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Institutional Report

Research Status at Wadia Institute of Himalayan Geology (WIHG), Dehradun During 2015-2019

KALACHAND SAIN*, RAJESH SHARMA, SUSHIL KUMAR, D P DOBHAL, VIKRAM GUPTA, PRADEEP SRIVASTAVA, R JAYANGONDAPERUMAL and KAPESA LOKHO
Wadia Institute of Himalayan Geology, 33, General Mahadeo Singh Road, Dehradun 248 001, India

Fig. 1: The campus of Wadia Institute of Himalayan Geology at Dehradun

The Institute

The Wadia Institute of Himalayan Geology (WIHG) at Dehradun is an autonomous institution of the Department of Science & Technology (DST), GoI, which came into being in 1968. It has been pursuing basic researches to unravel the orogenic processes of majestic Himalaya and to provide improved understanding on seismogenesis, geodynamic processes, climate-tectonic interactions, evolution and extinction of life, ore formation, glaciology, river system, natural hazards (landslides, floods, and earthquakes), anthropogenic impact etc. towards the well-being of population and safeguarding the properties and structures in the Himalaya and adjoining regions. The research activities to understand the mountain building processes and shed light on above topics are based on observations made by using rudiments of structural geology, petrology, paleontology, stratigraphy, sedimentology, geomorphology, different branches of geophysics, remote sensing etc.

In the backdrop of wide-ranging claims on the likely impact of climate change on Himalayan glaciers and their far-reaching consequences on the Indian economy, the DST has established the *'Centre for Glaciology'* at WIHG. The Institute has been nurturing a earthquake monitoring and precursory study system in an integrated manner by hosting '*Multi-Parametric Geophysical Observatory (MPGO)'* at Ghuttu (Tehri), Uttarakhand. This is a unique set up to perceive changes in subsurface properties that may lead to earthquake precursory

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*Author for Correspondence: E-mail: kalachandsain7@gmail.com

study in the Himalayan region. The WIHG has established as many as 54 Broad Band Seismographs and 16 Acceleragraphs spread over H.P., Uttarakhand, J&K, Punjab, Haryana and Arunachal Pradesh. Similarly, around 17 GPS instruments are installed in H.P., Uttarakhand, J&K and Ladakh. The Institute is well equipped with sophisticated analytical instruments facilities run by competent scientists and technicians. The labs are being utilized by the research scientists of Wadia as well as researchers from state and central universities and other organizations. Some important instruments available in the Institute are LA-MC-ICP-MS, Stable Isotope Mass Spectrometer, EPMA, ICP-MS, XRF, SEM, XRD, Raman Spectrometer, TL/OSL, Magnetic Susceptibility meter etc. The institute also provides consultancy services for engineering projects, drinking and groundwater surveys, natural hazards, road and rail alignments in the Himalaya and adjoining region. The campus of WIHG is shown in Fig. 1. The vision of the Institute is "**Questing for Himalayan Seismogenesis, Geodynamics, Natural Hazards, Climate Variability and Natural Resources through Geoscientific study to fulfill the Societal Needs and pursue Basic Sciences.**" The research activities of WIHG are mainly focused on the following themes:

Theme 1: Geodynamic Evolution of the Himalaya and adjoining mountains

The activities under this program deal with the deformation of crust in the context of fold and thrust belts, melt generation, metamorphism at various levels, and deep structures. It involves studies on the rate of Himalaya's uplift and related crustal shortening that is characterized by several stages of deformation on grain to outcrop scale. The deformation stages are also expressed in the form of degree and spatial pattern of metamorphism that rock sequences of the Himalaya exhibit, and thus act as a proxy record of the time and rock exhumation due to the evolution of the Himalaya. Understanding of inverted metamorphic sequences and their bearing on tectonics help in explaining the orogenic processes of the Himalaya.

Theme 2: Indian Monsoon-Tectonic Interaction and Exhumation of the Himalaya

For the Himalaya-Tibet orogenic system, there has been a long-standing debate on the inter-relation between monsoon precipitation patterns and the exhumation rate across the Himalaya. Recent studies show that tectonic deformation, climate and life interact in ways that are sometimes profound but not so obvious. The erosion of mass from the Earth's surface may determine if the tectonic deformation has taken place at a rapid space. Consequently, heavy precipitation, fast erosion and active faulting are predicted to be spatially correlated in an active orogenic belt like the Himalaya. There lies a challenge whether the continental scale changes result from the movement of Inter-Tropical Convergence Zone (ITCZ) or the focused erosion and its impact on crustal exhumation or from the deep-seated mantle-bound processes or all of these. Therefore, the institute pursues contemporary research in establishing the (i) amount and style of crustal deformation and uplift in the Himalaya using fluvial archives, (ii) reconstruction of high-resolution record of past climatic variations using peat, lakes, speleothems, ocean records, and dendrochronology, and (iii) hinterland-sink relationship through time.

Theme 3: Earthquake Precursors Studies and Geohazard Evaluation

Due to the plate movement along the Himalaya, the elastic strain energy is being built continually, the release of which results in earthquakes. The Indian part of the Himalaya has experienced four great earthquakes during the last century. However, no great earthquake has occurred in the Garhwal-Kumaun region during the recent period, leaving behind a seismic gap between the Kashmir-Himachal and Bihar-Nepal regions. We need to establish whether the seismic gap exists and if so, what will be its consequences. To identify the surface manifestation of past large earthquakes, which were enough to produce surface rupture along the Himalayan arc, paleo-earthquake studies that involve timing, size, and lateral extent of earthquake ruptures along the Himalayan frontal thrust fault need to be carried out. The paleo-seismic histories help to understand neotectonics, such as the regional patterns of seismicity and tectonic deformation, as well as the seismogenic behavior of specific faults. Further, it is necessary to evaluate the seismicity pattern by delineating sub-surface structures and discontinuities pattern from seismological as well as other geophysical studies to mitigate the effects of a probable future earthquake. The dense broadband seismic (BBS) station network of WIHG in the NW Himalaya has made it feasible to investigate this along with the area-specific velocity structure using local, regional and teleseismic earthquakes.

Besides, the Himalayan region is undergoing sprout of developmental activities. Therefore, it is essential to carry out geo-engineering studies, including engineering geological mapping, rock mass classification, rock assessment for engineering purpose, landslide studies etc. for sustainable development.

Theme 4: Biodiversity and Environmental Linkages

Biodiversity comprises many plants, animals, and microbes that unite the atmosphere, geosphere and hydrosphere into one environmental system making it possible for millions of species including the humans. This has diversity within and among the fossil taxa and paleo-ecosystems. Numerous lines of evidence have established that life has changed through time, and explains its evolution. Signatures of past lives are found preserved in sediment archives. Major stratigraphical boundaries are delineated based on distinct biotic turnover events (extinctions and recoveries). Good understanding of paleo-diversity across the major boundaries (e.g., PC/C, K/T, P/E etc.) and also pre- and post- India-Asia collision is important not only for stratigraphic correlation but also for the evolution of life and paleo-geographic reconstructions. The sedimentary records preserve the biodiversity-environment-paleogeography link at different time scales for Neoproterozoic-Cambrian and Cenozoic intervals. Himalaya is an excellent natural laboratory for testing the evolutionary hypotheses, diversification, extinction, recoveries, migrations and their linkages with changes in paleo-environment and paleogeography. The scientific activities under this program involves (i) evolution of early life, (ii) understanding post-Gondwana drift of Indian plate, (iii) collision and pre-collision biotic and landscape reconstruction, food habits, and climatic change, (iv) biotic migration *vis-a-vis* uplift of the Himalaya, and (v) stratigraphy of sedimentary successions of the Himalaya.

Theme 5: Himalayan Glaciers: Their Role in Indian Monsoon Variability and Geohydrological Changes in the Ganga Basin

The Himalayan glaciers are vast and now have been termed as the Third Pole of the world. The fluctuations in the heat budget of the atmosphere may have a profound effect on the glacial advances and retreat, and hence on the Indian Monsoon. The glacial records are also essential to understand the changes in aerosol, greenhouse gas concentrations, and albedo variations. Since the sustained development of economically useful natural entities is an ecological and socio-cultural necessity, it is essential to understand the environment and processes which control and affect their occurrences. Therefore, the study on natural resources such as water (solid and liquid phases) and minerals are significant. Under the present scenario of global warming, the WIHG focuses on several studies: (i) component of glacial melt into the hydrological budget of the Himalayan river systems, (ii) high resolution in-situ hydrological investigations and laboratory data including conventional and isotopic tracers of water resources (groundwater, surface water, and precipitations), (iii) glacial movements and mass balance, (iv) paleo-glacial history and climate variability.

Major Research Output

Theme 1: Geodynamic Evolution of the Himalaya and Adjoining Mountains

The zircon U-Pb ages and Hf isotopic compositions of felsic units of the Abor volcanic rocks (AVR) in the Eastern Himalayan Syntaxis, NE India, reveal the relationship between the AVR and the Kerguelen plume activity (Fig. 2). New geochemical and geochronological data show that the AVR was emplaced at the early stage (~132 Ma) of eastern Gondwana breakup caused by the Kerguelen plume activity. They were emplaced in the continental rift tectonic setting. The depth of the magma source is confirmed near the spinel stability zone. The Abor volcanic rocks are positively comparable with other flood basalts that were formed by the outbreak of the Kerguelen plume. This study supports that the Kerguelen plume affected a large area of Eastern India, Western Australia and Antarctica during the early stage of the Gondwana breakup.

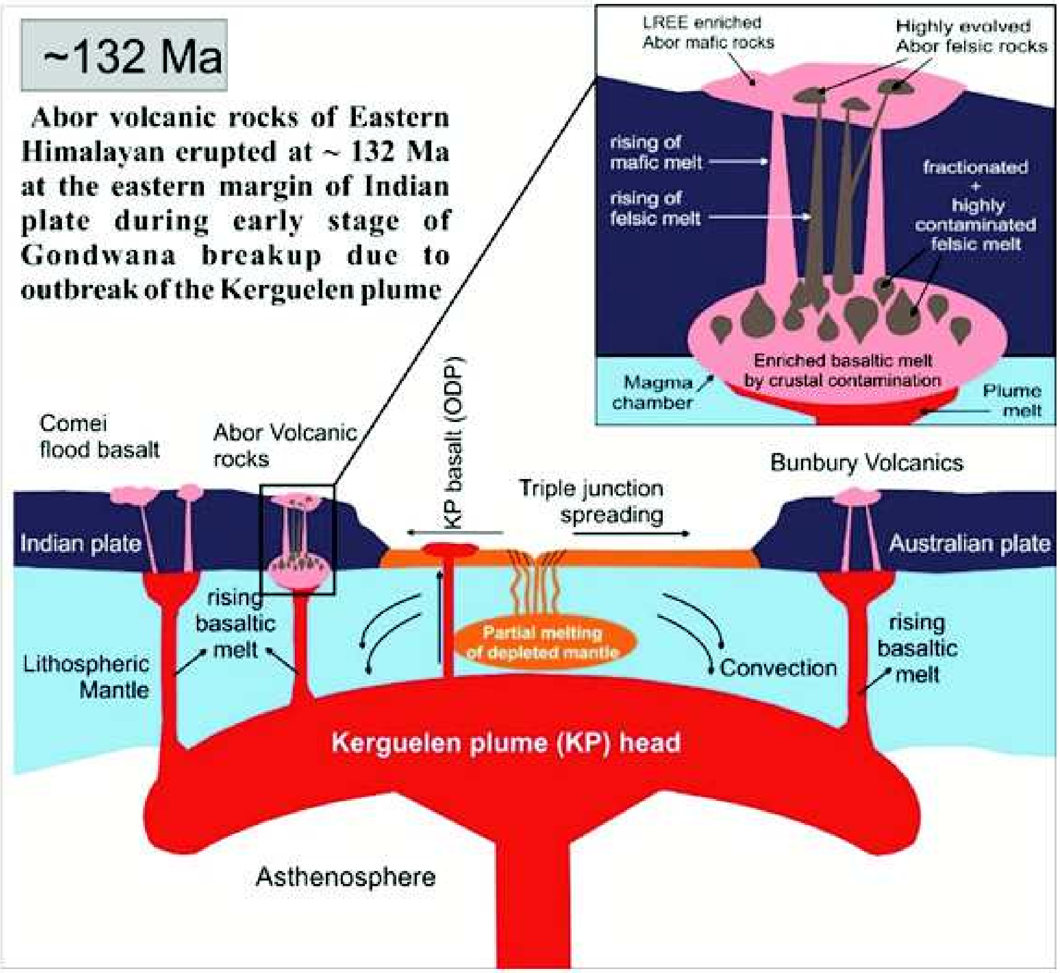


Fig. 2: Schematic model of tectono-magmatic evolution of Abor Volcanic Rockshaving linkage to the Kerguelen plume activity. Note the generation of Comei-Bunbury Large Igneous Province (LIP) magmatism (~ 132 Ma) between the north-eastern Greater India and south-western Australia

The study of ultramafic rocks from the base of the Ladakh ophiolite shows phase stability of beta-olivine, derived from the mantle transition zone (410-660 km). The transport mechanism is suggested via dunite channels along mantle adiabat in the focused convective flow below the spreading center. At the upward movement of the material from >410 km depth, C-H and H_2 primary fluids precipitate diamond due to change in ambient redox condition. The peridotite hosted by dunite divulging the ultramafic nature at the basal part of Ophiolite in the suture zone complex retains the signature of mantle upwelling. This shows direct bearing on the collision dynamics of the Himalaya.

The Main Central Thrust Zone (MCTZ) in the Alaknanda valley, NW Himalaya, affected the Lesser Himalayan Crystalline Sequence and has a gradual transition to the structurally overlying Higher Himalayan Crystalline Sequence (HHCS). Pseudo section modelling and garnet isopleth thermos-barometry of pelitic rocks yield peak metamorphic conditions of 6.3-7.5 kbar and 550-582 °C in the MCTZ, and 8.0-10.0 kbar and 610-650 °C in the basal part of the HHCS. The results indicate continuity in the P-T field gradient across the contact between the MCTZ and HHCS (Fig. 3). The observations are consistent with a recently proposed thermo mechanical model in which temperature in the shear zone rises due to viscous heating and pressure increases as a result of the weakening of the rocks.

Exhumation of P-T path of the sillimanite rocks in the Karakorum metamorphic complex has been

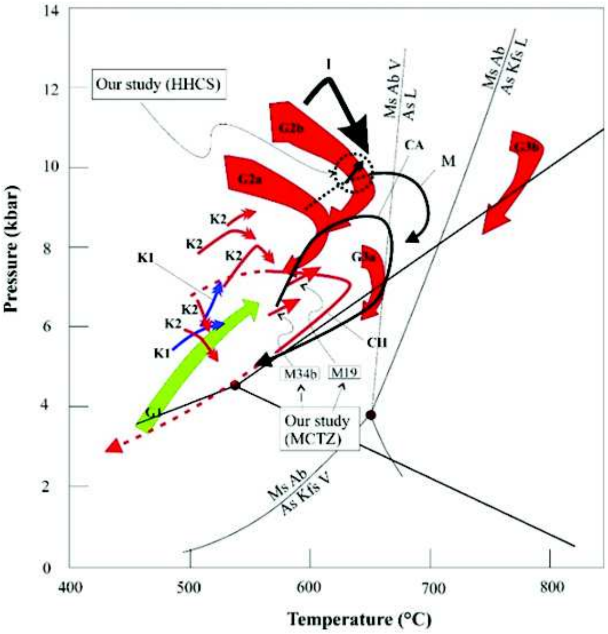


Fig. 3: The P-Tpaths of MCTZ and lower HHCS rocks in the Alaknanda valley, NW Himalaya (present study), and different sections of the Himalayas. G1 from LHS, G2a and G2b from MCTZ, G3a and G3b from HHCS - eastern Nepal; K1 from lowermost MCTZ, K2 from lower and middle MCTZ - central Nepal; CH from LHCS, Sutlej valley - NW Himalaya; I from lower HHCS - far-eastern Nepal; CA from lower HHCS - western Nepal; M from lower HHCS - central Nepal. For details see Thakur *et al*., (2015)

constrained from thermodynamic modeling, geothermobarometry, and fluid inclusions study. Metamorphic conditions for metapelites are shown by boxes (Fig. 4) and are compared with the study by others.

Talc deposits in the Deoban Formation of inner Lesser Himalaya in Kumaun were formed by low-grade, regional burial metamorphism of the siliceous magnesium bearing carbonates consisting of magnesite and dolomite. The peak temperature of 300^{o} to 340^{o}C, pressure of 2 to 2.2 kbar and a low X_{CO2} are estimated for the talc–magnesite assemblage. Lazulite, a phosphate mineral of ornamental importance, has been reported from the vicinity of a highly tectonized zone of the Main Central Thrust (MCT) in the Himalaya. The syntectonic growth of this lazulite with the Himalayan shearing occurred in a low salinity H_2O-CO_2 metamorphic fluid regime with moderately enriched ΔD‰. The study also implies that this refractory mineral can sustain fluid inclusions within it against intense deformation conditions, such as in the MCT.

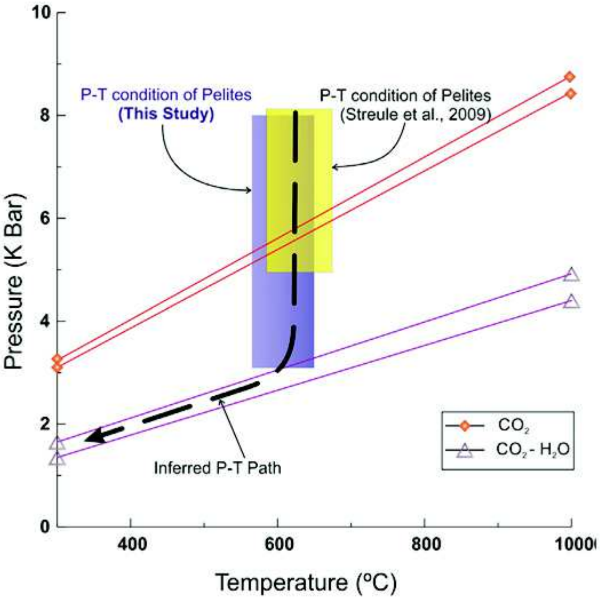


Fig. 4: The P-T condition of Pelites (present study) compared with the published research by others

Theme 2: Indian Monsoon-tectonic Interaction and Exhumation of the Himalaya

Landscape evolution of the mountains responds to a continuum made by glacial-periglacial and foreland dynamics. These morphologic processes evolve with changing climate and tectonic configuration of the Himalayan fold and thrust belt. Accordingly, the past and present (i) major river systems like the Indus, the Brahmaputra, and the Ganga, (ii) large and small lakes covering the spectrum of climate and geomorphology of the Himalaya, and (iii) speleothem based climate records were studied. A model explaining the formation of fill and strath terraces implying the neotectonic evolution of the Himalaya was proposed and received a comprehensive global response. It suggested that the southern front of the Himalaya is following a critical taper wedge model with an out-of-sequence deformation. The work also indicated that the high rate of river incision at NW Syntaxes might be controlling the riverine landscape on Ladakh. Further, the high resolution climate records, spanning over the Holocene, were generated using the peat, lakes and speleothems. Notably, a 35 ka speleothem record created from the Mawmluh cave of Meghalaya provided a first monsoon record from a continental archive suggesting a close correspondence between

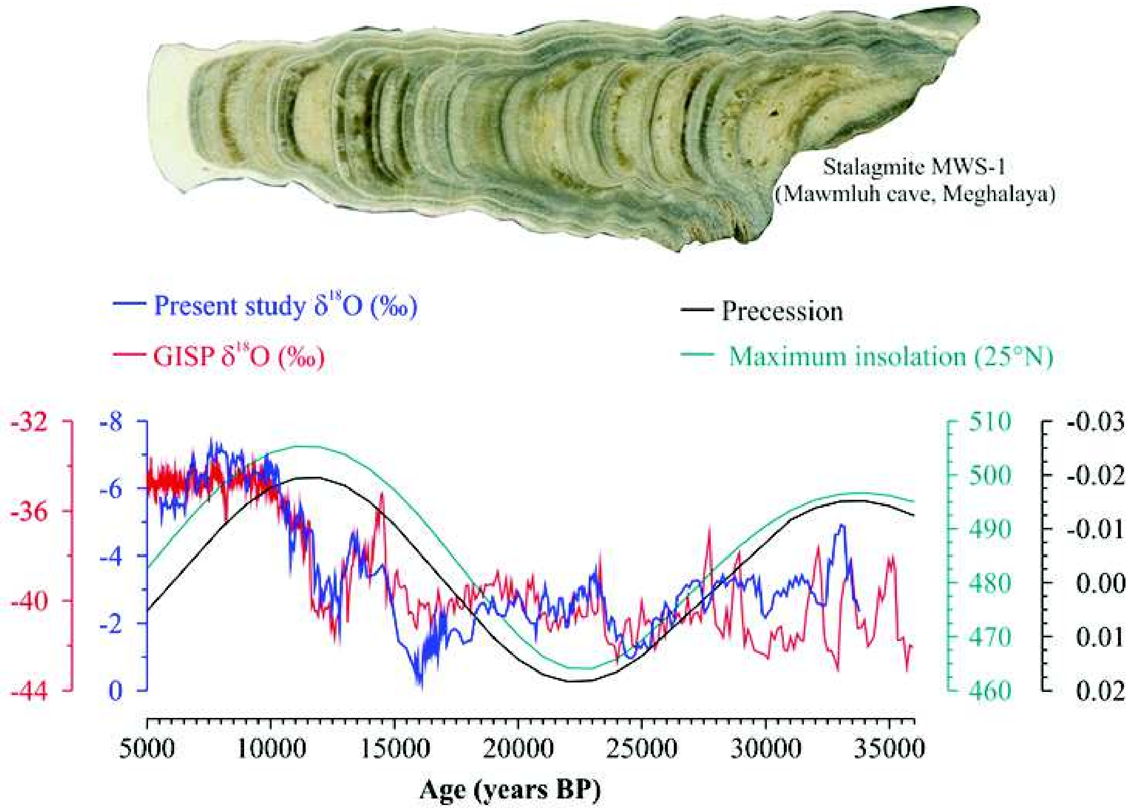


Fig. 5: $\delta^{18}O$ proxy record of stalagmite. Indian summer monsoon variability (blue colour) using the stalagmite MWS-1 from the Mawmluh Cave, Meghalaya (Dutt *et al.*, 2015) compared with that of the Greenland Ice Sheet Project 2 (GISP2) core $\delta^{18}O$ data (red colour), maximum solar insolation at 25°N (cyan colour) and orbital precession (black colour) published by others

the variability in Solar Insolation and monsoon strength (Fig. 5).

Theme 3: Earthquake Precursors Studies and Geohazard Evaluation

The Main Himalayan Thrust (MHT) separating the downgoing Indian plate from the overriding Himalayan wedge is accountable for the occurrences of earthquakes in the Himalayan seismic belt. All mega thrust sheets of the Himalaya sole down at a depth to merge with the MHT. Thus, the MHT accumulates a substantial amount of elastic strain energy, which is released from time to time by several large and great earthquakes in the Himalaya. Most of these earthquakes occur at shallow depth coinciding with the mid-crustal ramp structure on the MHT. However, due to the paucity of high-resolution geophysical data, the geometry of MHT is poorly understood in large parts of the Himalaya. To investigate the geometry of MHT beneath Satluj valley in NW Himalaya, we carried out a passive seismic study based on receiver function (RF) analysis along with a NE-SW profile consisting of 18 seismological stations. The study reveals a gentle north dipping structure of the MHT (depth range ~16 to 27 km) imaged between the Sub and Higher Himalaya in contrast to the reported ramp structure of the MHT beneath the Garhwal and Nepal Himalaya. The ramp structure is, however, identified further north, beyond the South Tibetan Detachment (STD) where the depth of MHT is ~38 km. This is significantly a different structure of the MHT beneath the Satluj valley, which is attributed to the effect of the under-thrusting of the Delhi-Hardwar Ridge (DHR). Conspicuously, no strong or massive earthquake is observed during 1964-2016 in this segment of the Himalayan Seismic Belt (HSB) indicating a relationship between the ramp structure of the MHT and the seismicity.The RF modelling and Common Conversion Point (CCP)

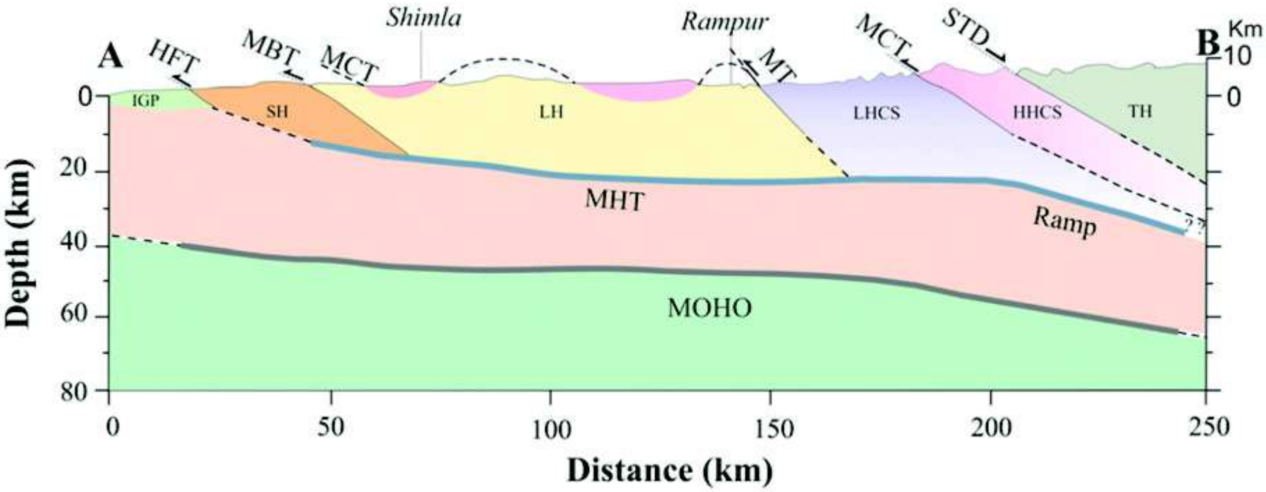


Fig. 6: Cross-section of litho-tectonic units - MHT and Moho from RF results along line A-B (Hazarika *et al.*, 2017). The gently dipping MHT shows a ramp beyond the South Tibetan Detachment (STD). The Moho shows gradual dipping from south to north

stacking image of RFs show an increase of crustal thickness from ~44 km near the Himalayan Frontal Thrust to ~62 km in the Tethyan Himalaya. The geometry of Moho and MHT has been depicted in the following cross-section (Fig. 6).

Establishing the timing of past earthquakes along the CSG is critical in assessing regional seismic hazards for areas proximal to the HFT that have both large populations and vast properties. Further more, it is of particular interest due to an apparent long-term quiescence that advocates the potential for impending large-scale rupture. The paleo-seismological studies from seven trench sites into a coherent OxCal age model for large-magnitude ruptures along the CSG indicate that the western half of the CSG probably ruptured during the historical event corresponding to an earthquake in 1344 CE.

The multi-proxy study provided the first evidence for 1950 A.D. primary surface faulting along the Himalayan Frontal Thrust (HFT), NE Himalaya at Pasighat. This suggests that great earthquakes accommodate the convergence between the southern Tibet and stable India along the MHT to the HFT. This study corroborates the first instance of using the post bomb radiogenic isotopes to help identify earthquake rupture. The surface ruptures of great earthquakes along the Himalaya arc and locations of paleo-seismological trenches are shown in Fig. 7.

The Himalaya is infested with numerous landslides and related mass movement, which are widely considered as the principal mass wasting agents in the valleys experiencing the varied influence of tectonics and climate. However, the pattern of landslides is rarely addressed in the literature that may act as the surface manifestation of the interrelationship among the tectonics, climate and lithology. Hence, the spatial distribution of landslides in the context of these was studied. It is observed that, in general, the length, width, area and volume of landslides increase while traversing from Lesser Himalaya to Higher Himalaya and the Tethyan Himalaya along the southwest to northeast transact, with an abrupt increase in dimensions near the hanging wall side of the Munsiyari Thrust and the Main Central Thrust (Fig. 8). This distinct change near these regional faults pertains to spatially varying litho-tectonics and climatic conditions, as this side receives high uplift and higher rainfall. The area-volume scaling relationship was also estimated and understood.

Theme 4: Biodiversity and Environmental Linkages

The Paleocene-Eocene Thermal Maximum (PETM), one of the most notable and widely documented global warming events in the geological history, occurred at the beginning of the Eocene (~56 Ma), which caused substantial changes in the biota and geochemistry. It is marked worldwide by a negative isotopic excursion

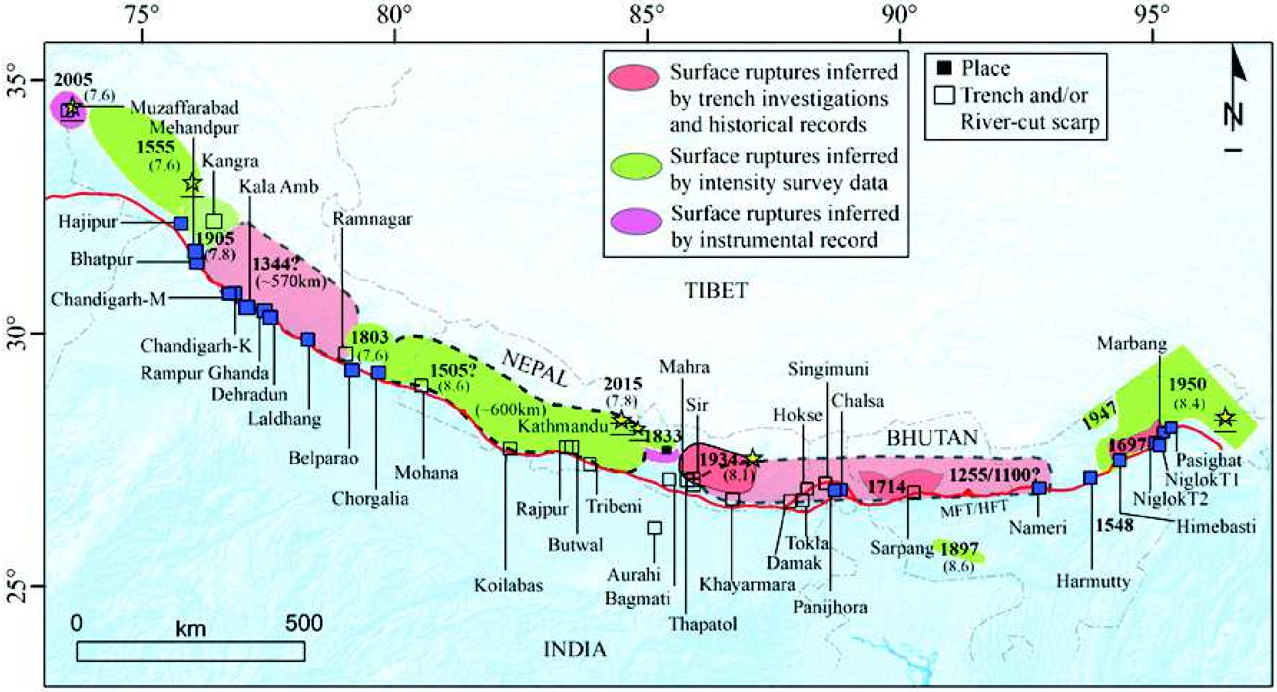


Fig. 7: A simplified map showing surface ruptures due to great earthquakes and locations of paleo-seismological trenches (Solid Blue square) excavated so far by WIHG along the Himalayan front. Surface rupture of CE 1344 (Jayangondaperumal *et al.*, 2018) and CE 1697 (Priyanka, 2018; Pandey *et al.*, 2019). Historical earthquakes were discovered through trench investigation along the Himalayan Frontal Thrust (see Jayangondaperumal *et al.*, 2018 for further details)

of δ^{13}C, bloom of the dinoflagellate *Apectodinium*, turnover of larger foraminifera, diversification of planktic foraminifera, and carbonate dissolution of calcareous test shells, decrease in carbonates and increase in abundance of silicates and phyllosilicates, etc. There was a gap in identifying the PETM in the Himalaya even though some Himalayan sections are known to have Paleocene-Eocene transition beds. The basal part of the late Paleocene-middle Eocene Subathu Group, exposed at the village Kurla near Subathu in Himachal Pradesh (NW sub-Himalaya), was investigated for biotic, mineralogical, and geochemical signatures of this abrupt warming event. The results show carbon isotope excursion (CIE) of 3.4%, the occurrence of index dinoflagellate genus *Apectodinium*, and carbonate dissolution of larger benthic foraminifera. The mineralogical changes across the Paleocene-Eocene transition exhibit an increase in quartz and phyllosilicates and a decrease in carbonates. The geochemical study shows (i) increase in SiO2, Al2O3, K2O and Fe2O3, (ii) reduction in CaCO3, (iii) decreasing trend of Si/Al, Fe/Al, and Mg/Al ratios, (iv) increasing trend of K/Al, Ti/Al, and Zr/Al ratios, (v) changes in trace element abundance, (vi) maximum chemical index of alteration (CIA) of 85-89%, and (vii) increase in abundance of rare earth elements (Fig. 9). The dataset mentioned above is very close to the PETM and even reflects its probable onset and peak phases. However, it is insufficient to identify the PETM in the studied section. Nevertheless, the study is the first attempt from a Himalayan section and brings out much new information.

Theme 5: Himalayan Glaciers: Their Role in Indian Monsoon Variability and Hydrological Changes in the Ganga Basin

Glaciers are most sensitive to climate change and therefore are important markers of climate fluctuation in space and time. Climate change has an increasing influence on the stability of the Himalayan glaciers that may affect the livelihood of mountain people. Deciphering the impact of climate change and a continuous melting of glaciers need to be understood for accurate estimation of ice volume changes and its response to the climate. In the Indian part of the Himalaya (IHR), there are ~10,000 glaciers. Our institute has been carrying out a detailed study on

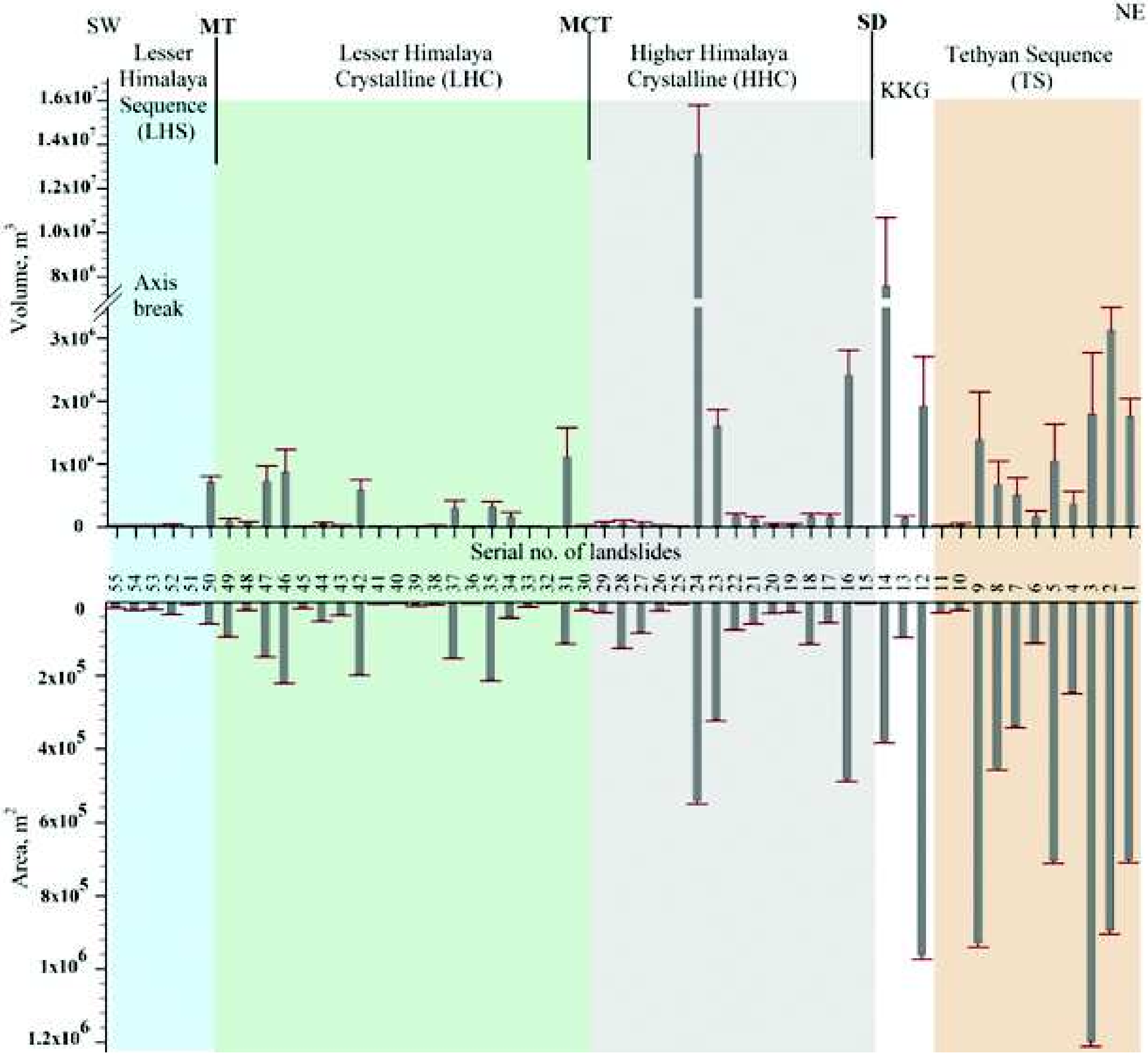


Fig. 8: Dimensional distribution of landslides from southwest to northeast in the Himalaya

several glaciers for the dynamic changes due to climate variability and the societal implications. The fluctuations in the heat budget of the atmosphere may have a profound effect on the glacial advances and retreats. Since the glaciers are perennial sources of freshwater, the study of natural water resources in the form of snow and ice, their dynamics and behavior due to the climate processes with space and time are critical. Under the present scenario of global warming, we have focused on (i) glacial mass balance and surface change, (ii) glacial meltwater & hydrological budget, (iii) high resolution in-situ hydrological investigations and laboratory data including conventional and isotopic tracers of water resources (surface, sub-surface and precipitations) and (iv) glacial history and climate variability.

Dynamics of mass balance and its components carried out on several glaciers during the period 2015-2018, show negative mass balance in all the studied glaciers ranging between –0.32 m and –072 m w.e. a^{-1}. Fig. 10 shows the mass balance of Chorabari glacier during the period 2016-2017. The continuous loss of glacier mass indicates that the melting is more than the snow accumulation. It is observed that there are not many differences in annual summer melting

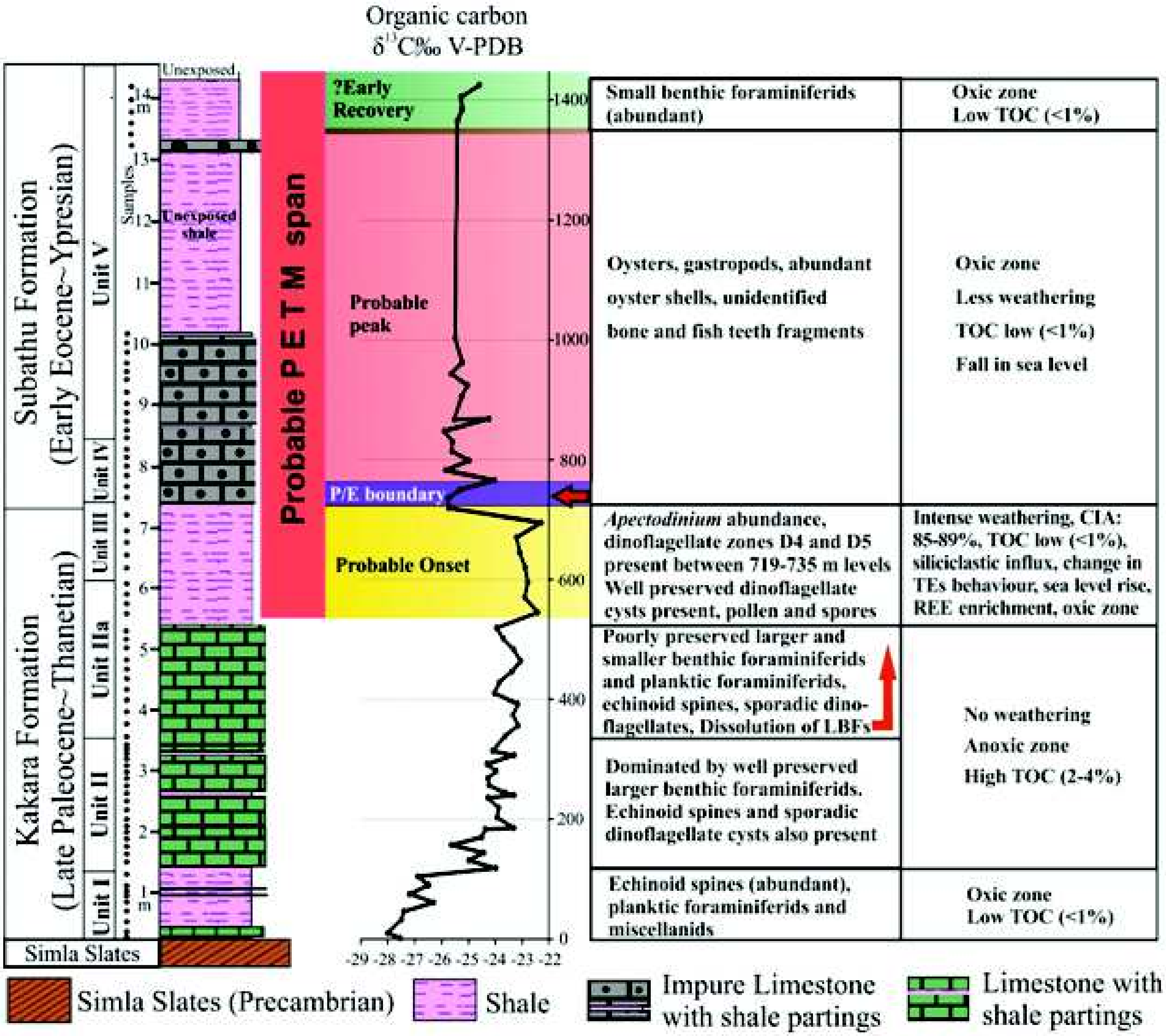
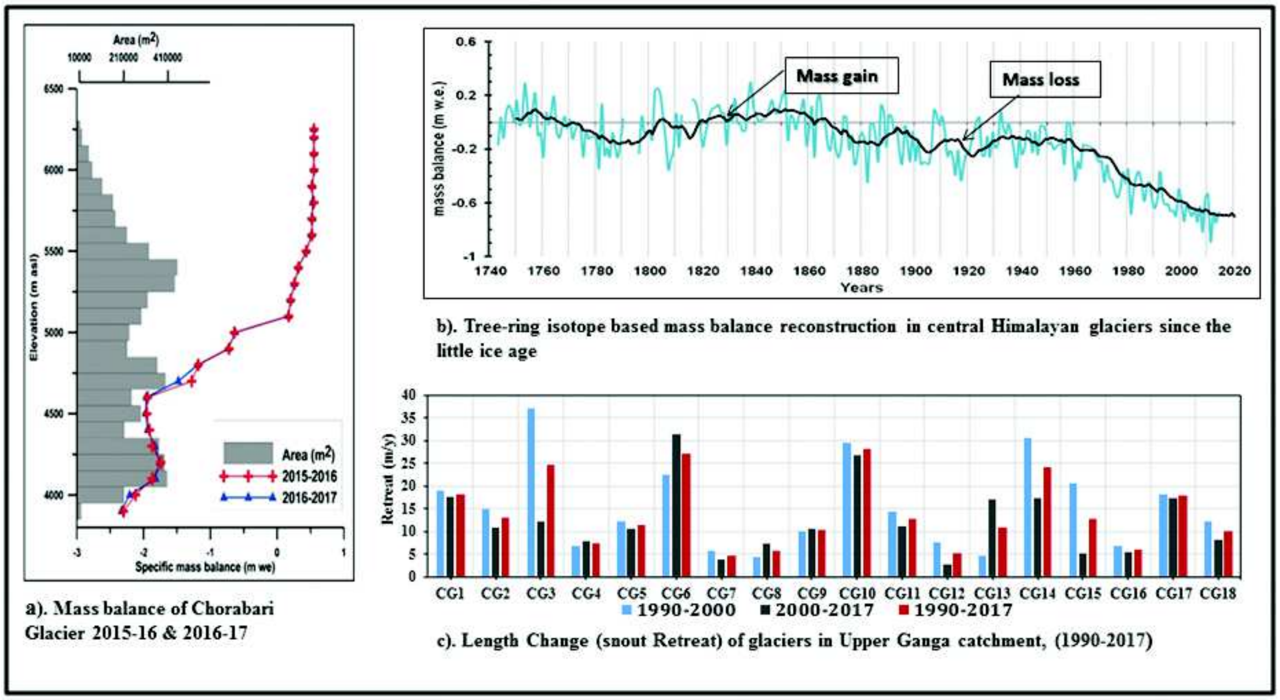


Fig. 9: The P/E boundary and various phases of the probable PETM span in the Subathu Group of the Kurla section, Delgi (Subathu), inferred using mainly geochemical and limited paleontological data

but winter snow accumulation varies from year to year. The net winter accumulation measured for the study period slightly decreases (1-2%) compared to previous years as the Equilibrium Line Altitude (ELA) is ascendant. The ascending and descending of ELA or snow line also specifies the amount of snow cover during the period. The actual mass balance behavior based on tree-ring isotope fromDokriani glacier was also reconstructed, and the study shows a strong trend of negative mass balance since the late 1960s, which is also supported by current mass balance trend (Fig. 10a and b).

Snout retreat is another critical component to determine the changes in length, aerial extent as well as altitudinal alteration of the glacier surface over the period. The changes in length of 18 glaciers in the upper Ganga basin in the central Himalayas from 1990 to 2017 were estimated using the satellite remote sensing data. The results indicate that the total glaciated area decreased from 313.34 ±7.95 km^2 in 1994 to 306.36 ±8.04 km^2 in 2015, whereas retreat rates varied from 4.75 ± 2.25 to 28.25 ± 2.25 m a^{+1} with an average rate of 13.91 ± 2.25 m a^{+1} during this period (Fig. 10c). Further, it is also observed that the debris-covered area of each glacier increased from



a). Mass balance of Chorabari Glacier 2015-16 & 2016-17

b). Tree-ring isotope based mass balance reconstruction in central Himalayan glaciers since the little ice age

c). Length Change (snout Retreat) of glaciers in Upper Ganga catchment, (1990-2017)

Fig. 10: Glacier mass balance trend (a and b) and terminus (snout) fluctuation (c) in the Upper Ganga Basin, Central Himalaya

86.56 ± 1.29 to 97.99±1.75 km^2 and the average snowline altitude ascended by 67 m during 1990-2017.

Meltwater discharge data were collected at the existing gauging site of studied glaciers during summer (May-October). The velocity area method was used to estimate the mean discharge in the river. The stage-discharge relationship for few glaciers has been developed to calculate discharge for the available water level records of 2014. The mean monthly discharge observed during the study period for different months showed fluctuating trend i.e. May, June, July, August, September and October are 1.1, 3.0, 9.8, 11.8, 4.7 and 2.2 m^3/s respectively. The studies carried out so far in the IHR reveal that most of the studied glaciers are in the recession phase. However, the recession rate is highly heterogonous. Considering the current climatic trend, the glaciers in the region are likely to recede with an accelerated phase in the future. Hence, continuous, systematic and long term studies are required to monitor their response to climatic perturbations closely.

Acknowledgments

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4. Agnihotri R, Dimri A P, Joshi H M, Verma N K, Sharma C, Singh J and Sundriyal Y P (2017) Assessing operative natural and anthropogenic forcing factors from long-term climate time series of Uttarakhand (India) in the backdrop of recurring extreme rainfall events over the northwest Himalaya *Geomorphology* **284** 31-40
5. Agrawal S, Srivastava P, Meena N K, Rai S, Bhushan R, Misra D K and Gupta A K (2015) Stable (ä13C and ä15N) isotopes and Magnetic Susceptibility record of late Holocene climate change from a lake profile of the northeast Himalaya *Journal of Geological Society of India* **86** 696-705
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