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Status Report

Evolution of the Himalaya

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Two main geodynamic processes have controlled evolution of the Himalaya, Trans-Himalayan and Karakoram terrains due to underthrusting of the Indian Plate beneath the Asian Plate: (i) accretion and subduction in the Trans-Himalayan and Karakoram Mountains along the Shyok Suture Zone (SSZ) and Indus Tsangpo Suture Zones (ITSZ), and (ii) continental collision in the Himalaya. The Shyok (SSZ) and Indus Tsangpo Suture Zones (ITSZ) mark the junction of these plates in the north and south, respectively (Ahmad *et al*., 2008; Jain and Singh, 2009). During the Himalayan collision tectonics, the Main Central Thrust (MCT) brought the remobilized continental crust of the Indian Plate — the Himalayan Metamorphic Belt (HMB), over the Proterozoic-Palaeozoic Lesser Himalayan sedimentary belt, which in turn, overrode the Cenozoic Sub-Himalayan belt along the Main Boundary Thrust (MBT). Subsequently, the Himalayan Frontal Thrust (HFT) carried the Sub-Himalayan foreland basin over the Indo-Gangetic Plains and links the seismicity with the overall Himalayan tectonics.

Key Words : Himalayan Geodynamics; Suture Zones; Proterozoic-Cenozoic Tectonics and Evolution

1. Introduction

This report presents the effort of numerous National Groups, which investigated the "Evolution of the Himalaya" individually or in collaboration with various international groups, and provided information on the following topics: (i) Regional Tectonics (ii) Magmatism (iii) Lesser Himalayan tectonics (iv) Proterozoic sedimentary successions (v) Tethyan Himalaya (vi) Cenozoic sedimentation and tectonics (vii) Exhumation and (viii) Paleoseismology.

2. Tectonics

Tectonic signatures of an initial Late Mesozoic subduction of the Neo-Tethys during Early Cretaceous-Lower Eocene along the SSZ and ITSZ are preserved with the intervening Dras–Shyok volcanic island arc (Ahmad *et al*., 2007; Jain and Singh, 2008, 2009). New geological observations and U-Pb SHRIMP zircon dates of 75 and 68 Ma and between 20 and 13 Ma from the Karakoram Shear Zone (KSZ) along the Nubra-Shyok Rivers constrain timing of initial suturing of this terrain and Trans-Himalaya between 75 and 68 Ma (Jain *et al*., 2007; Jain and Singh, 2009). A complex geological history of movements is recorded here since ~75 Ma with very significant role in the overall India-Asia convergence with extensive dextral ductile shearing along this zone with numerous shear indicators (Roy *et al*., 2010).

Emplacement of younger calc-alkaline Trans-Himalayan Ladakh Batholith largely followed during ~60 and 58 Ma with minor younger phases till 47 Ma (Singh *et al*., 2007; Upadhyay *et al*., 2008, Ravikant *et al*., 2009; White *et al*., 2011a). Final closure of the Neo-Tethys took place during the India-Asia collision along the ITSZ (Jain and Singh, 2009).

Within the Pangong migmatite-granodiorite of the Karakoram Fault Zone (KFZ), granodiorite leucosomes escaped from migmatite due to noncoaxial deformation under simple shear regime and later by low-temperature near-surface re-activation, and subsequently intruded by felsic veins (Sen *et al*., 2009).

Based on magnetotelluric (MT) profile in the Tso Morari, Ladakh and Karakoram regions, Arora *et al*. (2007)

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record serpentenization/graphite zones on limbs of the Tso Morari dome in the upper crust, sub-vertical and northeast dipping conducting ITSZ, and a mid-crustal conductor with partial melt or aqueous fluids along very low resistivity zone further north. Based on records of shear-wave velocities from regional earthquakes in western Himalaya and Tibet, an apparently continuous low-velocity layer (LVL) with 7-17% velocity reduction at ~30 km depth was worked out from the Tethyan Himalaya to the Tibetan plateau (Caldwell *et al*., 2009). This matches the previously-determined low resistivity zone from magnetotelluric studies with presence of 3-7% melt in a channel in the upper-middle crust; both the studies indicate an overall possible mid-crustal partial molten crust underneath these terrains due to impingement of the Indian Plate along the Main Himalayan Thrust at depth.

A new tectonic geological cross-section resulted from the HIMPROBE Program in the NW Himalaya (Fig. 1).

In the northern most parts of the Himalayan Metamorphic Belt (HMB), the Tso Morari Crystallines (TMC) record 8 Ma continual zircon crystallization since ~53.3±0.7 Ma when it underwent UHP metamorphism at ~ 100 km depth beneath the Trans-Himalaya to amphibolite-facies metamorphic conditions at 45.2±0.7 Ma (Leech *et al*., 2007 and references therein). Five major fluid types in coesite-bearing TMC range from high-salinity brine, N2, CH_4, CO_2 and low-salinity aqueous fluids, and were trapped during deep subduction to >120 km and exhumation (Mukherjee and Sachan, 2009). Subducting Indian lithosphere produced brines prior to achieving maximal depths, where gaseous phases dominated fluids, instead. Subsequently, it released CO_2-rich fluids during fast exhumation and infiltrated by low-salinity aqueous fluids near surface.

Well-preserved mesoscopic ductile and brittle ductile shear zones reveal conjugate sinistral and dextral sense of movements in crystalline rocks of the MCT Zone of Garhwal Higher Himalaya, generated by NNE-SSW horizontal compression (Srivastava and Tripathy, 2007).

In Sikkim, the Lesser Himalayan Duplex (LHD) transported crystalline thrust sheets, marked by the MCT 1 and MCT 2, farther southwards than other parts of the Himalaya (Mitra *et al*., 2010). Such lateral variations in the LHD geometry imply differences in kinematic and shortening history of the Lesser Himalaya. Matin and Mazumdar (2009) presented evidences of elastico-frictional or quasi-plastic deformation from the Gondwana rocks during emplacement of Jorthang frontal horses in the LHD

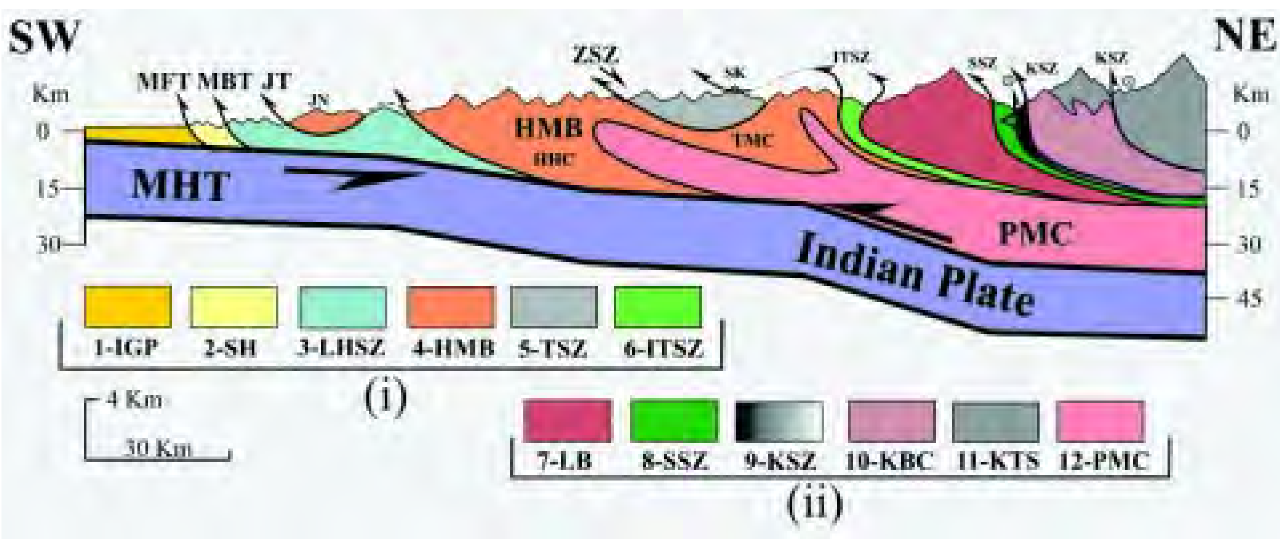

Fig. 1: Geological cross-section through the NW Himalaya and Karakoram. Himalayan Collision tectonic zone: 1-Indo-Gangetic Plains (IGP), 2-Sub-Himalayan Cenozonic foreland basin (SH), 3-Lesser Himalayan Sedimentary Zone (LHSZ), Himalayan Metamorphic Belt (HMB) including Lesser Himalayan Jutogh Nappe (JN), 4-Higher Himalayan Crystalline (HHC) Belt and Tso Morari Crystallines (TMC), 5-Tethyan Sedimentary Zone (TSZ), Trans-Himalayan tectonic units, 6-Indus Tsangpo Suture Zone (ITSZ) and Spongtang Klippe (SK), 7-Ladakh Batholich Complex (LB), 8-Shyok Suture Zone (SSZ), Asian Plate Margin, 9-Karakoram Shear Zone, 10-Karakoram Batholith Complex (KBC), 11-PaleoMesozoic Karakoram Tethyan sequence, 12-Partially Molten Crust (PMC). Subducting Indian Crust (IC) given in blue colour. Symbols : MFT-Main Frontal Thrust, MBT-Main Boundary Thrust, MCT-Main Central Thrust, ZSZ-Zanskar Shear Zone, MHT-Main Himalayan Thrust. Please note vertical exaggerate above 0 km to show topography. Partial melt on mid-crust and extension of the Indian Plate beneath Karakjoram and further north-east are constrained from magnetotelluric and teleseismic receiver function analysis after Arora *et al*. (2007) and Caldwell *et al*. (2009). Data are integrated with geology collected during the HIMPROBE Program.

under shallower crustal conditions,associated with footwall of the Ramgarh thrust in the Rangit window in Sikkim. An unusually complete inverted Barrovian sequence in Sikkim Lesser Himalaya with a number of interlayered different bulk compositions yield consistent pressures and temperatures by different methods, where these increase continually up to the highest grade (Dasgupta *et al*., 2009). The metamorphic field gradients are positive between 60 to 70ºC in Sikkim; inverted metamorphism is explained by channel flow type tectonics.

Terrane-defining Trans-Himadri Detachment Fault (T-HDF) system in northern Kumaun behaved differently at different point of time in compressional regime as a plane of decoupling of easily yielding sedimentary pile of the Tethys basin from its rigid basement of the Vaikrita crystalline complex (Valdiya and Pande, 2009).This extensional fault zone is characterized by (i) brecciation and mylonitization, (ii) gravity-driven normal faults and northward collapse of folds in the hanging wall, (iii) attenuated and eliminated of two critical stratigraphic horizons of footwall, (iv) occurrence of large plutonic bodies of granite, (v) various young geomorphic characters indicating repeated reactivation of this system.

Different sectors of the Himalaya record Late Pleistocene neotectonic activity as manifestations of ongoing geodynamic deformations in the Himalaya, linking it with palaeoseismology and present-day seismicity. Along the active faults, palaeoseismicity is recorded by liquefaction and fluidization in lacustrine deposits of Lahaul-Spiti and Ladakh (Singh and Jain, 2007), identification of tectonic, climatic, landslides and dammed lakes in Spiti valley along the Kaurik-Chango normal fault between 14-6 ka and ~50-30 ka (Phartiyal *et al*., 2009a, b) and sand dykes of 800±130 years BP due to coseismic hydraulic fracturing in fluviolacustrine deposits near Yamuna Tear Fault (Joshi *et al*., 2009) records. Soft sediment deformational structures, entrenched meanders, formation of terraces at different levels along the Kameng River, high wavelength/amplitude ratios of channels/ palaeochannels, triangular faceted cliffs, higher drainage density etc. characterize the neotectonic activity (Agarwal *et al*., 2009; Srivastava and Misra, 2008). Other evidences include fluvial aggradation in Ziro Lake valley in Arunachal Himalaya between 22-10 ka due to neotectonically active transverse normal faults (Srivastava *et al*., 2009), tectonic activity along the Main Boundary Thrust (MBT) and HFT during the Holocene in central Arunachal (Agarwal *et al*., 2009), out-of-sequence thrusting on surface-breaking faults at ca. 20 ka north of the Main Frontal Thrust in the Darjeeling Sub-Himalaya (Mukul *et al*., 2007), and role of neotectonics in drainage evolution (Phartiyal and Kothiyari, 2011). In the Kumaun Himalaya, drainage pattern, fault scarps and uplifted Quaternary alluvial fans etc., reveal ground block tilting in southeast and northwest directions across the North Almora Thrust due to neotectonism (Agarwal and Sharma, 2011).

3. Himalayan Magmatism

The Himalayan plutons are classified into four major groups according to their age and tectonic placement: (i) Proterozoic granites (2200-1800 Ma), (ii) Early Palaeozoic or Late Pan-African granites (550-450 Ma), (iii) Trans-Himalayan plutonic complex (103-40 Ma), and (iv) Collision-related leucogranites (25-15 Ma).

Proterozoic Granites

Recent trace-elements and geochronology of leucogranite in the Jutogh Group of Sutlej valley indicate crustal melting at ca. 1810 Ma before deposition of the Greater Himalayan Sequence, which is correlated with the Lesser Himalayan Sequence with Proterozoic metamorphism, overprinted at 10.5±1.1 Ma by the Himalayan orogeny (Chambers *et al*., 2008).

SHRIMP U-Pb zircon ages from basal parts of the Higher Himalayan Crystallines (HHC)-Wangtu granitoid, Lesser Himalayan sedimentary sequences–Bandal granitoid and the Kullu-Bajura mylonite at base of the MCT along the Sutlej Valley indicate anorogenic magmatic signatures ~1860 Ma (Singh *et al*., 2009). Some zircon crystals contain older cores up to 2600 Ma, and even a 3000 Ma core, indicating reworking of ensialic Archaean crust during assembly of the Columbia Supercontinent between 2.1 and 1.8 Ga. During the Himalayan collisional tectonics, reworked Archaean and Palaeoproterozoic crust was imbricated and placed adjacent to each other. Based on ages of igneous intrusions and volcanic rocks, Kohn *et al*. (2010) argued existence of a continental Palaeoproterozoic arc setting in lower Lesser Himalayan sequence. An arc model further underscores the profound unconformity separating lower-upper Lesser Himalayan rocks, indicating that this arc may have formed stratigraphic base of the northern Indian margin. In turn, this may indicate disposition of the Indian plate adjacent to North America in the ca. 1800 Ma supercontinent Columbia.

Melt for granodiorite rocks from the eastern Almora Nappe, Chhiplakot and Askot klippe in Kumaun was generated by subduction, involving hydrous partial melting of a Palaeoproterozoic amphibole- and/or garnet-bearing mafic source with involvement of sediments from the subduction zone (Rao and Sharma, 2009, 2011).

Petrological and geochemical investigations of crystalline klippe in Garhwal by Islam *et al*. (2011) revealed comparison with the Ramgarh Group and Baragaon mylonitic gneisses of Himachal.They proposed that gneissic bodies represent tectonic sliver of an older basement, emplaced regionally within the cover sequence as wedges at different structural levels throughout the Lesser Himalaya, and has a wider implication for understanding of Proterozoic basin modeling of the Lesser Himalayan domain.

In the NE Himalaya, Yin *et al*. (2010a, b) obtained zircon ages of 1745-1760 Ma, 825-878 Ma, 480-520 Ma, and 28-20 Ma from different plutons across the Shillong Plateau, Mikir Hills and Brahmaputra Valley. Correlation of these magmatic events and age-equivalent lithological units suggests that eastern segment of the Himalaya was constructed in situ by basement-involved thrusting, and is inconsistent with the hypothesis that high-grade rocks are derived from Tibet via channel flow.

Geochemical investigations of the Bomdila Group of Western Arunachal reveal that the Salari granite and Bomdila mylonite gneiss plutons are genetically unrelated, as the former appears to be derived from igneous source, whereas the latter is derived from sedimentary source (Bikramaditya Singh, 2010).

Trans-Himalayan Ophiolites, Ladakh and Karakoram Plutons

Based on mineral-whole rock isochron age, Ahmad *et al*. (2008) observed that the Nidar ophiolitic complex was an intra-oceanic arc subduction within the Neo-Tethyan Ocean during Late Jurassic-Early Cretaceous along the ITSZ as early as 140-32 Ma. This arc is marked by episodic magmatism from more basic (~140 Ma) through intermediate (Ladakh Batholith ~103 Ma) to more acidic (~50 Ma) when the Indian and the Asian plates collided. There appears to be some directional maturity from south (less mature) to more mature towards north, based on compositional variation of arc magmatic rocks, which may well support northward dipping subduction during the Cretaceous-early Tertiary. Furthermore, the Nidar ophiolite was generated in a supra-subduction zone setting and linked to the Dras intra-Tethyan volcanic arc further west (Zyabrev *et al*., 2008). Re-assessment of radiolarian taxonomy and biostratigraphy reveals an upper Barremian to upper Aptian range for the Nidar volcano-sedimentary section, which compares well with U-Pb age of 124±1 Ma for ophiolite from the Xigaze area. The sedimentary successions of both ophiolites bear resemblance in record of associated arc volcanism.

The Khardung, Tirit and Panamik granites in Ladakh and Karakoram exhibit subduction-related geochemical characters (Rao and Rai, 2009). The Khardung granite is produced due to re-melting of crustal rocks of volcanic arc affinity, while the Tirit and Panamik granites represent transitional tectonic environment from primitive to mature arc. Detailed geochemical studies of the Hbl-Bt orthogneiss of Shyok-Darbuk area of Ladakh reveals that these are typical Andean-type granitoids, while late phase granites of Miocene age are generated from intracrustal partial melting of hybrid magma source (Daga *et al*., 2010). The leucosome of migmatite and Darbuk leucogranite are coeval.

Microgranular enclaves (ME) from the Ladakh Batholith are products of multistage magma mingling and mixing processes and concomitant fractional differentiation of several batches of mafic and felsic magmas, formed in open magma chamber(s) in subduction setting (Kumar, 2010). Composite ME indicates multiple mafic to hybrid magma intrusions into partly crystalline magma chambers. Pillowing of mafic melt against leucocratic (aplitic) residual melt strongly suggests mafic magma intrusion in nearly-crystallized condition of pluton.

The Ladakh Batholith represents subduction-related Andean-type magmatism, intruding an island arc setting before the continent-continent collision of Indian and Asian Plates. SHRIMP U-Pb zircon age from a granodiorite near its northern boundary with the SSZ is 60.1±0.9 Ma, whereas a diorite from its southern boundary near the ITSZ yields 58.4±1.0 Ma age (Singh *et al*., 2007). Al-in-hornblende barometry indicates depth of crystallization for diorite to be 16±1 km and granodiorite to be around 8±1 km indicating post-crystallization northward tilting of the batholith. Additional U-Pb zircon ages from this batholith fall into four distinct groups between c. 67 and c. 45 Ma (Upadhaya *et al*., 2008) and indicate growth by subduction-related continuous magma pulses throughout Paleocene and Middle Eocene (Lutetian). Likewise, multiple subduction events have occurred preceding the collision of Greater India with Karakoram terrane that consumed the Neo-Tethyan Ocean between Early Cretaceous and Eocene time (Ravikant *et al*., 2009). Undeformed granodiorite yielded zircon U-Pb ages of 68 and 64 Ma with εHf(t) values of +6.4 and +10.3, and three diorites near Leh and Darbuk gave ages of 50.4-51.0 Ma and εHf(t) values of +7.4 to +8.9 indicating the Paleocene-Eocene as most important period of granitic magmatism from a juvenile source. White *et al*. (2011a) obtained more U-Pb SHRIMP zircons ages to indicate that emplacement of granitoids in this batholith occurred between 66 Ma and 46 Ma with continuation of I-type magmatism until at least ~46 Ma, implying that India had not accreted to Eurasia by 46 Ma.

Indirect approach to constrain age of collision in the Himalaya is to date zircon from the UHP metamorphosed continental crustal material of the Tso Morari Crystallines, which subducted to at least 90-120 km at 53.1±0.1 Ma, thus bringing collisional age to be no later than ~57 Ma with steeper subduction dip angle (Leech *et al*., 2007).

K-Ar biotite ages for the Ladakh batholith in Khardung La range from 49.3±1.1 to 51.2±1.1 Ma and from 60.8±1.3 to 65.8±1.4 Ma for granites and diorites in Hundar area (Thanh *et al*., 2010). Calc-alkaline granites from Panamik of the Karakoram block yielded K-Ar biotite ages of 95.7±2.1 and 96.7±2.1 Ma, suggesting that the granites are members of plutons (90–120 Ma), emplaced during subduction of the Neo-Tethyan oceanic plate under this block.

Fission track (FT) dating of apatite and zircon from this batholiths yield oldest apatite ages of 23.1±1.1 and 25.4±2.6 Ma from highest Khardung La and Chang La, and youngest ages of 11.8±1.1 Ma and 9.2±0.9 Ma from lower elevations of the same sections (Kumar *et al*., 2007). These yield slow cooling and low exhumation rates of 0.1 mm/a. Zircons FT ages are 41.4±2.3, 43.8±3.4 and 31.7±2.7 Ma, indicating a younging of ages from west to east.

Rao and Rai (2009) presented typical Andean-type subduction-related geochemical characteristics of the Khardung, Tirit and Panamik granites from Shyok and Karakoram in spite of these belonging to different lithotectonic units. Melting of crustal rocks of volcanic arc affinity has played an important role in origin of Khardung granite, which is more evolved, while the Tirit and Panamik granites represent transitional tectonic environment from primitive to mature arc.

Daga *et al*. (2010) suggested that Eocene to Late-Cretaceous met-aluminous Hbl-Bt orthogneiss (OG) of the Karakoram granitoids show geochemical characteristics of Andean-type granitoids. Miocene late phase granitoids (porphyritic granite, coarse leucogranite, two-mica±garnet leucogranite dykes) are generated from intracrustal partial melting of hybrid magma source, involving dominantly orthogneiss (derived from mantle source) and subordinate amounts of metapelites (crustal source). Migmatite leucosome and common leucogranite of nearby Darbuk pluton are coeval, which record syntectonic melt flow through the deforming crust.

Upadhyay (2009) dated a granite plug as 24.52±0.40 Ma, intruding the Shyok volcanic in the Shyok suture zone of the Saltoro Hills, and suggested that this body may be related to younger granitic bodies of 25 and 17 Ma from Baltoro and Tangtse-Muglib plutonic rocks of the Karakoram block.

Ravikant *et al*. (2009) published U–Pb zircon ages of 101-103 Ma from tonalite-granodiorite enclaves within the Karakoram Batholith with $\varepsilon_{Hf}(t)$ values of –2.3 to –3.7, indicating their generation by partial melting of the Karakoram basement. However, samples around Darbuk, yielded ages of 16.6-19.1 Ma with $\varepsilon_{Hf}(t)$ values of -8.5 and -10.5, indicating an input of ancient crust from the Indian Plate. Granodiorite within the Karakoram metasedimentary sequence yields zircons ~74Ma, $\varepsilon_{Hf}(t)$ of +5.4 from the Tangtse gorge and granite has 63 and 56 Ma and $\varepsilon_{Hf}(t)$ of +6.8 and +6.0 indicate similar geochronological and isotopic characteristics to those of the Ladakh Batholith and derivation from both ancient and juvenile continental crusts since at least the Mid Cretaceous. See also Jain and Singh (2008).

White *et al*. (2011b) have shown that the Indian rocks outcrop to the north of the ITSZ. New SHRIMP U-Pb ages suggest that inherited zircon age spectrum from mylonitic gneiss in southern part of the Karakorum Batholith is similar to those obtained from the Himalayan Terrane and is apparently of Gondwanan affinity. Several continental ribbons (including the Karakorum Terrane) were probably rifted from the northern margin of Gondwana and accreted to Eurasia prior to India.

Whole-rock ^{40}Ar-^{39}Ar studies on the Khardung and Shyok volcanics reveal disturbed age-spectra in the latter due to young thermal disturbance due to Karakoram fault activation at ~14 Ma (Bhutani *et al*., 2009). Thick rhyolitic and ignimbritic flows of the Khardung volcanics yielded undisturbed age-spectra and good plateau-ages of 52.8±0.9 and 56.4±0.4 Ma as the time and duration of emplacement of these volcanics over thickened margin of continental crust.

Calc-alkaline plutons across the KF in Shyok-Nubra confluence area yield K-Ar biotite ages from 49.3±1.1 to 51.2±1.1 Ma for the Ladakh Batholith in Khardung La and from 60.8±1.3 to 65.8±1.4 Ma for granite and diorite in Hundar area (Thanh *et al*., 2010). K-Ar ages of the Hundar igneous complex are within range of 46-70 Ma of the Ladakh Batholith near Leh town and the plutons across the KF in the Shyok-Nubra confluence, indicating that it is a part of the Ladakh arc. The calc-alkaline granite from Panamik of Karakoram block yield K-Ar biotite ages of 95.7±2.1 and 96.7± 2.1 Ma, suggesting that these are members of the northern Pakistan plutons (90-120 Ma). These bodies in Panamik region yield K-Ar biotite and muscovite ages ranging from 9.18±0.21 to 9.45±0.21 Ma and represent reactivation of the KF.

In the Lohit plutonic complex in Arunachal (NE Himalaya), Gururajan and Choudhuri (2007) identified three arc-related magmatic phases. Earliest gabbro-quartz diorite and hybrid rock phases were generated in subduction setting through fractionation of basaltic parent under high water pressure. Trondhjemiteis formed by melting of oceanic crust that underplated the arc leaving garnet and amphibole in residue. Leucogranite has formed by anatectic melting of mixture of leucotonalite and metasediments during collision event.

Collision-related Leucogranites

U-Pb zircon age of the Malari leucogranite in Garhwal indicates its emplacement at 19.0±0.5 Ma (Sachan *et al*., 2010), who interpreted the cessation of ductile normal shearing along the STDS by 19 Ma in the critical taper model setting. Internal weakening of the wedge was likely to be caused by partial melting, thereby creating a brief interval of flattening and ductile extension in rear of the wedge.

4. Lesser Himalayan Tectonics

Detailed structural analysis of crystalline rocks of the Se La Group and Dirang Formation in west Kameng district along the Bomdila-Tawang and Kimin-Ziro-Tamen-Doparijo sections in Arunachal presents a vivid picture of thrust-related deformation (Srivastava *et al*., 2011). Close to the MCT four deformation phases are identified, where kinematic indicators show a top-to-SSE sense of movement. They also identified two new thrusts, viz., the Tawang and Se La Thrusts as imbricates like other parts of the Lesser Himalaya.

Microtextures in mylonites from Garhwal and Kumaun are developed due to intracrystalline creep and grain boundary migration (Srivastava and Srivastava, 2010). In Lesser Himalayan Crystallines of central Almora Nappe, unmylonitized metamorphics reveal main regional metamorphism from chlorite-biotite to sillimanite-K-feldspar zone with P and T changing from 450ºC/4 kbar to 500-709ºC/4.0-7.9 kbar (Joshi and Tiwari, 2009). As these are intruded by the 560±20 Ma Almora Granite with contact metamorphism, they postulated that dominant regional metamorphism in this nappe is of pre-Himalayan (Precambrian!) age. Within the same nappe, dark coloured veins of pseudotachylite are irregular and folded in vicinity of the South Almora Thrust zone, and seem to have formed during friction-related heating due to thrust movement by rapid crystallization of melts (Agarwal *et al*., 2011).

Small-scale structures and the microstructures are used to determine shear sense of the Almora Crystalline Zone, which records top-to-south ductile shearing in southern parts and a distinct top-to-north shear sense overprinting in northern parts (Agarwal *et al*., 2010). It suggests backthrusting for the synformal nature of this sheet, where successive stages of development of folds and their later modification into shear folds are also significant.

The Main Boundary Thrust (MBT) Zone in SE Kumaun is an imbricate structure, having tectonic wedges of the Sub-Himalayan sediments and the Lesser Himalayan amphibolite (Shah *et al*., 2012). This zone comprises development of folds in two coaxial sets and their modification into sheath-like folds, and kinematic indicators like fault striae and the slip lineation on shear surfaces. Palaeostress analyses are consistent with a wrench accompanied N-NNE directed subhorizontal shortening due to presence of an oblique/lateral ramp that defines a steeply dipping transfer zone between two frontal ramps in the MBT.

5. Proterozoic Sedimentary Successions

The Proterozoic sedimentary successions are essentially exposed in the Lesser and partly in the Tethyan Himalaya domains. The Proterozoic Lesser Himalayan basin is unique due to its exceptionally long stratigraphy at least from Palaeoproterozoic to early Phanerozoic, and has sedimentary record over a period of nearly 1000 Ma. The important aspects are: (a) there were no apparent deposition after Cambrian except some patches of Permian strata till Upper Cretaceous, and (b) parallelism of sedimentation, magmatism and basin-genesis aspects with that of the northern extreme of the Peninsular Basin. In totality, post-Vendian (between 650–542 Ma) part of the Lesser Himalaya is relatively fairly constrained and understood in terms of litho- and bio-stratigraphy, sedimentology, structure, tectonics and isotopic constrain. However, pre-Vendian between ~1800-650 Ma part is least attended owing to some inherited geological problems.

A glaciogenic origin of Blaini Formation is supported by relatively abundant striated clasts and local preservation of polished and striated pavement on the underlying Simla Group clastics. The cap dolostone is isotopically light with respect to both ^{13}C and ^{18}O with strong covariance. New $^{207}Pb/^{206}Pb$ detrital zircon ages from diamictite of the Blaini Formation provide a maximum depositional age limit of 692±18 Ma (Etienne *et al*., 2011).

U-Pb detrital zircon ages from cratonic succession of the Vindhyan Supergroup, Aravalli succession, Ganga Supergroup and the “inner” and “outer” Lesser Himalayan successions show similar depositional ages and display strikingly similar age distribution all through the region (McKenzie *et al*., 2011). Differences in the isotopic value between the lithotectonic zones relate primarily to differences in the depositional age of the constituent rocks, and that all parts of the Himalaya were in sediment-source continuity with the Indian craton from beginning of the late Palaeoproterozoic to the early Cambrian.

A Palaeoproterozoic palaeosol horizon in the Himachal Himalaya along the basement-cover contact is represented by a 2-5m thick sericite schist (Bhargava *et al*., 2011) along the contact of the 1866±10 Ma Jeori-Wangtu-Bandal Gneissic Complex (JWBGC) and the overlying sericite quartzite of the Manikaran Formation (Rampur Group), interstratified with 1800±13 Ma tholeiitic flows in its basal part. It is inferred that the Palaeoproterozoic metamorphism was a regional event in the Himalaya at a time when the Indian Plate was part of the Nuna Supercontinent.

Many penecontemporaneous deformational structures in Proterozoic sediments of the Lesser Himalaya are interpreted as seismites (Ghosh *et al*., 2010). In comparable Palaeoproterozoic Damtha Group of rocks shows widespread seismites described as SSDS (soft sediment deformation structures) over a large aerial domain suggesting the action of a regional triggering agent like earthquake. These are perhaps the oldest seismites recorded from the Himalayan domain (Ghosh *et al*., 2010, 2011).

The Palaeoproterozoic arc model of the evolution of the Lesser Himalayan sequence, underscores the profound unconformity separating the lower from the upper Lesser Himalayan rocks, indicating that the arc may have formed the stratigraphic base of the northern Indian margin (Kohn *et al*., 2010). This therefore suggest disposition of the Indian plate next to the North American Plate in ca.1800 Ma supercontinent Columbia.

Small size spicules in terminal Proterozoic Gangolihat Dolomite of Kumaun Lesser Himalaya indicate the existence of small ancestral sponges (Tiwari, 2008) during Neoproterozoic (Tiwari and Pant, 2009). Fossils of entire sponges are still not known from the Neoproterozoic era.

The Neoproterozoic Buxa Dolomite from northeastern Lesser Himalaya shows significant positive C-isotope ratios ($\delta^{13}C$=+3.7 to +5.4‰ PDB) and remarkable consistency in the $\delta^{18}O$ fluctuation within a narrow range (between –8.9 and –7.2‰ PDB; Tewari and Sial, 2007). These results correspond to the Terminal Proterozoic C-isotopic fluctuation, followed by oscillations during the Precambrian-Cambrian transition in the Lesser Himalaya of the Eastern Gondwana. Schopf *et al*. (2008) demonstrated evidence of early life in the Proterozoic Buxa Dolomites in the form of microfossils.

Fluid inclusion and geochemical studies of the Proterozoic Nagthat siliciclastics of the Lesser Himalaya suggest a granitic source (Verma and Sharma, 2007). Primary Q1 aqueous brine inclusions and Q3 H_2O-CO_2 fluid with 0.9 gm/cm^3 CO_2 density in detrital quartz grains characterize the protolith as granite or metamorphic rocks. H_2O-NaCl fluids participated in cementation history with quartz overgrowth between 198º and 232ºC indicating the effects of maximum burial. The observed inclusion morphology is attributed to a decrease in the external pressure related to isothermal decompression uplift.

6. Tethyan Himalaya

Ever since the Zanskar and the Spiti regions were made accessible to foreigners there is sudden spurt in the scientific studies along this sector. A summary of such activities is given below:

Cambrian

Peng *et al*. (2009) updated the trilobite taxonomy and biostratigraphy of Parahio Valley and Zanskar. They described new genera and species of trilobites which were useful in correlation with other Cambrian successions of the world and to suggest new paleogeographic reconstructions. Singh (2008a, 2009a) identified and described two Cambrian trilobite biozones, viz. *Lejopygelaeivigata* and *Proagnostusbulbus* in Zanskar and Kurgiakh valleys in addition to report of several new trilobite faunal elements, viz., *Lisogoragnostushybus*, *Diplagnostusplanicauda*, *Neoanomocarellaasiatica*, *Parablackwelderialuensis*, *Eoptychoparia* cf. *jinshanensis*, *Lisana* cf. *yuanjiangensis*, *Dorypygeperconvexalis* and *Pianaspissinensis.* Numbers of progradational cycles were identified along the Parahio Formation (Cambrian); each cycle reflects a progressive increase in sand content, degree of oxygenation, hydrodynamic energy and dearth of food (Singh, 2009a, b). He also identified a major eustatic sea level rise (named Teta Transgression) during the deposition *Lejopygelaeivigata* zone, which is synchronous with globally recognized eustatic event (Singh, 2011a). The study revealed proximity of Indian margin with southwest China (outboard microcontinent) and Australia. Parcha (2008) presented a succinct status of trilobites and their importance in the Cambrian biostratigraphy.

In Bhutan, new trilobite assemblage, so far the youngest in the Himalaya, along with brachiopodswas reported by Hughes *et al*. (2011). The faunal data from Bhutan also support a continuity of the northern Gondwanan margin across the Himalaya.

Rich assemblage of ichnofossils has been reported from the Zanskar Valley by Parcha and Singh (2010) and Singh (2009b), who established inter-relationship of ichnofacies, lithofacies and alternating energy conditions due to recurring storm event. The post-depositional *Arenicolites* ichnofacies is preserved within the high-energy storm beds of shoreface environmnt. It commonly overlies fair weather assemblage of pre-depositional *Cruziana* ichnofacies of relatively more offshore deposits; the latter contains more diverse and varied behavioral signatures of various deposit feeders (Singh, 2009b). Singh (2009c) also discussed significance of stratigraphically important ichnofossils Phycodes in Zanskar Valley. Parcha and Shivani (2011) described ichnofossils assemblage from the Parahio Valley and have discussed their significance in the Cambrian successions.

From the Zanskar area sixteen Cambrian ichnogenera are identified, the frequency of the traces and the trilobites is inversely proportional (Parcha and Singh, 2010).

From the lesser known Jadhganga Valley in Uttarkhand, Upadhyay and Parcha (2012) have reported *Dimorphichnus* isp. and *Rusophycus* isp. along with *Cruziana* and worm trails. Based on this assemblage an Early Cambrian age is assigned for the sediments enclosing the ichnofossils.

Paleostrain analyses of calcite twins across the Cambrian-Ordovician unconformity and of Carboniferous in the Tethyan part reveal Cambrian deformation in the former and the Cenozoicin the latter; both indicate similar deformation fields (Paulsen *et al*., 2007).

Based on the ages of detrital zircons, Myrow *et al*. (2010) worked out the probable provenance and mixing of the sediments in the Tethyan belt of Bhutan.

Ordovician

From the Thango Formation (=Thaple), basal part of which is considered fresh water deposit by some previous workers, Singh (2008b) reported a diminutive collection of marine pelmetazoan columnals in association with pentamerid brachiopods from the Zanskar region. These fossils constrain the Cambro-Ordovician regional hiatus between early Late Cambrian (~498 Ma) and early Ordovician (~478 Ma)-within a span of 20 My.

Bhargava (2008a) studied various aspects of the Palaeozoic successions in the Indian Plate. These contributions suggest: (i) the sequences from Cambrian to Carboniferous have comparable litho- and biofacies from Kashmir to Bhutan and across the depositional dip, (ii) the Tethyan Basin shelf was not only broad but also had a very gentle slope, and (iii) the post-Panjal sequence in Kashmir shows shallower facies and is therefore different from the Spiti-Zanskar facies.

Bhargava (2011) dealt with various aspects of Cambrian-Silurian sequences of the Tethyan basin which included the study of the basin configuration, paleogeographic setup, tectonics and paleoclimatic reconstructions. He concluded: (i) the siliciclastic Ordovician sequence was reworked in a shallow marine environment and represents a foreland basin, (ii) the Cambrian-Ordovician break in Bhutan seems to be of larger duration, (iii) the Kashmir region was located in strike extension of the Spiti-Zanskar segment and got sheared during the Early Permian and brought to lie at its present position by the reactivated Permian Shear, and the successor Zanskar Shear.

Triassic

The detailed work on the Triassic succession was initiated in 2000. Later focus is on the Early Triassic in the muddy section of the Spiti and is therefore important in demarcating the Induan-Olenekian boundary, based on integrated ammonoids, chemostratigraphy and conodont biostratigraphy (Krystyn *et al*., 2007, 2008). The study across this boundary, demarcated on the basis of faunal changes, reveals a positive C-isotopic values with accompanying negative excursions.

Jurassic-Early Cretaceous

A Late Valinginian transgressive event was recognized in the sequence stratigraphic context in the Spiti Valley (Pathak *et al*., 2011). Jai Krishna *et al*. (2011) concluded that the Tethyan margin of the Indian subcontinent included northern margin of the Madagascar during Jurassic at its western extreme, in addition of the margins of its presently understood constituents (i.e. India, Pakistan, Nepal, Bhutan, S. Tibet). During Jurassic, the Tethyan margin of the Indian subcontinent represented the central/axial component of the Gondwana Tethyan margin in the neighborhood of North and East Africa in the west and Sula-New Guinea-NW Australia in the east.

Cretaceous

Raju *et al*. (2009a, b) tabulated stratigraphic details, paleobathymetry, paleoenvironment and hiatuses and their duration during the Phanerozoic. Raju (2011) dealt with biochronostratigraphy, biochronozones (datums), biochrons and various stages of the Indian Cretaceous including the Tethys Himalaya. The Himalayan region was marked by magmatic activity of a vast dimension (Karakoram, Ladakh batholiths and Dras Volcanics. According to Raju (2011) the final breakup and spreading between Greater India and Australia commenced during the Late Valanginian/Early Hauterivian which led to initiation of modern Indian Ocean, opening of new basins and subduction of the Indian Plate during the Cenomanian.

Misra *et al*. (2011) prepared a mega chart defining the shale sequences that could be of use in the search of shale gas in the Tethyan Himalayan succession. An updated account of the lithostratigraphy, fossil contents and structure has been published by Bhargava (2008b). A compilation of the Tethyan sector can be found in Singh (2009d).

Quaternary

Sangode and Mazari (2007) studied the effects of climatic variations on mineral magnetism in the lake deposits of Kioto in the Spiti Valley.

Bhargava *et al*. (2010) summarized various geological and bio-events in the Tethyan part including the evolution of the landforms and other geomorphic features in the Lahaul and Spiti Valleys.

7. Cenozoic Sedimentation and Tectonics

The Himalayan foreland basin (HFB) developed in response to flexure rigidity, buckling and failure of the Indian plate due to large crustal load of advancing thrust sheets, and is extensively studied for variability in depositional setting, thrusting events, exhumation and intensification of the Indian monsoon.

Marine Subathu Formation dated as Late Thanetian to Middle Lutetian with an upper age limit of 40 Ma, is overlain by the continental succession of the Dagshai Formation. The contact between Subathu and Dagshai formations is either unconformable with a hiatus of ~12 Ma. Kumar *et al*. (2008) inferred an erosional discontinuity at the Subathu-Dagshai contact that could be as small as ≤3Ma (Bera *et al*., 2008), and marked the sequence boundary below the white sharp-based sandstone. Vivid increase in the input of orogenic detrital grains at the beginning of the alluvial Dagshai implied an abrupt hinterland uplift and retreat of the Subathu sea to the farther edge of the Himalayan foreland basin (Bera *et al*., 2008; Kumar *et al*., 2008). Based on the study of palaeosols in the Lower Cenozoic succession, Singh *et al*. (2007, 2009) suggested temporal changes from humid to tropical climate during northward drift of the Indian plate.

Progressive effects of crustal thickening and exhumation of Himalayan source rocks are reflected in detrital-zircon fission-track (FT) ages from the Lower Cenozoic Sub-Himalayan foreland basin as a consequence of the India-Asia collision (Jain *et al*., 2009). Oldest transgressive marine Paleocene-Eocene Subathu Formation (57-41.5 Ma) contains ca. 50 Ma detrital-zircon youngest peak, derived from the Indus Tsangpo Suture Zone and Ladakh Batholith of the Asian Plate. However, Ravikant *et al*. (2011) recorded U-Pb spectra in the zircons of the Subathu Formation showing Cretaceous to Eocene ages. First imprint of collision-affected Himalayan Proterozoic basement on the Tethyan sedimentary led to the deposition of Oligo-Miocene Dagshai and Kasauli sediments with sudden changes in the provenance.These rocks show dominant 30 and 25 Ma young peaks, with distinct unconformity spanning ~10 m.y. between Subathu and the Dagshai Formations.

The overlying Siwalik continental molasses represent a coarsening upwards succession from mudstone–sandstone couplets (Lower Siwalik) to sandstone dominated (Middle Siwalik) to conglomerate, sandstone and mudstone (Upper Siwalik) facies throughout the NW Himalaya (Kumar *et al*., 2011). It was demonstrated that temporal and spatial variation in sedimentation patterns in the Lower Siwalik with more than 50% mudstone was derived from north with low sediment accumulation and larger accommodation space between ~13 and 10 Ma. The Middle Siwalik was deposited by large braided streams with low accommodation space during ~10 and 6 Ma. The Main Central Thrust (MCT) re-activation caused uplift and basin-ward thrust sheet migration. It resulted in altered foreland basin slope, accommodation space and sediment supply with development of orographic barriers that accelerated monsoon system to enhance seasonal sediment supply and accelerated the hinterland exhumation. The Upper Siwalik is in tandem with the intensified monsoon, hinterland uplift and development of intra-foreland thrust system during ~6 and 0.5 Ma. Relatively high accumulation and sediment supply, concomitant with onset of deposition of Lesser- and Sub-Himalayan-derived sediments is characteristic in the proximal foredeep due to intense deformation along MBT. Sudden influx of coarse detritus between ~6 and 5 Ma, represents frequent hyper-concentrated floods, which transported boulder size clasts into the basin.

Shukla *et al*. (2009) suggested the transformation of river pattern from meandering to anatomizing to braided in the Lower Siwalik succession. Sinha *et al*. (2007, 2008) suggested that sedimentation in the Ravi re-entrant took place in response to pulsating tectonics, and the present-day topography was developed before 12 Ma.

Petrography and geochemistry of the Neogene Siwalik fluvial succession (12.77-4.48 Ma) in the Ravi re-entrant suggest that the Higher, Lesser and Lower Tertiary formations supplied detritus since 12.77 Ma in response to thrusting of Chail Thrust and Main Boundary Thrust (Sinha *et al*., 2007). The $\delta^{18}O$ variations in soil carbonates reveal ongoing intense monsoon system since 12.77 Ma, followed by a phase of aridity at 9.1 Ma. Presence of fresh and weathered feldspar, limestone, basic volcanics and mica, both in humid and arid phases indicate rapid deposition and preservation.

Ghosh *et al*. (2009) related occurrence of various suites of detrital components with thrusting events along Chail Thrust in the Kangra sub-basin. Ranjan and Banerjee (2009) demonstrated that in the Lower Siwalik and part of the Middle Siwalik of the Kangra and Dehra Dun re-entrant, the Higher Himalayan Crystalline sequence (HHCS) was the primary source area with minor contributions by the meta-sedimentary succession of the Lesser Himalaya. Later, the source terrain switched positions during deposition of upper part of the Middle Siwalik and Upper Siwalik. These two prominent source terrains supplied sediments in steadily changing proportion through time. East of Ganga River, Jalal *et al*. (2011) inferred that major supply of sediments was from the Lesser Himalayan rocks including the crystalline bodies.

Based on stable isotope geochemistry, Sinha *et al*. (2008), Sanyal *et al*. (2010) and Sanyal and Sinha (2010), reconstructed monsoonal fluctuation events during the Late Miocene to Late Pleistocene. This suggested multiple phases of monsoonal intensification with peaks at 10.5, 5.5 and 3 Ma after which the strength of the monsoon decreased to modern day values with minor fluctuations.

8. Exhumation

There is increasing number of low-temperature thermochronological exhumation studies from different sections across NW-Himalaya during 2007-2011 following the dedicated works by the Kurukshetra University (Patel *et al*. 2007; 2010; 2011a, b, c). This laboratory is now a "National Facility on Low-temperature Thermochronology (Fission Track Dating)".

It is noted that the NW-Himalaya is climatically wet region and receives uniform precipitation except the Suru-Doda valleys in the arid regions of Zanskar, Jammu and Kashmir. Suru-Doda, Chenab-Bhot and Sutlej valleys are characterized by dome/window structures such as Suru dome, Kishtwar and Larji-Kulu-Rampur windows respectively.

Thermochronological studies in the NW-Himalaya suggest that exhumation of the HHC has been rapid (>2 mm a^{-1}) and relatively similar along strike since ~4 Ma (Patel *et al*., 2011a and references therein), as most of the Apatite FT (AFT) ages in the HHC are <5 Ma. The youngest AFT ages are found within the core of the dome and window structures, while ages becoming older away from these structures. One important point to observe here is that the Suru-Doda valleys are located in a zone of dry climate with minimum precipitation-controlled erosion. Similar pattern of age distribution is observed across the Kishtwar and Larji-Kuku-Rampur windows. These clearly indicate that amplification of dome has influenced the exhumation pattern, a conclusion derived earlier by Jain *et al*. (2000).

Recent exhumation studies along Dhauliganga valley revealed that this region has behaved uniformly since the Pliocene (Patel and Carter, 2009) and no differential movement occurred on either side of the Vaikrita Thrust. Studies along the Darma and Kaliganga valleys in Kumaon (Patel *et al*., 2007 and 2011a) and from Goriganga valley (Patel and Carter, 2009) show thrust sense of movements along the VT and MCT/Munsiari Thrust (MT) with distinct groups of ages on either side of these thrusts in the Kumaon Himalaya.

Detrital-zircon fission-track (FT) thermochronology has been attempted for the first time in this laboratory from the early Cenozoic Sub-Himalayan foreland basin in NW-Himalaya of Simla Hills (Jain *et al*., 2009).

In the Lesser Himalayan Crystalline (LHC), exhumation of the Chiplakot Crystalline Belt (CCB), located to the south of the Main Central Thrust (MCT)/ Munsiari Thrust (MT) in Kumaon suggest a complex erosional and denudation history within the upper 3-4 km of crust. The FT ages indicate that the CCB was thrust into place earlier than the Middle Miocene, i.e. at the time of development of the MCT. Since then, these rocks have remained within the upper 3 km of crust and were undergoing moderate to slow erosion and exhumation (Patel *et al*., 2007).

Apatite and Zircon Fission Track (AFT and ZFT) data from western Arunachal Himalaya of Kameng region across the Higher Himalayan Crystallines (HHC) (AFT: 1.4±0.2 to 2.9±0.3 Ma and ZFT: 4.5±0.5 and 8.9±1.3 Ma) are very similar to the NW-Himalaya (Patel *et al*., 2010). FT ages from Lesser Himalayan Sequence (LHS) (AFT: 5.6±0.6 and 12.4±1.3 Ma and ZFT: 10.9±0.6 and 14.1±1.1 Ma) are older than the HHC. In this region, fast exhumation has been observed in the HHC since ~2 Ma, despite its location in rain shadow zone of the Shillong Plateau. The southern part of this zone, i.e. the LHS experienced an order of magnitude slower exhumation rates during the same time. Major temporal variations in exhumation between Bhutan and the area studied in western Arunachal Himalaya exist and are sensitive to tectonic variation.

Further southeast in the Subansiri River catchment area, AFT ages range from 2.1±0.3 to 12.2±1.2 Ma with youngest samples coming from the Lesser Himalayan window exposed below the HMB (Pebam *et al*., 2008). In the northern parts, the MCT hangingwall samples have young ages of 2.2±0.3 and 3.5±0.3 Ma. In the south, the Daporijo Gneiss (DG) yielded the AFT age of 5.2±0.6 Ma in the immediate vicinity, while the ages become as old as 12.2±1.2 Ma down south. These ages suggest variable cooling rates across the lithounits of the Eastern Himalaya during late Miocene. High temperature thermochronology has been constrained by Rb-Sr muscovite and biotite mineral ages, which are 24.9±0.02, 22.7±0.02 and 20.4±0.02 Ma from the the LH gneiss, DG and HHC, respectively (muscovite), while their biotite ages range from 9.2 to 18.7 Ma. Youngest biotite ages of 9.2±0.02 and 9.5±0.02 Ma are from the HHC.

9. Paleoseismology

Seismicity of the Himalaya is of inter-plate type and related to ongoing collision between the Indian and Tibetan Plates that has resulted in five major earthquakes along the Himalaya during the past 110 years: (i) the 1897 M_w 8.1 Assam, (ii) the 1905 Kangra (M_w ~7.8), (iii) the 1934 Bihar-

Nepal (M_w=8.1), (iv) the 1950 Assam (M_w ~8.4) earthquakes and (v) the recent M 7.6 earthquake of October 8, 2005 (Fig. 2).

Investigations of active tectonic character of the Himalayan Frontal Thrust (HFT) and its palaeoseismology have been the main emphasis along entire length of the Himalaya (Malik *et al*., 2007, 2008, 2010a, b; Jayangondaperumal and Thakur, 2008; Jayangondaperumal *et al*. 2008; Misra *et al*., 2011; Philip *et al*., 2011), and NE Himalaya including Arunachal Pradesh and Assam (Mukul *et al*., 2007; Reddy *et al*., 2009; Kumar *et al*., 2010; Jayangondaperumal *et al*., 2011; Rajendran and Rajendran, 2011). Till date, ~15 trenches have been excavated to provide scattered data on paleoseismic events along the Himalayan front.

Farthest liquefaction features associated with the 2005 Kashmir earthquake were observed by Malik *et al*. (2007) in Jammu region, where Jayangondaperumal and Thakur (2008) found additional evidences of two historical earthquakes near Simbal Camp in Jammu Range front. Jayangondaperumal *et al*. (2008) have mapped the 2005 Kashmir earthquake sand blows, and reported two palaeoearthquakes events (Event-I and II) by trenching liquefaction features related to 2005 Kashmir earthquake. Event-I occurred during AD ~1100, while Event-II was assigned an age of 2000 yrs BP.

Trenching across the HFT near the Chandigarh segment revealed the occurrence of major earthquake around 1300-1400 AD (Malik *et al*., 2008). Further work on active fault in meizoseismal zone of the 1905 Kangra

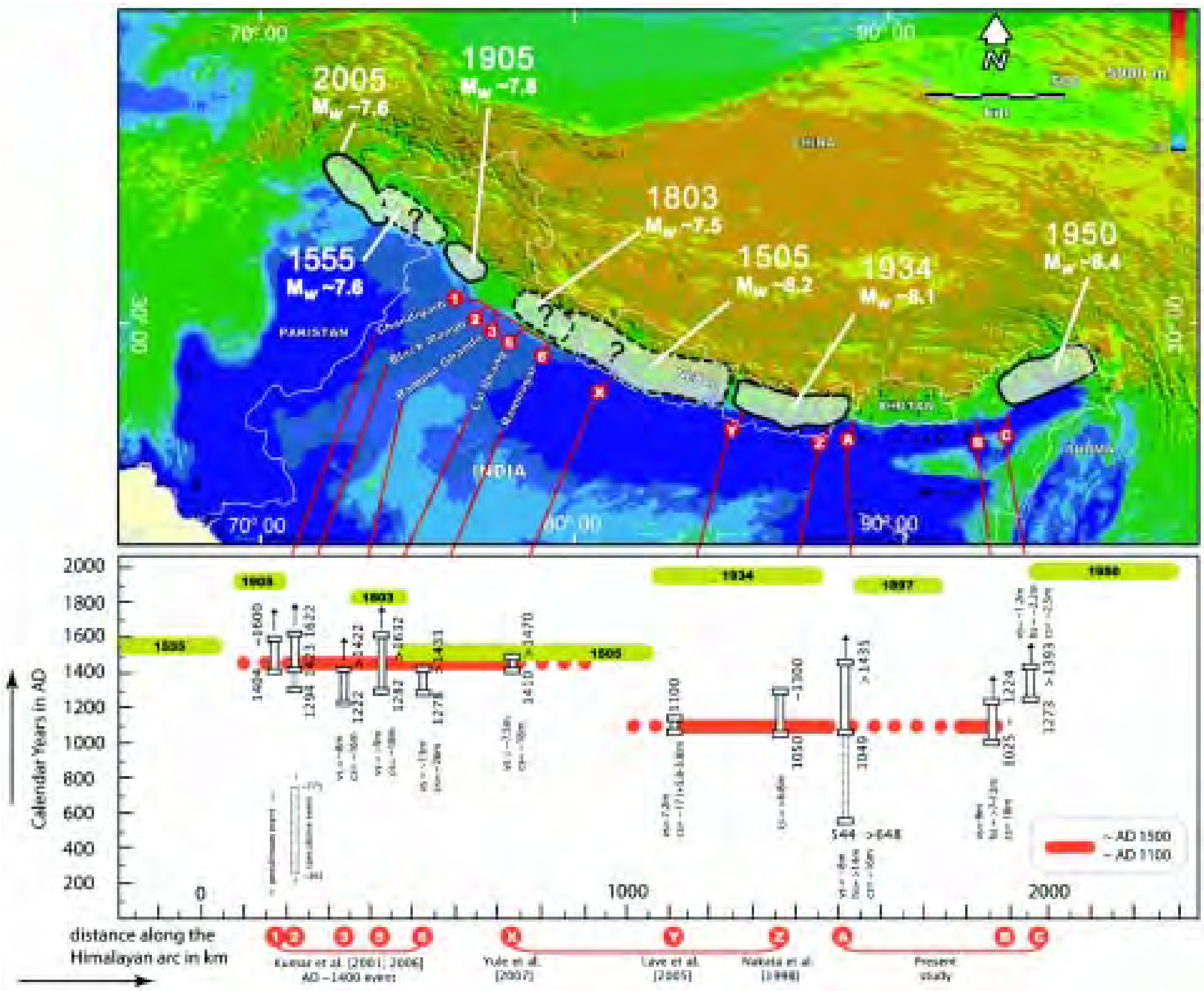

Fig. 2: Summary of Paleoseismic investigations along the Himalayan Front with locations (top) and slip, vertical separation chronology of observed ruptures in the multiples trenches are shown in bottom (Kumar *et al*., 2010).

Earthquake (Mw 7.8) along the HFT at Hajipur indicated the presence of two parallel NNW-SSE striking active faults as imbrications of the HFT, which have displaced young flood plain of the Beas River. Historical earthquake events 2600-8000 yr B.P. (Before Present), around 400 yr B.P. and before 300 yr B.P (1500-1600 A.D.) were inferred from the trenched fault zone. They also inferred a slip rate of 7.6±1.7 mm/yr, shortening rate 6.9±1.4 mm/yr and recurrence interval of 1160±250 yr.

In the Pinjaur Dun along the Nalagarh Thrust at Nalagarh, Philip *et al*. (2011) trenched across this thrust and dated the deformed and un-deformed sediments from trenched fault zone by the OSL method. They found evidences of late Pleistocene earthquake and suggested immediate attention in paleoseismic study in this fast developing mountainous industrial belt.

In the southeastern Kumaun Himalaya, Mishra *et al*. (2011) documented diversified soft-sediment liquefaction deformation structures within magnetostratigraphically-dated (4-5 Ma) Siwaliks in nearest vicinity of the Main Boundary Thrust (MBT). These structures show progressive increase in abundance and complexity towards the thrust, and are evidences for paleoseismicity and reactivation event on the Main Boundary Thrust.

Multiple trenches were excavated covering ~1500 km of the HFT in the NW Himalaya for paleoseismologal studies indicating that most recent movements occurred between 1200 AD and 1700 AD (Fig. 2; Kumar *et al*., 2006). Random radiocarbon ages from these trenches do not allow fixing the upper bound on particular earthquake, but they putatively correlated with the 1505 AD event. The large co-seismic displacement (~9-10 m) and length of rupture are comparable to typical mega-thrust events along the subduction zones with a recurrence interval about 1000-3000 years for this kind event.

Using direct dating of fault-zone gouge and strath terrace deposits in Darjeeling Hills, Mukul *et al*. (2007) concluded that (i) present mountain front in the Darjeeling sub-Himalaya was emplaced by ca. 40 ka, and (ii) out-of-sequence deformation on surface-breaking faults north of the MFT began ca. 20 ka and has probably continued since.

In the NE Himalaya, field evidences of liquefaction were searched for past earthquakes in meiszoseismal region of the Great Assam 1950 earthquake by Reddy *et al*. (2009), who documented the 1548 AD and 1697 AD earthquakes from this region.

Multiple trenches for paleoseismic investigations were studied in meizoseismal areas of the 1934 Bihar-Nepal and 1950 Assam earthquakes for nearly 500 km along the HFT (Kumar *et al*., 2010). At two sites, age of surface rupture, though broad, correlated with the 1100 AD surface rupture. At Harmutty Tea Garden trench site, age of ruptures was younger than 1270 AD, with speculation of events within meiszoseismal zone of the 1950 Assam earthquake.

Evidences for great surface rupturing earthquake were observed at Pasighat along the HFT in Arunachal (Jayangondaperumal *et al*., 2011), where a scarp was primarily formed in a single large earthquake post-10112 cal yr BP (Before Present), followed by an earthquake event post-2009 cal yr BP. Withstanding the uncertainty in timing of earthquakes, they documented occurrence of large scarp-forming earthquakes. Possibility of the tilting of sediments that occurred post-2009 cal yr B.P. as the result of the historical 1950 Assam earthquake cannot be overruled.

Liquefaction features indicating paleosesimic events were also observed in the Lohit Valley in extreme northeast by Rajendran and Rajendran (2011) to indicate at least two events. Further, they presented the evidence for last major earthquake in the central Himalaya during AD 1119-1292 not in the 1505 AD, as suggested previously, and thus Central Himalayan gap of plate boundary events is real.

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