UPPER CRUSTAL STRUCTURE AND SHORTENING IN THE HIMALAYAN THRUST BELT IN KUMAUN, NORTHWESTINDIA

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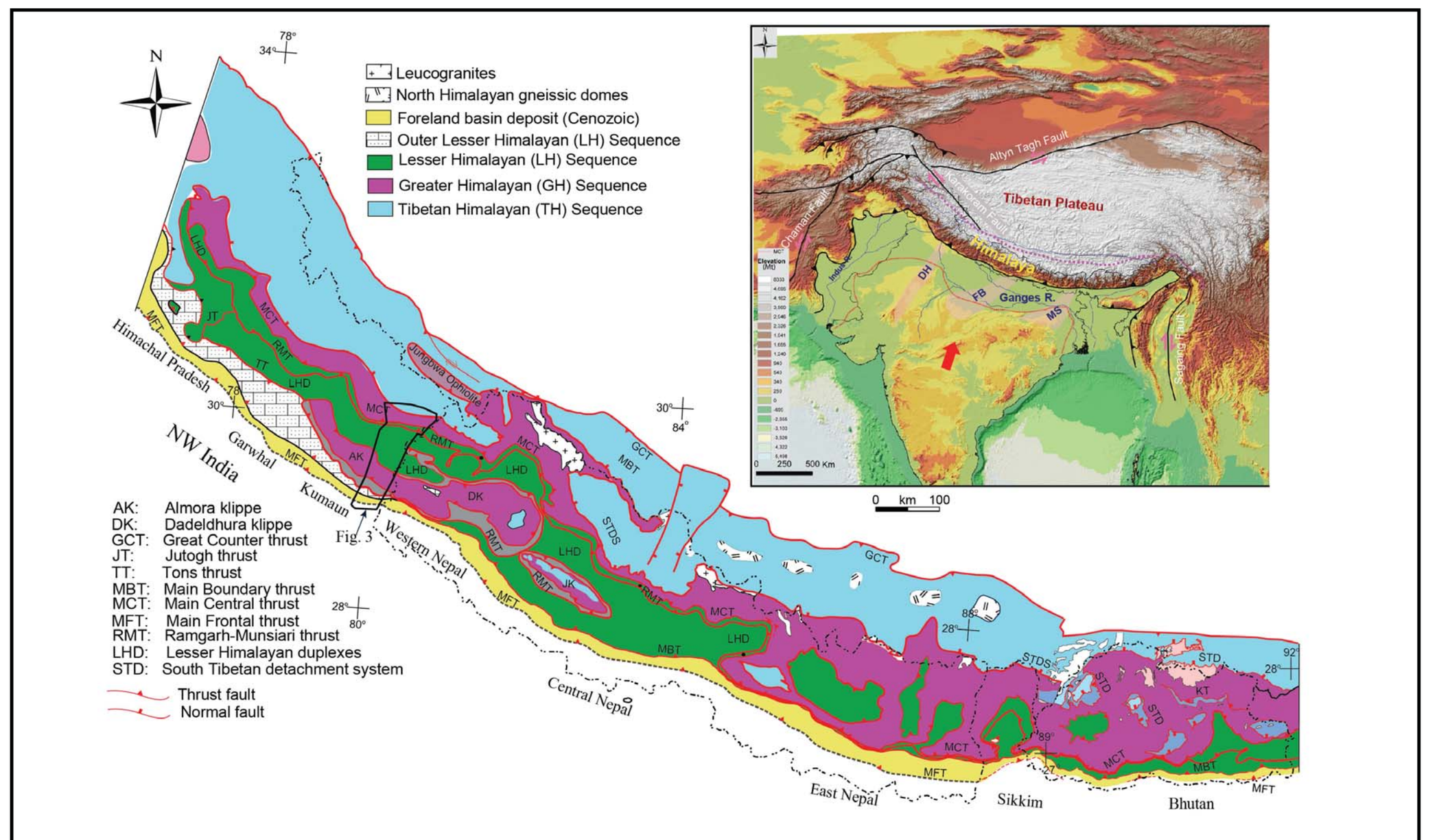
Abstract:

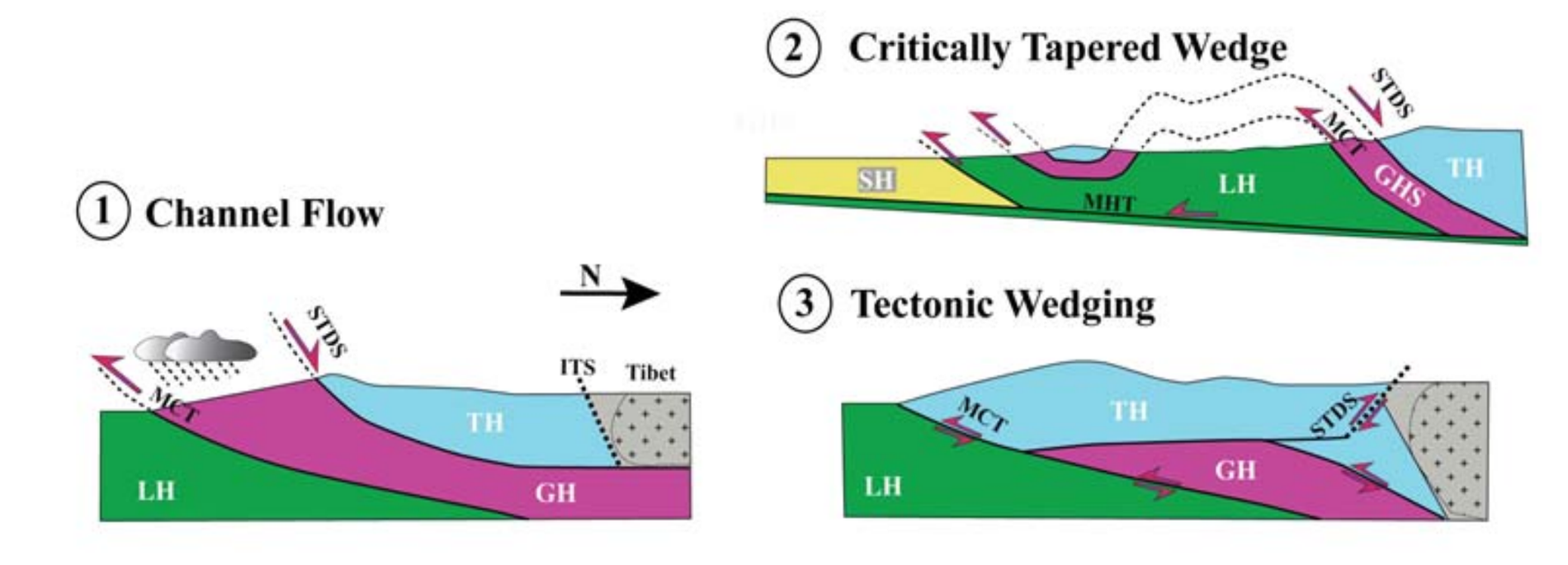
Existing structural models of the Himalayan thrust belt in Kumaun, northwest India,are based on outdated Himalayan tectonostratigraphy. We reassess the tectonostratigraphy of Kumaun based on new and existing U-Pb zircon and whole rock Nd data, and present a new structural model and kinematic history for this part of the thrust belt. The Ramgarh, Berinag, Chiplakot and Munsiari Formations are part of the same, once continuous stratigraphic unit, which was dissected and turned into the Ramgarh-Munsiari thrust sheet and other thrust sheets in the Lesser Himalayan duplex. They are all Paleoproterozoic Lesser Himalayan rocks, contain ca. 1850 Ma granite of continental arc affinity, and have whole rock εNd values from -20 to -25.Our new structural model shows a hinterland dipping duplex system that accommodated 541-575 km or 79-80% of shortening between Main Frontal thrust and South Tibetan Detachment system with each system accommodating the following minimum amount of shortening: the Main Central thrust-128 to 163 km, Ramgarh-Munsiari thrust - 112 km, Lesser Himalayan duplex - 270 km, Main Boundary thrust -8 km, Subhimalayan thrust system -~22 km. By adding in shortening from the Tethyan Himalaya, we estimate a total minimum shortening of 674-751 km. The roof thrust, which is the Ramgarh-Munsiari thrust, and the Lesser Himalayan duplex are breached by erosion separating the Paleoproterozoic Lesser Himalayan rocks of the Ramgarh-Munsiari thrust into isolated klippen. This thrust carries Lesser Himalayan rocks 120 km southward from the footwall of the Main Central thrust, folded underneath the Almora klippe, to the hanging wall of the Main Boundary thrust. The Ramgarh-Munsiari thrust structurally underlies the Main Central thrust and together forms a coupled roof thrusts for the Lesser Himalayan duplex best displayed to the north and south of the Almora klippe. The reconstruction demonstrates that propagation of the thrust belt occurred from north to south with minor out of sequence faulting, supporting an in-sequence model for growth of the Himalayan thrust belt.

Purpose of this study:

Upper crustal shortening variations along the Himalayan arc provide data for testing predictions of how convergence is accommodated throughout the Himalaya, and the estimate of material available to construct the Tibetan Plateau (DeCelles et al., 2002). Amount of upper crustal shortening is equivalent to the length of subducted lower crust and mantle lithosphere of Indian Plate (Robinson et al., 2006), and the shortening magnitude may control the width of the Tibetan Plateau (DeCelles et al., 2002).This study reassesses the structural architecture and shortening estimates of the Himalayan FTB in Kumaun, northwest India with new structural data, new and available geochronology that refines the stratigraphy of this area (Célérier et al., 2009; McKenzie et al., 2011; Mandal et al., 2014a and b), and an existing geophysical data (Caldwell et al., 2013). Kumaun is a critical area to study the kinematic evolution and estimate maximum shortening because it is located in the central part of the Himalayan arc and may have accommodated the maximum amount of shortening recorded in the Himalaya. The geochronologic and isotopic data determine the stratigraphic architecture, solve first order stratigraphic issues, and evaluate existing cross- sections in northwest India (Srivastava and Mitra, 1994; Célérier et al., 2009). A line-length balanced cross section and palinpastic reconstruction provides a viable model for the structural geometry, minimum slip along faults and a new estimation of minimum shortening in Kumaun and correlation with other parts of the Himalaya. With the aid of revised chronostratigraphy, the new structural interpretation of Kumaun, NW India, provides a foundation to test which growth models better fits in this part of the Himalaya.



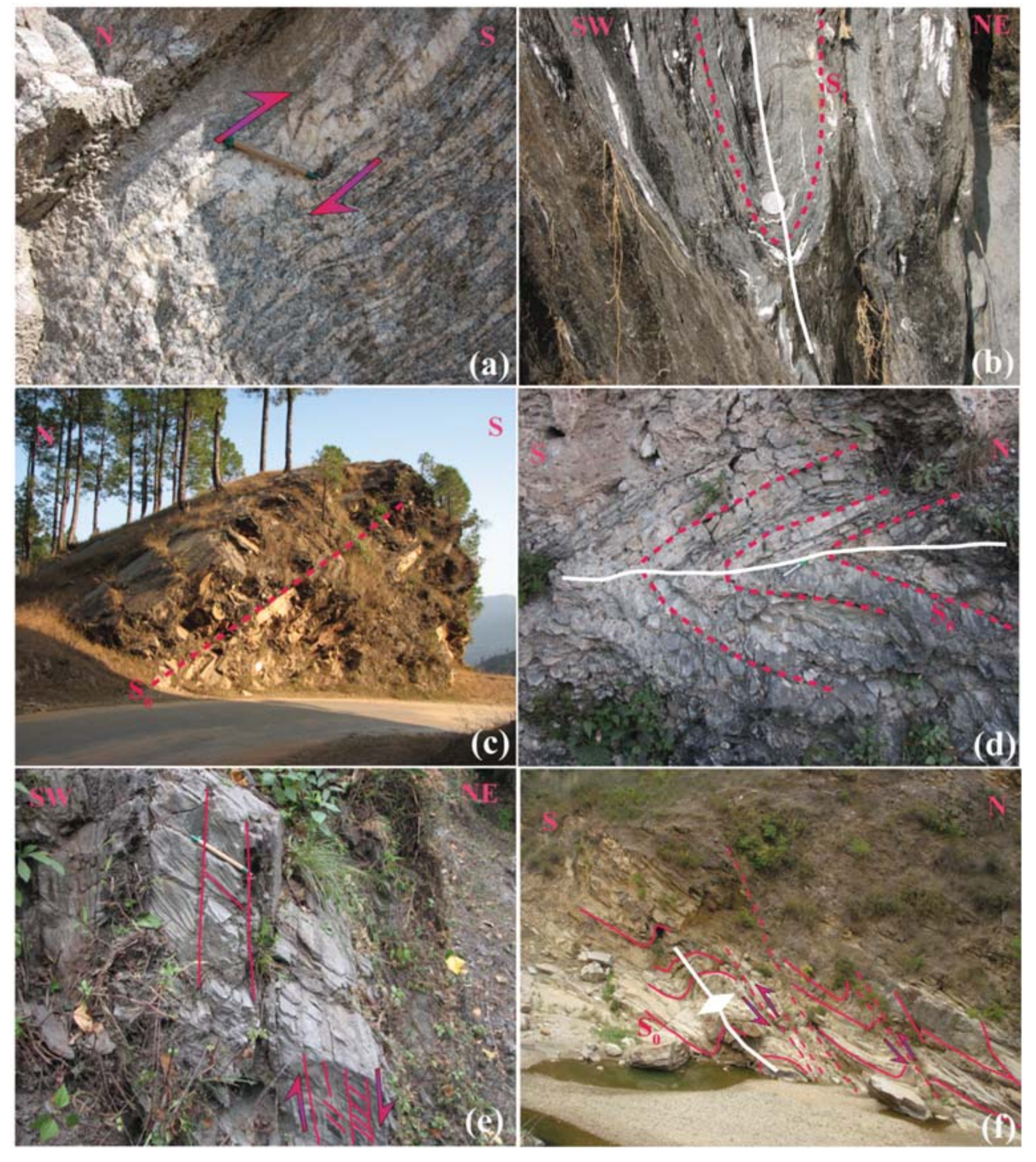
Digital elevation model (using ASTER Global digital elevation dataset) of India and adjoining areas. The Himalayan FTB is south of the Tibetan Plateau stretches along the arc for ~2,500 km. The red dash line delineates the present day northern limit of exposed the Indian craton, and pale pink areas represent basement ridges underneath the Indo-Gangetic plain (Godin and Harris, 2014). DH: Delhi-Haridwar Ridge; FB: Faridabad Ridge; MS: MungerSaharsa Ridge. (b) Generalized tectonostratigraphic map of the Himalaya (modified from Robinson and Pearson, 2013). Study area is shown in black polygon



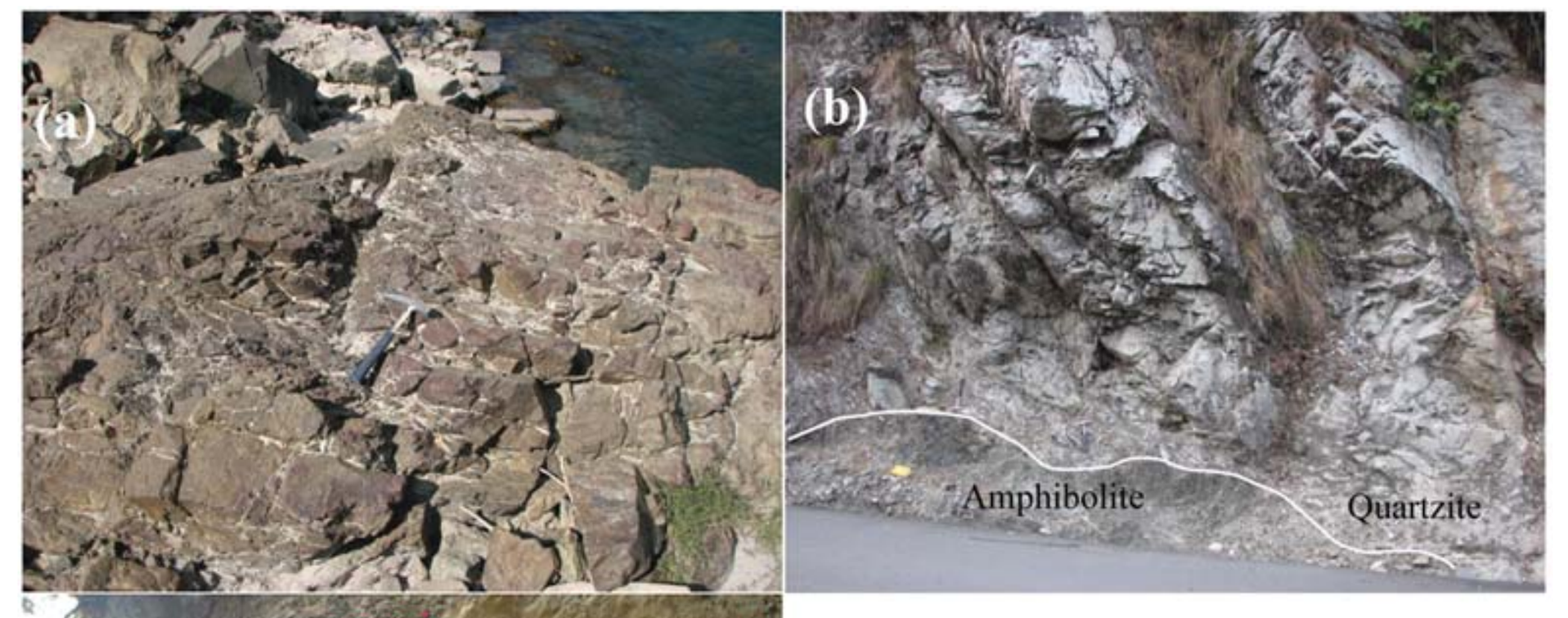
Tectonic models of the Himalaya (modified from Webb et al., 2011) showing emplacement of the GH rock.1. Channel flow model (focused denudation) (Nelson et al., 1996; Beaumont et al., 2001); 2. Critically tapered wedge model (DeCelles et al., 2001; Gehrels et al., 2003); 3. Tectonic wedging model (Yin, 2006; Webb et al., 2007).Abbreviations: MBT - Main Boundary thrust; MCT - Main Central thrust; STDS - South Tibetan Detachment system; ITS- Indus-Tsangpo suture; SH-Subhimalaya; LH-Lesser Himalaya; GH-Greater Himalaya; TH-TethyanHimalaya.

Generalized stratigraphy of Kumaun, India with thickness of various units organized from north to south along the cross section line.

	Unit name	Lithology	Thickness (m)
Tethyan Himalaya	Martoli Formation/Budhi Schist (Haimanta equi.) — STDS	Unemetamorphosed Cambrian greywacke, sandstone, and shale (Valdiya et al., 1999)	
Greater Himalaya	Badrinath/Pindari Fm, Pandukeshwar Fm, Joshimath Fm (Vaikrita Gp.) — MCT	Sillimanite-bearing augen gneiss; Micaceous-quartzite; Kyanite-bearing gneiss (Spencer et al., 2012)	10500
Lesser Himalaya	Munsiari Fm — Munsiari thrust	Garnet mica schist, calc silicatem quartzite, and granite-gneiss	~7000
	Berinag Fm — Berinag thrust	Sericitic quartzite, schistose quartzite, garnet-schist, granite gneiss, and mafic sills	900
	Mandhali Fm, Gangolighat Fm, Rautgara Fm (Damtha Gp) — north Almora thrust	Green to black carboncaeous phyllite, slate and minor limestone; Stromatolite bearing cherty dolomite and dolomitic limestone; Thick to thin-bedded muddy quartzite, brown and gray phyllite, and mafic sills	3000; 2250
Greater Himalaya	Champwat/Almora Granitoids, Saryu-Gmulikhet Fm (Almora Gp) — south Almora thrust	Cambro-Ordovician granite; Green phyllite, mica schist, carbonaceous schist, quartzite	~1000
Lesser Himalaya	Nathuakhan Fm, Debguru porphyroid (Ramgarh Gp) — Ramgarh thrust	Green phyllite, thick to thin bedded muddy quartzite; Granite-granodiorite augen gneiss	500
	Krol Fm	Black- red shale, sandstone, cherty limestone	640
	Blaini Fm	Grayish-black shale and sandstone, pink dolomite	660
	Bhowali Quartzite, Bhimtal metavolcanics (Nagthat Fm)	Clean, coarse- to medium quartzite, mafic sills	1500
	Chandpur Fm	Muddy quartzite, gray- to brown phyllite, and slate	2050
	Amritpur granite — MBT	Granite-granodiorite augen gneiss	
Subhimalaya	Upper member (Siwalik Gp.)	A coarsening up sequence of mudstone, sandstone and conglomerate	~2300
	Middle member (Siwalik Gp.)		~2300
	Lower member (Siwalik Gp.)		1800
	Lugadgad (Dumri/Kasauli equi.) — MFT	Green-sandstone, minor mudstone	300



(a) Mylonitic granite gneiss from MCT hanging wall. Small scale asymmetric fold within the thicker (pink) layer shows the shear sense. 15 cm pen for scale. (b) Isoclinal fold parallel to the schistosity from the Munsiari Formation, near sample location SM11-039. 2.5 cm coin for scale (c) Regional dipping panel of bedded Berinag Formation quartzite, 5 m wide road for scale. (d) Folded bedded Deoban Formation dolomite showing kink style geometry that is used to model the structural geometry (Fig. 10a). (e) Brittle fractured Mandhali Formation phyllite with S surfaces, 15 cm pen for scale (f) Asymmetrical fold, from the southern margin of the Almoraklippe, with south vergent folds indicates top-to-the-south shear sense. Looking down into a river bed.



(a) Fault cataclasite from the north of the Almora klippe (Saryu River), which places Ramgarh Gp. of rocks against Rautgara Formation, 30 cm hammer for scale. (b) Intensely brittle fractured quartzite from the emplacement of the MBT, 30 cm hammer for scale. (c) South vergent asymmetrical fold (outline fold with black line and put directions on figure from the MFT hanging wall, 30 cm hammer for scale.

Locality information for the samples used in U-Pb zircon geochronology and whole rock Nd analyses. Abbreviations: DZ: detrital zircon; IZ: igneous zircon; Nd: Neodymium

Sample	Coordinates		Unit	Lithology
	°N (dd.ddddd)	°E (dd.ddddd)		
SM11-032 (DZ)	29.798761	80.415655	Mandhali Fm.	Pebbly quartzite
SM11-045 (IZ)	30.029030	80.578234	ChiplakotKlippe	Augen gneiss
SM111-48 (IZ)	30.130862	80.245917	MunsiariFm.	Granite-granodiorite augen gneiss
SM11-58 (DZ)	29.458224	79.583645	Nathuakhan Fm.	Gray quartzite with mud partings
SM11-59 (IZ)	29.436516	79.562599	Debguru Fm.	Granite-granodiorite augen gneiss
SM11-035 (Nd)	30.068653	80.606967	VaikritaGp. (GH)	Pelitic schist
SM11-039 (Nd)	30.062817	80.587733	Munsiari Fm.	Pelitic schist
SM11-046 (Nd)	30.166358	80.250152	VaikritaGp. (GH)	Pelitic schist/schistose gneiss
SM11-049 (Nd)	30.107226	80.243676	Munsiari Fm.	Schistose gneiss

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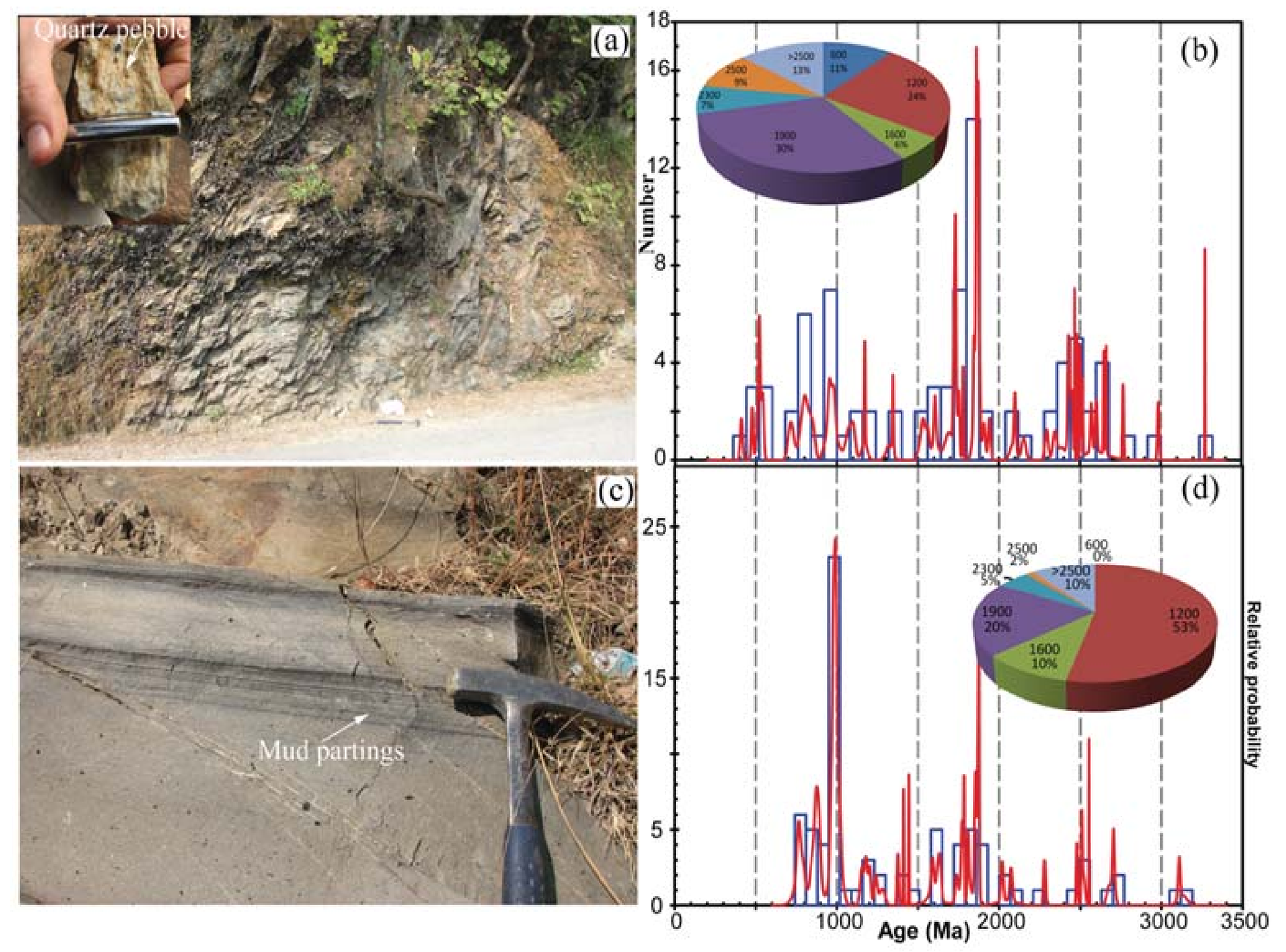
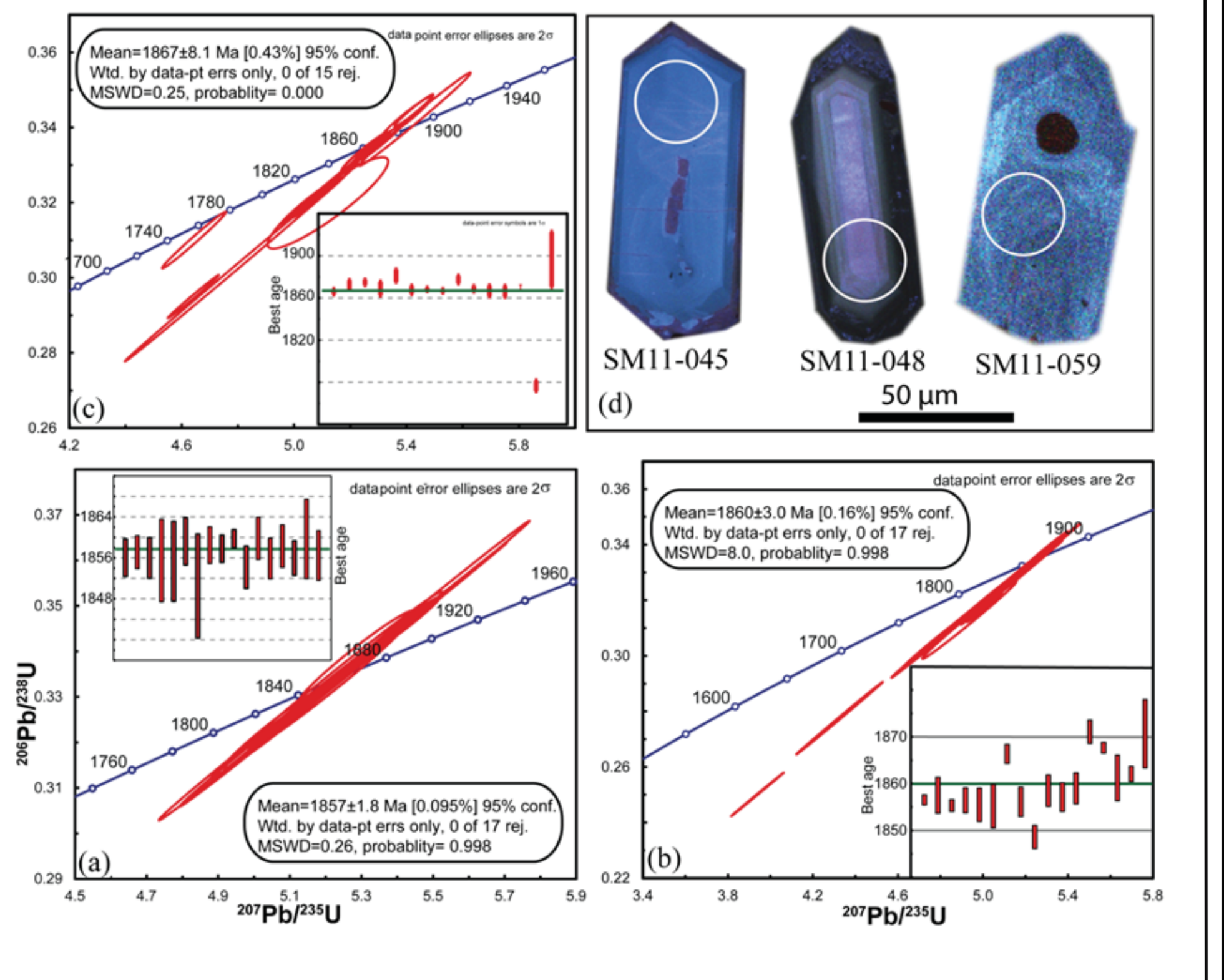
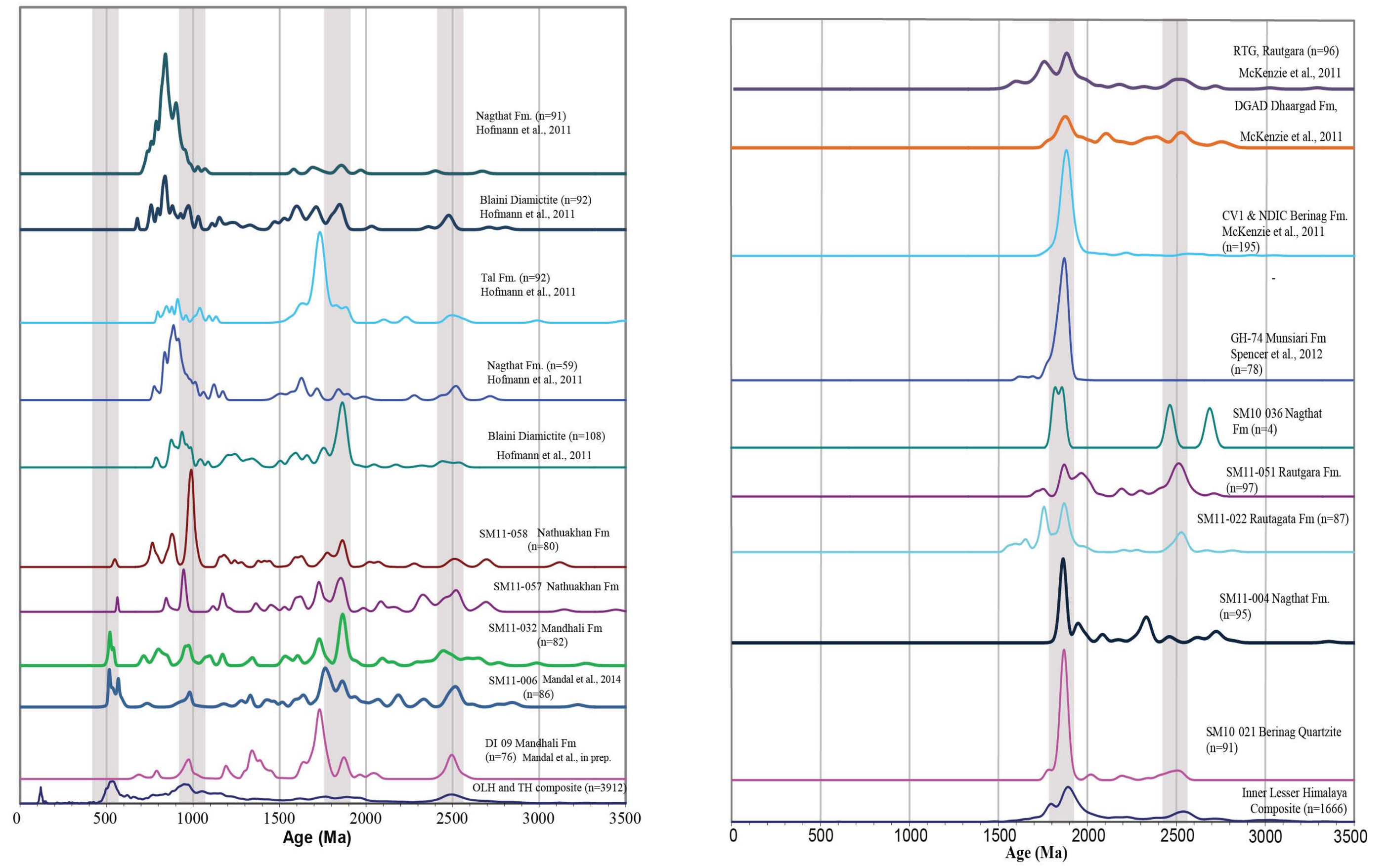


(a) Photographs of SM11-032, a pebbly quartzite unit in the inset, and a photograph of the outcrop with a 30 cm hammer laying on the road for scale,5 cm long pen for scale in the inset; (b) SM11-032 detrital zircon age spectra with pie chart (inset), showing distribution of age populations; (c) Photographs of SM11-058, a muddy quartzite unit with rock hammer for scale, and (d) SM11-058 detrital zircon age spectra with the pie chart (inset).



U-Pb Concordia plots and respective weighted average (insets) of igneous rock samples: (a) SM11-045, from the Chiplakotklippe, (b) SM11-048, from the Munsiari Formation, (c) SM11-059, from the Debguru porphyry, and (d) representative cathodoluminescence images of sample SM11-045, SM11-048, and SM11-059



Composite U-Pb detrital zircon spectra of inner and outer LH units from Kumaun and Garhwal, NW India

Whole rock Nd isotopic analysis results

Sample	Sm (ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	± (abs stderr)	$\varepsilon_{Nd(0)}$	±
SM11-035	5.96	31.9	0.1129	0.511805	0.000005	-16.0	0.10
SM11-039	6.48	32.8	0.1193	0.511454	0.000007	-22.9	0.14
SM11-046	5.09	25.4	0.1213	0.511854	0.000006	-15.1	0.12
SM11-049	8.29	50.5	0.0992	0.511320	0.000006	-25.5	0.12

Conclusions

We present a new mapping and a structural interpretation based on our revised chronostratigraphy in Kumaun, northwest India and finds that:

1) The Ramgarh, Berinag,Chiplakot and Munsiari Formations, including the augen gneiss, are part of a once continuous Paleoproterozoic rock unitand translated toward the south on the Ramgarh-Munsiari thrust. Growth of the underlying Lesser Himalayan duplex deformed the thrust sheet and erosion isolated the unit into thrust sheets and synformal klippen.

2) The Almora thrust sheet is composed of Greater Himalayan rock and the RamgarhMunsiari thrust sheet is composed of Paleoproterozoic inner Lesser Himalayan rocks. Greater Himalayan rocks have U-Pb ages of ca. 800 Ma and epsilon Neodymium values of ~-11, while the Paleoproterozoic inner Lesser Himalayan rocks have U-Pb ages of ca. 1800 Ma and epsilon Neodymium values of ~-24.

3) The Almora thrust sheet exhibits a flat-on-flat relationship with the underlying Ramgarh-Munsiari thrust sheet, and the Ramgarh-Munsiari thrust sheet exhibits a flat-on-flat relationship with underlying Lesser Himalayan rocks that subsequently form the Lesser Himalayan duplex. Growth of the Lesser Himalayan duplex folded the overlying unit to form the Almoraklippe and conformably folded the Ramgarh-Munsiari thrust sheet that crops out to the north and south of Almora klippe

4) The FTB in Kumaunis a forward propagating thrust system, typical of thin-skinned style tectonics, and there no evidence of basement involved tectonic styles.

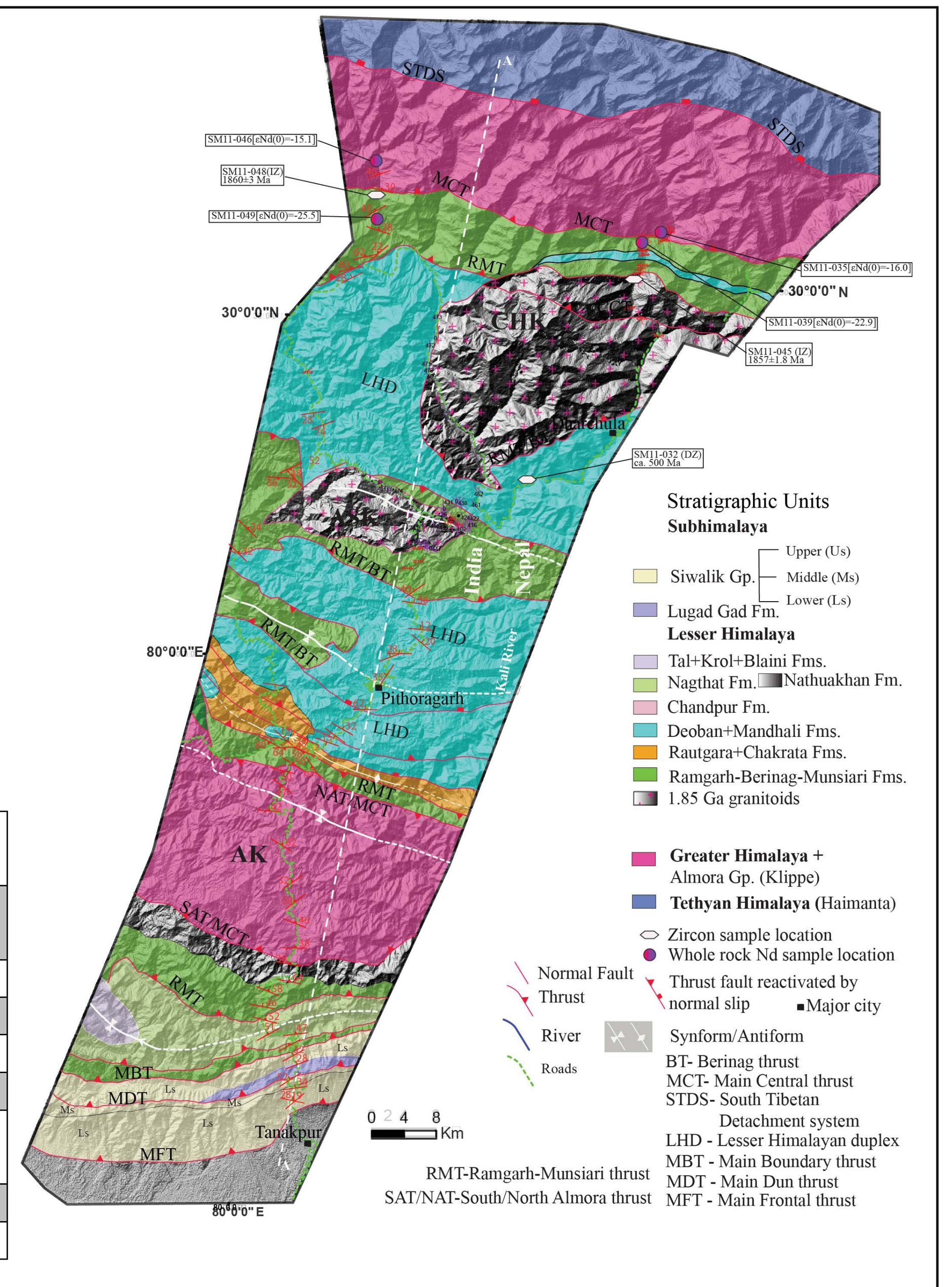
5) The Lesser Himalayan duplex has 270 km of minimum shortening. We estimate a total minimum shortening from the Main Frontal thrust to the South Tibetan Detachment system of541-575 km, and by adding shortening in the Tethyan Himalaya emerge with a total minimum shortening between 674-751 km in Kumaun.

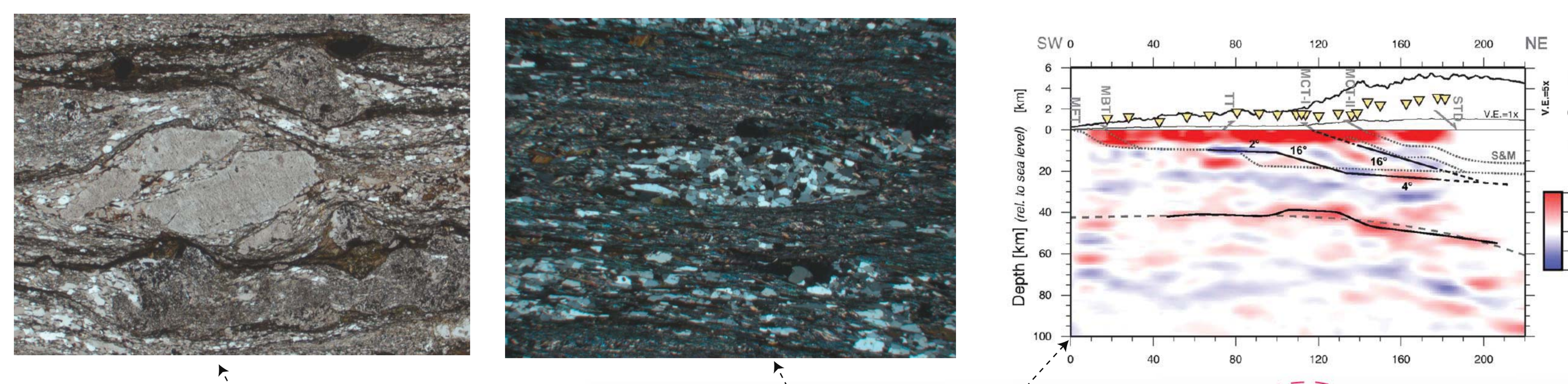
Estimation of shortening along the cross section line

Structures	L_f	L_0	Shortening(km)	Shortening (%)
Main Frontal thrust	8.3	15.8	7.5	47.2
Main Dun thrust	4.8	19.7	14.9	75.8
Main Boundary thrust	1.5	9.0	7.6	83.3
Ramgarh-Munsiari thrust	51.7	163.9	112.2	68.5
Lesser Himalayan Duplex	59.7	329.8	270.1	81.9
**Main Central thrust maximum	15.2	178.4	163.2	91.5
*Main Central thrust minimum	15.9	143.5	128.4	89.4
Total Minimum Shortening	141.2	681.7	540.6	79.3
Total Maximum Shortening	141.2	716.6	575.4	80.3
Shortening in the TH	-	-	133-176	-
Total shortening	-	-	674-751	-

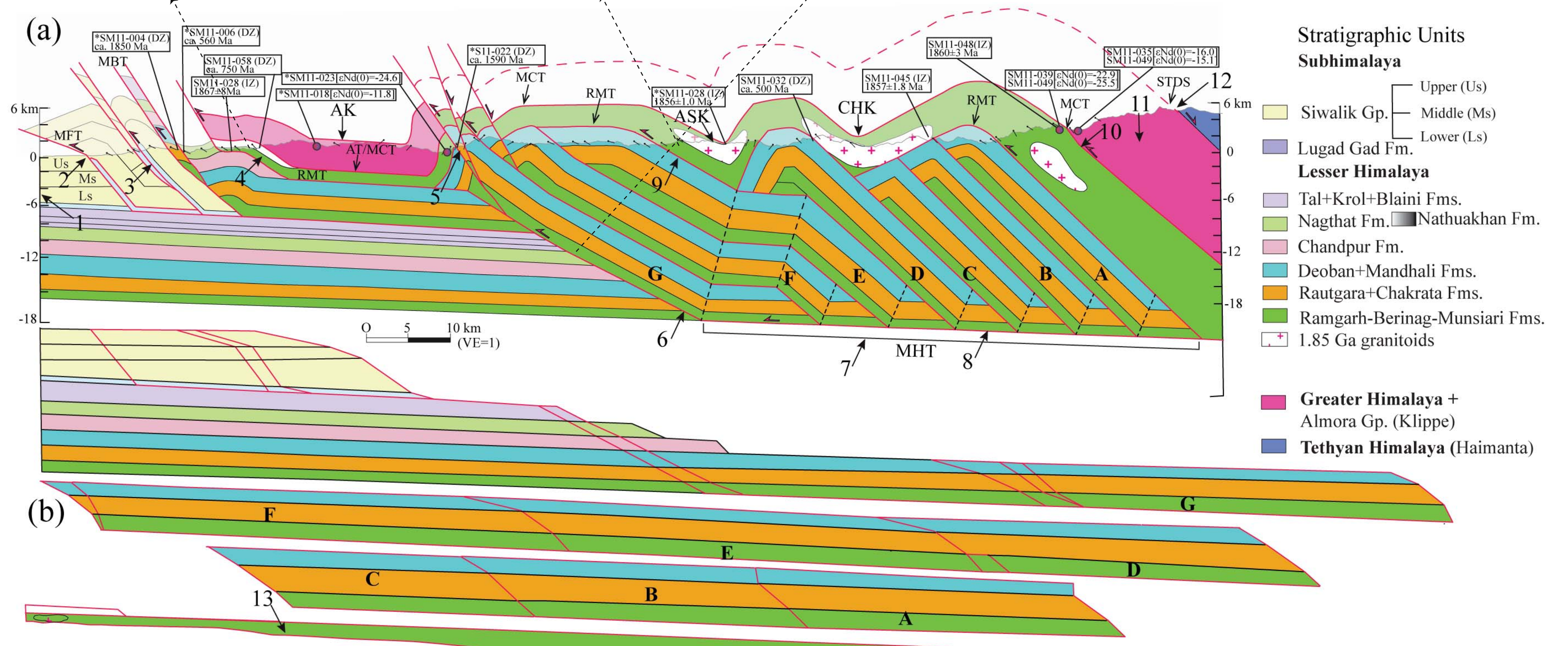
Compilation of shortening estimates along Himalaya

Location	SH+LH in km (in %)	SH+LH+GH in km (in %)	References
Kumaun-Garhwal, India	161 (65%)	354-421 (76-79%)	Srivastava and Mitra (1994)
Western Nepal	393 (77%)	691-780 (79-84%)	Robinson et al. (2006)
Sikkim	253 (76%)	249 (82%)	Mitra et al. (2010)
Bhutan	164-267 (52-66%)	138-209 (70-75%)	Long et al. (2011)
Central Nepal	284 (53%)	400 (75%)	Khanal et al. (2013)
Himachal Pradesh, India	-	518 (72%)	Webb (2013)
Pakistan	-	470 (64%)	Coward and Butler (1985)
Kumaun, India	412(76%)	540-575(79-80%)	This Study





Location and geometry of the mid crustal ramp derived from Caldwell et al. (2013) based on CCP receiver functions.



14. Ca. 1850 Ma associated granitoids occurs in various locations along the RMT.
12. Location of the STDS is adopted from Patel et al. (2007, 2011). 13. The RMT cut up-section to the south.
11. Treating GH rocks as a slab of rock carried by the MCT, thus, provide only minimum shortening.
10. The MCT proximal footwall and haningwall rocks are deformed in ductile style.
8. The average dip of the MHT ranges between 3⁰-4⁰(Caldwell et al., 2013). 9. The geometry of the southerlimb of the Askot klippe is controlled by the mid-crustal ramp geometry.
7. The location of LHD matches with the microseismicity data (Feldl, 2005), which shows a nw-se linear trend in western Nepal and Kumaun.
6. Geometry and upper crustal ramp location of the MHT is interpolated from crustal scale receiver function geophysical image of Garhwal (Caldwell et al., 2013).
5. Out of sequence faulting, north of the Almora klippe is based on field observation (Fig. 9a), and presnce of ca. 1600 Ma Rautgara Quartzite (Mandal et al., 2014a)
4. Minimum southward extent of the RMT, south of the Almora klippe, is based on 1.85 Ga granitoids and associated metasediments.
3. Presence of intra-formation thrust within Lugad Gad formation is interpreted due to structural repitition.
2. The location of the MFT is based on break in surface slope beween the Indo-Gangetic plate to the south and Siwalik Hills to the north in DEM model (Fig. 3)
1. The thickness of the Siwalik Group in the cross section is derived by map patterns and from the Ujhani deep well data (Sastri et al., 1971), near Budaun, Uttar Pradesh India ~150 sw from the cross section line.