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ABSTRACT BOOK

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Cover Image: *Panoramic view of Mt. Everest from the Tibetan side* (Photo by Chiara Montomoli)

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Geological study of the Bhada Khola watershed, Bardiya district, Mid-western Nepal

Acharya M.*[1], Baral N.[1] & Paudyal K.R.[1]

[1]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: acharya11.manjari@gmail.com

Keywords: Main Frontal Thrust, Sub-Himalayan zone, clast imbrication.

Geological mapping at a scale of 1:25,000 was conducted in the Bhada Khola watershed of Bardiya District, Province No. 5, Nepal, to establish the area's stratigraphy and geological structures. Geologically, the study area encompasses the Sub-Himalaya in the north and the Indo-Gangetic Plain in the south. In the studied section, the Terai Plain is subdivided into the Bhabar Zone and the Middle Terai, whereas only the Lower Siwalik rock sequence is observed as part of the Sub-Himalaya. The Lower Siwalik is composed of medium- to thick-bedded, variegated fossiliferous mudstone with occasional bands of calcareous shale interbedded with medium-bedded, fine- to medium-grained sandstone in shades of yellowish-brown, grey, and purple. The Bhabar Zone, the northernmost part of the Terai plain, is dominated by coarse sediments such as boulders, cobbles, pebbles, and coarse sand, deposited by a gravelly braided river system sourced from the bedrock of the Siwalik and Mahabharat Range. The Middle Terai zone is characterized by the predominance of pebble, cobble, and sand deposits, alternating with layers of clay. The principal geological structure observed in the study area is the NW–SE trending Main Frontal Thrust (MFT), which marks the boundary between the Bhabar zone to the south and the Lower Siwalik unit of the Sub-Himalaya to the north. In the study area, primary sedimentary structures include lateral accretion and horizontal stratification, while secondary structures consist of bioturbation, clast imbrication, slaking, spheroidal weathering, thrust faults, and disturbed zones. The adverse conditions of debris flow and desertification in the Bhabar area are closely associated with the effects of thrust and shear zones.

Geochemical and petrographic insights into the Gondwana rocks of the Barahakshetra–Ranitar area, eastern Nepal Himalaya

Adhikari D.*[1,2], Thomas H.[3], Rana H.[4], Soni A.[3] & Paudel L.P.[1]

[1]Central Department of Geology, Tribhuvan University, Nepal. [2]Department of Geology, Central Campus of Technology, Tribhuvan University, Nepal. [3]Department of Applied Geology, Dr. Harisingh Gour Vishwavidyalaya, India. [4]Indian Geologist Survey Geological Society of India.

Corresponding author email: dronaadhikari92@gmail.com

Keywords: Gondwana, Barahakshetra - Ranitar, Eastern Nepal Himalaya, Geochemical.

The Barahakshetra–Ranitar area in eastern Nepal presents a rare exposure of Gondwana sequence rocks within the outer Lesser Himalaya. This study integrates detailed field mapping, petrography, and geochemical analyses to decipher the depositional environment, stratigraphic framework, and tectonic implications of these sediments. The investigated sequence, up to 800 meters thick and laterally extending about 13 km, comprises three distinct formations—Kokaha Diamictite, Tamrang Formation (with the Baraha Volcanics), and Sapt Koshi Formation. Three samples, each of sandstone and volcanoclastic sandstone along with one samples each of diamictite and shale have been studied petrographically and geochemically. Petrographically, the Kokaha Diamictite, shows monocrystalline quartz, lithic fragments, feldspar, and a significant matrix component. The overlying Tamrang Formation reveals angular to subangular grains of quartz, feldspar, and volcanic lithics, often embedded in a calcite-rich matrix. The youngest unit, the Sapt Koshi Formation shows poorly sorted, carbon-rich framework grains and cement, fine-grained matrices, and the presence of chert and volcanic fragments. The bulk of the sediments for the investigated rocks were derived from the purely sedimentary source where the protolith of these rocks falls in the wacke to arkose field. These sediments were found to be sourced from the interior part of a craton or shield and recycled platformal sediments which were derived from both passive and active margin settings.

Structural modeling and restoration of brittle deformation in the NW Himalaya (Pakistan) using geological and seismic data

Ahsan N.[1], Mahmood T.*[2] & Miraj M.A.F.[1]

[1]Institute of Geology, University of the Punjab, Lahore, Pakistan. [2]Oil & Gas Development Company Limited (OGDCL), Pakistan.

*Corresponding author email: Tariq Mahmood (tariq.mahmood@ogdcl.com)

Keywords: Geological mapping, imbricate structures zonation, seismic data modeling, phases of deformation, shortening/restoration.

The tectonic evolution of the NW Himalayas presents significant challenges in understanding the structural deformation across various tectonostratigraphic zones along the leading edge of the Indian Plate. The basement and cover sequence of metasedimentary rocks, exposed between the Main Mantle Thrust and the Panjal Thrust, underwent extensive ductile deformation in the NW Himalaya. A significant gap persists in the restoration of the brittle deformation zone between the Panjal Thrust and the Salt Range Thrust due to insufficient comprehensive geological mapping, multiple deformation phases, molasse overburden, stratal terminations against paleo-highs, and limited utilization of geophysical datasets (seismic and gravity). This study focuses on the classification of structural styles, phases of deformation, and restoration of structural zones within the Hazara, Kashmir, and Potwar basins. Geophysical data indicate that basement-related normal faults developed during different episodes, with orientations of NNW-SSE in the Kashmir basin and NEE-SWW in the Potwar and Hazara basins. These normal faults formed ramp-flat geometries, contributing to the structural formation in the brittle deformation zone during the Himalayan orogeny. The main phase of northward-directed thrusting, uplift, unroofing, and folding occurred over five distinct deformation phases, impacting both ductile and brittle deformation zones. The initial phase included the Hazaran orogeny, followed by the brittle deformation (2.6 to 0.4 Ma) of the Hazara, Kashmir and Potwar basins, and culminated in the development of the Hazara Kashmir Syntaxis in the final deformation phase. The distance between the Panjal Thrust and the Salt Range Thrust spans 160 km. At the Eocene level, the restored lengths are as follows: 100 km for the Hazara Platform, 76 km for the Hazara Kashmir Syntaxis, and 193 km for the Potwar Platform. The half-restored value for the Hazara Kashmir Syntaxis is subsequently included in the total cumulative restoration length, reaching 331 km for the brittle deformation zone.

Micro-mesotectonic fabric of the Higher Himalayan Rocks: case study from Swat Valley, North Pakistan

Ali A.[1] & Salam H.[1,2]

[1]Department of Geology, University of Peshawar, 25120, Pakistan. [2]Department of Geology, Khushal Khan Khattak University, Karak, 27000, Pakistan.

Corresponding author email: hikmat.salam@kkkuk.edu.pk

Keywords: microstructures, microtectonics, Himalayan orogeny, metamorphic cycles.

Micro–mesoscopic investigation of the multiply metamorphosed and deformed Cambrian to Triassic rocks exposed in the Swat Valley encompasses at least three well defined tectonic and accompanied metamorphic cycles since initial collision between the Indian Plate and Kohistan Island Arc (KIA). The early S1 foliations preserved in garnet porphyroblasts and microlithon of the main matrix S2 crenulation cleavages are obscured at outcrop scale by D2. Microscopically S2 foliations are preserved in garnet porphyroblasts and the main matrix foliations. Post D2 domes that developed as a result of crustal extension in the northern margin of the Indian Plate exhumed regionally pervasive S2 tectonic fabric. The same exhumation exposed the metamorphic core complex of the Indian Plate in the Kotah and Loe Sar Domes. These domes are wrapped by the Swat Tourmaline Granite (STG) that developed as result of the crustal thickening associated anatectic processes. S2 parallel kyanite grains indicate that the D2 tectonic event went with upper amphibolite facies metamorphic conditions and pre–dated the Kotah and Loe Sar Domes culmination tectonic event. The D3 deformation event resulted in S2 crenulations, L23 intersection lineations and syn–S3 growth of biotite, garnet, staurolite, kyanite and weakly developed sillimanite growth in the pelitic unit and tourmaline in the STG and lower part of the Marghazar Formation. The upper amphibolite facies metamorphic conditions in the Kashala and Marghazar Formations near the domes and greenschist facies conditions in the Saidu Formation and Mélange zone along the MMT illustrate that the upper amphibolites facies conditions rocks are exhumed by the Indian Plate basement rocks protrusion in the cores of the Kotah and Loe Sar Domes. Episodic reaction textures preserved in porphyroblasts and chlorite, biotite, garnet, staurolite, kyanite and sillimanite metamorphic index minerals yielded clockwise P–T path for the Alpurai Group Metasediments (AGM).

Reevaluating the India-Asia Collision in the Pakistani western Himalayas: Provenance Shifts and Sedimentary Constraints Indicating a Collision Age of ~56 Ma

Ali N.*[1,2], Sobel E.R.[1], Bernhardt A.[3], Ghani H.[4], Sajid M.[2] & Gerdes A.[4]

[1] Institute of Geosciences, University of Potsdam, Germany. [2] Department of Geology, University of Peshawar, Pakistan. [3] Institute of Geological Sciences, Freie University Berlin, Germany. [4] Geoscience Center, Georg-August-Universität Göttingen, Germany. [5]Institute of Geosciences at Goethe University in Frankfurt, Germany.

Corresponding author email: nowrad.ali@uni.potsdam.de

Keywords: India-Asia collision, provenance, western Himalayas.

The timing of the India-Asia collision along the western Suture remains debated (60 to 40 Ma). Provenance analysis of Mesozoic and Cenozoic stratigraphic sequences in the Sulaiman and Katawaz basin—now forming the Sulaiman and Katawaz fold-thrust belts—offers key constraints on this crucial tectonic event. Both belts preserve a continuous sedimentary record without major unconformities that documents the pre-, syn- and post-collisional events in the region. To examine the collisional record, we analyzed the detrital zircon U-Pb ages and $\varepsilon Nd_{(0)}$ signatures of Jurassic to Miocene strata. These data are interpreted alongside of zircon (U-Th)/He thermochronology data from Triassic strata exposed in the Zhob structural window of the northern Sulaiman fold-thrust belt.

These analyses help to distinguish between potential source terrains of these sediments, including the Indian craton, uplifted tectonostratigraphic units of the Himalayas, the southern margin of the Asian plate, and the Kohistan Ladakh Arc. The detrital zircon U-Pb age distribution from the Cretaceous Pab Formation is dominated by Precambrian to early Paleozoic age components (1Ga - 500Ma) which are diagnostic of the Indian craton and uplifted tectonostratigraphic units of the Himalayas, representing the northern parts of India. The detrital zircon U-Pb age distribution (1 Ga-500 Ma) from the early Paleocene Ranikot closely resembles that of the Pab Formation, with additional late Paleozoic zircon U-Pb ages (~Ma-Ma) indicating input from the Tethys Himalayas. The first occurrences of late Jurassic to early Paleocene zircons (115 Ma - 64 Ma), are observed in the early Eocene Ghazij Formation, that show major shift in the source region. In the Oligocene Chitarwatta Formation, a distinct peak of Jurassic to late Eocene zircon ages (186-36 Ma) are observed, along with minor peaks comprised of older ages (3421-225 Ma) that suggest continuous supply of sediment from the new sources.

The detrital zircon ages from the Eocene Nisai Formation in the Katawaz fold-thrust belt show a distinct peak of early Eocene to late early Jurassic zircons (55 Ma to 178 Ma) with minor peaks of older zircons. The Oligocene Khojak Formation is characterized by a distinct peak of early Oligocene to Jurassic (32 Ma to 194 Ma) with additional minor peaks of older zircons (3572-308 Ma). The $\varepsilon Nd_{(0)}$ values from Jurassic to Miocene sediments exhibit a shift from highly negative values (-17.174 to -12.094) in Jurassic to Early Paleocene samples to less negative values (-11.958 to -8.2905) from the Paleocene-Eocene transition (~56 Ma) to the Miocene.

Our detrital zircon data, $\varepsilon Nd_{(0)}$ results, and available paleocurrent and sedimentary facies data from the literature, combined with new zircon (U-Th)/He age (~Ma) from the Zhob window in the Sulaiman fold-thrust belt, confirm an early Eocene shift in sediment provenance. This shift marks a transition from a purely Indian source (craton and Himalayan sources) to increasing contributions from the Kohistan-Ladakh Arc and the Asian plate, including the Afghan Block, in the western Himalayas. A similar change in sediment sources has been documented in other parts of the northwestern Himalayas, indicating a single continuous basin in the foreland of the western and northwestern Himalayas. Based on the micropaleontological depositional age of the Ghazij and Nisai formations, our results support a collision age of ~56 Ma for the India and Asia in the western Himalayas.

Geothermal implications of the thermal structure of lithosphere in northern Pakistan

Anees M.*[1,2], Hindle D.[2], Meneses Rioseco E.[1], Kley J.[2], Leiss B.[2] & Shah M.M.[3]

[1]Leibniz Institute for Applied Geophysics, Hannover, Germany. [2]Department of Structural Geology and Geothermics, Geoscience Centre, Georg-August-Universität Göttingen, Germany. [3]Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan.

Corresponding author email: muhammad.anees@liag-institut.de

Keywords: geothermal energy, thermal modeling, northern Pakistan.

Northern Pakistan, encompassing the Himalaya, Kohistan, and Karakoram terranes, represents a geologically complex region where crustal thickening, tectonic exhumation, and radiogenic heat production (RHP) critically influence the lithospheric thermal structure. Despite its geothermal potential, surface heat flow data remains sparse, necessitating numerical thermal modeling for subsurface assessment. This study employs 1D steady-state conductive and transient advective-conductive thermal models alongside 2D conductive simulations to estimate the geothermal gradient and isotherm distribution. Models are constrained using surface RHP data and lithospheric parameters derived from regional geophysical studies.

The 1D models reveal that variations in the lithosphere-asthenosphere boundary (LAB) depth between 150 and 250 km have minimal impact on upper crust temperatures, while the thickness of the heat-producing layer (HPL) substantially affects geothermal gradients. A 15 km thick HPL elevates temperatures to 430°C at 10 km depth and surface heat flow to 103 mW/m², underscoring the significance of radiogenic sources in thermal structuring. Pseudo-2D thermal models illustrate lateral isotherm shifts and identify zones of enhanced heat flow linked to crustal thickening and exhumation, particularly in the Nanga Parbat Massif. Here, elevated geothermal gradients (>100 mW/m²) suggest the potential for medium to high enthalpy geothermal systems. Furthermore, valleys with significant topographic relief are identified as promising zones for geothermal exploration, where shallow drilling could access temperatures exceeding 200°C.

These findings highlight the geothermal viability of northern Pakistan's orogenic domains, emphasizing the role of radiogenic heating and crustal deformation in subsurface thermal regimes. Future work should prioritize geophysical surveys to better constrain lithospheric structure and optimize geothermal resource assessments.

Genesis of nodularity in the Middle Eocene Neo-Tethys carbonate rock unit: A case study from the Kohat Plateau, Pakistan

Awais M.*[1], Hanif M.[2], Adnan M.[2], Ishaq M.[2] & Rizwan M.[3]

[1]Department of Geology, University of Swabi, Khyber Pakhtunkhwa, Pakistan. [2]National Centre of Excellence in Geology, University of Peshawar, Khyber Pakhtunkhwa, Pakistan. [3]State Key Laboratory of Continental Evolution and Early Life, Department of Geology, Northwest University, Xi'an 710069, China.

Corresponding author email: awais.geo89@gmail.com

Keywords: nodular limestone, diagenesis, Eocene, Kohat Formation, Kohat Plateau, Pakistan.

Geological field investigation of the Eocene Kohat Formation has been conducted in the Kohat Plateau (Pakistan) at different outcrop sections i.e. Shadi Khel, South Lachi and Usterzai. The studied limestone is ridge forming throughout the studied sections. On the outcrop scale, the Kohat Formation is dominated by limestone and marls / shale. The limestone intervals are showing distinct configurations including thin bedded (very rare), medium – thick bedded, massive, wavy bedded and nodular. In general outcrops are bedded, however, the bedding is composed of different limestone nodules. The nodular characteristic of the Kohat Formation has various forms such as based on size, shape, connectivity and association with fractures. There are nodules of different sizes varying from very small to very large. Likewise, variety of limestone nodule shapes are noticed, for example, elongated, lensoidal, spherical, pillow shaped. Certain nodules are showing pinch and swallow structures without any break in the lateral direction along bed(s). However, certain nodules are separated by marly / argillaceous material and also some nodules (localized interval) are found isolated in marly intervals. Furthermore, limestone nodules are deformed and divided by fractures. In this study, two genetic types of nodules are noticed i.e. first nodules group is related with fracturing and meteoric diagenesis and second nodules group is related with burial and tectonic compressions. It is assumed that the limestone nodules are remnants of earlier continuous carbonate beds that were later on fractured and dissolved along these fractures and hence nodules were formed.

Constraining the Indo-Burmese Convergence: Thermochronological Evidence from Eocene Detrital Fission Tracks

Ayyamperumal R.*[1,2] & Gnanasambandan N.[1]

[1]Nivetha Institute of Earth and Environmental Sciences, Kovilpatti, Tamil Nadu, India. [2]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, P.R.China.

Corresponding author email: director@niees.org.in; ramamoorthy@lzu.edu.cn

Keywords: Detrital Fission Track, Indo-Burmese, Barail sandstones, Exhumation, Provenance, Northeast India.

Nagaland is part of the northern extension of the Indo Myanmar range (IMR). This area is representative of several orogenic upheavals in the Cretaceous-Tertiary that form a relatively young and mobile land belt. Nagaland is the most recent crustal reaction to the collision of the Indian and Burmese Plate. Barail formation emerged at the active margin of the Indo-Burmese plate convergence. Most of the available tectonic replica proposes that thermal formation and uplift of the Northeastern. We aimed at the highlights of exhumation and sedimentation, and its other host processes like provenance characteristics of the Barail sandstones from Nagaland, India. Systematic geological mapping of approximately 50 square meters has been carried out in the study area. A geological map of the study area was made on a scale of 1:50,000 in the Indian Topsheet No.58M/4 survey in the Kohima district of Nagaland. The region was mapped according to need and accessibility by taking the traverses along the highways, footpaths and across the ranges. In this study, four quarry samples disseminated in various folds in the Barail Group yielded the ages ranging from 37.4±1.5Ma to 49.9±2.4Ma and younger than their predecessor sedimentary deposition ages(86.92-181.81Ma).The binomial distribution clearly stated that from 46.0to32.0Ma,the grain ages tted peaks are usually dominated by the young peak .Combined with an interpretation of the origin, the detrital zircon of the young peak age and rocks indicated that most significant uplifting of the Barail Group occurred during Eocene to the Oligocene, almost timed to coincide with the colliding of the Indo-Burmese plate more around ~35-50Ma.Such findings have been consistent with the current geology of Naga Hills in the province of Nagaland.

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Timing of India-Asia collision: Evidence from an early Eocene (~55 Ma) terrestrial vertebrate fauna from western India

Bajpai S.*[1] & Rautela A.[1]

[1]Department of Earth Sciences, Indian Institute of Technology, Roorkee (Uttarakhand), India.

Corresponding author email: sunil.bajpai@es.iitr.ac.in

The timing of the India-Asia collision remains a hotly debated topic with estimates varying from ~65 to 35 Ma based on multiple lines of evidence, including the end of marine sedimentation, sediment provenance changes, paleomagnetic data, and high-pressure Himalayan metamorphic rocks. New data on fossil vertebrates clearly suggest that India's northward drift and collision triggered significant faunal shifts, including the emergence and diversification of new mammalian communities on the Indian subcontinent. A key discovery made in recent years is the early Eocene (~55 Ma) terrestrial mammal fauna from the Vastan lignite mine, Gujarat state, western India, representing South Asia's oldest known Cenozoic terrestrial mammal record. This fauna includes primitive members of placental mammal orders such as artiodactyls, perissodactyls, and primates (APP taxa). In Holarctic regions, these mammalian groups first appeared around the Paleocene-Eocene boundary (~56 Ma), coinciding with a period of intense global warming. Some of the land mammal taxa from Vastan such as tapiroid perissodactyls nyctitheriids and lagomorphs, suggest strong Asian affinities. The close relationship of the Vastan tapiroid *Cambaylophus* with *Orientolophus* from the earliest Eocene (Bumbanian ALMA) of China, and that of the nyctitheriid *Indonyctia* from Vastan with *Voltaia* from the late Paleocene (Gashatan) of Kazakhstan, suggests that a sub-aerial contact or some form of proximity between two the Indian and Asian landmasses must have been in place at least by 55 Ma or even earlier. Faunal and floral exchanges between these landmasses were facilitated by the intervening crustal blocks, particularly the Kohistan-Ladakh Island Arc, as also suggested by recent evidence of fossil palms from Tibet. This suggests that the collision between India and Asia began close to the Paleocene-Eocene boundary (56 Ma) or earlier.

Threats of Paleo landslides reactivation to the Himalayan people; insight into Sindhupalchok District of Nepal

Bhandari B.P.*[1], Regmi M.[1] & Dhakal S.[2]

[1]Central Department of Environmental Science, Tribhuvan University, Kathmandu Nepal. [2]Department of Geology, Trichandra Multiple Campus, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: bbhandari@cdes.edu.np

Keywords: Landslide reactivation, settlement threat, Nepal Himalaya, soil investigation.

The reactivation of old landslides has emerged as a major problem in the Nepal Himalaya in recent years. A large number of peoples have been living on the old landslide deposits since long and they are facing the challenges of landslide reactivation in the Himalaya. This study focuses the deformation mechanism of reactivated landslides and threat to the people in the Sindhupalchok District of Nepal. Between 2019 and 2023, ninety four distinct ancient landslide deposits were reactivated in the study region during the monsoon period. The reactivated landslides were identified from the satellite imageries and several field visits. The remolded soil samples from fifteen major reactivated landslides were collected from the field. The multistage direct shear test of unsaturated soil was conducted to obtain shear strength parameters. The physical properties of landslide were obtained by visual observation and direct measurement methods.

The soil samples exhibit a cohesion value that ranges from 3 to 9.5, whereas the angle of internal friction varies between 17 and 27. The soil exhibited a plasticity index ranging from 3 to 6. Out of all the samples, ten are loose and non-compact, while five samples are in a dense state. The findings of the gradation study indicate that the soils are characterized as clayey sands (SC) with a relatively low plasticity index and a low cohesion. The average rainfall amount in the monsoon period from 2015 to 2023 ranged from 2250 mm to 2900 mm. The rainfall amount in the early monsoon period increased dramatically from 2018. The catastrophic rainfall in the pre-monsoon after the long-term dry season caused the surface deformation in the study area. Furthermore, unconsolidated soil with low cohesion and low plasticity index deformed due to the 7.8 magnitude Gorkha earthquake and subsequent aftershocks. Altogether, 154 houses and 482 people are under the threat of paleo-landslide reactivation in the study region.

Unraveling Progressive Deformation Stages from Deformed rocks in Sikkim Himalaya: Some Results and Way Forward

Bhattacharyya K.*[1*], Parui C.[1,2] & Ghosh P.[1,3]

[1] Department of Earth Sciences, Indian Institute of Science Education and Research (IISER) Kolkata. [2.] Structures & Basins, Multidimensional Geoscience, Discovery Program, Mineral Resources, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. [3.] Sakariya Mines and Minerals, Kolkata.

Corresponding author email: kathakali@iiserkol.ac.in

Keywords: Shortening , strain, kinematic evolution.

Deformed rocks record their progressive deformation paths which are challenging to decipher due to overprinting and often obliteration of incremental deformation stages. We investigate localization and partitioning of deformation in the Darjeeling-Sikkim Himalayan orogenic wedge and kinematic evolution of internal shear zones to understand their implications during Himalayan orogeny.

Based on transport-parallel retrodeformable, regional balanced cross-sections we estimate a minimum shortening of ~403-450 km (~80%) in the Sikkim Himalaya, with the Lesser Himalayan duplex (LHD) contributing to ~72% of this shortening (Parui & Bhattacharyya, 2018). Approximately 78–91 km of shortening is recorded as penetrative strain in the Lesser- and Sub-Himalayan thrusts (Parui et al., 2022). Penetrative strain progressively decreases from the internal to the external thrusts with changing deformation conditions. Strain increases toward the basal thrust zone within each thrust indicating strain localization. Strain ellipsoids are folded along with the thrusts indicating the strain initiated before folding. The layer-normal shortening (LNS) strain dominates the internal thrusts. A combination of LNS and layer-parallel shortening (LPS) strain exist in the low-strained external thrust sheets. Shortening is partitioned differently across scales; the LHD records the highest thrust-sheet scale shortening, while the roof thrust toward the hinterland records the highest grain-scale shortening.

Multiple incremental strain markers reveal that the internal shear zones follow decelerating strain paths. Additionally, slip-transfer and structural culmination formed during growth of immediate footwall structures contribute to the kinematic evolution of internal shear zones. The same shear zone records along-strike variation in its kinematic path due to varying immediate footwall geometry. Next, we validate these interpretations in 15 well-studied, similar internal shear zones from other major orogenic belts. Internal shear zones that act as roof thrusts of duplexes or have stacked imbricate structures in their immediate footwall, generally record relatively higher strain, greater translation and greater pure shear component toward the later stage than similar shear zones without such footwall structures (Ghosh and Bhattachryya, 2022). Thus, deciphering comprehensive kinematic evolutionary paths of internal shear zones require understanding of immediate footwall structures. Additionally, studying kinematic paths of internal shear zones may provide insights into the geometry of immediate footwall structures when they are blind. We propose that consideration of the degree of footwall connectivity, and how it may affect the kinematics of an overlying roof thrust could be an important way forward for understanding long-term wedge dynamics.

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Petrogenesis of Granites from the Palung area Central Nepal with its Deformational History

Bhattarai A.[1], Paudyal K.R.[1] & Paudel L.P.[1]

[1]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: arjun.755707@cdgl.tu.edu.np

Keywords: Leucocratic granite, Lesser Himalayan Granite, Deformation history.

Orogenic events are imprinted in the medium to coarse crystalline leucocratic granite in the Palung area of Central Nepal which defines its genesis. The granite has intruded the metamorphic rock like Schist and quartzite of Precambrian age. The coarse crystalline granite lies at the edge of the granite body. Petrographic observations of the granite reveal a mineral assemblage dominated by quartz, potassium feldspar, plagioclase, muscovite, and biotite, with accessory minerals such as tourmaline, garnet, and zircon. The microscopic view of the different minerals in granite shows that the granite is formed in a syn-tectonic environment and has record of the post-tectonic activity. New mineral formation at the boundary of an existing mineral with destruction of its shape, reflects the metasomatic activity. The feldspar and mica in the western part of granite have developed the kaolin clay due to tectonic stress (effect of Mahabharat Thrust) and hydrothermal activity. The kaolin formation in the Palung-Kulekhani area mostly belongs to hydrothermal alteration and supergene weathering. The metasomatism leads to irregular boundaries in biotite and other minerals along their boundaries. The low grade metamorphism in feldspar causes the Carlsbad twining. The metasedimentary rocks mostly garnetiferous schist with aluminous rich minerals are the main marker of the xenolith in granite. The cross-cut in the country rock and deformational structures in xenoliths are assigned a younger age of the granite than the rock of the Bhimphedi Group. Such aluminous minerals like muscovite, garnet with almost absence of hornblende, show the S-type granite associated with continental collision zones (in an orogenic belt).

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Melt-driven Major Element Metasomatism of Compositionally Zoned Garnet and Metamorphic Timescales: New Insights into Ultra-hot Subduction Initiation of the Neo-Tethys

Bhowmik S.K.*[1], Pradhan B.[1] & Das D.[1]

[1]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India-721302.

*Corresponding author email: santanukbhowmik@gmail.com

Keywords: metamorphic sole rock, ultra-high temperature metamorphism, garnet zoning, coupled dissolution-reprecipitation, diffusion chronometry; timescales.

Major and trace element compositional zonation in garnet provides a wealth of information on the mechanism of its growth and re-equilibration, and, in the process, pressure - temperature – time - fluid evolutionary history of mountain-building processes - past and present. Compositional zoning of garnet can result from processes - during its growth under changing P-T-fluid conditions, post-growth intracrystalline diffusion and fluid/melt-mediated coupled dissolution-reprecipitation (CDR). Relating the measured garnet compositional zoning, therefore, to the three processes is critically important for reconstructing metamorphic P-T paths, interpretations of garnet Sm-Nd and Lu-Hf dates and obtaining metamorphic timescales. At extreme thermal conditions ($T \geq 900$ °C), the features of compositional zoning in garnet either due to its growth or re-equilibration during the CDR process are mostly obliterated in major elements, limiting their applications in deducing thermal histories of orogenic belts. In this study, we undertake an integrated textural, major element mineral compositional, and diffusion chronometry studies of metamafic sole rocks, in close proximity to wedge mantle peridotites, from the Nagaland-Manipur Ophiolite Belt, NE India. We demonstrate a unique preservation of a very complicated major element compositional zoning of garnet in these rocks that is utilized to deduce the high-temperature cooling history of the Neo-Tethyan subduction zone at its infancy. The sole rocks record a P-T history of subduction burial to mantle depths, prograde heating and associated hornblende dehydration melting, culminating in ultra-high temperature (UHT) granulite facies peak metamorphism (T_{Max} ~ 930-960 °C at ~ 1.4 GPa) and post-peak cooling and partial exhumation to ~ 1.2 GPa, ~ 730 °C. We interpret the textural and garnet compositional zonation in terms of four stages of garnet evolution. Stage 1: Garnet growth along the prograde heating path, with larger crystals (grain diameter ~ 4.5 mm) preserving growth zonation [X_{Mg}=0.22, Sps_{06} Grs_{26} (C) → X_{Mg}=0.33-0.34, $Sps_{02\text{-}03}$ $Grsr_{30}$ (OC)→ X_{Mg}=0.50, $Sps_{00\text{-}01}$ Grs_{21} (R)] even at UHT metamorphic conditions. Stage 2: Melt (tonalitic?)-induced Mg-metasomatism as part of a coupled dissolution-re-precipitation mechanism of the growth-zoned garnet core at the metamorphic peak. The newly grown re-equilibrated garnet (~500 **µm** width) of locally idioblastic habit, and symmetrically disposed on either side of inter-connected melt-pathways, reveals flat compositional distribution, corresponding to the metamorphic peak (X_{Mg} = 0.48-0.50, Sps_{01} $Grs_{20\text{-}21}$). The CDR process also led to the modification of the original Mg, Fe and Mn zoning of the remnant garnet core. Stage 3: Cation diffusion across garnet rim and the contact matrix clinopyroxene and garnet (cf. newly grown magnesian garnet) - garnet (partially modified remnant ferroan garnet core) couple along the cooling path. Stage 4: Broadly synchronous with stage 3, partial dissolution of garnet from all the three stages to produce retrograde hornblende. We have applied diffusion chronometry along the retrograde P-T-t path to fit the garnet-clinopyroxene and garnet-garnet diffusion zoning. Simultaneous fitting of both types of diffusion zoning has yielded a robust estimate of extremely rapid cooling history (cf. 20000-25000 °C/Myr) of the ultra-hot metamorphic sole rocks. Such high-resolution timescale of the high-temperature cooling history (960 → 730 °C) of metamorphic sole rocks has not been accessible until now. We attribute this rare preservation of the nascent state of ultra-hot subduction initiation within the south-eastern arm of the Neo-Tethys to the extremely rapid cooling history of the subduction zone.

Normal shearing in the North Himalayan Gneiss Domes (SE Tibet): a progressive shift from the Cuonadong to the Yalaxiangbo domes

Carosi R.*[1], Chen J.[1-2], Montomoli C.[1], Iaccarino S.[1], Cao H.[2] & Kylander-Clark A.[3]

[1] Dipartimento di Scienze della Terra, Università di Torino.[2] Institute of Geology, CAGS Beijing, China.[3] University of Santa Barbara CA, USA.

Corresponding author email: rodolfo.carosi@unito.it

Keywords: South Tibetan Detachment, North Himalaya Gneiss Domes, petrochronology.

The Cuonadong and Yalaxiangbo gneiss domes are two North Himalayan Gneiss Domes (NHGD) located in the eastern Himalaya. They exhibit similar tectonic architectures, characterized by an upper ductile-to-brittle and a lower ductile detachment, both showing a top-to-the-northeast sense of shear associated with the South Tibetan Detachment System (STDS). This shear sense is consistent on both the southern and northern limbs of the domes.

The upper tectonic unit, located above the upper ductile-to-brittle detachment, comprises unmetamorphosed to low-grade metamorphic Triassic–Lower Cretaceous slates and metapsammites belonging to the Tethyan Himalayan Sequence. The middle tectonic unit, sandwiched between the upper and lower detachments, includes mylonitic granite, staurolite–garnet–two-mica schist, and biotite–plagioclase gneiss, all affected by the ductile, top-to-the-north extensional shearing of the lower detachment. The lower tectonic unit consists of mylonitic gneiss, leucogranite plutons, dikes, and sills.

In situ U–(Th)–Pb monazite petrochronology from sheared samples, obtained via LASS–ICP–MS, constrains the activity of the lower detachment in the Yalaxiangbo dome to ~19–18 Ma, and shearing along the upper detachment to postdate ~16–15 Ma (Chen et al., 2018). The detachment system is therefore composed of two distinct shear zones, activated at different times and structural levels. Our data document a progressive migration of deformation from deeper to shallower levels (Cottle et al., 2015; Kellett & Grujic, 2012; Iaccarino et al., 2017; Chen et al., 2018).

In the Cuonadong dome, located approximately 40 km south of the Yalaxiangbo dome, shearing in the lower ductile zone began earlier, at ~25–20 Ma, indicating a northward migration of extensional deformation. This resulted in an earlier exhumation of the Cuonadong dome compared to the Yalaxiangbo dome, though through similar mechanisms. Both detachment systems were subsequently folded during the latest stages of dome exhumation.

New data also suggest that the timing of normal-sense shearing varies not only along the E–W direction (Iaccarino et al., 2017; Kellett et al., 2019), but also vertically—between ductile and brittle levels—and along a N–S axis, with younger ages recorded toward the north in the NHGD.

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Iaccarino S. et al. (2017) - Pressure-Temperature-Deformation-Time Constraints on the South Tibetan Detachment System in the Garhwal Himalaya (NW India). Tectonics, 36, 2281-2304.
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Deep Strike-Slip Seismicity Along Himalayan Lineaments: Revisiting the Structural Role of Transverse Features

Catlos E.J.*[1], Haproff P.J.[2] & Hubbard M.[3]

[1]Department of Earth and Planetary Sciences, Jackson School of Geosciences, The University of Texas at Austin, USA [2]Department of Earth and Ocean Sciences, University of North Carolina Wilmington, USA. [3]Department of Earth Sciences, Montana State University, USA.

Corresponding author email: ejcatlos@jsg.utexas.edu

Keywords: Himalayan lineaments, seismic hazard, tectonics.

Himalayan seismicity is traditionally attributed to thrusting along the Main Himalayan Thrust (MHT), with earthquakes linked to slip along ramps and flats within the fold-thrust belt (Bilham, 2019). However, growing evidence from focal mechanisms and deep seismic events indicates a role for faulting along transverse lineaments that cut across major Himalayan structures (see tinyurl.com/HimalayaLineaments for locations). Lineaments are linear geomorphic expressions; unless definitively proven, they are not classified as faults or would be termed such.

Historically, Himalayan lineaments have been poorly understood, but the Mw7.8 2015 Gorkha earthquake renewed interest in their potential as active faults or ancient structures influencing rupture dynamics. This Gorkha rupture was bounded by the Judi and Gaurisankar lineaments, which appear to have acted as structural barriers (Avouac et al., 2015; Mugnier et al., 2017). Some place the epicenter of the Gorkha earthquake directly on the Judi lineament (Mugnier et al., 2017). The National Earthquake Information Center places the epicenter on the Thaple lineament near its intersection with the Main Central Thrust (MCT). The MCT, a major crustal-scale fault, plays a key role in accommodating crustal shortening in the Himalaya. Similarly, the Mw7.3 Dolakha aftershock (12 May 2015) epicenter and several other Gorkha aftershocks are located where the Gaurisankar lineament intersects the MCT. Both lineaments were assigned as pre-Himalayan faults in Indian basement rocks.

To better understand these and other Himalayan lineaments, we used the spatial analysis of over 30 years of seismic data to evaluate the activity of >200 mapped lineaments, focusing on deep (>40 km) events to minimize the influence of shallower thrust-related activity along the MHT, MCT, or other Himalayan fault systems. Seven lineaments are identified as highly active (>15 events within 10 km). These are the Gaurisankar, Thaple, and Arun lineaments in central Nepal, the Martadi lineament in western Nepal, and the Thrizino, Old Brahmaputra, and Bomdila lineaments in northeastern India (Assam). Two lineaments (Old Brahmaputra and Bomdila) have well-defined mapped extensions into the Indian Craton.

Many Himalayan lineaments trend NE–SW or NW–SE, and intersections between these trends coincide with deep earthquakes. While earthquake depth estimates may carry significant uncertainty, all lineament crossings in our analyses show evidence of deep events (>40 km), with some intersections recording events at depths exceeding 100 km. Despite potential variability in depth determination, the consistent association of deep seismicity with lineament intersections suggests a structural control that warrants further investigation. Their apparent control over deep seismicity and influence on rupture segmentation may have significant implications for our understanding of Himalayan architecture and future hazard assessments.

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Detrital Garnet Thermobarometry (DGT) of the Siwalik Group in Surai Khola of Nepal: Insights into Provenance and Exhumation from the Himalayan Foreland Basin

Catlos E.J.*[1], Sorkhabi R.[2], Locmelis M.[1,3], Priimak L.D.[1] & Pitambar Gautam[4]

[1]Department of Earth and Planetary Sciences, Jackson School of Geosciences, The University of Texas at Austin, USA [2]Energy and Geoscience Institute, The University of Utah, USA. [3]Department of Earth and Planetary Sciences, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, USA. [4]The Hokkaido University Museum, Hokkaido University, Japan.

Corresponding author email: ejcatlos@jsg.utexas.edu

Keywords: garnet, Siwalik Group, detrital, thermobarometry, Himalayan provenance.

Detrital garnet thermobarometry (DGT) applies phase equilibria to generate pressure-temperature (P-T) conditions from detrital garnet compositions, assuming bulk rock geochemistry and past mineralogy based on provenance. DGT advances provenance analysis by enabling direct comparisons of detrital garnet P–T to those from potential sources rather than relying solely on compositions. We applied DGT to Siwalik Group garnets along the Surai Khola (central Nepal), which preserves a high-resolution record of Himalayan erosion history, paleoclimate, and paleodrainage evolution from the Middle Miocene through the Pleistocene (Szulc et al., 2006).

Many Surai Khola provenance studies have used detrital garnet presence and compositions to track the exhumation of metamorphic rocks associated with the Greater Himalaya Crystallines and Lesser Himalayan Sequence due to activity along the Main Central Thrust. Here we report the analyses of almandine-spessartine garnets with low Mg and Ca contents in all Surai Khola samples (3.8 Ma – 9.5 Ma). This type of garnet is characteristic of evolved melts (Schönig et al., 2021). Using DGT, two of these garnets yield core conditions of 520–528°C at 3.2–3.6 kbar. In the Himalaya, similar garnets from the High Himalayan leucogranites also record low emplacement P (~3.8 kbar; Yan et al., 2022). Preserving almandine-spessartine garnets across the Siwalik stratigraphy suggests that detritus derived from magmatic exposures consistently contributed to sedimentary deposition over time. Consequently, DGT provides additional circumstantial evidence for a previously overlooked magmatic contribution. Further, Himalayan igneous assemblages are enriched in accessory minerals (zircon, apatite, monazite, xenotime, rutile) essential for critical mineral studies (Zhang, 2024). Recognizing these contributions increases the likelihood that the Siwalik Group contains minerals beneficial for both tectonic reconstructions and mineral exploration.

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Integrating the metamorphic records of pelitic and metabasic sequences from the Zanskar Himalaya, Suru Valley region, NW India

Cawood I.P.*[1,2], Weller O.M.[3], Waters D. J.[2,4], St-Onge M.R.[2,5], Searle M.P.[2,4,6], Mackay-Champion T.[2], Palin R.M.[2], Ahmad T.[7] & Zhao G.[1]

[1]NWU-HKU Joint Centre of Earth and Planetary Sciences, Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong. [2]Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK. [3]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK. [4]Museum of Natural History, University of Oxford, Parks Road, Oxford, OX1 3PW, UK. [5]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada. [6]Camborne School of Mines, University of Exeter (Cornwall campus), Penryn, Cornwall, TR10 9EZ, UK. [7] Wadia Institute of Himalayan Geology, Dehradun 248 001, India.

Corresponding author email: ipcawood@hku.hk

Keywords: Orogenesis, metamorphism, Himalayan metamorphic core, phase equilibrium modelling.

The metamorphic record of Earth's crust preserves an archive of past tectonic processes, offering insights into dynamic processes such as crustal thickening, deformation, and exhumation during orogenic evolution. Pelitic and metabasic rocks serve as ideal recorders of these processes due to their widespread occurrence and reactive chemical compositions, allowing for robust reconstruction of pressure–temperature (P–T) paths. Integrating data from both rock types offers dual advantages: providing an internal consistency check, and potentially capturing different but complementary records of the P-T evolution. The Suru Valley region, NW India, represents an optimal location to study a near-complete Barrovian metamorphic cycle, as it preserves extensive kyanite-grade metamorphic assemblages related to the early collision record of the Himalayan orogen, alongside later sillimanite-grade assemblages that equilibrated during exhumation. This metamorphic record is deciphered by integrating petrography and phase equilibrium modelling of pelitic and metabasic compositions across a range of structural levels and metamorphic grades.

Following the onset of collision, deformation and metamorphism propagated southwestward, with increasing metamorphic grade toward structurally lower levels. At the lowest grade, garnet- and hornblende-zone assemblages record prograde metamorphism at 525–583 °C and 7.32–9.55 kbar during rapid crustal thickening. Intermediate-grade rocks (staurolite and kyanite zones; oligoclase and upper to middle garnet+plagioclase zones) reached 576–706 °C and 8.52–11.58 kbar, reflecting thermal relaxation and a shallowed metamorphic field gradient (~47 °C $kbar^{-1}$). The highest-grade, sillimanite and sillimanite+K-feldspar zones; lower garnet+plagioclase zone assemblages attained conditions of 621–684 °C and 9.25–14.37 kbar before decompressing near-isothermally to 653–700 °C and 5.64–6.52 kbar. These P–T paths record a prolonged interval of thermal equilibration under near-isobaric conditions at high-pressures, necessitating rapid and significant crustal thickening with limited erosion during the early evolution of the orogen. The dominance of kyanite and rarity of low-pressure assemblages suggest that decompression paths remained within or near the kyanite stability field, indicating fluid-limited, late-stage, near-isothermal decompression likely driven by mechanical erosion and uplift along the Zanskar Shear Zone.

In addition, a regional trend of reduced H_2O activity (aH_2O) is inferred from phase equilibrium modelling across both rock compositions in the Suru Valley region, likely reflecting CO_2- or saline-rich fluids, possibly derived from intercalated carbonate-poor and/or graphite-rich lithologies. Reduced aH_2O shifts dehydration reactions to lower temperatures and melting reactions to higher temperatures. The resulting shift in the position of the predicted solidus may reduce the propensity of melt producing reactions that take place at peak conditions, restricting melt volume and ultimately influencing the rheology and tectonic evolution of the orogen.

Revised Lithostratigraphy and Paleo-Lakes of the Pokhara Valley: A Scientific Perspective

Chettri R.K.*, Sah R.B. & Paudyal K.R.

Corresponding author email: raj.k.chettri@gmail.com

Keywords: Quaternary stratigraphy, paleo-lakes, geomorphic features, Pokhara Valley.

Pokhara, nestled within the intermontane basin of the Lesser Himalaya in Nepal, showcases a dynamic geological landscape defined by its significant terraced topography. Spanning approximately 50 kilometers from its upper to lower reaches, the valley presents a rich stratigraphic record of Quaternary sediments. A contemporary lithostratigraphic framework for the Pokhara Valley has been meticulously developed, incorporating diverse geological and geomorphic factors. The framework integrates key characteristics such as the geomorphic features of the deposits, the relative elevation of terraces above the riverbed, and sedimentary attributes including composition, structure, and texture. Complementary geological cross-sections and columnar sections were systematically prepared to illustrate these stratigraphic units. This effort has culminated in the classification of Pokhara Valley sediments into ten distinct lithostratigraphic units: Begnas, Siswa, Tallakot, Phurse, Ghachok, Pokhara, Gagangauda, Mardi Khola, Tal Khola, Rupakot and Chankhapur Formations. While several units derive their names from prior studies, others have been newly established based on the findings of this research. These formations collectively represent sedimentary deposits from the Quaternary period. Notably, the Pokhara Formation, found along tributaries, exhibits a wide range of sediment textures, from coarse to fine. This formation is further subdivided into three sub-units, each defined by type sections. The development of a detailed geological map at a 1:25,000 scale, complemented by geological cross-sections, has provided a spatial understanding of the valley's stratigraphy.

A particularly striking feature of the Pokhara Valley's sediments is the fine-grained deposits associated with paleo-lake environments and river damming events, which are evident in certain tributary regions. These deposits suggest that the valley experienced several phases of lacustrine activity, river damming, and glacial washout damming during its geological history. To elucidate these findings, several conceptual models are proposed to explain the origins and evolution of these paleo-lakes.

Mechanism of Geothermal Activity based on Geochemical and Isotopic data in the Northwestern Himalaya, India

Choudhary S.[1], Thakur M.[1], Romano P.[2], Tantillo M.[2] & Klemperer S.L.[3]

[1]Department of Geology, Panjab University, Chandigarh 160014, India. [2]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Sez. di Palermo, 90146 Palermo, Italy. [3]Department of Geophysics, Stanford University, Stanford, CA 94305-2215.

Keywords: Geothermal systems, Northwestern Himalayas, Helium isotopes ($^3He/^4He$), Thermochronology, Fault-controlled circulation, Exhumation.

Geothermal systems in the Himalayas can be categorized into two primary types: graben settings associated with extensional tectonics, and regions adjacent to or underlying the Main Central Thrust (MCT). In the Northwestern Himalaya, particularly within the Sutlej-Spiti River basin, the graben setting is defined by the Kaurik Chango Normal Fault (KCNF), whereas the MCT is exposed in the deeply incised valleys lower down the Sutlej River. The origin and mechanisms driving geothermal activity in these settings remain debated. Our study investigates hot springs in the Sutlej River basin to constrain their sources, employing helium-isotope geochemistry and integrating published datasets, including thermochronological, hydrogen-oxygen isotope (δD–$\delta^{18}O$), and geochemical data.

Helium-isotope analyses from both settings indicate exclusively crustal origins, with **$^3He/^4He$ ratios (Rc/Ra)** ranging from 0.02 to 0.03. Published δD–$\delta^{18}O$ data and Na-K-Mg geothermometry suggest shallow meteoric recharge and water–rock interactions at depths of <10 km. However, B/Cl ratios are elevated in graben settings implying deeper, fault-controlled, fluid circulation, whereas lower ratios near the MCT reflect shallower pathways and minimal deep input. Thermochronological data reveal rapid exhumation in the MCT region, likely driven by climate-enhanced erosion or a “tectonic aneurysm”. Geothermal activity near the MCT is likely sustained by rapid exhumation and shallow faulting, particularly along active structures like the Karcham Normal Fault Zone (KNFZ). In contrast, the graben settings exhibit slower exhumation rates.

We suggest that Himalayan geothermal systems are sustained by distinct mechanisms: fault-controlled deep fluid circulation in graben (extensional tectonics) versus exhumation-driven shallow fault circulations near the MCT.

Richard Strachey's contribution to Himalayan geology

Clark-Lowes D.[1]

[1]History of Geology Group, Geological Society of London.

Corresponding author email: d.clarklowes@nubianconsulting.co.uk

Keywords: Strachey, geological maps, cross sections, Himalayan ranges.

It is well known that Richard Strachey (1817-1908) made what must be considered the first geological transect of the Himalayan ranges (Strachey, 1851; Edmundson, 2019). The importance of Strachey's work is reflected in the significant contribution he made to the often overlooked Geological Map of British India, assembled by G B Greenough in 1855 (*General Sketch of the Physical and Geological Features of British India*). What is perhaps less well known is what geological concepts Strachey was able to draw on in creating his cross section, what family history of geological researches and what network of contemporary geological correspondents informed his approach.

Research into Richard Strachey's family reveals a history of involvement in geology, particularly that of his ancestor, John Strachey (1671-1743), whose theory of rock formations, which he termed 'stratum', and pictorial geological cross-sections through his Somerset estate, gave Richard Strachey a significant geological background.

Study of Strachey's correspondence reveals the complex range of influences that shaped his thinking. Whilst these included the work of William Smith, whose important geological map of England, Wales and some of Scotland (and notably his cross section) was published in 1815, there were many others whose work was profoundly influential in Strachey's thinking. In this talk I will explore these strands of thought.

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Strachey R. (1851) – On the geology of part of the Himalaya Mountains and Tibet. Quarterly Journal of the Geological Society of London, 7 292-310.

≤ c. 103-95 Ma Forearc sedimentation in the Nagaland-Manipur Ophiolite Belt, NE India: Implications for Subduction Initiation tectonics within the South-Eastern arm of the Neo-Tethys

Das D.*[1], Bhowmik S.K.[1], Pradhan B.[1], Lukose L.[1], Yadav S.[1] & Upadhyay D.[1]

[1]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur.

Corresponding author email: deepd9949@gmail.com

Keywords: forearc sediment, detrital zircon geochronology, Manipur ophiolite belt.

The Manipur segment (cf. MOB) of the Nagaland-Manipur Ophiolite Belt (NMOB), a southern extension of the Nagaland Ophiolite Belt, constitutes a significant geological feature within the Indo-Myanmar Ranges. This study utilizes the field relation, petrographic, mineral chemistry, and detrital zircon geochronology of sandstones from the Tusom CV area of the Manipur Ophiolite Belt to establish the forearc sedimentation and its significance in the subduction initiation within the south-eastern arm of the Neo-Tethys. Field and petrological observations show that these sandstones, which are in close spatial association with mantle peridotites and metamorphic sole rocks, are of lithic to sub-lithic arenite compositions. The lithic components consist of basaltic rock fragments, radiolarian cherts, shale fragments and mineral grains of zircon, garnet, epidote, spinel, phengite, titanite, allanite, pyroxene, and apatite. Garnet of six compositional varieties has been identified. These are - type-1 ($Prp_{8-11}Alm_{56-69}Sps_{02}Grs_{19-33}$), type-2 ($Prp_{0-3}Alm_{55-64}$ $Sps_{35-41}Grs_{1-2}$), type-3 ($Prp_{40-41}Alm_{52-53}Sps_{01}Grs_{05-06}$), type-4 ($Prp_{25-27}Alm_{59-61}Sps_{01}Grs_{13-14}$), type-5 ($Prp_{21-25}Alm_{47-52}Sps_{09-14}Grs_{13-18}$), and type-6 ($Prp_{00}Alm_{60-62}Sps_{08-11}Grs_{28-31}$). Aluminous and chrome spinels show a compositional variation in $Cr^{\#}$ from 0.26 to 0.62. While most of the zircon grains show bi-pyramidal terminations with characteristic oscillatory zoning, a few is represented by structureless subrounded grains. Detrital U-Pb zircon ages show two dominant age populations at c. 95 ± 1 Ma, and 103 ± 1 Ma, with minor age peaks at c. 3533 Ma, 1564 Ma, c. 1274-1091 Ma, c.570 Ma and c. 236-225 Ma. We relate the textural, mineral compositional and age data of the sediments with relatively short transportation and deposition in a tectonically active environment, and a provenance that ranges from suprasubduction zone ophiolitic crust through abyssal peridotites to back arc basin basalts to HP/LT metamorphic rocks (cf. eclogites and blueschists) in the accretionary wedge of the Nagaland segment of the ophiolite belt. The two zircon age populations (at c.95 and c. 103 Ma) in the sediments coincide with the subduction-related magmatic events (90-108 Ma) in the Wuntho-Popa Arc (WPA) of the central ophiolite belt of the Indo-Myanmar Ranges. We integrate these findings along with the age of the ophiolite crust formation at c.116-119 Ma in the MOB to suggest a two-stage process of Neo-Tethyan fore-arc sedimentation in the Early Cretaceous – (a) formation of an ophiolitic crust during subduction initiation as the basement of the Manipur forearc basin at c.116-119 Ma and (b) beginning of terrigenous sedimentation at ≤ c.95-103 Ma, reflecting the onset of topographic growth and erosion of the Wuntho-Popa Arc.

Sedimentary Provenance of the Mesozoic and Cenozoic stratigraphy,Tethyan Fold Thrust Belt, South-Central Tibet

Davis S.*[1], Robinson D.M.[1] & Metcalf K.[2]

[1]Department of Geological Sciences, The University of Alabama, Tuscaloosa. [2]Department of Geological Sciences, California State University, Fullerton.

Corresponding author email: sdavis27@crimson.ua.edu

Keywords: Tethyan, Provenance, Detrital Zircon.

During the India-Asia collision, the northern part of Greater India, which contained the Tethyan Himalaya, was deformed from ~60-30 Ma into the Tethyan fold-thrust belt (TFTB) (Kapp and DeCelles, 2019). However, details on the preexisting stratigraphic architecture, timing and style of collision between India and Eurasia are limited. It is also unclear how sedimentary provenance varies from north to south, across strike, and from east to west, along strike in the Tethyan Himalaya. In order to understand the components of the TFTB, we collected samples from Triassic, Cretaceous, and suspected Tertiary rocks in the TFTB from three different transects with an along strike distance of ~125 km. Nine samples yielded zircon for maximum depositional ages (MDAs) and age spectra. Four samples from Triassic rocks are from both the northern and southern Triassic units from the three transects to determine if there is a difference in provenance between areas north and south of the gneissic domes. From Cretaceous rocks, we have three samples, one from each transect, from which we correlate the MDAs and age spectra. In addition, we have two samples from two different transects in rocks that are marked as Tertiary rocks on the geologic map. The age and provenance of these synorogenic sedimentary rocks provide key constraints on the development of the TFTB. With these new detrital zircon U-Pb ages, we correlate Mesozoic and Cenozoic units along and across strike, determine the provenance of Tethyan rocks, and provide insight into the stratigraphic evolution of northern Greater India.

Kapp P. & DeCelles P.G. (2019) - Mesozoic–Cenozoic geological evolution of the Himalayan–Tibetan orogen and working tectonic hypotheses: American Journal of Science, 319, 159–254.

Tectonic and Climatic coupling on bedrock gorge incision in the western Himalayan interiors

Dey S.*[1,2], Godard V.[2,3], Thiede R.C.[4], Das S.[1], Bookhagen B.[5], Scherler D.[6] & ASTER team[2]

[1] Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India. [2] Aix Marseille University, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France. [3] Institut Universitaire de France (IUF), Paris, France. [4] Institute of Geosciences, Christian Albrechts University, Kiel, Germany. [5] Institute of Geosciences, University of Potsdam, Germany. [6] Helmholz Zentrum, GFZ Potsdam, Germany.

Corresponding author email: saptarshi@gg.iitkgp.ac.in

Keywords: landscape evolution, terrestrial cosmogenic nuclides, optically stimulated luminescence, active faulting, climate change.

Incision of bedrock-river gorges is often linked to tectonic and/or climatic forcing processes. However, this has been challenging to verify within the Himalaya, where tectonics and climate-driven erosion is coupled. With new ^{10}Be surface exposure ages from the deeply incised river gorge of the Chenab River near the Kishtwar Window in the western Himalaya, we document a time-averaged incision rate of 3.3±0.3 mm/yr over the last ~100 kyr. Similarity between these 10^4-year incision rates and previously published 10^6-year Apatite Fission Track exhumation rates suggest a first-order control of tectonic processes driving bedrock incision. Various morphometric parameters and field observation also indicate recent active uplift along the western margin of the Kishtwar Window. These findings also agree with modern-day catchment-averaged denudation rates are also higher (1.8 – 3.0 mm/yr) along the western margin of the window compared to the surroundings (≤1.0 mm/yr). All these evidences, point towards a dominant tectonic control, most likely related to duplex growth on landscape evolution near the Kishtwar Window. Looking at our new data in more detail, our obtained incision rates could be also interpreted to reveal strong temporal fluctuations in fluvial incision rates varying between ~1 and +4 mm/y on millennial timescales. Interestingly these periods with high incision rates temporally correlate with periods of strong insolation and strengthened monsoon. We suggest that climate variability modulates millennial-scale bedrock incision rates, but long-term landscape incision/ evolution in this case is dictated by tectonic uplift – most likely related to long-term duplex growth.

Dey S. et al. (2021) - Implications of the ongoing rock uplift in NW Himalayan interiors. Earth Surface Dynamics, 9, 463-485.

Gavillot Y. et al. (2018) - Late Cenozoic foreland-to-hinterland low-temperature exhumation history of the Kashmir Himalaya. Tectonics, 37, 3041-3068.

Gavillot, Y. (2014) - Active tectonics of the Kashmir Himalaya (NW India) and earthquake potential on folds, out-of-sequence thrusts, and duplexes.

Leland J. et al. (1998) - Incision and differential bedrock uplift along the Indus River near Nanga Parbat, Pakistan Himalaya, from ^{10}Be and ^{26}Al exposure age dating of bedrock straths. Earth Planet. Sci. Lett., 154, 93-107.

Paleostress Inversion of the Hettangian-Messinian Rocks, Hazara-Kashmir Basin, NW Himalayas, Pakistan

Ejaz A.*[1] , Ahsan N.[1] & Miraj M.A.F.[1]

[1]Institute of Geology, University of the Punjab, Lahore (54590) Pakistan.

Corresponding author email: ayesha.mphil.geo@pu.edu.pk

Keywords: Paleostress inversion, Hazara Kashmir Syntaxis, Slip analysis, Slickensides, Compressional stress regime.

Understanding the relationship between structural evolution and the orientation of paleostresses is crucial for developing tectonic models in the study area. This research focuses on analyzing slip and stress reorientation using plane solutions to determine the position of the principal stress axis (σ1) within fracture patterns in rocks along the Hazara Kashmir Syntaxis in the NW Himalaya, Pakistan. The paleostress inversion technique is employed to interpret the paleostress conditions based on fault slip data collected in the field. To obtain the Pressure, Tension, and Null axes, as well as the stress ratio and principal stress axis (σ1), we utilized the Right Dihedron Method with the Win-Tensor software. This interactive computer program aids in fracture analysis and the reconstruction of paleostress, offering valuable insights into the developed fracture patterns.

The deformational history of the Hazara Kashmir Basin suggests an early collision between two India-Asia, resulting in episodic deformation characterized by an NE-SW structural trend. The northern boundary of Hazara Kashmir Basin is marked by Panjal Thrust whereas the southern boundary is marked by the Main Boundary Thrust (MBT). The area between these thrusts is the primary focus of this research. Various stratigraphic units juxtapose in the Hazara Kashmir Syntaxis (HKS), demonstrating a strike-slip component through imbrication caused by thrusts. Slickenside data was gathered from over 20 locations, resulting in a total of 109 readings, including plunge and azimuth values. The collected data includes the orientation (dip amount, direction, and strike) of fracture planes, as well as the density of fractures within a specific area and the material filling the fractures. The stress regime analysis of the Hazara Kashmir Syntaxis and Neelum Valley areas, utilizing the PBT Axes Method, Right Dihedron Method, and Rotational Optimization Method, reveals consistent findings of a compressional stress regime. In the Hazara Kashmir Syntaxis, the stress regime is identified as radial compressive with σ1 sub-horizontal and σ2 and σ3 vertical. Similarly, in the Neelum Valley, the results confirm a pure compressional stress regime with perpendicular PBT axes. These results enhance the understanding of tectonic stress distribution and geological dynamics in these regions.

Reconstructing the Paleoenvironment of the Lower-Middle Swat Valley: new Insights into the Rise of the Gandhara Culture

Fellin M.G.*[1], Faccenna C.[2], Battistel D.[3], Iori E.[4], Olivetti V.[2], Olivieri L.M.[4], Scherler D.[5] & Sembroni A.[6]

[1]Department of Earth and Planetary Sciences, ETH Zürich. [2]Department of Science, Roma Tre University. [3]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscoari University of Venice. [4]Department of Asian and North African Studies, Ca' Foscoari University of Venice. [5]Earth Surface Geochemistry Section, GFZ Potsdam. [5]Servizio Geologico d'Italia, ISPRA.

Corresponding author email: giuditta.fellin@eaps.ethz.ch

Keywords: landscape evolution, archeology, sedimentary processes.

The lower-middle Swat Valley in northern Pakistan lies parallel to the Main Mantle Thrust, with the Kohistan Arc exposed along its northern flank and Indian Plate rocks along the southern margin. This region constitutes the historical heartland of the Gandhara culture, which began to flourish approximately 3,000 years ago. Over several decades, the ISMEO Italian Archaeological Mission in Pakistan has collected extensive archaeological and geological data from the area.

In this study, we present a first attempt to integrate this multidisciplinary dataset within a geological framework, aiming to explore the paleoenvironmental and climatic conditions that may have contributed to the emergence and development of the Gandhara culture. Our approach combines geomorphological and stratigraphic field observations with new geochronological and geochemical analyses.

We will discuss how sedimentary processes, landscape evolution, and climatic variability potentially intersected with cultural development in the valley. This integrative analysis is intended to provide a foundation for further investigation into the role of environmental factors in shaping early complex societies in the region.

Metamorphic evolution and fluid production in anatectic metapelite xenoliths from the Tibetan Plateau (northern Karakorum, China)

Ferrando S.*[1], Pasero F.[1], Maffeis A.[2], Frezzotti M.L.[2], Groppo C.[1] & Rolfo F.[1]

[1]Dipartimento di Scienze della Terra, Università di Torino, Italy. [2]Dipartimento di Scienze dell'Ambiente e della Terra, Università di Milano-Bicocca, Italy.

Corresponding author email: simona.ferrando@unito.it

Keywords: COHN fluid, graphite, lower crust.

The aim of this work is to investigate the role of water and carbon during crustal anatexis at the amphibolite-to-granulite facies transition by classical metamorphic petrology in crustal migmatites and by fluid inclusion study in their peritectic minerals. In particular, we studied anatectic graphite-bearing metapelite xenoliths hosted in lamprophyric dykes from the Shaksgam valley, northern Karakorum (Xinjiang, China) (Pognante, 1990; Rolfo et al., 2014) to investigate the metamorphic evolution and the fluid-melt production occurred in the upper part of the lower crust of the Tibetan plateau.

The anatectic graphite-bearing metapelites are porphyroblastic and weakly foliated. They mainly contain Grt, Pl, Qz, Kfs, and accessory rutile and graphite. Although chemically homogeneous, the pophyroblastic Grt includes rare Bt and Ky relics in the core, fluid inclusions (s.l.) at the core-rim transition, and Sil needles in the rim.

A fluid inclusion study based on petrography, BSE imaging, EDS analysis and micro-Raman spectroscopy has been performed on the inclusions randomly distributed at the Grt core-rim transition. Theseare dark to light-coloured multiphase inclusions, with dimensions of 5-20 µm in diameter, and occur in association with elissoidal Gr flakes or Gr+Qz or Gr+Ap. They show negative crystal shape and local evidence of decrepitation. The inclusions contain variable proportions of CO_2, N_2, carbonates, graphite, apatite, pyrophyllite, chlorite, biotite, quartz, feldspars, ilmenite, Fe-Mg oxide, Na/Ca sulfate.

Microstructures, mineral assemblages and fluid inclusion study suggest metamorphic re-equilibration of the graphite-bearing metapelites at HP-HT conditions and subsequent partial melting and COHN fluid production through mica dehydration and graphite oxidation.

Pognante U. (1990) - Shoshonitic and ultrapotassic post-collisional dykes from northern Karakorum (Sinkiang, China). Lithos, 26, 305-316, https://doi.org/10.1016/0024-4937(91)90035-J.

Rolfo F. et al. (2014) - A geological cross-section north of Karakorum, from Yarkand to K2. J.Virtual Expl., 47, paper 1, https://doi.org/10.3809/jvirtex.2014.00336.

Stable isotope paleoaltimetry of the Bhutan region

Fidalgo J.C. *[1], Gébelin A.[1], Grujic D.[2], France-Lanord C.[3], Dupont-Nivet G.[4], Ruffet G.[4] & Alexandre A.[5]

[1]Université de Lorraine, CNRS, UMR7359, GeoRessources, F-54000 Nancy, France. [2]Department of Earth Sciences, Dalhousie University, Halifax, NS, Canada B3H 4J1. [3]Université de Lorraine, CNRS, UMR7358, CRPG, F-54000 Nancy, France. [4]Géosciences Rennes, CNRS, UMR6118, Univ. Rennes, France. [5]Aix Marseille University, CNRS, CEREGE, Aix-en-Provence, France.

Corresponding author email: jean-charles.fidalgo@univ-lorraine.fr

Keywords: South Tibetan Detachment, Hydrogen isotope, Triple oxygen isotopes, Miocene topography.

Long-term climatic evolution and atmospheric circulation patterns are primarily influenced by the topography of the largest mountain ranges. This study aims to quantify the Miocene topographic evolution of the eastern part of the Bhutan Himalayas, resulting from complex interactions at the atmosphere-hydrosphere-biosphere-lithosphere interface. We acquired stable isotope paleoaltimetry estimates based on a technique that recovers the isotopic composition of ancient meteoric water, which has been shown to scale in a predictable way with elevation. Our "geologic archive" of such ancient meteoric waters is the South Tibetan detachment (STD) in Bhutan (e.g. Kellett et al., 2009), which, in the Mount Everest region, represented a major hydrothermal system involving meteoric fluids during its Miocene activity (Gébelin et al., 2017).

Here, we use a multidisciplinary multi-scale approach combining petrostructural analysis, hydrogen and oxygen isotopes, Raman spectroscopy, and geochronological data (U/Pb and Ar/Ar) to determine the fluid source and the timing of mineral water isotope exchange. $\delta D_{muscovite}$ values as low as -178 ‰ from metapelites and leucogranites indicate that the STD was infiltrated by meteoric fluids sourced at high elevation. This signature of surface-derived fluids is strengthened by low salinity water (0,48 - 2,29 wt% eq. NaCl) from fluid inclusions and low $d^{18}o_{muscovite}$ values from 8,5 ‰ and 10,7‰ typical for muscovite interacting with meteoric water.

Our paleoelevation estimates, deduced using well-established methods (D/H on silicate) (e.g. Dusséaux et al., 2021) and a new approach such as the triple oxygen isotope (^{16}O, ^{17}O, ^{18}O) (Chamberlain et al., 2021), indicate that the mean elevation of the Bhutan region was higher than it is today during the Middle Miocene.

Kellett, D. et al. (2009) – Miocene structural reorganization of the South Tibetan detachment, eastern Himalaya: Implications of continental collision. Lithosphere, 1 (5), 259-281, https://doi.org/10.1130/L56.1.

Gébelin, A. et al. (2017) - Infiltration of meteoric water in the South Tibetan Detachment (Mount Everest, Himalaya): when and why? Tectonics 36, 690–713, https://doi.org /10.1002 /2016TC004399.

Dusséaux, C. et al. (2021) - Late Carboniferous paleoelevation of the Variscan Belt of Western Europe. *Earth and Planet. Sci. Lett.*, 569, 117064, https://doi.org/10.1016/j.epsl.2021.117064.

Chamberlain, C.P. et al. (2021) – Triple oxygen isotope paleoaltimetry of crystalline rocks. Front. Earth Sci., 9:633687, https://doi.org/10.3389/feart.2021.633687.

Mesozoic and Cenozoic deformations of the Tethyan sequence in the Kali Gandaki Valley, Nepal Himalaya

Fodor L.*[1,2], Barmuta J.[3], Krobicki M.[4] & Starzec K.[4]

[1]HUN-REN Institute of Earth Physics and Space Sciences, Sopron, Hungary. [2]Eötvös University, Institute of Geography and Earth Sciences, Department of Geology, Budapest, Hungary. [3]Institute of Geological Sciences, Polish Academy of Science, Kraków, Poland. [4]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Kraków, Poland.

Corresponding author email: lasz.fodor@yahoo.com

Keywords: structural geology, Jurassic, Lupra Fault.

Structural investigations of the Mesozoic interval of the Tethyan Sedimentary Sequence (TSS) of the Thakkhola Graben between Jomsom and Kagbeni villages allowed us for (1) the identification of previously unreported deformation phase (D1) affecting the Triassic and Lower Jurassic strata prior to their tilting, and (2) kinematic description of Cenozoic map-scale faults striking sub-orthogonal to graben-bounding extensional faults (D2). Conjugate normal faults, joints, and veins affected variously tilted layers, including overturned Upper Triassic beds (on both sides of the Kali Gandaki Valley, ~1–2 km north of Jomsom). Tilt test of fault-slip data of the D1 phase always indicate fracturing before the tilting of the Mesozoic layers. Between Jomsom and Eklebathi, syn-sedimentary thickening of Lower Jurassic beds of the hanging wall was documented. Important thickness variations of several stratigraphic units occur, which could also be connected to normal faulting. After back-tilting, the fault-slip data document ~N–S extension, although E–W extension also occurs locally. These extensional structures were overprinted by thrust or strike-slip faults, indicating their older age. These structures can be connected to the Tethyan rifting during the Early(?) Jurassic, although a somewhat younger age could not be excluded.

North of Jomsom, the Triassic to Jurassic sequence is repeated three times by sub-vertical to steeply north-dipping faults. One of them is the Lupra Fault, whose kinematics is still not clear (Godin, 2003). Rarely preserved striae on exposed surfaces of fault gauges of the main faults suggest dip-slip separation, so their strike-slip origin was not confirmed. Fault-gauge dating by the K-Ar method is under preparation. The faults have layer-parallel segments but can also cut the stratigraphy at a low angle. The northern hanging wall contains Triassic to Lower Jurassic formations, while in the southern block the stratigraphy goes up to Callovian or Oxfordian. Together with the steep dip, this may point to thrusting before a major part of the Cenozoic folding. Back-tilting of striated faults may suggest a NNE–SSW compression. In this scenario, this deformation could be connected to the D1 or D2 deformation phase of Godin (2003).

The post-folding structures document continuation of the N–S to NE–SW compression but also the E–W extension related to the formation of the Thakkhola graben. Due to ambiguities in the relative chronology of fractures, the sequence of deformation is not resolved.

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This is the contribution No. 1. of the scientific initiative of the Himalayan Academy.

Godin L. (2003) - Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya. J. Asian Earth Sci. 22(4), 307-328. https://doi.org/10.1016/S1367-9120(03)00066-X.

Increasing hazards in the rain-shadow side of the Himalayas: how to be prepared to Climate Change? Focus on 2023 flood in Kagbeni (Mustang District), Nepal

Fort M.*[1]

[1]Département de Géographie, UFR GHES, Université Paris-Cité, UMR 8586 PRODIG, 75205 Paris Cedex 13, France.

Corresponding author email: fort.monique@gmail.com

Keywords: debris-laden flood, sampling, climate change.

In the Himalayas, recent trends of global warming are mostly expressed by three main types of natural disasters: Glacial Lake Outburst floods, Rock and Ice-collapse from high mountain walls, and disastrous floods, which may be cascading downstream catchments. If these disasters are frequent in the southern, monsoon side of the Himalayas, they are now developing on the northern rain-shadow side.

Our focus is on Mustang District (Nepal), and more specifically on the debris-laden flood of the Jhong Khola (Aug. 13, 2023), a left bank tributary of the Kali Gandaki River. This flood has significantly affected the village of Kagbeni (2810 m, 420 inhabitants), with damage to property and infrastructures worth about USD 7.4 million. We show that, in a catchment characterized by highly contrasted bedrock and landforms, this exceptional flood was caused by two triggers, (i) heavy rainfall events and (ii) landslides, the combination of which have generated a landslide outburst flood. Cascading impacts have developed all along the >15 km long channel, with alternances of debris deposition and bank erosion. The volume of debris transported was estimated at 647,000 m^3, followed by rapid post-flood re-incision (215,000 m^3). In Kagbeni, the impacts of the flood were amplified by two important, aggravating factors: the destruction of the road bridge leading to Upper Mustang, and the recent changes in urbanization due to tourism development, with settlements in the "freedom space" of the Jhong Khola torrential River. About 29 houses, 1 motorable bridge, 1 steel truss bridge, and 3 temporary bridges were destroyed, while more than 25 cows and other livestock were killed. Fortunately, human lives were spared because the community was warned by relatives and friends living upstream to move to safe places before the mud and sludge hit the village (Fort et al., submitted).

Considering the possibility of reoccurrence of such hyper-concentrated floods in Kagbeni (and elsewhere), we suggest (i) to apply the concept of "functional space of a river" and develop it at the Nepal scale: this means delimiting and maintaining the natural "freedom space" of rivers and streams and keeping them free of construction; (ii) either to improve the design of the bridges, or consider the fords as a better, technical, financial and sustainable option. (iii) More generally, this case study illustrates well the fact that climate change can no longer be denied, so it would be necessary to (iv) increase the number of high-altitude (>3,500 m) weather stations in Nepal and ensure they are properly maintained; (v) similarly, setting up flood monitoring would help following discharge fluctuations in relation with precipitation. All these points could be included in the strategy developed by the National Platform for Disaster Risk Reduction (NPDRR) of Nepal.

Fort M. et al. (submitted) - The Kagbeni flood event (August 13, 2023), Mustang District (Nepal): Triggers, sediment cascades, aggravating infrastructures and disaster risk management.

Carbonates in turbidites of the Bengal Fan and erosion of Himalayan carbonated formations since Miocene

France-Lanord C.*[1], Galy A.[1], Galy V.[2], Limonta M.[1-3], Rigaudier T.[1], Ryb U.[4] & Tachambalath A.[1]

[1] Centre de Recherche Pétrographiques et Géochimiques, Université de Lorraine CNRS France. [2] Woods Hole Oceanographic Institute, MA-USA. [3] Laboratory of Provenance Studies, Department of Earth and Environmental Sciences, Università di Milano-Bicocca, Italy. [4] The Freddy and Nadine Hermann Institute of Earth Sciences, The Hebrew University of Jerusalem, Israel.

Corresponding author email: christian.france-lanord@univ-lorraine.fr

Keywords: Erosion, weathering, isotopic geochemistry, deep sea drilling, IODP Expedition 354.

The Bengal Fan records the Himalayan erosion through the accumulation of turbiditic sediments. Himalayan river sediments are transferred from the Bangladesh delta to the shelf and submarine canyon, the Swatch of No Ground, from where turbidity currents drive sediments along channel levees and disperse sediment over 3000 km south of the delta. On land, the Ganga and Brahmaputra rivers export particulate carbonate resulting from the physical erosion of limestone, marls and marble present mainly in the Tethys Himalaya and lesser Himalaya. Downstream, the river also incorporates pedogenic/authigenic carbonates generated in the floodplain (Ryb et al. 2024). In spite of high runoff, these rivers reach carbonate saturation and export particulate carbonate to the ocean. The modern Ganga River exports ≈ 3 wt. % of calcite and dolomite whereas the Brahmaputra dissolves most of its detrital carbonate load. In the Bengal Fan, detrital carbonates are easily sorted from marine carbonates thanks to their low $d^{18}O_{V\text{-}PDB}$ acquired during metamorphic stage or in pedogenic stage. The carbonate content of Holocene sediments is comparable to that of the modern rivers and is higher in LGM sediments, likely reflecting lower weathering intensity during this period (Lupker et al. 2013).

The IODP Expedition 354 drilled seven sites over an E-W transect (8°N/≈3600 mbsl) in the Bengal Fan composing a Neogene record of erosion. There, large variations of carbonate proportion are observed with maxima around 10 wt. % reached during the upper Miocene. C & O isotopic analyses of the carbonate load of the turbidite reveal a complex variability with 50% of the samples with $d^{18}O$ between -12 and -8‰, and $d^{13}C$ between -2 and 0‰ characteristic of the detrital carbonate. Other samples display mixing trends towards biogenic carbonate or a diagenetic endmember with high $d^{18}O$ around -2‰ and low $d^{13}C$ around -8‰. The deconvolution of this triple endmember mixing allows to estimate the proportion of Himalayan detrital carbonate through time. Combined with carbonate Δ_{47} (Ryb et al. 2024) and $^{87}Sr/^{86}Sr$ data, this shows that carbonates from the Tethys Himalaya were dominant and abundant (4-7%) during the Miocene. During Pliocene, the carbonate proportion drops to about 3% and carbonates from the Lesser Himalaya appear as a source of carbonates. While we can rule out the hypothesis of lower weathering of carbonate during Miocene, these data suggest that exposure of the Tethys Himalaya to erosion was higher during Miocene that in the modern situation. In addition the erosion of the Lesser Himalaya appears significant in the carbonate load during Pliocene.

Lupker,M. et al. (2013) - Increasing chemical weathering in the Himalayan system since the Last Glacial Maximum. Earth Planet.. Sci. Lett., 365, 243–252, https://doi.org/10.1016/j.epsl.2013.01.038

Ryb U. et al. (2024). Late Miocene Uplift and Exhumation of the Lesser Himalaya Recorded by Clumped Isotope Compositions of Detrital Carbonate. Geoph. Res. Lett., 51, e2024GL109643. https://doi.org/10.1029/2024GL109643.

Dhaubadi Ooidal ironstone/ Iron ore deposit, Gandaki Province, Nepal

Gaire P.*[1], Bhandari S.[2] & Thapa S.K.[1]

[1]Dhaubadi Iron Company Limited, Nepal. [2]Department of Mines and Geology, Nepal.

Corresponding author email: pashupatigaire11@gmail.com

Keywords: Lesser Himalaya, Melpani Formation, Oolitic hematite, Dhaubadi Ooidal Ironstone.

The geologically Olitic hematite mineralization lies in the inner belt of Lesser Himalaya sequence which is the Melpani formation is equivalent to the Amile formation of the Tansen Group (Sakai 1983), and late Cretaceous to Paleocene age. The Melpani Formation is the rocks comprises black to olive green claystone green quartzite thick-bedded with white quartzite and black shales interbed with hematite bands. White grey ferruginous quarzitic sandstone and grey to dark grey shale with the basal conglomerate. hematite Mineralization zone lies in the middle parts of the formation along with intercalation with a north dipping non-ferruginous quartzite and slate. The genetic types of the Dhaubadi Iron deposits are sedimentary metamorphosed hematite-magnetite thin-bedded to massive and are interbedded with grey to olive green quartzite and greenish-grey to gray slates. The iron ore is compact fine to coarse-grained Oolitic and siliceous whuch consists ofclast and faint gradation indicative of a current deposition environment. The grain of Oolitic hematite is generally fine disseminated to oolitic texture and mainly occurs as intergrowth with or inclusion in silicate, chamosite, and phosphate-bearing minerals.

Dhaubadi Iron ore is characterized by ooidal texture and average chemical grade (average 35% total iron content). Ooid is defined by Wikipedia as "small (commonly ≤2 mm in diameter), spheroidal, "coated" (layered) sedimentary grains, usually composed of calcium carbonate, but sometimes made up of iron- or phosphate-based minerals. Ooids usually form on the sea floor, most commonly in shallow tropical seas. After being buried under additional sediment, these ooid grains can be cemented together to form a sedimentary rock called an oolite. The texture of Dhaubadi Ooidal Ironstone exhibit unique ooidal structures with the nucleus of quartz grain, whereas rim is surrounded by ferrous minerals which might have accumulated in a "snowball" fashion from tiny crystals in the sediment or water. Overall texture depicts silica grain as clast and ferrous mineral as matrix.

Sakai H. (1983) - Geology of the Tansen group of the Lesser Himalaya in Nepal: Memoirs of the Faculty Science, Kyushu University, Series D, 25, 27–74.

Hot springs and their tectonics settings: an overview from Nepal Himalaya

Gajurel A.P.*[1], Girault F.[2], France-Lanord C.[3] & Upadhyaya B.[4]

[1]Department of Geology, Tri-Chandra Multiple Campus, Tribhuvan University, Nepal. [2]Paris Cité University, Paris, France. [3]University of Nancy, Vandoeuvre-lès-Nancy, France. [4]Water Resources Research and Development Centre, Minister of Energy, Water Resources and Irrigation, Pulchowk, Lalitpur.

Corresponding author email: apgajurel@fulbrightmail.org

Keywords: Hot spring, tectonic unit, Nepal Himalaya.

The Siwalik, the Lesser Himalayan Sedimentary Sequence (LHSS), the Higher Himalayan Crystalline Sequence (HHCS), and the Tibetan Tethys Himalayan Sedimentary Sequence (TTHSS) are the four tectonic units that make up the Nepal Himalaya. From south to north, these units comprise 16 to 1 Ma sedimentary continental molasse deposits, 1.8 to 1.1 Ga meta-sedimentary deposits that are about 14 km thick, 0.9 to 0.5 Ga amphibolite-grade metamorphic rocks with about 25–15 Ma leucogranite, and Cambrian to Cretaceous 10 km thick Tibetan Tethys Himalayan sediments in Nepal Himalaya. Major Himalayan megathrusts that delineate these tectonic units at the bottom and top include the South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT), respectively appear from north to south. An overview of Nepal's hot spring distributions in terms of geology and large-scale tectonic structures is the aim of this paper, which focuses on the physical and geochemical properties of the hot springs, particularly their temperature and chemical variability in relation to the lithology and tectonic setting. The temperature and lithology of these hot springs will also be assessed based on the physiographic characteristics of the Nepal Himalaya. In the Nepal Himalaya, the Main Central Thrust zone is mostly where hot springs are located. Few hot springs that appear from sandstones and gravel deposits may be found in the Siwalik zone, in contrast to the Terai plain, where hot springs are uncommon. The Higher and Lower Himalayan sequences, on the other hand, are the site of a large number of hot springs. Hot springs in the Higher Himalayan Crystalline sequence are encased in schists, quartzites, and gneisses, whereas meta-sandstones and quartzites are prevalent in the Lesser Himalayan hot spring outlet area. Ninety-nine hot springs are located above the MCT in the High Himalayan Crystalline sequence, and one hundred are located below the MCT in the Lesser Himalayan sequence (LHS). From the Tibetan Tethys Sedimentary Sequence (TTSS), eleven hot springs have been identified. At their discharge, some hot springs can reach temperatures of up to 70 degrees Celsius. In this work, we will further investigate the role of relief in meteoric water circulation.

Structural Evolution of Mud-Intrusive and Mud-Extrusive System in the Makran Accretionary Wedge: Tectonic Insights from the India-Arabia-Eurasia Triple Junction

Gardezi S.A.H.*[1,2,3], Luan X.[4] & Sun Z.[5]

[1]Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China. [2]University of Chinese Academy of Sciences, Beijing, China. [3]Azad Jammu and Kashmir Directorate, Geological Survey of Pakistan, Muzaffarabad, Pakistan. [4]College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao, China. [5]Guangzhou Marine Geological Survey, China Geological Survey, Nansha District, Guangzhou China.

Corresponding author email: ahsangardezi2504@gmail.com

Keywords: Makran Accretionary Wedge, Mud-intrusive and mud-extrusive system, Fluid migration.

The Makran Accretionary Wedge (MAW) in Pakistan and Iran, formed by the north-dipping subduction of the Arabian Plate beneath the Eurasian Plate, provides optimal conditions to investigate the structural evolution of mud-intrusive and mud-extrusive systems (MIES) within an ultra-slow subduction zone. The convergence, initiated during the Late Cretaceous with a renewed phase of subduction since the Middle Miocene, led to intense tectonic imbrication, which deformed the pre-existing strata. This has resulted in the deformation of pre-existing strata and the development of complex structural features, including piggyback basins filled with growth strata, preserving a continuous record of tectono-sedimentary interactions.

This study utilized two-dimensional seismic reflection profiles, satellite imagery, and bathymetric data to map and characterize the geometry, spatial distribution, and connectivity of surface and subsurface mud-structures within the MAW. We define 'MIES' as a complex plumbing system of mud-related structures such as mud-volcanoes (MVs), mud-diapirs (MDs), feeder-pipes, gas-chimneys, mud-chambers etc., linked through vertical and lateral feeder networks to their source rocks, particularly the Makran Turbidite Deposits (MTDs). These MTDs, rich in hemipelagic mud, became overpressured due to tectonic loading and compaction, driving mud and/or fluid migration through fracture networks and structural discontinuities into the MIES.

Our analysis identifies four main classes of mud-structures: (i) deeply rooted, high-energy MVs sourced directly from the MTDs, (ii) low-energy MVs sourced from shallower levels, (iii) multisource MVs, and (iv) multisource MDs. These structures commonly exhibit conical, bifurcating, and Christmas-tree-like geometries that taper upward, with inclination angles between 75° and 105°, and are spatially aligned with thrust-related anticlines and north-dipping faults, indicating strong structural control. The active migration of overpressured mud and fluids contributes to the formation of mini-basins and enhances slope instability through gravitational faulting, especially near the coast. Additionally, ongoing fluid migration is indicated by the presence of bottom-simulating reflectors, suggesting active thermogenic gas generation within the MAW.

This research highlights the critical importance of understanding MIES for hydrocarbon exploration, environmental risk assessment, and broader geodynamic interpretations. The MAW is an example of typical MIES, influenced by compressional tectonics and a unique sedimentary architecture, might be applicable to understand mud-structures elsewhere.

Spatial and temporal distribution of Channel conglomerates from the Xigaze forearc basin and constraint on the erosion rate in the Late Cretaceous Gangdese arc

Ge Z.Y. *[1,2] & Jiang H.H.[1]

[1]State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. [2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China.

Corresponding author email: gezivi0910@163.com; jiang.hehe@mail.iggcas.ac.cn

Keywords: Gangdese arc, Xigaze forarc basin, channel conglomerate.

The Late Cretaceous is characterized by prolonged extreme greenhouse climate conditions, referred to as a "hothouse Earth" phase in geologic history. Development and termination of this hothouse period has been proposed to be driven by tectonic dynamics of the Neo-Tethyan and circum-Pacific subduction systems. However, quantitative constraints on the influence of crustal evolution on climate remain limited.

The Gangdese arc in southern Tibet, China, is developed during the northward subduction of the Neo-Tethyan oceanic lithosphere beneath the Eurasian continental lithosphere. The major magmatic flare-up took place between 100 and 80 Ma, in synchronous with the culmination of the Late Cretaceous hothouse condition. The main body of an arc-proximal forearc basin, the Xigaze Basin, was developed around the same time, with the majority of the detritus sourced from the magmatic arc. The development of this simple source-to-sink sedimentary system might provide key information in understanding the mechanisms in the termination of the greenhouse condition.

Channel conglomerates represent depositional facies attributed to accelerated erosional processes. In this study, we investigated the temporal and spatial distribution of major channel conglomerate-sandstone packages along three north-south-trending traverses in the eastern Xigaze basin. The goal is to provide a quantitative assessment of the erosion rate in the Gangdese arc during its magmatic climax, and further explore its climatic effect. Detrital zircon U-Pb geochronology was conducted for the sandstone adjacent or within the conglomerate to constrain the deposition age, as well as the transit time required for source-derived magmatic rocks to be eroded and delivered into the forearc basin (Δt). The results suggest the channel packages were developed predominantly during two-to-three episodes of fast erosion between 100 and 90 Ma basin-wide. Transit time recorded in examined samples ranges between 25 and 63 Myr. Given an average of ~15 km emplacement depths (h) of the Late Cretaceous intermediate-felsic intrusions within the Gangdese batholith indicated by Al-in-hornblende thermobarometry from existing dataset, denudation rates ($v=h/\Delta t$) of the Gangdese arc can be determined at 0.24–0.60 km/Myr.

Fluid-rock-deformation interactions in the fossil Zanskar detachment footwall (NW India) as a proxy of tectonic regime and past topography

Gébelin A.*[1], Law R.D.[2], Webster T.J. [3], Stahr III D.W.[2], Mulch A.[4,5], Teyssier C. [6] & Mauguin O.[7]

[1]Université de Lorraine, CNRS, UMR7359, GeoRessources, F-54000 Nancy, France. [2]Dept. of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA. [3]School of Environment, Earth and Ecosystem Sciences, The Open University, MK7 6AA, UK. [4]Senckenberg Biodiversity and Climate Research Centre, 60325 Frankfurt, Germany. [5]Goethe University Frankfurt, Institut für Geowissenschaften, 60438 Frankfurt, Germany. [6]Dept. of Geosciences, University of Minnesota, Minneapolis, MN 55455-0149, USA. [7]Géosciences Montpellier, Plateforme MAGE, Université de Montpellier, CNRS, UMR 5243, Montpellier, France.

Corresponding author email: aude.gebelin@univ-lorraine.fr

Keywords: South Tibetan Detachment, Hydrogen isotope, Quartz c-axis fabrics*,* Miocene topography.

The South Tibetan detachment (STD) parallels the west-east trending axis of the Himalayan range over > 1500 km and represents an untapped source of information for understanding the Cenozoic evolution of coupled climatic and tectonic processes of the world's highest mountain range.

Here, we present hydrogen isotope (d^2H) geochemistry, microstructural observations, quartz c-axis fabric deformation thermometry and EPMA data from NW India that document intense meteoric fluid-rock-deformation interactions within the upper part of the hot (~480±50°C) Zanskar detachment zone (ZDZ) footwall which, from Dezès et al. (1999), was active from ~22 to ~20 Ma. In contrast to low δ^2H values characterizing synkinematic hydrous silicates from the top of the ZDZ footwall, biotite and muscovite grains collected at greater depths yield high δ^2H values reflecting a signature of deep crustal fluid. These contrasting hydrogen isotope results can be correlated with quartz and muscovite microstructures as well as EPMA data, highlighting high iron and magnesium and low aluminum contents for muscovite at the top of the section compared to those at the bottom of the section.

Deformation temperatures estimated using the opening angle of quartz c-axes fabrics increase from 483°C at the top of the section to 681°C at the bottom; this gradient corresponds to the combined effects of crustal thinning, low-angle normal faulting/shearing, and refrigeration by convective circulation of surface fluids. The trend in the δ^2H values from low δ^2H values at the top of the section to high δ^2H values toward the bottom is interpreted to reflect lower time-averaged meteoric water-rock ratios with increasing structural depth and at temperatures of isotopic exchange that likely increased downward but are not well defined.

Calculated δ^2H_{water} values as low as -97‰ suggest that the Zanskar area was standing at least above 2500 m mean topographic elevation during the early Miocene. When compared with previous data obtained from Mount Everest, these results suggest that the Zanskar region was likely lower than the Mt Everest region during the Early to Middle Miocene, but still represented a regional topographic high.

Dèzes, P. J., Vannay, J.C., Steck, A., Bussy, F. et Cosca, M. 1999 - Synorogenic extension: Quantitative constraints on the age and displacement of the Zanskar shear zone (northwest Himalaya). Geol. Soc. Am. Bull., 111, 364-374, https://doi.org/10.1130/0016-7606(1999)111<0364:SEQCOT>2.3.CO;2.

The Tibetan–Himalayan paleotopography: The "TIBETOP" Project

Gébelin A.*[1], Dupont-Nivet G.[2], Licht A.[3], Rivera L.[1], Fidalgo J.C.[1], Moreau K.[2], Feng Z.[4], Xiaomin F.[4], Lavé J.[5], France-Lanord C.[5], Alexandre A[3], Grujic D.[6], Mercadier J.[1] & Ruffet G.[2]

[1]Université de Lorraine, CNRS, UMR7359, GeoRessources, F-54000 Nancy, France. [2]Géosciences Rennes, CNRS, UMR6118, Université de Rennes, France. [3]Aix Marseille University, CNRS, CEREGE, Aix-en-Provence, France. [4]Institute of Tibetan Plateau research, Chinese Academy of Sciences, Beijing, China. [5]Université de Lorraine, CNRS, UMR7358, CRPG, F-54000 Nancy, France. [6]Department of Earth and Environmental Sciences, Dalhousie University, Halifax, NS, Canada B3H 4R2.

Corresponding author email: aude.gebelin@univ-lorraine.fr

Keywords: Tibetan Plateau, Eocene and Miocene elevation, Coupled basin-detachment systems.

The "TIBETOP" project funded by the French National Research Agency aims to reconstruct the past topographic evolution of the world's highest Himalaya Mountains and Tibetan plateau that represent a natural laboratory to obtain models linking topography, geodynamic processes, drainages, biodiversity, and climate.

Different topographic growth scenarios have been proposed for the Himalayan-Tibetan orogen, and a fierce debate currently exists among several international groups, including our own. This lack of consensus can be attributed to: 1) the still limited spatial and temporal paleoelevation data, primarily concentrated in sedimentary basins, leaving the paleotopography of the surrounding mountain ranges virtually unconstrained; 2) the poor dating and stratigraphic correlations of most study sites; 3) the reliability of paleoaltimetry proxies that, if altered (e.g. diagenetic recrystallization, post deformation isotope exchange,…) , can lead to unreliable isotopic signatures.

This project proposes to unlock these limitations by applying new game-changing paleoaltitude proxies to new priority targets from the Eocene to the Miocene near-surface record and deeper crustal high-grade metamorphic rocks exhumed along high-strain zones. In addition to revising paleoaltitudes, new Ar/Ar and U-Pb ages from both basins and adjacent exhumed high-grade tectonites will be acquired to better understand the spatiotemporal evolution of fluid-rock-deformation interactions from the Earth's surface down to the middle and lower crust. This, in turn, will provide new insights on crustal-scale transport of fluids and exhumation processes.

Here, we will first present a compilation and reappraisal of the existing regional paleoelevation data, including stable isotope data from basin records as well as structural context, exhumation and fluid-rock deformation interactions at different interfaces of the continental crust. We will then present new data from the first field campaign conducted during the summer of 2025 in the Nyainqentanglha massif, North Himalayan gneiss domes, and the Lunpola basin.

An overview on the Miocene to Pliocene spatio-temporal structural evolution of the Western Himalayan Orogen in Pakistan: New evidence from low temperature thermochronology

Ghani H.*[1], Razzaq S.S.[1,6], Ali N.[3,4], Ghani M.[1,5], Ishfaq M.[1], Irum I.[3], Dunkl I.[2], Sobel E.R.[3], Kley J.[1] & Sajid M.[4]

[1]Department of Structural Geology and Geothermics, Georg-August University of Göttingen, Germany, [2]Department of Sedimentology, Georg-August University of Göttingen, Germany, [3]Institute of Geosciences, University of Potsdam, Germany, [4]Department of Geology, University of Peshawar, Pakistan, [5]Geological Survey of Pakistan, Peshawar Pakistan, [6]Institute of Geology, University of Azad Kashmir, Muzzafarabad Pakistan.

Corresponding author email: Humaad.ghani@uni-goettingen.de

Keywords: Himalaya, Main Central Thrust. Main Boundary Thrust, Exhumation.

Over the past decade, our research has focused on elucidating the large-scale spatiotemporal evolution and characterizing the style of deformation, magnitude of shortening, and the influence of pre-existing anisotropies in guiding deformation in the Western Himalayan Orogen. Our approach involves regional geological mapping, interpretation of seismic reflection profiles, construction of balanced cross-sections, and integration of apatite (U-Th-Sm)/He (AHe) and fission track (AFT) dating techniques. The results suggest that the Main Central thrust was active between ~29 Ma and ~18 Ma in the hinterland region. Deformation propagated toward the foreland on the Main Boundary Thrust (MBT) and older thrusts between ~12 and 8 Ma with the exception of specific zones in the Kashmir and Hazara regions, where the activity continued until 5 Ma. The southward younging deformation continued between ~8 and ~5 Ma on the internal faults of the Kohat-Potwar fold and thrust belts. During the Pliocene to Pleistocene, deformation was active on the Salt Range, Kotli, Bagh-Balakot, Samana and Karak faults in the Western Himalayas, and as well as in the Indus syntaxis. The limited thermochronology dataset from the Western Himalayan Axial fold and thrust belt (Sulaiman and Kirthar) suggests that deformation there is younger than ~12 Ma. The data suggest either that deformation propagated late in the region, roughly around the time of formation of the MBT in the Main Himalayan Range or that a significant part of the stratigraphy that records earlier deformation has been eroded from the region. Therefore, some stratigraphic signatures of uplift present along the India-Asia boundary in the Sulaiman and Kirthar fold and thrust belt need further investigation. The northern part of Suleiman and central part of Kirthar show focused exhumation since Pliocene to Pleistocene times.

Thermochronologic Constraints on the Deformation History of the Kirthar Fold-and-Thrust Belt, Balochistan, Western Pakistan

Ghani M.*[1,4], Ghani H.[1], Sobel E.R.[2], Kley J.[1], Dunkl I.[3], Hindle D.[1], Razzaq S.S.[1] & Ishfaq M.[1]

[1]Department of Structural Geology and Geothermics, Georg-August University of Göttingen. [2]Institute of Geoscience, University of Potsdam, Germany. [3]Department of Sedimentology and Environmental Geology, Georg-August University of Göttingen. [4]Geological Survey of Pakistan.

Corresponding author email: mukhtiar.ghani@geo.uni-goettingen.de

Keywords: Kirthar Fold and Thrust Belt, low-temperature thermochronology, thin-skinned deformation, thick-skinned.

The western fold-and-thrust belt (FTB) of Pakistan is structurally divided into the Sulaiman FTB in the north and the Kirthar FTB in the south, separated by the Quetta syntaxis. Despite its significance, no comprehensive deformation, exhumation and erosion model has yet been proposed.

In this study, we investigate the spatiotemporal structural evolution of the Kirthar FTB and the adjoining Katawaz Basin for the first time by integrating balanced cross-sections with low-temperature thermochronology (Apatite U-Th-Sm/ He (AHe), Fission track (AFT), and Zircon U-Th/He (ZHe)) age data. Our dataset (at the time of writing) includes 14 AHe, 9 AFT, and 4 ZHe surface ages, supplemented by 18 AFT, 56 vitrinite reflectance (VR), and 9 Rock-Eval (Ro) samples from foreland wells across the project area.

In the Northern Kirthar, partially reset Eocene AHe ages (31.6, 38.3, 16.4 Ma) and an AFT age of 135 ± 34 Ma, combined with unreset ZHe ages (187.7-424.6 Ma) from Cretaceous samples, indicate shallow burial and preserved signatures of pre-Oligocene uplift. In contrast, Central Kirthar records resetting of Paleocene to Oligocene samples with AHe ages (~6–8 Ma), however; the AFT (~119 ± 43 Ma) and ZHe ages ages (63-433 Ma) show partial resetting, suggesting Late Miocene to Pliocene rock uplift from ~3 km depth. In the Southern Kirthar, the westernmost samples near to India-Asia boundary yield Oligocene AHe ages of 5.3 ± 1.7 Ma, AFT ages of 23.3 ± 8.3 Ma, and un-reset ZHe ages (202.0 to 390.7 Ma), suggesting burial of ~3 km before exhumation. However, range-front samples show different patterns with a partial reset age (21.2–6.5 Ma) for, hanging-wall Oligocene and footwall Miocene samples show unreset older AHe ages. In the Katawaz Basin, deeper burial (~3-5km) is evident in the northern sector, while southern sectors experienced only limited burial, insufficient to reset AHe and AFT ages.

In conclusion, In the Northern Kirthar FTB, an early post-Paleocene to Early Eocene uplift likely halted sedimentation and preserved pre-Miocene signatures of deformation. The Central Kirthar records Late Miocene to Pliocene (~8–5 Ma) out-of-sequence thrusting. The Southern Kirthar exhibits Late Miocene deformation (~6 Ma) in the hinterland, but limited burial at the range front.

Glacial and landslide controls on the geomorphology of the Himalayan lakes: Insights from Lakes Rara and Phoksundo, western Nepal

Ghazoui Z[1]., Gemignani L.*[2], Carcaillet J.[1], Fort M.[3], Carosi R.[4] & van der Beek P.[1-5]

[1]Grenoble- Alpes University, ISTerre, 38000 Grenoble, France.[2]Department of Biological, Geological and Environmental Sciences (BiGeA), University of Bologna, Italy. [3]Département de Géographie, Université Paris Diderot - SPC, Paris, France. [4]Dipartimento di Scienze della Terra, University of Turin, Italy. [5]Institute for Geosciences, University of Potsdam, Germany.

Corresponding author email: lorenzo.gemignani@unibo.it

Keywords: Himalayan lakes, glacial landforms, terrestrial cosmogenic nuclides.

Reconstructing paleoenvironmental changes in remote Himalayan regions of western Nepal remains challenging, due to limited accessibility and sparse data. This study investigates Quaternary depositional environments, landforms, and sedimentary fills in glacial lakes Rara and Phoksundo, as well as in the Bheri and Suli Gad Valleys (Mugu-Karnali and Dolpo Districts, Nepal) to address regional glacial dynamics and climatic drivers. New surface-exposure dating using the Terrestrial Cosmogenic Nuclides (TCN) ^{10}Be and ^{36}Cl and morphological analysis of the deposits show that Rara Lake formed via glacial erosion during Marine Isotope Stage (MIS) 4 (60–75 ka). The configuration of geomorphic markers (e.g., cirque headwalls, lateral moraines) indicates a NW-flowing cirque glacier occupying the basin. Phoksundo Lake, in contrast, originated during the Last Glacial Maximum (LGM; 21–22 ka) through a combination of glacial erosion and glacial-interglacial rock avalanche damming of the valley, as evidenced by hummocky landslide deposits overlying glacial till. Moraine remnants in the Bheri and Suli Gad valleys are used to estimate maximum glacial extents and associated Equilibrium-Line Altitudes (ELA); we find that the reconstructed ELA for the Suli Gad glaciers was significantly lower than that for the Bheri glaciers, suggesting that the latter were less sensitive to climate change than the former. Finally, we show that the extent of glaciers during the LGM in western Nepal was larger than previous estimates from other Himalayan regions, which is possibly linked to the unique location of western Nepal, being influenced by both the westerlies and the Indian Summer Monsoon. Our findings refine paleoclimate models by highlighting western Nepal's distinct glacial response to Quaternary climate shifts, driven by its transitional position between monsoonal and westerly dominated systems and orographic configuration.

Integrated Geomorphic and Geotechnical Approach for Exploring Deep-seated Gravitational Slope Deformation around the Budhigandaki High Dam Reservoir, Central Nepal Himalaya

Ghimire N.* [1], Dahal R.K.[1] & Paudel L.P.[1]

[1]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: ghimring@gmail.com

Keywords: DGSD, gravitational slope, geomorphic features, rock mass characteristics, Himalaya, Budhigandaki Basin.

Deep-seated Gravitational Slope Deformation (DGSD) is a critical geomorphic process in tectonically active mountain belts and a potential precursor to catastrophic land-mass movement in the steep mountain terrain (Demurtas et al. 2021). This study examines DGSD phenomena in the Budhigandaki river basin at and around the high-dam abutments and reservoir rim, located within a structurally complex and seismically active section of the Lesser Himalaya, characterized by steep terrain, deeply incised valley and the terrains composed of low-grade metamorphic rocks. A multi-disciplinary approach combining high-resolution remote sensing, detailed geomorphic mapping, field-based structural surveys, and subsurface geotechnical investigations data were used to explore the state of nature of the DGSD in the research area. Diagnostic surface features- including double ridges, uphill-facing scarps, linear depressions, uneven slope characteristics, toe bulging and disturbed drainage patterns were identified through satellite imagery as well as field observation/measurements to validate in the field (Gori et al.2014). Subsurface investigations such as exploratory core drilling, in-situ testing, and test adit drifting including discontinuity survey for rock mass analysis revealed that DGSDs are strongly associated with weathered rock formations consisting of foliated, tightly folded and multi stressed quartzite, dolomite, and phyllite and rock masses exhibiting intense jointing and tectonic shear zones. Notably, weak planar discontinuities aligned with slope orientation enhanced potential gravitational movement.

Evaluation of the geotechnical data from six different test tunnels (total length 1150 m) confirmed the widespread jointing in quartzite, phyllite, and siliceous dolomite, particularly in the upper left abutment zones, indicating stress relief linked to historic deformation (Hasegawa et al. 2009.) Two major tectonic shear zones were identified within the test galleries based on joint characteristics such as orientation, persistence, openness, and infilling materials. Although the DGSD currently appears dormant, these features indicate significant past slope deformation. This study highlights the complex interplay between geomorphological imprints, lithological weaknesses, and tectonic overprinting in the evolution of DGSDs. The integrated geomorphic and geotechnical approach provides valuable insights for slope stability assessment and infrastructure planning in high-risk.

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Frequencies and Mechanisms of Slope instabilities along the Muglin-Narayanghat Highway of Nepal Himalaya

Ghimire P.C.*[1,2], Poudyal K.N.[2] & Dhital M.R.[3]

[1]Department of Civil Engineering, Institute of Engineering, Tribhuvan University Lalitpur, Nepal. [2]Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [3]Department of Geology, Tri-Chandra Campus, Tribhuvan University Kathmandu, Nepal.

Corresponding author email: pcghimire@ioe.edu.np

Key Words: Road, Slope instabilities, Mechanism, Time series analysis, Nepal Himalaya.

Nepal lies in the active Himalayan region that occupies 1/3rd. part of Himalaya, where the construction of roads has notably increased and the frequency of slope instabilities also increased. The instabilities, includes landslides, rockfalls, rocktopple, debris flow are commonly observed along roads of the Nepal Himalayas. Present study investigates the frequencies and mechanisms of slope instabilities along Muglin-Narayanghat Highway of Nepal Himalaya. The study applies time series analysis to examine the mechanisms and frequencies of different instability types, along the road. The research employs specific software tools Q-GIS, DIPS, WAVELET to analyze the landform, geological setting, geological structures, and characteristics of the soil and rocks. The study reveals that the mechanism of instability along the road are translational slides, debris flows, and rockfalls/rockslides occurring repeatedly after road construction and expansion.

Crustal fluids in the Nepal Himalaya and sensitivity to the earthquake cycle

Girault F.*[1], France-Lanord C.[2], Adhikari L.B.[3], Gajurel A.P.[4], Upreti B.N.[5], Paudyal K.R.[4], Agrinier P.[1], Losno R.[1], Groppo C.[6,7], Rolfo F.[6,7], Thapa S.[1,8], Tamang S.[1,6], Assayag N.[1], Cordier L.[1], Robert M.-M.[1], Bhattarai M.[3], Bhattarai S.[3], Pokharel T.[3], Jha M.[3] & Perrier F.[1]

[1]Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, Paris, France. [2]Centre de Recherches Pétrographiques et Géochimiques, Université de Nancy, CNRS, Vandoeuvre-lès-Nancy, France. [3]Department of Mines and Geology, Kathmandu, Nepal. [4]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal. [5]Nepal Academy of Science and Technology, Kathmandu, Nepal. [6]Department of Earth Sciences, University of Turin, Italy. [7]Institute of Geoscience and Geohazard, Turin, Italy. [8]Division of Geosciences and Environmental Engineering, Luleå University of Technology, Luleå, Sweden.

Corresponding author email: girault@ipgp.fr

Keywords: thermal springs, metamorphic CO_2 emissions, MCT zone, spatial organization, earthquake cycle.

The Nepal Himalaya exhibits numerous geothermal zones over its 800 km strike, located in the vicinity of major thrust fault systems. The hydrothermal sites are characterized by a high thermal gradient and show various surface manifestations including thermal springs, travertine deposits, hydrothermal alteration, 'tectonic' fumaroles, and diffuse degassing structures. The released gas is primarily carbon dioxide (CO_2), along with steam and trace gases, such as hydrogen sulfide, radon, and helium. The isotopic signature of the CO_2 suggests that it is produced by metamorphic activity at depths of several kilometers. The CO_2 then percolates toward the surface along fault and fracture networks, where it can mix with infiltrated meteoric waters before degassing at shallow depths. Hydrothermal activity exhibits large-scale spatial organization related to the seismic segmentation of the chain. Catastrophic events, such as large earthquakes, influence the temporal variations of hydrothermal activity. Hydrothermal systems are valuable for studying past, present, and future Himalayan orogenic activity, as well as active metamorphic and alteration processes.

Anatectic (silico)-carbonatites generated by in-situ partial melting of calc-silicate rocks (Greater Himalayan Sequence)

Groppo C.*[1], Tursi F.[1], Frezzotti M.L.[2], Maroni A.[1], Nerone S.[1] & Rolfo F.[1]

[1]Department of Earth Sciences, University of Torino. [2]Department of Earth and Environmental Sciences, University of Milano Bicocca.

Corresponding author email: chiara.groppo@unito.it

Keywords: anatectic carbonatites, liquid immiscibility, Greater Himalayan Sequence.

High temperature metamorphism and anatectic processes are ubiquitous within the upper structural levels of the Himalayan belt, as documented by the widespread occurrence of migmatites and granites in the Greater Himalayan Sequence (GHS) (Kohn, 2014). Experimental studies, petrological investigations and predictions from thermodynamic modelling (e.g., Groppo et al., 2012) have all contributed to our current understanding of partial melting processes in the GHS pelitic lithologies. In contrast, anatectic processes in carbonate-bearing rocks (e.g., marls) are rarely investigated, although carbonate-bearing protoliths represent relevant components of the GHS sedimentary sequence (e.g., Groppo et al., 2017; Rapa et al., 2017).

In this contribution, we present mesostructural, microstructural and geochemical evidence documenting in-situ partial melting of calc-silicate rocks derived from marly sediments now exposed in the upper GHS and metamorphosed at ca. 750-800 °C, 0.7-0.8 GPa (e.g., Groppo et al., 2012). Petrographic and geochemical observations show unequivocal evidence of immiscibility between silicate and carbonate liquids preserved at the outcrop scale, shedding light on the complex evolution of mixed silicate-carbonate sedimentary protoliths during anatexis.

Our results demonstrate that: (1) liquid immiscibility is a viable mechanism to generate (silico)-carbonate melts at upper crustal conditions during collisional orogeny; mixed silicate-carbonate sediments (i.e., marls) are the ideal precursor rocks for generating significant volumes of anatectic carbonatites. This is due to the abundance of OH-bearing minerals whose breakdown expands the miscibility gap, triggering the carbonate-silicate liquid unmixing. (2) The crystallization products of these (silico)-carbonate liquids are dominated either by CO_3-bearing silicates (i.e., scapolite-rich domains) or by calcite (i.e., calcite-rich domains). The volumetrically more significant scapolite-rich domains are relatively rich in SiO_2 ($SiO_2 \approx 45$ wt%) and derive from the early crystallization of the silico-carbonate melt. Instead, the volumetrically minor calcite-rich domains represent the final crystallization products of the residual carbonate liquid. On a broader perspective, this study suggests that anatectic (silico)-carbonatites could be widespread in the upper structural levels of the GHS, although previously unrecognized, and highlights that a detailed petrologic investigation is the fundamental prerequisite for their identification.

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Groppo C. et al. (2017) - Metamorphic CO_2 production in collisional orogens: petrologic constraints from phase diagram modeling of Himalayan, scapolite-bearing, calc-silicate rocks in the NKC(F)MAS(T)-HC system. Journal of Petrology, 58, 53-83, https://doi.org/10.1093/petrology/egx005.

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Exhumation of Continental UHP-rocks: Insights from Phengite and Zircon Geochronology in the Tso Morari Massif

Grujic D.*[1], Arkula C.[2], Cruz-Uribe A.[2] & Rubatto D.[3]

[1]Department of Earth and Environmental Sciences, Dalhousie University, Halifax, Canada. [2]School of Earth and Climate Sciences, University of Maine, Orono, USA. [3]Institute of Geological Sciences, University of Bern, Bern, Switzerland.

Corresponding author email: dgrujic@dal.ca

Keywords: rubidium–strontium, Himalaya, in situ geochronology.

Metamorphic assemblages in mafic eclogite from the Himalayan ultra-high-pressure (UHP) Tso Moriri Massif (TMM; commonly misspelt Tso Morari in the literature) indicate peak pressure–temperature (P–T) conditions of ~2.6–2.8 GPa and 600–620 °C (O'Brien, 2019). However, significantly higher peak pressures >4.5 GPa have also been proposed (O'Brien, 2019). Various geochronological methods constrain the timing of prograde UHP metamorphism to between ~57 Ma and 53 Ma, with eclogite-facies conditions persisting until ~47–43 Ma (Bidgood et al., 2024). Nevertheless, early geochronological studies suggest that amphibolite-facies conditions were reached by ~47 Ma, implying very rapid decompression (De Sigoyer et al., 2000).

Despite this, few studies have examined the structural pathways that may have facilitated the exhumation of the TMM to mid-crustal levels. To reconcile the apparently diachronous and inconsistent age data and to better understand the exhumation history of the TMM, we conducted U–Pb zircon and rutile dating on eclogites, along with *in situ* Rb–Sr white mica dating on both eclogites and mylonites from the massif's upper shear zone.

Our U–Pb zircon data confirm the persistence of eclogite-facies conditions until ~48 Ma. The *in situ* Rb–Sr dating of white mica from the shear zone yields ages of 38 ± 7 Ma and 32 ± 3 Ma. Complementary geothermometry by Raman spectroscopy of carbonaceous material and quartz microstructure analyses indicate deformation temperatures in the shear zone between 450 and 550 °C (Long et al., 2020).

We propose that shearing along the top of the TMM occurred between ~38 and 32 Ma, marking a transition from amphibolite to greenschist-facies conditions of the UHP terrane. This shearing phase was likely distinct from the earlier exhumation process, which involved rapid decompression followed by rapid cooling.

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An active transtensional fault system across the northeastern margin of the Tibetan Plateau and its tectonic implications

Guo P.*[1], Han Z.[1], Niu P.[1], Jiang W.[2] & Ma H.[1]

[1]State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China Earthquake Administration, Beijing 100029, China. [2]National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing 100085, China.

Corresponding author email: guopengpoli@163.com

Keywords: active fault, tectonic deformation, NE Tibetan Plateau.

The Tibetan Plateau moved northeastward and collided with the Gobi-Alashan block to the north, forming a strong oblique compression and producing the NWW-trending Qilian Shan orogen and thrust- strike-slip fault system (e.g., Allen et al., 2017; Tapponnier et al., 2001). However, recent studies showed the northeastern margin of the Tibetan Plateau may have a more complex tectonic style and develop fault systems with other strikes (Guo et al., 2020; Gao et al., 2022).

A newly discovered Tianzhu transtensional fault system (TTFS) cuts across the NWW-trending Qilian Shan orogen and thrust- strike-slip fault system near the Gulang-Tianzhu area on NE Tibetan Plateau. Using high-resolution satellite images, geomorphic mapping, trenching, and radiocarbon and OSL dating, we found that the TTFS consists of the Western Tianzhu Basin, Xuanmahe, Eastern Gulang, and Haxi faults, exhibiting active oblique normal faulting during the late Quaternary. The TTFS experiences at least normal and left-lateral slip rates of 1.0±0.2 mm/yr and 3.1±0.2 mm/yr, respectively, and it is capable of producing earthquakes of Mw 7.2 or higher. The deformation patterns and mechanisms of large earthquakes differ on both sides of the TTFS. GPS velocity profiles show that the velocity components of the nearly perpendicular fault system are generally larger on the east side than on the west, with a rate difference of approximately 2.1-2.7 mm/yr. It is believed that the TTFS plays an important role in accommodating the differential deformation of the NE Tibetan Plateau.

Undergoing the long-term tectonic evolution, the dynamic mechanism has changed on the northeastern margin of the Tibetan Plateau. In the latest deformation period, the northeastern margin of the Tibetan Plateau was not only subjected to NE-SW-trending shortening but also to NWW-SEE-trending extension or tearing caused by the differential block movement, forming the TTFS. The fault system was believed to be the product of the latest tectonic movement on the NE Tibetan Plateau. The corresponding relationship between deep and shallow structures from the geological, seismic, and geophysical data show the TTFS and the Bayanwulashan and Langshan range-front faults in the northeast are likely to constitute a regionally evolving tension-shear fault system, weakening the stability of the Gobi-Alashan block.

The discovery of TTFS provides new insights into the tectonic deformation and expansion pattern of the NE Tibetan Plateau and its influence on the surrounding blocks. Our proposed tectonic style and role of the transtensional fault system enrich our understanding of types of transfer faults that cut through orogens around the world.

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Gao F. et al. (2022) - Faulted landforms, slip-rate, and tectonic implications of the eastern Lenglongling fault, northeastern Tibetan Plateau. Tectonophysics, 823, 229195, https://doi:10.1016/j.tecto.2021.229195.

Depth-dependent variation of seismogenic fault behavior revealed by two phases of pseudotachylytes in the central section of the South Tibetan Detachment System

Guo Y.[1,2], Chu Y.*[1,2], Lin W.[1,2], Lei Y.[1,2], Liu T.[1,2] & Guo L.[1,2]

[1]State Key Laboratory of Lithospheric Evolution and Environmental , Institute of Geology and Geophysics, Chinese Academy of Sciences, China. [2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences.

Corresponding author email: chuyang@mail.iggcas.ac.cn

Keywords: Paleoseismic deformation, pseudotachylyte, South Tibetan Detachment System.

The South Tibetan Detachment System (STDS), one of the largest detachment systems in the world, plays a critical role in controlling the Himalayan orogenic processes (Burchfiel et al., 1992). The STDS exhumed middle crustal seismogenic section to the surface, providing a unique window to investigate paleoseismic slip and coseismic rupture, and further to understand earthquake mechanisms.

This study focuses on the pseudotachylytes identified in the leucogranites from the Ra Chu and Cimulang of the Qomolangma section and reveals two phases of pseudotachylytes during the STDS activity, detachment-parallel Ra Chu pseudotachylytes, and detachment-perpendicular Cimulang pseudotachylytes. Structural and geochemical analyses on the Ra Chu pseudotachylytes indicate that they were formed by frictional melting at temperatures <1,100 °C, associated with tourmaline vein injections. During their formation, fluids infiltrated along fault surfaces, reduced mineral melting points, and lubricated the fault, as evidenced by abundant tourmaline grains in both pseudotachylyte and cataclasite matrix. The Ra Chu pseudotachylytes were formed at the brittle-ductile transition zone around 17 Ma (Liu, 2023), while the Cimulang pseudotachylytes were developed in a shallower brittle domain at ~ 14 Ma. These two phases of pseudotachylytes document rapid exhumation of the STDS in the Qomolangma region within 3 million years.

Pseudotachylyte and ultramylonite in the Ra Chu section exhibit consistent top-to-the N kinematics. Mylonite formed by ductile shearing represents the dominant deformation style of the STDS, while the pseudotachylyte formed by brittle fracturing is attributed to coseismic deformation and fluid-assisted rock fragmentation during seismic rupturing. Ultramylonite marks high-strain zones within the rock, where shear stress increases from 71.71 MPa in the surrounding rock to 85.31 MPa at ultramylonite margins. The connection of pseudotachylyte and ultramylonite during the same slip event is governed by fluid-induced weakening, shift in rock deformation mechanisms, and the weakening of crustal strength by pseudotachylyte. Viscous creep and frictional melting coexist at the brittle-ductile transition depth, as a result of alternating fault slip behaviors under similar environment. Additionally, structural features such as tourmaline injection veins and fault mirrors—potential indicators of paleoseismic events—have been identified across the STDS. We therefore propose that fluids play a critical role in controlling paleoseismic activity within the STDS. Firstly, contrasting rock rheology creates brittle fractures that allow fluid rich in tourmaline to inject into the shear zone. Then the weakened shear zone and increased pore pressure both facilitate paleoseismic rupturing as evidenced by pseudotachylytes. At the post-seismic stage, creep controls the fault activity and forms ultramylonite until the stress accumulates to trigger another seismic event.

Burchfiel C. et al (1992) - The South Tibetan detachment system, Himalayan orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt. GSA Special Papers 269, https://doi.org/10.1130/SPE269-p1.

Liu C. (2023)- Rare-metal mineralization and metallogenic mechanism of the leucogranites in the Qomolangma region. PhD thesis. Nanjing University.

Tectonic activity and Seismic Hazard of the Main Pamir Thrust (MPT) in the western Himalayan syntaxis

Han Z.*[1], Guo P.[1] & Niu P.[1]

[1]State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China Earthquake Administration, Beijing 100029, China.

Corresponding author email: zjhan0904@163.com

Keywords: Main Pamir Thrust, tectonic deformation, western Himalayan syntaxis.

The arcuate Pamir, located in the western Himalayan syntaxis, is a region with vast crustal shortening, doubled crust thickness, huge topographic elevation, synorogenic extension, and strong seismic activity. The tectonic evolution of the Pamir is primarily characterized by terrane accretion, significant deformation, and northward overthrusting caused by the ongoing convergence between the India indenter and the Eurasian plate. The northern margin of the Pamir salient has indented northward by ~300 km during the late Cenozoic, accommodated by south-dipping intracontinental subduction along the Main Pamir Thrust (MPT) coupled to dextral strike-slip faults on the eastern flank of the orogen and both sinistral strike-slip and thrust faults on the western flank (Burtman & Molnar, 1993; Sobel et al., 2011). However, the spatiotemporal evolution and faulting activity of the MPT in the late Quaternary is poorly constrained.

The 220 km-long MPT is located at the forefront of the Pamir-West Kunlun active tectonic belt, extending along the Maerkansu River in the upper reach of the Kezilesu River and the front of the West Kunlun Mountain. The MPT features a northeastward-protruding arc, with its strike changing from nearly east-west in the west to northwest in the east. The tectonic activity along the MPT began around 25~20Ma (Sobel et al., 1997). Previous studies suggested that the MPT remained strongly active during the early and middle Pleistocene, as shown by the thrusting of Paleozoic strata over early Pleistocene gravel layers. With the formation of a newly active belt along the eastern margin of the West Kunlun Mountain, the leading edge of the nappe structure advanced into the thrust-fold belt far away from the foothill, and the MPT no longer had signs of activity during the late Quaternary. Our research shows that the MPT cuts the terrace T1. On the fault outcrop, gravels exhibit oriented alignment, the fault plane is clear, and the fault strikes 220-240° with a dip of 30-45°. The fault displays thrust slip with no significant horizontal strike-slip motion. The latest active period of the fault should be the Holocene. In Oytak Village, the fault caused terraces T1, T2, and T3 to experience varying degrees of arching deformation.

Currently, earthquakes are rare near the MPT, and no events with a magnitude greater than 6.0 have been recorded since 1973. The fault slip rates in the Pamir from an integrated GNSS velocity field confirmed the significant crustal shortening along the Pamir's northern boundary, that is the MPT, but the minor strike-slip motion on the eastern boundary (Wang et al, 2024). The incoordination in currently tectonic deformation across different segments of the MPT reflects that, following the *M*7.3 earthquake in the western segment in 1974, the central and eastern segments are likely in a locked state, posing a potential risk for a major earthquake.

Burtman V.S. et al. (1993) - Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. Special Paper Geol. Soc. Am., 281. 76 pp. https://doi.org/10.1130/SPE281-p1

Sobel E.R. et al. (2011) - Late Miocene–Pliocene deceleration of dextral slip between Pamir and Tarim: Implications for Pamir orogenesis. Earth Planet. Sci. Lett., 304, 369-378. https://doi:10.1016/j.epsl.2011.02.012

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Wang D. et al. (2024) - Recent block kinematics and fault slip rates in the Pamir, Central Asia, from an integrated GNSS velocity field. Tectonics, 43, e2024TC008475. https://doi.org/10.1029/2024TC008475.

Preliminary field evidence for orogen-perpendicular, cross-faulting in central Nepal

Haproff P.J.*[1], Hubbard M.[2], Catlos E.J.[3], Pandey S.R.[4], Devkota P.[4] & Gajurel A.P.[4]

[1]Department of Earth and Ocean Sciences, University of North Carolina Wilmington, USA. [2]Department of Earth Sciences, Montana State University, USA. [3]Department of Earth and Planetary Sciences, University of Texas at Austin, USA. [4]Central Department of Geology, Tribhuvan University, Nepal.

Corresponding author email: haproffp@uncw.edu

Keywords: cross fault, lineament, strike-slip fault.

Several Himalayan researchers have reported the occurrence of >100-km-long, NE- and NW-striking transverse lineaments that cross major rock units and orogen-parallel thrusts. Such features are often co-located with increased landslides and seismicity, along with abrupt spatial terminations in the main rupture and aftershocks of the 2015 Gorhka earthquake (e.g., Mugnier et al., 2017). Himalayan lineaments are hypothesized to be the surface expressions of orogen-scale, basement faults that segment the Main Himalayan thrust and control rupture dynamics. These features may also explain orogen-parallel breaks in Himalayan structural geometry, deformation timing, kinematics, and metamorphism (e.g., Godin et al., 2019). Previous field observations confirm that some lineaments are Cenozoic strike-slip fault systems, such as the >100-km-long, NNE-striking Benkar fault zone in eastern Nepal (Giri et al., 2024). Characterizing Himalayan lineaments is critical for improving our knowledge of potential geohazards, natural resources, and orogen-parallel variations in Himalayan construction.

In this study, we performed preliminary fieldwork in Melamchi Valley, located directly NE of Kathmandu, central Nepal, to investigate whether lineaments previously identified from field and satellite observations are faults. There, we observed N- to NE-striking, brittle-ductile faults with dominant strike-slip kinematics. One key exposure in southern Melamchi Valley features a >100-m-wide, NE-striking, subvertical fault zone within garnet schist and gneiss of the Lesser Himalayan sequence. The fault zone features a ~10-m-wide core composed of gouge and closely-spaced, medium- to high-angle (47–89°) fault surfaces. Fault-surface striations plunge 24–39° to the SW. About 25 km to the N, we similarly observed a narrow zone of steep (70°), SE-dipping, brittle faults with shallow (12°), NE-plunging striations within gneiss of the Greater Himalayan Crystalline complex. These high-angle, SE-dipping faults appear to truncate NE-dipping (37–50°), brittle normal faults with down-dip striations.

These observations may reflect the presence of an orogen-scale, strike-slip fault system, analogous to the Benkar fault zone in eastern Nepal. The observed faults may link with reported, NE-striking lineaments in the Kulekhani reservoir area to the southwest (Devkota et al., 2025) and occur as segments of the previously-identified, NE-striking Kathmandu lineament. Further investigation is required to constrain fault expressions, extents, kinematics, displacements, and timings.

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Giri B. et al. (2024) - The Benkar fault zone: An orogen-scale cross fault in the eastern Nepal Himalaya. Lithosphere, 4, https://doi.org/10.2113/2024/lithosphere_2023_299.

Godin L. et al. (2019) - Influence of inherited Indian basement faults on the evolution of the Himalayan Orogen. Geol. Soc. London, SP, 481, 1, 251-276, https://doi.org/10.1144/SP481.4.

Mugnier J.L. et al. (2017) - Segmentation of the Himalayan megathrust around the Gorkha earthquake (25 April 2015) in Nepal. J. Asian Earth Sci., 141, B, 236-252, https://doi.org/10.1016/j.jseaes.2017.01.015.

Oligocene to mid-Miocene Uplift and exhumation along the reactivated Main Mantle Thrust in the Swat Valley (Northern Pakistan)

Hernández-Chaparro D.*[1], Faccenna C.[1 2], Olivetti V.[3], Fellin M.G.[4] & Ghani H.[5]

[1]Dipartimento di Scienze, University of "Roma TRE", Rome, Italy. [2]Lithosphere Dynamics, Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ), Potsdam, Germany. [3]Department of Geosciences, University of Padova, Padua, Italy. [4]Institute for Geochemistry and Petrology, ETH Zürich, Zurich, Switzerland. [5]Department of Structural Geology and Geothermics, Geoscience Center, Georg-August University of Göttingen, Göttingen, Germany.

Corresponding author email: dhenandezchapa@uniroma3.it

Keywords: Apatite (U-Th)/He thermochronology, Extension-related exhumation, Main Mantle Thrust reactivation.

Extension-related tectonic exhumation during and after continental collision is a common yet debated feature of orogenic sutures. Unraveling the kinematic and exhumation history of reactivated sutures provides useful constraints to assess their role in orogenic collisional belts.

In the Swat Valley (western Himalayan syntaxis - northern Pakistan), the Main Mantle Thrust (MMT) - the Eocene collisional suture between the Indian Plate and Kohistan Island Arc (KIA)- experienced later reactivation as a normal fault in the Oligocene. Current models diverge in interpreting this reactivation and its regional significance: (1) some propose progressive dextral strike-slip motion with minor normal offset (typically less than a few meters; DiPietro et al., 2008;2021), while (2) others suggest episodic normal reactivation that partially facilitated unroofing of high-grade rocks in the NW Himalaya (e.g., Anczkiewicz et al., 2001). Sparse thermochronology in the Swat Valley points to fault-related exhumation between ~29 and 15 Ma, with no differential cooling across the MMT after 15 Ma (Zeitler et al., 1982). However, the driving mechanisms of reactivation, kinematics, and timing (episodic vs. protracted) remain poorly constrained.

To provide further constraints, we integrate structural analysis, apatite (U-Th)/He thermochronology, and thermal modeling. We recorded over 150 kinematic indicators in ductile fabrics—including mineral stretching directions—across ~55 localities in the Swat Valley, measured fault orientations including more than 80 slip vectors (e.g., slickenlines) at 10 sites along the E–W– trending Kohistan Fault segment of the MMT zone. The combined data document ductile-to-brittle reactivation of the MMT dominated by normal faulting, with subordinate oblique-slip components and intense cataclastic deformation.

Single-grain apatite (U-Th-Sm)/He ages range from 7.6 ± 0.1 to 25.8 ± 0.1 Ma, with median ages between ~10.0 Ma and ~20.5 Ma, showing an increasing trend with elevation. Thermal modeling supports Oligocene to mid-Miocene cooling. Our data indicate that the MMT underwent reactivation as a normal fault starting in the Oligocene and continuing into the mid-Miocene, possibly reflecting the final stages of unroofing and exhumation in the Swat Valley.

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DiPietro J.A. et al. (2021) - Geologic history and thermal evolution in the hinterland region, western Himalaya, Pakistan. Earth-Science Reviews, 223, 103817, https://doi.org/10.1016/j.earscirev.2021.103817.

Zeitler P.K. et al. (1982) - Unroofing history of a suture zone in the Himalaya of Pakistan by means of fission-track annealing ages. Earth Planet. Sci. Lett., 57, 227-240, https://doi.org/10.1016/0012-821X(82)90187-X.

Geochemical characterization of metavolcanics from the Wangtu Gneissic Complex, NW Himalaya suggests Proterozoic arc magmatism along the northern Indian cratonic margin

Hifzurrahman*[1] & Sen K.[1]

[1] Wadia Institute of Himalayan Geology, 33 GMS Road, Dehradun, 248001.

Corresponding author email: khan.hifz@gmail.com

Keywords: Wangtu Gneissic Complex (WGC), Geochemistry, Lesser Himalaya, Subduction Zone, Columbia.

Wangtu Gneissic Complex (WGC) in the Himachal Lesser Himalaya, NW India hosts a spectrum of Paleoproterozoic volcanic assemblages contemporaneous with crustal derived granite magmatism. Here, we present a comprehensive geochemical and petrogenetic analysis of the WGC metavolcanic rocks to evaluate their origin, magmatic evolution, and tectonic significance. Their composition is characterized by enrichment in light rare earth elements (LREEs) and depletion in high field strength elements (HFSEs) such as Nb, Ti, and Ta, indicating subduction-related magmatism. Mg# values (56–62) suggest fractional crystallization of the parent magma, with minimal crustal contamination, as evidenced by low Nb/La and high Y/Nb ratios. Elemental mobility analysis confirms that high-field strength elements such as Zr, Nb, and Yb remained stable, preserving the primary magmatic signature. Our results presented new insights into the spatially associated mafic magmatism relative to the earlier studies. The detailed geochemical investigation of the volcanic flows indicates that melting has initiated from the spinel lherzolite source under dehydrating slab melting phase. The tectonic discrimination diagrams support a continental arc setting. This study enhances our understanding of the geodynamic evolution of the proto-north Indian continental margin with respect to amalgamation of the super continent Columbia during the Paleoproterozoic, providing new insights into the role of subduction-related processes in the Lesser Himalayan Sequence.

Eastern Hindu Kush Microtectonics: multifaceted evolution in metapelite textures and assemblages

Hildebrand P.*[1] & Searle M.P.[2]

[1]149 Third Street, Mutare, Zimbabwe. [2]Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, UK.

Corresponding author email: peterhild@gmail.com

Keywords: Hindu Kush, microtectonics, metapelite, texture, mineral assemblage.

A complex orogenic evolution for the eastern Hindu Kush, spanning at least the Jurassic to the present has been demonstrated through mapping and geochronology, (e.g. Hildebrand et al., 2001, 1998; Zanchi et al., 1997, 2000; Gaetani et al., 1993, 1996; Treloar et al., 1989; Pudsey et al., 1985, 1986; Petterson and Windley, 1985). Early Jurassic and early Cretaceous U-Pb monazite ages suggest regional metamorphism pre-dated India-Kohistan-Asia collision (~135-126 Ma; Hildebrand et al., 2001) and may have been related to the collision of the Hindu Kush terrane with the Pamir – southern Karakoram. Cenozoic two-mica (± garnet, tourmaline) leucogranites at Gharam Chasma dated at 24 Ma are the only known Cenozoic magmatism in the Hindu Kush (Hildebrand et al., 1998) and correlate with widespread Miocene crustal melting along the Baltoro Karakoram (Searle et al., 2010).

Along the NW Frontier of Pakistan, from Tirich Mir in the NE and extending to the SW along the border with Afghanistan and bounded to the SE by the Tirich Mir Fault Zone, lies a thick package of dominantly pelitic rocks, often graphitic, deposited in an anoxic basin environment, probably the SW extension of the Palaeozoic Wakhan slates, (e.g. Buchroithner et al., 1986, Gaetani et al., 1993). These pelitic rocks show moderate to intense deformation and corresponding metamorphic grades of low, sub-biotite, through medium garnet-staurolite, to higher sillimanite and even K-feldspar migmatites.

The metapelitic rocks exhibit an intriguing microtectonic history, including assemblages typical to these bulk compositions spanning varying metamorphic grade, as well as disequilibrium of phases. Linking geological mapping and microstructures with petrology, thermobarometry, and U-Pb geochronology we suggest various possible P-T paths and tectonic scenarios prior to the India-Asia collision along an Andean-type continental margin.

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The structure and seismic hazard of the Chittagong Coastal Fault - the frontal thrust of the Indo-Burmese forearc system

Hossain M.S.*[1], Khan M.S.H.[1], Sultana Z.[1] & Shetu D.Y.[1]

[1]Department of Geological Sciences, Jahangirnagar University.

Corresponding author email: sakawat@juniv.edu

Keywords: seismogenic gap, focal mechanism solution, paleostress.

The Indo-Burmese forearc system (IBR) results from the hyper-oblique subduction/collision between the Indian and Burmese plates and is one of the youngest and most active accretionary-type fold-thrust belts in the world, with the potential to generate major to great earthquakes (Steckler et al., 2016; Hossain et al., 2020). While the collisional front of the IBR forearc system is well defined north of 25°N and south of 19°N latitude, its location between 19°N and 25°N latitude remains poorly constrained. Among the faults that have been individually proposed as the collisional front of the IBR, the Chittagong Coastal Fault (CCF) appears to be the most geologically plausible candidate, however, its geometry, kinematics, slip rates, and seismic activity are not well understood. Resolving these uncertainties is critical not only for identifying the collisional front but also for characterizing the active deformation pattern, improving geodynamic models, and enhancing seismic hazard assessments in this densely populated region.

To establish the CCF as the frontal thrust of the IBR, we mapped the fault trace and documented its geometry, kinematics, and slip rates of the CCF based on analyses of satellite imagery, field observations, and geophysical datasets. These observations indicate that the CCF is a NNW–SSE-oriented, ~500 km long, west-verging, east-dipping active reverse fault that has been active for the last ~2 Ma (Maurin & Rangin, 2009). Focal mechanism solutions and fault-slip data inversion suggest purely compressional reverse kinematics, with a subhorizontal ENE-trending σ_1 axis (Hossain et al., 2022). The fault geometry, kinematics, shortening rate, presence of mud volcanoes, and historical and instrumental seismicity collectively confirm that the CCF is the frontal thrust of the IBR forearc system between 19°N and 25°N latitude, with a distinct 120–150 km long seismogenic gap in its northern segment. This study provides a foundation for an improved understanding of the collisional front of the IBR.

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No oceanic-subduction-related Yidun arc in the eastern Tibetan Plateau

Hu X.*[1], Wen D.[2], Pan Y.[1], Garzanti E.[3], Dong X.[1], Ma A.[1], Deng T.[1] & Zhao Z.[1]

[1] State Key Laboratory for Critical Earth Material and Mineral Deposits, School of Earth Sciences and Engineering, Nanjing University, 210023, Nanjing, China. [2] State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, 330013, Nanchang, China. [3] Laboratory for Provenance Studies, Department of Earth and Environmental Sciences, University of Milano-Bicocca, 20126, Milano, Italy.

Corresponding author email: huxm@nju.edu.cn

Keywords: eastern Tethys, Eastern Tibet, tectonic, magmatic arc.

The discrimination of ancient magmatic arcs from igneous bodies is essential for accurate paleogeodynamic reconstructions. This study tested the tectonic framework of the widely accepted Yidun arc hypothesis in the eastern Tibetan Plateau. The Yidun arc-type magmatism, along the eastern side of the Zhongza terrane, consists of high-K metaluminous rocks with a narrow Late Triassic age range (235–200 Ma). Hf isotopes in Late Triassic igneous zircon from the Yidun magmatic rocks arc indicate crustal reworking. Lower–Middle Triassic deep-sea turbidites are intruded by a suite of Late Triassic granitoid rocks. Detrital modes and U–Pb age spectra of detrital zircons are like those in the similar age Songpan-Ganzi turbidites to the east, consistent with southward-flowing paleo-drainage with detritus sourced in the northern Qilian-Kunlun orogenic belt. Triassic turbidites in the Zhongza and Songpan-Ganzi terranes are notably younger than Late Triassic arc-like igneous rocks. Geological evidences point to the formation of the Late Triassic suite of igneous rocks through syn-collisional magma genesis rather than sustained subduction of oceanic lithosphere. This study underscores the need to proper geological investigations before interpreting orogenic magmatic rocks as arc-related and consequently inferring the existence of either eastward or westward subduction zones where oceanic lithosphere is consumed.

Topographic and Structural Expression of Cross Faults in the Himalaya

Hubbard M.*[1], Gajurel A.P.[2], Mukul M. [3], Srivastava V.[4], Paudel L.P.[5], Haproff P.J.[6] & Catlos E.J.[7]

[1]Department of Earth Sciences, Montana State University. [2]Department of Geology, TriChandra Campus Tribhuvan University. [3]Department of Earth Sciences, IIT Bombay. [4]Department of Earth and Environmental Sciences IISER Bhopal., [5]Central Department of Geology Tribhuvan University, [6]Department of Earth and Ocean Sciences, University of North Carolina Wilmington, [7]Jackson School of Earth Sciences, University of Texas.

Corresponding author email: mhub@alum.mit.edu

Keywords: Himalaya, tectonics, natural hazard.

In addition to the major range-parallel thrust faults, the Himalaya has many faults that strike at a high angle to the orogen (Hubbard et al., 2021). Geophysical evidence suggests that these faults may play a role in limiting the lateral propagation of thrust fault rupture, thus limiting earthquake magnitude. With numerous north-south river drainages, these faults also play a role in increasing the landslide hazard along these valley walls. In many locations, the faults are well expressed topographically, which is why early maps have some named lineaments that now coincide with mapped cross-fault structures. In this presentation, we explore the varying structural and topographic expression of a selection of cross-fault features from Sikkim to Central Nepal. In Sikkim, the Gish fault coincides with the transition from a recess to a salient (Mukul, 2010). This structure strikes NE-SW and is expressed as a brittle, left-lateral fault zone overprinting an earlier ductile shear zone. It aligns with the Yadong Gulu rift to the northeast. In eastern Nepal another recess-salient transition has been proposed to correlate with a cross-fault, the Kosi Fault (Mukul et al., 2018). A lineament aligned with the proposed Kosi fault continues northward toward the Kanchenjunga region. Preliminary mapping in that region shows NE-striking brittle deformation along near-vertical planes. To the west, the NNE-striking Benkar fault system is well-exposed as brittle-ductile fabric where deformation is concentrated on sillimanite-rich planes with a dextral, normal sense of shear in the Khumbu region of eastern Nepal. The fault makes a dip slope in the Khumbu region, which may also be the site of past landslides. To the south along the strike of this structure, the exposures show significant brittle deformation resulting in ~10-meter-wide gouge zones (Giri et al., 2024). Topographically, the Benkar fault system is expressed as a lineament recognized by previous authors. Further west, the Melamchi valley also has an associated topographic lineament quite close to the valley floor in places. South of Melamchi Bazar, the structure is exposed as a ~50m wide brittle fault zone. Ductile shear fabric is also seen on this structure further north as near vertical northeast-striking planes near Nakote. The lineament passes through a large landslide east of Melamchi Gaon, which was reactivated during catastrophic flooding in 2021. Several NE-striking brittle fault zones are exposed around the Kulekhani reservoir south of Kathmandu. These faults also follow topographic lineaments. Analysis of satellite imagery and topographic data shows that many of the NS-striking lineaments align with major sites of mass wasting such as the Sabche rock avalanche in the Annapurna region or the Khumjung landslide in the Khumbu. Because these cross faults may enhance the landslide hazard and may play a role in seismic partitioning, it is important that future work focus on detailed mapping to understand how extensive the cross faulting is and how the faulting relates to lineament occurrence. We emphasize the need for further field studies along lineaments that are orthogonal to the orogen.

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The form of the north Indian margin prior to Himalayan collision: evidence from widespread Neopoterozoic and early Palaeozoic rocks

Hughes N.C.*[1] & Myrow P.M.[2]

[1]Dept. of Earth and Planetary Sciences, University of California, Riverside, CA 92521, USA. [2]Dept. of Geology, Colorado College, Colorado Springs, CO 80903, USA.

Corresponding author email: nigel.hughes@ucr.edu

Keywords: Cambrian, stratigraphy, detrital zircon, fossil, lithotectonic zone.

Sedimentary rocks and sedimentary protolith in Himalaya span depositional ages from Paleoproterozoic to Recent, and unroofing of the oldest of these rocks has occurred in the southcentral region of the orogen, orthogonal to the collision of India with Asia. Westward, beyond the western Himalayan syntaxis, deformation of the north Indian margin was less severe, yielding a more complete record of the condition of the margin during the Neoproterozoic to early Paleozoic. Beginning in 1990, our integrated stratigraphic, geochronological, and palaeontological analysis of the geological system most widely represented in the orogen and on the Indian craton, the Cambrian, has focused on facies and stratigraphic relationships across the margin prior to the Himalayan collision. Results of all approaches are consistent with a northern deepening passive margin succession. Evidence suggesting that rocks of this age, found in both the Greater Himalaya and Tethyan Himalaya, were part of a terrane separate from that of the Indian craton is scant. Here we draw attention to similarities between the Cambrian successions of Pakistan with those of the central Himalaya, and to the existence of Cambrian sedimentary rocks south of the Himalayan Frontal thrust, which are indisputably part of the Indian craton. Facies differences in late Neoproterozoic to Ordovician rocks on both sides of the Panjal/Khairabad fault (PKF) in Pakistan mimic those between the Lesser and Tethyan Himalaya in the central Himalaya. The absence of high-grade metamorphic rocks, accreted oceanic crust, or any other features indicative of a crustal suture along the PKF argues for a continuous northern Indian margin. Cambrian facies across the Salt Range Thrust and also across the possible Main Boundary Thrust equivalent in Pakistan are consistent with northern deepening along a continuous passive margin.

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Hughes N.C. et al. (2019) - Cambrian geology of the Salt Range of Pakistan: linking the Himalayan margin to the Indian craton. Geol. Soc. Am. Bull. 131, 1095-1114, https://doi.org/10.1130/B35092.1.

High-Temperature, Low-Pressure Shear Zones in the Greater Himalayan Sequence (Eastern Nepal): First Constraints on P–T–D-t Conditions

Iaccarino S.[*1], Montomoli C.[1], Pippo E.[1], Carosi R.[1], Cottle J.M.[2] & Lanari P.[3,4]

[1] University of Turin, via Valperga Caluso, 35 - 10125 Turin, IT, [2] Department of Earth Science, University of California, Santa Barbara, USA, [3] Institut für Geologie, University of Bern, Baltzerstrasse 1+3, 3012 Bern, CH. [4] Institute of Earth Sciences, University of Lausanne, Géopolis, 1015, Lausanne, CH.

Corresponding author email: salvatore.iaccarino@unito.it

Keywords: Shear Zones, Greater Himalayan Sequence, petrochronology.

The medium- to high-grade metamorphic core of the Himalayan belt is represented by the Greater Himalayan Sequence (GHS). Thanks to its excellent 3D exposure, the GHS is a key natural laboratory to investigate middle–lower crustal architecture in orogenic settings. Traditionally interpreted as a tectonically coherent unit, recent studies (Carosi et al., 2010; Montomoli et al., 2013, 2015) challenge this view, revealing internal complexity and composite tectono-metamorphic histories.

This study presents preliminary results from Eastern Nepal, integrating field observations, microstructural analysis, pseudosection and iterative thermodynamic modelling, and monazite petrochronology. The investigated rocks include garnet–sillimanite- and cordierite-bearing anatectic paragneiss affected by high-temperature / low-pressure ductile shear zones. These structures display a normal-sense shear (both top-to-the-S and top-to-the-N) and are associated with mylonitic fabrics formed under upper amphibolite facies conditions (~700 °C). Syn-kinematic mineral assemblages and quartz–feldspar dynamic recrystallization provide further support for deformation at these conditions. Phase equilibria modelling (P–T–X pseudosections) and iterative thermodynamic modelling indicate a pre-shearing metamorphic peak under medium-pressure, melt-present conditions in the upper amphibolite to granulite facies. This even was followed by non-coaxial shearing during decompression and minor cooling.

In situ U–Th–Pb monazite petrochronology constrains the timing of deformation to between the Oligocene and Miocene, suggesting that strain localization occurred progressively after melt extraction in migmatitic terranes.

These HT–LP extensional shear zones likely played a significant role in the internal thinning and exhumation of the GHS and contribute to the broader understanding of crustal flow and strain partitioning during Himalayan orogenesis.

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Geodynamic evolution and intense mantle depletion in a supra-subduction zone: The Early Cretaceous Nidar Ophiolite Complex, NW India

Imayama T.*[1], Sato A.[1], Dutta D.[1], Kaneda Y.[2], Watanabe S.[2,3], Hasegawa T.[2], Minami M.[4], Wakasugi A.[4,5], Wakaki S.[6,7] & Yi K.[8]

[1] Institute of Frontiers and Sciences Technology, Okayama University of Science. [2] Graduate School of Science and Engineering, Ibaraki University. [3] Mount Fuji Research Institute. [4] Institute for Space-Earth Environmental Research, Nagoya University. [5] Gangoji Institute for Cultural Properties. [6] Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology. [7] Research Department, National Museum of Japanese History, National Institutes for the Humanities. [8] Geochronology Team, Korea Basic Science Institute.

Corresponding author email: imayama@ous.ac.jp

Keywords: Supra-subduction zone, Nidar Ophiolite, extreme mantle depletion.

The Early Cretaceous Nidar Ophiolite Complex (NOC) in south Ladakh provides important insights into the geodynamic evolution of the Neo-Tethyan Ocean in response to subduction initiation. Although previous studies have identified the NOC as a supra-subduction zone (SSZ) ophiolite, the tectonic relationship between the SSZ setting and the former spreading center remains poorly understood. Here, we present new data on mineral and whole-rock compositions, Nd-Sr isotopes of igneous rocks, and detrital zircon ages from the overlying volcanosedimentary rocks in the crustal section of the NOC. The gabbros, characterized by low SiO_2 content, display ultra-depleted light rare earth elements (LREE) patterns with pronounced negative Nb, Zr, and Ti anomalies. These findings suggest the presence of an extremely depleted mantle source, likely associated with the first partial melting of refractory Jurassic mantle lithosphere with pre-existing depletion signatures during subduction initiation. The dolerites and basalts are characterized by relatively high SiO_2 and low CaO, with nearly flat to slightly depleted LREE patterns indicating normal mid-ocean ridge basalt-like compositions. Normal zoning in plagioclase, similar εNd (t) values (+7.8 to +8.7), and increasing Yb content relative to Ce/Yb and Tb/Yb ratios suggest that fractional crystallization produced the doleritic and basaltic melts. High-Mg andesites likely formed through second partial melting of a metasomatized mantle wedge, coupled with later magmatic recharge into the earlier basaltic magmatism. This interpretation is supported by magmatic temperatures of 1065–1080 °C in clinopyroxenes and the reverse zoning patterns in plagioclase. The NOC underwent a regional hydrothermal alteration, forming secondary albite, actinolite, epidote, and chlorite. The timing of subduction initiation in the NOC is constrained by concordia zircon U–Pb ages of 136.2 ± 1.6 Ma from the volcanosedimentary rock. In the Th/Yb–Nb/Yb diagram, the Early Cretaceous NOC samples plot within fields ranging from the mantle array to island arc tholeiite, similar to the Spongtang ophiolitic mélange but contrasting with the calc-alkaline series of the Late Cretaceous Dras arc. We propose that the compositional variation and temporal relationships of the Cretaceous SSZ magmatism in southern Ladakh reflect the lifecycle of SSZ ophiolites, as observed in other SSZ ophiolites, rather than the results developed in the two-separate subduction zones as previously reported. The Nidar-Spongtang ophiolites and the Dras arc primarily record magmatic responses to subduction initiation and mature subduction, respectively, within the same island arc complex during 140–78 Ma.

Linking Structural Restoration and Thermochronology to Decode the Deformation and Exhumation History in the Western Kohat Fold and Thrust Belt, Pakistan

Ishfaq M.*[1], Ghani H.[1], Kley J.[1], Dunkl I.[2], Razzaq S.S.[1] & Ghani M.[1]

[1]Department of Structural Geology and Geothermics, University of Göttingen, Germany. [2]Department of Sedimentology and Environmental Geology, University of Göttingen, Germany.

Corresponding author email: ishfaqm.geo@gmail.com

Key words: Thermochronology, Deformation, Exhumation, Cross-sections.

This research focuses on the northwestern segment of the Himalayan foreland belt in Pakistan, the Kohat Fold and Thrust Belt (KFTB), where the style and sequence of deformation since the Miocene differ significantly from the rest of the Himalayas (Robinson et al., 2023; Ghani et al., 2018). Sequentially restored balanced cross-sections, integrated with apatite (U-Th-Sm)/He (AHe) thermochronology, are employed to jointly interpret the deformation history and exhumation pattern in the study region. The preliminary results show that the resetting age of AHe is late Miocene-Pliocene and Pleistocene in the northern and central KFTB respectively, while they are partially reset in the Khisor Ranges the western part of the Range front. In the Surghar Ranges (the central part of the Range front) the ages appear as reset in early Miocene time which is older than the previously reported AHe age (Ghani et al., 2021).

These patterns suggest out-of-sequence deformation and high exhumation in the northern and northwestern KFTB. The variation in low-temperature thermochronological ages along strike in the central KFTB is likely due to salt-tectonics activity in the eastern Kohat and limited toward the western KFTB. The age constraints in the Range front (from Salt Ranges to Khisor Ranges) suggest shallow burial in the east and west and deep burial in the northern segment of the range front (along the Surghar Thrust).

The ongoing apatite fission track thermochronology will provide additional constraints on the spatio-temporal evolution of the region.

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Hornblendite Occurrences in the Cretaceous Kohistan Island Arc of the NW Himalaya in Pakistan

Jan M.Q.*[1,2] & Ullah R.[3]

[1]NCE Geology, University of Peshawar, Peshawar, Pakistan. [2]China-Pakistan Joint Research Centre on Earth Sciences, Islamabad, Pakistan. [3] Geological Survey of Pakistan, Quetta, Pakistan.

Corresponding author email: mqjan@yahoo.com

Several hornblendite bodies occur in the southern part of the Kohistan island arc. The largest (3-10 km^2) of these, located at Tora Tigga (TT) and Timergara in Dir, and Mahak in Swat, are associated with peridotites and pyroxenites which are emplaced in metagabbros. In the Indus Valley, the Chilas and Jijal mafic-ultramafic complexes host large bodies of hornblendites near Lutar and Jijal, respectively. Only the Mahak, TT, and Jijal hornblendites have been studied in variable detail and are described here as case studies. At Mahak, a cluster of eight hornblendite bodies (up to 700 x 300m) and a few Hbl-diopsidite bodies are hosted in metagabbros. The monomineralic, coarse-grained hornblendites grade into metagabbros through Pl-hornblendites. They do not appear to be cumulate and may be related to hot ascending fluids or conduits of magma-rock interaction. The TT hornblendite and associated dunite, peridotites, and pyroxenites (±Ol, ±Hbl) are emplaced in a large metagabbro pluton containing abundant Hbl and local networks of coarse-grained hornblendite, Hbl-Pl pegmatite and felsic dykes. The two main bodies of hornblendite (±Pl, ±Pxn), covering 2.5 km^2, are medium-grained to pegmatitic. In comparison, the Jijal hornblendites (±Grt, ±Cpx, ±Pl) occur as a ~500m thick unit at the top of the ultramafic section (dunite, harzburgite, websterite, abundant diopsidite, and subordinate chromitite). Hornblendites can form as, 1) magmatic cumulates, 2) interaction of cumulates and intercumulus magma, and 3) interaction between rising basaltic magma or hot fluids and ultramafic cumulates/mantle (i.e., melt-rock reaction). The bulk evolution of the TTC and Jijal accords well with the experimentally derived cumulate lines of descent and continuous differentiation, based on SiO_2 vs. Mg#, Al_2O_3, CaO relations, and corresponds with lower arc crustal cumulates formed at 7–12 kbar (Müntener & Ulmer 2018, AJS 318). But at least in the case of the Jijal complex, where hornblendites are younger than the other ultramafic rocks (Yamamoto & Nakamura, 2000, GSL Spec. Pub.170; Dhuime et al. 2009, J. Petrol. 50), melt-rock reaction may well have operated.

Lost arcs of the Tethys? Insights from U-Pb garnet geochronology of Kohistan Arc

Javaid W.*[1], Millonig L.[1] & Marschall H.[1]

[1]Institute of Geosciences, Goethe University Frankfurt.

Corresponding author email: waqasjavaid94@gmail.com

Keywords: U-Pb age, garnet geochronology, kohistan arc.

Recent advancements in high resolution laser ablation techniques coupled with high sensitivity ICP-MS have made it possible to quickly analyze sub-milimeter scale garnet grains in-situ on polished thin sections to date regular metamorphic garnets of pyrope-almandine series with incredibly less U concentrations of 1-15 ng/g with a L-intercept age precision of typically <3 % (Millonig et al. 2020). The U–Pb system in garnet has been demonstrated to have a high closure temperature in excess of the peak temperature of 930 ºC and even 1100 ºC in the granulite terrains investigated (Marschall et al. 2022). We have applied the newly developed U–Pb garnet dating method to the garnet-bearing crustal rocks that are abundant in the lower section and upper sections of the Kohistan Arc representing a unique geological domain which offers a window into the evolution of intra-oceanic arcs throughout the stages of construction, subduction, back-arc rifting and subsequent collision.

In our study, the garnet granulite samples from Jijal Complex reveal weighted mean age of 108 ± 3.9 Ma. This U-Pb garnet age is slightly older than various reported ages of ~95 Ma obtained from other geochronometers which confirms robustness of U-Pb garnet geochronology to keep age records. Recently, there is a debate about existence of an early Jurassic ghost arc in Tethys which was lost by subduction before formation of Kohistan Arc and Indian-Eurasian collision. Bosch et al. (2011) report that the Kohistan arc initiated around 135 Ma but zircon as old as 175 Ma was inherited from pre-subduction crust. Lately, a 182 ± 3 Ma recycled zircon was dated from lower crustal section of the Kohistan Arc which is interpreted to come from the same lost early Jurassic arc consumed during subduction (Ding et al. 2020). We report the first non-zircon evidence of this lost arc by dating a garnet bearing sample from Kamila Amphibolite sequence of Kohistan Arc having garnet age of 96.24 ± 2.72 Ma (1.30 MSWD) which is cosistent with previous age constraints. However, the same sample shows a second trendline on isochron plot with L-intercept age of 181.6 ± 24.8 / 24.9 Ma. Although the uncertainity is on the higher side, still the age is significantly older than initiation age of Kohistan Arc i.e. 135 Ma and hints towards inherited garnet component experiencing later stage metamorphism.

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Ding X. et al. (2020) - Identification and Origin of Jurassic (~182 Ma) Zircon Grains from Chromitite within the Peridotite of the Jijal Complex, Kohistan Arc in North Pakistan. Minerals, 10(12), 1085. https://doi.org/10.3390/min10121085.

Marschall H. et al. (2022) - The petrochronologic potential of LASS-ICPMS U-Pb dating of garnet and evidence for an ultra-high closure temperature. EGU22. https://doi.org/10.5194/egusphere-egu22-12199.

Millonig L. et al. (2020) - Exploring Laser Ablation U–Pb Dating of Regional Metamorphic Garnet – The Straits Schist, Connecticut, USA. Earth Planet. Sci. Lett., 552, 116589. https://doi.org/10.1016/j.epsl.2020.116589.

On the tectonic and climatic controls of silicate weathering in the Late Cretaceous Gangdese arc

Jiang H.H.*[1], Wang J.[1], An W.[2], Sun G.[3] & Ge Z.Y.[1,4]

[1]State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. [2]School of Resources and Environmental Engineering, Hefei University of Technology, Hefei, China. [3]College of Oceanography, Hohai University, Nanjing, China. [4]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China.

Corresponding author email: jiang.hehe@mail.iggcas.ac.cn

Keywords: silicate weathering, Gangdese arc, Tibet, Late Cretaceous, erosion rate.

Continental arcs form prominent topographic highs through magmatic orogeny and often act as major erosion "hotspots," supplying vast amounts of terrestrial clastic material to the oceans. Their development plays a critical role in regulating the oceanic alkaline budget, thereby influencing the global carbon cycle and climate. Recent advances and debates have focused on the interplay between physical denudation and chemical weathering in mountainous regions. Modern river catchment observations suggest that rapid denudation and/or runoff can "hinder" silicate weathering by limiting reaction time within the weathering column. However, the relationship between physical erosion and silicate weathering over different timescales—particularly at the million-year tectonic scale—remains poorly constrained, including whether it follows a near-linear or non-linear trend and how it impacts long-term weathering fluxes.

We present a case study from the Xigaze forearc basin in southern Tibet, China—a simple-provenance catchment developed at mid- to low latitudes under a hot-house climate. The basin evolved during the Late Cretaceous, following a major magmatic flare-up in the adjacent Gangdese arc, which supplied most of the basin's detritus. Fine-grained sediments (mudstone, shale, and siltstone) were sampled along a ~4 km thick stratigraphic column, and major and trace element compositions of the silicate fractions were analyzed. Silicate weathering proxies, such as the chemical index of alteration (CIA) and mobile/immobile element ratios (e.g., K/Al, Ca/Ti), suggest moderate silicate weathering intensity throughout the Late Cretaceous (CIA = 60–80). These proxies show long-wavelength cyclic variations, with lower weathering intensities often coinciding with intervals enriched in coarse-grained deposits (sandstones, conglomerates, and local slumps), indicative of accelerated erosion in the source region.

Despite a negative correlation between silicate weathering intensity and erosion/deposition rates, the silicate weathering flux (5-60 tons/km2/yr) is strongly positively correlated with erosion rate (0.05 to 0.5 km/Myr), consistent with a supply-limited weathering regime during Late Cretaceous arc evolution. We propose that first-order variations in chemical weathering intensity within the Xigaze section were primarily controlled by fluctuations in erosion rates in the Gangdese arc, driven by tectono-magmatic processes associated with Neo-Tethyan subduction. The intensified hydrologic cycle under the Cretaceous hot-house climate likely contributed to maintaining this predominantly supply-limited state.

Geological study of metallic mineral deposits in Gulmi district, Lesser Himalaya, Western Nepal

Kandel D.*[1], Lamsal S.[1], Luintel S.[1], Gautam A.[1], Nepal R.[1] & Poudel K.R.[1]

[1]Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal.

*Corresponding author email: dhurbaso45@gmail.com

Keywords: Lesser Himalaya, polymetallic mineral, mineral economics, Western Nepal.

The Lesser Himalaya of Nepal has a significant potential for metallic minerals ore deposits such as iron, copper, lead, zinc, cobalt, nickel, gold, silver, uranium, and rare earth elements (Sah and Paudyal, 2019). This study covers the Tamghas-Neta-Suwarbhumar section of the Gulmi district for investigating different metallic minerals including their genesis and potential economic value. This study was conducted through geological mapping at a scale of 1:25,000 aiming to prospect the metallic mineral resources in the Gulmi area. Traverse where conducted and samples from old audit mines and exposed ore were collected. A detailed laboratory sample analysis was carried out using polished and thin sections in the petrological microscope.

Three major lithological rock units; the Benighat Slate, the Tamghas Dolomite, and the Resunga Formation are attributed to low-grade metamorphic rocks like slate, phyllite, dolomite and quartzite of the Nawakot Group (an autochthonous sequence). Similarly, the Bastu Formation, the Purkotdaha Formation and the Chaurjahari Formation consist of dolomite-marble, quartzite and biotite-garnet schist from the Jajarkot Thrust Sheet (an allochthonous sequence). Major structural units include the Jhimruk Khola Thrust (equivalent to the Mahabharat Thrust in central Nepal) and the Khamlek-Resunga Syncline.

The dominant metallic ore deposition is hydrothermal veins primarily hosted within dolomite and quartzite rocks which show both stratabound and stratiform characteristics. Key mineralization zones are reported as Dhaithum Copper, Resunga Ban Polymetallic, Bhadegau Polymetallic, Suwarbhumar Polymetallic Bhakhre Khani Copper, Netagau Polymetallic and Falhale-Chapte Polymetallic deposition. These mineralized zones hold economically important metals like copper, silver, lead, iron, cobalt, nickel, and gold where cobalt and nickel could be strategic minerals, due to global demand in clean energy transition for a sustainable environment.

Sah R.B. & Paudyal, K.R. (2019) -. Geological control of mineral deposits in Nepal. J. Nepal Geol. Soc., 58, 189-197.

Metamorphic Fabrics and Field Relation of Ulleri Augen Gneiss of West-Central Nepal

Karki A.*[1], Adhikari S.P.[2], Giri A.[2], Pandey S.R.[2], Paudyal K.R.[2], Thomas H.[3] & Paudel L.P.[2]

[1, 2] Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [3] Department of Applied Geology, Dr.Harisingh Gour Vishwavidyalaya (A Central University), Sagar (M.P.), India.

Corresponding author email: karkialina26@gmail.com

Keywords: Ulleri Augen Gneiss, microstructures, Main Central Thrust (MCT), shearing, metamorphic fabric

The Ulleri Augen Gneiss, a Precambrian blastomylonitic augen gneiss named after Ulleri village in Western Nepal, represents a key lithological unit of the Lesser Himalayan Sequence with complex origin and tectonic evolution. Despite decades of study, its genesis remains contentious, with competing hypotheses suggesting a volcano-sedimentary origin, magmatic intrusions, or the result of ancient island arc–arc-continental margin interactions. Addressing this research gap, the present study integrates detailed field observations and microstructural analyses to unravel its deformation history and tectonic significance. The main objective is to examine the metamorphic fabrics and structural relations of the Ulleri Augen Gneiss with its surrounding rocks to infer the tectonometamorphic processes it has undergone. Fieldwork involved regional geological mapping at a scale of 1:25,000 to delineate the spatial distribution and contact relationships of the gneiss, followed by petrographic analysis of oriented thin sections. The microstructures reveal key shear sense indicators such as rotated porphyroclasts, domino structures, mica fish, ribbon quartz, and multiple generations of S-C foliations, all consistently suggesting a top-to-the-south sense of shear associated with the propagation of the Main Central Thrust (MCT). Quartz grains exhibit both dynamic and static recrystallization, indicating progressive deformation under a broad thermal regime. The presence of brittle features such as fractured feldspars and micro-faults within a dominantly ductile matrix suggests overprinting of deformation phases. Intrusion of recrystallized quartz veins and the occurrence of xenoliths imply magmatic activity during or after deformation, further complicating its history. Field relations show both concordant and discordant contacts with surrounding lithologies, highlighting structural complexity and multiphase deformation. In conclusion, the Ulleri Augen Gneiss records a rich history of tectonometamorphic evolution marked by ductile shearing, brittle overprints, and magmatic events, contributing critical insights into the geodynamic framework of the Nepal Himalaya.

Insights into the Paleocene sedimentary successions eastern Tethys, Pakistan

Khan M.J.*[1,2], Ghazi S.[3], Yang X.[1] & Mehmood M.[4]

[1] Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China. [2] University of Chinese Academy of Sciences, Beijing 100049, China. [3] Institute of Geology, University of the Punjab, Lahore, 54590, Pakistan. [4] Università degli Studi di Napoli Federico II, Napoli, 80138, Italy.

Corresponding author email: jehangirkhan1848@yahoo.com

Keywords: Lithofacies, provenance, depositional environment.

The marine sedimentation during the Eocene and Paleocene along the eastern Tethys is now part of the north India and Pakistan (Mehmood et al., 2023). The lithologies that resulted in the closure of eastern Tethys hold a record of collisional events (Ahmad et al., 2020). The collisional events have been recorded by the sedimentary succession along the NW margin of Indian plate and western margin of the Afghan block (Sarwar et al., 2024).

This study presents a comprehensive petrographic and sedimentological analysis of sandstone samples from the Paleocene succession, focusing on the provenance, diagenesis, and depositional environment of the deposits. Thin-section petrography revealed that the sandstones are primarily composed of quartz, with minor feldspar, lithic fragments, and accessory minerals. The sandstones are mostly medium to coarse-grained, well to moderately sorted, and predominantly subangular to subrounded, with minimal rounded grains. Diagenetic alterations, including compaction, dissolution of feldspar, and cementation by quartz and calcite, were observed. Mechanical compaction and quartz cementation are the dominant diagenetic processes, while feldspar dissolution provided silica for quartz cementation in later stages.

The provenance analysis, using QFL and QmFLt diagrams, classified the sandstones as quartz arenites, litharenites, and sublitharenites, suggesting an igneous and metamorphic source, primarily from the Malani Range. The study indicates that the sedimentary composition and diagenetic features reflect a craton interior or recycled orogen source area, with tectonic uplift and recycling of igneous and metamorphic rocks influencing the grain characteristics.

Facies analysis identified four major facies associations: Delta Plain/Distributary Mouth Bar, Delta Front, and Pro Delta, each reflecting different depositional environments ranging from fluvial to marine. The facies analysis and petrographic data suggest that the sandstones were deposited in a proximal fan-delta setting, with episodic sediment gravity flows, and that the source area remained consistent throughout the Paleocene succession, shaped by regional tectonic activity and climatic conditions.

Ahmad S., et al. (2020) - The sedimentological and stratigraphical analysis of the Paleocene to Early Eocene Dungan Formation, Kirthar Fold and Thrust Belt, Pakistan: implications for reservoir potential. J. Sedim. Environ., *5*, 473-492.

Mehmood M., et al. (2023) - Sedimentary Facies, Architectural Elements, and Depositional Environments of the Maastrichtian Pab Formation in the Rakhi Gorge, Eastern Sulaiman Ranges, Pakistan. J. Marine Sci. Eng., 11, 726. https://doi.org/10.3390/jmse11040726.

Sarwar U. et al. (2024) - Sedimentological and sequence stratigraphic analysis of late eocene kirthar formation, Central Indus Basin, Pakistan, Eastern Tethys. Earth Sci. Res. J., 28, 29.

Formation mechanism of rainfall and snowmelt jointly induced Bicharh Nallah debris flow, North Pakistan

Khan M.U.*[1,2], Chen N.[1,3] & Khan T.A.[2,4]

[1]State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610299, China. [2]University of Chinese Academy of Sciences, Beijing 100049, China. [3]International Cooperation Center for Mountain Multi-Disasters Prevention and Engineering Safety, Yangtze University, Wuhan 430100, China. [4]Research Center of Digital Mountain and Remote Sensing Application, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China.

Corresponding author email: muhibkpk@yahoo.com

Keywords: Debris flow, · Bicharh Nallah, · Rainfall, · Snowmelt, · Freeze–thaw erosion.

Heavy and intense rainfall commonly triggers debris flow events, but the relationship between gentle rainfall, snowmelt water, and freeze–thaw erosion in high-altitude cold regions of northern Pakistan remains unexplored. A devastating debris flow from Bicharh Nallah hit the village of Sherqilla in northern Pakistan on July 5, 2022, and killed 8 people and destroyed 10 houses completely and 250 houses partially. The Bicharh Nallah debris flow (Sherqilla village) in Ghizer district is used as a case study to find out what makes this size debris flow happen in a cold region and how it is affected by rainfall, snowmelt water, and freeze–thaw erosion. This work was done through fieldwork investigation, laboratory work, and statistical analysis. The debris flow dynamic characteristics such as peak discharge, velocity, and density were calculated as 430.82 m^3/s, 5.11 m/s, and 1.74 g/cm^3, respectively. We determined that rainfall acts as a direct triggering factor. Snowmelt water was quantitatively calculated, which contributed to triggering the debris flow. This study revealed that gentle rainfall and snowmelt water are direct triggering factors in the debris flow outbreak in Bicharh Nallah of Sherqilla village. Long-duration, extreme, and severe freeze–thaw erosion provided enough loose soil conditions for the triggering and formation of debris flow. The regional tectonics, geology, and local topography indirectly contributed to the development and amplification of Bicharh Nallah debris flow.

Assessment of hydrocarbons in Produced Water, Sadqal Oil and Gas Field, Fateh Jang, Pakistan

Khan S.A.*[1] & BiBi R.[2]

[1]Earth and environmental Sciences Department Bahria University, H-11/4 Campus Islamabad, Pakistan. [2]Environmental Management system Pvt. Ltd., Islamabad Pakistan.

Corresponding author email: saidakbar2008@yahoo.com

Keywords: Produced water, hydrocarbons, GC MS, impacts.

Produce water without treatment from oil and gas fields causes contamination of the environment. This study was conducted to analyze the hydrocarbons present in produce water of Sadqal Oil and Gas Field, Fateh Jhung, Pakistan. Produced water samples were collected from outside the oil and gas field, from various locations including two ponds and their outgoing stream. Hydrocarbon analysis was conducted through GC-MS, area normalization method. Detailed analysis through GC-MS indicate that aromatic hydrocarbons were found in significant percentage in produce water of oil and gas field. Saturated hydrocarbons and aromatic hydrocarbons found in a relatively higher percentage than unsaturated and cyclic hydrocarbons. Produce water samples without treatment contain 46% aromatic hydrocarbons.

Water samples were collected in 1.5-liter glass bottles from various points. Points of water sample include inlet, outlet, and ponds areas. Six points were selected for collection of produce water samples discharged directly into stream outside the boundary of oil and gas field. It includes the inlet, pond A, pond B, inlet of pond B, outlet of pond B and external stream. These water sample prevented from sunlight to avoid any change in physicochemical properties of water sample (Khan et al., 2015 & Plata et al., 2008). Five composite soil samples (≈ 1 kg) in zip lock polythene bags from selected points were collected by digging 0-15 cm deep. Soil samples were collected from points which were near inlet, pond A, pond B, between pond A and B and external stream. These points were at a zero-meter distance from produce water pond area and located in different directions (i.e., East, West, and South). At the North of pond areas, it was hard rock land.

Results suggest that care should be exercised in the disposal and release of produced water containing these organic substances into the environment because of the potential toxicity of many of these substances. To reduce environmental impact there is a need to provide proper treatment for the removal of hydrocarbons from produce water so that their impacts on soil can be reduced (Kim et al., 2013).

Khan S.A et al. (2015) - Geochemical impact assessment of produced water of Sadqal oil and gas field on the soil surrounding the storage ponds in Fateh Jang area, Punjab, Pakistan. J. Himal. Earth Sci., 48, 2, 75-84.

Plata D. L. et al. (2008) - Photochemical Degradation of Polycyclic Aromatic Hydrocarbons in Oil Films. Environ. Sci. Technology, 42, 2432-2438.

Kim K.H. et al. (2013) - A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. J. Environ. Int., 60, 71-80.

Lithostratigraphy and sandstone petrography of the sub himalaya along trijuga valley, eastern Nepal

Khanal S.*[1,2], Acharya R.[3], Kandel S.P.[1] & Paudel L.P.[1]

[1] Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [2] Solitaire Mines and Minerals Pvt. Ltd, Kathmandu, Nepal. [3] Department of Mines and Geology, Kathmandu, Nepal.

Corresponding author email: saurav.saroj20@gmail.com

Key words: Sub-Himalaya, pepper and salt, sub-litharenite.

The present study describes the lithostratigraphy and petrography of sandstone of the Sub-Himalaya along the Trijuga Valley, eastern Nepal. Geological route mapping and geological mapping are conducted to establish the lithostratigraphy and the rock succession of the study area is divided into Lower Siwalik, Middle Siwalik and Upper Siwalik members. The Lower Siwalik is composed of fine- grained greenish grey calcareous sandstone, variegated mudstone and grey, brown and purple siltstone. The Middle Siwalik mainly comprises of medium- to coarse-grained pepper and salt sandstone with large cross-lamination, tree trunks, coal patches and dark grey colored siltstone and mudstone. Pebbly sandstone is also present. The Upper Siwalik comprises of matrix supported pebble to cobble size conglomerate.

The petrographic study of thin sections of sandstone of the area show that the sandstone belongs to the sub-litharenites and sub-arkose. They are dominantly composed of quartz, feldspar, rock fragments and miner amount of other accessory minerals like chlorite, garnet etc. Upward trend of grain size shows source is nearer to sedimentary basin and have covered less distance.

Genesis and Parental Affinity of Bauxite Deposits of the Salt Range, Pakistan

Khubab M.*[1], Wagreich M.[1], Iqbal S.[1,3], Schöpfer K.[1] & Ullah M.[2]

[1]Department of Geology, University of Vienna, Austria. [2]Department of Lithospheric Research, University of Vienna, Austria. [3]Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan.

Corresponding author email: Khubabm91@univie.ac.at

Keywords: Bauxite, Mineralogy, Geochemistry, Ore genesis, Parental Affinity.

Well-developed bauxite deposits are reported from the Salt Range as well as the Lesser and Sub-Himalayas of Pakistan. One such deposit is located in the central Salt Range, at the contact between the Permian Wargal Formation and Paleocene Hangu Formation (Kazmi and Abbas, 2001).

These bauxites were studied and sampled at three outcrop sections: one from Chambalwala Mohar (CMB) and two from the Arara area (ATB and AKB). The deposits occur as lenses and are typically composed of three stratigraphic layers: (1) a dark red layer (L-1), (2) a composite conglomeritic layer consisting of multiple brownish, creamy to maroon beds of varying sizes (L-2), and (3) a kaolinite-rich clayey layer (L-3). Results from optical microscopy, XRD, and SEM/EDX reveal that the basal layer contains kaolinite, hematite, and goethite as major minerals, with minor amounts of muscovite, anatase, and rutile. The middle conglomeritic layer primarily consists of kaolinite, boehmite, hematite, gibbsite, goethite, alunite/natroalunite, and zaherite, with anatase and rutile as minor constituents. The top clayey layer is dominated by kaolinite, anatase, hematite, goethite, and quartz. Geochemical analysis using ICP-MS reveals elevated concentrations of Al_2O_3, Fe_2O_3, SiO_2, and TiO_2. The average oxides concentrations in L-1 are 27.23% Al_2O_3, 29.74% Fe_2O_3, 26.18% SiO_2, and 1.99% TiO_2. In L-2; 39.19% Al_2O_3, 10.16% Fe_2O_3, 28.36% SiO_2, and 2.99% TiO_2; and in L-3; 27.55% Al_2O_3, 11.31% Fe_2O_3, 39.96% SiO_2, and 2.37% TiO_2. Trace elements, including Th, U, Ga, Y, Zr, Nb, Hf, V, and Cr, exhibit a positive trend when normalized to upper continental crust (UCC) values across all sections. The Rare Earth Element (REE) concentrations average 331.71 ppm in L-1, 68.51 ppm in L-2, and 510.77 ppm in L-3.

Field observations and analytical data suggest that the genesis of these deposits occurred in two episodes. The basal dark red massive layer indicates in situ lateritization, with enrichment in ultra-stable heavy minerals such as zircon, tourmaline, rutile, monazite, and mica. This layer is mineralogically mature with bauxitic components, but lacks typical bauxitic textures. In contrast, the conglomeritic layers are both texturally and mineralogically mature, and are characterized by various-sized pisoids and ooids within a pelitomorphic-microgranular matrix.

The Zr-Cr-Ga ternary diagram (özlu, 1983) suggests a parental affinity with acidic to intermediate/argillaceous rocks. Meanwhile, plots of Eu/Eu* versus TiO_2/Al_2O_3 and Eu/Eu* versus Sm/Nd (Viers and Wasserburg, 2004; Babechuk et al., 2014) indicate that the deposits resulted from the weathering of sediments derived from upper continental crust sources, including cratonic sandstone and shale.

Babechuk M.G. et al. (2014) - Quantifying chemical weathering intensity and trace element release from two contrasting basalt profiles, Deccan Traps, India. Chem. Geol., 363, 56-75.

Kazmi A.H. & Abbas S.G. (2001) - Metallogeny and mineral deposits of Pakistan. Islamabad, Pakistan: Orient Petroleum.

Özlü N. (1983) - Trace-element content of "Karst Bauxites" and their parent rocks in the Mediterranean belt. Mineral. Depos., 18, 469-476.

Viers J. & Wasserburg G. J. (2004) - Behaviour of Sm and Nd in a lateritic soil profile. Geoch. Cosmoch. Acta, 68, 2043-2054.

Rapid Late Pleistocene frontal fault growth and Sutlej drainage reorganization in the western Himalaya: Implications for the evolution of Himalayan drainage systems

Kordt J.*[1], Dey S.[2], Bookhagen B.[3], Rugel G.[4], Lachner J.[4], Vivo-Vilches C.[4,5], Panda S.K.[6], Chauhan N.[6] & Thiede R.C.[1]

[1]Institute of Geosciences, Kiel University, Kiel, Germany. [2]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India. [3]Institute of Geosciences, University of Potsdam, Potsdam, Germany. [4]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany. [5]Faculty of Physics, University of Vienna, Vienna, Austria. [6]Physical Research Laboratory, Ahmedabad, India.

Corresponding author email: jonas.kordt@ifg.uni-kiel.de

Keywords: fluvial terrace dating, anticline uplift, Sub-Himalaya.

River-network reorganization is a key process to maintain drainage connectivity in tectonically active mountain ranges. The southern Himalayan front has experienced several drainage diversion events that changed river courses in response to fault uplift at the wedge-margin and dictated the growth of mega fans in the footwall. Today the sedimentary regime south of the Himalayan mountain front shows differences along strike: large Himalayan rivers in the east are transport-limited and characterized by active mega fans, while supply-limited regimes form incised river channels into the former active fans in the west.

In this study, we dated Late Pleistocene sediments in the western Himalaya to reconstruct the last drainage-network reorganizations of the Trans-Himalayan Sutlej River. Late Quaternary faulting along the Himalayan Frontal Thrust (HFT) and associated back-thrusting has uplifted the paleo-Sutlej sediments and preserved them as a low-relief surface on top of a frontal anticline. We present new luminescence (n = 11) and paired cosmogenic nuclides (^{10}Be and ^{26}Al) (n = 10) chronologies combined with field mapping and geomorphic analyses to constrain rapid changes of the paleo-Sutlej River. We observe sediment deposition from ~ 47-30 ky on the presently elevated anticline and in the neighboring piggyback basin to the northeast. We determine the latest evidence of a paleo Sutlej channel traversing the growing anticlinal structure to 26.5 ± 3.5 ky dated by an abandoned fan surface. We are able to constrain the averaged minimum uplift rate on the anticline to 6.5 ± 2 mm/y. We also identified a second younger erosional surface on the anticline (14.8 ± 2.2 ky) that we relate to drainage reorganization due to tilting of the anticline surface during uplift.

Our new chronology and observations show the channel response during a Late Pleistocene rapid growth phase of the HFT and a shift from a transport-limited to a supply-limited regime. We propose that the observed deflection history of the Sutlej illustrates a mechanism how Himalayan rivers have been deflected in the geologic past.

Late Pleistocene terrace formation and Holocene mass movements recorded in the Ravi drainage basin in the northwestern Himalaya

Kordt J.*[1], Dey S.[2], Bookhagen B.[3], Rugel G.[4], Lachner J.[4], Vivo-Vilches C.[4,5], Panda S.K.[6], Chauhan N.[6] & Thiede R.C.[1]

[1]Institute of Geosciences, Kiel University, Kiel, Germany. [2]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India. [3]Institute of Geosciences, University of Potsdam, Potsdam, Germany. [4]Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany. [5]Faculty of Physics, University of Vienna, Vienna, Austria. [6]Physical Research Laboratory, Ahmedabad, India.

Corresponding author email: jonas.kordt@ifg.uni-kiel.de

Keywords: fluvial terrace dating, Late Pleistocene, Holocene.

River flow and sediment transport within the Himalayan mountain belt show rapid changes due to active tectonics, changes in monsoonal strength, and deglaciation/glaciation cycles. In our study we focus on the Ravi and Suil Rivers that host sediment archives in the form of fluvial terraces. Both catchments are on the lee of the first orographic barrier in the northwestern Himalaya. We aim at understanding the spatial and temporal storage of the Late Quaternary sediments with a combination of field mapping, luminescence dating (n=12), and cosmogenic nuclide dating (n=36). We reconstruct changes in river height and constrain different fluvial aggradation and incision cycles. In combination with previous luminescence dating by (Joshi et al. 2022), we identified a total of 9 different terrace levels throughout the basin that have been deposited since the Late Pleistocene. The OSL ages show that the end of fluvial aggradation of the two most dominant terrace levels is at ~ 29 ky (~ 140 – 160 m above present-day base level of the Ravi) and at ~ 13 ky (~ 60 – 80 m above present-day base level). Our new cosmogenic nuclide data from the tops of all Ravi and Suil terrace levels, except two ages, yield Holocene ages ranging from 1 to 7 ky. In combination with field observation the data reveals that most terrace tops are either covered by more recent colluvium or have been affected by surface erosion during the Holocene. We propose that variations in glacial cover is a key factor for deposition of the terrace material during deglaciation, when moraines became available for transport via meltwater streams. We suggest that the monsoon intensification during the Holocene is the main reason for the observed mobilization of middle Holocene colluvium (~ 5 - 7 ky) found on most of the exposed terrace tops.

Joshi M., et al. (2022) - Climate-tectonic imprints on the Late Quaternary Ravi River Valley Terraces of the Chamba region in the NW Himalaya. J. Asian Earth Sci., 223, 104990, https://doi.org/10.1016/j.jseaes.2021.104990.

The Early Jurassic *Lithiotis*-type bivalves biostromes along Kali Gandaki Valley (Thakkhola region, northern central Nepal)

Krobicki M.*[1], Starzec K.[1], Iwańczuk J.[2], Rožič B.[3], Žvab Rožič P.[3] & Kwietniak A.[1]

[1]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Poland. [2]Polish Geological Institute–National Research Institute. [3]Faculty of Natural Sciences and Engineering, University of Ljubljana, Slovenia.

Corresponding author email: krobicki@agh.edu.pl

Keywords: Early Jurassic, bivalve biostromes, Kioto Carbonate Platform.

In the Thakkhola region (upper part of the Kali Gandaki Valley of north-central Nepal) there are classic Jurassic and Cretaceous Eastern Tethys sections of sedimentary sequence are exposed within the northernmost and highest tectonic units of the Himalayas [so-called: Sedimentary series (zone) of the Himalayan (Tibetan) Tethys (=Tibetan sediment zone), Tethyan Sedimentary Series, Tethyan Himalayan Sequence, Tethyan Sedimentary Sequence]. This unit has limited extent in Nepal with the best sections being found in the Annapurna-Dhaulagiri, Dolpo and Manang regions.

Alongside Kali Gandaki Valley – between Jomsom and Kagbeni villages – where the continous, deepening upward sedimentary sequence of the uppermost Triassic–Upper Jurassic units occur – the Early Jurassic Jomsom Formation (Pliensbachian–Early Toarcian; 200-400 m in thickness) is represented by fossiliferous, bioclastic and oolitic (with cross-bedding structures)/oncolitic massive limestones deposited in extremely shallow-marine and/or lagoon environments of a subtropical carbonate platform. The term Jomsom Limestone has been first used in 1964 and is a consistently used name until today but others preferred the older name Kioto Limestone (= Kioto Carbonate Platform).

The Jomsom Formation contains unique giant *Lithiotis*-type bivalves, and occur within lens-shaped biostromes, which have been discovered recently in two sections along Kali Gandaki Valley (previousely, such bivalves have only been reported from other parts of the Nepalese Himalaya – in Dolpo and Manang regions). Taphonomic and autecological analysis of bivalve-rich biostromes based on semi-quantitative observation of shell orientation and density, indicates a dominance of parauthochthonous assemblages, with a few localities even preserving shells in life position.

These gigantic bivalves (*Lithiotis*, *Cochlearites*, *Lithioperna*, *Mytiloperna*, *Gervileioperna*) are the most significant representatives of primary builders of shallow marine and/or lagoonal bivalve mounds/biostromes („reefs”) in various locations around the Pangea in Pliensbachian-Early Toarcian time. In comparison, in Europe they are known from Alpine Spain, Italy, Slovenia, Croatia, Albania, Greece, Turkey where they constitute part of the Early Jurassic Alpine-Dinaridic-Hellenidic carbonate platforms characterized by various types of shallow-water carbonate environments, including similar peritidal to subtidal regimes.

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The Early Permian peperites within the Panjal Traps of Kashmir Valley, NW Himalaya, India

Krobicki M.*[1], Ahmad T.[2], Chauhan H.[2], Dar R.A.[3], Bhat M.I.[4], Paudel L.P.[5] & Upreti B.N.[6]

[1]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Poland. [2]Wadia Institute of Himalayan Geology, Dehradun, India. [3]Department of Earth Sciences, University of Kashmir, India. [4]Islamic University of Science and Technology, Awantipora, J&K, India. [5]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal. [6]Nepal Academy of Science and Technology, Kathmandu.

Corresponding author email: krobicki@agh.edu.pl

Keywords: peperites, volcanogenic rocks, submarine eruptions, breakup of Pangea.

Peperites represent a distinctive type of volcano-sedimentary association, characterized by sharply bounded volcanic fragments (commonly basaltic) interspersed with sedimentary deposits. These peculiar rock-types result from submarine basaltic eruptions on the sea floor intruding into unconsolidated, water-saturated carbonate mud, thereby forming a contemporary assemblage with the surrounding sediments. Typically, peperites coexist with other volcano-sedimentary rock types, including basaltic pillow lavas, pyroclastic debris flows, and volcanoclastic or pyroclastic turbidites, which serve as crucial chronological markers for volcanic events when associated limestones are dated using fossils.

In the NW Indian Himalaya, the Panjal Traps span around 10,000 km^2, predominantly distributed across the Kashmir Valley, Pir Panjal and Zanskar ranges. Volcanic sequences around the Kashmir Valley reach up to ~3000 m in thickness, while eastern exposures are comparatively thinner ~300 m (Stojanovic et al., 2016; Shellnutt et al., 2021). A prominent and continuous volcanic sedimentary section occurs at Guryul Ravine (Srinagar vicinity), recording a marine transition between Permian and Triassic units. These uppermost Panjal Traps comprise basaltic pillow lavas interspersed with peperites, manifesting as whitish limestones marked by numerous small, sharply bounded basaltic fragments. The overlaying strata include siliceous novaculites, succeeded by Middle Permian units. Radiometric analyses date the Panjal Traps to the Early Permian (ca. 289 Ma) (Shellnutt, 2016).

On the other hand, Zanskar Himalaya, notably around Rangdum and Padum, the Panjal Traps feature basaltic pillow lavas (at Rangdum) and pāhoehoe lava horizons (at Padum), highlighting a volcanogenic episode associated with rifting and the impending separation a >13,000 km-long string of lenticular-shaped, ribbon-like Cimmerian Continent concurrent with the Neotethys Ocean opening by sea-floor spreading (Chen & Xu, 2021). Correlating these Early Permian volcanogenic phenomena with other Himalayan occurrences (e.g., Phe, Nar-Tsum, Bhote Kosi, Manaslu, Arbor, Selong) is vital for deciphering the geodynamic evolution along the peri-Gondwanan southern Tethyan margin and first step of breakup of Pangea.

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This is the contribution No. 5. of the scientific initiative Himalayan Academy.

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Partial Melting and Leucogranite Generation in the Higher Himalayan Crystallines along Sutlej Valley: Insights from Zircon Geochronology and Petrogenesis

Kushwaha A.*[1,2], Putlitz B.[2], Ulyanov A.[2], Baumgartner L.P.[2], Singh S.[1] & Epard J.L.[2]

[1]Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee – 247 667, India. [2]Institute of Earth Sciences, University of Lausanne, Geopolis, Lausanne 1015, Switzerland.

Corresponding author email: amankush1995@gmail.com

Keywords: Zircon, leucogranite, migmatite.

Partial melting of metasedimentary rocks in the Higher Himalayan Crystallines (HHC) along the Sutlej Valley generated leucogranite magmas that significantly influenced crustal differentiation and deformation during Himalayan orogenesis. Field relationships suggest widespread anatexis and intrusion of leucogranites, especially from the middle to upper structural levels of the HHC in Sutlej Valley. However, the timing and genetic relationship between migmatites and leucogranites remain poorly constrained in this region. To understand the crustal melting in HHC along the Sutlej Valley, we used LA-ICP-MS U–Pb dating and trace element analysis of zircon from migmatitic leucosomes and leucogranites. Zircons from leucosomes yield dispersed rim ages (~29–19 Ma), while those from leucogranites mostly cluster at ~19–17 Ma. Most zircons, except some in leucosomes, exhibit prismatic shapes and oscillatory zoning, confirming a magmatic origin. However, nearly all Himalayan-age rims display anomalously low Th/U ratios (<0.10), a trait generally linked to metamorphic zircon. Widespread occurrence of low Th/U ratio in magmatic-textured grains across multiple samples challenges the conventional use of Th/U to infer magmatic vs sub-solidus origin of zircon.

In leucogranites, trace element patterns show no clear correlation between Th/U and U content or ΣLREE, suggesting that fractionation or early monazite saturation alone cannot explain the low Th/U. Instead, a positive correlation between Th/U and Ce anomaly (Ce/Ce*), a redox proxy (Trail et al., 2012), appears in a few leucogranites. Ti-in-zircon thermometry further reveals a positive correlation with Th/U ratio and Ce anomaly and decreasing temperatures from mantle to rim, suggesting zircon crystallisation during cooling. This trend may reflect a redox-driven mechanism where, under oxidising conditions, U^{4+} is partially oxidised to U^{6+} (Houchin et al., 2024), which is more incompatible in zircon, resulting in lower U incorporation and hence higher Th/U. As the system cools and becomes more reducing, U^{4+} is retained in the zircon structure, lowering the Th/U ratio in rims.

On the other hand, in leucosomes, the older zircon rims are rounded and homogenous in CL, suggesting a sub-solidus origin (Corfu et al., 2003), and the younger rims (~19 Ma) are oscillatory zoned. Leucosome-hosted zircons show increasing crystallisation temperatures with time, suggesting increasing temperature from 29 to 19 Ma. Together, these findings suggest leucogranites and migmatites reflect different phases of a melting history, with zircon in leucosomes recording transition from sub-solidus growth to partial melting and zircon in leucogranites recording peak/post-melting history.

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Structural Architecture and Microstructural Features of the Jajarkot Thrust Sheet, Western Nepal

Lamsal S.*[1], Bhandari G.[1], Kandel A.[1] & Paudyal K.R.[1]

[1] Central Department of Geology, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: geosunil91@gmail.com

Keywords: thrust kinematics, microstructures, metamorphism, Nepal Himalaya.

The Jajarkot Thrust Sheet of western Nepal, located in the Lesser Himalaya, represents a significant allochthonous tectonic unit that offers valuable insights into Himalayan tectonics, structural development, and metamorphic evolution. Initially regarded as an isolated outlier of the Greater Himalayan Sequence emplaced over the Lesser Himalaya along the Main Central Thrust (MCT) (Fuchs & Frank, 1970; Sharma et al., 1984), the region still lacks comprehensive studies on its stratigraphy, structure, and microstructures.

This study aims to clarify the lithostratigraphy, structural framework, and deformation history of the Jajarkot Thrust Sheet through detailed field mapping at a 1:25,000 scale and petrographic analyses of systematically collected samples. Thin sections were prepared and examined at the Central Department of Geology, Tribhuvan University. The analysis reveals dynamic recrystallization and top-to-the-south ductile shearing, indicating an inverted metamorphic sequence and elevated deformation temperatures near the structurally regional discontinuity. The Jhimruk Khola Thrust (JKT), mapped in this region, acts as a major tectonic boundary, correlating with the Mahabharat and Dubung Thrusts of central and west-central Nepal. It juxtaposes medium-grade metamorphic rocks of the thrust sheet against low-grade Lesser Himalayan metasediments. The thrust sheet comprises schist, quartzite, and marble, structurally overlying the Nawakot Group, which includes the Benighat Slates with Runkha Carbonate, Tamghas Dolomite, and Resunga Formation (Lamsal et al., 2023).

Four lithostratigraphic units are identified: the Bastu, Purkotdaha, Chaurjahari (with Arkhaban Member), and Thabang Formations. These units exhibit polyphase deformation: D1–D2 phases are related to pre-Himalayan events, while D3–D5 phases occurred during Himalayan orogenesis. Microstructures such as S–C fabrics, mica fish, mantled porphyroblasts, and snowball garnets confirm consistent south-directed shearing. Quartz microstructures—undulose extinction, grain boundary migration, and subgrain rotation provide a higher deformation in the rocks of the region. Metamorphic zoning includes garnet-grade rocks near the thrust front, with inverse metamorphism (M2) in the footwall and prograde (M1) to retrograde (M3) metamorphism in the hanging wall. The presence of fossiliferous Tethyan rocks (Jaljala Formation) in the northwest may suggest tectonostratigraphic links with the Kathmandu Nappe for root zone interpretation.

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Microbial controls on carbonate coated grains: Insights from the Miaolingian Zhangxia Formation (North China Platform)

Latif K.*[1], Riaz M.[2] & Xiao E.[3]

[1]1National Centre of Excellence in Geology, University of Peshawar, Peshawar 25130, Pakistan. [2]State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China. [3]Key Laboratory for Polar Science, MNR, Polar Research Institute of China, Shanghai 200136, China.

Corresponding author email: khalidlatif@uop.edu.pk

Keywords: Oncoids, Cyanobacteria, Miaolingian Zhangxia Formation.

Oncoids are microbial carbonates distinguished from ooids by their relatively larger size and the presence of rough laminae within the cortex. These spherical, stromatolite-like structures form through successive lamination in high-energy environments, such as the oolitic grainstones of the Miaolingian Zhangxia Formation in the North China Platform. Their co-occurrence with millimeter-scale ooids in these high-energy shoals reflects conditions conducive to microbial growth during relative sea-level decline.

The oncoids exhibit centimeter-scale sizes, oval to round shapes, and micritic laminated fabrics. Their cortices, composed of alternating 20–40 μm thick micrite-spar layers, preserve a high density of calcified sheaths of filamentous cyanobacteria, particularly *Girvanella*.

Thin-section analysis classifies these oncoids into three morphological types: concentric laminar, lateral growth, and multicore oncoids. Additionally, three types are identified based on *Girvanella* distribution: *Girvanella*-core oncoids, *Girvanella*-cortex oncoids, and *Girvanella*-full oncoids. These microbial fossils provide valuable insights into the calcification of extracellular polymeric substances (EPSs), which form photosynthetic biofilms and, subsequently, microbial mats—key processes in oncoid development. Additionally, the presence of pyrite indicates the involvement of heterotrophic bacteria, reflecting microbial diversity within the mats.

While microbial influence on oncoid formation is well-documented, its role in ooid formation remains less clear due to diagenetic alterations. During cyanobacterial bloom of the period, microbial mats also contributed to the formation of constructive micrite envelopes around ooids, individual grains, and their aggregates, consistent with previous attributions of Cambrian ooid formation to filamentous calcimicrobes. Although microbial mats facilitated micrite envelope formation, direct evidence for their primary role in ooid genesis remains limited.

This study underscores the significance of microbial fossils, particularly calcified cyanobacterial sheaths, in understanding oncoid formation. It also highlights key differences in the formation mechanisms of ooids and oncoids: while ooids predominantly develop in the water column, oncoids grow on the seafloor and are more influenced by benthic microbial processes. Unlike radial ooids, the absence of radiating fibrous calcite in oncoid cortices further suggests a distinct formation mechanism.

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Giant collapses of high Himalayan peaks and their impact on the Himalayan landscapes

Lavé J.*[1], Huber M.[1], Khatiwada S.[2] & Scholtès L.[3]

[1]CRPG-CNRS, Nancy, France. [2]Tribhuvan University, Nepal. [3]Laboratoire Magma et Volcan, Clermont, France.

Corresponding author email: jerome.lave@univ-lorraine.fr

Keywords: Giant rockslides, high Himalayan summit.

Although the topographic evolution and erosion dynamics of the Himalayan range have been extensively documented, it is not known how the very high Himalayan peaks erode. Some conceptual models assume that intense periglacial processes involve regressive erosion of high peak headwall at rates dictated by valley-floor downcutting of glaciers. However, recent data indicate that frost-cracking intensity decreases with elevation, suggesting instead that highest Himalayan peaks are free of erosion, raising the question of their long-term evolution. Here, we report geological evidence for two Holocene giant rockslides that occurred in the Annapurna Massif (central Nepal), involving total rock volume of ~23 and ~18 km3 respectively and that decapitated high paleosummits, culminating most probably above 8000 m altitude for the first one. Our data demonstrate that the main mode of high-altitude erosion could be catastrophic mega-rockslides, leading to the sudden reduction of the high peaks elevation by several hundred meters and ultimately preventing the high Himalayan peaks from growing indefinitely (Lavé et al., 2023). This erosion mode, associated to steep slopes and high relief, arises from a higher mechanical strength of the high-peak substratum, probably due to the presence of permafrost at high altitude and the absence of bedrock weathering. In addition to their direct impact on the evolution of the High Himalayan landscape and ridgeline, giant rockfalls can also have major implications for the evolution of downstream rivers and natural hazards through massive sediment supply; but this effect mainly depends on the location of the rockfall within the range.

Lavé J. et al. (2023). Medieval demise of a Himalayan giant summit induced by mega-landslide. Nature, 619, 94-101, DOI: 10.21203/rs.3.rs-1918601/v1.

Outward growth of the NE Tibetan Plateau: Insight from the Jinta Basin sedimentary record (NW China)

Li X.[*2, 3*], Chen D.[, 2], Pan B.[, 2], Garzanti E.[3], Wang K.E.[1], Chen D.[1], Fu X.[1], Mo Q.[1], Hu D.[1], Huang D.[1] & Liu W.[1]

[1] Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China. [2] Shiyang River Basin Scientific Observing Station of Gansu Province, Lanzhou, 730000, China. [3] Department of Earth and Environmental Sciences, University of Milano Bicocca, Milan, 20126, Italy.

Corresponding author email: lixh2021@lzu.edu.cn

Keywords: Jinta Basin; Sedimentary evolution; Magnetostratigraphy; Arid denudation plain; Outward growth of Tibetan Plateau.

The surface uplift and outward growth of the Tibetan Plateau in response to the earliest Cenozoic India-Asia collision reshaped the landscape of Eurasia and significantly affected the Asian monsoon system, inland aridification, and global climate change.

Constraining when compressive tectonic stress started to affect the outermost frontier area of the northeastern Tibetan Plateau is crucial to understand whether the northeastern Tibetan Plateau was uplifted simultaneously with the India-Asia collision or has undergone progressive northeastward expansion. The subsidence and infilling history of the distal sub-basin between the northeastern Tibetan Plateau and the Beishan Block is the key to test those contrasting views.

In this study, a 262-m-long drill core (LJZ) was recovered from the Jinta Basin, in the subsident area between the tectonically active northeastern Tibetan Plateau and the relatively stable Beishan Block. Sedimentological and high-resolution magnetostratigraphic analyses indicate that the sedimentary succession started to be deposited at 3.4 Ma. The sediment accumulation rate increased from 36 to 114 mm/ka while facies changed upward from basal braided river to ephemeral lake, dryland river terminus system, braided rivers at ~3.0, ~1.7, ~1.2 Ma, respectively. Initial subsidence of the Jinta Basin at 3.4 Ma indicate that the arid denudation plain was disrupted as a result of northeastward tectonic propagation, while deposition of coarse-grained braided river sediments before 3.0 Ma was driven by Late Pliocene climatic cooling. Between 3.0 and 1.2 Ma, fine-grained lacustrine and dryland river terminus sediments with higher accumulation rates suggests accelerated flexural subsidence and basin-ward propagation of tectonic stress after 1.7 Ma. The return of coarse-grained braided river sediments after 1.2 Ma was mainly forced by climate change since Mid Pleistocene Transition, which further enhanced and overpowered tectonic effects after 0.78 Ma.

Combined with the tectono-geomorphological evolution history of the northeastern Tibetan Plateau, the evolution testified by sedimentary facies and sediment accumulation rate of the Jinta Basin testifies to the progressive northeastward growth of the Tibetan Plateau, with Late Cenozoic evolution of the basin resulting from the interplay between tectonic and climatic forcing.

Crustal Melt Presence and Removal Controls Crustal Strength and Influences the Development of Deformation Mode in the Himalayan Orogen

Li Y.[1], Robinson D.M.*[1], Ding L.[2] & Metcalf K.[3]

[1]Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama, USA. [2]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China. [3]Department of Geological Sciences, California State University Fullerton. California, USA.

Corresponding author email: dmr@ua.edu

Keywords: Crustal strength, Himalaya, Leucogranite, deformation mode.

Understanding how crustal strength varies and interplays with tectonic processes is critical for continental orogenic studies. The Himalayan orogen is an ideal region to investigate this issue. Coeval with widespread crustal melting and leucogranite intrusion during Oligo-Miocene time, the Himalaya experienced crustal shortening with both long thrust sheets and short duplex and imbrication thrust sheets, crustal thickening and high-grade metamorphism, and significant surface elevation gain from <2000 m to >5000 m.

In this study, we combine thermodynamic and rheological calculations with wedge mechanics to investigate how Himalayan Cenozoic leucogranite melting and melt-removal affect crustal strength and thereby influence large-scale tectonism. Integrating the previous studies of Himalayan crustal deformation, tectono-metamorphism, and paleo-elevation reconstruction, our results reveal three key phases: 1) Rising geothermal gradients during ~60-30 Ma crustal thickening weakened the mid-lower crustal strength that potentially triggers the initiation of the Himalayan structural discontinuities since ~40 Ma, replacing the Tethyan fold-thrust belt as the primary convergent strain accommodator along the Himalaya; 2) Early-stage broad leucogranite melting during ~30-20 Ma weakened the mid-lower crustal strength, producing a supercritical wedge that promoted across-strike lengthening of low-elevation (<2000 m) Himalayan taper accommodated by the N-S directed normal faulting along the South Tibetan detachment and the Gangdese rift basins and far-traveled long basal thrust sheets along the Main Central thrust since ~30–25 Ma; 3) Melt-removal and extraction coeval with widespread leucogranite intrusion during ~20-10 Ma substantially strengthened the mid-lower crust, transitioning the wedge from supercritical to subcritical states, thereby maintaining the growing high-elevation taper and shifting deformation mode from long thrust sheets along the Main Central and Ramgarh-Munsiari thrusts to foreland-propagated short imbrication/duplex thrust sheets in Lesser Himalayan rocks. A relatively strong Himalayan mid-lower crust, existing both before broad melting and after melt-removal, rims the softer South Tibet crust at depth, likely influencing far-field tectonism. These observations highlight how the transition from melt-presence to melt-removal significantly affects orogenic crustal strength controlling major tectonism and demonstrate that the vertical rheological structure during melt-removal differs substantially from conventional quartz and feldspar analogs.

Oxygen isotopic composition of single detrital quartz grains: a new tool in detrital provenance studies (Bengal Fan, IODP Expedition 354).

Limonta M.*[1, 2], France-Lanord C.[2], Galy A.[2], Gurenko A.[2], Bouden N.[2] & Garzanti E.[1]

[1]Laboratory for Provenance Studies, Department of Earth and Environmental Sciences, University of Milano-Bicocca.
[2]Centre de Recherches Pétrographiques et Géochimiques (CRPG), CNRS – Université de Lorraine, Vandœuvre-lès-Nancy.

Corresponding author email: mara.limonta@unimib.it

Keywords: Oxygen isotopes, Provenance analysis, Himalayan orogen.

Quartz is the most abundant mineral in sedimentary rocks and it survives weathering and diagenetic processes (Clayton et al., 1978), making it a reliable tracer for sediment provenance studies. However, conventional and advanced methods for determining quartz origin—such as petrography, cathodoluminescence, and laser ablation spectrometry—have achieved limited success.

This study introduces a new protocol for analyzing the oxygen isotopic composition of individual detrital quartz grains aiming to evaluate quartz's potential as a provenance indicator across magmatic, metamorphic, and sedimentary domains and to improve source-to-sink reconstructions. Although single-grain analysis is commonly used in detrital thermochronology (e.g. Blum et al., 2018; Najman et al., 2019), it has not yet been applied to major minerals like quartz using traditional isotopic tracers.

The proposed method has been tested on modern sediments carried by rivers draining the Himalayan orogenic belt, as well as on Bengal Fan turbidites collected during IODP Expedition 354. By analyzing the oxygen isotopic fingerprints of individual quartz grains, distinct signatures of different Himalayan tectonic units (Greater Himalaya, Lesser Himalaya, Tethys Himalaya, and the Trans-Himalayan Batholiths) have been revealed. This approach allows us to quantify each domain's contribution to the Bengal Fan turbidites and to provide insight into sediment mixing, offering a higher resolution of sediment provenance than bulk analysis techniques.

Approximately 200 quartz grains were analyzed per sample from rivers that drain distinct Himalayan tectonic domains using LG-SIMS ion microprobe to characterize oxygen isotopic variability, thus providing a good fingerprint of the source rocks in the detrital record. Around 150 grains per sample from the Bengal Fan were examined to assess how the contributions of different Himalayan sources have evolved over time.

These new data, integrated with bulk sediment and single-mineral approaches, significantly improve provenance resolution and shed light on the erosional history of the Himalayan-Tibetan orogen. This new method offers valuable support to traditional quartz-based provenance tools (such as luminescence properties, OH-defect analysis, and petrographic features), and complements established techniques including petrography, heavy mineral analysis, elemental geochemistry, and isotope geochemistry—enhancing the discrimination of detrital quartz from felsic igneous, metamorphic, or sedimentary origins.

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Najman Y. et al. (2019) - Spatial and temporal trends in exhumation of the Eastern Himalaya and syntaxis as determined from a multitechnique detrital thermochronological study of the Bengal Fan. Bulletin, 131, 1607-1622, https://doi.org/10.1130/B35031.1.

Seismicity, Seismotectonics, and Focal Mechanism Solutions in the Northern Himalayas, Pakistan

Lisa M.*1

*1Department of Earth Sciences, Quaid-i-Azam University (QAU), Islamabad (45320), Pakistan

Corresponding author email: lisa_qau@yahoo.com, mlisa@qau.edu.pk

Keywords: Seismicity, Seismotectonic, focal mechanism solution, Northern Himalayas

The northern Himalayan region of Pakistan, including Azad Jammu and Kashmir, Khyber Pakhtunkhwa, Gilgit-Baltistan, and the Hazara Division, is situated at the active junction of the Indian and Eurasian plates. This geodynamic setting makes it one of the world's most seismically active areas, marked by complex fault interactions and frequent moderate to large earthquakes. Understanding seismicity, seismotectonics, and focal mechanisms is essential for accurate hazard assessment and effective risk mitigation.

Seismicity is mainly concentrated along major tectonic structures such as the Main Boundary Thrust (MBT), Main Central Thrust (MCT), and Indus-Kohistan Seismic Zone (IKSZ). Most earthquakes are shallow to intermediate in depth, with about 84% occurring above 70 km. In contrast, the Hindu Kush region shows deeper seismicity, with events reaching 244 km, indicative of ongoing subduction. Earthquake frequency follows the Gutenberg-Richter distribution, with many moderate events (magnitude 4.0–5.0) and fewer high-magnitude ones (>6.0), which, though rarer, pose greater risk.

The seismotectonic framework is shaped by the ongoing convergence of the Indian and Eurasian plates (Bilham, 2001), resulting in significant crustal shortening and a complex network of fold-and-thrust belts. The MBT and MCT accommodate this convergence, with the MBT acting as a key detachment fault (Hussain et al., 2008). Other contributing structures include the Chaman Fault to the west and the Salt Range Thrust to the south. Several active fault segments have been mapped, and seismicity is generally higher in hinterland zones. The presence of both surface and blind thrust faults increases overall seismic hazard.

Focal mechanism studies clarify fault orientations and stress regimes (MonaLisa et al., 2004). Analysis of key events in northern Pakistan indicates a dominance of strike-slip faulting, mainly left-lateral, followed by thrust and, less commonly, normal faulting. These events often originate in the lower crust, especially beneath the Hindu Kush, where deep deformation is active. The regional stress field is largely compressive, oriented from NNW–SSE to N–S, consistent with plate convergence. In southern areas like the Salt Range and Potwar Plateau, reverse and thrust faulting reflect ongoing crustal thickening due to collision.

Deterministic seismic hazard assessments, using earthquake catalogs, fault data, and focal mechanisms, consistently identify high-risk zones along active faults and tectonically complex areas. Notably, the Hazara–Kashmir syntaxis and Hindu Kush stand out due to intense deformation and fault interaction. Past and recent studies (e.g., MonaLisa et al., 2007) emphasize the need for robust seismic risk models, strict building codes, and thoughtful urban planning.

In summary, the northern Himalayan region of Pakistan is shaped by intense tectonic convergence, active faulting, and deep subduction, making it highly susceptible to sesismic hazards. Ongoing geophysical monitoring, integrated research, and proactive risk managment strategies are essential to reduce vulnerability and protect communities and infrastructure from future seismic events.

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Sediment burial-induced dolomitization and implications for Eocene paleoelevation of the Qiangtang terrane, central Tibet

Ma A.*[1], Li L.[2], Li G.[1], Zheng B.[1], Li K.[1], Hu X.*[1]

[1]State Key Laboratory of Critical Earth Material Cycling and Mineral Deposits, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China. [2]Department of Earth, Environmental and Geographical Sciences, University of North Carolina at Charlotte, Charlotte, NC 28223, USA.

Corresponding author email: alma@nju.edu.cn; huxm@nju.edu.cn

Keywords: carbonate diagenesis, thermochronology, carbonate clumped isotopes.

Authigenic carbonates in hinterland basins are valuable archives of paleo-surface water isotope composition and temperature, which play crucial roles in reconstructing paleoelevation. However, these carbonates are highly susceptible to diagenetic alternation shortly after deposition and during burial, some of which, e.g., micro-recrystallization, dolomitization, and bond reordering, are difficult to detect without a well-constrained basin thermal history. Here, we integrate carbonate clumped isotope thermometry with apatite U-Th/He and fission-track thermochronology, from a well-exposed sedimentary basin in Qiangtang terrane, central Tibet, where a well-constrained age-depth model indicating rapid tectonic subsidence with >2 km sediments deposition in early to middle Eocene time. This is followed by rapid exhumation to the surface by latest Eocene. Sediment burial caused resetting of apatite U-Th/He ages and partial resetting of apatite fission-track ages, concurrent with open-system dolomitization and recrystallization of lacustrine carbonates. Calculated oxygen isotope values of the diagenetic fluids yield positive $\delta^{18}O$ between +1.04‰ and +5.89‰ and were interpreted to indicate basin brine and/or cooled magmatic hydrothermal fluid. Our study highlights 1) the great potential of the combination of low-temperature thermochronology and clumped isotope thermometry in determining carbonate diagenesis history; and 2) open-system burial diagenesis of lacustrine carbonate pose significant challenges for paleoelevation reconstruction in active orogenic settings.

Textural maturity analysis of detrital sediments from the Kaligandaki and Karnali River, two major river basins of Nepal Himalaya

Maharjan S.[1] & Tamrakar N.K.*[1]

[1]Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal.

Corresponding author email: naresh.tamrakar@cdgl.tu.edu.np

Keywords: sorting, textural maturity, textural inversion.

Rivers formed after the collision of the Indian-Eurasian plate during the Eocene continually flow across various tectono-stratigraphic units of the Himalaya (Valdiya, 1999). The sediments along the river channel are the result of weathering, disintegration, and erosion of the source rock. Before deposition, sediment undergoes different reworking phases during transportation, resulting in shape modification (Folk, 1980). Studies have shown that sediment particles are generally well sorted, rounded, and spherical as they are transported downstream owing to abrasion and selective transport processes (Friedman & Sanders, 1978). Thus, the transportation mode and depositional environment can be analyzed from textural signatures. This study aimed to investigate the textural characteristics of sands within the Karnali and Kaligandaki River Basin, focusing on variations in grain size, shape, and maturity along its downstream course, from the high-altitude Tibetan Plateau through the mountainous and hilly midstream regions to the Indo-Gangetic Plain. Approximately 500 g of sand-sized sediment samples were collected along the mainstream and its tributaries from both rivers. Size measures, including sorting, were obtained using phi values. A binocular microscope was used to obtain roundness and sphericity data.

In both river basins, the median size decreased and sorting improved downstream. Grain roundness remained subangular to angular throughout the river course along the Karnali River, whereas it remained subangular in the Kaligandaki River, suggesting ongoing transport and abrasion. The overall maturity trend of the Karnali River sands does not exhibit a consistent trend of increasing maturity along the downstream course. Instead, the maturity status of the sediments remained mostly submature throughout the river course. However, the Kaligandaki sand tends to have enhanced maturity in its downstream regions, which is due to moderately well-sorted to well-sorted sediments. Some tributaries of the Karnali River have a significant role in inversing the maturity status, while the Kaligandaki experiences no role of the tributaries in changing the textural maturity trend downstream.

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Oxygen and hydrogen isotopes in fluid inclusions record surface uplift of the Himalaya in the South Tibetan Detachment shear zone (Ramba Dome, Northern Himalaya)

Melis R.*[1], Mulch A.[1,2], Chen F.[3], Vonhof H.[4] & Zhang B.[3]

[1] Senckenberg Biodiversity and Climate Research Centre (BiK-F), Senckenberg, 60325 Frankfurt/Main, Germany. [2] Institute for Geosciences, Goethe University Frankfurt, 60438 Frankfurt/Main, Germany. [3] Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, 100871 Beijing, China. [4] Department of Climate Geochemistry, Max Planck Institute for Chemistry, Mainz, Germany.

Corresponding author email: r.melis@hotmail.fr

Keywords: Stable isotope paleoaltimetry, quartz fluid inclusions, South Tibetan Detachment.

The Himalayan orogen, with an average elevation of ~5 km and peaks rising above 8 km, is a critical region for understanding the interactions among geodynamic, climatic, and surface processes that have shaped Earth's topography since the Cenozoic. Reconstructing its surface uplift history is essential to decipher the feedbacks between mountain building, global climate evolution, and the intensification of the Asian monsoons. However, paleoaltimetry reconstructions, whilst essential, are still elusive in the Himalaya, where commonly applied paleoaltimetry proxy materials are rarely preserved. The lack of paleoaltimetric data is hence partly due to the restricted number of methods and their associated biases. As oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopic compositions of precipitation scale with elevation, calculating past $\delta^{18}O$ or $\delta^{2}H$ values of such meteoric waters provides a key to reconstructing paleoelevation. Paleoaltimetry approaches rely on the assumption that the isotopic composition of certain geological proxy materials such as e.g. carbonates, fossilized teeth, hydroxylated minerals formed in equilibrium with meteoric waters. In this study, we use quartz-hosted fluid inclusions in quartz veins to directly measure the $\delta^{18}O$ and $\delta^{2}H$ values of paleoprecipitation trapped in shear zone rocks during deformation. This approach overcomes key limitations of existing methods by providing direct access to the stable isotope composition of ancient precipitation in two isotope systems.

We analyzed $\delta^{18}O$ and $\delta^{2}H$ values of paleoprecipitation trapped in fluid inclusions of hydrothermal quartz veins from the South Tibetan Detachment (STD) shear zone in the Ramba Dome (Northern Himalaya). Structural and microthermometry data show that the veins formed syntectonically with STD activity between the early and middle Miocene. Isotopic analyses indicate a meteoric origin for the fluids. $\delta^{18}O$ and $\delta^{2}H$ fluid values exhibit a decreasing trend towards the detachment and indicate that the STD was the dominant fluid flux pathway allowing meteoric water to permeate the extending crust. The isotope data define two distinct meteoric fluid populations: (1) low δ-values, consistent with high-altitude Himalayan precipitation, and (2) comparatively higher values. This isotopic difference is consistent with a model of regional surface uplift from approximately 3 km to at least 5 km over the duration of STD activity between the early and middle Miocene. Such inferred surface uplift is contemporaneous with detachment of the Indian lithospheric slab beneath the Himalaya, pointing to a key role of slab dynamics in driving the vertical growth of the orogen. Our results align with other regional paleoaltimetric estimates for the same time interval (e.g. Ding et al., 2017, Gébelin et al., 2013, Melis et al., 2023) and demonstrate that fluid inclusions in hydrothermal quartz offer a robust and direct archive of past meteoric water compositions.

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Petrochronology of Shear Zones: Insights from the Himalayas

Montemagni C.*[1] & Villa I.M.[2,3]

[1]Dipartimento di Scienze della Terra, Università di Firenze. 2Dipartimento di Scienze dell'Ambiente e della Terra, Università di Milano-Bicocca. [3]Institut für Geologie, Universität Bern.

Corresponding author email: chiara.montemagni@unifi.it

Keywords: shear zones, petrochronology, $^{40}Ar/^{39}Ar$ dating.

Constraining the timing of deformation in crustal-scale shear zones is fundamental for reconstructing the tectonic evolution of orogenic belts. In the Himalayas, the South Tibetan Detachment System (STDS) and the Main Central Thrust (MCT) record complex histories of strain localization, metamorphism, and fluid interaction. In this contribution, we present an integrated approach combining $^{40}Ar/^{39}Ar$ geochronology and detailed microstructural analyses to date deformation in crustal-scale shear zones. We highlight the complementary roles of $^{40}Ar/^{39}Ar$ stepwise heating and in situ laser ablation techniques: step-heating enables compositional fingerprinting of distinct mineral generations, while laser ablation provides spatially resolved ages that can be directly linked to deformation-related microstructures (Montemagni & Villa, 2025).

Microstructural observations and chemical mapping reveal that syn-kinematic mica recrystallization and retrogression in samples from the Alaknanda Valley (Garhwal Himalaya) often occur at sub-millimeter scales. The interpretation of apparently discordant age data is guided by integrating microtextural, compositional, and isotopic information. The inferred history of the MCT shear zone includes an early mica generation crystallizing at ≥16 Ma, a syn-kinematic recrystallization forming the main foliation at ~9 Ma, and a post-deformational coronitic mica overgrowth at ~6 Ma. Reliable dating of shear zone activity depends on recognizing microstructural context, avoiding isotopic mixing, and accounting for fluid-assisted dissolution–precipitation processes.

$^{40}Ar/^{39}Ar$ dating of syn-kinematic and post-deformational micas, selected through detailed petrographic and microstructural characterization, allows us to constrain the timing of STDS and MCT activity in the Alaknanda Valley. Our results support the diachronous nature of the STDS and MCT in the Garhwal Himalaya, where ductile shearing along the STDS ceased at least 7 million years before deformation along the MCT in the same transect (Montemagni et al., 2018, 2019).

This study demonstrates that a microstructurally and compositionally constrained $^{40}Ar/^{39}Ar$ approach is essential for resolving complex deformation histories in major Himalayan shear zones. It allows identification of successive generations of mica and provides crucial insights into the timing and mechanisms of crustal-scale shear zone activity during orogenic evolution.

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Montemagni C. & Villa I.M. (2025) - Dating deformation by the 40Ar/39Ar method: a review. It. J. Geosci., https://doi.org/10.3301/IJG.2025.06.

Constraining the Multistage Evolution of a Regional Shear Zone: The Case of the South Tibetan Detachment System

Montomoli C.[1*], Iaccarino S.[1], Montemagni C.[2], Nania L.[3] & Carosi R.[1]

[1] Dipartimento di Scienze della Terra, Università di Torino (Italy). [2] Dipartimento di Scienze della Terra, Università di Firenze (Italy). [3] Geological Survey of Canada (Canada).

Corresponding author email: chiara.montomoli@unito.it

Keywords: South Tibetan Detachment, crystallographic preferred orientation,strain hardening.

The South Tibetan Detachment System (STDS) is one of the most spectacular examples of a low-angle normal fault on Earth, placing lower high-grade metamorphic rocks of the Greater Himalayan Sequence in contact with the upper, very low-grade to non-metamorphic rocks of the Tethyan Himalayan Sequence. It plays a primary role in the exhumation of the metamorphic core of the belt and, for a long time, was considered coeval with the lower Main Central Thrust, which is characterized by an opposite sense of movement.

Its architecture is quite complex, and it has previously been described in the Everest area—where it is spectacularly exposed—as consisting of a lower ductile shear zone and an upper brittle fault.

Detailed investigations along several sectors of the belt highlight that the upper brittle fault did not develop everywhere. Meso- and microstructural analyses on oriented thin sections provide new data regarding the development and tectonic evolution of the South Tibetan Detachment System in these areas.

Microstructural analyses, combined with crystallographic preferred orientation, paleopiezometric, and vorticity analyses, reveal a complex, multi-stage tectonic evolution (Nania et al., 2024). Two different stages of non-coaxial deformation have been recognized, during which the STDS experienced deformation from deeper to shallower structural levels with decreasing temperatures.

The first stage, at deeper structural levels, occurred under low differential stress values (<15 MPa), while the second stage is characterized by significantly higher differential stress (>100 MPa). Cooling, accompanied by increasing differential stress, has been interpreted as evidence of the progressive exhumation of the STDS, during which strain hardening occurred. This allowed ductile shearing to persist at shallower levels without localization into an upper brittle fault.

In addition, geochronological investigations (Carosi et al., 2013; Iaccarino et al., 2017; Montemagni et al., 2018) show that, in several study areas, the STDS is not coeval with the lower Main Central Thrust, opening new perspectives on the exhumation processes of the Himalayan belt.

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Fate of subducted continental crust: a study from Himalayan Suture Zone rocks

Mukherjee B.K.

Wadia Institute of Himalayan Geology, Dehradun, India.

Corresponding author email: barun@wihg.res.in

Keywords: Himalaya, gneiss, zircon.

The present study highlights U-Pb ages of the successive overgrowth of zircons guided by metamorphic minerals, are recovered from the gneissic complex of Indus suture zone, eastern Ladakh, NW Himalaya. The gneissic complex is primarily composed of quartzo-feldspathic rocks representing low to medium grade metamorphism whereas its enclosed mafic eclogite show subduction related ultrahigh-pressure (UHP) metamorphism. The gneissic rock demonstrates tendency to pervasively retrogress during the recrystallization at the low grade metamorphism. Unlike the UHP eclogite, gneisses are prone to the alteration and lacks direct imprint of the subduction signatures, in result most of the chemical and isotopic signals seen erased. It is therefore, the evolution of the host gneisses and the search of HP-UHP minerals in the subduction complex, have become challenging and crucial. Nonetheless, the poor preservation of UHP mineral assemblages in the gneisses resists the correct assessment of successive metamorphic evolution and hinders establishing the direct linkages with the age data and its metamorphic events. This is the most intriguing issues, which requires a systematic study. And it is all the more essential part, constraining the maximum extent of pressure and temperature conditions might have experienced by the low resistant felsic crustal rock in the subduction system. Thus it is challenging, whether protracted subduction of low density felsic rock makes recycling and/ or exhume from the shallower surface or from the mantle depth of the Earth.

To address this debated issue, zircons of the gneisses are studied. The zircons CL structure and its preserved metamorphic minerals inclusion indicates subduction related metamorphic responses in the host gneisses. The characteristic Raman spectra of the mineral inclusions demonstrates, overgrown part of zircons preserve quartz-coesite, c-polymorphs, phengite and other metamorphic minerals, resembles UHP grade metamorphism. The distribution pattern of these minerals in the zircons show consistent with the Th/U ratios ranging 0.30 to 0.01 from core to rim, recognizes subduction induced metamorphic overgrowths in the zircons, suffices UHP condition of pressure >3 Gpa. The zircon U-Pb ages of metamorphically grown part yields *c*. 45-42 Ma, these data interpretation on the Himalaya tectonic suggests, continued and in situ subduction of buoyant crustal gneiss of the Indian plate till c. 45 Ma.

Effects of the India-Asia collision: Magnitude and timing of movement on the Sagaing Fault, Myanmar

Najman Y. [1], Luan X. *[2], Sobel E.R.[3], Millar I.[4], Garzanti E.[5], Zapata S.[6], Vezzoli G.[5], Saw Mu T.L.P.[7] & Day W.A.[8]

[1]LEC, Lancaster University, UK. [2]College of Earth Science and Engineering , Shandong University of Science and Technology, China [3]Institute of Geosciences, University of Potsdam, Germany. [4]NEIF, BGS Keyworth, UK, [5]Dept Earth and Environmental Sciences, University of Milan Bicocca, Italy, [6]Faculty of Natural Sciences, Universidad del Rosario, Bogotá, Colombia, [7]Independent, Myanmar, [8]Geology Dept, University of Yangon, Myanmar.

Corresponding author email: xluan@sdust.edu.cn

Keywords: Sagaing Fault, Irrawaddy River, Central Myanmar Basin, Indo-Burman Ranges.

Motion on the Sagaing Fault has been linked to India's indentation into Asia and subsequent extrusion tectonics (Tapponnier et al., 1982). Yet the duration and magnitude of motion along the Sagaing Fault is debated. Many papers favour onset of motion in mid Miocene or later (e.g. Bertrand and Rangin, 2003) based on linkage to Andaman Sea rifting. Using modern rates of motion of ~20 mm/yr from GPS data, that would indicate a maximum displacement of <150 kms. However, offset of various proposed distinct markers across the fault suggest displacement of 300-400 kms indicating either faster rates of motion in the past, or earlier onset of motion (e.g. Morley and Arboit, 2019).

Utility of offset markers to determine magnitude of displacement suffers from either uncertainties regarding correlation of lithological units across the fault or use of markers that only provide a record over a short time period. The debated use of the offset between the upper Irrawaddy headwaters and Chindwin Rivers, first proposed by Maung (1987), potentially allows for a longer time period of consideration. With this hypothesis, the Irrawaddy headwaters used to flow into the Chindwin drainage before beheading by movement of the Sagaing Fault. Central to testing this hypothesis are provenance studies that demonstrate prior flow of the upper Irrawaddy into the Chindwin drainage. Whilst previous work has indeed demonstrated input from the Mogok Metamorphic Belt (MMB), typical of the upper Irrawaddy drainage, in Neogene sedimentary rocks of the Chindwin drainage, these studies were undertaken at locations where alternative interpretations can explain the data. We therefore undertook a provenance study of Neogene rocks in the Chindwin drainage basin at its northern extent, where any evidence of input from the MMB can be more confidently interpreted as the result of the palaeo-Irrawaddy flowing into the Chindwin valley. We coupled this with thermochronological data from the adjacent Indo-Burman Ranges (IBR) to determine when exhumation of, and thus input from the MMB by recycling from the IBR, rather than from direct input from the Irrawaddy, could have commenced.

We conclude that the upper headwaters of the palaeo-Irrawaddy did previously flow into the Chindwin drainage. Therefore the degree of offset between the Irrawaddy headwaters and the upper Chindwin river can be used to determine magnitude of displacement on the Sagaing Thrust. This drainage was in place since at least the early Miocene and ceased, with beheading of the upper Chindwin drainage at ≤10 Ma. With 340 kms of displacement, this equates to averaged motion over this time interval of 34mm/year. Currently, motion is distributed between the Sagaing Fault (18-20 mm/year) and younger faults to the west. Given the total motion between India and Sundaland is currently 38 mm/year, a greater proportion of total accommodation must have been taken up by the Sagaing Fault in the past.

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Origin of Spinel – Muscovite – Anorthite intergrowths in Calc-pelitic schists in the Lesser Himalayan Sequence of the Western Arunachal Himalayas: Tectonic Significance

Nayak R.*[1], Choudhary A. [2] & Bhowmik S.K.[1]

[1]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur. [2]Geological Survey of India, Hyderabad.

Corresponding author email: rituparnanayak44@gmail.com

Keywords: mid-crustal heating, thermal gradient, double-layered corona.

In the present study, the origin of Spl-Ms-An (mineral abbreviations after Kretz, 1983) intergrowths, in a calc-pelitic schist sample from the Jang area in the Lesser Himalayan Sequence of the Western Arunachal Himalayas (WAH) has been investigated using an integrated approach of textural, mineral compositional, mineral reaction modelling, geothermobarometry and phase equilibria modelling studies. The rock has a mineral association of Pl (An_{36-92}) + Bt [X_{Mg}=0.51-0.53; Ti(c.p.f.u.) = 0.12-0.16)] Ilm ($Ilm_{92}Pyrophanite_{04-03}Hem_{05-04}$) + growth-zoned Grt ($Sps_{16-05}Prp_{08-15}Grs_{16-13}Alm_{60-67}$) + St ($X_{Mg}$=0.21) + Kfs ($Or_{99-98}Ab_{02-01}$) + Chl ($X_{Mg}$=0.50-0.55) + Ms ($Pa_{04-02}Cel_{13-12}Ms_{83-78}$) + Spl ($Gah_{14-10}Spl_{22-20}Herc_{65-62}Mag_{04-03}$) + Spn + Ep ($Ps_{31}$) + Tur ($X_{Mg}$=0.55-0.50). The rock is unique in the sense that it records the stability of metamorphic K-feldspar in association with garnet and staurolite, in metamorphic conditions below the solidus, and also the association of zincian spinel with muscovite and anorthite, as part of a diffusion-controlled, double-layered corona (spinel + muscovite intergrowths as an inner layer and anorthite as an outer layer around staurolite.

The rock records four stages of metamorphic evolution: (a) Formation of growth-zoned porphyroblastic garnet by the reaction Chl + Pl_1 + Ep + Ms + Qtz → Grt + Bt + Pl_2 + H_2O (R1). (b) Localised development of staurolite porphyroblasts in domains with relatively higher Al and Zn concentrations by the reaction, Grt + Chl + Ms = St + Bt + H_2O (R2). (c) Development of metamorphic K-feldspar. (d) Formation of spinel - muscovite + anorthite intergrowths by a reaction, St + Pl_1+ Ep + Kfs/Bt + H_2O = Spl + Ms + Pl_2 (cf. An_{92}) (R3). Phase equilibrium modelling of an effective bulk rock composition of the Spl-Ms-An intergrowths reveal that the sequential formation of staurolite and the progress of the reaction R3, together indicate a phase of mid-crustal heating. We combine this finding with the P-T conditions of the different stages of garnet growth to suggest a two stage prograde metamorphic evolution of this crustal section of the WAH – an initial stage of mid-crustal (P~6 kbar) heating (from T<545 ^oC to T~ 595 ^oC) and a later stage of steep burial to the peak metamorphic condition (T_{Max} ~ 670 ^oC at P~8.6 kbar). We discuss the geodynamic significance of the tectonic thickening of a thermally perturbed mid-crust, along a relatively cooler thermal gradient.

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Petrological oddities from the Himalaya explained using a multi-method approach coupled with thermodynamic modeling

Nerone S.*[1], Groppo C.[1], Ágreda-López M.[2], Petrelli M.[2], Lanari P.[3], Berger A.[4], Markmann T.[4] & Rolfo F.[1]

[1]Dipartimento di Scienze della Terra, Università di Torino. [2]Dipartimento di Fisica e Geologia, Università di Perugia. [3]Institute of Earth Sciences, University of Lausanne. [4]Institute of Geological Sciences, University of Bern.

Corresponding author email: sara.nerone@unito.it

Keywords: thermodynamic modeling, trace elements, metamorphic processes.

The diversity of metamorphic conditions recorded at different structural levels (i.e., from amphibolite-facies conditions in the Lesser Himalayan Sequence, LHS, to granulite-facies conditions and anatexis in the Greater Himalayan Sequence, GHS; Kohn, 2014) makes the Himalaya an ideal natural laboratory for investigating different metamorphic processes that occurred during collisional orogeny.

Here, we will present three case studies focusing on uncommon petrological issues investigated using different methodological approaches. From lower to higher structural levels, these include: (i) the coexistence of chloritoid and biotite in metapelites from the Upper-LHS, (ii) the occurrence of garnet with a peculiar flat habit grown under sub-solidus conditions in metapsammites from the Upper-LHS, and (iii) trace element zoning recorded in kyanite from migmatites exposed in the GHS.

Forward thermodynamic modeling combined with detailed microstructural and microchemical analyses using optical microscopy, CL, SEM-EDS, EPMA-WDS, LA-ICP-MS maps and/or EBSD, allow the processes responsible for the development of these features to be understood. For the first case study, the interplay between equilibrium and kinetics can explain the occurrence of the chloritoid+biotite assemblage (Nerone et al., 2023), with H_2O-undersaturated conditions expanding the biotite stability towards lower temperature, and thermal overstepping of the chloritoid-consuming reaction resulting in its metastable persistence at higher temperature. In the second case study, post-growth deformation, coalescence or dissolution-reprecipitation can be ruled out for the growth of the flat garnet, with the nutrients availability during the metamorphic reaction(s) appearing to be the most important controlling factor. In the third case study, the kyanite zoning domains characterized by different amounts of Cr, V and Fe can be related to different kyanite-forming reactions during the anatectic history, i.e., subsolidus growth, muscovite dehydration melting, and melt crystallization (Nerone et al., 2025).

The results obtained demonstrate the advantage of using a multi-method approach coupled with thermodynamic modeling to understand apparently odd and/or poorly studied metamorphic features.

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Nerone S. et al. (2025) - Multi-Stage Growth of Kyanite in Migmatites Interpreted by Integrating Forward Thermodynamic Modelling and Trace Element Signature. J. Metam. Geol., 43, 315-339, https://doi.org/10.1111/jmg.12810.

Geochemical Interactions of Selenium-Rich Soils with Heavy Metals: Implications For Global Environmental Pollution and Human Health

Nusrat N.*[1], Xingyuan L.[1] & Xiaozhong H.[1]

[1]College of Earth and Environmental Sciences, Lanzhou University, 730000, P.R China.

Corresponding author email: nusrat2024@lzu.edu.cn

Keywords: Selenium-Rich Soils, Geochemical interactions, Environmental pollution.

Selenium (Se) is a redox-sensitive trace element vital for antioxidant defense and immune function. However, its narrow range between essential and toxic levels complicates its environmental behavior (Johnson et al., 2010). Global rock analyses show Se concentrations from 0.23 to 57.00 µg/g (mean = 17.29 ± 15.52 µg/g), with slate and chert having the highest levels, and carbonate rocks the lowest (Johnson et al., 2010). Selenium is geochemically linked with cadmium (Cd), arsenic (As), and vanadium (V), and shows depletion with lead (Pb), reflecting lithology-driven patterns (Johnson et al., 2010). Strong correlations with carbon in carbonate ($R^2 = 0.87$) and slate ($R^2 = 0.77$), and with sulfur in chert ($R^2 = 0.59$), highlight host rock influence on Se mobility (Johnson et al., 2010). Spatial data reveal region-specific risks. In Asia, particularly China and India, Se-rich soils often co-occur with Cd and As, heightening dietary exposure (Johnson et al., 2010; Angon et al., 2024). African regions face similar challenges from mining and agriculture (Angon et al., 2024).

Europe sees widespread Se deficiency, except in former mining zones (Johnson et al., 2010). North America's Great Plains and Rockies raise concerns over aquatic bioaccumulation, while Australian Se patterns reflect aridity and varied parent materials (Johnson et al., 2010). Mineralogically, Se binds to pyrite, illite, and organic matter under reducing conditions, increasing retention. Oxidized settings, particularly with Cd and As, enhance its mobility and bioavailability (Johnson et al., 2010; Angon et al., 2024). Addressing Se's dual challenges requires integrated, region-specific strategies linking soil science, agriculture, and public health (Angon et al., 2024; Fordyce, 2007).

Johnson C.C. et al. (2010) - Symposium on 'Geographical and geological influences on nutrition'Factors controlling the distribution of selenium in the environment and their impact on health and nutrition: Conference on 'Over-and undernutrition: Challenges and approaches'. Proceedings of the Nutrition Society, 69(1), 119-132.

Angon P.B. et al. (2024) - Sources, effects, and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon, 10(7).

Fordyce F. (2007) - Selenium geochemistry and health. Ambio, 94-97.

Depositional Environment and Geodynamic Implications of the Late Neoproterozoic Volcano-Sedimentary Succession in the Northeastern Anti-Atlas, Morocco: Similarities with the Himalaya Sindreth Basin, Northwest India

Ousbih M.*[1,2], Ikenne M.[3] & Askkour F.[3]

[1]Applied Geology and Remote Sensing Team, Moulay Ismail University, Faculty of Sciences and Techniques, Errachidia. [2] Geodynamics, Georesources and Heritage Team – 2GP, Moulay Ismail University, Faculty of Sciences and Techniques, Errachidia. [3]Laboratory of Applied Geology and Geo-Environment Department of Geology, Ibn Zohr University, Faculty of Sciences, Agadir.

Corresponding author email: m.ousbih@umi.ac.ma

Keywords: late Neoproterozoic, northwest India, Morocco.

Field mapping and lithofacies descriptions of Late Ediacaran volcano-sedimentary rocks in the northeastern Anti-Atlas provide insights into the post-collisional Panafrican orogeny. These rocks share notable similarities with the Neoproterozoic Sindreth Basin in northwest India. Approximately 1.8 km of cores were drilled into the Imiter Mine Succession (IMS) and meticulously analyzed. The IMS comprises a significant sequence of basic to acidic pyroclastic rocks, lava flows, sedimentary rocks, intrusions, and extensive dike swarms, delineating a transition from fluvial to lacustrine settings across four units (IMS I to IV).

IMS I feature basal conglomerates formed from the erosion of early Ediacaran greywackes basement, with minor tuffaceous sandstone intercalations indicating reworking under predominantly fluvial to alluvial conditions. IMS II is characterized by variable tuffs and lapilli mass flows, primarily deposited in lacustrine environments, with thick laminae and abundant slump structures indicating significant deposition rates. IMS III comprises pyroclastic fall deposits, likely from very proximal settings, while IMS IV marks the culmination of volcanic activity with thick rhyolitic ignimbrite and voluminous eruptions, possibly linked to syn-sedimentary tectonic events.

The Sindreth Basin in northwest India exhibits a half-graben structure flanked by the undeformed Malani Igneous Suite to the west and a corridor of contemporaneous Cryogenian ductile deformation and granite intrusion to the east. Lithologies within the basin include conglomerate, fanglomerate, debris flow, and lake deposits, accompanied by concurrent mafic and felsic lava flows. This study supports a continental setting for the basin's evolution, challenging recent subduction models, and suggesting a kinship with the Ouarzazate Group in the Anti-Atlas of Morocco. The parallels between the Sindreth Basin and the Anti-Atlas Ouarzazate Group suggest their possible proximity during the breakup of the supercontinent Rodinia and the final assembly of Gondwana.

Revised lithostratigraphy and age of the Gondwana sequence in the eastern Nepal Himalaya

Paudel L.P.[1,*], Adhikari D.[1], Niraula K.P.[1], Rai P.[1], Rijal N.[1] & Agnihotri D.[3]

[1]Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [2]Department of Geology, Central Campus of Technology, Tribhuvan University, Dharan, Nepal. [3]Gondwana Palaeobiology Department, Birbal Sahni Institute of Palaeosciences, Lucknow, India.

Corresponding email: lalupaudel67@yahoo.com

Keywords: Eastern Nepal, Lesser Himalaya, Gondwana, diamictite, Baraha Volcanics, *Ptilophyllum.*

The Gondwana sequence in eastern Nepal is exposed as isolated patches in the frontal part of the Lesser Himalaya at the hanging wall of the Main Boundary Thrust. The stratigraphic classification and age of the Gondwana sequence in this area have long been ambiguous and debated. The present study in the Barahakshetra-Ranitar and Takure areas of eastern Nepal aims to clarify the lithostratigraphy and ages of the Gondwana sequence. For this purpose, geological mapping at 1:25000 scale, route mapping at larger scales, direct measurement of stratigraphic sections, petrographic study, sedimentological study, study of plant fossil prints, and paleoflow analyses were carried out along four cross sections namely; Rakche Khola, Saptakoshi River, Kokaha Khola and Takure. Present study along with previously published U-Pb zircon ages reveals that the Gondwana sequence in the area can be divided into five formations namely the Kokaha Diamictite, Tamrang Formation (with Baraha volcanics), and Kali Khola Formation belonging to the Lower Gondwana and Sehera Khola Formation and Sapt Koshi Formation belonging to the Upper Gondwana. Baraha volcanics comprising of tuff, volcanoclastic sandstone, and agglomerate are the reworked volcanic materials probably from older volcanoes away from the depositional basin. The Tamrang Formation has been confirmed as of the Lower Gondwana based on the occurrence of Permian cold-water bivalve Eurydesma. The Sapt Koshi Formation previously thought as the oldest unit of the Gondwana is comparable with Late Cretaceous-Paleocene Amile Formation in the Tansen area. Upper Gondwana plant fossil Ptilophyllum has been reported for the first time from Sehera Khola in the Takure area.

Tectonics and/or climatic causes for the formation of the Kathmandu basin landform, Central Nepal

Paudel M.R.

Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: mukunda67@gmail.com

Keywords: Alluvial fan, lacustrine deltaic, debris-flow, three-stage fan, Pleistocene.

Very thick gravel deposits are widely distributed from the southern margin to the central parts of the Kathmandu basin, named as Itaiti Formation(Paudel and Sakai 2008). This deposit is more than 120 m thick and deposited around 1 Ma, which is dominated by three types of facies and fans. The first-stage fan is widely distributed near the mountain front where sediment aggradation is more active. The third stage fan is the youngest among the three fans and is distributed on the present top surface and has covered the lacustrine deltaic sequence of the Sunakothi Formation(Paudel and Sakai, 2009). Seven types of facies elements namely Gms, Gm, Gp, Sp, Sr, Sh, and Fl have been recognized among these three fans. Based on stratigraphic relationships among different geological formations, the first debris flow fans have been spreading over basement rocks and fluvial gravel facies before 1 Ma. This event has played a vital role in initiating an ancient lake in the Kathmandu basin. The second and third stage fans originated during the draining stages of the lake. The distal part of the second-stage fan and third stage fan are interfingering with the lacustrine delta towards the center of the basin. The first stage debris flow fan was most probably generated by the recent uplift of the Mahabharat range. These gravelly fan deposits and the uppermost Siwalik conglomerate deposits may be synchronous to recent tectonic events throughout the Himalayas. The second and third stage fans have been initiated not only by the tectonics but also by climatic which is indicated by sedimentological and stratigraphic relations among formations.

Paudel M.R. & Sakai H. (2008) - Stratigraphy and depositional environments of the basin-fill sediments in the southern marginal part of the Kathmandu Valley, central Nepal. Bulletin of the Central Department of Geology, Tribhuvan University, Kathmandu, Nepal,11, 61–70.

Paudel, M. R. and Sakai, H., (2009)- Stratigraphy and depositional environments of late Pleistocene Sunakothi Formation in Kathmandu Basin, central Nepal, Jour. Nepal Geol. Soc, 39,33–44.

Microplastics research along the route from Everest Base Camp to Everest summit

Paudel T.P.*[1], Gajurel A.P.[2], Guragain T.[1,3], Bhote D.F.L.[3] & Maharjan D.[1]

[1]Nepal Mountain Academy, Ministry of Culture, Tourism and Civil Aviation, Nepal. [2]Department of Geology, Tribhuvan University, Nepal. [3]Seven Summit Treks, Kathmandu, Nepal.

Corresponding author email: tanka.paudel@nepalmountain.edu.np

Keywords: contamination, Everest region, microplastics.

In Nepal, the famous Everest climbing route is primarily overcrowded during the peak climbing season. To get to the top of the world, climbers begin at the Everest Base Camp (EBC) and proceed via a number of base camps. Various types of microplastics have been carried by the expedition teams during each climbing season as part of their logistics and energy foods. This study fills a gap left by Napper et al. (2020) by beginning to investigate the types and concentrations of microplastics in snow, ice, and meltwater along the Everest climbing route. Listing the sources of microplastics along the expeditions' path was another of its main objectives. A total of fifteen samples were gathered in one-liter sterile glass containers. The elevation range covered by the sampling location includes a 20-meter buffer of the well-known climbing route and extends from EBC at 5,364 meters above sea level (m asl) to the summit of Everest at 8,848.86 m asl.

Particularly along the typical climbing route from Base Camp to the Everest summit, the Everest region is facing mounting environmental pressures from mountaineering, tourism, and glacial melt brought on by climate change. Gao et al. (2025) investigated microplastic pollution in the Mount Everest region, highlighting the influence of glacier meltwater in distributing these particles through riverine systems. It indicates there are worries about microplastic pollution because of the abundance of garbage, especially plastics, that has been extensively documented in this area.

It examines the various important knowledge gaps that still exist regarding microplastic pollution in the Everest region, including describing microplastics, determining probable sources and routes of microplastic pollution based on baseline concentrations and transport mechanisms, and thereby assisting in the development of policy and mitigation plans to lower risk and slow down the process. Because of the synthetic particles' global infiltration into freshwater, marine, and terrestrial ecosystems, it has actually become a serious environmental problem.

Gao T. et al. (2025) - Riverine microplastics in the Mount Everest region affected by glacier meltwater. J. Hazard. Mat., 450, 131209, https://doi.org/10.1016/j.jhazmat.2025.131209.

Napper I.E. et al. (2020) - Reaching New Heights in Plastic Pollution—Preliminary Findings of Microplastics on Mount Everest. One Earth 3, 621–630, https://doi.org/10.1016/j.oneear.2020.10.020.

The Future of Metallic Mineral Resources Development in Nepal: A Geological Appraisal from Copper Exploration in the Himalayas

Paudyal K.R.*[1], Lamsal S.[1], Regmi A.[1], Paudyal E.[1], Sharma U.[1], Paudel R.[1], Dhakal A.[1], Gyawali G.[1], Acharya M.[1], Paudel L.P.[1], Kaphle K.P.[1] & Sah R.B.[1]

[1] Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal

Corresponding author email: kabiraj.paudyal@cdgl.tu.edu.np

Keywords: metallic minerals, copper mineralization, polymetallic deposits, source and genesis, Nepal Himalaya

The exploration, exploitation, and sustainable utilization of metallic mineral resources are crucial for Nepal's long-term socio-economic development. Historically, Nepal engaged in small-scale mining of metallic ores such as copper, iron, lead, nickel, and cobalt, with exports extending to Tibet and India. Remnants of this legacy—such as slags and low-grade ores near old workings—are still visible today. Currently, several economic and sub-economic deposits of copper, iron, lead, and zinc have been identified, along with occurrences of gold, cobalt, nickel, uranium, lithium, and more than a dozen other metals.

This study aims to evaluate the status, distribution patterns, and geo-tectonic controls of metallic mineral deposits in Nepal, with a particular focus on copper mineralization in the central sector of the Nepal Himalaya. It also seeks to reinterpret the genesis of copper mineralization in light of recent exploration activities and findings, while laying a foundation for future research and development initiatives.

The methodology involved a review of existing data, geological mapping, and systematic sampling in selected areas. Petrographic analysis of thin and polished sections was conducted at Tribhuvan University, along with geochemical analysis of ore samples using Atomic Absorption Spectroscopy (AAS) and X-Ray Fluorescence (XRF) to determine copper concentrations. Key study sites include Ipa-Baraghare (Makwanpur), Nangre and Khani Khola (Kavre), Bhut Khola (Tanahun), Pandav Khani (Baglung), Baise Khani (Myagdi), Tamghas-Neta and Bharse (Gulmi), and Naubahini and Gaumukhi (Pyuthan), all of which exhibit characteristics of stratiform or stratabound copper mineralization.

Results show that copper deposits are primarily hosted in the Precambrian rock sequences of the Midland Group (Kuncha and Nourpul Formations), Bhimphedi Group (notably the Kulekhani Formation and associated marble units), and the Himal Group. Mineralization is commonly linked with metabasic and granitic rocks, suggesting both syngenetic and magmatic controls. Copper-bearing minerals such as chalcopyrite, bornite, covellite, azurite, and malachite—often associated with pyrite and arsenopyrite—are frequently observed. Copper content in the analyzed samples ranges from 0.25% to 5%.

This study underscores Nepal's significant yet underutilized potential in metallic mineral resources, particularly copper. It advocates for detailed exploration, responsible exploitation, investment in mineral-based industries, and international research collaboration to sustainably harness these valuable resources.

Tectonometamorphic Stages in the Nepal Lesser Himalaya: A Case Study from Thrust Sheets and Autochthonous Successions

Paudyal K.R.*[1], Carosi R.[3], Montomoli C.[3], Iaccarino S.[3], Lamsal S.[1], Acharya M.[1], Parajuli I.[2], Basnet B.[1], Sah R.B.[1] & Paudel L.P.[1]

[1] Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [2]Central Department of Environmental Science, Tribhuvan University, Kathmandu, Nepal. [3]University of Torino, Department of Earth Sciences, Italy.

Corresponding author e-mail: kabiraj.paudyal@cdgl.tu.edu.np

Keywords: deformation, polymetamorphism, inverted metamorphism, quartz microstructures, shear sense indicators, thrust tectonics.

The Lesser Himalayan thrust sheet presents a complex geological framework with distinct lithological and metamorphic histories. Based on rock composition and metamorphic grades, the thrust sheet can be categorized into two contrasting successions: (i) high-grade metamorphic rocks, including sillimanite-kyanite-bearing gneisses to granitic gneisses, thought to have roots in the Higher Himalaya, and (ii) a lower-grade sequence comprising garnet-grade schists and marbles at the base, transitioning to fossiliferous sedimentary rocks at the top. The provenance and root zone of the latter remain a subject of ongoing debate.

This study systematically investigates the deformation-related structures from outcrop to microstructural scales, documenting evidence of all five stages of Himalayan deformation (D1–D5). The D1 phase represents pre-Himalayan bedding-parallel foliation, induced by lithostatic pressure and sedimentary loading. D2 is characterized by north-south trending isoclinal folds, whereas D3 is linked with the emplacement of thrust sheets, synchronous with the Main Central Thrust (MCT) dynamics. The D4 phase corresponds to southward thrusting, generating regional-to-microscopic-scale folds and multiple shear sense indicators. Finally, D5 marks the exhumation of the Himalaya, accompanied by brittle shearing and cross-cutting fractures overprinting all previous structural features. Analysis of major and small-scale structures in several sections of the Lesser Himalaya is characterized by a polyphase deformation history.

Microstructural analysis of quartz grains provides critical constraints on these deformation events. Dynamic and static recrystallization features are evident, helping to delineate tectonic boundaries of thrust sheets. Quartz deformation bands, wavy extinction, grain boundary migration, and quartz rods serve as key indicators of progressive deformation. The study also revisits the long-standing debate on inverted metamorphism in the footwall of major thrusts, such as the Mahabharat Thrust in central Nepal, the Dubung Thrust in west-central Nepal, and the Jajarkot Thrust or its equivalents in western Nepal.

The Lesser Himalayan thrust sheets, and underlying autochthonous successions offer a natural laboratory for investigating polyphase deformation and polymetamorphic processes within a smaller region of the Nepal Himalaya. By integrating structural, metamorphic, and microstructural analyses, this study enhances our understanding of the Himalayan orogenic evolution, emphasizing the critical role of thrust tectonics in shaping the present-day architecture of the Nepal Himalaya.

From shortening to extension of the Tethyan Himalaya: Reconstructing the northern Indian passive margin

Pedini M.[1], Mazzoli S.[1], Grujic D.[2], Hetényi G.[3], Moreau J.[4]& Torvela T.[5]

[1]School of Science and Technology, Geology Division, University of Camerino, Camerino, Italy. [2] Department of Earth and Environmental Sciences, Dalhousie University, Halifax, Nova Scotia, Canada. [3] Institute of Earth Sciences, University of Lausanne, 1015 Lausanne, Switzerland. [4] Plastic@Bay, Eilean Siar - Isle of Lewis, HS2 9AJ United Kingdom. [5] School of Earth and Environment, University of Leeds LS2 9JT, United Kingdom.

Corresponding author email: matteo.pedini@unicam.it

Keywords: Tethyan Himalaya, Cross-section balancing, thrust tectonics.

The Himalayan orogeny, initiated by the collision between the Indian and Eurasian plates at around 50 Ma, stands as a fundamental example of continental collision and large-scale crustal shortening. Despite the critical role played by the Tethyan Himalaya fold-and-thrust belt in this context, the amount of crustal shortening accommodated within this domain remains poorly constrained. Balanced geological cross-sections are scarce, and often outdated, while the existing shortening estimates vary significantly, typically ranging from ~100 km to ~250 km (e.g., Ratschbacher et al., 1994). This uncertainty limits the ability to test tectonic models for the India-Asia collision and complicates efforts to reconcile geological shortening estimates in the Tethyan Himalaya with paleomagnetic reconstructions, which predict up to four thousand kilometers of plate convergence since 60 Ma (Poblete et al., 2021).

The Tethyan Himalaya Sequence (THS) is located between the South Tibetan Detachment System (STDS) to the south and the Indus-Yarlung Tsangpo Suture Zone to the north. THS consists of a Cambrian to Eocene sedimentary succession recording the evolution of the northern Indian passive margin, from early Permian rifting to passive drift. The STDS, evolving from a ductile to brittle shear zone, and the North Himalayan Gneiss Domes (NHGD), recording Late Miocene mid-crustal exhumation, both document the effects of mid-crustal flow associated with the development of a low-viscosity channel bounded by the STDS and the Main Central Thrust Zone (MCTZ) (Godin et al., 2006).

The south-vergent Gyirong-Kangmar Thrust (GKT), located south of the NHGD, is interpreted to place pelagic Mesozoic strata over shelf sediments. Its existence is inferred from this transition, which may reflect a major change in crustal thickness. Ratschbacher et al. (1994) suggested the GKT is a basement-involved thrust, although it is not apparent in the INDEPTH seismic profile (Hauck et al., 1998).

This study refines crustal shortening estimates across the THS and constrains the geometry of the basal detachment, providing new insights into the early structural evolution of the Himalayan orogen. Balanced and restored cross-sections were developed using 3DMOVE software, integrating geological mapping, field observations, and subsurface data. The study area extends longitudinally between the Kampa and Kangmar domes, where extensional structures related to the STDS locally overprint earlier thrust-related fabrics, necessitating careful structural restoration.

The results document significant crustal shortening and highlight a tectonic transition, supporting the interpretation that the compressional structures were overprinted during Miocene by low-angle extensional shear zones. Furthermore, the updated shortening estimates contribute to reconstructing the original length of the northern Indian passive margin prior to collision, offering critical constraints for the Himalayan tectonic evolution.

Godin L. et al. (2006) - Channel flow, extrusion, and exhumation in continental collision zones: an introduction. In: Law, R. D., Searle, M. P. & Godin, L. (eds) Channel Flow, Extrusion, and Exhumation in Continental Collision Zones. Geol. Soc., London, SP, 268, 1-23.

Hauck M.L. et al. (1998). Crustal structure of the Himalayan orogen at~ 90 east longitude from Project INDEPTH deep reflection profiles. Tectonics, 17, 481-500.

Poblete F., et al. (2021) - Towards interactive global paleogeographic maps, new reconstructions at 60, 40 and 20 Ma. Earth-Science Reviews, 214, 103-508.

Ratschbacher L. et al. (1994) - Distributed deformation in southern and western Tibet during and after the India-Asia collision. J. Geophys. Res., Solid Earth, 99(B10), 19917–19945.

On the Accelerating Foreshock Activity prior to the 7 January 2025 Mw7.1 Dingri, Xizang (Tibet) earthquake

Pettenati F.*[1], Sandron D.[1], Verza G.[2], Vuan A.[1] & Picozzi M.[1,3]

[1] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, Trieste, Borgo Grotta Gigante, 42/c 34010 Sgonico, Trieste, Italy. [2] EvK2CNR, Via San Bernardino, 145 24126 - Bergamo Italy. [3]Università degli Studi di Napoli Federico II - Corso Umberto I 40 - 80138 Napoli, Italy.

Corresponding author email: fpettenati@ogs.it

Keywords: foreshocks, normal fault, deep neural network.

Large earthquakes on normal faults are not uncommon in the Tibetan region. In Xizang (Tibet), four earthquakes with a magnitude of more than M6.4 have been recorded in the last twenty years, which were triggered by normal faults with large magnitudes. On January 7, 2025, a magnitude Mw7.1 earthquake occurred in western Xizang near Dingri (Yao et al., 2025), which is one of the largest normal fault events recorded in the instrumental era worldwide. The main earthquake and subsequent aftershocks were recorded by the IO.EVN (Pettenati et al., 2025) station near the Laboratory/Observatory Pyramid, which is located 6 km south of Everest Base Camp (Nepal). Given the proximity of the main earthquake focus to IO.EVN, approximately 80-90 km to the southwest, we set ourselves the task of recording and analysing the foreshocks recorded by the IO.EVN station for the period from 1 January 2023 to the main earthquake in the north-eastern sector of the pyramid. The recording of seismic activity prior to the main earthquake is significantly improved by the application of PhaseNET (Zhu and Beroza, 2019) a well-known unsupervised detection tool. The localization of the new events is carried out with the help of S-P travel times and a polarization analysis method. Near the epicentre, we report a long period of sparse low seismic activity until December 28, 2024, when an acceleration in the number of recorded events and a clustering near the nucleation of the main earthquake is observed. The b-positive (van der Elst, 2021) statistical analysis of the catalogue suggests a slow release and critical nucleation model for the pre-phase in the epicentral zone and rules out a "long-distance static stress transfer" model with the Himalayan zone as the direct causative agent.

Yao J. et al. (2025) - A preliminary catalog of early aftershocks following the 7 January. *M*S6.8 Dingri, Xizang earthquake. J. Earth Sci. XX, 1-15, open access, https://doi.org/10.1007/s12583-025-0210-9 .

Pettenati F. et al. (2025 -. The Seismic Station IO.EVN at Pyramid EvK2cnr (Everest): 10 Yr of Activity, Seismol. Res. Letters. 96, 1733–1746, https://doi.org/10.1007/10.1785/0220240111 .

van der Elst, N.J. (2021) - *B-positive*: A robust estimator of aftershock magnitude distribution in transiently incomplete catalogs. J. Geophys. Res., Solid Earth, 126, e2020JB021027. https://doi.org/10.1029/2020JB021027 .

Zhu W. & Beroza G. (2019) - PhaseNet: a deep-neural-network-based seismic arrival-time picking method. *Geophys. J. Int.,* 216, 1, 261–273. https://doi.org/10.1093/gji/ggy423.

Contrasting Prograde Burial-Heating History of High-temperature Metamorphic Sole Rocks in the Nagaland-Manipur Ophiolite Belt, NE India: Mechanical Coupling-Decoupling Processes during Ultra-hot Subduction Infancy

Pradhan B.*[1], Bhowmik S.K.[1] & Lukose L.[1]

[1]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur.

Corresponding author email: bisworanjanpradhan7@gmail.com

Keywords: metamorphic sole rock, ultra-hot subduction initiation, garnet zoning, contrasting Prograde P-T Path.

Metamorphic sole rocks represent thin (meter-scale) tectonic slices of amphibolite to granulite facies subducting oceanic crust that are welded beneath wedge mantle peridotites. These rocks have emerged as direct winess to the thermal and dynamic history in the intraoceanic subduction zone, immediately following subduction initiation, during which period, the thermal gradient remains distinctly warm. Based on peak P-T estimates in well-preserved ophiolite sections, the metamorphic sole rocks show a metamorphic zonation, from high-temperature (HT) soles (average T_{Max} at 800 ± 50 °C at P~ 1.0 ± 0.2 GPa), at the top, and in direct contact with the mylonitic wedge mantle peridotites to low-temperature (LT) soles (average T_{Max} at 600 ± 50 °C at P~ 0.5 ± 0.1 GPa), structurally downward. Recent recognitions of occurrences of metamorphic zonation and structural breaks within the HT sole unit offer critical new opportunities to study mechanical coupling-decoupling processes in nascent high-temperature subduction zones. In particular, the thermal evolution of the different subunits within the HT sole rocks, at the extreme thermal conditions (T ≥ 900 °C) remains poorly understood. This study utilizes the compositional zonation in garnet in two subunits (HT-1 and HT-2) of HT metamorphic sole rocks from the Nagaland-Manipur Ophiolite Belt to establish their thermal and burial histories and accretion processes during ultra-hot subduction infancy. The mafic granulite (cf. HT-1 subunit) directly underlies the wedge-mantle peridotite and garnet-clinopyroxene-bearing amphibolite (cf. HT-2 subunit) occurs structurally below the HT-1 rocks. Porphyroblastic garnets in both these rocks record growth zoning (rimward decreasing X_{Sps} and increasing X_{Mg} concentrations) with contrasting styles of grossular zonation. While garnets in HT-2 rocks show a continuous rimward increase in X_{Grs}, that in HT-1 records a composite pattern of an initial increasing and then a decreasing trend towards the garnet rim. The kinetically controlled thermobarometry and calculated P-T pseudosection using MORB composition, but adjusted to Mg# of the sole rocks have revealed two contrasting styles of clock-wise P-T path: (a) supra solidus, near isobaric prograde heating from ~ 780-800 °C, culminating in HP-UHT metamorphic conditions (~ 1.3-1.4 GPa, ~ 950 °C) and followed by retrograde cooling and minor decompression to ~ 730-750 °C at ~ 1.2 GPa for HT-1 and (b) a subsolidus combined prograde burial and heating path from ~ 0.7 GPa and ~ 545 °C to the metamorphic peak at ~ 1.2-1.3 GPa and ~ 750-780 °C, and post-peak combined cooling and decompression retrograde path to ~ 1.0 GPa and ~ 650-720 °C for HT-2. We collate the reconstructed P-T paths in the HT-1 and HT-2 rocks and the results of viscosity calculations to suggest a fundamental change in the heat transfer mechanism and associated accretion processes during subduction infancy. (1) After subducting to the mantle depths, the HT-1 rocks get accreted beneath the dry, hot and incipient lithospheric mantle, and undergoes near isobaric heating through advective heat transfer from the mantle, culminating in peak UHT metamorphism. (2) Hornblende dehydration melting during prograde heating leads to the production of ~20 vol% melt, melt-induced decoupling of the slab-wedge interface and partial exhumation and cooling of the HT-1 rocks. (3) During the exhumation of the HT-1 rock, the relatively cooler protoliths of the HT-2 rocks undergo burial and heating through conductive heat transfer and get accreted below the partially exhumed HT-1 rock with a depth interval of 1.2-1.3 GPa.

Asymmetrical Exhumation and Fault Dynamics Across the Western Himalayan Syntaxis: Insights from Low-Temperature Thermochronology on Orogenic Wedge Deformation

Razzaq S.S.[1,5*], Ghani H.[1], Kley J.[1], Dunkl I.[2], Sobel E.R.[3], Thiede R.C.[4], Ghani M.[1] & Ishfaq M.[1]

[1]Department of Structural Geology and Geothermics, Georg-August University of Göttingen, Germany. [2]Department of Sedimentology, Georg-August University of Göttingen. [3]Institute of Geosciences, University of Potsdam. [4]Christian Albrechts University of Kiel, Institute of Geosciences, Kiel, Germany. [5]Institute of Geology, University of Azad Jammu and Kashmir, Muzzafarabad, Pakistan.

Corresponding author email: syedsaqib.razzaq@stud.uni-goettingend.de

Keywords: Himalayan syntaxis, low-temperature thermochronology, exhumation, orogenic wedge.

The western Himalayan fold-and-thrust belt exhibits remarkable variability in the fault kinematics and related exhumation patterns. In the western syntaxis, particularly across the Potwar Plateau and Salt Range, our 42 new apatite (U-Th)/He (AHe) thermochronology results reveals a broad zone of remarkably consistent cooling ages (~4–6 Ma) across a wide transect extending from the Main Boundary Thrust (MBT) to the Salt Range Thrust (SRT; the local expression of the Himalayan Frontal Thrust, HFT or MFT). This spatially uniform signal suggests a temporally limited phase but spatially extended region of synchronous exhumation. We interpret this pattern as a result of deformation localized along a "local" low-friction basal detachment (the Eocambrian Salt Range Formation), which enables long-term translation on the emergent SRT/HFT without requiring significant internal wedge reorganization. The persistence of exhumation through this weak detachment contrasts with more mechanically stiffened and thicker wedges elsewhere in the Himalaya. In contrast, the eastern flank of the syntaxis (Kashmir Himalaya), from the MBT to the HFT, exhibits significantly younger and spatially variable AHe ages (~0.9–7 Ma), with young ages (0.9-3.5 Ma) concentrated in the frontal and rear zones, and relatively older ages in the central zone of the orogenic wedge. This spatial variability in exhumation, interpreted along with the surface geological, geophysical, and geomorphic evidence, suggest that orogenic wedge is segmented, where exhumation is driven by rock displacement along active roof backthrusts in the frontal zone, and internally by out-of-sequence faulting facilitated by focused erosion and reactivation of inherited basement structures. Based on our analyses, we propose that, in contrast to the western limb's synchronous and spatially uniform exhumation pattern controlled by translation above a low-friction basal detachment in a piggyback fashion, the exhumation in the Kashmir Himalayas is accommodated through distributed, diachronous uplift, reflecting a more internally reorganized and mechanically heterogeneous orogenic wedge. These contrasting exhumation patterns and wedge behaviors across the syntaxis point to an asymmetrical structural architecture and differing thickness of discrete parts of the sedimentary section (salt vs. clastic sediments) forming the foreland, modulated by feedback between erosion, fault kinematics, and wedge strength. Understanding this coupling is crucial for unraveling young orogenic evolution and helps in assessing seismic hazard risk across different segments of the western Himalaya.

Unraveling Mid-Miocene Exhumation of the Besham Complex Using In Situ White Mica Rb–Sr Geochronology

Rehman A.U.*[1,2], Marschall H.[1,2], Kutzschbach M.[1,2] & Gerdes A.[1,2]

[1]Department of Geosciences, Goethe-University Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
[2]Frankfurt Isotope and Element Research Center (FIERCE), Goethe-University Frankfurt, Frankfurt am Main, Germany

Corresponding author email: link2atta90@gmail.com

Keywords: Mica Rb-Sr dating, MMT, exhumation, Himalayan.

The thermal evolution of the northwestern Himalayan orogenic belt, particularly the Besham Complex within the Indus Syntaxis of Pakistan, remains a subject of active debate due to ambiguities in recording Cenozoic Himalayan metamorphism. Although this region lies in close structural proximity to the Main Mantle Thrust (MMT), where the Kohistan Island Arc (KIA) is thrust over Indian Plate-derived rocks, the expected high-temperature Himalayan metamorphic signatures are unevenly distributed or weakly preserved. Several prior studies (e.g., Palin et al., 2018; Treloar and Rex, 1990 & DiPietro et al., 2021) employing zircon, rutile, titanite and monazite U–Pb geochronology as well as amphibole and mica Ar–Ar dating have presented conflicting interpretations regarding the presence and extent of Himalayan metamorphic overprints.

For instance, DiPietro et al. (2021) represent titanite U-Pb ages 27 to 15 Ma and rutile U-Pb age 20 Ma, while Palin et al., (2018) only identify monazite U-Pb ages of 430 Ma and 270 Ma with no younger metamorphic imprints. However, Treloar and Rex, (1990) identified hornblende and mica Ar-Ar ages of 40 and 25 Ma, respectively and demonstrate that these rocks were reheated during the Cenozoic time of collision. Notably the younger U-Pb age data are derived from only a few selected localities, making it challenging to robustly evaluate the extent of Cenozoic metamorphism in the Besham Complex. Therefore, a broader sampling and more comprehensive geochronological coverage were adopted in this study to overcome this limitation.

We present new geochronological data based on in situ Rb–Sr dating of white mica (LA-ICP-MS/MS) combined with trace element geochemistry of mica. In contrast to Ar–Ar dating, this method circumvents the problem of age overestimation caused by excess argon, a known issue in Himalayan mica (Larson et al., 2023). Five distinct lithologies were systematically sampled at increasing distance to the MMT, including granitic gneiss, graphite schist and granodiorite

Our results from the Besham Complex yield white mica Rb–Sr ages ranging from 20 to 13 Ma, providing robust evidence for mid-Miocene cooling and exhumation. These ages correlate well with the exhumation ages for high-grade metamorphic terranes in the eastern Himalaya (Nepal), reported by Larson et al., (2023). The alignment of our findings with the broader Himalayan exhumation framework, together with the peak metamorphic age of 40 ±2.1 Ma from in situ U-Pb garnet dating, and 25 Ma and 20 Ma from in situ U-Pb rutile and apatite, respectively, indicate that the Besham Complex preserves a previously unresolved record of Cenozoic metamorphism and subsequent exhumation. This study thus provides new constraints on the thermal and tectonic evolution of the northwestern Himalaya and underscores the utility of in situ Rb–Sr dating to decipher complex orogenic histories.

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The activity of the Nalati fault from strike-slip to thrust folding within the Tianshan Mountains

Ren Z.*[1,2], Bao G.[1,2], Liu J.[1,2], Wang L.[1,2,3,4], He Z.[1,2], Ji H.[1,2], Guo L.[1,2] & Li X.[1,2]

[1]State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China. [2]Key Laboratory of Seismic and Volcanic Hazards, China Earthquake Administration, Beijing 100029, China. [3]Shandong Earthquake Administration, Jinan 250102, China. [4]Earthquake Risk Prevention and Control of Shandong Province, Jinan 250014, China.

Corresponding author email: rzk@ies.ac.cn

Keywords: nalati fault, Tianshan, activity.

The Nalun-Nalati-Hongliuhe suture zone forms the central axis of the Tianshan Mountains and has undergone rejuvenation during the Neotectonic period, making it an ideal location for studying the internal structural deformation of this mountain range. The suture zone represents a significant boundary fault with a long history of seismic activity. Since the Cenozoic era, tectonic movements have been active. The Kalawenguquan fault is an important late Quaternary active fault within the Nalun-Nalati-Hongliuhe suture zone. The western part named Kalawenguquan fault (Wang et al., 2024; Li et al., 2024), which is strike-slip dominated and located within the interior of the Tianshan Orgenic Belt. While the eastern part, we focused on the Bayin anticline, which is thrust folding dominated (Bao et al., 2024, Charreau et al., 2017).

Along the Kalawenguquan fault, we focus on the Tekes segment within the Ili Prefecture, utilizing remote sensing and field surveys to delineate its left-lateral strike-slip characteristics. Trench analysis and radiocarbon dating have revealed four significant paleoseismic events. By employing UAV mapping and the LaDiCaoz code, we have measured approximately 3.4 meters of horizontal displacement from a single seismic event. OxCal age correction has provided precise dating for these events with 95.4% confidence: Event E1 from 1406 to 5191 years Before Present (yr BP), E2 from 2435 to 6241 yr BP, E3 from 6723 to 7495 yr BP, and E4 from 7580 to 8133 yr BP. Our findings suggest ongoing Holocene activity and a high seismic risk for the Tekes segment of the Kalawenguquan fault.

We also studied on the Bayin anticline in the Youludusi Basin, a typical intermontane basin located within the eastern Tian Shan. The Kaidu River cuts through the Bayin anticline and has developed three levels of terraces (T1-T3) across the structure. By using cosmogenic nuclide and optically stimulated luminescence dating methods, the formation ages of terraces T1 and T3 are constrained to 11.54 ± 0.55 ka and 42 +7.0/-7.1 ka, respectively. When applying a listric thrust fault model to the Bayin anticline and using terraces as references, the vertical displacements are estimated to be 16.45 +6.46/-3.19 m (T1), 32.08 +12.85/-6.19 m (T2), and 95.93 +38.94/-18.6 m (T3), and the shortening amounts are 10.56 +8.33/-5.04 m (T1), 20.46 +16.68/-9.64 m (T2), and 61.24 +50.22/-28.93 m (T3). Based on this listric thrust fault model and terrace T1-T3 ages, the rate of fault slip controlling the growth of the Bayin anticline is determined to be 1.6 ± 1.0 mm/yr, and the crustal shortening rate of the anticline is 1.0 +0.7/-0.6 mm/yr. The estimated crustal shortening deformation of the Bayin anticline accounts for ~12% of the total deformation in the Youludusi Basin. In terms of the entire orogenic belt, the crustal shortening absorbed in the southern, central, and northern parts accounts for 24%-56%, 46%-71%, and 19%-74%, respectively, of the total strain across the eastern Tian Shan. Therefore, we believe that the Eastern Tianshan undergoes uniform deformation.

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From supra-subduction ophiolite to a differentiated intra-oceanic arc, the zircon record of the Nidar Ophiolite in Ladakh, Indian Himalayas

Reubi O.*[1], Buret G.[1], Epard J.L.[1], Buchs N.[1], Ulianov A.[1] & Müntener O.[1]

[1]Institute of Earth Sciences, University of Lausanne.

Corresponding author email: olivier.reubi@unil.ch

Keywords: Ladakh, ophiolite, island arc.

The Nidar ophiolite exhibits a complete section of the Neo-Tethyan oceanic lithosphere obducted between the Indian and Eurasian margins. The ophiolite sequence consists of an upper mantle unit dominated by harzburgite and dunite, overlain by a crustal sequence composed of layered and isotropic gabbro covered by pillow lavas. Hornblende gabbro and minor plagiogranites intrude the layered and isotropic gabbro, while pillow lavas are intruded by andesitic to rhyolitic dikes (Buchs & Epard, 2019). The ophiolite sequence is covered by beds of radiolarite and mudstone with intercalated ash-beds and leucocratic siltstone. The sequence progress upward to volcano-sedimentary sandstone and conglomerates composed either of basalt and radiolarite clasts or quartz-feldspar rich pebbles. Geochemically, the ophiolite unaltered mafic rocks display LILE enrichment relative to REE and HFSE, as well as Nb-Ta negative anomalies suggesting formation in a suprasubduction zone setting (Mahéo et al., 2004; Ahmad et al., 2008). The silicic rocks from the volcano-sedimentary cover show similar subduction-related features but are characterized by higher LILE enrichments and LREE/HREE ratios more typical of arc magmas. Zircons from intrusives in the ophiolite crustal sequence yield Valanginian to Barremian U-Pb ages. Detrital and volcanic zircons from the volcano-sedimentary cover show a predominant population with Aptian to Albian ages and a smaller Hauterivian to Aptian population. Trace element ratios and positive εHf in zircons from the volcano-sedimentary sequence indicate very limited crustal influence. The petrography and zircon data of silicic sedimentary sandstones and conglomerates indicate the proximity of the Nidar ophiolite to an eroding, differentiated intra-oceanic arc. The main phase of activity of this arc took place from the Aptian to Albian, about 10 Ma after the formation of the ophiolite crustal sequence.

Detrital zircons with age distributions and εHf comparable to the Nidar detrital zircons are documented for the Xigaze fore-arc basin in southern Tibet (Wu et al., 2010), whereas the Nidar Ophiolite zircon ages fall within the range of zircon ages of most Ophiolites of the Indus-Yarlung-Tsangpo suture zone. This suggests that an intra-oceanic arc significantly more prominent than suggested by present-day (and dated) outcrops in Ladakh and southern Tibet formed in early Cretaceous following a major phase of fore-arc crust formation.

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New Models for Northern Greater India and for Controls on Himalayan Deformation

Robinson D.M.*[1], Li Y.[1], Ding L.[2] & Metcalf K.[3]

[1]Department of Geological Sciences, University of Alabama, Tuscaloosa, Alabama, USA. [2]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China. [3]Department of Geological Sciences, California State University Fullerton. California, USA.

Corresponding author email: dmr@ua.edu

Keywords: Himalayan thrust belt, Greater India, Leucogranite, deformation mode.

Two problems in the Himalayan-Karakorum-Tibet research community have produced a multitude of research articles, and likely will continue to produce articles as more data become available. The first problem is determining the composition of northern Greater India prior to the India-Asia collision. We add to the models by conducting a mass-balance analysis and combining that with previously published work to determine the width of northern Greater India. We determine that the evidence yields 2 possible configurations:1) an ∼1350±440 km wide and ∼23-30 km thick northern Greater India indicating an ∼2080±450 km wide Greater India with ∼500-1000 km wide oceanic basin systems in both Asia and northern Greater India; and 2) a ≥1815±630 km wide and ∼10-23 km thick Zealandia-type northern Greater India indicating a ≥2550±640 km wide pre-collisional Greater India without or with a limited ∼500-1000 km Xigaze back-arc oceanic basin. The former assumes no Cenozoic oceanic subduction initiation within northern Greater India and predicts multi-stage collision since ∼60 Ma. The latter predicts a single-stage collision at ∼60 Ma. Both configurations predict significant shortening on post-collisional northern Greater India. Li et al. (2023) detail these arguments.

Post-collisional shortening amounts since ~25 Ma are well known in the Himalayan thrust belt. However, we do not understand what controls how the shortening is accommodated within the orogen. This leads to the second problem, determining why some thrust sheets in Greater and Lesser Himalayan parts of the thrust belt are >100 km long and others <35 km. We determined that early-stage broad leucogranite melting during ~30-20 Ma weakened the mid-lower crustal strength, which produced a supercritical wedge. This promoted across-strike lengthening of the low-elevation Himalayan taper accommodated by detachment faulting, the South Tibetan Detachment system, and far-traveled long basal thrust sheets from ~30–25 Ma to 20-15 Ma, the Main Central and Ramgarh-Munsiari thrust sheets. Melt-removal and extraction coeval with widespread leucogranite intrusion during ~20-10 Ma substantially strengthened the mid-lower crust, which transitioned the wedge from supercritical to subcritical states. This maintained the growing high-elevation taper and shifted the deformation mode from long thrust sheets to foreland-propagated short imbrication/duplex thrust sheets. Beginning at ~20-15 Ma, the Lesser Himalayan duplex began to form and continued until ~5 Ma when the thrust belt propagated southward into the Subhimalayan rocks. Thus, the transition from melt-presence to melt-removal caused the transition from long thrust sheets to shorter thrust sheets in the Himalayan thrust belt. Li et al. (2025) provide the details of this study.

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Testimony of pre-Himalayan metamorphism in the High Himalayan Crystalline rocks of the Miyar Valley (NW India)

Robyr M.*[1]

[1]Institute of Earth Sciences, University of Lausanne, CH-1015 Lausanne, Switzerland.

Corresponding author email: martin.robyr@unil.ch

Keywords: ante-Himalaya, Miyar Valley, High Himalayan Crystalline.

Most of the tectonic, metamorphic and geochronological data suggest that the Himalaya is essentially the consequence of a single orogenic cycle associated with the India-Asia collision during the Cenozoic era. Therefore, metamorphic assemblages and tectonic structures across the Himalayan range are systematically considered as post-collisional geological records. However, over the last decades, several observations arguing for geological events predating the continental collision have become increasingly recurrent in the literature. Nevertheless, although some of these arguments are thoroughly documented, they are unduly ignored in the construction of models drawing the tectono-metamorphic evolution of the Himalayan range. Yet, the occurrence of a pre-Himalayan history would have considerable consequences on the classical models for the building of the Himalaya.

The recent discovery of inclusions of staurolite crystals in greenschist facies garnets from the Miyar Valley in Upper Lahul region (Himachal Pradesh; NW India) revives the debate on the existence of a pre-Himalayan metamorphism. Indeed, the occurrence of high-temperature staurolites included in greenschist facies garnets suggests that the High Himalayan Crystalline rocks experienced an amphibolite facies metamorphism prior the predominant Himalayan greenschist facies metamorphism observed in this part of the range.

In this study, phase petrology, microtectonic investigations combined with preexisting geochronological data infer that the crystallization of the included staurolite predates the growth of Himalayan garnets. These original data bring new arguments to bear on the long lasting debate of the existence of a Pre-Himalayan orogenic cycle. They lead to the conclusion that the growth of staurolite predates the continental collision between India and Asia and reflects a metamorphic event that belongs to a pre-Himalaya orogenic cycle (Robyr 2023).

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A 20 years long petrologic journey across the Himalaya in Nepal

Rolfo F.*[1], Groppo C.[1] & Mosca P.[2]

[1]Department of Earth Sciences, University of Torino. [2]CNR-IGG, Torino.

Corresponding author email: franco.rolfo@unito.it

Keywords: petrographic collection, lithological and metamorphic maps, central-eastern Nepal Himalaya.

Since 2005, following the legacy of our late colleagues Ugo Pognante and Bruno Lombardo, our research team organized some 30 geological expeditions in the nepalese Himalaya, aiming to investigate the lithostratigraphic architecture and the tectono-metamorphic evolution of the largest and youngest collisional orogen on Earth. Beside the classical trekking routes of Nepal (e.g., Annapurna, Manaslu, Langtang, Gosaikund, Khumbu, Mera Peak, Makalu, Tumlingtar-Lukhla, Khanchenjunga), we have walked along most of the off-the-beaten-path treks (e.g., Tsum Valley, Ruby Valley, Helambu, Panch Pokhari, Rolwaling, Numbur, upper Arun Valley, Milke Danda, Singalila) as well as along a number of new itineraries, specifically ideated in order to find the missing pieces in our puzzle-like geological map. This extensive, continuous and systematic fieldwork activity led us to collect more than 2500 samples from all the structural levels of the Himalaya (i.e., Lesser Himalayan Sequence, LHS; Greater Himalayan Sequence, GHS; Tethyan Sedimentary Sequence, TSS). A brief petrographic description is available for all collected samples, while more detailed petrological investigations performed on a selection of samples have been published in more than 25 scientific papers. This huge petrographic collection allowed us to investigate specific petrological processes occurred during the Himalayan orogeny, as for instance: partial melting at different crustal levels (e.g., Nerone et al., 2025), processes of carbon production, transfer, fixation and outgassing (e.g. Groppo et al., 2022), garnet nucleation overstepping and interplays between equilibrium and kinetics (e.g. Tamang et al., 2023). Moreover, we have been able to reconstruct the lithostratigraphy and the tectono-metamorphic evolution of the LHS and GHS in specific sectors of the nepalese Himalaya (e.g., Groppo et al., 2023).

Lithological and metamorphic information derived from our petrographic collection (e.g., type of protolith, occurrence of specific index minerals) led to the compilation of simplified geological sketch maps of central-eastern Nepal. Our samples are potentially available for any type of scientific collaboration.

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Elevation affects bacterial lipid-based environmental proxies: A Himalayan to Global perspective

Roy B.*[1,2], Thiede R.C.[3], Simon S.[1], Kumar A.[4], Moharana S.[5], Dey S.[6] & Elling F.J.[2]

[1]National Centre for Polar and Ocean Research, Headland Sada, Goa, India; [2]Leibniz-Laboratory for Radiometric Dating and Isotope Research, Christian-Albrechts-University of Kiel, Germany; [3]Department of Geosciences, Christian-Albrechts-University of Kiel, Germany; [4]Birbal Sahni Institute of Palaeosciences, Lucknow, India; [5]Discipline of Earth Sciences, Indian Institute of Technology Gandhinagar, India; [6]Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, India.

Corresponding author email: biswajitgeo92@gmail.com

Keywords: Himalaya, Summer Monsoon, Seasonality, Mean Growth Temperature, bacterial lipids.

Branched glycerol dialkyl glycerol tetraethers (brGDGTs) are bacterial lipids widely used as proxies to reconstruct past temperature and pH in terrestrial environments. However, global calibrations often reveal discrepancies between observed environmental conditions and proxy-based predictions, particularly across soils spanning latitudinal and elevational gradients. In mountainous regions, orographic barriers create distinct elevation-dependent environmental conditions, which may cause the growth patterns of brGDGT-producing bacteria to differ from latitudinal expectations.

To assess the role of elevation in influencing brGDGT signals, we investigated a transect across the Western Himalayas (300–5500 m) that naturally spans variations in soil properties, precipitation, temperature, and seasonality. While brGDGT-derived pH closely matches measured soil pH, brGDGT-derived temperatures deviate by –10 to +10 °C from observed mean annual temperatures across our transect and other Himalayan sites. These deviations correlate with cumulative heat, quantified as growing degree days above 0 °C (GDD_0).

A global analysis of soils and peats (n=1795) further demonstrates that GDD_0 strongly influences brGDGT methylation patterns across both elevational and latitudinal transects, introducing seasonal biases toward colder-season signals in warm climates (high GDD_0) and warmer-season signals in cool climates (low GDD_0). Additionally, scatter in brGDGT-based temperature estimates increases where elevation-driven orographic effects create localized variability in bacterial growth conditions. These non-uniform growth environments, induced by regional topographic controls, can locally modify broader climate signals, contributing to biases and scatter in global brGDGT calibrations and paleotemperature/paleoelevation reconstructions.

Textural and geochronological study of white mica in the east-central Nepal Himalaya: compound in situ Rb/Sr and K/Ca geochronology

Roy S.*[1], Barnes C.J.[1] & Larson K.[1]

[1]Department of Earth, Environmental, and Geographical Sciences, University of British Columbia Okanagan, Kelowna, BC, Canada.

Corresponding author email: shreya.roy@ubc.ca

Keywords: Himalaya, *in situ* Rb/Sr geochronology, *in situ* K/Ca geochronology.

The exhumed metamorphic core of the Himalayan orogen is predominantly composed of polymineralic meta-sedimentary and meta-igneous rocks, with mica being the most abundant phyllosilicate phase in all bulk compositions. These metamorphic rocks are pervasively deformed, with a tectonic foliation typically defined by the alignment of white mica and biotite laths. Both phases can also occur as porphyroclasts or recrystallized grains within shear bands. Evidence of ductile deformation is preserved in both types of mica, characterized by dislocation creep-induced intracrystalline plastic deformation including undulose extinction, kink bands and folds. The two micas commonly occur as intergrown phases, with biotite in some rocks variably replacing white mica.

Rb/Sr geochronology of mica (Larson et al., 2023) was performed in situ on three specimens from different structural levels across the Main Central Thrust (MCT) zone of the east-central Nepal Himalaya. Different microstructures including relict and recrystallized mica were selected for analysis. In all specimens, biotite yields young, Himalayan isochron dates (c.15-6 Ma), whereas white mica analyses define older, over dispersed, pre-Himalayan isochron dates (c. 485-41 Ma). To test the robustness of the Rb-Sr dates, a newly developed in situ K-Ca geochronology (Zack and Hogmalm, 2016; Barnes et al., 2025) method was applied to the same white mica, which also returned pre-Himalayan isochron dates (c. 202-132 Ma). Such old white mica dates have not been reported from the Himalaya previously.

The dates obtained from both geochronological systems are consistent with the textures in the specimens wherein biotite is observed to replace white mica. Whereas the young biotite dates likely represent cooling or recrystallization associated with deformation and exhumation of the Himalayan mid-crust, the significance of the older white mica dates is less obvious. We speculate that the dates may: 1) reflect incomplete resetting of isotopic systematics during Himalayan orogenesis, or 2) record crystallization(re) during syn-rift magmatism events linked to the breakup of continental blocks from India during Jurassic Period. Regardless, in either case, the retentivity of the Rb/Sr and K/Ca systematics of white mica through the Himalayan overprint warrants further study.

Barnes C. et al. (2025) - Combined in situ K/Ca and Rb/Sr geochronology of potassic mica. EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-14442, https://doi.org/10.5194/egusphere-egu25-14442.

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Zack T. & Hogmalm K.J. (2016) - Laser ablation Rb/Sr dating by online chemical separation of Rb and Sr in an oxygen-filled reaction cell. Chem. Geol., 437, 120-133. http://dx.doi.org/10.1016/j.chemgeo.2016.05.027.

Installation and sedimentary evolution of the Early Jurassic carbonate platform on the India northern passive margin (Jomsom Formation, Kali Gandaki valley, Nepal)

Rožič B.*[1], Krobicki M.[2], Žvab Rožič P.[1], Starzec K.[2], Gale L.[1,3], Iwańczuk J.[4] & Kwietniak A.[2]

[1]Faculty of Natural Sciences and Engineering, University of Ljubljana. [2]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow. [3]Slovenian Geological Survey, Ljubljana. [4]Polish Geological Institute–National Research Institute, Warsaw.

Corresponding author email: bostjan.rozic@ntf.uni-lj.si

Keywords: carbonate platform, Lower Jurassic, microfacies, Jomsom Formation.

The studied succession is located in the Tethys Himalaya, i.e. a Phanerozoic low-grade (para)metamorphic and sedimentary sequence north of the South Tibetan Detachment fault. The entire Mesozoic sequence consists of alternating clastic and carbonate formations deposited along the Indian segment of the passive margin of Gondwana south of the Neotethys Ocean. Here, we present a detailedsedimentological study of the transition from the uppermost part of the Upper Triassic clastic Thini Formation to the Lower Jurassic carbonate Jomsom Formation (e.g. Gradstein et al., 1993), also known in the region as the Kioto Carbonate Platform. The study was carried out in Nepal, in the Kali Gandaki valley, a few kilometers north of the Jomsom village, within a relatively undeformed tectonic block situated just north of the Lupra Fault (Godin, 2003). It includes bed-by-bed logging (240 meters), microfacies and biostratigraphic studies.

The section begins with 20 meters of presumably end-Triassic quartz sandstone, showing pronounced cross-stratification, often of the herringbone type, indicating sedimentation in an estuarine environment. Upwards, we observe a rapid (?Lower Jurassic) transgression starting with a 10 meter thick intertidal sequence characterized by alternating fine clastics and limestone. The latter is either micritic (often with clastic admixtures and subaerial exposure) or lumachelle-like limestones. In the next 35 meters, cross-bedded ooidal limestones predominate, indicating sedimentation in high-energy marginal bars.

Upwards, the entire sequence is dominated by lagoonal (bioclastic, peloidal, intraclastic) limestones, but intertidal clastics and ooidal-bar limestones still occur. In the upper half of the logged section, these form deepening-upward parasequences, which start with intertidal clastics/limestones, pass through restricted lagoonal thin-bedded limestones into open-lagoon bioclastic thick-bedded limestones (often showing paleokarst cavities filled with fine clastics or/and calcitic spar). They end up either by paleokarst surfaces or cross-stratified ooidal limestone. In the topmost 15 meters, Pliensbachian *Lithiotis*-type bivalves start to occur, which were just recently discovered and described from the Kali Gandaki valley (Krobicki et al., 2025, see also this volume). The research was carried out in the frame of the IGCP 710 project and is the contribution No. 4. of the scientific initiative Himalayan Academy.

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A balanced cross-section across the Pakistan fold-thrust belt: interpreting the stratigraphy and structural framework of the Pakistan Himalaya

Schiffer W.J.*[1], Robinson D.M.[1] & Faisal S.[2]

[1]Department of Geological Sciences and Center for Sedimentary Basin Studies, University of Alabama, Tuscaloosa, Alabama, USA. [2]National Centre of Excellence in Geology, University of Peshawar, Peshawar, Pakistan.

Corresponding author email: wjschiffer@crimson.ua.edu

Keywords: Himalaya, Pakistan, fold-thrust belt.

Northern Pakistan remains an understudied frontier of Himalayan geology, especially in the hinterland between the Main Boundary thrust and the Main Mantle thrust. Fold-thrust belts are natural laboratories for understanding crustal shortening during continental collision, and the structural framework of the Himalayan fold-thrust belt north of the Main Boundary thrust in Pakistan is not well-understood. Stratigraphy varies along- and across-strike, and tectonostratigraphic relationships are not easily correlated to the rest of the Himalayan arc east of the Hazara-Kashmir syntaxis. Additionally, complex deformational and metamorphic histories challenge interpretation of true stratigraphic thicknesses.We present the first balanced cross-section from the Main Mantle thrust to the Salt Range thrust (Main Frontal thrust) in the Pakistan fold-thrust belt to assess crustal shortening and to provide a kinematic interpretation. Between the Main Mantle thrust and the Main Boundary thrust, we have interpreted a series of duplexes with roof thrusts. Duplexing of the Paleoproterozoic Besham Group in the footwall of the Main Mantle thrust creates a folded thrust contact between the overlying rocks of the Gandaf and Tanawal formations. This is consistent with our field observations and may represent the Main Central thrust in Pakistan. South of the Main Boundary thrust, the Potwar Plateau exhibits broad, open folding and little internal deformation due to Neoproterozoic salt acting as a ductile décollement.Our estimate of minimum shortening is 257–534 km across the entire fold-thrust belt. The range in our estimate is due to stratigraphic thickness ambiguities in the Proterozoic rocks in the footwall of the Main Mantle thrust. We further address tectonostratigraphic relationships with detrital zircon geochronology from strata that could be part of Greater, Lesser, or Tethyan Himalayan rocks.

Mount Everest: Tectonic Evolution, Uplift history, Exhumation, River Capture and Models

Searle M.P.*[1], Cottle J.M.[2], Jessup M.J.[3] & Law R.D.[4]

[1]Dept. Earth. Sciences, Oxford University, OX1 3AN, UK. [2]Dept. Earth Sciences, University of California, Santa Barbara, CA, USA. [3]Dept. Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, USA. [4]Dept. Geosciences, Virginia Tech. Blacksburg, VA24061, USA.

Corresponding author email: mike.searle@earth.ox.ac.uk

Keywords: Himalaya, Channel Flow, Low-angle normal faults, Mount Everest.

Mount Everest (8850 meters) is the highest mountain along the Himalayan chain and its uplift history is related to processes including tectonic uplift (thrusting, underplating), rock exhumation, glacier and river incision, surface uplift, and isostatic compensation as a result of unloading and erosion. Geochronological constraints define four periods during the thermal history: (1) crustal thickening, regional metamorphism (45-25 Ma), (2) mid-crustal melting, channel flow, rapid cooling (25-15 Ma), (3) relatively slow cooling (15-2 Ma), and (4) glaciation, increased rapid cooling (2-0 Ma). Mount Everest spans the Greater Himalayan Series metamorphic rocks and the base of the unmetamorphosed Tethyan sedimentary rocks in the Nepal-South Tibet Himalaya. Two north-dipping, low-angle normal faults cut the massif, the upper Qomolangma Detachment placing Ordovician sedimentary rocks above Everest Series greenschist – amphibolite facies rocks, and the lower Lhotse Detachment placing Everest Series schists above sillimanite gneisses, migmatites and leucogranites. The two faults merge northwards into one large ductile shear zone (South Tibetan Detachment). Pressure-temperature constraints and structural restoration shows that the fault acted as a passive roof fault during extrusion of the footwall. At least 120 km southward flow of footwall rocks occurred during the Miocene resulting in exhumation of rocks that were buried to 5.5 kbar (~18-22 km depth) below the detachment juxtaposing them against hangingwall rocks that are essentially unmetamorphosed. The low-angle normal faults were operative during north-south convergence and reflect exhumation of a locked passive roof fault, not to any crustal extensional processes. U-(Th)-Pb dating of peraluminous leucogranites exposed on Everest (21–20 Ma), Nuptse (~19–18 Ma) and along the Rongbuk valley (15.6–15.4 Ma) show that ductile extrusion occurred during the Early Miocene, with brittle faulting at <15.4 Ma, during exhumation. Geochronological data suggests that Mount Everest along with other Himalayan peaks has maintained high topography since the early Miocene. Uplift was dominantly caused by tectonic forces (thrusting, underplating) not by climatic forces. River capture (Arun, Sun Kosi) played little or no part in the uplift of Mount Everest.

Geodynamic Controls on Quaternary Thrusting in Southern Tibet and the Himalayas

Shanker D.*[1] & Kapur N.[2]

[1]Department of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee - 247 667, India.[2]Nipun Kapur, Analytics Consultant: Catastrophe Insurance and Real Estate; August Park Apt. A301, Near DRDO KG School, CV Raman Nagar, Bangalore 560093, India.

Corresponding author email: d.shanker@eq.iitr.ac.in

Keywords: South Tibetan Detachment (STD), Quaternary shortening, Stress simulations.

Thrust faulting dominated southern Tibet during the Cretaceous and Paleocene, leading to the development of the Gangdese and Renbu–Zedong Thrust systems. This phase of deformation largely ceased by the Miocene, transitioning to north-dipping, shallow normal faulting along the South Tibetan Detachment (STD) in the Higher Himalayas (Owens & Zandt, 1997). Notably, activity along the STD was contemporaneous with movement on the Main Central Thrust (MCT). By approximately 8 million years ago, thrusting in southern Tibet had nearly ceased, with little evidence of significant Quaternary shortening. In contrast, thrust activity has continued in the Himalayas into recent times.

To investigate the geodynamic controls (Nedoma 1997) on Quaternary thrusting in the Himalayas and southern Tibet, stress simulations were performed using two-dimensional, nonlinear elastic, homogeneous wedge models representing geological cross-sections of these regions. By systematically varying the basal strength in the models, the resulting stress distributions and failure patterns were analyzed. Simulations conducted under boundary conditions simulating crustal buildup in the Himalayas and Tibet reveal that, as basal strength decreases, the zone of thrust failure progressively retreats from the wedge front toward its base. These results support the hypothesis that spatial variations in basal strength stronger beneath the Himalayas and weaker beneath southern Tibet govern the extent and persistence of Quaternary thrusting (Bilham et al. 1998). Additionally, observational and thermal modeling data suggest a southward decrease in the strength of the Main Himalayan Thrust (MHT), potentially due to partial melting along the fault. Nevertheless, the specific stress magnitudes and locations of failure remain sensitive to the chosen model parameters and boundary conditions (Shanker et al., 2002).

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Railway Networking in Nepal Himalaya: Challenges and Future prospect

Shamra D.R.[1] & Tamrakar N.K.*[1]

[1]Central Department of Geology, Tribhuvan University, Kirtipur, Kathmandu, Nepal.

Corresponding author email: naresh.tamrakar@cdgl.tu.edu.np

Keywords: Railway Network, Quartzite Ballast, Nepal Himalaya.

The development of railway network in the Nepal Himalaya represents a transportation opportunity for regional connectivity, trade facilitation, and national economic growth. Nepal railway network system is now undergoing strategic expansion. Key projects such as the East-West Railway (945 km), Raxaul–Kathmandu Railway (136 km), and Kerung–Kathmandu Railway (170 km) aim to connect major economic hubs and link Nepal with its neighboring countries (GoN, 2024). This is a trade corridor between India and China, and Nepal can be potential to position a vital trade transit hub in South Asia. Urban transport proposed Kathmandu Metrorail. However, the railway development faces significant challenges because Nepal has complex geology of active tectonics and hazardous (seismic and landslide) terrains (Stöcklin, 1980), limited technical expertise, funding constraints, and political delays in project implementation. Despite of these hurdles, the future prospects of railway development in Nepal are promising. The expansion of highways and hydropower infrastructure supports easier access and energy supply for railway operations. Nepal's own resources—such as cement, iron ore and ballast materials—can be utilized to reduce reliance on imports (Guo et al; 2022). As industrial cities and urban centers grow, railways offer a mass transit solution for goods and people. In this perspective, quartzite dominant five quartzite stratigraphic units of Nepal Himalaya were sampled and extensively tested for physical and mechanical properties, durability and petrography. Quartzite is hard, durable and high resistance rock (Howard, 2005). The evaluation made indicated promising prospects of quartzite railway ballasts. International collaboration, application of modern technology, utilization of domestic resources and extensive exploration of construction materials throughout Nepal are recommended.

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Terrane characterization across NW Himalaya along Sutlej Valley, Himachal Himalaya

Singh S.[1], Mohan Prabha S.[2], Singhal S.[3] & Kushwaha A.[1]

[1]Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee – 247 667, India, [2]Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, 63000 Clermont-Ferrand, France, [3]Petrology and Geochemistry Division, Wadia Institute of Himalayan Geology, 33 GMS Road, Dehradun 248 001, India.

Corresponding author email: sandeep.singh@es.iitr.ac.in

Keywords: Detrital Zircon, U-Pb dating, Sutlej Valley, NW-Himalaya.

In an effort to ascertain the patterns of accretion of unique terranes across the Jutogh Thrust/Main Central Thrust (MCT), and the South Tibetan Detachment System (STDS), unweathered,hard-rock samples were collected across identified stretches of the Sutlej Valley, from Jhakri— Jeori (basal part of the Higher Himalayan Crystallines), Karcham — Kashang (upper part of the Higher Himalayan Crystallines), and Morang — Spello (Lower part of the Tethyan Sedimentary Sequence). Along Sutlej Valley the HHC is made up of two prograde metamorphic packages that are separated by the Vaikrita thrust at a middle structural level. Near Jhakhri the Main Central thrust (MCT) is exposed separating quartzite of the Kulu-Rampur window with garnet-mica schist. The lower package above MCT are also known as the Munsiari or Jutogh Formation locally in the Sutlej valley. The rocks of this group are mostly mica schists and paragneisses in amphibolite facies having key minerals like garnet and staurolite and exposed close to Jeori near the Chaura Thrust (CT), which is separating this lower package with Wangtu Granite Complex. Beyond Wangtu Granite Complex near Karcham and above the Vaikrita Thrust (VT), there is another high grade metamorphosed package of the Vaikrita Group with sillimanite – K-feldspar zone with migmatite generation. In the north close to South Tibetan Detachment System (STDS), Cambro-Ordovician Akpa and Kinnar Kailash granite have intruded. Beyond STDS Haimanta Group of rocks are exposed. They are comprised of interlayered pelitic schists and psammitic schists with minor calcareous layers. The metamorphic grade of the Haimanta Group decreases upward through the section. Only metasedimentary samples have been collected and processed from Sutlej Valley. The samples were further processed using standard mineral separation procedures to separate out zircon crystals using breaking, crushing, milling, Wilfley table, Frantz separation, and heavy liquid separation. Zircon was hand-picked from the mineral concentrate and mounted in Teflon. The Teflon mounts were then polished using progressively finer diamond pastes. Further including SEM imaging, U-Pb analysis, data processing, and interpretation were carried out.

The detrital zircon plots clearly indicate three different trends indicating basal part of the HHC i.e. Jutogh Formation of rocks which are equivalent to Munsiari Group of rocks along with distinct pattern of Vaikita Group (upper part of HHC) and Haimanta Group of rocks. Pb-Loss model of Jutogh Formation (Basal part of HHC) indicating thermal event at around 500 Ma and around 45 Ma. Pb-Loss model of Vaikrita Group of Rocks (Upper part of HHC) indicating thermal event at around 480 Ma and 45 Ma (prominent) and also show mixed data during earlier time. Pb-Loss model of Tethyan Sedimentary Sequence (Haimanta Group indicating thermal event at around 480 Ma and 30 Ma (prominent).

Sedimentary and tectonic records of paleoseismic events in the Quaternary deposits of the Kali Gandaki (Thakkhola Valley) central Nepal Himalaya

Starzec K.*[1], Kwietniak A.[1], Krobicki M.[1], Barmuta J.[2], Fodor L.[3,4], Upreti B.N.[5] & Gajurel A.P.[6]

[1] Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Poland. [2]Institute of Geological Sciences Polish Academy of Sciences, Poland. [3] HUN-REN Institute of Earth Physics and Space Science, Hungary. [4], Institute of Geography and Earth Sciences, Department of Geology, Eötvös University, Budapest, Hungary. [5]Nepal Academy of Science and Technology, Nepal. [6]Central Department of Geology, Tribhuvan University, Kathmandu, Nepal.

Corresponding author email: kstarzec@agh.edu.pl

Keywords: seismites, Thakkhola Graben, Quaternary.

Even though Nepal is a country that spans through the Himalayan range, which is an undoubtfully active collision zone, the information on the natural seismicity in this region is scarce, and hazard assessments, although intuitively high, may be estimated with high epistemic uncertainty. The general understanding of Nepal's seismicity is based on the earthquake catalogue, in which there is very little information on paloseismicity, and the instrumental period has rather high magnitudes of completeness. These factors make the comprehensive understanding of Nepalese seismicity very problematic.

We attempt to supplement the incomplete paleoseismological records that are crucial for understanding the complexity of the seismic cycle and can improve seismic hazard estimation in Nepal. Paleoseismicity relates to the information in the geological record of past seismic events, such as seismites and indirect geological indicators. The Quaternary deposits, outcropped in the middle of the Kali Gandaki Valley (central Nepal), seem to be suitable for such studies. These sediments, which extend for more than 23 km along the valley, were deposited in the periodic Marpha paleolake, that developed at the end of the Pleistocene as a result of massive damming of the Kali Gandaki Valley by the rock avalanche (Fort, 2000). Total thickness of the lake sediments reaches over 400 m (Fort, 2000). The semi-consolidated sediments mostly consist of silts, fine to coarse sands and gravels, rarely sandy loams or muds of fluvio-lacustrine origin.

The preliminary studies conducted along the 140-meter-thick section exposed near the village of Thini (right bank of the Kali Gandaki) enabled us to find several levels of well-preserved soft-sediment deformation structures that include both ductile and brittle deformations. The former include structures related to dewatering, i.e. flame-like structures and lamination disturbed by water-escape structures, also load structures (load casts and ball-and-pillow structures), as well as folds and convolute lamination. The brittle deformations comprise microfaults and breccias. Based on their character and the geological context, these deformations can be attributed to seismites. In an outcrop on the western side of the valley near Jomsom the sediment deformation features are associated with discrete, planar conjugate faults with dm-sized displacements. Their origin is probably related to the seismicity caused by the activity of the adjacent active fault (Thakkhola fault) that runs along the Kali Gandaki Valley from the Nepalese to Tibetan territory. Further systematic studies of the spatial and temporal distribution of seismites along the Kali Gandaki Valley are promising in terms of recovering the occurrence of seismic events in this part of Nepal.

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Raising the roof of the world: intra-crustal Asian mantle supports the Himalayan-Tibetan orogen

Sternai P. *[1,2], Pilia S.[3], Ghelichkhan S.[4], Bouilhol P.[5], Menant A.[6], Davies D.R.[4], Ostorero L.[1], Vaes B.[1], Esposito R.[1], Garzanti E.[1], Cloetingh S.[7] & Gerya T.[8]

[1]Dipartimento di Scienze dell'Ambiente e della Terra, Università di Milano-Bicocca; [2]GFZ German Research Centre for Geosciences, Potsdam, Germany; [3]College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum and Minerals; Dhahran, Saudi Arabia; [4]Australian National University, Research School of Earth Sciences; Acton, Australia; [5]University of Lorraine, CNRS, CRPG, 54000, Nancy, France; [6]Géoazur, Université Côte d'Azur, IRD, CNRS, Observatoire de la Côte d'Azur; Valbonne, France; [7]Department of Earth Sciences, Utrecht University; Utrecht, The Netherlands; [8]Department of Earth Sciences, ETH-Zurich; Zurich, Switzerland.

Corresponding author email: pietro.sternai@unimib.it

Keywords: crustal doubling, lithospheric mantle, continental subduction.

The Himalayan-Tibetan orogen formed via the ongoing collision of India and Asia. Its colossal elevations stem from buoyant crustal roots that doubled in thickness during continental collision, widely believed to result from Indian crust under-thrusting its Asian counterpart and Asian crustal thickening. However, a single crustal layer of up to ~70-80 km thickness conflicts with experimental-rheological and observational constraints, especially if related to the vertical juxtaposition of Indian and Asian crusts. For instance, crustal thickness above ~40 km implies reduced strength of the continental lithosphere, which becomes unable to sustain a plateau the size of Tibet throughout much of the Cenozoic. In addition, the geochemistry and association of ultramafic xenoliths and K-rich magmas from Southern Tibet indicates the presence of mantle material between ~50-80 km depths. The mechanisms controlling the rise and persistence of Earth's highest orogen, therefore, remain enigmatic. Here, new fully-coupled numerical petrological-thermomechanical geodynamic models reconcile the wealth of available structural and petrological constraints through viscous underplating of Indian crust beneath Asian lithosphere, which together supply buoyancy and strength to raise and support the Himalayas and Tibet. We further convert our geodynamic models into receiver functions and shear waves velocity maps that match, to a first order, the available geophysical data from the Himalayas and southern Tibet. We propose that viscous underplating of Indian crust beneath Asian lithosphere, not crust, forms the overall architecture of the Himalayan-Tibetan orogen.

Eastern Himalayan -Meghalayan Tethys in India and Western Alpine Tethys in Adriatic Platform, Trieste, Italy : Comparative Paleocene –Eocene foraminifera, shallow tidal carbonate sedimentation, isotope chemostratigraphy and paleobiogeography

Tewari V*[1]

[1]Former Professor, Geology Department, Sikkim University, Gangtok, Sikkim-737102, India. Former Scientist G., Wadia Institute of Himalayan Geology, Dehradun-248001, Uttarakhand, India.

Corresponding author email: Professorvct54@gmail.com

Keywords: Himalayan Tethys, Meghalaya, Paleocene – Eocene, Foraminifera.

The Cretaceous - Paleogene sedimentary basins of the eastern Tethys in Northeastern India are well developed in the Assam – Arakan region in parts of Assam, Meghalaya ,Arunachal Pradesh, Manipur-Nagaland Orogenic Belt, Mizoram and Mikir hills. The thick sedimentary succession was deposited in shallow shelf, richly fossiliferous inner and outer carbonate ramps with larger benthic foraminifera and algal biofacies. In the Western Tethyan Himalaya (Jammu & Kashmir and Ladakh) and as marine transgressions in the Lesser Himalaya (Subathu) also the Late Cretaceous –Paleogene sediments are recorded.The anti-clockwise northward flight of India continued during this period. The Cretaceous – Tertiary Boundary is well developed in the Um Sohryngkew section of the South Shillong Plateau, Meghalaya. In this thick K/T boundary succession, several fossiliferous beds of the gastropods, ammonoids, echinoids, sauropod dinosaur bones and foraminifera- algal limestone has been recorded. The fish remains are found associated with the shallow marine benthic foraminifera of Paleocene age from Mawsmai. The Komorrah Limestone Mine in the Um Sohrynkew section represent shallow-marine tidal sedimentation in the South Shillong shelf during Paleocene to Late Eocene in which Langpar, Therria, Lakadong, Umlatdoh, Narpuh, Prang and Kopilii Formations in ascending order were deposited without any sedimentological break. The carbon, oxygen,and mercury (Hg) isotope chemostratigraphy of the Lakadong and Umlatodoh Limestones from Eastern Tethys sea of Meghalaya, India is of global significance and comparable with the major biotic, isotopic and paleoclimatic events recorded in western Tethys.

The Late Cretaceous – Eocene carbonate facies with brecciated miroalgal- stromatolitic and foraminiferal assemblage of the Western Tethyan Alpine realm (Padriciano section, Adriatic platform in Italy, Dolenia-Vas section in Slovenia and other sections in Carpathians) is correlated with the eastern shallow Neotethys in Meghalaya. However, deeper marine facies are found in some parts of Upper Disang and Upper Bhuban formations in the Mizo hills.The sediments of the inner and outer shelf are well developed in the eastern Tethyan realm in Garo, Khasi and Jaintia hills of the Shillong Plateau in Meghalaya. The paleobiogeography of South Asian Tethyan realm and its correlation with Western Tethys is reconstructed. The Indo-Myanmar Orogenic Belt (IMOB) represents the eastern suture of Indian plate, and it was formed due to the collision of the Indian plate with the Myanmar plate. The Naga-Manipur ophiolites have been assigned to range in age from Upper Cretaceous to Eocene on the basis of faunal assemblages (radiolarian, planktonic foraminefera) and C- isotopic ratios in the Olistolithic blocks of pelagic limestone and cherts. The Lower Disang sediments were intermixed with pelagic cherts and limestone. The flyschoid Disang Formation gradually merges into the post-orogenic molassic Barail Group of rocks. The tectonic model for the subduction of the Indian Plate below Myanmar micro Plate is interpreted for the Eastern IMOB.

Plio-Pleistocene accelerate fluvial incision of Southern Tibet cause the reactivated rise of the Greater Himalaya?

Thiede R.C.*[1], Scherler D.[2,3]& Glotzbach C.[4]

[1]Institute of Geosciences, Kiel University, Kiel, Germany. [2]Helmholtz Zentrum Potsdam, Deutsches GeoForschungs Zentrum GFZ, Germany, [3]Institut für Geographische Wissenschaften, Freie Universität Berlin, Germany, [4]Institut für Geowissenschaften, Universität Tübingen, Germany.

Corresponding author email: rasmus.thiede@ifg.uni-kiel.de

Keywords: Plio-Pleistocene fluvial incision, South Tibet, uplift.

The Himalaya is the highest and steepest mountain range on Earth and forms today efficient north-south barrier for moisture-bearing winds. 1D-thermokinematic modeling of new zircon (U-Th)/He bedrock-cooling ages and >100 previously published mica $^{40}Ar/^{39}Ar$, zircon and apatite fission track ages from the Sutlej Valley region document a consistent rapid decrease in exhumation rates that initiated at ~17-15 Ma across the entire Greater and Tethyan Himalaya and the north-Himalayan Leo Pargil dome. The observed and modelled decrease yield rates from >1 km/Myr to <0.5 km/Myra across the entire study area. Therefore a key-finding is that since the middle Miocene a 10-million-year-period of slow exhumation in the upper Sutlej Valley coincides with a period of internal drainage in the south-Tibetan Zhada Basin further upstream, which we interpret to be a consequence of tectonic damming – most likely caused by the growth of Lesser Himalayan duplex to the south. Comparison with other data from the High Himalaya and Southern Tibet along strike suggests that by ~15 Ma, southern Tibet was high, located in the rain shadow of the High Himalaya and eroding slowly for at least 10 Ma. Our modelling results suggest that exhumation rates in the upper Sutlej Valley accelerate again at ~5-3 Ma, and allowed the Sutlej River to re-establish external drainage of the Zhada Basin. Also beside the Zhada Basin several Neogene basins in Southern Tibet switch to external drainage, rapid fluvial incision and sediment excavations at this time. Recent studies agree with a reactivated uplift of High Himalaya by this time. As by Miocene time both the High Himalaya and South Tibet have been uplifted to present day mean elevation only additional intensified erosion and mass removal could have enabled reactivated faulting and accelerated uplift of Greater and Tethyan Himalaya. Our new finding document that the location of tectonic deformation processes controls the first order spatial pattern of both climatic zones and erosion across the orogen. Therefore, we think that the rise of Greater Himalaya is linked to the deceleration of exhumation in Southern Tibet and climate driven renewed fluvial incision of High Himalaya and Southern Tibet enabled the reactived uplift recognized since the Pliocene.

Comprehensive Geophysical Interpretation and Reservoir Characterization of the Ranikot Formation in the Southern Indus Basin, Pakistan: Insights into Hydrocarbon Potential and Geological Framework

Ullah A.*[1,2,3] & Wang Y.F.[1,2,3]

[1] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, P. R. China. [2] University of the Chinese Academy of Sciences, Beijing 100049, P. R. China. [3] Innovation Academy for Earth Science, Chinese Academy of Sciences, Beijing 100029, China.

Corresponding author email: Atta@mail.iggcas.ac.cn

Key words: Seismic interpretation, Spectral Decomposition, Seismic Inversion.

The goal of this study is to evaluate a thorough examination of the Ranikot Formation in the Mehar Block, located in Pakistan's Lower Indus Basin's Kirthar fold belt. To achieve this, seismic interpretation was utilized to investigate subsurface geometry and structural patterns. Petrophysical analysis of the Mehar-01 well revealed promising hydrocarbon zones, characterized by a shale volume of 40%, an effective porosity of 17%, and a hydrocarbon saturation of 61%. Spectral decomposition at frequencies of 22 Hz and 27 Hz successfully detected thin beds and sand channels. A comparative analysis of seismic inversion techniques revealed that the model- based approach provided superior bed continuity, with an error of 0.09, compared to the maximum likelihood sparse spike method, which resulted in sharper bed delineation but had a higher error of 0.17. Additionally, impedance volumes were translated into porosity volumes using PNN, indicating a porosity range of 13-20%. These results underscore the Ranikot Formation's significant potential as a hydrocarbon reservoir in this region.

Source-to-Sink and Sediment Dynamics in the Thar Desert, NW Himalaya

Usman M.*[1], Clift P.D.[2], Pastore G.[3] & Garzanti E.[3]

[1,3]Department of Biological, Geological and Environmental Sciences (BiGeA) at Interdepartmental Centre for Environmental Sciences Research (CIRSA), University of Bologna, Italy. [2]Department of Earth Sciences, University College London, London C1E 6BT, UK.[3]Department of Earth and Environmental Sciences, University of Milano-Bicocca, Milano 20126, Italy.

Corresponding author email: u.sikandar786@gmail.com

Keywords: Thar Desert, Sediment dynamics, Source-to-Sink, NW Himalaya.

The Thar Desert is a major sediment depocenter in southwestern Asia and borders the Indus drainage system to its east. It is unclear where the sediment that built the desert is coming from, and when the desert experienced phases of construction. Major deserts must be supplied with sediment in order to accrete and the Thar Desert that lies east of the Indus River in SW Asia is expected to be largely derived by supply from that major drainage. In particular, we seek to establish the role of the South Asian monsoon in the initial formation and subsequent expansion of the desert. Here we integrate bulk-petrography and heavy-mineral data with U-Pb ages of detrital-zircon, to understand how the desert relates to the major potential sediment sources in the Himalayan orogen and to the major rivers that surround it. Bulk petrography and heavy mineral data from eolian sand in Cholistan (NE Pakistan) show close similarity with that of Himalayan tributaries, whereas eolian sand in Sindh (S Pakistan) contains heavy-mineral suites close to those of Indus sand largely supplied by erosion of the Karakorum and Kohistan. Kohistan is a particularly rich source of heavy minerals and is thus over-represented in sediment budgets based on that proxy alone. U-Pb ages of detrital-zircon fail to show a sharp difference between dune sands in Sindh and Cholistan, except for revealing somewhat greater supply from the Himalaya in Cholistan and from the Karakorum, Kohistan and Nanga Parbat in Sindh. Zircon ages are similar in Sindh Desert sand and in the Indus Delta and are most similar in deltaic sand dated as 7 ka or older. In parallel, the age signature of Cholistan sands resembles more that of older river channels found along the northwestern edge of the desert (e.g., paleo-Ghaggar-Hakra) than that of modern Himalayan tributaries (e.g., Sutlej). Both Cholistan and Sindh sands suggest that the sediment supply to the desert was greater in the early Holocene when the monsoon was stronger. The southwesterly summer monsoon turned out to be the most effective agent of eolian transport and recycling of Indus delta sediments entrained towards the central and northern parts of the desert.It is difficult to resolve the competing influence of fresh sediment supply in the mainstream of the river compared to recycling from the desert when trying to account for the net supply sediment from the Indus to the Arabian Sea.

Petro-hygro-chronology and paleoaltitude of the Zanskar gneiss

Villa I.M. *[1,2], Stahr III D.W.[3] & Webster T.J.[4]

[1] Centro Universitario Datazioni e Archeometria, Università di Milano Bicocca, 20126 Milano, Italy. [2] Institut für Geologie, Universität Bern, 3012 Bern, Switzerland. [3] Dept. of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA. [4] School of Environment, Earth and Ecosystem Sciences, The Open University, MK7 6AA, UK.

Corresponding author email: igor.villa@unibe.ch

Keywords: geochronology, paleoaltitude, Zanskar.

The Zanskar GHS gneiss lies SW of the Zanskar Shear Zone (ZSZ), a part of STD. Age data are few and far between, mostly unconnected to µm-scale petrology. The orthogneiss near Padum is Ordovician, P-T=770-550 °C (1a Pognante et al. 1990). Cenozoic metamorphic peak at Nun-Kun is 25-28 Ma (1b Searle et al. 1992). Isolated monazite ages (1c Robyr et al 2006) scatter 50-21 Ma, but low-resolution SIMS ages are unsupported by petrology. Monazite needs high resolution (2c Williams et al. 2007) to discriminate relict and neoformed patches. The Gumburanjum granite is ~20 Ma, followed by brittle deformation at 19.8 Ma (1d Dèzes et al. 1999).

Stahr (2a Stahr 2013) collected micas along a ~1 km traverse in Haptal. EPMA element maps define the petrologic context: micas are mosaics intergrown with feldspar & talc at the <5 µm scale. We report multichronometric Rb–Sr and 39Ar–40Ar petrochronology. Ar isotopes reveal K < stoichiometry and high Ca/K & Cl/K ratios in alteration phases, correlating with Ar*/K ratios. Bt 500 m below ZSZ has a Rb-Sr age of 20.0±0.1 Ma, identical to the 39Ar–40Ar ages of both Bt & Ms. This triple coincidence proves that 20 Ma is the formation age (2d Villa et al 2023). Despite alteration (element maps, Ar-Ar systematics), Bt≈Ms ages of 19.5-20 Ma are reliable.

Low δD on the same micas (2b Webster et al. 2018) points to infiltration of high-altitude meteoric water into gneiss. Interlinked questions: when did meteoric infiltration occur? What was the paleoelevation?

δD changes at ca. 400 m structural distance below ZSZ do not correlate with the constant ages. Therefore infiltration of light hydrogen occurred after all Ar chronometers had been set. If water reacts with micas above the mica isograd (Tbt~400 °C), a new mica generation recrystallizes; at T<Tbt, talc/smectite are formed. As element maps show talc/smectite, the latest water infiltration occurred at low T. Measurements of H diffusivity (3b Graham 1981) predict that δD is smoothed away at Tc = 280 °C, if a second H-bearing phase acts as a H sink. In the gneiss this phase is only µm-sized clay. Thus infiltration could have occurred at any T, Tbt>T>Tc.

Large-scale rock permeability only occurs in the brittle regime (3d Ingebritsen & Manning 2010), T<300–400 °C; this confirms low-T δD exchange. Laboratory δD(T) of water-mica exchange at 850-400 °C (3a Suzuoki & Epstein 1976) on non-descript mica samples would allow to reconstruct meteoric δD from the reaction T, but the T–δD correlation deviates from linearity below 450 °C; no data below 400 °C were obtained; any extrapolation to T<Tc (3b Graham 1981) is arbitrary. Deuterium disproportionation between mica and alteration clay (3f Huston & Gutzman 2023 & refs) would lower the measured δD of the mica.

Paleoelevation estimates are more complex than lab data: air humidity, evapo-condensation, air temperature-altitude gradient, monsoon seasonality, and snowmelt-vs-rain origin of the water all have effects of several tens ‰ and make the response function non-linear (3c,e Gonfiantini et al. 2001 Voss et al. 2020). Despite uncertainties, paleoaltimetry of the Nepal Himalaya in the Miocene (4a Garzione et al. 2000) and Tibet in the Eocene (4b Rowley & Currie 2006) agrees with Zanskar being about as high as the present day since the Late Oligocene.

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[2] Stahr 2013 PhD thesis, Virginia Tech; Webster &al 2018 Abstr, 33rd HKT, Lausanne; Williams &al 2007 Annu Rev Earth Planet Sci 35, 137–175; Villa et al 2023 J Metam Geol 41, 401-423

[3] Suzuoki & Epstein 1976 Geochim Cosmochim Acta 40, 1229-1240; Graham 1981 Contrib Min Pet 76, 216-228; Gonfiantini et al. 2001 Chem Geol 181, 147–167; Ingebritsen & Manning 2010 Geofluids 10, 193-205; Voss et al. 2020 J Hydrol 586, 124802; Huston & Gutzman 2023 Isotopes in Economic Geology, Springer

[4] Garzione et al. 2000 Earth Planet Sci Lett 183, 215-229; Rowley & Currie 2006 Nature 439, 677-681

The Stratigraphic Record of Eastern Tethys Closure and Himalayan Uplift in Pakistan

Wadood B.*[1]

[1]Department of Geology, University of Swabi, Anbar-Swabi, 23561, KPK, Pakistan

Corresponding author email: bilalwadood@uoswabi.edu.pk

Keywords: Himalayan foreland basin, eastern Tethys, provenance, Cenozoic tectonics, Pakistan.

The closure of the eastern Tethys and the ensuing India–Eurasia collision during the Paleogene initiated one of the most significant orogenic events in Earth's history, the rise of the Himalayas. Northern Pakistan occupies a key position along this convergent margin, preserving a rich sedimentary archive that chronicles the tectono-sedimentary evolution of the Himalayan foreland basin system. This study integrates biostratigraphic, sedimentological, stratigraphic, and provenance data from key Cenozoic successions in the Potwar Plateau, Kohat Basin, and Hazara-Kashmir region to decipher the depositional response to Himalayan uplift. The transition from shallow marine to fluvio-deltaic and alluvial facies reflects the progressive retreat of the Tethyan seaway and the establishment of a flexural foreland basin. Stratigraphic discontinuities, coarsening-upward sequences, and shifts in paleocurrent directions point to episodic uplift and intensifying erosion of the nascent Himalayan hinterland. Petrographic and heavy mineral analyses, supported by published detrital zircon data, indicate a diachronous influx of orogen-derived detritus, tracing the unroofing history of Higher and Lesser Himalayan sources. These changes are temporally linked to major regional tectonic phases, including mid-Miocene exhumation pulses and thrust propagation. By reconstructing the sedimentary record of Himalayan orogenesis in Pakistan, this work provides a high-resolution view of the feedbacks between tectonics, erosion, and basin development in a classic collisional setting. The findings contribute to broader understanding of foreland basin evolution and sediment routing in response to continental-scale plate convergence.

Low total REE zircon formed in equilibrium with hornblende in granulitized eclogites: Implications for exhumation rates

Wang J-M.*[1], Rubatto D.[2,3], Lanari P.[3,2], Tian Y.-L.[1], Chen Y.[1] & Fu-Yuan Wu F.-Y.[1]

[1]State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, 100029 Beijing, China. [2] Institute of Geological Sciences, University of Bern, Baltzerstrasse 3, CH-3012, Switzerland. [3] Institute of Earth Sciences, University of Lausanne, Géopolis, CH-1015, Lausanne, Switzerland

Corresponding author email: wangjiamin@mail.iggcas.ac.cn

Keywords: Zircon; Eclogite; Amphibole.

Exhumation rates of high-pressure rocks are paramount in determining plate tectonic processes, which requires absolute chronology of metamorphic stages. U-Pb geochronology of zircon and other accessory minerals has proven successful in dating different metamorphic stages, thus constraining geological rates. A common strategy to link U-Pb ages to metamorphic stages uses rare earth element (REE) patterns in the dated minerals. In this study, the changes in the REE composition of accessory and rock-forming minerals in response to changing assemblages have been investigated in granulitized eclogites and gneisses from the Ama Drime Massif, central Himalaya. Phase equilibrium modelling shows that the eclogite-facies assemblage formed at 660–720°C and 1.6–1.9 GPa (M1), was overprinted at high-pressure granulite-facies (M2) and then ultra-high temperature conditions of >900 °C and 0.8–1.1 GPa (M3) and finally re-equilibrated at conditions of 780–810 °C and 0.8–1.0 GPa (M4). In the countryrock orthogneisses, monazite records partial resetting during granulite-facies overprinting at 26–19 Ma and melt crystallisation at 16–13 Ma, supported by textures, mineral inclusions and trace elements. In the associated granulitized eclogites, zircon records only granulite/amphibolite facies overprinting at ~14 Ma, and titanite and rutile record cooling to 580–630 °C at 12.5–9 Ma. Granulite/amphibolite facies zircon has a low total REE relative to the protolith zircon, primarily due to the growth of REE-rich hornblende (total REE 80–260 μg/g), which removed 67–92% of the REE from the system. The low total REE of granulite/amphibolite facies zircon is comparable to the flat HREE reported for garnet-rich eclogite-facies zircon, and distinguishing these zircon types requires quantitative mineral volume estimates and other criteria. These findings may imply slower exhumation rates for some eclogite-facies terranes, such as the Tso Morari Himalaya and Papua New Guinea, than previously reported.

Wang, J.-M. et al.(2024) - Low total REE zircon formed in equilibrium with hornblende in granulitized eclogites: Implications for exhumation rates. Earth and Planetary Science Letters 648, 119084, https://doi.org/10.1016/j.epsl.2024.119084.

Constraints on the timing of the Great Counter-thrust from low-temperature thermochronology in the eastern Himalaya

Wei J.[1], Wang A.*[1], Grujic D.*[2] & Wang G.[1]

[1]Hubei Key Laboratory of Critical Zone Evolution, School of Earth Sciences, China University of Geosciences.[2]Department of Earth Sciences, Dalhousie University.

Corresponding author email: anwang@hotmail.com (AnnWang), dgrujic@dal.ca (Djordje Grujic)

Keywords: Himalaya, Great Counter thrust, low-temperature thermochronology.

The Great Counter thrust (GCT), as the northern boundary structure of the Himalaya, plays a critical yet poorly understood role in the Himalayan orogenic evolution(e.g. Beaumont et al., 2001; Webb et al., 2007). Determining the timing of the GCT activity is a key to understanding its dynamic mechanism. Field investigations in the eastern Himalaya reveal that the GCT is a south-dipping brittle thrust system with top-to-the-north sense, which separates the Tethyan Himalayan sequence (THS), ophiolitic mélange, Oligocene-Miocene Kailas formation, and Gangdese batholith from south to north.

Contrasting exhumation patterns between the hanging wall and footwall of the GCT can provide critical constraints on the timing of its activity. Here, we report new low-temperature thermochronological data from 10 samples of the THS in the hanging wall and 3 samples from the Gangdese batholith in the footwall, employing zircon and apatite fission track and apatite (U-Th)/He dating. Combined with the QTQt thermal history modelling, our results reveal that the THS underwent two phases of rapid exhumation during the early Miocene (~23-16 Ma) and the late Miocene (~10-8 Ma). In contrast, the Gangdese batholith rocks experienced reheating from ~23 Ma until 15 Ma, followed by rapid exhumation at ~10 Ma.

The early Miocene reheating of the footwall rocks was possibly caused by GCT-related loading, coinciding with the rapid exhumation of rocks in the hanging wall. This synchronicity suggests that the GCT was active during ~23-16 Ma. In contrast, the rapid exhumation during ~10-8 Ma affected both sides of the GCT, implying a late Miocene regional event in southern Tibet, which may have been driven by either enhanced incision by the Yarlung River or the initiation of south-north trending rifting.

Beaumont C. et al. (2001) - Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. Nature, 414(6865), 738–742, https://doi.org/10.1038/414738a.

Webb A. et al. (2007) - The leading edge of the Greater Himalayan Crystalline complex revealed in the NW Indian Himalaya: Implications for the evolution of the Himalayan orogen. Geology, 35(10), 955–958, https://doi.org/10.1130/G23931A.1].

Underthrusting Indian Continent Explains Late Eocene to Oligocene Exhumation Difference between the Western and Central Tibetan Plateau

Xue W.[1, 2], Najman Y.[3], Hu X.*[2], Persano C.[4], Stuart F.[5], Wildman M.[4], Tang G.[1], Gong L.[1] & Wang Q.[1]

[1] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS), Guangzhou, China. [2] School of Earth Sciences and Engineering, Nanjing University, Nanjing, China. [3] Lancaster Environment Centre, Lancaster University, Lancaster, UK. [4] School of Geographical and Earth Sciences, College of Science and Engineering, University of Glasgow, Glasgow, UK. [5] Scottish Universities Environmental Research Centre, East Kilbride, UK

Corresponding author email: huxm@nju.edu.cn

Keywords: Tibetan Plateau, thermochronology, exhumation.

The role that underthrusting of continental material has played in the development of high-elevation plateaux is much debated.The Himalayan-Tibetan orogen is a key research area that is closely associated with the underthrusting of the Indian continent beneath Asia. Geophysical studies suggest that the regional extent of the underthrusting Indian crust beneath the Tibetan Plateau shows an east-west variation in the modern-day setting (e.g. Klemperer et al., 2022); the leading edge of the Indian crust extends to the north of the Jinshajiang suture in the west but only south of the Bangong-Nujiang suture in the east. However, whether the differential underthrusting has exerted a heterogeneous impact on the evolution of the Himalayan-Tibetan orogenic belt remains uncertain, and resolving this will enhance our understanding of the links between deep dynamic processes and the evolution of large orogenic belts on Earth.

Through comprehensive analysis of published and new multi-technique mid- to low-temperature thermochronological data and exhumation history modeling, we show distinct differences in exhumation history of the central and western regions of the Tibetan Plateau during the Cenozoic (45–20 Ma). The central Tibetan Plateau has experienced slow exhumation since ~45 Ma continuing to the present. The western Tibetan Plateau underwent moderate-to-rapid exhumation at 45-20 Ma with rates exceeding present-day values by an order of magnitude. We exclude major large strike-slip faults and climatic forcing as primary controls on these regional exhumation differences. Using rock cooling ages and eruption age of (ultra) potassic lavas as proxies for early exhumation and continental underthrusting, respectively, and combining them with geophysical imaging data, we propose that the divergent exhumation patterns during the period of 45-20 Ma are attributed to differential underthrusting of the Indian crust along its strike.This finding effectively explains the disparities in modern drainage systems, topography, and crustal thickness between the western and central Tibetan Plateau, while also contributing novel insights into the influence of continental underthrusting on the formation of high-elevation plateaus.

Klemperer S. et al. (2022) - Limited underthrusting of India below Tibet: $^3He/^4He$ analysis of thermal springs locates the mantle suture in continental collision. Proceedings of the National Academy of Sciences, 119, e2113877119, https://doi.org/10.1073/pnas.2113877119.

Petrogenesis of Crustal Rocks from the Northern Luqu Ophiolite within the Yarlung-Tsangpo Suture Zone, Southern Tibet and Implications for the Neo-Tethys Evolution

Zhang C.*[1,3], Liu C.-Z.[1,2,3], Liu T.[1,3], Ji W.-B.[4], Zhang Z.-Y.[1] & Wu F.-Y.[1,3]

[1]State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China. [2]Laoshan Laboratory, Qingdao 266237, China. [3]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China. [4]Department of Geology, Northwest University, Xi'An 710069, China

Corresponding author email: zhangchang@mail.iggcas.ac.cn

Keywords: Yarlung-Tsangpo Ophiolites; Dolerite; Basalt; Leucogabbro; Gabbro Melting, Neo-Tethys.

Ophiolites provide insights into the lithosphere of vanished oceans and serve as key archives for reconstructing their evolutionary histories. In southern Tibet, ophiolites exposed within the Yarlung-Tsangpo Suture Zone are interpreted as remnants of the Cretaceous Neo-Tethyan lithosphere. However, origin and source characteristics of these lithospheric remnants remain controversial. This study presents new geochemical data from crustal rocks (dolerites, basalts, and leugogabbros) within the Luqu section of the Xigaze ophiolites. The northern Luqu section preserves intact crustal sequence dominated by doleritic dykes, sill complexes, and massive to pillowed lavas. Notably, minor leucogabbro intrusions within the dolerites were identified. Geochemical analyses reveal that the dolerites and basalts exhibit flat to moderately depleted LREE patterns, consistent with derivation from a depleted mantle source. The leucogabbros yield crystallization ages (132 –125 Ma) overlapping with those of the mafic dolerites (~125 Ma) and other YTSZ crustal sequences (134–120 Ma). Mineralogically, they contain high-Mg# clinopyroxene, high-An plagioclase, and amphibole, suggesting hydrous parental melts. The leucogabbro display distinct isotopic compositions — unradiogenic Sr-Hf coupled with enriched Nd. Petrological and geochemical evidence indicates these leucogabbros originated via partial melting of lower crustal gabbros, with contributions from enriched components within their sources. Gabbro solidus was likely lowered by infiltration of seawater-derived hydrothermal fluids, a process facilitated by detachment faults in ultraslow-spreading settings. These faults enable seawater penetration, enhancing fluid-rock interaction and melt hybridization. Our findings suggest that mafic rocks and leucogabbros in the Xigaze ophiolites were sourced from distinct mantle domains within an ultraslow-spreading ridge.

Pervasive Early Eocene Gangdese volcanic rocks, southern Tibet: implication for Early Eocene Climatic Optimum (EECO)

Zhang S.H*[1], Ji W.Q.[1], Chen H.B.[1,2] & Wu F.Y.[1,2]

[1]State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China. [2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, 100049, China.

Corresponding author email: zhangshaohua@mail.iggcas.ac.cn

Keywords: EECO, Linzizong, Decarbonation, Driving mechanism.

The Early Eocene Climatic Optimum (EECO) between 52-50 Ma (Zachos et al., 2001), had temperatures ca.9-12°C higher than the present day with consequences for the Cenozoic carbon cycle and global climate. However, there is still controversy regarding deciphering the main driving mechanism of the EECO, with Mid-Oceanic Ridges (MORs), Large Igneous Provinces (LIPs), Continental rifts, silicate weathering, and continental arc volcanism and its associated metamorphic decarbonation all considered as possible drivers. A recent review paper suggested that pervasive Early Eocene Linzizong volcanic rocks in the Gangdese arc, southern Tibet were a key driving mechanism for the EECO (Zhang et al., 2022).

In this study, we conducted detailed fieldwork on the Gangdese volcanic rocks distributed nearly 1200 km from east to west in Tibet, and undertook geochronological and geochemical analyses out of the samples. In combination with geological materials (reports and maps) and previously published data, the spatial and temporal distribution of the Early Eocene Gangdese volcanic rocks were reconstructed.. The results showed that the Gangdese volcanic rocks erupted at ca.52-50 Ma, consistent with proposed timing of the EECO and that volcanism was distributed across Tibet with an area and volume of 16572 km^2 and 129264 km^3, respectively. Subsequently, the carbon flux of the Early Eocene Gangdese volcanic rocks was determined by two different methods, the results indicate that the carbon flux can be up to 28.1 TgC/yr, which is a minimum estimate (Wong et al., 2019). Recently, these Early Eocene volcanic rocks were discovered to extend from Tibet to Sumatra (> 6000 km), Southeast Asia (Zhang et al., 2019). As a result, the estimated decarbonation C flux is up to 81-112.4 Tg C/yr, which is comparable with the C flux during the Late Cretaceous Thermal Maximum (Lee et al., 2013; Jiang and Lee, 2019). In summary, a compilation of our new and published data, combined with quantitative calculations show a potential link between pervasive Early Eocene Gangdese volcanic rocks and the EECO. Particularly if the Early Eocene volcanic rocks extend to Sumatra.

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Spatial distribution and regional tectonic significance of the newly discovered Kalawenguquan fault in the interior of the Tian Shan Mountain Range, Western China

Zhongtai H.*[1,2], Xingao L.[1,2,3], Zhikun R.[1,2], Linlin L.[3], Lei W.[1,2], Haomin J.[1,2], Xiaoxiao Z.[1,2], Long G.[1,2] & Liangliang W.[4]

[1]State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration. [2]KeyLaboratory of Seismic and Volcanic Hazards, Institute of Geology, China Earthquake Administration. [3]National Institute of Natural Hazards, Ministry of Emergency Management of China. [4]Institute of Disaster Prevention.

Corresponding author email: hzt@ies.ac.cn

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Quantifying the geometrical and kinematic aspects of faults within the Tian Shan is crucial for investigating the tectonic deformation patterns in the region. Through remote sensing image analysis using GaoFen-7 (GF-7) data and field geological surveys, we determined the geometric distribution and fault properties of the Kalawenguquan fault. The newly discovered Kalawenguquan fault spans more than 400 km and mainly strikes in the NEE direction, with some localized segments in the NE direction. The fault plane dips southward at angles ranging from 55° to 85°. The Kalawenguquan fault is a recently discovered Holocene active fault in the Tian Shan and is a thrust and left-lateral strike-slip fault. Based on geological survey findings and sediment dating data from the late Quaternary, the Kalawenguquan fault has a vertical sliding rate of approximately 0.41 mm/a. The left-lateral strike-slip rate was calculated to be 0.6-1.4 mm/a. We detected that at least two paleoseismic events occurred on the fault since 5.4 ± 0.4 ka. In the range of 41°-45° latitude, 45% of the crustal shortening in the Tian Shan is absorbed by the internal structure.

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