CHAPTER - II

TECTONIC SETUP

2.1. Introduction

Reconstruction of Indian plate motion relative to Asia reveals an abrupt decrease in convergence rate from ~15 to ~ 4 – 5 cm yr⁻¹ at ca. 50 Ma (Molnar and Tapponnier, 1975; Patriat and Achache, 1984; Copley et al., 2010) following collision of the Indian plate with the Asia plate (Searle, 1991; Garzanti et al., 1996; Hodges, 2000; Yin and Harrison, 2000). This rapid change in the rate of convergence coincided with a major rearrangement of plate boundaries in the Indian Ocean (DeMets et al., 1990; Copley et al., 2010). Subsequent to slow down or cessation of convergence through early Miocene time (McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Patriat and Achache, 1984; Schluter et al., 2002), the Indian plate, perhaps with partly coupled Burma plate, resumed its northward journey and increased its obliquity and convergence rate (McCaffrey, 1991; Hall, 1997; Diamant et al., 1992) in middle Miocene time. This renewed convergence reached its critical value in the Late Miocene (Levchenko, 1989), and caused widespread deformation in the northeastern Indian Ocean (Weissel et al., 1980; Gordon et al., 1990; Deplus et al., 1998; Hintersberger et al., 2010), opening of Andaman Sea (Raju et al., 2004; Khan and Chakraborty, 2005), reorganization of Central Myanmar Basin (Khan, 2004), initiation of grabens in southern Tibet and Himalayas (Burchfiel and Royden, 1985; Yin, 2000; Hintersberger et al., 2010) and rapid uplift of the Himalayas and Tibetan plateau (Harrison et al., 1992; Molnar et al., 1993). A 20° clockwise rotation of the motion vectors of India occurring before 7 Ma (DeMets et al., 1990) associated the initiation of shortening between India and Australia as evidenced from the dating of a wide spread unconformity (Leg 116 Shipboard Scientific Party 1987) and that marks the onset of deformation along the eastern equatorial Indian Ocean. The collision resulted in the final closure of the Tethys Ocean, southward imbrications of the Indian crust, and northward continental subduction of Indian crust and mantle beneath Asia (Valdiya,
1988; Willet and Beaumont, 1994). Since this collision, India has indented ~ 3000 km into Asia, producing a combination of lateral escape and crustal thickening that has given rise to the largest uplifted topographic features with an average elevation of 5 km on Earth (e.g., Molnar and Tapponnier, 1975; Peltzer and Tapponnier, 1988; Harrison et al., 1992; Fielding et al., 1994; Tapponnier et al., 2001).

The Himalayan orogen coincides with the 2500 km long topographic front at the southern limit of the Tibetan Plateau. It consists of five broadly parallel litho-tectonic belts, separated by mostly north-dipping faults (Fig. 1 of Godin et al., 2006). The Himalayan metamorphic core, termed the Greater Himalayan Crystalline (GHC), is bounded by two parallel and opposite-sense shear zones that were both broadly active during the Miocene (Hubbard and Harrison, 1989; Searle and Rex, 1989; Hodges et al., 1992, 1996). The MCT zone marks the lower boundary of the GHC, juxtaposing the metamorphic core above the underlying Lesser Himalayan sequence. The STD system defines the upper boundary roof fault of the GHC, marking the contact with the overlying unmetamorphosed Tethyan sedimentary sequence. The apparent coeval movement of the MCT and STD, combined with the presence of highly sheared rocks and high grade to migmatitic rocks within the GHC, has led many workers to view the GHC as a north-dipping, southward-extruding slab of mid-crustal material flowing away from the thick southern edge of the Tibetan Plateau, towards the thinner foreland fold-thrust belt (Burchfiel et al., 1992; Hodges et al., 1992; Graseman et al., 1999; Grujic et al., 1996, 2002). This Greater Himalayan sequence composed of 15-20 km thick slab of crystalline rocks, which has been thrust southwards along the MCT, overriding the Lesser Himalayan formations, and the topography rises steeply to about 4.5 km, above which lays the perennial snows. The northernmost fault zone is the MCT, which marks a transition from the high-grade metamorphic Greater Himalayan Sequence in the north to the lower-grade Lesser Himalayan sequence in the south (Wobus et al., 2005). More southerly structures the MBT and the MFT, developed progressively in a north-south sequence (Wobus et al., 2005). The MBT separates the Lesser Himalayas, which has an average elevation of 2.5 km. The Lesser Himalayas is considered to be a zone of sandwiched between MBT and MCT. The MFT (which is the surface trace of the MHT) marks the limit between the undeformed sediments lying on the Indian basement and those that have been scraped off and involved in the
Siwalik (Sub-Himalayas) fold belt (Cattin et al., 2001). Cattin et al. (2001) reported that the Middle and Lower Siwalik molasses, which crop out just north of the MFT, are more compact than the younger molasses (upper Siwalik) south of the MFT.

Lyon-Caen and Molnar (1983) proposed through analysis of gravity anomaly that the Indian plate was weakened and bent to ~ 10-15° at a position ~50 km south of the Indus Tsangpo Suture (ITS), apparently a result of collision that detached the crust from the mantle, as the cold mantle part of Indian lithosphere slides beneath the Himalayas. The detached crust has been thus folded at its front and a detachment plane originated. The buoyant resistance appears to have been so strong that the back part of the moving plate broke up along the basement-cover contact, giving rise to this plane of decoupling (Valdiya, 1988). According to Seeber et al. (1981), the detachment fault represents a decollement dipping gently below the Greater and Lesser Himalayas at a depth of about ~15 to 20 km. Downdip from the Lesser Himalayas the detachment becomes steeper and eventually bends back to merge with a sub-horizontal aseismic zone beneath the Tethys Himalaya and Tibet (Fig. 2.1b). The most familiar regional crustal discontinuities, the MBT and the MCT all along the east-west extension of the Himalayas experienced southward movements of tectonic blocks during the orogenesis of the Greater and Lesser Himalayas. The MCT documented repeated slicing and displacement with crustal stacking in piggyback manner, which uplifted the deep-seated basement to make the loftiest mountain Himadri (Valdiya, 1988). The repeated intraplate movements including neotectonics (Gansser, 1981; Valdiya, 1981) characterized the zone of MBT where whole pile of thrust sheets started deforming by strike-slip and vertical movements on tear faults along fractures oriented transverse to the orogen. Presently, the major discontinuity along the Himalayas is the regional MFT that marks the southern edge of the Himalayan foothills (Nakata, 1989; Nakata et al., 1990), where the neotectonic movements are quite active.

2.2 South-North Subdivision of the Study Area

The Himalayan fold-and-thrust belts (Fig. 2.1a) are a classic landform caused by collision between the Indian and Asian plates during early Eocene period (Dewey and Bird, 1970), and subsequently, there was evolved five lithotectonically and physiographically distinct tectonic assemblages or sub-provinces over different tectonic
episodes. These include the Sub-Himalaya, Lesser Himalaya, Greater Himalayan Crystalline (GHC), Tethys Himalaya (THS), and Trans-Himalaya (Gansser, 1964, Thakur, 1992). All the tectonic provinces are fault bounded and accommodate ~30 - 50% of India-Asia plate convergence (Banerjee and Bürgmann, 2002; Zhang et al., 2004). These faults viz. the MFT hanging wall, MBT hanging wall, MCT hanging wall, and STD hanging wall were likely activated in a forward propagating sequences. A major normal fault separates the Tethyan sedimentary cover from the Greater Himalayan crystalline units; initially called the North Himalayan Normal Fault (Burg et al., 1984), its later appellation as the the South Tibetan Detachment (STD) is more commonly used in the literature (Burchfiel et al., 1992). Motion on the STD is thought to have resumed sometime between 15 and 20 Ma (Searle et al., 1997). The STD juxtaposes the THS above and the GHC below (Burg et al., 1984; Hodges et al., 1996; Searle, 1999). The north-south evolution processes along this Himalayan diffuse boundary involved stepwise southward migration of thrust systems (Fig. 2.1): the MCT (23 Ma →), the MBT (11 Ma →), and the MFT (6 Ma) (Molnar, 1984; Meigs et al., 1995; Hodges et al., 1996; Wesnousky et al., 1999) (Fig. 2.1).

The major Himalayan faults separate the following different layers with contrasting geology.

1. Indo-Gangetic Plain;
2. Sub-Himalaya (Tertiary strata);
3. Lesser Himalaya (nonfossiliferous low-grade metamorphic rocks);
4. Greater Himalaya (crystalline complex consisting of gneisses and aplitic granites);
5. Tethys Himalaya (marine, fossiliferous strata);
6. Trans-Himalaya (Cretaceous–early Tertiary Gangdese batholiths/Trans-Himalayan plutonic belt in southern Tibet; Burg et al., 1983; Allègre et al., 1984; Dewey et al., 1988; Yin and Harrison, 2000); and
7. Southern Tibet
Figure 2.1 (a) Showing the tectonic map of the Himalaya reconstructed after Gansser (1964), Valdiya (1980), Verma and Kumar (1987), Gahalaut and Kundu (2012). The shaded areas in the inset map on top right represents the study area. The topographic elevation is shown by the colored scale on left bottom corner. Solid arrows represent the convergence velocity direction of the Indian plate with respect to the Asian plate (after DeMets et al., 1994). Barbed solid triangle represents the thrusting. (b) Simplified section across the Himalaya illustrating the subduction of Indian lithosphere beneath southern Tibet (after Owens and Zandt, 1997; Johnson, 2002; Thiede et al., 2004; Bollinger et al., 2006; Robert et al., 2009; Zhang and Klemper, 2010; Hammer

2.2.1 Indo-Gangetic Plain

The Indo-Gangetic Plain is a 200–300 km wide active foreland part receiving sediments from both the Himalayan orogen and the Indian Peninsula Highlands of the Indian Craton, and a fraction of the material is transported and ultimately delivered to the Bengal Fan. The plains of Ganga foredeep are separated from the Sub-Himalaya by the MFT. The entire Himalayan foreland has been divided into four sub-basins: the Indus Basin covering the drainage area of the Indus River, the Ganga Basin covering the drainage area of the Ganges River, the Brahmaputra Basin covering the drainage area of the Brahmaputra River, and the Bengal Basin covering the joined Brahmaputra–Ganga River south of the Rajmahal–Garo gap (Yin, 2006). The most prominent subsurface structural high is the Delhi–Muzaffarnagar ridge that forms the drainage divide between the Indus and Ganges Rivers. The basement of the active Himalayan foreland basin is irregular, with several subsurface ridges extending from the Peninsula Highlands northwards to the Himalayan front. These structural highs generally trend at high angles to the Himalayan range and have structural relief locally exceeding 2 km in an east-west direction parallel to the Himalayan thrust front (Raiverman, 2000). The basement highs beneath the Indo-Gangetic depression are being subducted beneath the Himalayan range along the MFT; they may have controlled the map pattern of the major Himalayan thrusts and the along-strike variation and concentration of seismicity below the Himalayan range (Johnson, 1994; Pandey et al., 1999; Avouac, 2003). Basement ridges beneath the Indo-Gangetic depression are either Precambrian in age (e.g., Rao, 1973) or have been developed in the Cenozoic (Duroy et al., 1989; Raiverman, 2000). The structural highs such as the Sargodha ridge immediately south of the Salt Range in Pakistan have been interpreted as segments of a flexural bulge of the underthrusting Indian lithosphere (Yeats and Lawrence, 1984; Duroy et al., 1989). Although a forebulge may have been locally produced by bending of the Indian
lithosphere beneath the westernmost and south-central Indo-Gangetic depression as indicted by gravity data (Duroy et al., 1989; Mishra et al., 2004), its topographic expression may be much smaller than the basement ridges (Yin, 2006). Basin fills in the Indo-Gangetic depression are dominantly Neogene sediments of the Siwalik Group and rest unconformably on top of Paleocene to lower Eocene strata, Precambrian granitic rocks of the Indian craton, Proterozoic shallow marine sequences of the Vindhyan Group, and Permian strata of the Gondwana sequence (Raiverman, 2000).

2.2.2 Sub-Himalaya

North of the Indo-Gangetic Plain, the Sub-Himalaya is a zone of thin-skinned tectonics bounded to the south by the MFT and to the north by the MBT (e.g., Delcaillau, 1986; Mugnier et al., 1999; Lavé and Avouac, 2000). The Sub-Himalaya consists of Tertiary molasse including siltstones, sandstones, and conglomerates have been scraped off the basement, folded, and faulted at the front of the advancing range, forming a typical foreland fold-and-thrust belt over the Indian basement (Yin, 2006). In places, the fold belt involves slices of pre-Tertiary sediments, which are reddish-maroon quartzites and gray shales with some doleritic intrusions (Lavé and Avouac, 2000), very similar to Vindhyan units (Sastri et al., 1971). These observations indicate that the decollement underlying the fold belt must lie on top of the Indian basement. The ruggedly youthful Sub-Himalayan domain is characterized by steep slopes, swift-flowing consequent streams and deep valleys of antecedent rivers (Valdiya, 1988).

2.2.3 Lesser Himalaya

The Lesser Himalaya is made up of foliated metasediments of probably Precambrian and partly Palaeozoic sedimentaries overthrust by vast thick sheets of metamorphics and their injected Precambrian-old Palaeozoic granites (Valdiya, 1988; Yin, 2006). The Lesser Himalaya subprovince shows a mild and mature topography with gentle slope towards the north. The region is characterized by several nappes of metamorphic rocks brought southward over long distances by imbricate thrusting (e.g., Le Fort, 1975; Valdia, 1976, 1989; Gansser, 1981). The rocks are considerably folded and fractured. The main Himalayan Seismic Belt is mostly confined within the MBT and MCT zones (Ni and Barazangi, 1984). Several crystalline thrust sheets were thrust on
top of the Lesser Himalaya. They form generally pinched synformal klippen. The stratigraphic division of the Lesser Himalayan Sequence (LHS) by Heim and Gansser (1939) and LeFort (1975) includes the nonfossiliferous low-grade metasedimentary rocks. These strata are overlain by Permian to Cretaceous strata which are often referred to as the Gondwana Sequence (Gansser, 1964).

2.2.4 Greater Himalayan Crystalline

The MCT separates the Lesser Himalayan from the Greater Himalayan domain on the north. The Great Himalayan complex composed of high-grade metamorphic that are extensively injected and migmatized by mid-Tertiary granite (Valdiya, 1988). The high-grade GHC rocks generally form a continuous belt along the east-trending axis of the Himalayan range, but they also occur as isolated patches surrounded by low-grade Tethyan Himalayan strata (Honegger et al., 1982; Steck et al., 1998; Di Pietro and Pogue, 2004). The Metamorphic grade in the GHC first increases upward in its lower part and then decreases from the middle to upper part towards the STD (Hubbard, 1989; LeFort, 1996). In Himachal Pradesh along the Sutlej River in NW India, inverted metamorphism appears to span the whole GHC from MCT zone to the STD (Vannay and Grasemann, 1998). Deformed and undeformed early to middle Miocene Leucogranites are widespread in the GHC, but they are mostly concentrated in the very top part of the GHC (Ganseer, 1964, 1983; LeFort, 1975, 1996; Scaillet et al., 1990, 1995; Guillot et al., 1993, 1995; Parrish and Hodegs, 1996; Searle et al., 1997, 1999a,b; Murphy and Harrison, 1999; Dezes et al., 1999; Grujic et al., 2002).

2.2.5 Tethys Himalaya

The Tethyan Himalayan Sequence consists of Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks interbedded with Paleozaic and Mesozoic volcanic rocks (Baud et al., 1984; Garzanti et al., 1986, 1987; Gaetani and Garzanti, 1991; Garzanti, 1993, 1999; Brookfield, 1993; Steck et al., 1993; Critelli and Garzanti, 1994; Liu and Einsele, 1994, 1999). The 10-15 km thick sedimentary pile of the Tethys Zone is split into a multiplicity of imbricate thrust sheets, each characterized by isoclinal or overturned to recumbent folds with attendant disharmonic deformation near planes of dislocation (Heim and Ganseer 1939; Valdiya and Gupta, 1972). The THS can be
divided into four subsequences: (1) Proterozoic to Devonian pre-rift sequence characterized by laterally persistent lithologic units deposited in an epicratonal setting; (2) Carboniferous–Lower Jurassic rift and post-rift sequence that show dramatic northward changes in thickness and lithofacies; (3) Jurassic–Cretaceous passive continental margin sequence; and (4) uppermost Cretaceous–Eocene syn-collision sequence (Liu and Einsele, 1994; Garzanti, 1999).

The lithostratigraphy of the THS changes both along and perpendicular to the Himalayan orogen. Brookfield (1993) notes that sedimentation of the THS in the Indian Himalaya is markedly different east and west of the Nanga Prabat syntaxis prior to the onset of the Indo-Asian collision. The Tethys Himalaya lies further north of the Greater Himalaya. The northern margin of the Tethys Himalaya is sharply defined by Indus-Tsangpo Suture. The Indus Suture, further to the north, is represented by intensely deformed and vertically dipping rocks of the ocean floor and intimately associated sediments that had accumulated in a deep ocean-trench in front of the Asian landmass. Possibly, there was an island arc adjacent to this trench, which was sandwiched and eventually welded to the colliding continents (Valdia, 1976).

2.2.6 Trans-Himalayan Zone

Prior to its collision with India, the southern margin of Asia was marked by a continental arc that developed as a consequence of the northward subduction of Neo-Tethys oceanic crust (Dewey and Bird, 1970; Tapponnier et al., 1981). The Trans-Himalayan zone consists of volcanic and plutonic elements of this arc. The last pre-Himalayan accretion event was the collision of an island-arc complex, now represented by the Kohistan-Ladakh terrane, along the Shyok suture zone in Late Cretaceous time (Treloar et al., 1989b; Rolfo et al., 1997). East of long 80°E, the continental arc is represented principally by the Gangdese batholith of southern Tibet. The best-studied sector of the Gangdese batholiths is the southern Lhasa block dominated by the Trans-Himalaya plutonic belt. At present, the Lhasa and Kohistan-Ladakh terranes are juxtaposed by the right-lateral Karakoram fault system, one of the most spectacular structures in the orogeny. Geochronologic data (Schärer and Allègre, 1984; Xu et al., 1985; Coulon et al., 1986; Copeland et al., 1995) suggest that the most intense period of magmatic activity in the Trans-Himalayan continental arc was older (latest Cretaceous)
in the west and younger (early Tertiary) in the east and that the cessation of arc magmatism occurred earlier in the west (late Paleocene) than in the east (middle Eocene). Thus the collision of India occurred earlier in the west than in the east (Rowley, 1996).

2.2.7 South Tibet

The broad region of the southern Tibetan Plateau lies between the ITS zone and the crest of the Himalaya. Neogene–Quaternary intermontane basins occur throughout the Himalaya and southern Tibet. They can be divided into three broad categories: (1) extensional basins just north of the Himalayan crest that are related to the approximately east-striking South Tibetan fault system (Burchfiel et al., 1992); (2) basins associated with kinematically linked displacement on northwest- and northeast-striking strike-slip faults and north-trending rift systems in southern Tibet (Mohr and Tapponnier, 1978; Fort et al., 1982; Armijo et al., 1986); and (3) “thrust-top” or “piggy-back” basins lying north of the Himalayan thrust front and south of the range crest (Burbank et al., 1997). South Tibet is marked by complex arrays of synthetic and antithetic splay faults that divide the immediate hanging wall of the basal detachment into extensional riders. The cumulative extension represented by such hanging-wall features may be of comparable magnitude to the slip on the basal detachments (Hodges et al., 1998; Girard et al., 1999; Searle, 1999). Most data suggest that the South Tibetan fault system was active by Miocene time (Armijo et al. 1986; Hodges et al., 1998; Searle et al., 1997; Murphy and Harrison, 1999; Walker et al., 1999). Among the most poorly characterized extensional features in southernmost Tibet are roughly east-striking, north-dipping normal faults that occur sporadically throughout the region north of the Himalayan crest and south of the Indus-Tsangpo suture (Hodges, 2000).