UPPER CRUSTAL SHORTENING AND FORWARD MODELING OF
THE HIMALAYAN FOLD-THRUST BELT ALONG
THE BUDHI-GANDAKI RIVER
CENTRAL NEPAL

by

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A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Geological Sciences
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2009
ABSTRACT

Geologic mapping along the Budhi-Gandaki River in central Nepal reveals 6 significant structures: 1) South Tibetan Detachment system; 2) Main Central thrust; 3) Ramgarh thrust; 4) Lesser Himalayan duplex including the Trishuli thrust; 5) Main Boundary thrust; and 6) Main Frontal thrust system. A balanced cross-section between the South Tibetan Detachment system and Main Frontal thrust reveals that the region has a minimum total shortening of 76% or 420 km. The breakdown of the accommodation of shortening on each thrust is as follows: Main Central thrust - 115 km; Ramgarh thrust - 120 km; Lesser Himalayan duplex including the Trishuli thrust - 156 km; Main Boundary thrust - 10 km; Main Frontal thrust system - 19 km.

In order to validate the balanced cross-section, a reconstruction program was used to forward model the system. By moving faults with appropriate amounts of displacement over a reasonable configuration of undeformed stratigraphy from the hinterland to foreland, the deformation of the Himalayan thrust belt along the Budhi-Gandaki River cross-section is reproduced. The forward modeling program moves hanging wall rock over stationary footwall rock using each individual fault identified in the balanced cross-section. Hanging wall rock deforms as it is thrust over footwall structures. Using forward modeling, the cross-section has a shortening estimate of 412 km or 75%. The two shortening estimates are virtually identical indicating the balanced cross-section along the Budi-Gandaki River is viable and admissible.
DEDICATION

This thesis is dedicated to everyone who helped me and guided me through the trials and tribulations of creating this manuscript. In particular, my family and close friends who stood by me throughout the time taken to complete this masterpiece.
LIST OF ABBREVIATIONS

Bt: Biotite
Fld: Feldspar
GBM: Grain Boundary Migration
Grt: Garnet
MFT: Main Frontal Thrust
MBT: Main Boundary Thrust
MCT: Main Central Thrust
MDT: Main Dun Thrust
MHT: Main Himalayan Thrust
Ms: Muscovite
Qtz: Quartz
RT: Ramngarh Thrust
SR: Subgrain Rotation
STDS: South Tibetan Detachment System
ACKNOWLEDGEMENTS

I would like to thank a number of people who helped me complete this research. I am very thankful to Dr. Delores M. Robinson for providing me valuable time, guidance, and support in all perspectives while doing this project. Similarly, I am very thankful to Dr. Timothy Masterlark, Dr. Amy Weislogel, and Dr. Aaron Martin for being my thesis committee and encouraging me at various occasions. I would like to thank the Department of Geological Sciences Advisory board, Graduate School and Capstone International for providing funding for this research. I am grateful to Midland Valley for providing access to the reconstruction program. I am also grateful to Pramod Simkhada, Prabhat Chandra Neupane, and Hari Kandel for giving their valuable time during field research. I greatly appreciate Dr. Santa Man Rai, head of the Department of Geology, Tribhuvan University, Tri-Chandra campus for providing facilities to prepare thin sections of rocks. I would also like to thank Joe Lambert for his help in taking photographs of thin sections. I am very thankful to Ghanashyam Neupane for his invaluable support to complete this research. I thank my wife for her patience and support she have given me during writing of this thesis. And last but not least, I would like to thank all who helped me in some way complete this work.
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1. Introduction

Nepal occupies the north-central position of south Asia and is geographically located between India to the south and Tibet (China) to the north (Fig. 1a). Low elevation plains are characteristic of southern Nepal, and the highest continental mountains in the world are present in northern Nepal. These mountains are a product of the Himalayan-Tibetan orogeny, a Paleocene- Holocene continent-continent collision. Nepal is located in the central part of the 2400 km long Himalayan arc, is 800 km in length and approximately 200 km in width. At ~55 Ma (Najman et al., 2006 and references therein), India and Asia began to collide along the Indus suture zone (e.g. Le Fort, 1975; Harrison et al., 1992; Parrish and Hodges, 1996). South of the suture zone lies the Himalayan thrust belt which consists of series of south vergent, southward propagating thrust faults (Fig. 1b) that developed in response to ongoing subduction of Indian plate beneath the Asian plate (Gansser, 1964; Coward and Butler, 1985; Searle, 1991; Srivastava and Mitra, 1994; Yin and Harrison, 2000). Because of the ongoing convergence, uplift, and climate interactions, the Himalayan orogenic system may be the world’s best geological field laboratory and is the focus of integrated research involving structural geology, sedimentology, thermobarometry, geochronology and geophysics.

Geologic studies in the Nepal Himalaya thrived after Nepal opened its borders to foreign researchers in the 1950’s. Early researchers spent years working in rugged terrain and produced a stratigraphic and structural framework, prepared preliminary geologic maps, and interpreted the tectonic evolution of the region (e.g, Auden, 1935; Hagen; 1951, 1969; Bordet et al., 1961; Gansser, 1964; Hashimoto et al., 1973; Brunel, 1975; Le Fort, 1975; Stöcklin and Bhattarai, 1980; and Colchen et al., 1986). This work forms a
basis for modern geologic studies. Most studies concentrate on the central part of Nepal and have a small-scale focus. Despite the focus of work over the past decade, fundamental questions remain to be answered for central Nepal including the stratigraphic and structural continuity along strike, the origin of the Paleo- to Mesoproterozoic Lesser Himalayan units, the existence and location of the Ramgarh thrust, the structure and location of Main Central thrust, the amount of shortening accommodated in the fold-thrust belt, and the kinematic sequence of deformation. A comprehensive two dimensional framework of the structural evolution of the central Nepal Himalayan fold-thrust belt has not been developed yet.

Figure 1. a) Location of the Nepal Himalaya. b) Generalized geologic map of the Nepal Himalaya (modified from Robinson et al., 2006). The box represents the study area and the bold line is a cross-section line.
Studies along the Himalayan arc that employ an understanding of the structural architecture using the concepts of fold-thrust belt development (Dhalstrom et al., 1969; Boyer and Elliott, 1982) have been conducted in Pakistan (Coward and Butler, 1985), northern India (Srivastava and Mitra, 1994), eastern Nepal (Schelling and Arita, 1991; Schelling, 1992), western Nepal (DeCelles et al., 2001; Robinson, 2006; 2008), central Nepal (Pearson, 2002) and western Bhutan (McQuarrie et al., 2008). These orogen-scale studies provide a useful method for understanding the deep structures of the mountain belt and calculating amount of upper crustal shortening after the Indo-Asia collision. The shortening values reported on the above studies can be used to identify along strike variability of structures and amount of shortening. These variations in shortening might explain the response of lithosphere to collision and location of maximum deformation in the Himalaya.

Research for this study was conducted along three rivers, the Budhi-Gandaki, Malekhu, and Manahari (see Plate 1), which cut across the Himalaya from north to south. The geology along these rivers is understudied because of the rugged terrain, small foot trails, and lack of basic infrastructure. The objectives of this research are to prepare a balanced cross-section and a forward model for the structural evolution of the central Nepal fold-thrust belt along the Budhi-Gandaki, Malekhu, and Manahari Rivers. Although numerous studies have been carried out for small areas of the region in the past, a regional scale study combining stratigraphy and structure is lacking. The cross-section is based on detailed structural mapping along a north-south transect of the fold-thrust belt. Mapping of the area includes the major orogen scale structures: Main Frontal thrust, Main Boundary thrust, Ramgarh thrust, Trishuli thrust, Main Central thrust, South
Tibetan Detachment system, Kathmandu klippe, Kathmandu synclinorim, and Gorkha-Pokhara anticlinorium. Published ages of the rock units and unroofing data relatively constrain timing of the thrust movement. Thermobarometric data are used to understand the depth of the rock units prior to deformation and structural data are used to portray the present day architecture of the Himalaya.

1.1 Geologic Setting

The Himalayan-Tibetan orogeny originated when the Tethys ocean subducted northward beneath the Asian plate, and the crust of the Indian and Asian plates began to collide at ~ 55 Ma (Powell and Conaghan, 1973; Coward and Butler, 1985). The Himalayan fold-thrust belt lies south of the Indus suture zone and extends along strike from Nanga Parbat, Pakistan in the west and Namche Barwa, Tibet in the east. The collision is accommodated by slices of the Indian upper crust and adjacent terranes imbricating on top of another to form a deformed pile of upper crustal material. Deformation first started in the Tibetan part of the fold-thrust belt during the Middle Eocene to Oligocene (55-25 Ma) (Ratchbacher et al., 1994). During the Late Oligocene (25 Ma), the deformation shifted toward the southern part of the Himalayan fold-thrust belt. In the southern part of the Himalayan fold-thrust belt, the deformation is first accommodated by the Main Central thrust in late Oligocene to early Miocene time (25-16 Ma) (Harrison et al., 1992; Hodges et al., 1996; Coleman, 1996; Guillot, 1999) and successively propagated towards the foreland producing major thrust faults (Fig. 2). All thrusts connect to the décollement, the Main Himalayan thrust, which is a subhorizontal shear zone above Indian basement (Zhao et al., 1993) at 5-6 km depth beneath the Indo-Gangetic Plain across central Nepal’s modern foreland basin (Lavé and Avouac, 2000;
Avouac, 2003) and ~35-40 km in south Tibet (Zhao et al., 1993; Brown et al., 1996; Nelson et al., 1996).

India and Asia continued convergence at the rate of 5 cm/yr estimated from the magnetostratigraphy (Patriat and Achache, 1984), and the collision was accommodated by major faults along the Himalaya (Brunel et al., 1983; Macfarlane et al., 1993; Hodges et al., 1996, 2000; DeCelles et al., 1998a). GPS measurements show that the present crustal shortening of the central Nepal Himalaya is 2 mm/yr (Larson et al, 1999). The ongoing crustal shortening of the Himalaya is also manifested by large earthquakes with magnitude Mw > 8 such as Bihar Nepal earthquake in 1934 and Kangra earthquake in 1905 in India.
Figure 2. Geologic Map of the Himalaya from Pakistan to the western part of Nepal. Major faults are marked and abbreviations in the upper right corner of the map (Hodges, 2000).
1.2 Tectonostratigraphy

Tectonostratigraphic division of the Himalayan orogen is based on packages of rocks bounded by orogen scale thrust faults. Gansser (1964) divided the Himalayan orogen into four zones (Fig. 3). Each zone is then further divided into formations based on lithology and age. From south to north, the four tectonic divisions of the Himalayan orogen are: 1. Subhimalaya; 2. Lesser Himalaya; 3. Greater Himalaya; 4. Tibetan Himalaya.

Figure 3. Tectonostratigraphic division of the Himalaya from Nanga Parbat to the west and Namche Barwa to the east (Gansser, 1964). Equivalent abbreviations using in this study are as follows: Tibetan-Tethys Himalaya = Tibetan Himalaya, Higher Himalaya = Greater Himalaya, Lesser Himalaya = Lesser Himalaya, Siwaliks = Subhimalaya
1.2.1 Subhimalaya

The Subhimalaya is the southernmost zone of the Himalayan orogen, and consists of a foreland basin system that incorporated syntectonic sediments during Middle Miocene to Pliocene time (~14-2 Ma). The Subhimalaya zone is bounded by Main Frontal Thrust (MFT) to the south and Main Boundary Thrust (MBT) to the north and is defined by subparallel ridges called the Siwalik hills in central Nepal. As the Himalaya uplifted, sediment shed from the growing mountains collected in a flexural foredeep to the south. These sediments lithified and now form the Subhimalaya or Siwalik Group. In central Nepal, the Siwalik Group has a total thickness of 3500-5500 m (e.g. Corvinus, 1988, in Surai Khola; Gautam and Appel, 1994, in Tinau Khola; Tokuoka et al., 1986, in Arungkhola; Harrison et al., 1993, in Bakeya Khola), and are divided into three lithostratigraphic units: lower, middle, and upper (Auden, 1935; Hagen, 1969, DeCelles et al., 1998a). In the study area, the Siwalik Group is ~5000 m thick and coarsens upward from the lower to the upper units.

According to paleontological and magnetostratigraphic studies, deposition of Siwalik Group began ~15 Ma and continued to ~1 Ma (Tokuoka et al., 1986; Gautam and Roesler, 1999). However, Ojha et al. (2008) suggested on the basis of magnetostratigraphic data that the age of Siwalik Group in western Nepal is ~13.5-2 Ma. The lower-middle Siwalik unit boundary ranges from ~11 Ma to 8 Ma (Harrison et al., 1993; Ojha et al., 2000, 2008). The middle-upper Siwalik unit boundary age varies from ~2.5 Ma to 4.1 Ma (Appel et al., 1991; Quade et al., 1995). The age of the lower-middle and middle-upper Siwalik unit boundaries vary by location which suggests diachronous deposition of the Siwalik Group.
In the study area, all three units of the Siwalik Group are present along the Manahari Khola (see Plate 1). The area to the south of the Rapti River was inaccessible due to flooding during the field session. Thus, the geologic map in this study uses the data of Shrestha et al. (1984) in this inaccessible region. The Subhimalayan rock in the study area is 27 km wide. Stratigraphic thickness of Siwalik Group varies by location and ranges between 3.5- 6 km (Tokuoka et al., 1986; Lavé and Avouc, 2000). Based on surface mapping and subsurface data in the study area, the estimated thickness of the lower Siwalik unit is 2200 m, the middle Siwalik unit is 1200 m thick, and the upper Siwalik unit is 1650 m thick for a total thickness of the Siwalik Group of 5050 m. The thickness of the lower Siwalik unit increases towards the mountain front and reaches ~ 8 km (see Plate 2) due to deposition in the flexure foredeep (Avouc, 2003).

1.2.1.1 Lower Siwalik unit

This unit consists of fine- to medium-grained gray sandstone with variegated mudstone forming nearly uniform sedimentary cycles with a thickness of 50 cm-2 m (Fig. 4a). Sedimentary structures such as cross-stratification, ripple laminations, ripple marks, (Fig. 4b) and raindrop imprints are present. Some mudstone beds are rich in plant fossils. Together these features indicate deposition of the unit in a meandering river system (Nakayama and Ulak, 1999). Spheroidal weathering is common in the mudstone beds. A few marl beds of about 35 m thick are present in the upper part of the lower Siwalik unit. Generally, beds dip 50° north.
Table 1: Stratigraphic Division of the Subhimalaya

<table>
<thead>
<tr>
<th>Siwalik Group</th>
<th>Rock Type</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>Conglomerate</td>
<td>2.3-1.8*</td>
</tr>
<tr>
<td>Middle</td>
<td>Coarse grained sandstone</td>
<td>11-2.3*</td>
</tr>
<tr>
<td>Lower</td>
<td>Interbeded fine-grained sandstone and mudstone</td>
<td>14.6-11**</td>
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*Ojha et al. (2000; 2008)
** Gautam and Roesler (1999)

1.2.1.2 Middle Siwalik Unit

This unit consists of medium- to coarse-grained, mica-rich “salt and pepper” sandstone with bed thicknesses of tens of meters. These beds are sparsely intercalated with mudstone of 30-50 cm thick. The sandstone generally shows planar laminations, trough cross stratification (Fig. 5a), and ripple laminations. Grain size of the sandstone generally increases from medium-grain to coarse-grained upsection. Pebbly (0.5-1.5cm) sandstone is present in the upper part of middle Siwalik unit. Proportionally, mudstone decreases upsection. The deposition of middle Siwalik unit is attributed to a braided river system (Nakayama and Ulak, 1999). The sandstone is calcite cemented yielding relief of up to 900 m. Beds dip >75° northward upsection and the contact between middle and upper Siwalik unit in the Manahari River (see Plate 1) is almost vertical.

1.2.1.3 Upper Siwalik Unit

This unit consists of massive, thick beds (1-5 m) of pebble and cobble conglomerate (4-20 cm) with intercalations of 0.5-1 m sandstone and mudstone (Fig. 5b). The basal contacts of sandstone bed cut and scour the conglomerate and probably represent a paleochannels (DeCelles et al., 1998b). The gravel clasts are sub-rounded to rounded, are derived from the Lesser Himalayan rock (DeCelles et al., 1998a), and size
increases from 4-20 cm upsection. The upper Siwalik unit is interpreted as alluvial fan deposits near the mountain front (Gautam and Roesler, 1999).

Figure 4. a) Interbedded sandstone with mottled mudstone, b) Current ripple marks in the lower Siwalik unit mudstone (30 cm rock hammer for scale).
Figure 5. a) Cross-stratification in coarse-grained middle Siwalik unit sandstone, 30 cm rock hammer for scale; b) Pebble-cobble conglomerate in the upper Siwalik unit, men for scale.
1.2.2 Lesser Himalayan Rock

The Lesser Himalayan rock is bounded by the Main Boundary thrust (MBT) to the south and Main Central thrust (MCT) to the north and consists of unmetamorphosed to greenschist facies rock with a stratigraphic thickness of ~10 km (Upreti, 1999). In the study area, the Lesser Himalayan rock mainly consists of a hinterland dipping duplex north of the Kathmandu klippe. The width of the belt containing Lesser Himalayan rocks depends on how much of the synformal klippe is eroded. West of 85° longitude, the Lesser Himalayan rocks are exposed in a 70 km wide belt, and east of 85°E longitude where most of the fold-thrust-fold belt is composed of the Kathmandu klippe (Fig. 1b), the rocks are exposed in 10 km belt.

1.2.2.1 Lower Lesser Himalayan rock

The lower Lesser Himalaya consists of mid-grade greenschist metasedimentary rocks of Paleoproterozoic age. The presence of kyanite 300 m in the hanging wall of the Ramgarh thrust indicates amphibolites facies. Lower Lesser Himalaya composes almost 75% of the Lesser Himalayan rock exposed in the study area (Plate 1). The rock units are predominantly siliciclastic with a stratigraphic thickness of ~4-6 km. The lower Lesser Himalaya in the study area consists of the Kunchha and Robang Formations.

*Kunchha Formation*

The Kunchha Formation consists of an ~3.2 km thick (Upreti, 1999) package of rocks composed primarily of phyllite, phyllitic metasandstone, gritty phyllite, and impure quartzite. The overall color of the Kunchha Formation is yellow-green to light blue which is distinguishable from the overlying phyllite in the Robang Formation due to the lighter
color and coarser grain size. The impure quartzite consists of quartz, feldspar, and mica, is abundant throughout the study area and composes the core of the Gorkha-Pokhara anticlinorium (Plate 1). Phyllite in the lower part of the Kunchha Formation is intercalated with gritty phyllite, and is the distinguishing characteristics of this formation. The gritty phyllite mainly contains of quartz, feldspar, and tourmaline which are loosely lithified in the phyllitic matrix. The Kunchha Formation is highly deformed and contains S-type 15-20 cm folds and crenulation cleavage (Figs. 6a, 6b). Pearson (2002) found graphitic phyllites in the vicinity of Ramgarh thrust (RT) in the Langtang area ~50 km to the east which was not present in the study area. Amphibolite and the Ulleri augen gneiss found by Le Fort (1975) and Stöcklin (1980) are not present. However, Shrestha et al. (1984) mapped the Ulleri augen gneiss 10 km east of the Baseri village (Plate 1). The Ulleri augen gneiss is granitic augen gneiss that contains of porphyrblasts of plagioclase feldspar, quartz, and mica, and intruded at ~1830 Ma (Le Fort and Rai, 1999; DeCelles et al., 2000).
Figure 6. a) Crenulation cleavage in the Kunchha Formation, 8cm lighter for scale; b) S-type fold in the Kunchha Formation, penny for scale.
Robang Formation

The Robang Formation is a ~500-3000 m thick package of sericitic-chloritic, calcareous phyllite with interbedding of thin to thick (15 cm-1 m) bedded Dunga quartzite. The Dunga quartzite is a pure, white quartzite with occasional trough and planar cross-stratification. Graphitic phyllite is abundant in the footwall of the MCT. White quartz blebs and ribbons are common in the phyllites. Near the village of Malekhu (see Plate 1), the phyllite is intruded with a ~20 m thick amphibolite. Greenish-white, soapy, talcose phyllite is present along the Prithivi Highway in the Malekhu area. The Dunga quartzite is relatively thick bedded and has total thickness of ~3 km towards the northern limb of the Gorkha-Pokhara anticlinorium whereas it is relatively thin and contains more intercalated phyllites in the southern limb in Malekhu area. The Robang Formation is bounded at its base by the RT and at its top by the MCT. Flow structures with abundant garnet and kyanite are present in the northern part near the Tatopani area (Figs. 7a, 7b; location, see Plate 1). In this study, the Dunga quartzite beds, mafic volcanic sills and dikes and phyllite are collectively treated as Robang Formation.
Figure 7. a) Kyanite in the Robang Formation of the Ramgarh thrust sheet, penny for scale; b) Garnets in the Ramgarh thrust sheet, 30 cm rock hammer for scale.
1.2.2.2 Regional Stratigraphic Correlation and Age of Lower Lesser Himalaya

Previous researchers (Stöcklin, 1980; Arita, 1983; Sakai 1985; Dhital and Kizaki, 1987) adopted different names for similar lithologic packages in central, western, and eastern Nepal. The stratigraphic correlation of the lower Lesser Himalayan units is problematic because of the lack of age constraints and different rock types present across Nepal (Table 2). The lower Lesser Himalayan rock consist primarily of quartzite and phyllite. In western Nepal, the basal unit is a quartzite, the Kushma Formation, which is overlaid with a phyllite, the Ranimata Formation (Upreti, 1996; DeCelles et al., 2001, Robinson et al., 2006). Zircons from the Ulleri Augen gneiss, which intruded the Ranimata Formation yield crystallization age of ~1831 Ma and detrital zircons from the Kushma Formation has age distribution peak at 1866 Ma (DeCelles et al., 2000). Thus the Kushma and Ranimata Formation have depositional age between ~1866 and 1831 Ma. In central Nepal, the basal unit is the Kunchha Formation (Burgy, 2009). However, this formation is not present across Nepal, only in select areas of central Nepal and not in the study area. Near the city of Pokhara, the Kushma Formation is younger than the Kunchha Formation (Burgy, 2009). The Robang Formation in central Nepal correlates to the Ranimata Formation of western Nepal (Stöcklin, 1980; Shrestha et al., 1984). In the study area, the Robang Formation contains thick beds of Dunga quartzite which possibly correlate to the Kushma Formation deposited after ~1760 Ma constrained from the detrital zircons (Burgy, 2009). Stöcklin (1980) and Upreti (1996; 1999) placed the Robang Formation and associated Dunga quartzite beds at the top of the Lesser Himalayan sequence in the central Nepal region. DeCelles et al. (2000) suggested that the contact of the Robang Formation with the underlying Malekhu Formation is structural
and not depositional based on the detrital zircon age from the Robang Formation. The Dhunchhe schist in the Langtang area ~50 km east of the study area, which is equivalent of Kunchha Formation, has a detrital zircon age peak of 1867-1878 Ma (Parrish and Hodges, 1996). In this study, because of the detrital zircon age data of ~1875 Ma (Burgy, 2009), the Kunchha Formation is reconstructed as the oldest unit of the Lesser Himalaya and because of structural constraints, the Robang Formation and associated Dunga quartzite beds are reconstructed as the distal facies of the Kunchha Formation which was deposited synchronously with the Kushma and Ranimata Formations in the western Nepal Himalaya.

1.2.2.3 Upper Lesser Himalayan Rock

The Upper Lesser Himalayan rock consists of both siliciclastic and carbonate rocks with carbonates dominating the top of the section. The upper Lesser Himalaya consists of the Fagfog, Dandagaon, Nourpul, Dhading, Benighat, and Malekhu Formations from bottom to top.

*Fagfog Formation*

The Fagfog Formation is a fine-to coarse-grained (0.3-0.8 mm), thin-to thick-bedded (20-85 cm), white quartzite with orange tints intercalated with thin-bedded (1-2 cm) green phyllite and a thickness of ~350 m. It is well exposed on a fresh road cut to the village of Dhading in Thopple Khola. At this exposure, the Fagfog Formation has ripple marks (Fig. 8), cross-stratification, and cross-laminations. Stöcklin (1980) observed the Fagfog Formation in the study area along the Budhi-Gandaki River but that exposure was covered by vegetation during field work for this study.
Table 2. Lithostatigraphic correlation of the Lesser Himalayan units across Nepal (modified from Pearson, 2002)

<table>
<thead>
<tr>
<th>Age</th>
<th>Informal Units This study</th>
<th>Western Nepal (DeCelles et al., 2001)</th>
<th>Central Nepal (This study)</th>
<th>Eastern Nepal Modified from Schelling (1992)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Proterozoic</td>
<td>Upper Lesser Himalaya</td>
<td>Lakarpata Group</td>
<td>Malekhu Fm.</td>
<td>Tumlingtar Group (including Ulleri augen Gneiss)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Syangia Fm. (&lt;1.68 Ga)</td>
<td>Nourpul Fm.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Galyang Fm.</td>
<td>Dandagaon Fm.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sangram Fm.</td>
<td>Fagfog Fm.</td>
<td></td>
</tr>
<tr>
<td>Early Proterozoic</td>
<td>Lower Lesser Himalaya</td>
<td>Ranimata Fm</td>
<td>Robang Fm.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(including Ulleri augen Gneiss)</td>
<td>Kunchha Fm.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kushma Fm.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Ripple marks in the Fagfog Formation, 30 cm rock hammer for scale.

_Dandagaon Formation_
The Dandagaon Formation is an ~1100 m package of argillaceous to fine-grained quartzitic phyllite, dark blue-green to gray phyllite with subordinate olive-green to gray slate that weathers with reddish tints. Thin (10-30 cm) bands of calc-phyllite and dolomite are present at the top of the section in the Dandagaon Formation. When compared to the Kunchha Formation, the Dandagaon Formation is darker, does not contain quartzite and has lenses and nodules of segregated quartz.

**Nourpul Formation**

The Nourpul Formation is ~600 m thick and contains phyllite, quartzite and carbonate. Overlying the Dandagaon Formation is a purple quartzite that contains cross-stratifications and planar laminations (Fig. 9a). Thin (2-5 mm) laminations of green and purple phyllitic slate intercalated with the quartzite contain mud cracks (Fig. 9b) and ripple marks. The middle part of the formation contains predominantly dark green, to blue-gray, to red phyllite with variable amount of quartzite and carbonate. The quartzite is impure, micaceous and is intercalated with phyllite. The carbonate on top of the middle part has 5-20 cm thick beds of white, green, and pink color intercalated with thin bands (10-20 cm) of green phyllite. The carbonate is usually dolomitic and extremely fine-grained. The upper part of the formation contains dolomite and dolomitic quartzite intercalated with green phyllite dominates. Pink-green bands of dolomite and phyllite are present on a fresh outcrop in Thopal Khola. The contact with the overlying dolomite of the Dhading Formation is transitional.
Figure 9: a) Mud cracks in the Norpul Formation, 7 cm brunton compass for scale; b) Cross-stratifications in the Nourpul Formation, penny for scale.
Dhading Formation

The Dhading Formation is ~500 m thick, and contains thin-to massive-bedded (0.15-3.0 m) bluish-gray-white, fine-grained dolostone (Fig. 10). Thin (10-20 mm) bands of chert are intercalated with the dolostone that give a banded appearance to the rock near Trishuli River north of the Malekhu. In upper part of the formation, finely laminated stromatolites are present. The dolostone is highly fractured in lower part of the formation and contains bands of light gray argillaceous slate. The stratigraphic contact with the overlying Benighat Formation is sharp.

Figure 10. Massive bedded, fractured dolomite in the Dhading Formation, 30 cm rocks hammer for scale.
Benighat Formation

The Benighat Formation is ~1000 m thick, and consists of thin to thick (0.15-1 m) bands of dark gray slates intercalated with dark graphitic slates. This carbonaceous slate weathers a rust color. Very few thin (10-15 mm) bands of quartzite are observed in lower part of the formation. The middle part of the formation consists of blue-gray, thick-to massive-bedded (1-3 m) limestone, and is referred to as the “Jhiku Carbonate” by Stöcklin (1980). The top of the formation consists of mesoscale (2-5m) folds. The contact with the overlying Malekhu Formation is gradational.

Malekhu Formation

The Malekhu Formation is the youngest unit of upper Lesser Himalaya sequence, and consists of ~500 m of dolomitic limestone intercalated with thin-to medium-bedded (10- 40 cm) green phyllite. The lower part of the formation consists of thinly bedded, bluish-gray, platy limestone intercalated with < 2cm thick beds of green phyllite. The middle part of the formation consists of medium to massive (0.5-2 m) bedded siliceous limestone and dolostone intercalated with thin-to medium-bedded (10-40 cm) green-gray phyllite. In Thopal Khola, the contact between the Malekhu Formation and the overlying Robang Formation is a fault contact in contrast with gradational contact suggested by Stöcklin (1980).
1.2.2.4 Regional Stratigraphic Correlation and Age of the Upper Lesser Himalaya.

The Fagfog Formation of the central Nepal is equivalent of Sangram Formation of the western Nepal (Table 2). The Dandagaon Formation is equivalent of Galyang Formation of western Nepal. The correlation of Fagfog and Dandagaon Formations with Sangram and Galyang Formations of the western Nepal is straightforward due to similarity in lithological characteristics (Upreti, 1999). The Nourpul Formation in the central Nepal (Stöcklin, 1980) is equivalent to the Syangia Formation mapped by Shrestha et al. (1984). The Syangia Formation is the name used in western Nepal (DeCelles et al., 2001). Upreti (1999) suggested that the Nourpul and Syangia Formations have similar lithology and are lateral equivalents. The Dhading, Benighat and Malekhu Formations are lumped together as Lakhapatra Group in western Nepal (Shrestha et al., 1984; 1987). The lithostratigraphy is well defined in Kathmandu area, central Nepal with a clear boundary between the Dhading, Benighat and Malekhu Formations. In this study, the stratigraphic nomenclature of Stöcklin (1980) is used.

Depositional ages of the upper Lesser Himalayan rocks are poorly constrained due to lack of fossils. The Fagfog Formation yields a detrital zircon age of ~1800 Ma (Burgy, 2009). Detrital zircon (U-Pb) age populations of the Syangia Formation in western Nepal have an age peak at ~1680 Ma (DeCelles et al., 2000; 2001). Therefore, the depositional age of Nourpul Formation in the central Nepal must be younger than ~1680 Ma.
1.2.3 Greater Himalayan Rock

The Greater Himalayan rock is separated from the structurally overlying Tibetan Himalayan zone by the South Tibetan Detachment system (STDS), which is a series of brittle-ductile normal faults. The base of the Greater Himalayan rock is thrust over rock of the Lesser Himalayan unit along the MCT. The Greater Himalayan rock consists of greenschist to amphibolite grade schist, gneiss, and quartzite north of the MCT. The rock in the Kathmandu klippe is of relatively lower metamorphic grade (chlorite-garnet) and has similar (-10.65 to -15.10) εNd isotopic signatures and crystallization and detrital zircon ages (480-1250 Ma) to the Greater Himalayan rock north of the (Pearson, 2002 and Gehrels, et al., 2006).

1.2.3.1 Rock in the Kathmandu Klippe

The rock of the Kathmandu klippe is referred to as the Bhimphedi Group by Stöcklin (1980). It consists of metasedimentary rocks intruded by plutons at various stratigraphic levels. The thickness of the exposed unit in the study area is ~3.5 km. The total thickness of the klippe is between ~10 km (Stöcklin, 1980) and ~6.5 km (Pearson, 2002). Generally, the metamorphic grade of the klippe decreases up-section from a garnet-amphibolite grade at the bottom of the sequence to a sericite-chlorite grade on the top of the sequence.
Raduwa Formation

The Raduwa Formation is the lowermost unit of the Kathmandu klippe and always bounded by the MCT on the bottom. It consists of green-gray, crystalline garnetiferous mica schist. Quartz blebs and ribbons are abundant on the bottom. Quartz boudinage and ptygmatic folds are abundant throughout the formation. A few micaceous gray quartzite (~20 m) beds are intercalated on top of the formation, which has a red color upon weathering. Garnets are abundant on bottom of the Raduwa Formation and have a diameter of up to 1cm. Stöcklin, (1980) suggested the thickness of the Raduwa Formation varies from 0-2000 m. In the study area the formation is ~300 m thick which is equal to the thickness mapped by Pearson (2002). The contact of the Raduwa Formation with the underlying Lesser Himalayan rock is tectonic so rocks are generally associated with a zone of shearing and mylonitization (Stöcklin, 1980). The formation has a gradational contact with the overlying Bhainsedobhan Formation.

Bhainsedobhan Formation

The Bhainsodobhan Formation is a thin-to thick- (0.15- 85 cm) bedded, coarse crystalline (up to 2 mm), white with lenses of pink, ~400 m thick marble. The marble consists of mica and pyrite as accessory minerals in the study area whereas Stöcklin (1980) noted magnetite, galena, copper sulphides, malachite and azurite near Bhainsedobhan village, the type locality of the formation. The formation extends all the way around the western closure of the Kathmandu klippe (Stöcklin, 1980) to the northern flank of the klippe. At the bottom and top of the formation, the marble is thinly bedded
(10-20 cm) and intercalated with biotite and occasionally garnetiferous schist. The formation has gradational contact with the overlying Kalitar Formation.

*Kalitar Formation*

The Kalitar Formation is dark green-gray mica schist intercalated with impure dark gray micaceous quartzite with a thickness of ~850 m. Garnet crystals are observed near the base of the formation and are not present up section. Thin-to medium- (10-50 cm) bedded, pale-green quartzite (Pandrang quartzite) with partings of schist is present just above the base of the formation. Thin to thick (0.8-80 cm), bluish-gray, fine-to coarse-grained marble bands (Bhimsen dolomite) of ~30 m are present. Stöcklin (1980) reported conglomerate beds (Jhurikhet conglomerate) with in the Kalitar Formation that are not present along the Malekhu River. The contact with the overlying Chisapani Formation is gradational.

*Chisapani Formation*

The Chisapani Formation is a ~300 m thick white to pale-green, fine-grained quartzite intercalated with partings of schist. Small (1-2 mm) garnet crystals are present near the contact with an augen gneiss in the upper portion of the formation. The formation is a marker horizon between the underlying Kalitar Formation and overlying quartzite of the Kulekhani Formation. Cross-beds are common in the Chisapani Formation. The formation has a transitional contact with the overlying Kulekhani Formation.
**Kulekhani Formation**

The Kulekhani Formation is 900 m thick, and consists of dark green to gray, thin (15-30 cm) bedded, micaceous quartzite and quartzitic schist. Garnet crystals (1-3 mm) in the schist are present near the base of the formation. The proportion of quartzite increases upsection. In the middle of the formation, plunging mesoscale (up to 5 m) folds are present (Fig. 11a). Cross-stratifications and ripple-laminations are prominent in upper part of the formation. The formation has gradational contact with the overlying Markhu Formation.

**Markhu Formation**

The Markhu Formation is 550 m thick, and consists of, thin- to thick- bedded (20 cm-1.5 m), white to pink marble intercalated with a subordinate amount of schist and quartzite. The schist and quartzite are generally dark in color, fine-grained, and calcareous. Stöcklin (1980) found worm tracks and mudcracks; however, these are not present in the study area. The formation is well-exposed on the southern limb of the Kathmandu klippe ~200 m upstream from the confluence of the Malekhu and Khani Kholas (see Plate 1). The marble bands as found by Stöcklin (1980) are not present in the northern limb. However, the marble bands may have pinched out before reaching Malekhu Khola. Several mesoscale (5-10 m) folds are present in the formation complicating measurement of the orientation. The contact with the overlying Tistung Formation is gradational.
Figure 11. a) Mesoscale plunging folds in the Kulekhani Formation, 30 cm rock hammer for scale; b) Tangential cross-stratification in the Tistung Formation, 15 cm pen for scale.
**Tistung Formation**

The Tistung Formation is at the top of the strata of the Kathmandu klippe, and consists of phyllite, slate, and quartzite. The quartzite is medium (20-50 cm) bedded, intercalated with thin (10-20 cm) phyllite and has planar, ripple and trough cross-stratifications (Fig. 11b). Mesoscale (4-8 m) folds are present along the Malekhu Khola. The metamorphic grade generally decreases from biotite-grade at the bottom to chlorite-grade at the top of the Tistung Formation. In the uppermost portion, biotite disappears and is replaced by sericite and chlorite making this part soft and less indurated. At the contact with the Agra granite (see below), hornfels are present (Fig. 12a). A measure of true thickness of the Tistung Formation in the study area is not possible because erosion has removed the top of the formation; however, the thickness in the type locality is ~3000 m (Stöcklin, 1980) and ~2300 m 15 km east of the study area (Pearson, 2002).

**Agra Granite**

Six large granitic intrusions exist in the Kathmandu klippe along with few small satellite intrusions (Stöcklin and Bhattarai, 1982). The Agra granite is observed at the western closure and near the core of the Kathmandu klippe (see Plate 1). The granite is porphyritic with 2-3 cm plagioclase feldspar phenocrysts. Biotite is common; however, muscovite and tourmaline are generally absent. The granite cross-cuts the country rocks. Xenoliths are present in the granite. The xenoliths are dark colored meta-sandstone and schist (Fig. 12b). Some dike intrusions are present near the main granitic intrusion that cuts across the foliation of country rock at a 10-15° angle. The age of the granite is 470-512 Ma (Gehrels et al., 2006).
Figure 12. a) Hornfels in the Tistung Formation, 21 cm open brunton compass for scale; b) Biotite rich Agra granite with a siltstone xenolith from the Tistung Formation, 30 cm rock hammer for scale.
1.2.3.2 Affinity and Age of the Kathmandu Klippe

The rocks of the Kathmandu klippe are equivalent to the Jajarkot and Dadeldhura/Karnali klippen (Fig. 1b) in the western Nepal (Stöcklin, 1980; Shrestha et al., 1984; 1987). Previous workers (e.g., Gansser, 1964; Stöcklin, 1980; Schelling, 1992) define the Kathmandu, Dadeldhura/Karnali, and Jajarkot klippen as erosional outliers of the Greater Himalayan rock. Upreti et al. (1999) suggests that the rocks in the klippe are generally of lower metamorphic grade and thus, are not the southern continuation of Greater Himalayan rock. However, Robinson et al. (2001) used $\varepsilon$Nd isotopic characteristics to show the rocks in the Dadeldhura klippe have $\varepsilon$Nd(0) values of -7.6 to -11.8. Similarly Pearson et al., 2002 suggested $\varepsilon$Nd(0) values of -10.65 to -15.10 from the Raduwa Formation of the Kathmandu klippe. The Greater Himalayan rocks in the central Nepal Himalaya have $\varepsilon$Nd(0) values of -19 to -5 (Parrish and Hodges, 1996). The $\varepsilon$Nd(0) values of the klippe are within the range of the Greater Himalayan rock and must have a Greater Himalayan affinity.

The age of the Agra granite in the Malekhu area has been dated at 480±4 Ma (Gehrels et al., 2003; 2006). The age of other granites in the Kathmandu klippe are 473-485 Ma (Le Fort et al., 1986; DeCelles et al., 2000; Johnson et al., 2001, Gehrels et al., 2006). Monazite inclusions in garnet from the Kalitar Formation yield an age of 490± 22 Ma (Gehrels et al., 2006). Detrital zircons collected from sandstone in the Tistung Formation yield an age cluster of 480-490 Ma, and the Chisapani Formation has age clusters of 860-1240 Ma (Gehrels et al., 2006).
1.2.3.3 Rocks North of the Main Central Thrust

Rocks north of the MCT are high grade metamorphic rocks and are also referred to as “Central crystalline”, “Higher Himalayan gneisses”, and “Tibetan slab”. Le Fort (1975) divided the Greater Himalayan zone into three units—Unit I, II and III (Table 3).

Table 3 Lithostratigraphy and age of the Greater Himalaya (modified from Robinson et al. 2001)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithostratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit III</td>
<td>Garnet-tourmaline augen orthogneiss, migmatitic, quartzo-feldspathic sillimanite bearing schist, and calc-silicate gneiss</td>
</tr>
<tr>
<td></td>
<td>ca. 480-500 Ma*</td>
</tr>
<tr>
<td>Unit II</td>
<td>Diopsode-garnet-amphibolite bearing calc-silicate gneiss and marble</td>
</tr>
<tr>
<td>Unit I</td>
<td>Kyanite-garnet bearing pelitic gneiss and migmatite, abundant quartzite</td>
</tr>
<tr>
<td></td>
<td>ca. 830 Ma*</td>
</tr>
</tbody>
</table>

* DeCelles et al., (2000)

Unit I

Unit I forms the base of the Greater Himalayan sequence, and consists of predominantly mica schist, calc-schist, quartzite, gneiss and migmatite. In the study area, the lower part of the formation consists of intercalations of 0.15 -1 m bands of garnetiferous two-mica schist (Fig. 13a) and medium bedded (30 cm) quartzite. Quartz blebs, ribbons, and ptygmatic folds are very common in the garnetiferous schist. The schist extends ~300 m north of the MCT above which the unit is dominated by medium to massive (0.3-2.5m) bedded micaceous quartzite with cross-bedding and tangential cross-stratifications (Fig. 13b). The upper part of the Unit I is dominated by garnetiferous schist, banded gneiss and migmatite (Fig. 14a). Pegmatitic veins with abundant tourmaline cut across the gneiss and migmatite. Small patches of leucosomes are also
Figure 13. a) Garnetiferous schist and crenulation cleavage 200 m into the hanging wall of the MCT, penny for scale; b) Cross-bedding in quartzite ~8 km into the hanging wall of the MCT in Unit I, 30 cm rock hammer for scale.
common near the top of the formation. The thickness of the Unit I in the study area is ~20 km. The depositional age of the Unit I is Neoproterozoic with the youngest detrital zircon age of ~ 831 Ma (Parrish and Hodges, 1996; DeCelles et al., 2000). However, Martin et al. (2005) showed some younger detrital zircons (~600 Ma) in Unit I in the Annapurna region of central Nepal.

*Unit II*

The dominant rock type in Unit II is banded calc-silicated gneiss along with minor marble, calc-schist and orthoquartzite. This unit is thin, ~500 m, and is without marble bands in the study area. Thick (30-50 cm) bands of calcsilicate gneiss intercalated with augen gneiss are present. Generally, the topography has deep stream valleys in this formation due to erosion in the calcschist. This unit is well developed along the Kaligandaki River with medium to thick (30-100 cm) beds of calc-gneiss intercalated with 50 cm thick marble. The unit was deposited between 830-500 Ma (DeCelles et al., 2000).

*Unit III*

This unit consists of nearly homogeneous intrusions of augen-orthogneiss (Fig 14b) and pegmatite, and is traceable from eastern to central Nepal over a distance of 800 km (Le Fort et al., 1986), in Bhutan (Gansser, 1983) and in Zanskar, India (Pognante et al., 1990). The plagioclase augen in the gneiss are $\leq$ 10 cm in diameter. The unit is intruded by ~22-25 Ma leucogranite (Hodges et al., 1996; Searle et al., 2003; Searle and
Figure 14. a) Banded gneiss with leucosome in Unit I, 30 cm rock hammer for scale; b) Garnetiferous augen gneiss with pegmatitic vein in Unit III, Greater Himalaya, 30 cm rock hammer for scale.
Szulc, 2005). Copeland et al. (1990) and Harrison et al. (1995) reported a similar leucogranite “Manaslu leucogranite” ~7 km west of the STDS in the study area. The age of Unit III is ~485-512 Ma (Le Fort et al., 1986; Parrish and Hodges, 1996; DeCelles et al., 2000; Gehrels et al., 2003). Rb-Sr dating of the unit yielded an age of 513±30 Ma (Le Fort et al., 1986). Monazite inclusions in garnet from the Unit III yielded slightly younger age of 483.6±9.1 Ma (Godin et al., 2001). The age is similar to the ~473-485 Ma for the Agra granite in the Kathmandu klippe (Gehrels et al., 2006).

1.3 Structures

The structural architecture of the central Nepal Himalayan zone is controlled by movements on the major thrusts. From south to north, these thrusts are: the Main Frontal thrust, Main Boundary thrust, Trishuli thrust, Lesser Himalayan duplex, Ramgarh thrust, Main Central thrust, and South Tibetan Detachment system.

1.3.1 Subhimalayan Thrust System

The thrust system in the study area consists of two thrust sheets (Plates 1 and 2). The southern thrust sheet is bounded by active MFT to the south and Main Dun thrust (MDT) to the north. The MFT is the southernmost boundary of the Himalaya and places sandstone of the middle Siwalik unit over modern alluvial sediments. Although the MFT is not exposed at the surface, it is mapped at the topographic front of the Siwalik Hills (Schelling et al., 1991). Beds dip at 20-25° northward between the MFT and MDT (Shrestha et al., 1984). Flooding during the field research rendered this part of the thrust system inaccessible. Data used to prepare balanced cross-section is from Shrestha et al. (1984). The northern thrust sheet is bounded by MDT to the south and MBT to the north.
The MDT places older lower Siwalik unit over the younger upper Siwalik unit. Because the MDT carries the lower Siwalik unit in its hanging wall, the thrust must originate at the base of the Siwalik Group. In the study area, the MDT is inferred because of the repetition of stratigraphy but it is buried beneath sediments of the Rapti River (Plate 1). However, the MDT is well exposed 40 km SE from the study area (Pearson, 2002). Rock in the northern thrust sheet has a 65-87° northward dip, and has a monoclinal structure except some small 5-10 m folds in the lower Siwalik unit. Pearson (2002) suggested a listric shape for the MFT. The balanced cross-section also shows the listric geometry (see Plate 2). Some researchers propose blind thrusts beneath the Indo-Gangetic plain (e.g. Seeber and Armbruster, 1981; Bashyal, 1998); however, Lavé and Avouac (2001) suggested no possibility based on geomorphic evidence of recent crustal deformation in central Nepal. The MFT and MDT merge into a single décollement (Mugnier et al., 1992). The décollement lies above the Indian basement and is 5-6 km under the Siwalik Group (Avouac, 2003). This depth to the décollement is consistent with the drill log data in Raxaul (Sastri et al., 1971), the balanced cross-section in Hetaunda-Amlekhgaung (Pearson, 2002) and this study. The MFT was active from Mid Pliocene-Holocene time (~2 Ma-present day) (Lavé and Avouac, 2000).

1.3.2 Main Boundary Thrust

The MBT thrust Lesser Himalayan rocks in the hanging wall over Subhimalayan rocks in the footwall (Fig. 15). In the study area, the MBT is exposed ~300 m NW from a large bend in Manahari Khola (Plate 1) where the Benighat Formation of the Lesser Himalaya is placed over steeply dipping younger upper Siwalik unit conglomerate. Pearson (2002) found that the Lesser Himalayan unit in contact with MBT is the
Dandagaon Formation ~40 km east of the study area. In this study area, the unit in the hanging wall of the MBT is the Benighat Formation as described by Stöcklin (1980). The unit consists of graphitic slate which is characteristic of the Benighat Formation. Shrestha et al. (1984) also show the unit as Benighat Formation. South of the Kathmandu klippe, the MBT has Benighat, Malekhu, and Robang Formations in the hanging wall; however, as shown in Plate 2, the older Lesser Himalayan units are buried at depth.

Figure 15. Main Boundary thrust in the Manahari area. Trees for scale. The MBT places older gray-colored Benighat Formation of the Lesser Himalayan rock over weathered conglomerate of the upper Siwalik unit. (Photo view towards NE, the motion of the MBT is toward the viewer).
1.3.3 Lesser Himalayan Duplex and Trishuli Thrust

The majority of the Lesser Himalayan rock that crops out in the central Nepal Himalaya lies north of the Kathmandu klippe in a broad anticlinorium defined as the Gorkha-Pokhara anticlinorium (Pêcher, 1977). The anticlinorium is a hinterland-dipping duplex interpreted from structure of the Lesser Himalayan rock, the MCT, RT, and earthquake seismology. The duplex has four broad culminations at the surface which consist of asymmetrical and overturned folds (Plate 2). These types of culminations are common in the Greater and Lesser Himalayan rock in the Himalayan orogen (Johnson, 1994). These culminations indicate the presence of duplex at depth in fold-thrust belt (Boyer and Elliot, 1982). Four horses, each containing the entire Lesser Himalayan sequence, are present in central Nepal and each horse has a thickness of ~7 km. The northern boundary of the duplex begins in the footwall of the RT, and the southern boundary is just north of the Kathmandu klippe at the contact between the Kunchha and Fagfog Formations (see point 8 and 12 in Plate 2). The southern boundary displays overturned rocks that are result of tilting of the Trishuli thrust sheet due to emplacement of the horses during the duplex formation. In the anticlinorium, no faults cut across the Kunchha Formation at the surface. The roof thrust, the Trishuli thrust, carries all formations in the Lesser Himalayan rock. At the base of the thrust sheet within the Kunchha Formation, there are 1-15 m folds and crenulation cleavage. Existence of the Trishuli thrust in the central Nepal is described in Pearson (2002). However, Pearson (2002) suggested the Trishuli thrust sheet as well as the Lesser Himalayan duplex is composed solely of duplexed Kunchha Formation rocks. Kohn et al. (2004) also suggested upper Lesser Himalayan rocks under the RT in Langtang area, ~50 km east of
the study area. In addition, at the southern boundary of the Lesser Himalayan duplex, the southern limb of the Trishuli thrust sheet, an entire sequence of the Lesser Himalayan rock is present. Based on the field observations and stratigraphic constraints (see section, 1.2.2.3), the entire upper Lesser Himalayan rock is used in the Trishuli thrust and in the Lesser Himalayan duplex. DeCelles et al. (2001) and Robinson et al. (2001; 2003; 2006) suggested the existence of the Lesser Himalayan duplex in the western Nepal Himalaya.

1.3.4 Ramgarh Thrust

The Ramgarh thrust (RT) is an intra-Lesser Himalayan thrust system that emplaces lower Lesser Himalayan rock over upper Lesser Himalayan rock in central Nepal. This thrust is described in Kumaon region of India (Valdiya, 1980; Srivastava and Mitra, 1994), western Nepal (DeCelles et al., 2001; Robinson et al., 2001; 2003; 2006; 2008), central Nepal (Pearson, 2002; Kohn et al., 2004; Kohn, 2008; Pearson and DeCelles, 2005; Martin et al., 2005). The thrust sheet is parallel to the MCT and with the hanging wall lying flat on top of the footwall, which is composed of the underlying Malekhu Formation in the study area. In the northern part of the study area, the RT carries a thick band (0.5- 3 km) of white quartzite with interbands of green phyllite thrust over the undifferentiated upper Lesser Himalayan rock (point 11 in the Plate 2). The footwall of the RT is highly sheared and contains flow structures. Abundant garnets (>1 cm) with a few kyanite crystals (4-6 cm) are present ~100 m and 500 m, respectively, above the RT (Figs. 7a, 7b). In the Malekhu area near the southern boundary of the Lesser Himalayan duplex, the RT is thrust on top of the Malekhu Formation (Fig. 16).
Figure 16. Ramgarh thrust in the Malekhu area which placed older Dunga Quartzite over younger Malekhu Formation, 1.5 m gabion wall for scale. The photograph is taken on the northern part of the Kathmandu klippe where the thrust is folded under the synclinorium.

The dominant lithology in the RT sheet in the Malekhu area is phyllite with ~30 m white Dunga quartzite beds at the base of the section. The top of the section has Dunga quartzite intercalated with 10-15 cm green phyllite layers and ~20 m thick amphibolite intrusions. A 1.5 m band of sheared amphibolite is observed ~20 m into the footwall of the RT in the Malekhu area. The dominant lithology and thickness of the RT sheet gradually changes from more quartzitic to more phyllitic from north to south along the Budhi-Gandaki River.

In central Nepal, the Trishuli thrust is the roof thrust for the Lesser Himalayan duplex whereas in western Nepal and Kumaon, India, the RT is the roof thrust for the
Lesser Himalayan duplex (DeCelles et al., 2001; Robinson, et al., 2001; 2003; 2006; Srivastava and Mitra, 1994). The Trishuli thrust is only identified in the central Nepal so the fault might merge with the RT in western Nepal and Kumaon, India.

1.3.5 Main Central Thrust

The MCT, in addition to the RT and Lesser Himalayan duplex, accommodates much of the shortening in the Himalaya. The thrust juxtaposes high-grade Greater Himalayan rocks over the lower Lesser Himalayan rocks in a flat-on-flat geometry. The ~58° northward dip of the fault is due to tilting and uplifting of the MCT during the development of the Lesser Himalayan duplex (DeCelles et al., 2001; Robinson et al., 2003). Many researchers describe the MCT as a broad shear zone with structural and metamorphic discontinuities. Hasimoto et al. (1973) and Arita (1983) suggested two parallel thrusts, the Upper Main Central thrust and Lower Main Central thrust, which is equivalent to the Munsiai and Vaikrita Thrust in India (Valdiya, 1980) and in this study equivalent to the MCT and RT. Le Fort (1975) and Colchen et al. (1986) have only one MCT equivalent to the Upper Main Central thrust. Heim and Gansser (1939); Robinson et al. (2001; 2006; 2008); Pearson (2002); and Martin et al. (2005) define the thrust as a tectonostratigraphic boundary that separates Lesser and Greater Himalayan rock.

Ambiguity as to the location of the MCT is an issue because rocks on either side of the MCT are deformed for several kilometers (Arita, 1983; Macfarlane et al., 1992; Inger and Harris, 1992; Hodges et al., 1996; Catlos et al., 2001); however, through isotopic and detrital zircon studies (Ahmad et al., 2000; Robinson et al., 2001; Pearson, 2002; Martin et al., 2005) one can unequivocally determine if the unit is Greater Himalayan or Lesser Himalayan and therefore, determine the location of the MCT.
Le Fort (1975) and Pêcher (1977) describe the MCT in this study area as a ductile shear zone where a significant break in metamorphism is absent. However, the MCT places Unit I of the Greater Himalayan rock over the Robang Formation of the lower Lesser Himalaya north of the Gorkha-Pokhara anticlinorium (see Plates 1 and 2). Foliations in the rock on either side of the MCT are parallel and have a dip of ~60° northward. A hanging wall flat of the Greater Himalayan rock rests in fault contact on a parallel footwall flat of the Lesser Himalayan rock. Rocks to the north and south of the MCT show a mylonitic fabric with top to the south sense of shear (Fig. 17). The MCT
may carry Greater Himalayan rock into the Kathmandu klippe (see previous discussion in section 1.2.3.2). In Malekhu Kholo and the Kakanda area, the MCT on the northern part of the Kathmandu klippe, locally called the Mahabharat thrust, juxtaposes rock of the Raduwa Formation of the Greater Himalayan zone over the Robang Formation of the lower Lesser Himalayan rock.

1.3.6 South Tibetan Detachment System

The South Tibetan Detachment system (STDS) is a low angle top-to-the-north fault system structurally above Greater Himalayan rock. The fault is a plastic-brittle normal fault juxtaposing the metasedimentary rocks of the Tibetan Himalayan zone in the hanging wall with kyanite/sillimanite grade metamorphosed Greater Himalayan rock in footwall. In the study area, the Annapurna Sanctuary Formation of the Tethyan sequence is in the hanging wall and the Unit III of the Greater Himalayan rock on footwall. The bottom of the Annapurna Sanctuary Formation is metamorphosed due to movement on the STDS. In kinematic models, movement on the STDS is defined as a gravitational driven extension, occurring subparallel to the transport direction of the dominant compressional faults during convergence (Burchfiel et al., 1992; Hodges et al., 1993; Grujic et al., 1996). In dynamic models, the STDS is described as an upper boundary of a midcrustal low velocity channel which is exhumed to the surface due to focused erosion on the topographic front (Beaumont et al., 2001).
2. Methods

2.1 Regional Balanced Cross-section

A balanced cross-section was prepared on the basis of thickness and orientation data collected during field mapping (Plate 1). Additional data are from maps of Stöcklin and Bhattarai (1982) and Shrestha et al. (1984). Other published maps from central Nepal (Rai et al., 1998; Upreti and Le Fort, 1999) ~50 km east from this study are used to correlate stratigraphy and structure. The cross-section is line-length balanced and does not incorporate micro- or mesoscopic strain. The cross-section is pinned in the south by undeformed Siwalik Group rock in the foreland basin drilled in the Raxaul area (Sastri et al., 1977). Geometry and depth of the décollement is constrained from the micro-seismicity as discussed in section 2.1.2. All major structures observed in the field are present in the cross-section.

Field data for the southern Siwalik belt from the MFT to the MDT are from Shrestha et al. (1984). The map (Plate 1) contains the inferred MDT and field data measured from the northern Siwalik belt. The contact between the Subhimalaya and Lesser Himalaya rocks was present in the field and shown on the map. All mapped thrusts were extended to meet the décollement at depth. The rock units were extended above the present day surface using minimum lengths; in order to minimize shortening for each unit. Similarly, surface data for rocks north of the MBT were taken directly from field measurements.

Undeformed lengths of the rock units were obtained from the restoration of the cross-section from foreland to hinterland. Reconstruction of the cross-section started with
the Subhimalayan rock. Each unit of the Siwalik Group from the MFT to the MDT was measured and stretched adjacent to undeformed strata south of the MFT. Similarly, each unit of the Siwalik Group from the MDT to the MBT was measured and stretched adjacent to the MDT. North of the MBT, the southernmost horse of the Lesser Himalayan duplex was restored first. The other Lesser Himalayan horses were reconstructed in sequence from south to north. After the Lesser Himalayan duplex, rocks of the Trishuli thrust sheet were restored into an undeformed state, followed by the Ramgarh thrust sheet. Finally, rocks of the Kathmandu klippe and the Greater Himalayan rock were restored. The restoration of the deformed Himalayan rock into undeformed state is shown in Plate 2.

2.1.1 Assumptions

The depositional ages of the Kunchha and Robang Formations are 1870-1800 Ma (see section 3.2.1.2) which is constrained from the detrital zircon age from the quartzite. The cross-section is based on the assumption that the Robang Formation and associated Dunga quartzite is a distal facies variation of the Kunchha Formation. The stratigraphic composition of the Trishuli thrust sheet which is also a northern limb of the Gorkha-Pokhara anticlinorium, is unclear due to intense deformation and metamorphism. Thus, stratigraphy of the Trishuli thrust sheet in the footwall of the Ramgarh thrust in the northern part of the cross-section is based on the thickness and stratigraphy of the Lesser Himalayan rocks seen in the southern exposure of the Trishuli thrust sheet in the Malekhu area. The Trishuli thrust sheet is located under the Kunchha Formation north of the Kathmandu klippe. Although the Greater Himalayan rocks consist of bed parallel
displacement, ductile shear and internal folding, the unit is restored as a slab because the work needed to determine the deformation is beyond the scope of this study.

2.1.2 Constraints

The depth to the basal décollement was determined by extending the stratigraphic thickness of the Siwalik Group to depth (Schelling and Arita 1991; Schelling, 1992; Harrison et al., 1993; Mugnier et al., 1999; Lavé and Avouac, 2000), and from well log data in Raxaul area of India (Sastri et al., 1971), 43 km southeast of the MFT in the study area. The depth to the basal décollement is 5300 m in this study which is consistent with other studies in central Nepal (Appel et al., 1991; Schelling, 1992; Pearson, 2002). Lyon-Caen and Molnar (1985) computed the dip of the décollement from a flexural elastic bending model and found a dip of ~2.5° which is consistent with the seismic interpretation of a line in the Raxaul area acquired by the Department of Mines and Geology, Nepal (cited by Lavé and Avouac, 2000). Pandey et al. (1995; 1999) interpreted a ramp-flat geometry of the décollement from the microseismicity underneath the Himalaya. A dense concentration of the micro-seismic activities at shallow depths between 5 and 20 km corresponds to flat-ramp transition. There are two ramps in the décollement (Avouac, 2003), one is the MFT and the other is at ~10-20 km depth underneath the Kathmandu klippe. The ramp connects flat of the décollement underneath the Siwalik zone to the flat of the décollement underneath the Lesser and Greater Himalayan zone. The dip of the décollement under the Kathmandu klippe is ~5° which is supported by microseismic activity (Ni and Barazangi, 1984; Pandey et al., 1995; 1999), and is consistent with other published balanced cross-sections across the Nepal Himalaya (Schelling and Arita, 1991; DeCelles et al., 2001; Pearson, 2002; Robinson et al., 2006).
Hauck et al. (1998) suggested an increase in the dip of the décollement to ~9° and the depth of the décollement to be 35-40 km in South Tibet (Zhao et al., 1993). The depth of the décollement underneath the Lesser Himalayan duplex is ~22 km constrained from earthquake seismology (Pandey et al., 1995; 1999). This value is consistent with the balanced cross-section of Pearson (2002) which is 50 km west of this study.

2.1.3 Sources of Error

The cross-section does not include micro-and meso-scale folds in the Lesser Himalaya because the folds are small (3-10 m) and could not be mapped at the 1:25,000 scale. The Greater Himalaya consists of various kinds of rock types and contains internal deformation and bed parallel displacement. These displacements and ductile simple shear may accommodate as much as 100 km of shortening in the Greater Himalayan rocks (Manickavasagam et al., 1999) and are not incorporated in the cross-section. For simplicity, the Greater Himalaya is viewed as a block of rock and balancing is done in bulk. Hanging wall cut-offs of the major thrusts are not exposed in the field area due to erosion. Thus, the true line length of the thrust sheets is unknown. However, a minimum amount is used in the cross-section in order to minimize shortening.

Some researchers hypothesize that there is an intra-Greater Himalayan thrust in the Himalaya that forms the Kathmandu klippe. In this two thrust model, the thrust underneath the klippe would not be equivalent to the MCT. Rai et al. (1998) and Upreti and Le Fort. (1999) suggested the possibility that the MCT lies structurally above the Kathmandu klippe and another thrust locally known as “Mahabharat thrust” lies underneath the Kathmandu klippe. Kohn et al. (2004) suggested that the Kathmandu klippe is transported along Langtang thrust, which is ~18 km north of the MCT. The first
two thrust model assumes the root zone of the intra-Greater Himalayan thrust is in
between the RT and MCT above the present day topography. Conversely, the one thrust
hypothesis states that all the rock of Greater Himalayan affinity was transported along the
MCT. This means that the MCT is the same as the thrust under the Kathmandu klippe.
The two thrust model increases the complexity and also increases the amount of
shortening of the Himalaya. For simplicity, the one thrust hypothesis is used in this study
and treats all Greater Himalayan rock as being the hanging wall of the MCT.

2.2 2D Move

The 2D Move program is a structural analysis and modeling program that allows
line-length and area balancing of cross-section. Both structural restorations and forward
modeling can be carried out within the program. In this study, the program was used for
kinematic analysis and to test the validity of the balanced cross-section as discussed in
section 2.1.

2D Move is a user-dictated program. The user can move a block of rock over a
fault plane with a specified amount of displacement. Because the Himalaya has major
faults with southward direction motion parallel to movement along major faults, the
“fault-parallel flow” option was used to move the rock sheets. The fault-parallel flow
assumes laminar flow over a fault ramp. Each fault plane is divided into discrete dip
domains, and any change in the dip of the fault plane is marked by a dip bisector. The
flow line is connected on different dip bisectors equidistant from the fault plane and is
also parallel to the fault plane. In the program, only the units in the hanging wall
translate along the fault plane and are deformed. The footwall remains undeformed and is
not translated. Thus, the user can displace units above a fault but cannot control deformation in the hanging wall.

The restored length of the Himalaya was imported into the 2D Move program. The section was scaled and traced in the program. The traced section was rotated to the burial depth of the Greater Himalayan rocks (Fig. 18a). Greater Himalayan rock experienced pressure of 6-12 kbar in the central Nepal Himalaya (Igner and Harris, 1992; Macfarlane et al., 1995; Rai et al., 1998; Kohn et al., 2004; 2008). Based on the pressure data from central Nepal, the depth of Unit I in the Greater Himalayan rock was buried to at least 36 km. Next, the units were deformed in forward propagating sequence. The position and geometry of each fault in the reconstruction was used to move the rock sheet in the model. A +ve value of displacement moved the fault as a normal fault whereas a –ve value moved the fault as a reverse fault. Thus, –ve values produced thrust fault geometries. Each subsequent fault deforms all units in the hanging wall, including units carried by “older” faults. The process was iterative and repeated until a satisfactory geometry was obtained to match geological realtionships as dictated by field work.

2.2.1 Model Parameters and Simplification

The deformation in the forward model begins with the activation of the MCT that places Greater Himalayan rock over the RT sheet. Rocks of the Kathmandu klippe are structurally above the RT thrust sheet and the southern edge of the klippe is emplaced over the entire length of the RT sheet. The true length of the MCT and RT might be greater than what is shown on the cross-section because motion on the MBT caused the hanging wall cutoffs to be uplifted and eroded.
In the original geometry of the Indian passive margin which extended northward from the Indian subcontinent, MCT rocks are placed immediately northward of the RT sheet rocks which are placed immediately northward of the Lesser Himalayan duplex rocks. However, the positions of these contacts are uncertain. The positions shown in the reconstruction are the minimum locations of these contacts; however, each contact may have been much further to the north in the passive margin reconstruction. Thus, shortening may be much greater than the minimum estimate in this study. DeCelles et al. (2000) and Gehrels et al. (2003) suggested that the contact between Greater Himalayan rocks and rocks in the RT sheet was originally a suture; whereas Parrish and Hodges (1996) suggested the contact was originally stratigraphic. Presently, the boundary is the MCT, and Greater and Lesser Himalayan rocks are parallel in the hanging wall and footwall of the MCT.

2.3 Strain Analysis

The rocks in the hanging wall and footwall of MCT and RT accommodate shear strain which can be analyzed in the microscopic level. The microstructures and deformation are used as shear sense indicators to determine the direction of motion of major thrust faults.

Oriented rock samples were collected from the study area during mapping. Rock samples were cut across the foliation plane and polished and then converted into thin-sections. These thin-sections were used to analyze qualitative strain accommodated by the rocks during movement (shortening) along the thrust faults. Mineral identification,
foliations, textures, shear sense indicators, and deformation bands were determined. Photomicrographs of the thin-sections were taken with appropriate orientations.

3. Results

3.1 Shortening Estimates

Restoration of the cross-section into a flat-lying, undeformed state yields a minimum estimate of the original length of these units at 551 km. The deformed length of the cross-sections (final length) is 131 km. Therefore, the total amount of shortening in the cross-section is 420 km, or 76%. Three major thrusts accommodate most of the shortening, the MCT, RT and Trishuli thrust from north to south. The MCT has a minimum of 115 km of shortening; whereas the RT and Trishuli thrust have ~120 km and ~94 km, respectively. The horses in the Lesser Himalayan duplex accommodate 62 km of shortening. The MBT experienced ~10 km shortening whereas the MDT and MFT accommodate ~12 km and ~7 km respectively.
3.2 2D Move Model

The first displacement in the forward model is the emplacement of Greater Himalayan rock 118 km along the MCT (Figs. 18b, 18c). Slip is then transferred into the Lesser Himalayan rocks. The RT is thrust over future Lesser Himalayan duplex rocks 120 km to the south (Figs. 18d, 18e). After RT emplacement, the Trishuli thrust, the roof thrust for the future Lesser Himalayan duplex is thrust 98 km southward became active (Figs. 18f, 18g). The slip is transferred to the horses in the Lesser Himalayan duplex. From north to south, the three horses have displacements of 19, 18 and 10 km, respectively (Figs. 18h, 18i, 18j). As the duplex builds, Lesser Himalaya rocks are exhumed and the northern limb of the Kathmandu synclinorium and the rocks of the Trishuli thrust sheet are folded (Fig. 18h, 18i, 18j). The fourth horse in the duplex forms MBT. The MBT moves 10 km and that motion folds the Kathmadu klippe into a synclinorium (Fig. 18k). A splay thrust of the MBT inferred from the exposed stratigraphy is active after the MBT (Fig. 18l). The displacement is then transferred to the MDT which slips 8 km and also divides the Siwalik Group rock into northern and southern belts (Fig. 18m). Next the MFT slipped 9 km and placed the Siwalik Group rock unit over unconsolidated Quaternary deposits (Fig. 18n). The final configuration after movement of the MFT corresponds to the present day structure of the central Nepal Himalaya (Fig. 19).
A. Initial configuration ~55 Ma

B. MCT starts to slide over RT sheet ~25 Ma

C. MCT moves over RT sheet ~121 km

D. RT moves over LH = 20 km, ~16 Ma

E. RT moves over Trishuli sheet ~120 km

F. Trishuli thrust sheet moves over LH = 20 km ~12 Ma

G. Trishuli thrust moves over LH = 98 km

H. First horse moves = 18 km

I. Second horse moves = 18 km

J. Third horse moves = 10 km

K. MBT moves = 10 km, ~5 Ma

Figure 13. 2D move kinematic sequence of the Budhigandaki Section, central Nepal. Each rock unit is defined in figure A. Figures are without vertical exaggeration. Abbreviations: MCT-Main Central Thrust; RT- Ramgarh Thrust; LH- Lesser Himalayan; MBT- Main Boundary thrust; MDT- Main Dune Thrust; MFT-Main Frontal thrust
Figure 19. Comparison between the balanced cross-section and 2D move generated cross-section. The vertical tie lines are drawn for comparison. The figures are without vertical exaggeration.
3.3 Deformation

Rocks in the vicinity of the northern part of the MCT are highly sheared as illustrated by oval shaped garnet grains from 300 m into the hanging wall of the MCT (Fig. 20a). The garnet grain shows top to the south sense of shear in the hanging wall of the MCT (Fig. 20b). S-C fabrics in the photomicrograph are parallel to each other due to pervasive deformation. A thin section of Lesser Himalayan rock from the northern RT sheet in the immediate footwall of the MCT shows strong lattice-preferred orientation of quartz grains of the Dunga quartzite (Fig. 21a). Muscovite grains define the lineation and quartz grains define continuous foliation. The quartz grains show grain boundary migration (Fig. 21a) and subgrain rotation recrystallization (Fig. 21b). Elongation of the quartz grains are in top left to bottom right which indicates the southward movement of the RT. A similar quartzite from the Robang Formation near the village of Malekhu also shows lattice preferred orientation (Fig. 21b). In this case, the quartz grain elongates from top right to bottom left because of folding of the RT sheet along with the Kathmandu klippe (see Plate 2). The grain size of the Dunga quartzite near the Malekhu area is smaller than the Dunga quartzite near the MCT zone. The deformation in the Dunga quartize is greater than quartzite ~8 km above the MCT in the Unit I (Fig. 22a). This bigger grain size and greater intensity of deformation is due to recrystallization of the rock during motion along the RT which experienced $9.3\pm4.8$ kbar of pressure at temperature of $692\pm238^\circ C$ (Macfarlane, 1995). Amphibolite in the Malekhu area ~10 m below the RT shows strong deformation and has top-right to bottom-left sense of shear stress indicating southward thrusting before the folding of the thrust sheet (Fig. 22b).
Figure 20. a) Oval garnet in Unit I, Greater Himalaya 300 m into the hanging wall of the MCT, direction of motion is shown by arrow; b) Highly sheared garnet in Unit I, 200 m into the hanging wall of the MCT, direction of motion is shown by arrow ((Qtz = Quartz, Mst = Muscovite, and Grt = Garnet). Each thin-section is oriented south to the left. All photographs are taken in cross-polarized light.
Figure 21. a) Lattice-preferred orientation of quartz grains in the Dunga quartzite of the RT sheet in the northern part of the study area. The quartz grains (qtz) are elongated in top-left to bottom-right orientation; b) Elongated quartz grains in the Dunga quartzite of the RT sheet near Malekhu area. Quartz grains are elongated in top-right to bottom left direction. Each thin-section is oriented south to the left. All photographs are taken in cross-polarized light (Qtz = Quartz, Mst = Muscovite, GBM = Grain boundary migration recrystallization, SR = Subgrain rotation recrystallization).
Figure 22. a) An undeformed quartzite from the Greater Himalaya, Unit I, ~8km north of the MCT, for comparison with the Dunga quartzites; b) Sheared amphibolite with very deformed augen shaped feldspar grain ~ 10m below the RT in Malekhu area. Each thin-section is oriented south to the left. All photographs are taken in cross-polarized light. (Fld = Feldspar).
4. Kinematics and Timing of Fault Motions

Crustal thickening of the Tibetan part of the Himalayan fold-thrust belt and burial metamorphism in the Greater Himalaya occurred between 55 Ma to 25 Ma (Ratschbacher et al., 1994). Deformation then propagated southward into the Himalayan fold-thrust belt, as recorded in synkinematic garnet growth during burial metamorphism (Harrison et al., 1998) in Greater Himalayan rock. Leucogranites intrude the Greater and Tibetan Himalaya, and U-Pb dates on zircons from intrusions which cross-cut the STDS constrain the age of the activation to ~22 Ma in the Kaligandaki area (Nazarchuk, 1993; Harrison et al., 1995). This age is consistent with a crystallization age of 22.1 Ma of the leucogranite in Annapurna area, central Nepal (Godin et al., 2001). About 7 km west of the study area, the Manaslu granite of age 24-19 Ma (Searle and Godin, 2003) cross-cuts the STDS and up to the Triassic unit of the Tibetan Himalaya (Le Fort, 1975; Colchen et al., 1986). However, recent mapping in the area shows no cross-cutting relationship of the Manaslu Granite with the overlying STDS and constrained the age of motion on the STDS to be younger than ~ 18 Ma (Searle and Godin, 2003).

A Th-Pb age of a monazite inclusion in a garnet in the foot wall of the MCT is ~22 Ma along the Marsyangdi River, central Nepal (MA 45, Catlos et al., 2001). These data are consistent with U-Pb ages for monazite and zircon (20 and 15 Ma) from gneiss and leucogranite in the Langtang area (Macfarlane et al., 1992) and 22.5 Ma in the Modikhola area (Hodges et al., 1996). Rb-Sr dating of muscovite from the Langtang valley yields similar activation age (23 Ma) for the MCT (Igner and Harris, 1992). Bernet et al. (2006) suggested ~16 Ma for the movement of the MCT from zircon fission track ages obtained from synorogenic sediment of Siwalik Group, western Nepal. Kohn et al.
(2004; 2005; 2008) suggested an age of ~16 Ma for the activation MCT in central Nepal based on in situ $^{232}$Th/$^{208}$Pb dating of monazite. U-Pb dating of single and multigrain fractions of monazite and thorite from an undeformed pegmatitic vein crosscutting the planar fabric of MCT yielded crystallization age of 21±0.5 Ma in the Kaligandaki area, central Nepal (Nazarchuk, 1993). In western Nepal, the rock in the Dadeldhura klippe, passed through the Ar closure temperature for muscovite at 25 Ma (SR 124; Robinson et al., 2006; Fig 3). Thus, the age of activation of the MCT is from ~16-25 Ma. Based on metamorphic monazites in the Greater Himalayan rock, Kohn et al. (2005) interpreted an intra-Greater Himalayan thrust called the Langtang thrust, active at 22-23 Ma.

The RT became active as slip was transferred south of the Main Central thrust system. The RT is the roof thrust of the Trishuli thrust sheet and must have emplaced prior to Lesser Himalayan duplex. The activation age of the RT might be in between ~16-11 Ma, the upper age limit is based on $^{40}$Ar/$^{39}$Ar age muscovite from the Dumri Formation which underlies the RT sheet in western Nepal (DeCelles et al., 2001). However, Catlos et al. (2001) has an age from a monazite inclusion in garnet from the hanging wall of the Ramgarh thrust of ~8 Ma. In central Nepal, in situ dating of monazite yields activation age ~11-9 Ma of the RT (Kohn et al., 2004). In western Nepal, $^{40}$Ar/$^{39}$Ar age spectra of a sample from a Ramgarh thrust sheet in the footwall of the MCT ranges from 17-7 Ma (sample SR 123, Robinson et al., 2006) and is interpreted to represent timing of slip on the RT. Bernet et al. (2006) interpreted ~16 Ma detrital zircon fission track age analysed from the foreland synorogenic sediment is related to cooling of the Lesser Himalayan rock after the emplacement of Ramgarh and Dadheldhura thrust in western Nepal.
The Trishuli thrust became active as slip was transferred south of the RT and became the roof thrust of the Lesser Himalayan duplex. The thrust sheet passively folded the RT and MCT so the thrust must post date emplacement of the RT sheet. DeCelles et al. (1998a) suggested the Lesser Himalayan duplex was erosionally breached by ~11-12 Ma based on the occurrence of Lesser Himalayan detritus in the foreland basin, which is a minimum age for displacement on Trishuli thrust sheet. The age is consistent with ~10-12 Ma obtained from provenance analysis of synorogenic sediment and cooling age of detrital Muscovite from Siwalik Group rock and modern river sediment in western Nepal (Szulc et al., 2006). In situ $^{232}$Th/$^{208}$Pb dating of monazite in central Nepal Himalaya yields an activation age of ~7-8 Ma for the Lesser Himalayan duplex (Kohn et al., 2004) and the post age of the duplex formation is ~3.5 Ma (Kohn, 2008).

The MBT became active as slip was transferred south of the Lesser Himalayan duplex. Also, the MBT cut rocks from the lower part of the upper Siwalik unit rock in this study area, and ~4.3-2.3 Ma Middle Siwalik unit in the Hetaunda area (Pearson, 2002). Earliest deposition of the upper Siwalik unit ranges from ~2.5 Ma to 4.1 Ma (Roesler et al., 1997; Ojha et al., 2008). Thus, the age of the initiation of the MBT in central Nepal is ~4.1 Ma and it remained active until 2 Ma. The slip is transferred further south of the MBT to the Subhimalayan thrust system including the MFT and the MDT. The MFT is active from mid Pliocene-Holocene time (Lavé and Avouac, 2000).
The magnitude of shortening of the central Nepal Himalaya from the MFT to the STDS is 420 km or 76%. Most studies report the orogen-scale MCT and some report the RT but few have reported another orogen-scale thrust, the Trishuli thrust. In this study, the MCT has 115 km of shortening; the RT has 120 km of shortening; and the Trishuli thrust has 94 km of shortening. Pearson (2002) found that the Trishuli thrust, the roof thrust of the Lesser Himalayan duplex and the Lesser Himalayan duplex has 17% of the total shortening in the central Nepal fold-thrust belt. This study shows that 17% of the total shortening is accommodated only by the Trishuli thrust, and the horses in the duplex contribute 11%. In total, Lesser Himalayan duplex and the Trishuli thrust contribute 28% of the total shortening. Pearson (2002) suggested that the entire Lesser Himalayan duplex and Trishuli thrust contain only the Kunchha Formation. In this study, based on the upper Lesser Himalayan rocks exposed just north of the Kathmandu klippe, the Trishuli thrust and the horses in the duplex consist of a complete Lesser Himalayan rock. Macfarlane et al. (1992) and Kohn et al. (2004) also suggested the upper Lesser Himalayan rock north of the Kunchha Formation in the Langtang area, central Nepal.

The shortening estimate from this study is similar to that suggested for central Nepal, Kathmandu area (488 km or 76% Pearson, 2002), western Nepal (418-493 or 72%-76%, DeCelles et al., 2001), Api, Chainpur and Simikot sections, western Nepal (485-743 km or 74-77%, Robinson et al., 2006, 2008). Srivastava and Mitra, (1994) estimated 354-421 or 76%-79% of shortening in the Kumaon-Garhwal region, western Himalaya. McQuarrie et al. (2008) suggested 359 km or 74% of shortening of the Bhutan Himalaya from the MFT to the STDS, again note the similar percentage of shortening.
Coward and Butler (1985) obtained a shortening of 470 km (64%) between the MFT and the STDS in northern Pakistan. Shortening estimates from the eastern Nepal Himalaya are 245-280 km (59-65%, Schelling and Arita, 1991). When the overall percentage of shortening deviates from the average of 74%, that suggests that either major structure were not recognized or the kinematics are different in that part of the Himalaya. In eastern Nepal, Schelling and Arita (1991) did not recognize the RT and combined the RT and MCT sheet together. Murphy and Yin (2003) suggested 176 km of shortening in the Tibetan Himalayan part of the fold-thrust belt and Indus suture zone from India-Nepal-China border to Mount Kailas in southwest Tibet. Similarly, Ratschbacher et al. (1994) suggested 133-139 km of shortening in the central Tibet between STDS and the Indus suture zone. Manickavasagam, et al. (1999) suggested 100 km of shortening within the Greater Himalayan rocks. Adding shortening estimates for the Tibetan Himalaya and Greater Himalaya yield a total of ~653-659 km of shortening in the study area.

The result of these studies does not support the hypothesis that the eastern Himalaya should accommodate a larger amount of shortening due to counterclockwise motion of the Indian Plate and oblique collision with the Asian plate (Srivastava and Mitra, 1994). Plate tectonics reconstructions and paleomagnetic data of the India-Asia collision show that 2500±900 km of shortening has been accommodated between southern Tibet and the Indian shield (Patriat and Achache, 1984; Besse and Courtilliet, 1988) since the collision of the India and Asia at ~55 Ma. Of this amount, ~800 to ~1200 km of shortening is accommodated by the Himalayan fold-thrust belt between the Indus suture zone and the MFT (DeCelles et al., 2001). The shortening estimate from this study is similar to the shortening estimates of 628-667 km from the MFT to the STDS in
western Nepal (DeCelles et al., 2001). The Api, Chainpur, and Simikot sections from the western Nepal Himalaya yields 661-919 km of shortening including the Tibetan Himalaya (Robinson et al., 2006, 2008) which is nearly equal to the lower limit of the shortening estimate from the paleomagnetic data. This shows the amount of shortening is maximum in the central portion of the Himalaya and the shortening gradually decreases towards the eastern and western syntaxis. A compilation of the shortening estimates of the Himalayan fold-thrust belt is shown in Table 4.

Forward modeling checks the admissibility and validation of the balanced cross-section. Figure 19 compares the final deformation model produced in 2D Move (Fig. 18n) with the balanced cross-section (Plate 2). The model contains all the major structures mapped in the field. Major thrust faults such as the MCT, RT, and Trishuli thrust are successful predicted; however, MCT is shifted ~3 km north in the model. Though the location of the RT is well predicted, the forward model fails to produce the steep dip of the thrust sheet in the northern part of the cross-section (point 12, Plate 2). The Lesser Himalayan duplex, which caused folding of the Trishuli thrust due to emplacement of the horses in the duplex, is well predicted. The slip on each horse is 3-5 km less than the balanced cross-section. The Kathmandu klippe is predicted with a fold in the southern limb. However, the steep dip on the northern limb of the klippe and adjacent Trishuli thrust sheet could not be reproduced. The model did not predict the overturned beds of the southern limb of the Gorkha-Pokhara anticlinorium (see Plate 2, point 8). The MBT,
Table 4. Compilation of Shortening Estimates for the Himalayan Fold-Thrust Belt

<table>
<thead>
<tr>
<th>Authors</th>
<th>Location</th>
<th>Northern Boundary</th>
<th>Southern Boundary</th>
<th>Shortening estimates</th>
<th>% shortening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coward and Butler (1985)</td>
<td>Pakistan</td>
<td>Main Mantle thrust*</td>
<td>Main Frontal thrust</td>
<td>470 km</td>
<td>64</td>
</tr>
<tr>
<td>Ratschbacher et al. (1994)</td>
<td>China: central Tibet</td>
<td>Indus Suture</td>
<td>South Tibetan Detachment system</td>
<td>133-139 km</td>
<td>52-54</td>
</tr>
<tr>
<td>Srivastava and Mitra (1994)</td>
<td>India: Kumaon and Garhwal</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>470 km</td>
<td>76-79</td>
</tr>
<tr>
<td>DeCelles et al. (2001)</td>
<td>Far western Nepal</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>418-493 km</td>
<td>72-76</td>
</tr>
<tr>
<td>Schelling and Arita (1991)</td>
<td>Eastern Nepal</td>
<td>South Tibetan Detachment system</td>
<td>Main Frontal thrust</td>
<td>185-245 km</td>
<td>59-65</td>
</tr>
<tr>
<td>Schelling (1992)</td>
<td>Eastern Nepal</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>210-280 km</td>
<td>58-65</td>
</tr>
<tr>
<td>Pearson (2002)</td>
<td>Central Nepal</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>488 km</td>
<td>76</td>
</tr>
<tr>
<td>Robinson (2006)</td>
<td>Western Nepal (Api)</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>601-674 km</td>
<td>77</td>
</tr>
<tr>
<td>McQuarrie</td>
<td>Bhutan</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>563-624 km</td>
<td>76</td>
</tr>
<tr>
<td>Robinson (2006)</td>
<td>Western Nepal (Chainpur)</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>711-796 km</td>
<td>74</td>
</tr>
<tr>
<td>Robinson (2006)</td>
<td>Western Nepal (Simikot)</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>359 km</td>
<td>74</td>
</tr>
<tr>
<td>McQuarrie</td>
<td>Central Nepal</td>
<td>South Tibetan Detachment System</td>
<td>Main Frontal thrust</td>
<td>420 km</td>
<td>76</td>
</tr>
</tbody>
</table>

*Main Mantle thrust= Indus Suture
MDT and MFT are well predicted as shown in Figure 19. The model predicted the folded structure of the northern Siwalik zone rock and a monocline structure in the southern Siwalik zone as seen in the cross-section (Plate 2).

The amount of crustal shortening calculated from 2D move is 408 km which roughly corresponds to 420 km of shortening calculated from the balanced cross-section. The undeformed length of the Himalaya is 543 km and the deformed length generated by the program is 185 km. The total amount of shortening is 75%. The amount of shortening accommodated in the 2D Move model by the MCT, RT, Trishuli thrust, and the LH duplex is 117 km, 120 km, 95 km, 55 km, respectively, (Table 5). In addition, the amount of shortening accommodated by the MBT, MDT and MFT is 6 km, 7 km, and 8 km, respectively (Table 5). The Lesser Himalayan duplex accommodates 7 km of shortening less than the balanced cross-section which might be due to insufficient displacement added in the horses in the forward model. By adding positive displacement on the MCT, the present day location of the MCT and the Agra granite of the Kathmandu klippe might be predicted accurately. Comparison of the amount of shortening estimated from the balanced cross-section and the shortening predicted by the reconstruction program is shown in Table 5.
Table 5. Comparison of the Amount of Shortening

<table>
<thead>
<tr>
<th>Structures</th>
<th>Cross-section (Km)</th>
<th>2D Move (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Frontal thrust</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Main Dun thrust</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Main Boundary thrust</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Trishuli thrust</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td>Lesser Himalayan Duplex</td>
<td>62</td>
<td>55</td>
</tr>
<tr>
<td>Ramgarh thrust</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Main Central thrust</td>
<td>115</td>
<td>117</td>
</tr>
<tr>
<td>Total shortening</td>
<td>420</td>
<td>408</td>
</tr>
</tbody>
</table>

The sheared garnet and deformed quartz grains in the photomicrograph (Figs. 20a, 20b, 21a, 21b) suggest top to the south sense shear of the MCT and the RT. Martin et al. (2005) also suggested the southward motion of the MCT in the Annapurna area using thin section of rocks near the MCT. The quartz grains in the Dunga quartzite in the Robang Formation are recrystallized through a combination of grain boundary migration and subgrain rotation. Extensive dynamic recrystallization of the Dunga quartzite is also shown in Pokhara and Bhainsedobhan area, central Nepal (Pearson, 2002). This recrystallization of the quartz grains and the deformation of the underlaying amphibolites are associated with the movement of the RT. The orientation of the quartz grains support that the RT moved top-to-the-south sense of shear in the northern part in the footwall of the MCT.
6. Implications

The forward modeling suggests that a conventional wedge model (Davis et al. 1983) for the structural evolution of the Himalaya is sufficient to explain the structures observed in the field. As shown by the forward model, sequential motion on the thrusts from one stage to the next is sufficient to produce the Himalayan fold-thrust belt. Thermal-mechanical models for the Himalayan-Tibetan orogenic system propose ductile extrusion of midcrustal rock driven by focused erosion at the topographic front (Beaumont et al., 2001). In the Budi-Gandaki section, no large scale ductile flow structures are present at the surface. Leucosome and migmatite are locally present in Unit I. However, quartzite in Unit I of the Greater Himalaya still retains the cross bedding and laminated structure (Fig. 13b).

The rock of the Kathmandu klippe has Greater Himalayan affinity as discussed in section 1.2.3.2. In this study, the MCT is folded underneath the klippe, and assumes that the klippe and the crystalline rock of the Greater Himalaya are carried by the same thrust, the MCT. The rocks in the klippe have bedded stratigraphy with sedimentary structures still preserved (Fig. 11b). Robinson and Pearson (2006) also pointed out bedded stratigraphy and lack of upper bounding shear zone in the klippe and suggested that channel flow could not have occurred in the klippe.

In the forward model and kinematic model of Robinson et al. (2003, 2008), Greater Himalayan rocks were emplaced prior to the activation of the RT between ~25 to ~16 Ma. Channel flow and exhumation of the Greater Himalaya must have ended by that time. However, Jamieson et al. (2004) suggested that channel flow continues to the
present day. Ductile fabrics in the Himalaya are not present after ~17 Ma (Searle et al., 2003) which suggest that the channel flow process could have ended around 17 Ma. The forward model in this study does not rule out the possibility of the channel flow prior to activation of RT; however, the present architecture of the Himalaya can be achieved by only using a conventional wedge model.

7. Conclusions

1) The central Nepal Himalaya consists of six major structural elements: South Tibetan Detachment system, Main Central thrust, Ramgarh thrust, Lesser Himalayan duplex including the Trishuli thrust, Main Boundary thrust and the Main Frontal thrust from north to south.

2) The Budhi-Gandaki cross-section accommodates a minimum of 76% or 420 km of shortening in the Himalayan fold-thrust belt between the South Tibetan Detachment system and the Main Frontal thrust. The Main Central thrust accommodates 115 km of shortening; the Ramgarh thrust accommodates 120 km of shortening; the Trihsuli thrust accommodates 94 km of shortening; and the Lesser Himalayan duplex accommodates 62 km of shortening. The Main Boundary thrust, Main Dun thrust and Main Frontal thrust accommodate 10 km, 12 km and 7 km respectively.

3) The Main Central thrust has long been recognized as an orogen-scale thrust. However, the Ramgarh and Trishuli thrust sheet accommodate around 100 km of shortening each and are also orogen-scale thrusts.

4) Analysis of photomicrographs in the hanging wall and footwall of the Ramgarh thrust and Main Central thrust indicates top-to-the-south sense of shear.
5) Deformation of the central Nepal Himalaya is replicable using the 2D move reconstruction program. The balanced cross-section has a shortening estimate of 420 km, 76%, while the 2D Move program has an estimate of 408 km, 75%. The difference between the two values is not statistically meaningful. Therefore, the reproduction of the balanced cross-section in the 2D Move forward model shows that the cross-section is viable, admissible, and structurally valid.

6) The Himalayan fold-thrust belt propagated from north to south in a forward propagating sequence as is expected in a conventional wedge model. The forward model also shows forward propagation of the Himalayan thrust belt to gain present day architecture.
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Plate 2. Blended Cross section through the central Nepal fold-thrust belt. Location of Cross-Section Line (NE-SW) is shown in Map. Key features of the cross sections are highlighted by numbered points, which are explained in the text.

Restored cross section NE-SW. No vertical exaggeration.