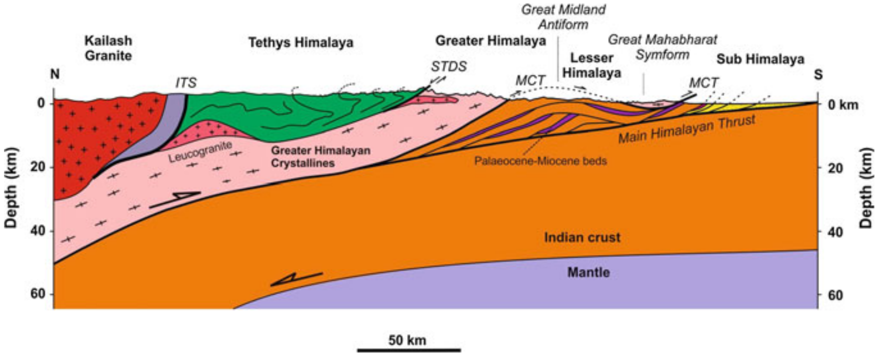

Fig. 2 Schematic geological cross-section across Himalaya showing main structural features. ITS: Indus-Tsangpo Suture; STDS: South Tibet Detachment System; MCT: Main Central Thrust

Greater Himalayan Crystallines are equivalent essentially to the Crystalline Nappes of Fuchs and Frank (1970), Fuchs (1981), or the Tibetan Slab of Lombard (1958), Bordet (1961), and Le Fort (1971, 1975).

In the Nepal Himalaya, the Greater Himalayan thrust sheet gave rise to two large open folds (Fig. 1): the Great Midland Antiform in the inner zone and the Great Mahabharat Synform in the outer belt (Hagen 1969; Dhital 2015). Subsequent erosion has obliterated most part of the antiform and some part of the synform. Consequently, a number of Lesser Himalayan horses detached from the MHT are exposed in various tectonic widows. The horses are forming antiformal stacks in the inner zone, whereas other contractional faults emerging from the MHT have developed secondary duplexes and imbricate fans towards the foreland (Dhital and Kizaki 1987; Johnson 1994; DeCelles et al. 1998; Robinson and Martin, 2014).

2 Great Midland Antiform and Tectonic Windows

In response to rapid Himalayan upheaval, the antecedent rivers were forced to relentlessly incise their course, causing further isostatic imbalance (England and Molnar 1990). This process removed the Greater Himalayan thrust sheet and exhumed the underlying Lesser Himalayan sequence in tectonic windows. In the Northwest Himalaya, Auden (1934) recognised first the tectonic window at Solon where the Pachmunda and the Krol synclines are separated by an anticline. Similarly, West (1939) mapped the tectonic window of Shali (north of Simla). Berthelsen (1951) drew a generalised geological section through the Northwest Himalaya where he showed many nappes and windows in the Sutlej River valley.

In the Nepal Himalaya, the Great Midland Antiform has successive culminations and depressions marked by tectonic windows and bridges (Fig. 1 and Table 1). Hagen (1969) mapped many tectonic windows, including those of Bajhang, Okhaldhunga, Arun, and Taplejung. A solitary small klippe of the Greater Himalayan Crystallines is located to the northwest of the Kali Gandaki–Trishuli confluence (Fig. 1). The klippe was witness to the extensive erosion of the Greater Himalayan thrust sheet in West Nepal by the Kali Gandaki, Marsyangdi, Budhi Gandaki, and Trishuli rivers. Similarly, in East Nepal, the Sun Koshi, Tama Koshi, and Dudh Koshi have collectively carved a large tectonic window of Okhaldhunga.

Table 1 Main culminations and depressions of Great Midland Antiform

S. No	Principal antecedent river	Culmination (tectonic window)	Depression (tectonic bridge)
1	Mahakali (or Kali)	Mahakali	Dallekh
2	Seti	Bajhang	Kolti
3	Karnali	Galwa	Jumla
4	Bheri	Bheri	Dhorpatan
5	Trishuli	Trishuli	Gosainkund
6	Koshi	Okhaldhunga	Bhojpur
7	Arun	Arun	Jirikhimti
8	Tamar	Taplejung	Chyangthapu

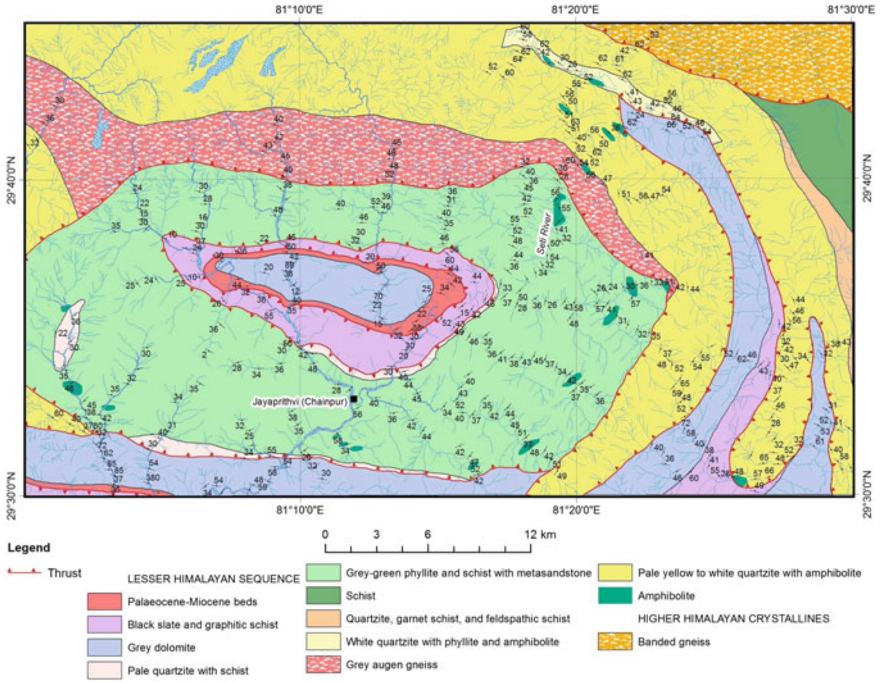

Fig. 3 Geological map of Bajhang tectonic window showing the younger strata in the core. *Source* Modified from Khan (1996, 2000)

2.1 Tectonic Windows of West Nepal

Heim and Gansser (1939) and Gansser (1964) investigated the Mahakali tectonic window. Fuchs and Frank (1970) and Fuchs (1977) mapped in detail the Galwa and Bheri tectonic windows in West Nepal. They also discovered the Rukum Nappe in this region and post collisional Palaeocene–Miocene strata in the cores of the two strongly deformed windows. The Bajhang tectonic window (Fig. 3) is a classic example where the Paloaecene–Miocene rocks are exposed in its core. The oldest Lesser Himalayan sequence is represented by phyllites and biotite schists with some orthoquartzite, metasandstone, and amphibolite bands. Augen gneisses are injected in a thick pale quartzite sequence, which is thrust over the dolomites and slates.

2.2 Tectonic Windows of East Nepal

The Okhaldhunga, Arun, and Taplejung windows in East Nepal (Fig. 1) contain mainly Palaeoproterozoic schists and quartzites followed by black slates and graphitic schists with a few discontinuous quartzite bands. Sporadic granites and frequently occurring augen gneisses at various stratigraphic levels entail that the gneisses may differ in age. The uppermost part of Lesser Himalayan sequence is represented by amphibolites, feldspathic schists, garnet schists, and crystalline limestones. The Greater Himalayan Crystallines contain banded gneisses, migmatites, and other medium to high-grade rocks with some schist, quartzite, and marble bands.

In the Taplejung window (Figs. 1 and 4), the Palaeoproterozoic Kuncha Formation is composed of grey to dark green-grey *gritty* phyllite, chlorite schist, and biotite schist with thick to very thick quartzite bands and alternations (Fig. 5). The rock is strongly crenulated and contains boudinaged and folded quartz veins. Toward the lower part of Kuncha Formation appears the Subhang Khola Member, which is a lenticular unit containing pale yellow to light grey, fine-grained quartzite with phyllite and schist partings and thin bands. In the Kuncha Formation is intruded about 1.8 Ga old light grey to white medium-grained granite (Auden 1934; Upreti et al. 2003) with biotite and tourmaline. In the granite xenoliths of dark grey schist and quartzite are frequent.

The Kuncha Formation is transitionally succeeded by the Chilingdin Formation (Fig. 5) of grey, light grey, to pale yellow, thick- to very thick-banded quartzite alternating with phyllite, chlorite schist, and biotite schist. Generally the rock is massive. The Chilingdin Formation is followed stratigraphically upwards by the Phyame Formation of grey to dark grey, laminated garnet-biotite schist and graphitic schist with thin quartzite bands (Fig. 4). In this formation towards the southeast end of the map, grey augen gneisses or feldspathic schists are found with thin garnet schist, kyanite schist, and quartzite bands. The overlying Phidim Formation contains from a few metres to tens of metres thick, grey, green-grey to light grey feldspathic schist and quartzite with biotite, garnet, and sporadically kyanite (towards upper part). Extremely rare crystalline limestone bands are also present. In fact, this formation differs from the Phayme Formation mainly in its feldspar content. This formation is also affected by inverted metamorphism and in its upper levels occur light grey to pale quartzites or feldspathic quartzites with amphibolite. The amount and grain size of feldspar (mainly orthoclase) steadily increases from lower to upper horizons.

Above the MCT, the Greater Himalayan Crystallines are represented by the Prangbung Formation (Figs. 4 and 5) of grey to light grey, banded paragneisses with kyanite (in the lower part) and sillimanite. The gneisses contain purple garnets towards their lower horizons. Many pegmatite veins ranging in thickness from 5 cm to 10 m are injected parallel or slightly oblique to foliation. About 10–50 m thick marble and calcareous gneiss bands are sporadically observed in the lower part. The pegmatite veins consist of feldspar, quartz, muscovite, tourmaline, and occasionally gemstones including ruby and sapphire.

In the Taplejung window, inverted metamorphism (Schelling and Arita 1991) is ubiquitous and it gradually increases from the lower stratigraphic levels to the upper horizons. While moving structurally upwards, the grade of metamorphism is marked by the successive appearance of chlorite, biotite, and garnet index minerals in the Lesser Himalayan Sequence and kyanite and sillimanite in the Greater Himalayan Crystallines (Fig. 4). Most of the Kuncha Formation lies in the biotite zone and its upper part passes into the garnet zone. Though kyanite appears mainly in the lower

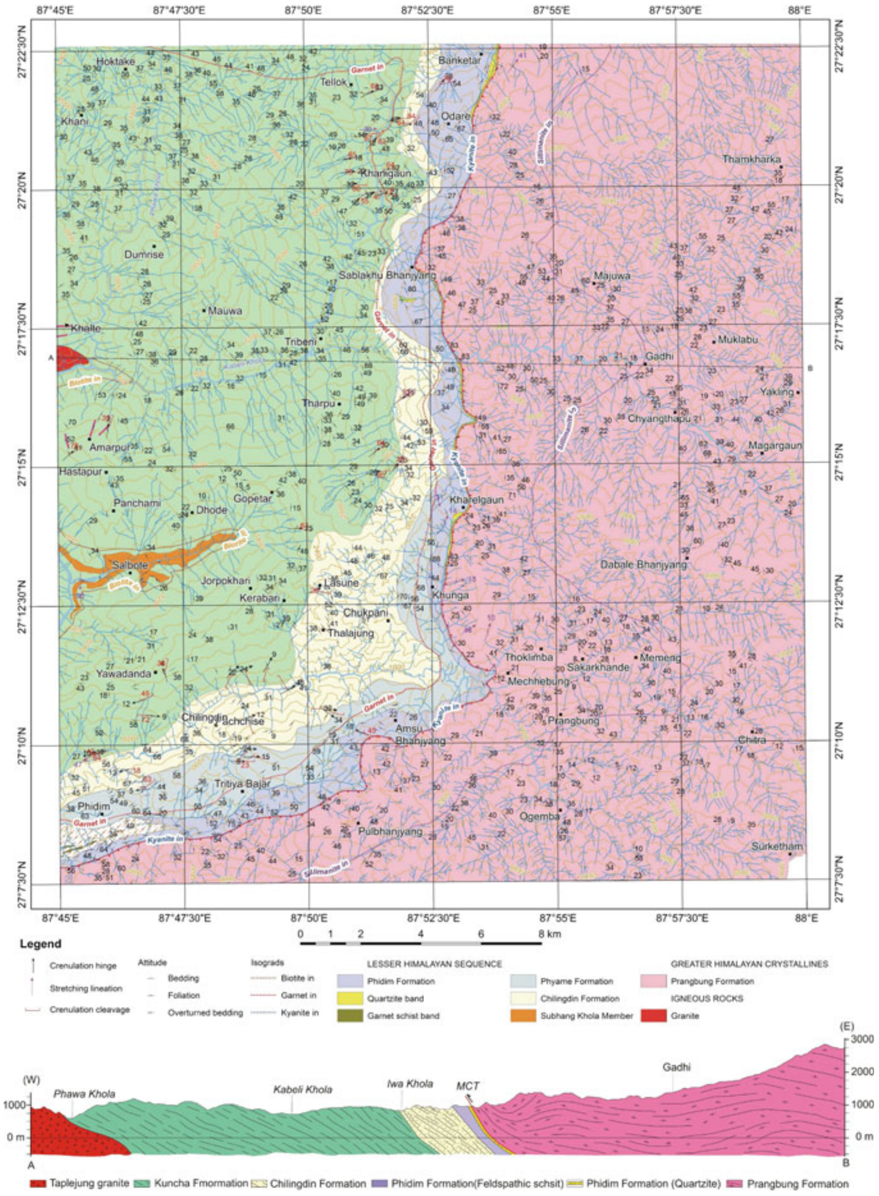

Fig. 4 Geological map and cross-section of part of Taplejung window in East Nepal. *Source* Modified from Dhital (2015)

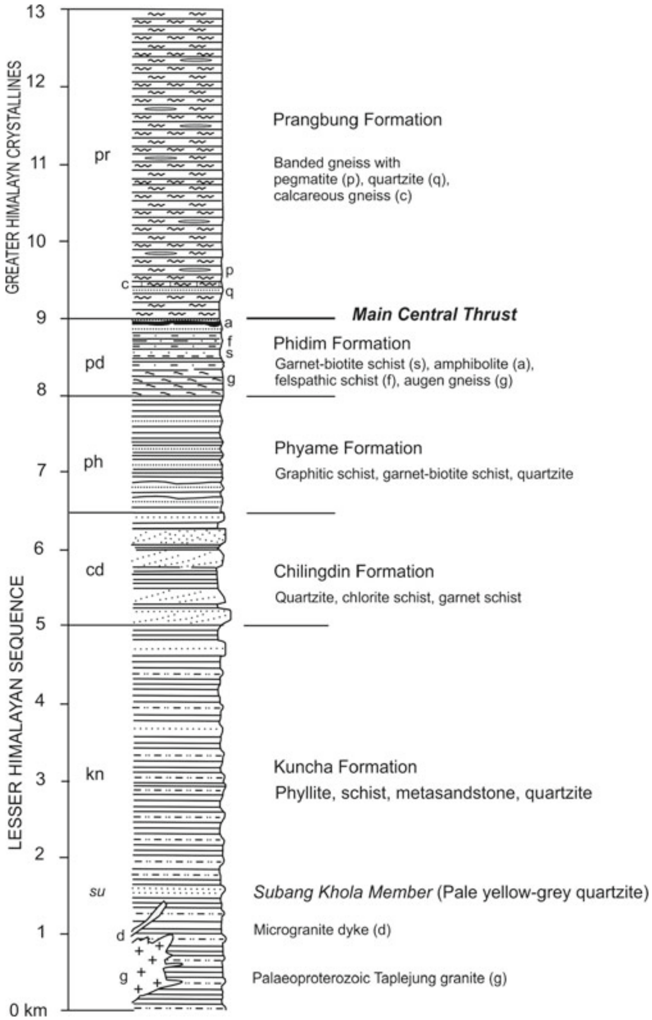

Fig. 5 Tectono-stratigrpahic column of the Taplejung tectonic window and surrounding region

portion of the Greater Himalayan Crystallines, in some instances it already occurs in the upper part of the Phidim Formation. Carosi et al. (2007) have also reported kyanite-bearing quartzites in the Lesser Himalayan sequences. Hence, the isograds obliquely cut the lithological units and they do not define the MCT.

The rocks of Taplejung window exhibit well developed foliation, crenulation cleavage, and stretching lineation (Fig. 4). The stereographic projection of main foliation (S_1) reveals that the window is a non-cylindrical fold (Fig. 6), resembling a large dome.

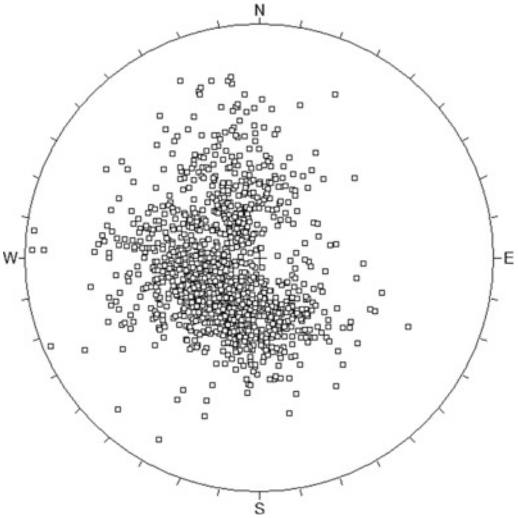

Fig. 6 Stereographic projection of 1339 main foliation (S_1) poles related to a first phase of deformation (D_1). Equal angle, lower hemispherical projection

The crenulation cleavage (S_2) in the Lesser Himalayan Sequence was formed during a second deformation phase (D_2) and its attitude is quite different from the orientation of main foliation (S_1) in the Lesser Himalayan as well as Greater Himalayan rocks. The crenulation cleavage (Fig. 7a, b) is steeply dipping essentially due NNW. Stretching lineations, crenulation hinges (representing F_2 folds), and mineral lineations are also observed in some part of the window (Fig. 4). Most of them are associate with the D_2 phase and their orientation is due ENE or WSW.

Many quartz veins are stretched parallel to S_1 and they have developed a boudinage structure during the D_1 phase. The boudins frequently occur in the metapelites as well as the metasandstones and quartzites of the Kuncha Formation, Chilingdin Formation, and Phidim Formation. These previously boudinaged quartz veins were subsequently folded. As a result, folded boudins are seen in the Kuncha Formation (Fig. 7a, b). The quartz boudins range in size from a few millimetres to a few centimetres. A widespread distribution of folded quartz boudins indicates that the region underwent the D_2 phase intense deformation after their emplacement. Since it is not possible for any progressive deformation (pure shear or simple shear) to switch from extension to compression (Ramsay 1967), the D_1 and D_2 phases must had been quite independent.

Infrequent ‘cross-laminae’ are observed in the gneisses of Greater Himalayan Crystallines (Fig. 7c) and such structures allude to their sedimentary origin. Due to D_2 phase shearing, sigma- and delta-type structures are well developed in the feldspar porphyroblasts of some banded gneisses (Fig. 7d).

Thus, the investigation of foliation, crenulation cleavage, lineation, and deformed quartz veins reveals at least two distinct phases of deformation in the region. Presumably, the D_1 phase was associated with the movement of MCT and the D_2 phase can be attributed to the formation of dome and its subsequent erosion to expose the Lesser Himalayan Sequence in the Taplejung tectonic window.

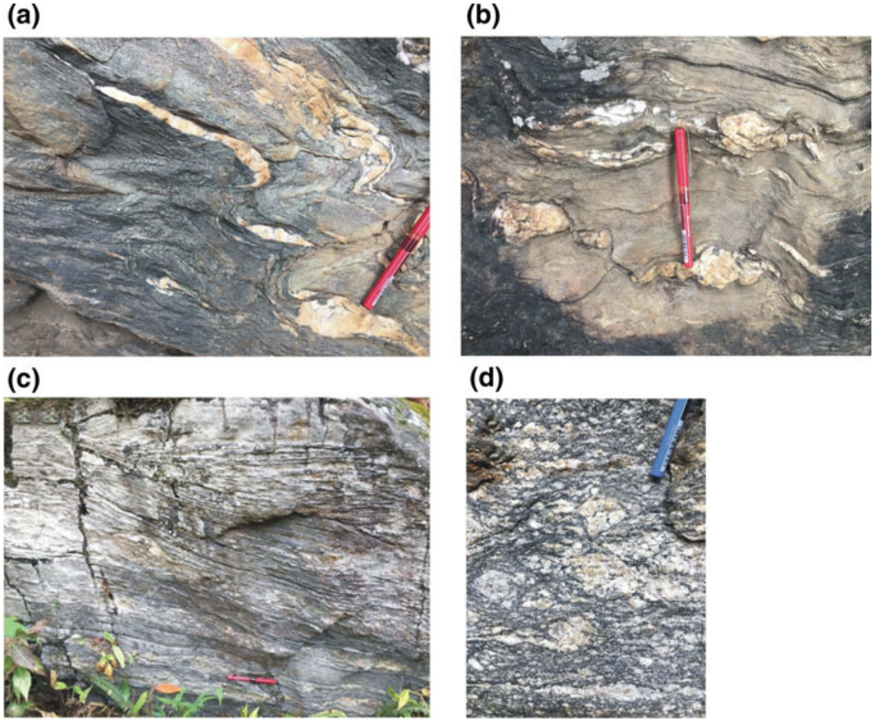

Fig. 7 **a**, **b** Folded boudins of quartz veins in Kuncha Formation. Crenulation cleavage of D_2 deformation phase is also well developed; **c** 'Cross-laminae' in banded paragneiss of Greater Himalayan Crystallines; **d** a delta-type structure in the gneiss of Greater Himalayan Crystallines

3 Great Mahabharat Synform and Klippen

After the seminal work of Heim and Gansser (1939) in the neighbouring tracts of Kumaun, India, many have attempted to decipher the main tectonic and stratigraphic features of Far West Nepal. Remarkably, Hagen (1969) defined from this region his Dadeldhura Autochthonous Zone where augen gneisses and granites preponderate. He also considered it to be connected laterally with the Galwa tectonic window. Fuchs and Frank (1970), Frank and Fuchs (1970) as well as Fuchs (1977, 1981) divided the metamorphic rocks into their Chail Nappes and the overlying Crystalline Nappes. Bashyal (1982, 1986) worked out the structure and stratigraphy of Far West Nepal and mapped the Bajhang Klippe, Parchuni Klippe, and Dadeldhura Nappe, from north to south respectively. He also showed that his Dadeldhura Nappe is the eastern continuation of the Almora Nappe of Gansser (1964) and Valdiya (1980). Since both the Dadeldhura Nappe and Kathmandu Complex (Stöcklin 1980) in Central Nepal are parts of the Great Mahabharat Synform, and contain Palaeozoic granites (Le Fort et al. 1983; Einfalt et al. 1993), they were taken to be equivalent units by a large number of investigators (e.g., Shrestha et al. 1987; Amatya and Jnawali 1994; Beyssac et al. 2004). Upreti and Le Fort (1999) came up with a rather different proposition in this regard. They defined a Lesser Himalayan 'rootless' nappe (comprising the rocks of Dadeldhura and Kathmandu Complex) and another overlying Greater Himalayan Crystalline Nappe rooted to the north. Likewise, DeCelles et al. (2000, 2001) and Robinson et al. (2006) designated their Ramgarh Thrust and overlying Dadeldhura Thrust (or MCT), and extended them throughout Nepal. Thus, the researchers have proposed several stratigraphic schemes and drawn the thrusts of their choice. As a result, the geology of Far West Nepal is tangled in confusion.

Recent field mapping in Far West Nepal revealed that the synformally folded Dadeldhura Nappe and klippen belong to the Lesser Himalayan Sequence of Proterozoic age (Fig. 1). They constitute a single folded roof thrust, consisting of phyllites, schists, quartzites, graphitic schists, amphibolites, and augen gneisses with blue and smoky quartz. In contrast to the Kathmandu Complex, inverted metamorphism profoundly affects the Dadeldhura Nappe and klippen, where it ranges from the chlorite grade at the lower structural level to the garnet or higher grade towards the top. Hence, to attribute these rocks to the Greater Himalayan Crystallines on the basis of the lone argument that they include Palaeozoic granites in the south limb of Great Mahabharat Synform is untenable. The Jutogh thrust sheet in the Simla area (Bhargava et al. 2016) and the Mandi granite (Mehta 1977) in the Himachal Pradesh, India, also occur in a similar setting.

The Mahabharat Synclinorium (Stöcklin 1980) in Central Nepal is part of the Great Mahabharat Synform and is made up of the Kathmandu Complex. It is a folded roof thrust. Erosion has also shredded the Greater Himalayan thrust sheet to yield many klippen resting over the Lesser Himalayan Sequence.

An example of the Great Mahabharat Synform is seen in Central Nepal, east of Kathmandu (Fig. 8), where the Lesser Himalayan Sequence is represented by the Nawakot Complex and the Greater Himalayan Crystallines and Tethyan succession are made up of the Kathmandu Complex (Stöcklin 1980). The Benighats (graphitic schsits with sporadic crystalline limestone bands) of Nawakot Complex are thrust over the Siwaliks (represented by Lower, Middle, and Upper Siwaliks), whereas the MCT brings the Kathmandu Complex over the Nawakot Complex. Here, the Kathmandu Complex commences with the Kalitar Formation (Kyanite schist and

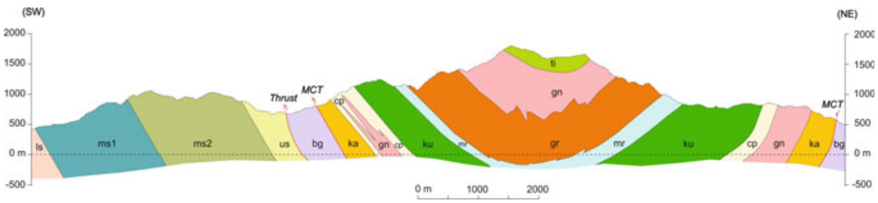

Fig. 8 Geological cross-section across the great mahabharat synform in the sun koshi-marin area of Central Nepal, east of Kathmandu.ls: Lower Siwaliks, ms1: middle siwaliks (lower member), ms^2: middle siwaliks (upper member), us: upper siwaliks, bg: benighats, ka: kalitar formation, gn: augen gneiss, cp: chisapani quartzite, mr: markhu formation, gr: palaeozoic granite, ti: tistung formation, MCT: Main Central Thrust

quartzite) and it is succeeded respectively by the Chisapani Quartzite, Kulikhani Formation (garnet-kyanite schist), Markhu Formation (schist, quartzite, and marble), and Tistung Formation (garnet schist and quartzite).

In Central Nepal, the metasediments of the Kathmandu Complex are affected by a regional metamorphism of Barrovian type (Stöcklin et al. 1982), which increases from the unmetamorphosed sediments on top to the coarsely crystalline garnet schists at the base of the section. In other locations, especially to the north and east of Kathmandu, kyanite- and sillimanite-bearing banded gneisses also appear towards the lower part of the Kathmandu Complex. The banded gneisses have an irregular distribution and they are the product of migmatisation of the metasediments (Stöcklin 1980). Palaeozoic granites intrude the Kathmandu Complex and they are closely associated with augen gneisses. Many of the augen gneisses have a similar granitic appearance and, in the Sun Koshi–Marin Section (Fig. 8) as well as in several other places, the granites and augen gneisses show imperceptible transitions, especially, when they are close to the MCT (Stöcklin et al. 1982).

4 Active Faults and Seismicity

Most of the convergence of India and Eurasia is accommodated within the Himalaya by movement on various active faults (Fig. 9). When the convergence is locked in some sector, the stored elastic energy is ultimately released in the form of tremors

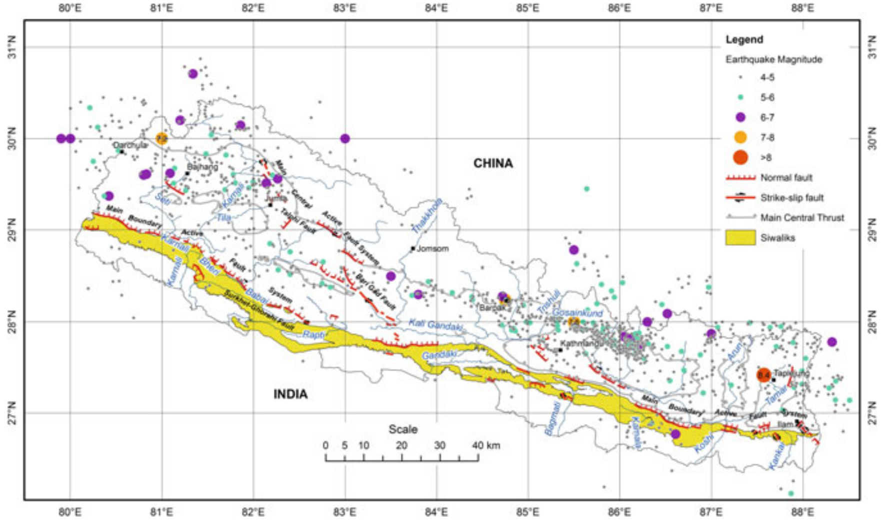

Fig. 9 Major active faults in Nepal (modified from Nakata 1982) and its background seismicity with a magnitude exceeding 4, occurred between 1995 and March 2016. Also are shown some known historic earthquakes exceeding magnitude 6. *Source* The Department of Mines and Geology, Kathmandu

along the mountain range and in its surroundings (Seeber and Armbruster, 1981; Pandey et al. 1995; Bilham et al. 1997). Active faults are found in the inner as well as the outer fold-and-thrust belt of the Himalaya and they are invariably related to the deformation of post-collisional Palaeogene–Neogene sediments. Therefore, post-collisional sediments played a significant role in the tectonic transport and contraction of Lesser Himalaya and Sub Himalaya (or Siwaliks). Shallow seismicity in the Nepal Himalaya is concentrated to the inner active fault zone, but not towards the foreland. Such selective distribution is presumably related to a stiffer roof extending to a depth of 35–40 km and compressed horses or thrust sheets that can store significant elastic energy.

The Himalayan Range and neighbouring tract have experienced many large tremors, namely the Nepal earthquake of 1833 with an estimated magnitude of 7.8 (Bilham 1995), the Shillong earthquake of 12 June 1897 with an estimated magnitude 8.7, the 1905 Kangra earthquake of estimated magnitude 8.0, the 1934 Nepal–Bihar earthquake of estimated magnitude 8.4, and the 1950 Assam earthquake of magnitude 8.5 (Oldham 1899; Middlemiss 1910; Auden 1934; Sharma and Malik 2006). On August 1988 the Udayapur earthquake of magnitude 6.6 struck East Nepal and its focal depth was estimated at 57 km (Dikshit 1991). The Gorkha earthquake of Mw 7.8 occurred on 25 April 2015 in Central Nepal and its focal depth was about 10–15 km (Adhikari et al. 2015; Avouac et al. 2015).

Microseismicity in Nepal is characterised by a narrow belt that follows approximately the front of the Great Himalayan Range. This kind of confined distribution reflects deformation between the upper and lower crusts along the MHT under the Lesser and Greater Himalaya (Pandey et al. 1999; Avouac 2003). Though the entire country is seismically active, there is a significant lateral variation. Microseismic activity is quite intense in East and Far West Nepal, whereas the (Bilham and England 1995) level of seismic activity is low in West Nepal. The earthquakes are generally shallower than 30 km and they are clustered around a depth of about 20 km. The frequency–magnitude relationship of microseismicity follows the Gutenberg–Richter law (Pandey et al. 1999), where the b-value varies between 0.75 and 0.95, and does not seem to change significantly over areas.

5 Intermontane Basins

Nepal hosts quite many intermontane basins, including the Thakkhola, Kathmandu, Pokhara, Hetaunda, Chitwan, Dang, Deukhuri, and Surkhet (Figs. 1 and 10). The basin of Thakkhola is a half-graben, the Kathmandu basin displays a classic centripetal drainage pattern and is filled up essentially with Pleistocene lake and fluvial sediments. The Pokhara basin contains the Holocene sediments accumulated by rivers, debris flows, and glacier lake outburst floods. The intermontane basins either within the Siwaliks or between the Lesser Himalaya and Siwaliks are imbricate fault-bound. Such basins are characterised by salients or convex-to-foreland curves and recesses or concave-to-foreland curves (Macedo and Marshak 1999) frequently

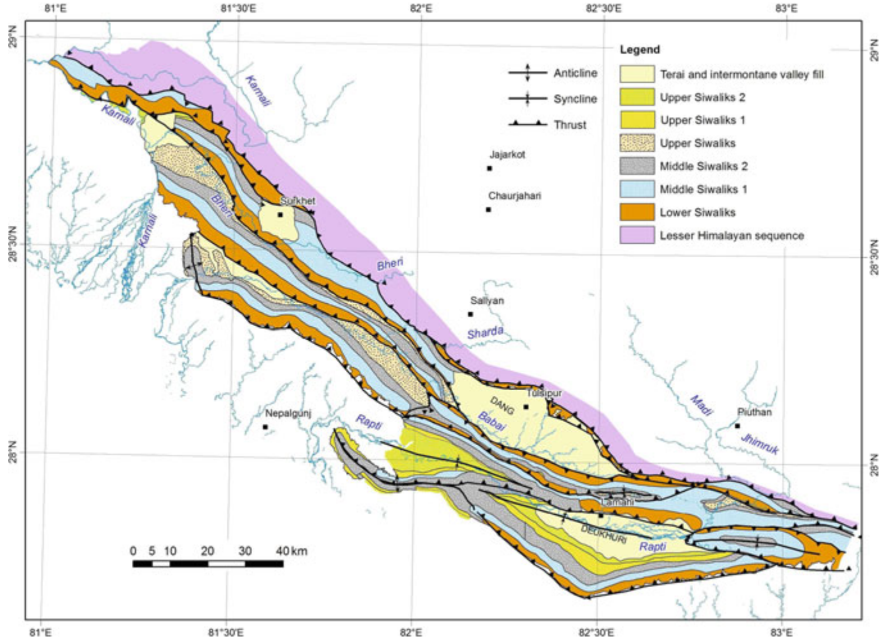

Fig. 10 Geological map of intermontane basins showing salients and recesses in West Nepal. *Source* Modified from Dhital (2015)

observed in the map view pattern of structural trend lines (thrusts, fold hinges, and bedding) in the Himalayan frontal fold-thrust belt of Nepal (Fig. 10). The salients are mostly of basin-controlled type and thickest basin fill is located at the apex of the salient.

5.1 Thakkhola Graben

Graben development in the Himalaya and Tibetan plateau is related to the convective removal of the lower portion of thick Asian lithosphere (Platt and England 1994), which helps east-west extension of the Tibetan plateau during the India-Asia collision (Coleman and Hodges 1995). This Cenozoic extension is responsible for the creation of grabens in Tibet and the northern part of Himalaya (Molnar and Tapponnier 1978). These normal faults have developed since 14 Ma in south Tibet (Coleman and Hodges 1995) and about 8 Ma (Harrison et al. 1997) or 4 Ma in Central Tibet (Yin et al. 1999). Generally, the normal faults either trend perpendicular to the Himalayan arc or strike north–south; but they also exhibit major deviations from these orientations (Kapp and Guynn 2004). The graben spacing decreases from south to the north systematically, which reflects the northward decrease in crustal thickness (Yin 2000).

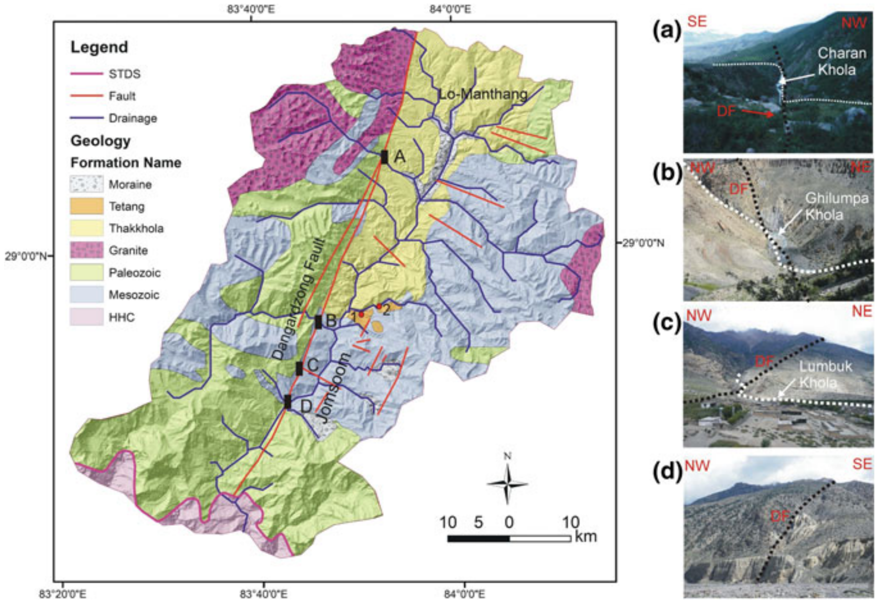

Fig. 11 Geological map of Thakkhola graben and trace of Dangardzong fault at different places along the strike of the fault. **a** Charan Khola changing its direction, **b** sharp bend of Ghilumpa Khola, **c** Lumbuk Khola changing its course, **d** small depression along the Dangardzong fault (DF). *Source* Modified from Adhikari (2009)

The Thakkhola graben (Figs. 1 and 11) is unique in the Himalaya and shows complex kinematic and geometric relationships with the South Tibet Detachment System (STDS) (Brown and Nazarchuk 1993; Patel et al. 1993) and the Dangardzong fault (Hurtado et al. 2001). This asymmetrical graben lies in the Palaeozoic to Cretaceous rocks of the Tethyan sequence between the STDS (Burchfiel et al. 1992) to the south and Indus-Tsngpo suture zone to the north. The graben is bounded by the Mustang-Mugu leucogranites (Le Fort and France-Lanord 1994) of 17.6 ± 0.3 Ma (Harrison et al. 1997) in the northwest of the graben while the basement is composed of a thick and nearly continuous early Palaeozoic to early Tertiary marine sedimentary succession deposited on the northern continental margin of the Indian plate. These rocks are crumpled, stacked, and deformed as a consequence of collision between India and Eurasia in the early Eocene (Garzanti et al. 1987; Searle et al. 1987). The graben is westerly bounded by the Dangardzong fault which was developed synchronously with the motion of the Annapurna Detachment during Miocene time (Hurtado et al. 2001). The minimum age of the east-west extension in this graben is ca. 14 Ma based on ^{49}Ar/^{39}Ar ages of hydrothermal muscovite that crystallized in one of the northeast-striking fractures (Coleman and Hodges 1995). Numerous other normal faults are responsible for the development of the graben along with N20°–40° trending faults (Colchen 1999).

The Dangardzong fault is clearly marked by a topographic depression in the western side of the graben and appears as a cluster of faults. The fault separates the Tethyan sequences and graben-fill sediments in the northern part of the graben and cuts through the Higher Himalayan crystallines on the southern part. The progressive decrease in the metamorphic grade from the biotite zone of greenschist facies to the chlorite zone of the footwall along the fault suggests a decrease of footwall exhumation towards the south (Hurtado et al. 2001). The mapping of this fault along the western margin of the graben is described below.

A sharp offset of the Charan Khola near Ghar Ghumba clearly indicates the presence of Dangardzong fault where fault breccia occurs in the riverbed, at the base of a quartzite cliff (Fig. 11a). Similarly, the Ghilumpa Khola sharply bends southwards and flows along the strike of the fault and then turns eastwards to the Kali Gandaki River making an offset of about 100 m (Fig. 11b). The fault places the grey fine-grained schists of Tilicho Pass Formation on its footwall and Createaceous quartzite of Chuck Formation on its hanging wall. The kinematic indicators in the bedrock show a normal sense of movement with some right-lateral strike-slip displacement (Hurtado et al. 2001).

About 1 km NW of Dongardzong, the Lumbuk Khola makes a sharp bend (Fig. 11c), where the fault strikes N26° E and dips 68° due SE. There are black schists and quartzites on its footwall and quartzites on the hanging wall. The fault has not been active since ca. 5.1 Ma (Hurtado et al. 2001). The footwall is brecciated near the Syang village (Fig. 11d), where its minimum age is estimated at 17.2 ka based on terrace chronology. The Dangardzong Fault terminates around 3.5 km northeast of Lete and 17 km SW of Syang, near Titi. The fault was delineated based on surface morphology, SPOT imagery and interpretation of talus and regolith lithology (Hurtado et al. 2001).

The prominent east-west striking Lupra fault was interpreted as a thrust that was later activated as a normal fault during the graben development (Godin 2003). Different syndepositional growth faults are widespread in the graben-fill sediments (Fig. 12). A northeast-southwest striking small-scale normal fault displaces the sub-

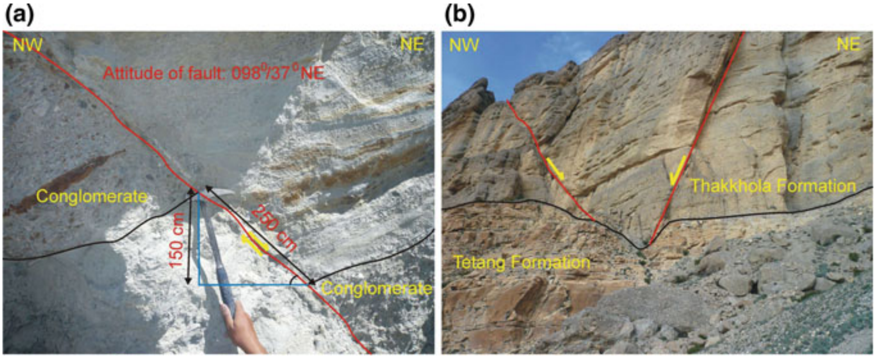

Fig. 12 Normal growth faults in basin-fill sediments. **a** Tetang formation, **b** Thakkhola formation

sequent beds by about 150 cm in the Tetang Formation, indicating the onset of east-west extension (Fig. 12a). Similarly, two east- and west-dipping normal growth faults in the Dhinkyo Khola section have displaced the imbricated conglomerate beds of Thakkhola Formation up to the unconformity between the Tetang and Thakkhola formations (Fig. 12b).

The Palaeozoic to Mesozoic basement rocks of graben are unconformably overlain by the Plio-Pleistocene graben-fill sediments distributed over 90 km in the north-south and 20–30 km east-west directions. They are characterised by more than 840 m of continental debris (Fort et al. 1982, Adhikari and Wagreich 2011b). The oldest sedimentary units of the graben are of the middle Miocene to upper Pliocene Tetang and Thakkhola formations (Fig. 11). Many researches have estimated the age of Tetang Formation at 11–9.6 Ma and the oldest age of Thakkhola Formation at 8 Ma based on magnetostratigraphy (Garzione et al. 2000) and the deposition of the Thakkhola Formation continued until at least 2 Ma (Yoshida et al. 1984). The gently (13–23°) northwest dipping sedimentary strata of Tetang Formation are separated by a low-angle (about 5°) unconformity representing a temporal gap of at least 2.6 Ma, beginning at ca. 9.6 Ma and ending after 7 Ma (Garzione et al. 2000) with the very gently (~13°) northwest dipping Thakkhola Formation (Fort et al. 1982; Adhikari and Wagreich 2011a).

The Tetang Formation is the oldest formation in this graben and it is well exposed around the Tetang village and Dhinkyo Khola (Fig. 11). Its thickness varies from a few metres to more than 200 m and it onlaps against the Cretaceous Chuck Formation. This formation is composed of a fining-upward sequence, consisting of pebbles and gravel of quartzite, shale, sandstone, and carbonates at the bottom and lacustrine sediments containing fine siltstone and limestone on the top. The accommodation space for the sediments may have been created as a response to normal faulting and footwall uplift associated with the STDS (Adhikari and Wagreich 2011a; Garzione et al. 2003). The Thakkhola Formation spreads towards the western and eastern parts of the graben, starting from the Tetang village up to Lomanthang and its distribution was strictly controlled by the Dangardzong fault in the western side. The thickness of the Tetang Formation is more than 620 m in the Chele village. The thickness decreases eastwards where it rests unconformably on the Tetang Formation and the Mesozoic rocks lying farther east (Adhikari 2009). The clast size in both imbricated and massive conglomerates decreases from south to north, but in them the frequency of silt layers increases. The thickness of layers indicates that the velocity and capacity of the river was strong in the central part compared to the northern margin of the basin. These sediments were deposited in alluvial fans, braided river systems, and fluvio-lacustrine to lacustrine environments.

6 Conclusions

The propagation of MCT toward the foreland has brought the Greater Himalayan Crystallines over the Lesser Himalayan Sequence forming a mega duplex, the floor thrust of which is supposed to be the MHT. The competent Greater Himalayan thrust sheet is gently folded to form the Great Midland Antiform towards the hinterland and the Great Mahabharat Synform towards the foreland. The interplay of thrusting, erosion, and folding has created a complex pattern of tectonic windows and klippen in the Nepal Himalaya. Erosion of the thrust sheet by antecedent rivers carved many tectonic windows and klippen. Post collisional Palaeogene-Neogene sediments occur in the outer as well as inner belt and they have played a significant role in duplex formation, neotectonic movement, and seismicity in the Himalaya. There are many intermontane valleys in the Nepal Himalaya that developed after collision of India with Eurasia. The Thakkhola graben is one of them and it was formed during Cenozoic east-west extension of the Himalaya.

Acknowledgements We thank Tribhuvan University and the Department of Mines and Geology, the Government of Nepal, for their support and laboratory facilities.

References

Adhikari BR (2009) Sedimentology and basin analysis of the Thakkhola-Mustang graben, Central Nepal. Unpublished Ph.D. thesis, submitted to Vienna University

Adhikari BR, Wagreich M (2011a) Facies analysis and basin architecture of the Thakkhola-Mustang graben (neogene-quaternary), Central Nepal Himalaya. Austrian J Earth Sci 104:66–80

Adhikari BR, Wagreich M (2011b) Provenance evolution of collapse graben fill in the Himalaya—the miocene to quaternary Thakkhola-Mustang graben (Nepal). Sediment Geol 233:1–14

Adhikari LB, Gautam UP, Koirala BP, Bhattarai M, Kandel T, Gupta RM, Timsina C, Maharjan N, Dahal T, Hoste-Colomer R, Canao Y, Dandine M, Guilherm A, Merrer S, Roudil P, Bollinger L (2015) The aftershock sequence of the 2015 April 25 Gorkha-Nepal earthquake. Geophys J Int 203:2119–2124

Amatya KM, Jnawali BM (1994). Geological map of Nepal, scale: 1:1000,000. Department of Mines and Geology, International Centre for Integrated Mountain Development, Carl Duisberg Gesellschaft e.V., and United Nation as Environment Programme

Argand E (1924) La tectonique de l'Asie. Congrès Géologique International, Belgique, Comptes Rendues de la 13ème Session, en Belgique 1922. H. Vaillant-Carmanne, Liège, pp 171–372

Arita K (1983) Origin of the inverted metamorphism of the lower Himalaya, Central Nepal. Tectonophysics 95:43–60

Auden JB (1934) The geology of the Krol Belt. Rec Geol Surv India LXVII(4):357–454 (with 9 plates, including a geological map in colours, scale: 1 inch = 2 miles)

Avouac J-P (2003) Mountain building, erosion and seismic cycle in the Nepal Himalaya. Adv Geophys 46:1–80

Avouac J-P, Meng L, Wei S, Wang T, Ampuero J-P (2015) Lower edge of locked Main Himalayan thrust unzipped by the 2015 Gorkha earthquake. Nat Geosci 8:708–711

Ballévre M, Manzotti P, Dal Piaz EV (2018) Pre-alpine (variscan) inheritance: a key for the location of the future valaisan basin (Western Alps). Tectonics 37:786–817

Bashyal RP (1982) Geological framework of far Western Nepal. Himal Geol Wadia Inst Himal Geol 12:40–50

Bashyal RP (1986). Geology of lesser Himalaya, far Western Nepal. In: Le Fort P, Colchen M, Montenat C (eds) Évolution des domains orogéniques d'Asie méridionale (de la Turquie à l'Indonésie), Livre jubilaire Pierre Bordet, Sciences de la Terre, Mémoire no. 47, Nancy, pp 31–42

Berthelsen A (1951) A geological section through the Himalaya: a preliminary report. Bull Geol Soc Den 12:102–104

Beyssac O, Bollinger L, Avouac J-P, Goffé B (2004) Thermal metamorphism in the lesser Himalaya of Nepal determined from Raman spectroscopy of carbonaceous material. Earth Planet Sci Lett 225(1–2):233–241

Bhargava ON (2000) The precambrian sequences in the Western Himalaya. Geol Surv India Spec Publ 55:69–84

Bhargava ON, Thöni M, Miller C (2016) Isotopic evidence of early palaeozoic metamorphism in the lesser Himalaya (Jutogh Group), Himachal Pradesh, India: its implication. Himal Geol 37(2):73–84

Bilham R (1995) Location and magnitude of the 1833 Nepal earthquake and its relation to the rupture zones of contiguous great Himalayan earthquakes. Curr Sci 69(2):101–128

Bilham R, Larson K, Freymueller J et al (1997) GPS measurements of present-day convergence across the Nepal Himalaya. Nature 386:61–64

Bilham R, England P (1995) Entertaining a great earthquake in western Nepal: historic inactivity and geodetic tests for the development of strain. J Nepal Geol Soc 11:73–88

Bordet P (1961). Recherches Géologiques dans L'Himalaya du Népal, Région du Makalu, Expéditions Françaises a l'Himalaya 1954–1955. Edition du Centre National de la Recherche Scientifique (C. N. R. S.), p 275 (with two geological maps in colours)

Brown RL, Nazarchuk JH (1993) Annapurna detachment fault in the Greater Himalaya of Central Nepal. Geol Soc Lond Spec Publ 74:461–473

Burchfiel BC, Zhiliang C, Hodges KV, Yuping L, Royden LH, Changrong D (1992) The South Tibetan detachment system, Himalayan Orogen: extension contemporaneous with and parallel to shortening in a collisional mountain belt. Geol Soc Am Spec Pap 269:1–41

Carosi R, Montomoli C, Visoná D (2007) A structural transect in the lower Dolpo: insights on the tectonic evolution of western Nepal. J Asian Earth Sci 29:407–423

Carosi R, Montomoli C, Iaccarino S, Visonà D (2018a) 20 years of geological mapping of the metamorphic core across Central and Eastern Himalayas. Earth Sci Rev 177:124–138

Carosi R, Montomoli C, Iaccarino S, Visonà D (2018b) Structural evolution, metamorphism and melting in the greater Himalayan sequence in central-western Nepal. Geological Society, London, Special Publications no 483. https://doi.org/10.1144/SP483.3

Colchen M (1999) The Thakkhola-Mustang graben in Nepal and the late cenozoic extension in the higher Himalayas. J Asian Earth Sci 17:683–702

Coleman M, Hodges K (1995) Evidence for Tibetan plateau uplift before 14 Myr ago from a new minimum age for east–west extension. Nature 374:49

Dal Piaz GV, Bistachhi A, Massironi M (2003) Geological outline of the Alps. Episodes 26:175–180

DeCelles PG, Gehrels GE, Quade J, Lareau B, Spurlin M (2000) Tectonic implications of U-Pb zircon ages of the Himalayan orogenic belt in Nepal. Science 288:497–499

DeCelles PG, Gehrels GE, Quade J, Kapp PA, Ojha TP, Upreti BN (1998) Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal. Geol Soc Am Bull 110:2–21

DeCelles PG, Robinson DM, Quade J, Ojha TP, Garzione CN, Copeland P, Upreti BN (2001) Stratigraphy, structure and tectonic evolution of the Himalayan fold–thrust belt in western Nepal. Tectonics 20:487–509

Dhital MR (2015) Geology of the Nepal Himalaya: regional perspective of the classic collided orogen. Springer, Berlin, p 498

Dhital MR, Kizaki K (1987) Structural aspect of the Northern Dang, lesser Himalaya. Bull Coll Sci Univ Ryukyus 45:159–182

Dikshit AM (1991) Geological effects and intensity distribution of the Udayapur (Nepal) earthquake of August 20, 1988. J Nepal Geol Soc 7:1–17

Einfalt HC, Hoehndorf A, Kaphle KP (1993) Rediometric age determination of the Dadeldhura granite, Lesser Himalaya, Far Western Nepal. Schweiz Miner Petrogr Mitt 73:97–106

England P, Molnar P (1990) Surface uplift, uplift of rocks, and exhumation of rocks. Geology 18:1173–1177

Fort M, Freytet P, Colchen M (1982) Structural and sedimentological evolution of the Thakkhola-Mustang Graben (Nepal Himalaya). Z Für Geomorphol 42:75–98

Frank W, Fuchs GR (1970) Geological investigations in West Nepal and their significance for the geology of the Himalayas. Geol Rundsch 59:552–580

Fuchs G (1977) The geology of the Karnali and Dolpo Regions, Western Nepal. Jahrb Geol Bundesanst Wien 120(2):1–103 (with 9 plates)

Fuchs G (1981) Geologic-tectonic map of the Himalaya. Scale: 1:2,000,000. Geol Bundesanst Wien

Fuchs G, Frank W (1970). The geology of West Nepal between the rivers Kali Gandaki and Thulo Bheri. Jahrb Geol Bundesanst 18:1–103 (with a geological map and cross-sections)

Gansser A (1964) Geology of the Himalayas. Interscience, New York, p 289

Garzanti E, Baud A, Mascle G (1987) Sedimentary record of the northward flight of India and its collision with Eurasia (Ladakh Himalaya, India). Geodin Acta 1:297–312

Garzione CN, DeCelles PG, Hodkinson DG, Ojha TP, Upreti BN (2003) East-West extension and miocene environmental change in the southern Tibetan plateau: Thakkhola graben, Central Nepal. Geol Soc Am Bull 115:3–20

Garzione CN, Dettman DL, Quade J, DeCelles PG, Butler RF (2000) High times on the tibetan plateau: paleoelevation of the Thakkhola graben. Nepal Geol 28:339–342

Godin L (2003) Structural evolution of the tethyan sedimentary sequence in the Annapurna area, Central Nepal Himalaya. J Asian Earth Sci 22:307–328

Goscombe B, Gray D, Hand M (2006) Crustal architecture of the Himalayan metamorphic front in eastern Nepal. Gondwana Res 10:232–255

Hagen T (1969) Report on the geological survey of Nepal. Volume 1: preliminary reconnaissance. Denkschiiften der Schweizerischen Naturforschenden Gesellschaft, Band LXXXVI/1, p 185 (with a geological map)

Harrison MT, Lovera OM, Grove M (1997) New insights into the origin of two contrasting Himalayan granite belts. Geology 25:899–902

Hashimoto S, Ohta Y, Akiba C (1973) Geology of the Nepal Himalayas. Saikon Publishing Co. Ltd., Tokyo, p 292 (with 6 plates including a geological map of Nepal (Plates 1 and 2) in colours, scale: 1:500,000)

Heim A (1922) Geologie der Schweiz. Verlag Chr. Herm. Tauchnitz, Leibzig, p 704

Heim A, Gansser A (1939). Central Himalaya: geological observations of the Swiss expedition 1936. Denkschriften der Schweizerischen Naturforschenden Gesellschaft, Band LXXIII, Abh. 1:245 (with geological maps in colors, sections, and plates)

Hurtado JM Jr, Hodges KV, Whipple KX (2001) Neotectonics of the Thakkhola graben and implications for recent activity on the South Tibetan fault system in the Central Nepal Himalaya. Geol Soc Am Bull 113:222–240

Johnson MRW (1994) Volume balance of erosional loss and sediment deposition related to Himalayan uplifts. J Geol Soc Lond 151:217–220

Kapp P, Guynn JH (2004) Indian punch rifts Tibet. Geology 32:993–996

Khan HR (1996) Geology of a part of Bajhang District, Far Western Nepal. Unpublished report (submitted to the Department of Mines and Geology, Kathmandu, Nepal, with a geological map on a scale of 1 inch to 1 mile)

Khan HR (2000) Geology of a part of Bajhang and Bajura Districts, Far Western Nepal. Unpublished report (submitted to the Department of Mines and Geology, Kathmandu, Nepal, with a geological map on a scale of 1 inch to 1 mile)

Le Fort P (1971) Les formations cristallophyliennes de la Thakkhola. In: Bordet P, Colchen M, Krummenacher D, Le Fort P, Mouterde R, Rémi M (eds) Recherches géologiques dans l'Himalaya du Népal, région de la Thakkhola. Centre National de la Reserches Scientifique, Paris, pp 41–48

Le Fort P (1975) Himalaya: the collided range. Am J Sci 275A:1–44

Le Fort P, Debon F, Sonet J (1983) The lower Paleozoic—Lesser Himalayan granitic belt: emphasis on the Simchar pluton of central Nepal. In: Shams FA (ed) Granites of Himalaya, Karakorum, and Hindu-Kush. Institute of Geology, Punjab University, Lahore, pp 235–255

Le Fort P, France-Lanord C (1994) Granites from Mustang and surrounding regions, Central Nepal. J Nepal Geol Soc 10:79–81

Lombard A (1958) Un itinéraire géologique dans l'Est du Népal (Massif du Mont Everest). Mémoires Société Helvétique Sci Natlles 82(1):107

Macedo J, Marshak S (1999) Controls on geometry of fold-thrust belt salients. Geol Soc Am Bull 111:1808–1822

Malusá M, Faccenna C, Garzanti E, Polino R (2011) Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps). Earth Planet Sci Lett 310:21–32

Manzotti P, Zucali M (2013) The pre-alpine tectonic history of the Austroalpine continental basement in the Alpelline unit (Western Italian Alps). Geol Mag 150:153–172

Mehta PK (1977) Rb–Sr geochronology of the kullu-mandi belts: its implications for the Himalaya. Sond Geologic Runds 66:186–195

Middlemiss CS (1910) The Kangra earthquake of 4th April 1905. Memoier Geol Surv India XXXVIII:1–409

Molnar P (2015) Plate tectonics. A Very Short Introduction, Oxford, p 136

Molnar P, Tapponnier P (1978) Active tectonics of Tibet. J Geophys Research Solid Earth 83:5361–5375

Nakata T (1982) A photogrametric study on active faults in the Nepal Himalayas. J Nepal Geol Soc 2:67–80 (Special Issue)

Oldham RD (1899) Report on the great Earthquake of 12th June 1987. Memoier Geol Surv India XXIV:1–379

Pandey MR, Tandukar RP, Avouac J-P, Lavé J, Massot JP (1995) Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophys Res Lett 22:751–754

Pandey MR, Tandukar RP, Avouac J-P, Vergne J, Heritier T (1999) Seismotectonics of Nepal Himalayas from a local seismic network. J Asian Earth Sci 17:703–712

Patel R, Singh S, Asokan A, Manickavasagam R, Jain A (1993) Extensional tectonics in the Himalayan orogen, Zanskar, NW India. Geol Soc, Lond, Spec Publ 74:445–459

Platt J, England P (1994) Convective removal of lithosphere beneath mountain belts-Thermal and mechanical consequences. Am J Sci 294:307–336

Ramsay JG (1967). Folding and fracturing of rocks. McGraw-Hill Book Company, New York, p 568

Robinbson DM, Martin AJ (2014) Reconstructing the greater Indian margin: a balanced cross-section in Central Nepal focusing on the lesser Himalayan duplex. Tectonics 33:2143–2168

Robinson DM, DeCelles PG, Copeland P (2006) Tectonic evolution of the Himalayan thrust belt in Western Nepal: implications for channel flow models. Bull Geol Soc Am 118:865–885

Schelling D, Arita K (1991) Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya. Tectonics 10:851–862

Schmid SM, Pfiffner OA, Froitzheim N, Schönborn G, Kissling E (1996) Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15:1036–1064

Searle MP, Law RD, Godin L, Larson KP, Streule MJ, Cottle JM, Jessup MJ (2008) The Himalayan main central thrust in Nepal. J Geol Soc Lond 165:523–534

Searle M, Windley B, Coward M, Cooper D, Rex A, Rex D, Tingdong L, Xuchang X, Jan M, Thakur V (1987) The closing of tethys and the tectonics of the Himalaya. Geol Soc Am Bull 98:678–701

Seeber L, Armbruster JG (1981) Great detachment Earthquake along the Himalayan arc and long-term forecasting. Earthq Predict: Int Rev Am Geophys Union 4:259–277

Sharma ML, Malik S (2006) Probabilistic seismic hazard analysis and estimation of spectral strong ground motion on bed rock in northeast India. In: Fourth international conference earthquake engineering, Taiwan, Paper No. 015, pp 1–10

Shrestha SB, Shrestha JN, Sharma SR (1987) Geological map of Mid-Western Nepal. Scale: 1:250,000. Department of Mines and Geology, Kathmandu

Stöcklin J (1980) Geology of Nepal and its regional frame. J Geol Soc Lond 137:1–34

Stöcklin J, Bhattarai KD, Singh-Chhetri V, Bhandari AN (1982) Photogeological map of part of Central Nepal. Scale: 1:100,000

Talalov VA (1972) Geology and ores of Nepal. UNDP report, Department of Mines and Geology, Kathmandu, 4 volumes (unpublished)

Upreti BN, Rai SM, Sakai H, Koirala DR, Takigami Y (2003) Early Proterozoic granite of the Taplejung window, far eastern lesser Nepal Himalaya. J Nepal Geol Soc 28:9–18

Upreti BN, Le Fort P (1999) Lesser Himalayan crystalline nappes of Nepal: problems of their origin. Geol Soc Am Spec Pap 328:225–238

Valdiya KS (1980) Geology of Kumaun lesser Himalaya. Wadia Institute of Himalayan Geology, Dehra Dun, p 291 (with a map in colours)

Webb AAG, Yin A, Harrison TM, Célérier J, Burgess P (2007) The leading edge of the greater Himalayan crystalline complex revealed in the NW Indian Himalaya: implications for the evolution of the Himalayan orogeny. Geology 35(10):955–958

West WD (1939) The structure of the Shali 'window' near Simla. Rec Geol Surv India 74(1):133–163 (with 4 plates and a geological map in colours; scale: 1 inch = 2 miles)

Yin A (2000) Mode of Cenozoic east-west extension in Tibet suggesting a common origin of rifts in Asia during the Indo-Asian collision. J Geophys Res: Solid Earth 105:21745–21759

Yin A, Kapp PA, Murphy MA, Manning CE, Mark Harrison T, Grove M, Lin D, Xi-Guang D, Cun-Ming W (1999) Significant late Neogene east-west extension in northern Tibet. Geology 27:787–790

Yoshida M, Igarashi Y, Arita K, Hayashi D, Sharma T (1984) Magnetostratigraphic and pollen analytic studies of the Takmar series, Nepal Himalayas. J Nepal Geol Soc 4:101–120. (Special Issue)