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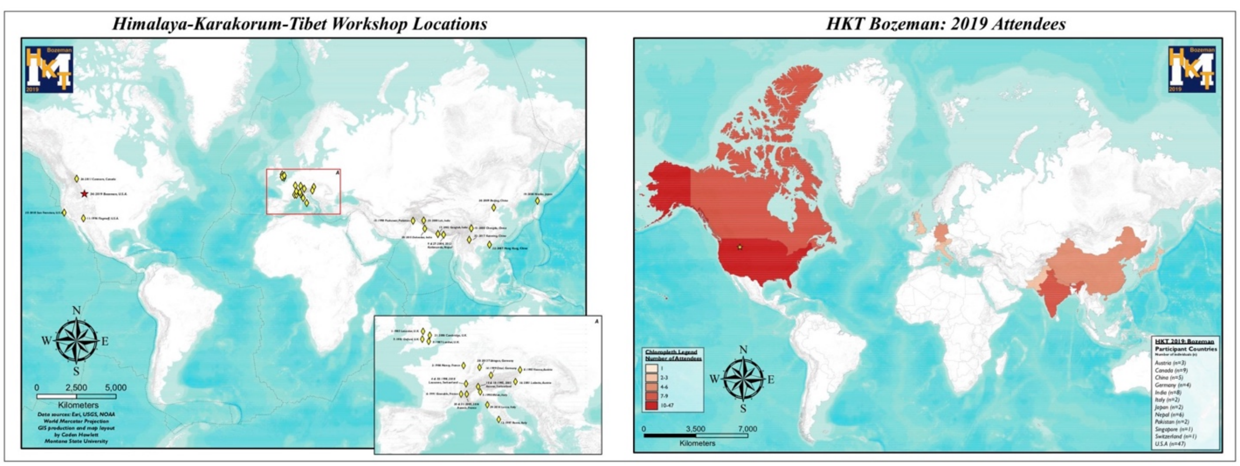

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New precise dating of the India-Asia collision in the Tibetan Himalaya at 61 Ma

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The timing of India-Asia collision onset, essential to model the topographic evolution of the Himalayan-Tibetan orogen and its environmental and paleogeographic effects, has been widely investigated through multidisciplinary approaches. The abrupt change of sediment provenance along the edge of the Indian continental margin was proved to be a most effective method to constrain collision onset robustly as 60-55 Ma.

Here we present integrated stratigraphic, provenance and geochronological data from the newly discovered Mubala section in Tibetan Himalaya, which preserves a continuous turbiditic and pelagic biogenic record of deep-marine setting deposited onto the northernmost Indian passive margin. Sandstone compositions, detrital zircon U-Pb age and Hf isotope signatures integrated with detrital Cr-spinel geochemistry, document a sediment provenance reversal from India to Asia, bracketed between ~ 62.7 Ma and 61.0± 0.3 Ma by detrital zircon U-Pb ages and zircon U-Pb SIMS ages from a tuffaceous layer ~30 m above the provenance reversal.

This newly obtained date constrains collision onset precisely as early Selandian in this locality. Together with the well-studied Sangdanlin section, the initial India-Asia collision is constrained at ~61 Ma in Tibetan Himalaya.

On the diversity of paleomagnetic results used for Greater India reconstruction

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Using paleomagnetic results we can quantify the former extent of the Indian and Asian continental margins, which in turn allows to date the continental collision of both plates and contributes to decipher the dynamic evolution of crustal shortening. Within the last decade numerous new Cretaceous to Eocene data from the Lhasa Terrane consolidated the paleomagnetic reconstruction of the southern Asian Plate margin pinpointing it at ~10° south of its present position. Much less paleomagnetic data are available from the Indian Plate margin. Results from the Late Cretaceous Zongshan Fm and in particular the Paleocene Zongpu Fm in the Tethyan Himalaya (TH) near Gamba in southern Tibet (Patzelt et al., 1996; Yi et al., 2011) suggested an ~1500-2000 km extended northern Indian Plate margin, the so-called 'Greater India' (GI). These results were frequently used as a constraint for India-Asia collision models. However, Huang et al. (2017) questioned the validity of these data because of possible remagnetization. The debate about the Gamba data and the remarkable discrepancy of recent Early Cretaceous results that range from no GI (Yang et al., 2015) to >2500 km GI extent (Meng et al., 2019) require critical assessment of how the existing paleomagnetic results should be rated and how we can achieve greater reliability. In this talk we will critically review both the Paleocene and Early Cretaceous data.

Van Hinsbergen et al. (2012) interpreted paleolatitudes derived from Early Cretaceous (minor GI extent) and Paleocene (~2000 km GI extent) paleomagnetic data as an indication for an oceanic basin that formed between the Indian Plate and the so-called 'Tethyan Himalaya Terrane', leading to a two-stage collision. We will discuss the validity of this hypothesis and reject a paleomagnetic "prove" as long as the considerable uncertainty of Early Cretaceous results is not explained. Due to the strong anticlockwise rotation of the Indian Plate since Early Cretaceous and the unknown direction of intracontinental shortening, the significance of Early Cretaceous data is limited. Even more disturbing is the large discrepancy of mean directions derived from the same unit (Lakang volcanics) in the TH of SE-Tibet. In fact, there is large potential to improve the Early Cretaceous paleomagnetic data base in the TH as this stratigraphic unit is available at many places along the TH.

The possibility to obtain paleomagnetic results from Paleocene is limited due to only three known locations in the TH where these younger units are preserved. While numerous studies in Tingri area were largely unsuccessful, the results from Gamba area are questioned. The latter can be hardly improved by additional sampling, but there might be possibilities to better explain the origin of the magnetic remanence. There are indications that remanence formation is not significantly younger than the rock age. Our new results from Zanskar area in the NW Himalaya (Dannemann et al., 2019) reveal a synfolding remanence in the Dibling Limestone, the Paleocene equivalent of the Zongpu Fm at Gamba. The resulting paleolatitude of remanence formation is at around 10-12°N and sets a northern limit for the initial folding in the western TH. Ongoing rock magnetic studies and microscopic observations might deliver further information about possible similarities of the remanence origin in the Zanskar and Gamba areas, and thus could also help to better re-interpret the Gamba results.

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Contrasting styles of India-Asia intracontinental subduction and orogenesis from the Hindu Kush and Pamir to the central Himalayan-Tibetan orogen

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The India-Asian collision zone contains marked differences in crustal structure from east to west along the orogen. The central part of the orogen is characterized by the wide Tibetan plateau of thickened crust as far north as the Tarim basin, and a comparatively narrow Himalaya. Further west in the Pamir structural evidence suggests that the plateau (here the Pamir plateau) has almost completely overthrust[1] an initially wide 'Alai terrane' (which we interpret to be, together with the Tajik basin, a lateral equivalent to the Tarim basin in the central part of the orogen). This leaves only the narrow Alai valley exposed at the surface. Finally, in the Hindu Kush, the westernmost part of the orogen, the Tajik basin remains relatively undeformed, and notably the width of the region of deformed Indian crust is small compared with the Himalayan equivalents to the east.

Tomographic images of the mantle under India and Asia, also show marked differences from east to west along strike of the orogen. In the central part of the orogen (~90°E), these images reveal thickened lumps of inferred continental lithospheric mantle (CLM) under the Lhasa terrane and India[2,3]. Further west, Indian CLM is inferred to have underthrust the plateau to the Bangong suture[2,3], and there are no obvious CLM lumps. Under the Pamir, the Indian CLM is inferred to have underthrust north to beneath the Alai Valley, where a south dipping slab of inferred Asian CLM is imaged[3,4]. Finally, under the Hindu Kush, the Indian CLM is inferred to be steeply subducting toward the north[4].

We use 2D thermo-mechanical mantle-scale geodynamical models to show that the differences in the crustal structures along the orogen and the differences in the inferred state of the mantle along the system are linked. In particular, we show that differences in the initial geometry of the accreted terranes between the Pamir and the central orogen can lead to contrasting styles of Asian CLM delamination, and subsequent Indian CLM underthrusting. Specifically, our models show that under the central orogen (where the terranes were initially wider) the underthrusting Indian CLM entrains with the CLM's of the northern Tibetan terranes (Songpan Ganze and Kunlun) leading to delamination and rollback of the composite Indian-Asian CLM, whereas in the narrower Pamir section, the Indian CLM completely underthrusts Asian terranes, including the Alai terrane CLM, as far north as the Tien Shan. In the central orogen, Indian/Asian CLM delamination and roll-back leads to cessation of Indian underthrusting and development of the thickened lump regions of CLM under the Lhasa terrane, whereas under the Pamir, Indian underthrusting eventually leads to removal of the Alai terrane CLM by south dipping subduction/delamination, in agreement with the tomography. Furthermore, cessation of Indian underthrusting under the central part of the orogen leaves the Tarim basin and its CLM relatively intact, whereas under the Pamir, Alai terrane delamination leads to nearly complete overthrusting of the Alai crust by the Pamir. Finally, for the westernmost part of the system, under the Hindu Kush, our models show that thinner 'fringe' Indian crust, comprising the western margin of India[4], is more likely to subduct (in agreement with the tomography) than underthrust, leaving the Tajik basin relatively intact, in keeping with its inferred Tarim basin equivalent further east.

Taken together these model results can be interpreted to show that the major differences in the style of orogenesis along the system can potentially be explained rather simply by relatively small changes in the initial geometry of the Asian terranes and the thickness of the Indian crust.

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Structural Geology of the Shillong Plateau, Northeastern India: A Laramide-Style, Basement-Involved Uplift in the Himalayan Foreland

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The India-Asia collision has resulted in remarkable structural uniformity along the Himalayan front, with the exception of the east and west ends of the Himalayan arc where huge topographic and structural recesses occur. The focus of this project is the Shillong Plateau in eastern Meghalaya State, northeastern India. The Shillong Plateau lies south of the frontal thrust system of the eastern Himalaya and west of the Indo-Burma fold-and-thrust belt, at the southern "mouth" of the eastern Himalayan recess (Assam/Namcha Barwa recess). This broad, basement-cored uplift occupies a position in the foreland between two impinging tectonic domains, very similar to those found in the impingement zone between Sevier and Laramide uplifts in the Rocky Mountains, USA. Is the structural geometry of the Shillong Plateau similar to well-studied Laramide uplifts, and how does it fit into the complex tectonic mosaic of the eastern Himalayan recess? To answer these questions, we have used diverse data sets that include lineaments, regional GPS, earthquake seismology, balanced cross-sections, heat flow and crustal rheology models, elevation, and geomorphology to inform our interpretation of the structural geometry and kinematics of motion within and around the plateau. Our "best fit" structural model for the Shillong Plateau is a ramp-supported, fault-propagation uplift, similar to Laramide uplifts like the ancestral Bridger Range in Montana. Regional patterns of contemporary deformation suggest a component of transpressional shortening between the Himalayan front to the north and the Indo-Burma Ranges to the east that led to the uplift of the Shillong Plateau.

Quantifying Stratigraphic Correlations and Provenance within the Ancestral Brahmaputra Delta, a Record of Eastern Himalayan Exhumation and the Onset of the Indian Monsoon

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The geologic record of continental collisions is preserved in peripheral foreland basins. As a collision progresses, peripheral basins are increasingly deformed, incorporated into the active orogen and recycled – providing a window into the long-term evolution of the orogen. The eastern margin of the Himalayan foreland has been significantly shortened from the combination of deformation along the active Himalayan front and flanking Indo-Burman ranges (IBR). Sedimentary rocks within the IBR record the late Cenozoic growth and exhumation of the eastern Himalayas and progradation of the ancestral Brahmaputra delta. Over the past decade, international studies of the rich stratigraphic record of the IBR has renewed interest in regional stratigraphic correlation of IBR sedimentary units to the more proximal Himalayan foreland sequences (e.g. Siwalik Group). We present new lithofacies descriptions, high-n U-Pb detrital zircon analyses (dzUPb), and maximum depositional ages constrained by detrital zircon and apatite fission track (dZFT, dAFT) analyses from Oligocene–Pliocene sediment within the IBR. To place the IBR strata in a regional tectonostratigraphic context, we use statistical tests (Saylor and Sundell, 2016) to correlate dzUPb age-distributions from IBR strata with previously published dzUPb data from equivalent age deposits in the Siwalik Group of the eastern Himalaya as well as with the modern Ganges and Brahmaputra river deposits. We present a composite tectono-stratigraphic map of the eastern Himalaya and IBR illustrating these correlations and further characterize the proportions of Himalayan source terranes present in dzUPb analyses from IBR strata using an inverse Monte Carlo unmixing model (Sundell and Saylor, 2017).

Results indicate that dzUPb age-distributions from fluvial, large braid-belt facies of the Tipam Group in the IBR are a close match to similar fluvial facies of the upper part of the late Miocene–Pliocene Middle Siwalik Group. Tipam Group dzUPb age-distributions also show a remarkable resemblance to modern Brahmaputra river deposits, confirming that it indeed represents the paleo-Brahmaputra braid-belt during the late Miocene–Pliocene. Shallow marine and intertidal deposits (IBR Surma Group) show dzUPb age-distributions that match those from the middle-Miocene Lower Siwalik and late Miocene lower part of the Middle Siwalik. Oligocene to early Miocene IBR deposits (Barail Group) do not share any resemblance in lithofacies or dzUPb age distributions to the Siwalik Group. However, their dzUPb age-distribution is similar to that of sediment from the modern Ganges river system. Thus, we interpret that the Barail group records Himalayan erosion prior to the middle Miocene development of a Brahmaputra-scale drainage in the eastern Himalaya. Results from dzUPb unmixing models show systematic trends in the proportions of Himalayan source terranes preserved in IBR strata. Both Lhasa terrane and Transhimalayan arc grains are present in all of the IBR formations, suggesting that transverse rivers have fed sediment from the Yarlung-Tsangpo suture zone to the IBR and paleo-Brahmaputra delta since the Oligocene. The proportion of Transhimalayan arc sediment increases up section from ~3% (Barail Group) to ~30% (Tipam Group). The proportion of Tethyan (THS) and Greater Himalayan (GHS) sediment generally decreases up-section from ~15-70% (Barail Group) to <10% (Tipam Group). We interpret that the middle Miocene stratigraphic transition from the Barail to the Surma group (~12 Ma) and the corresponding increase in the proportion of Transhimalayan grains at the expense of THS and GHS grains records headward expansion of the paleo-Brahmaputra watershed commensurate with increased discharge following a middle Miocene onset of the Indian Monsoon.

Detrital zircon U-Pb provenance of the Indus Group, Ladakh, NW India: Implications for the timing of India-Asia collision and early orogen processes

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The timing of India-Asia collision is greatly debated and knowing it is critical to elucidate early orogenic processes. In this study, we present 1225 new detrital zircon U-Pb ages to determine the provenance and timing of deposition of key Indus Group formations and discuss their implications for the timing of India-Asia collision. Detrital zircon U-Pb age spectra of the continental Indus Group in the India-Asia collision zone of northwest India, just north of the Tethyan Himalaya, suggest a hybrid India-Asia provenance. The southernmost magmatic provinces of Asia – the Ladakh, Karakoram and the Gangdese blocks provide the Mesozoic-Cenozoic zircons while the Tethyan Himalaya contributes the Precambrian zircons. Maximum depositional ages determined for four major Indus Group sequences – the Nurla, Hemis, Basgo, and Temesgam Formations, combined with previous biostratigraphic studies from the region, confirm that bulk of the syn-orogenic deposition in the Indus basin occurred between Early Eocene-Late Oligocene. The oldest Nurla Formation records the first arrival of Indian zircons on the Asian plate thereby indicating topographic buildup along the subducting Indian plate, and completion of India-Asia suturing in the Early Eocene. We also discuss the constraints provided by our U-Pb data on the timing of Tethyan Himalaya uplift and initiation of the Indus River.

Seismic Response of the Basin-fill Sediments and RC-buildings along a S-N transect in the Kathmandu Valley (Nepal)

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Severe ground shaking, for about a minute relating to 25th April 2015 Nepal-Gorkha earthquake was enough to cause heavy destruction in the Kathmandu valley. However, damages in the valley and adjacent areas were much less severe than was expected by an earthquake of this magnitude and rupture directivity. Kathmandu Valley being filled with fluvio-lacustrine sediments, nature and, the thickness of which vary both laterally and vertically, these variations largely affect the soil fundamental frequencies. Still, the role of the valley infill and the responses of the buildings are poorly understood. This study is intended toward a clear understanding between the subsurface geology, and its interaction with the overlying building structure in the Kathmandu valley. Ambient noise measurements have been carried out at 39 soil sites and in 28 RC-buildings along a south to north transect in the valley. Recordings were performed for 15 minutes at each site using a Lennartz LE-3D-5s seismometer connected to a City Shark II recorder. H/V spectral curves analyzed in 0.20 (Lennartz limit) – 25 Hz frequency band for the soil sites and in 1 – 25 Hz range for RC-buildings show no major possibilities of resonance effect in the valley. Few soil sites next to the river channels in the northern and southern part of the valley exhibit double resonance frequencies. A comparison has been made between experimental building fundamental frequency and theoretical frequency obtained from the Nepal Building Code (NBC105). The height of the building is identified as a major factor governing the fundamental period, and a linear relation has been established between the height of the building and its fundamental period. An outcome of this research is a further step towards the understanding of the seismic behavior of the valley sediments and the RC-buildings.

Past and Future Great Earthquakes in the Himalaya

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The current convergence rate between India and southern Tibet is sufficient to renew the occurrence of a great (Mw=8) earthquake in every 180-km-long segment of the Himalaya once per century. Since there are more than ten such segments, a great earthquake should occur somewhere in the Himalaya roughly once every ten years. The actual recurrence interval since 1500 AD averages one Mw>8 earthquake every125 years and none have occurred since 1950. Two decades of GPS measurements show that the ≈100-km-wide Himalayan décollement is locked to the Indian plate between the Main Frontal Thrust (MFT) and a region a little south of the Greater Himalaya, where elastic strain steadily accumulates between earthquakes. Thus we are now certain that creep processes cannot account for décollement slip. Moreover, major earthquakes, with magnitudes Mw≤7.8, such as those that occurred in 1803, 1833, 1905, 1947 and 2015 are also apparently unable to fully release this accumulating strain. The 2015 earthquake showed that the cumulative interseismic strain in non-MFT breaking earthquakes is merely shifted to the central décollement, where it acts as an ancestral reservoir to fuel future mega-quakes. Thus it has become increasingly clear that, for the Indian plate to descend beneath Tibet, the décollement must rupture in rare mega-quakes with magnitudes in the range 8.4<Mw<9.0. A review of the past five centuries of major earthquakes, when combined with the accumulating seismic slip deficit inferred from geodetic measurements, suggests that the current slip potential is presently equivalent to one 8.5<Mw<8.9 earthquake, or a combination of smaller earthquakes with similar moment release (e.g. seven 8<Mw<8.4). Although the locations of these future earthquakes can be fingered, and we know they are poised to go, we have few clues as to when they will occur. The paleoseismic history of Himalayan earthquakes is neither sufficiently long nor sufficiently precise to identify any helpful pattern in mega-quake recurrence. It would seem that a clearer view of future great earthquakes will almost certainly depend on the development of a ten millennia paleoseismic history. This is unlikely to be forged solely from the history of surface ruptures of the Main Himalayan Frontal thrusts, because some (perhaps many) great earthquakes must underpass the MFT to permit the southward advance of the Himalaya. Advances in quantifying earthquake magnitudes causal to seismites in Himalayan lakes, and the exhumation of the history of clastic dikes associated with liquefaction in the Ganges and Brahmaputra plains will contribute important supplemental constraints on constructing this crucial history of hazards. For example, the past two centuries of Himalayan earthquakes demonstrate that only for earthquakes with magnitudes exceeding Mw8.2 do widespread accelerations exceed Mercalli Intensity VIII in the sedimentary deposits fronting the Himalaya, and that the passage of these accelerations in 1897, 1934 and 1950 were interred in the sedimentary record as catastrophic lateral-spreading and liquefaction.

Tibetan and Himalayan Signals in the Detrital Zircon U-Pb Record of the Neogene and Quaternary Bengal Fan

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The Himalayan-sourced Ganges-Brahmaputra river system and the deep-sea Bengal Fan represent Earth's largest sediment-dispersal system. We have developed a detrital-zircon (DZ) U-Pb provenance record from the Bengal Fan, from cores collected during IODP 354 located 1350 km basinward of the shelf margin. This dataset consists of 25 DZ samples from Early Miocene to Middle Pleistocene turbidite sand, as well as samples from the modern Ganges and Brahmaputra Rivers, which serve as benchmarks against which the older record can be compared. We have also collected an additional 25 samples from the Plio-Pleistocene part of the record, which are not yet analyzed. Here we present primary published results, as well as some speculation of possible additional signals that are the subject of current research.

At the largest scale, after up to 2500 km of river transport, and 1350 km of transport in turbidity currents, the DZ record is interpreted to faithfully record the strong tectonic and climatic forcing associated with, and inherent to, the Ganges-Brahmaputra sediment-dispersal system. Our data also shows that signal transfer within this giant system is geologically rapid: the <10 Ma DZ U-Pb population in the fan records Plio-Pleistocene incision through, and exhumation of, the eastern Himalayan syntaxis. Zircons that crystalized ca. 5 Ma were exhumed, transported to, and deposited in the fan by ca. 2.5 Ma: most of the ~2.5 Myr lag time probably represents exhumation, and transport-related signal transfer was therefore geologically instantaneous. However, within this broader context, the DZ U-Pb record is biased towards glacial periods: for large rivers with broad shelves, delivery of sand to the deep sea is limited during interglacial sea-level highstands like that of the Holocene, and the sand-rich turbidite part of the record only accumulates during glacial periods when rivers extended across the shelf to connect with slope canyons in response to climate-forced sea-level fall. Moreover, only part of the Bengal Fan DZ record represents either the Ganges or the Brahmaputra, with most samples representing mixing of sediments from the two different systems: this mixing, or the lack thereof, represents autogenic avulsions on the delta plain that result in these two giant rivers delivering sediment separately to the shelf margin, or together as they do today. Hence, within the allogenic framework established by tectonic processes, the vigorous climatic system, and global climate-forced sea-level change, the record of sediment mixing or the lack thereof represents the fingerprint of autogenic processes on source-to-sink signal transfer.

We have identified more specific signals within the Plio-Pleistocene part of the DZ U-Pb record that are topics of ongoing investigation. First and foremost, present-day sediment transfer to the land-sea boundary is closely coupled to the monsoon. However, as noted above, the sand-rich turbidite record of the Bengal Fan is biased towards glacial periods, so monsoon signals may be significantly less relevant. We note, for example, that sandy turbidites of the Bengal Fan display the same DZ age populations and U-Pb age peaks that are present in modern river samples, but their proportions are significantly different: Pleistocene Bengal Fan data include (a) higher proportions of the <300 Ma population from Tibet, and (b) and lower proportions from the Lesser Himalaya Sequence and/or peninsular India. We speculate these differences reflect contrasts in the loci of sediment production in the modern interglacial climate with strong monsoon rains, vs. a glacial climate where erosion is closely coupled to higher-elevation cold-climate and glacial processes. Second, DZ U-Pb populations within the fan show a doubling of the <300 Ma population, which is derived mostly from the Gandese arc and its relatives in southern Tibet or the Indo-Burman Ranges. Do these increases represent: (a) increasing tectonically-driven Brahmaputra incision and integration with the Asian plate, (b) spatial changes in erosion patterns and fluxes due to the onset of Plio-Pleistocene glaciation, (c) lag times due to storage and flushing of sediment between Tibetan sources and the deep sea, (d) megafloods from drainage of Tibetan ice-dammed lakes, or (e) some combination of the above?

Analysis of shallow seismic waves to determine geotechnical site characterization in Kathmandu Valley

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The Kathmandu valley falls in one of the active collisional orogenic belt of the Himalayas that could cause strong earthquakes. The valley is an ancient lake deposit, measuring up to hundreds of meters of thick layers of soft soil with irregular layers of deposition that amplifies the resonant frequency of the earthquake spectrum and magnifies several times depending upon the intensity of shaking and characteristics of the sub soil. The devastating earthquake of April 25, 2015, followed by hundreds of aftershocks, killed around 9000 people and collapsed thousands of houses in the central Nepal. These earthquakes generated intense interest within the engineering and geological community due to reports of massive inhomogeneous patterns of ground failures and structural collapse in the Kathmandu valley. Given that a better understanding of the ground response to seismic waves provides the societies to prepare physically as well mentally to face large earthquakes, this work followed by a weeklong reconnaissance survey, was conducted to find out if the possible cause of destruction was due to soil deformation or structural defects during manufacturing. A frequency-based surface wave inversion method called multichannel analysis of surface waves (MASW) was used to create 2D surface-wave velocity models, geotechnical characterization and investigate the effect of lateral in-homogeneity on the propagation of the Rayleigh waves of near surface materials. Initially, data were processed and inversions of the shallow surface seismic waves were carried out to develop a shear wave velocity model. Compressional wave velocity (Vp) and shear wave velocity (Vs) were used to determine different geotechnical and elastic parameters for soil layers. These parameters are further employed to calculate allowable bearing capacity (q_a), elastic modulus (E), and the liquefaction susceptibility of soil. The result shows that the soil in the Kathmandu valley in the majority consists of clay, silt, sand or their mixtures with little or no gravel, and the ground water table depth ranges from less than a meter to more than 5 meters. It was found that during the period of the earthquake, the combined effects of low bearing capacity and low elastic modulus soil expanded its volume in the presence of water, ultimately reducing peak strength, and the allowable bearing capacity caused deformation. In some places, the soil layers within the shallow depth were found liquefied and lost the strength allowing the structures to fall. In the area where the soil had enough allowable bearing capacity, elastic modulus, and high depth of water table, the probable causes of collapse were due to structural defects or use of low quality construction material during building.

Seamount accretion and mélange formation in the Indus Suture Zone of Eastern Ladakh (NW Himalaya, India)

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Recent detailed geologic studies in Eastern Ladakh (Buchs and Epard, 2019; Buchs, 2019) between the Nidar Ophiolite in the Indus Suture Zone and the Tso Morari nappe belonging to the North Himalayan nappe stack has brought new data on the history and formation of the accretionary wedge related to the subduction of the Neotethys oceanic crust.

In Eastern Ladakh, evidences of a paleo-accretionary wedge are partly preserved in the Drakkarpo and Karzok-Ribil nappes. This paleo-accretionary wedge is formed during the northward subduction of the Neotethys oceanic crust from Early Cretaceous to Eocene. We propose a new definition for the Drakkarpo and Karzok-Ribil nappes and a paleogeographic kinematic reconstruction for the northern Indian passive margin and its transition to the Neotethys oceanic crust from Coniacian to Lutetian. The Drakkarpo nappe records traces of an accreted seamount with OIB-like alkaline volcanic rocks associated to thick volcanosedimentary deposits. The magmatic activity of the Drakkarpo oceanic island has been dated to Coniacian based on radiolarian-bearing chert interbedded in OIB-pillow lavas. The oceanic island migrated towards north as a seamount and was partly incorporated in the accretionary wedge above the subducting Neotethys oceanic crust during the Paleocene. Progressive subduction of the Indian continental margin triggered an uplift of the accretionary wedge and the formation of a piggy-back basin in the Ypresian time. This basin was progressively filled with rock fragments (from grain size to large boulders) generated from the gravitational collapse and erosion of the uplifted accretionary wedge to form a mélange. This sedimentary-type mélange contains also fragment of bioclastic limestones that have been dated from Early Ypresian (~55-51Ma) to Early Lutetian (~49-46 Ma) based on Larger Benthic Foraminifera. The Lutetian age represents the youngest marine sediments observed in the Indus Suture Zone.

The Karzok-Ribil nappe is made up also of formations related to a volcanic oceanic island and its associated volcanosedimentary series. This nappe is now included in the North Himalayan nappe stack and thrust on top of the Tso Morari and Tetraogal nappes.

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Oligocene to early Miocene mid-crustal detachments and strike-slip shear zones in the western Yunnan, SE Tibet

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It is generally believed that the extrusion of SE Tibet was bounded by the dextral Gaoligong and the sinistral Diancangshan-Ailaoshan-Red River strike-slip shear zones from the Oligocene to early Miocene. This study integrates structural analysis and geochronology in western Yunnan (China), southeast of the Tibetan plateau, where foliated pre-Oligocene basement rocks and Oligocene to early Miocene leucosomes are exposed. We found that Oligocene to Miocene flat-lying ductile shear zones in Tengchong and Baoshan-Simao blocks were kinematically related to steeply dipping strike-slip shear zones. N-S, NW-SE striking gneiss domes in Tengchong block and Baoshan-Simao block are cored by high-grade metamorphic rocks or pre-kinematic granite plutons. The gneiss domes in Tengchong block are bounded by top-to-NE detachments and dextral strike-slip shear zones, whereas the gneiss domes in Simao-Baoshan block are bounded by top-to-SE detachments and SE-trending sinistral strike-slip shear zones. Zircon U-Pb and $^{40}Ar/^{39}Ar$ ages demonstrate these flat-lying detachments and the strike-slip shear zones in the two blocks were mostly coeval (30 to 16 Ma) ductile deformation from amphibolites to green schist facies metamorphism. These indicate a contemporaneous oblique shearing at mid-crustal depth, causing the exhumation and extrusion of the Tengchong and Simao-Baoshan blocks.

key words: western Yunnan (China), ductile shear zones, Oligocene to Miocene, exhumation

Did the Central Anatolian Cankiri Basin form as a Result of an Oligocene-Miocene Rayleigh-Taylor instability?

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Recent advances describing the first-order geodynamic processes driving the development of orogenic plateaus have yet to be considered for Central Anatolia's Paleogene evolution. In 2018, we traveled to the Central Anatolian Cankiri Basin in order to re-evaluate the regions Paleogene paleogeography. The Cankiri Basin is an elliptical, greater than 2 km thick accumulation of poorly dated, Eocene – early Miocene accumulation of terrestrial rocks belonging to the Incik Formation. The terrestrial Incik Formation exhibits a typical unroofing sequence characterized by the up-section appearance of Jurassic zircons from the Central Pontides, late Cretaceous zircons from the accretionary wedge, and Eocene zircons from underlying volcanic rocks. Our preliminary results in the context of previous work indicate the Cankiri Basin transitioned from a forearc basin in the late Cretaceous to a foreland basin throughout Eocene times and finally to a hinterland basin in the Oligocene. Thick, intensely deformed evaporitic successions deposited in the Oligocene interfinger with the terrestrial Incik Formation and are beveled by a gently folded basin-wide angular unconformity, above which early-middle Miocene lacustrine rocks and subaerial basaltic lava flows are present. Based on these data, we hypothesize a thick, lithospheric welt formed beneath the Cankiri Basin in the Oligocene and foundered into the mantle by earliest Miocene times, indicating a ~10 Myr period of rapid subsidence followed by rapid uplift, erosion, and influx of intermediate-basic magmatism. If our hypothesis is correct, it implies that a high elevation, low relief, and internally drained plateau grew in north-central Anatolia as early as the Oligocene-Miocene Boundary (~23 Ma).

Crust Tilting and Exhumation of Gangdese Batholith Tracked by Bedrock Pressures

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In this study, newly obtained Al-in-hornblende emplacement pressures from Gangdese plutons along a ~E-W section (90^o-94^oE) immediately to the north of the Yarlung-Tsangpo suture are compiled together with the existing pluton emplacement and metamorphic pressures as well as their associated geochronologic information. The compilation reveals that the Gangdese Batholith (Lhasa-Niyingchi section) is titled. The western part of the section exposes crust of 2-4 kbars while the eastern part of the section exposes crust of 7-12 kbars. Such longitudinal trend of bedrock pressure is consistent with the bedrock geology in the study area. Greenschist-facies metamorphosed clastic-volcanic strata expose in the western part of the section while amphibolite to granulite-facies lower crustal rocks expose in the eastern part. Exhumation history of the Gangdese Batholith is constructed by binning adjacent pressure data with different ages. The results show that (1) During 100-70 Ma, the exhumation of the Gangdese upper crust is low (<0.1 km/Myr). Simple mass balance model suggests such low exhumation of the upper crust might reflect the balance between surface erosion (~0.3-0.6 km/Myr) and upper crust thickening of the same magnitude. Middle-lower crust at the same time experienced magmatic/tectonic burial due to the development of the continental arc. (2) During 50-25 Ma, the exhumation of the upper crust remains low (~0.2 km/Myr), which might reflect the southward shift of erosion front caused by Himalayan mountain building. The middle-lower crust at the same time experienced the second phase of burial due to the continent-continent collision. (3) Since 30 Ma, differential exhumation occurred along with the E-W profile. The western part still has a low average exhumation rate. Since ~10 Ma, the exhumation of the western part is minimal evidenced by the preservation of ~10-20 Ma copper porphyry deposits. The eastern part exhumed at an average rate of >1.5 km/Myr since 30 Ma. The fast exhumation of the eastern part is probably related to the fast surface erosion and/or slab dynamics at the Eastern Himalayan Syntaxis. It is suggested that the titling of the Gangdese Batholith is mainly achieved after 25-30 Ma. This study suggests that during the evolution of the Gangdese orogen, the upper and lower crust can behavior differently in term of exhumation and burial. The bedrock pressure-age data provide an alternative way to track regional exhumation and shed light on the surface erosion and crustal thickening in a magmatic orogen.

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

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The Cuonadong and the Yalaxiangbo gneiss domes are two North Himalayan Gneiss Domes (NHGD), in eastern Himalaya. They show similar tectonic units separated by an upper ductile/brittle and a lower ductile detachment, with a top-to-the NE sense of shear, linked to the dvelopment of the South Tibetan Detachment System. The sense of shear is the same on the southern and northern limbs of the domes. The upper tectonic unit, above the upper ductile/brittle detachment, includes unmetamorphosed to low-grade metamorphic Triassic-Lower Cretaceous slate and metapsammite of the Tethyan Himalayan Sequence. The middle tectonic unit, sandwiched between the upper and lower detachments, consists of mylonitic granite, staurolite-garnet-two mica schist and biotite-plagioclase gneiss affected by the ductile top-to-the north extensional shear of the lower detachment. The lower tectonic unit consists of mylonitic gneiss, leucogranite plutons, dikes, and sills.

By (LASS-ICP-MS) in situ U-(Th)-Pb monazite petrochronology from sheared samples, we constrained the activity of the lower detachment at ca. 19-18 Ma and the shearing along the upper detachment later than ca. 16-15 Ma (Chen et al. 2018) in the Yalaxiangbo dome. The detachment system is made up by two different shear zones activated in different times and at different structural levels. Our data testify a migration of the deformation from the lower portions to the upper ones (Cottle et al. 2015, Kellett and Grujic 2012, Iaccarino et al. 2017, Montemagni et al. 2018, Chen Jie et al. 2018). The ages of shearing of the ducitle shear zones in the Cuonadong dome, located nearly 40 km to the South with respect to the Yalaxiangbo dome point out an older activation of the lower ductile shear zone (ca. 25-20 Ma) and a migration of the normal shearing towards the North. This caused an earlier exhumation of the Cuonadong dome with respect to the Yalaxiangbo dome, with similar mechanisms. The two detachments are later folded during the latest stages of exhumation of the domes. New data point out that age of normal shearing not only varies from West to East (Iaccarino et al. 2017; Kellet et al. 2019) but varies along the same vertical section from ductile to brittle and along a N-S direction showing younger ages to the North in the NHGD.

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Medieval Seismicity on the Himalayan Frontal Thrust Fault at Lal Dhang, Uttarakhand, India

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The Himalayan Frontal Thrust Fault (HFT) lies at the active, tectonic boundary between Eurasia and the Indian subcontinent, and is the youngest member of a thrust fault system associated with the Himalayan orogenic belt. Several large-magnitude earthquakes have occurred on the HFT over the last two centuries but have not produced measurable vertical offsets at the ground surface. The presence of large fault scarps along the HFT, however, indicates that past earthquakes on the fault were not blind and may have been greater in magnitude than recent ruptures. This apparent change in seismic behavior has been the impetus for many recent studies, which have aimed to characterize the nature of previous earthquakes on the HFT in order to inform accurate assessment of the fault's seismic potential. Segments of the fault that have not experienced a great-magnitude earthquake in over a century are defined as seismic gaps, and much of the recent research has been focused on these areas due to the implied potential for impending rupture. The site of Lal Dhang is located along the western section of the Central Seismic Gap and is one of six sites included in a previous paleoseismological study on this segment of the HFT. The findings of that study, as reported for the site of Lal Dhang, exposed several areas of lingering uncertainty where additional research was needed. The current investigation aimed to address these issues by exploring the following lines of inquiry: 1) achieving greater temporal constraint on past earthquakes at Lal Dhang, 2) addressing disparities between the deformational features identified at Lal Dhang and those observed at surrounding sites, 3) analyzing possible rupture sequences to determine if the ~10-meter-high fault scarp at Lal Dhang was generated in one or more events, and 4) explaining an apparent discordance between scarp height and observable coseismic slip at the site. To address these issues, new research on the seismic history of the HFT at Lal Dhang was conducted, which included comprehensive geomorphological, paleoseismological and structural analyses of the site. This study was successful in demonstrating the reproducibility of the findings reported in the previous study, while also providing greater temporal constraint for medieval earthquakes at the site and exposing evidence of additional deformational structures that allowed for increased estimates of both coseismic slip and vertical separation. A detailed geomorphological study of the interaction between local fluvial terrace development and fault scarp generation was also undertaken and those results are presented here. While not conclusive, the deformational sequence revealed during this investigation suggests that multiple earthquakes may have occurred in rapid succession at the site during the medieval period, raising new questions as to the mechanisms involved. These topics, which include the potential existence of a segment boundary proximate to Lal Dhang, the possibility of multiple fault segments rupturing in a single event, and the additional complexities that this introduces for the future estimation of regional recurrence intervals are considered and discussed.

Paleomagnetic Record of Greater India in Paleocene limestones of the Western Himalaya

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Knowing the former extent of the continental margins is important for dating and understanding the India-Asia collision. Paleomagnetism is a well-established method for quantifying paleolatitudes and block rotations. Only few paleomagnetic data exist from rocks at the Indian plate margin with an age close to the collision. The results from Paleocene rocks of the Tethyan Himalaya (TH) at Gamba area in southern Tibet (Patzelt et al., 1996; Yi et al., 2011) were frequently used for determining the so-called “Greater India” extent, but they are lately under discussion because of secondary formation of magnetic minerals (Huang et al., 2017).

In 2018 we sampled the Dibling limestone in the Zanskar range (western TH) near the village of Dibling (34.00´N, 76.63´E). This formation was formed in the late Paleocene (62-57 Ma; Nicora et al., 1987) and corresponds to the studied Paleocene rocks at Gamba. Low degree of metamorphism (lowest in the western TH), a suitable rock age (close to collision), the location at western edge of the Indian plate, and a fold-thrust system (allowing fold tests) provide favourable conditions. In total 31 sites with 10 specimens each were collected. The so far analysed 21 sites show a characteristic remanence (ChRM) obtained by principle component analyses of thermal demagnetization paths between at 350°C and 550°C. Applying a stepwise fold test on 179 single specimen directions reveals a best grouping at 45% unfolding, which indicates a syntectonic origin of the ChRM. The best grouped population yields a single specimen (N=179) direction of D/I = 22.3°/22.9° with α_{95}=2.7 ° and k=15.9, and an overall site mean direction (N=21) of D/I = 22.1°/20.6° with α_{95}=7.4 ° and k=19.0 The corresponding paleolatitudes for the mean CHRM direction are at 12°N (single specimens) and 10.5°N (site mean directions). Expected paleolatitudes from the apparent polar wander path of India (Torsvik et. al., 2012) for the sampled position are between 4.7°S (60 Ma) and 10.5°N (50 Ma). The synfolding ChRM of the Dibling Fm most likely was acquired within this time span of 10 Myr. The resulting extent of Greater India at the north-western plate margin ranges between zero and ~1850 km. Further constraints on the age of the synfolding ChRM are needed to narrow down this possible time span.

Demagnetization of ten more sites are in progress. At the HKT meeting we will update our results. Moreover, we will present rock magnetic analyses and SEM observations to better understand the nature of the origin of the ChRM.

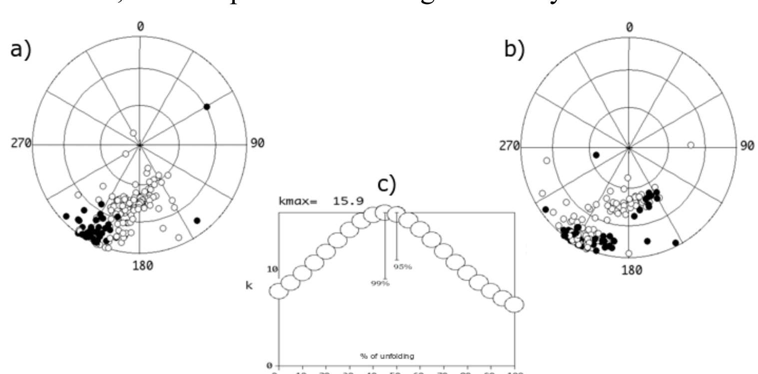

Figure 1: Single-specimen directions (N=179) for 21 sites, 6-10 specimens per site in equal area projection before (a) and after (b) tectonic correction. (c) Stepwise unfolding, showing a best grouped population at 45% unfolding with mean D/I directions of 22.3°/22.9° (α_{95}=2.7°) computed by PaleoMac (Cogne, 2003).

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Assessment of climatic variability on optimal N in long-term rice cropping system

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Climatic variability is one of the most significant factors influencing year-to-year crop production, even in high yielding and high-technology agricultural areas. Many studies have attributed variation in yield and crop response to N fertilizer in general terms to differences in varietal characteristics, but few attempts have been made to systematically disentangle the contributions of the genotype from other factors as climatic conditions. In this study, we used ORYZA V3 rice crop model to evaluate impact of climatic variability on optimum nitrogen application rate in rice cropping system. The results shows that, solar radiation and N management practices play important roles in the response of N in grain yield. Maximum and minimum temperature have less effect on the grain yield compared to the solar radiation. Optimum N was higher in the dry season compared with the early wet season. Optimum N rate for the grain yield was around 200, 150 and 100. Nutrient use efficiency (NUE) was higher in early wet season (EWS) and late set season(LWS) in higher rate of nitrogen compared to the dry season(DS). Observed grain yield and simulated grain yield was almost similar in both seasons. The ORYZA simulation model performs well for estimating optimum N application.

Key words: ORYZA v3, climatic variability, grain yield,

Landslide Mapping, Characterization and Prediction in Siwaliks Zone of Nepal

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Siwaliks is the southernmost and the youngest geological unit of Nepal Himalaya. As the activities of the major thrust systems of Nepal Himalaya is progressively shifting towards south, this youngest geological unit comprising of fluvial sedimentary rocks of Middle Miocene to Upper Pleistocene age has been highly deformed. Sandstone, mudstone and conglomerates are the major rock types which are folded and sheared at many places. This inherent tectonic and geological cause along with the anthropogenic factors like haphazard mining of construction materials, forest encroachment and excavation of road networks has currently exacerbated the degradation of this important mountain zone covering nearly 13% of the total area of Nepal. Realizing the fast rate of its degradation, Nepal government has considered the conservation of this zone as the aim of national pride.

President Chure Terai Madesh Conservation Development Board (PCTMCDB/GoN), which is authorized government body for the conservation of this zone, identified that landslides are the root causes of the degradation of Siwaliks and collaborated with the Tribhuvan University to conduct the landslide research in this zone. The study started from August 2015 and continued until September 2018 covering 22 administrative districts out of 36 districts where Siwaliks zone can be found. The ultimate goal of this research was to map the existing landslides, characterize them, rank the area in terms of the probability of the occurrence of landslide in future and conduct landslide risk mapping. The ranking of landslides in terms of urgency of treatment for disaster risk reduction and save from degradation of area was another important objective. Landslides inventory, landslide characterization, laboratory analysis and vulnerability and risk assessment were performed by the combination of desk study, field study and laboratory analysis. Google Earth and Rapid Eye Imageries were used for the landslide inventory mapping and Arc GIS was used for the further analysis and future prediction. Nearly ten thousand landslides were identified and mapped within the Chure area of 22 working districts. The smallest landslide size of mapped landslide is 400 square meter. These landslides were characterized according to the types of rocks involved, major deformation structures like folds, faults and thrusts, types of landslides, orientation of rock mass discontinuities, soil moisture, soil type, ground water condition etc. It is found that the landslides are highly influenced by the geology in terms of the type, size and numbers of landslides. Granular flow, debris fall and erosion induced landslides are found dominant in Upper Siwaliks; earth slides, mudflow and debris flow are the dominant landslide types in Lower Siwaliks. Rock slides and rock falls are found to be predominant in the Middle Siwaliks. Granular flow and erosion induced landslides were not reported in the literatures before. Laboratory analysis was performed to find the shear strength parameters of soil and rock mass in the landslide area.

Bivariate statistical method was used to find the landslide susceptibility maps of the study area. Spatial multi-criteria decision analysis was applied to carry out vulnerability assessment. The susceptibility and vulnerability maps were prepared in watershed level as well. Central and eastern part of Siwaliks is found to be highly vulnerable for landslides compared to the western part of Siwaliks. Risk Maps were prepared combining the susceptibility map and vulnerability maps. Such maps can be used for the landslide risk reduction strategies and early warning. Risk maps were also used for the prioritization of landslide mitigation. Out of nearly ten thousand landslides, nearly 150 have been identified to be prioritized in terms of urgency of treatment.

Keywords: landslides, Siwaliks, characterization, vulnerability, risk, landslide prioritization

Processes of initial collision and suturing between India and Asia

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The initial collision between Indian and Asian continents marked the starting point for transformation of land-sea thermal contrast, uplift of the Tibet-Himalaya orogen, and climate change in Asia. Following a comparison of the different methods that have been used to constrain the initial timing of collision, we propose that the tectono-sedimentary response in the peripheral foreland basin provides the most sensitive index of this event, and that paleomagnetism presents independent evidence as an alternative, reliable, and quantitative research method. In contrast to previous studies that have suggested collision between India and Asia started in Pakistan between ca. 55 Ma and 50 Ma and progressively closed eastwards, more recent researches have indicated that this major event first occurred in the center of the Yarlung Tsangpo suture zone (YTSZ) between ca. 65 Ma and 63 Ma and then spreading both eastwards and westwards. The Indian to Asian provenance shift and the presence of a possible foreland basin forebulge in the Hazara-Kashmir syntaxial provide strong evidence that India–Asia collision was underway in northern Pakistan at ca. 56–55 Ma. The shift of the sources and the changes in the foreland basin system in northeast India strongly suggest that the India–Asia collision in the Eastern Himalaya took place during or before the early Eocene (i.e., c. 56 to 50 Ma). In practice, however, scholars from different geoscience disciplines have tended to define this event from the point-of-view of their own research, leading to a wide range of estimates for the initial collision time between India and Asia. Here, we have recommended combining a range of multidisciplinary geoscience research as well as a number of authentication methods to study and date this event. In addition, future efforts must be made to reconstruct the whole evolutionary sequence of this collision as well as to place events into a distinct time series.

Lateral variability of Cenozoic strata in the Ganga foreland basin of Nepal controlled by transverse Indian basement structures

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The Himalayan orogen has been subdivided from east to west into along-strike segments with differing thicknesses, deformation styles, thermal evolution, and seismicity. Heterogeneities in the Indian plate, such as crustal scale basement faults and ridges, are possible causes for this lateral segmentation. Foreland basin stratigraphy can be used to investigate the behaviour of these basement features during basin development, and to test links between basement structure, along-strike segmentation of deformation, and lithospheric flexure in the developing orogen.

The seismic stratigraphy within and below the foreland basin across the entirety of Nepal is imaged through 2D seismic reflection data. The data have been depth-converted using time-depth relationships derived from wells, so as to highlight structures. Regionally interpreted surfaces include: two horizons internal to the Cenozoic succession; an angular unconformity at the base of the Cenozoic succession where older stratified units are truncated; and the nonconformity that separates sedimentary strata from acoustic basement representing Archean granitoids and Proterozoic gneisses. In addition, faults and deformation zones are identified in both the foreland basin strata and the underlying basement. Because much of the foreland basin fill was deposited in fluvial environments close to sea level, thickness can be used as a proxy for subsidence rate. The horizons have been used to produce isopach maps for each of the main stratigraphic intervals.

Our seismic interpretation shows that basement depth fluctuates dramatically, ranging from > 12 km to < 3 km. These variations define two sets of depressions and ridges, and several large graben. The Cenozoic succession thins and thickens in step with the basement below. Thickness maps of units within the Cenozoic succession reveal maxima above basement depressions, and minima above basement ridges, indicating that the basement features controlled accommodation in the foreland basin. Large tear faults in the Sub-Himalayan thrust system, interpreted to deform the foreland basin succession, are aligned with Indian basement features.

We interpret that basement-controlled differential subsidence has played (and likely continues to play) a significant role in the development of the Ganga foreland basin. Accommodation generation varied along strike during foreland basin fill, and was controlled by basement ridges or their bounding faults. Spatial localization of tear faults above basement ridges suggests that the ridges may influence lateral ramp and transfer zone distribution in the developing Himalayan foreland thrust belt.

Extension and metamorphic core complex formation in the upper plate of a collisional orogen: Timing of exhumation of Nyainqentanglha Shan, Lhasa Block, Tibet

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The Nyainqentanglha (NQTL) metamorphic core complex developed after continent-continent collision in the hanging wall within the Lhasa Block of Tibet. The NQTL range strikes NE-SW and is bound by a low-angle normal fault along its south-eastern margin, a km-thick ductile shear zone at the upper margin of the complex, which is overprinted by high-angle normal faults of the Yadong-Gulu rift, demonstrating oblique extension of the upper plate. The metamorphic core complex and also its hanging wall in the SE is mainly composed of (meta)plutonic rocks. In order to constrain the timing of the main phase of exhumation of the NGQT metamorphic core complex we dated minerals from 23 samples (mostly plutonic rocks) from a large elevation range. Samples are from a cross-section along the main ridge of the Nyainqentanglha Shan (7162 m), from the hanging wall of the detachment southeast of the core complex, and from the Qungmoganze (7048 m) area in the southwest part of the range. For 5 samples we determined LA-ICP-MS U-Pb ages, for 22 samples 62 Ar/Ar ages for amphiboles (Hbl), white mica (Mu), biotite (Bt) and K-feldspar (Kf). The hanging wall samples are from an elevation of 4270 m, samples from the central transect are from elevations between 4930 m and 6390 m, and from 5500 m to 6630 m in the Qungmoganze area.

The obtained U-Pb ages are 207 Ma for a two-mica granite from the NW part of NQTL, ages of ca. 66 Ma for two granite samples from the Qungmoganze area, and 20 – 24 Ma and 12 – 19 Ma for two granite samples from the central part of the range.

Ar/Ar ages from the hanging wall are ca. 46 Ma for Bt and 41 and 32 Ma for Kf, respectively. In the central core complex Hbl gave ages from 18 to 11 Ma, Mu 15 – 6 Ma, Bt 14 – 7 Ma and Kf 11 – 6.5 Ma. A phyllite from the western end of the core complex yielded an age of ca. 12 Ma. Ages display a general decrease from the NW towards the detachment fault in the SE and from higher to lower elevations, with the youngest ages coming from samples close to the detachment in the SE of the central transect. Most Mu and Bt ages are between 11 and 8 Ma. Ages of Mu, Bt, and Kf from the same sample are mostly close together, showing rapid cooling from ca. 400°C to 200°C, only Amph display clearly older ages. In the Qungmoganze area ages are significantly older with Mu of ca. 27 Ma, Bt 30 Ma, and Kf between 28 and 15 Ma.

The Ar/Ar ages are all cooling ages, as all dated rocks experienced temperatures higher than 500° C, and thus date part of the exhumation path. The samples from the hanging wall demonstrate cooling below ca. 300°C at 46 Ma and below ca. 200°C up to 30 Ma. Rocks in the Qungmoganze area cooled clearly later, to below 300°C at about 30 Ma and to below ca. 200°C up to 15 Ma. The central part of the NQTL metamorphic core complex displays magmatic intrusions of ages between 25 and 20 Ma and possibly as young as 12 Ma. Part of the dome started to cool below ca. 500°C at about 18 Ma and cooled below 300°C at 14 Ma. Samples from the deeper part of the dome and samples close to the detachment, which are strongly deformed in the ductile extensional shear zone, display the youngest ages of ca. 6-7 Ma for Mu, Bt and Kf, demonstrating their rapid cooling through the interval from ca. 400°C to 200°C at that time. These data thus constrain the onset of NW-SE directed extension in the Lhasa block before or at about 18 Ma, with magmatic intrusions at the same time. The main phase of active ductile extension and exhumation of the metamorphic core complex must be older than the youngest cooling ages of 6-7 Ma and probably close to the main age group from 8-11 Ma. Extension and formation of metamorphic core complexes in the Asian upper plate is thus younger than the main phase of ductile stacking within the Indian lower plate and apparently assisted by melting in the middle to lower crust of the Lhasa Block.

Structural evolution of Sub Himalaya in Pakistan: New evidence from low temperature thermochronology

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The Kohat and Potwar area represent the Sub-himalaya of Pakistan. The Sub-himalaya in Pakistan is wider between the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) than the Sub-himalaya of India and Nepal. In order to constrain the sequence and timing of structural evolution, we have constructed balanced cross-sections and conducted apatite (U-Th-Sm)/He(AHe) and apatite fission track (AFT) dating. We have systematically sampled Cambrian to Pliocene sandstones from different stratigraphic sections in the Salt, Surghar and Kohat Ranges for AHe and AFT dating. Inverse thermal modeling of data from the Salt Range suggests that the episode of Late Paleozoic Rifting reported in the Peshawar Basin of Pakistan, Kashmir and Zanskar area of India extended southward at least to the modern Salt Range. The thermochronology data is combined with structural reconstructions to interpret the Miocene - Pliocene history of the area, revealing new constraints for the sequence of thrusting in the Sub-himalaya. The range front in Kohat, known as Surghar Range, developed 2 Ma earlier than the MBT at 13 Ma. The development of the range front is correlated with a major angular unconformity in this area. The development of the MBT at 11 Ma is confirmed in the Kohat, marking the northern limit of the Sub-himalaya in the entire Himalayan fold and thrust belt. Deformation propagated south of the MBT on a double decollement in the Kohat compared to a single decollement in the Potwar. Deformation on the double decollements in the Kohat resulted in the development of duplexes between the upper and lower decollement and extensive erosion of strata above the upper decollement. The AHe and AFT ages suggest in-sequence deformation south of the MBT in the Kohat. At 4 Ma, deformation occurred on the MFT, developing the Potwar range front known as the Salt Range. The late stage expulsion of salt in the western Potwar resulted from the out-of-sequence movement on thrust ramps in the Kohat and normal faulting in the Kalabagh Fault zone. The spatial distribution of AHe and AFT ages combined with the structures shown in balanced sections suggest that the deformation in the Sub-himalaya was active on different structures at different times, causing an out-of-sequence evolution of the Sub-himalaya in Pakistan.

Geometry of the Main Himalayan Thrust and its stress dynamics as illuminated by aftershocks of the 2015 Mw 7.8 Gorkha earthquake

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2015 Mw 7.8 Gorkha earthquake highlights the seismic potential of the Himalayan fault system in Nepal. As damaging as it may be, it only ruptures downdip part of the Main Himalayan Thrust (MHT). Updip locked part of the MHT, however, remain unbroken, and potentially is brought close to the next large megathrust earthquake in this area. Therefore, it is more important than ever to better understand the fault structure, evolving stress dynamics, and how it may affect tectonics of the Himalayas. Geometry of the MHT is long debated, as it is fundamental to understand seismic cycle, seismicity, associated hazards, geomorphology and tectonics. After the Gorkha mainshock, we installed a dense seismic network with 45 seismic stations covering the entire rupture area. The network was operational for about a year, and recorded more than 15,000 aftershocks. This rich dataset provides us an opportunity to map out fault geometry and the state of stress in unprecedented resolution. In addition to locating earthquake using relative location algorithm, we computed more than 40 first motion focal mechanisms and moment tensor solutions. Based on the seismicity pattern and focal mechanisms, we propose a new model for the geometry of the MHT. This model involves two subhorizontal planes connected by a complex duplex structure containing steeply dipping imbricate thrusts. The duplex produces the majority of the aftershocks. Although focal mechanisms are generally consistent with this model, they do show significant variability when smaller aftershocks are considered. Moreover, seismicity rate and *b*-value show significant variations alongstrike. They reflect an evolving state of stress along the MHT with considerable heterogeneity.

Inverted temperature fields: deformational temperatures across the Lesser Himalayan Sequence in eastern Bhutan

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To explain the formation of an inverted metamorphic sequence we performed a study, which combined geothermometry with the thermochronology. The data are evaluated trough thermokinematic forward and inverse modeling to constrain the ranges of important geological parameters such as fault slip rates, the location and rates of localized crustal accretion, and the thermal properties of the crust. The case study was performed along a transect across the Lesser Himalayan Sequence (LHS) of the eastern Bhutan. The geothermometry included the Raman spectroscopy of carbonaceous material (RSCM) to determine the peak metamorphic temperatures and Ti-in-quartz thermobarometry and quartz texture opening angle geothermometry to determine the deformation temperatures. The thermal kinematic modeling was performed with PECUBE software and as thermochronologic constraints we used apatite and zircon U-Th/He and fission-track data and $^{40}Ar/^{39}Ar$ dating of muscovite.

To constrain the age at which these temperatures were attained we used the muscovite for $^{40}Ar/^{36}Ar$ thermochronology. However the quartz deformation thermometry is pressure dependent, while the closure temperature of muscovite for $^{40}Ar/^{36}Ar$ system highly dependents on cooling rate. Both parameters are difficult to accurately constrain in the down-dip shear zones. Combined with new and published thermochronological results, these parameters were calculated by three-dimensional thermal-kinematic modelling and the deformation temperatures and closure temperatures determined by iterative calculations. Thus obtained time-temperature paths lead us to propose a qualitative model for the evolution of the deformation temperature field in this segment of the Himalaya.

The inverted metamorphic field gradient is registered by various geothermometric systems and at different temperatures ranges indicating that the processes that formed the current (i.e., finite) metamorphic field gradient have lasted over an extended time period, along the retrograde metamorphic path, and have involved various processes at different stages:

(a) Synkinematic steepening and inversion of the isotherms in the vicinity of the crustal-scale shear zone.
(b) Locking in of the peak-*T* isotherms registered by the metamorphic assemblages.
(c) On-going pervasive ductile deformation characterised by general shear.
(d) Deformation of the peak-*T*-isotherms; formation of the quartz deformation-isotherms.
(e) Deformation focusing (i.e., progressive shear zone narrowing) may offset the peak-*T* isotherms.
(f) Retrograde ductile deformation still with an inverted temperature gradient but caused by progressive cooling of successively more internal and thus hotter rocks.

Stratigraphic expression of the Main Frontal Thrust in central Nepal: A 40,000 year record in the Bardibas area

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In 2014 and 2015, we conducted seismic reflection acquisition in central Nepal across the Bardibas Thrust segment of the Main Frontal Thrust (MFT) to constrain its geometry and kinematics. These seismic lines revealed a beveled fault propagation anticline buried by ~100 m of recent sediments in the hanging wall, coupled with growth strata in the footwall. To constrain the age of folding and thus the slip rate on this fault, we cored these near-surface sediments in 2017 and 2018. All holes were cored to NQ diameter (4.7 cm) and penetrated 50—100 m, with variable core recovery. Our goal is to date the sediments by ^{14}C and optically stimulated luminescence dating (OSL) to constrain both tectonics (slip rates along the Bardibas segment of the MFT) and sedimentation patterns (local changes in base level and depositional environment). Here, we report initial results.

A total of 10 boreholes were cored along the Lakshmi, Bhabsi and Ratu rivers. The Lakshmi (P1, P2) and Bhabsi river sections (P3-P5) are in the hanging wall of the Bardibas thrust, which at these locations lacks surface expression, while the shorter Ratu river section (P6-P10) extends across the blind tip of the thrust and into the immediate footwall. North of the Ratu section, the Bardibas thrust has uplifted the hanging wall, with fluvial terraces preserved above the current river level.

All sections exhibit an upper 12 – 31 m thick upper boulder gravel that is younger than 11 ka. Below this gravel package, sedimentation becomes more variable, with a mixture of boulder gravel, coarse-to-fine sand, and extensively-bioturbated siltstones suggestive of paleosols. ^{14}C ages from these variable clastics range from 12 ka to 48 ka, and OSL ages are broadly similar.

Along the Bhabsi river profile, 35-40 ka ^{14}C ages in each well define a time horizon that increases in depth from upstream, at the crest of the buried anticline (P3), to downstream (P5), mimicking the shape of the anticline and suggesting tilting of the time horizon by the fault below. Using this horizon as a reference layer, we do an area balance to estimate ~70-80 m of shortening on the detachment since 35 ka, with a resulting shortening rate of ~2 mm/yr (or about one fifth of the total Himalayan shortening budget), although this is a preliminary estimate.

Along the Lakshmi river profile, the downstream core at site P2 (near the blind fault tip) contains 25 m of near-continuous silt, clay, and fine sand, indicating pooling of sediments in a calmer, water-rich environment, different from all other sites. ^{14}C ages from the clay-rich units range from 25 – 40 ka. These argillaceous sediments suggest long-term ponding of sediment behind the fault tip, and are a possible target for paleoclimate investigations.

Along the Ratu river (footwall section), we find a similar upper 16-25 m thick <12 ka gravel unit, with highly variable clastic sedimentation below. At site P6, which sits at the foreland-facing flank of the anticline, near-vertical Upper Siwalik beds are encountered at 31 m and below. ^{14}C ages above the top-Siwalik unconformity range from 12 – 34 ka. At adjacent P7, a sub-vertical deformation band is observed in porous sands at 66 m, potentially suggestive of slip at seismic velocities.

Sediment accumulation rate is not constant through time, but long-term averages for these cores are ~1-2 mm/y for the last 40 ka, with a lower rate in the fine clay interval at P2. These cores suggest that fluvial fans, with local lacustrine sedimentation, have buried the Bardibas Thrust for most of the last 40 ka, and confirm that the regional shortening rate of 15 mm/year in central Nepal must be accommodated on more than one structure, likely including the Patu thrust and others to the north. Here we quantitatively constrain the contribution of the Bardibas thrust and the remaining slip budget.

Extended glaciation triggered West-East climate divergence in the NE Tibetan Plateau region during and after the Mid-Pleistocene Transition

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The NE Tibetan Plateau is largely dominated by arid areas, climatically controlled by the Westerlies and the winter monsoon. In contrast, the climate of the Chinese Loess Plateau (CLP) to the East is under the influence of the East Asia summer monsoon (EASM). Knowing the climate evolution in these regions and determining when and how possible West-East divergence happened, are crucial for understanding the processes of aridification in central Asia.

In this study we performed comprehensive linear and nonlinear analyses (statistical relationships through time, wavelet spectra, and recurrence quantification) on published and newly obtained data from a drill core (~2.7-0.08 Ma), and compare the evolution in the QB with EASM records from the CLP. The results indicate a similar drying trend of the lake system in the western QB and the EASM system before the beginning of the Mid-Pleistocene Transition. After ~1.2 Ma, increasingly drier intervals occurred in the QB, whereas the EASM in the CLP strengthened. We suggest that both systems (QB and EASM) responded to solar insolation due to facilitation of ice sheet expansion in phases of lower obliquity variation and lower degree of eccentricity as suggested by Zachos et al. (2001) and Pälike et al. (2006). During ~0.9-0.8 Ma, synchronous minima occurred in eccentricity and obliquity variation, which together with the coeval reduction in atmospheric CO_2 concentration could have favored the northern hemisphere glaciation and also the growth of ice sheets on the Tibetan Plateau. We assume that the resulting global and regional cooling led to prolongation of seasonal southward shift of the Westerly Jet, causing a decrease of atmospheric moisture supply to the QB. As a possible consequence, the water balance of the regional water cycle in the region of the QB that preserved the paleolake until the Quaternary became increasingly negative, eventually leading to the collapse of the Qaidam paleolake after ~0.6 Ma. On the other hand, the strength of the EASM that affects the region of CLP but does not reach the QB likely benefited from an increased land-sea pressure gradient due to glaciation.

Our results suggest that the Quaternary desiccation of the paleolake in the QB and the divergence between the QB and the EASM systems after ~1.2 Ma are a response to global cooling and northern hemisphere ice sheet expansion. Although the relief of the QB probably enabled the long-term stability of the Qaidam paleolake until the Quaternary, the influence of tectonic processes on the Quaternary climate evolution in these regions seems sub-ordinate.

Ref.: Zachos et al. (2001), Science 292, 274–278; Pälike et al. (2006), Science 314, 1894–1898.

Did mid-Cenozoic strata in the Central Pamir form in a bobber basin associated with local lithospheric delamination?

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Models have long predicted the occurrence of Rayleigh-Taylor-type instabilities in the mantle lithosphere, expressed as local, drip-like delamination events, which have been associated with bobber-type sedimentary basins. If at all preserved, such an episode should also be reflected in the magmatic record: potassic magmatism from the thermal perturbation caused by the descending mantle lithosphere, followed temporally by juvenile melt from the upwelling influx of asthenosphere. However, only in a few places have such delamination events been recognized in the magmatic or sedimentary record.

In the eastern Central Pamir, Oligocene (or younger) laminated siltstone and interbedded conglomerate may represent a record of such a local delamination event. Detrital zircon grains from these strata record a minor episode of juvenile (positive epsilon-Hf) magmatism at ca. 32 Ma that is not seen in either the regional detrital or igneous record of the Pamir, and which may be associated with nearby potassic plutonic rocks (42-36 Ma; Vanj complex). Given the convergent tectonic setting and crustal thickness at the time, the lack of other viable sources for juvenile melt, and the lithology of the sedimentary rocks, it was hypothesized that the 32 Ma magmatism was the result of late-stage, asthenosphere-derived melting related to the removal of negatively buoyant lithosphere, and that the strata formed in a related hinterland basin.

Preliminary detrital thermochronometric and geochemical data from these sedimentary samples provide tentative support for this hypothesis. Double-dating (U/Pb and U-Th/He) of zircon grains yielded a dominant 14 Ma cooling age, with a range of ages (interpreted together with their effective uranium concentration and U/Pb age) that are consistent with rapid burial after deposition at ca. 30 Ma, and subsequent exhumation at ca. 14 Ma. If this interpretation is correct, the thermal history of the basin is tightly constrained, since the data require prolonged residence in the partial retention zone for the zircon helium system such that some but not all grains were reset, which in turn requires both rapid and significant burial and exhumation. The rate and magnitude of this burial-exhumation history would be within the same order of magnitude as other proposed drip-related hinterland basins (e.g. in the South American Cordillera).

Additional zircon helium data and other low-temperature thermochronometric systems, particularly apatite helium and apatite fission track, provide means of testing the hypothesis, if datable grains can be recovered. Alternatively, the ca. 14 Ma cooling ages may also reflect different cooling and exhumation signal(s) of the source terrane(s) of the individual grains, rather than the cooling of the bulk sample, in which case the maximum deposition age of strata would be limited to ca. 14 Ma or younger. While this would not rule out the hypothesis that the magmatism was the result of local lithospheric delamination, it would also offer no support for it.

Investigating the Anaconda metamorphic core complex of western Montana--insights into the extension dynamics of convergent orogenic belts

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Post- and syn-convergent extension are widespread in orogenic belts across space and time. The crustal thickening and subsequent gravitational collapse of the North American Cordilleran hinterland led to large-magnitude extension and the development of a N-S trending belt of metamorphic core complexes during Paleocene-Eocene time. It is possible that northern Cordilleran core complexes were exhumed while Farallon-North American plate convergence rates remained high. Semi-analogous gravitational collapse and syn-convergent core complex development may be currently taking place in southern Tibet as a result of the India-Asia collision.

The extension dynamics—specifically the relationship between pluton emplacement and exhumation—of the Anaconda Metamorphic Core Complex (AMCC) in western Montana is not well understood. Detailed geologic mapping of a 1:24K quadrangle provides new insight into AMCC footwall structure and records previously undocumented cross-cutting relationships. Comparison of documented $^{40}Ar/^{39}Ar$ thermochronologic ages, previously interpreted to record cooling, with newly obtained U-Pb zircon geochronology ages from a suite of igneous rocks in the AMCC footwall places constraints on the relationship between magmatism and extension. Two samples of the two-mica Pintler Granite that dominates the footwall yielded ages of 60.54 ± 0.12 Ma and 61.12 ± 0.13 Ma. A strongly-foliated granodiorite dike and dacite dike cross-cutting the Pintler Granite yielded age of 46.61 ± 0.05 Ma and 51.27 ± 0.06 Ma, respectively. Igneous activity appears to predate and only briefly overlap with the oldest extension ages, indicating that pluton emplacement was primarily a cause of extension rather than a response. Comparison of the AMCC with other deeply exhumed core complexes around the world indicates variability in the timing and, therefore, relative influences of crustal thickening, partial melting, and magmatism on the initiation of extension.

Studying the variability in the timing and extensional deformation styles at different convergent margins may give insight into the broader extensional dynamics in convergent orogenic belts. The large-magnitude E-W extension and core complex exhumation that is occurring on north-trending rifts in southern Tibet provides a modern example of syn-convergent extension that we intend to compare and contrast to the core complexes of the North American Cordillera.

Evidence for Recent Dextral Slip along the Western Nepal Fault System in northwest Nepal

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New mapping at two sites in northwestern Nepal documents linear geomorphic landforms that are truncated and offset by active faults along the Western Nepal Fault System (WNFS). The WNSF is comprised of three primary segments, 1) a northwestern right-slip segment that traces from southern Mugu district to Juphal; 2) a region comprised of right-slip faults and extensional stepovers including the Dhaulagiri Southwest fault, Tarakot extensional stepover, and the Dhorpatan Hunting Reserve; and 3) a southern right-slip segment that includes the Bari Gad fault near Tansen. Field investigations in spring, 2019 focused on the neotectonic sites identified using satellite imagery and ASTER DEM along the northwestern right-slip segment from Talphi to Tibrikot.

At site 1 near Talphi, fault scarps, deflected stream channels, and shutter ridges delineate a ~20 km subvertical fault segment, striking ~N40W with a linear fault trace traversing areas of high topographic relief. Our field mapping documents two dextrally offset markers: an abandoned stream channel that is offset 330 ± 130 m and a terrace riser that is dextrally offset 75 ± 31 m. Approximately 60 km to the southeast at site 2 near Tibrikot, shutter ridges provide compelling evidence for dextral displacement along a ~N65W striking, steeply northeast dipping fault. Upstream of one of the shutter ridges our detailed field observations document a series of fluvial terraces, one of which is truncated and offset by two NW-SE striking antithetically dipping fault splays, recording 47 ± 13 m and 46 ± 33 m of dextral offset across the south and north splays, respectively.

Results from this study will inform seismic hazard risk analysis in Western Nepal and help to better understand areas of oblique convergence, continental slivers, and splay fault – all ubiquitous features of obliquely-convergent margins.

Himalayan Cross Faults: the role of highly oblique structures in a contractional orogen

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Collisional mountain belts around the world are dominated by thrust faults. The Himalaya is no exception. Many of these orogens also have faults that cut across the thrusts and have played various roles in the structural evolution of the mountain belts. In the Alps, oblique structures are extensional and have resulted in the exhumation of high-grade metamorphic rocks at sites such as the Simplon or Brenner faults (Mancktelow, 1987). The Zagros has a number of tear faults possibly related to Precambrian extensional structures or the salt tectonics (Jahani et al., 2017). Differential displacement along Appalachian thrusts is also attributed to tear faults (Mitra, 1988). While there has been documentation for several decades of the extensional faults in Tibet that are perpendicular to the convergence direction, it is only in the past few years that cross faults have been described in the Himalayan literature, south of the South Tibetan Detachment System. In the NW Himalaya, the Yamuna and Ganga faults cut the Main Frontal Thrust (MFT) and have ~20km and 11km of strike slip displacement, respectively (Sahoo et al., 2000; Srivastava et al., 2018). There is evidence supporting fault movement along the Yamuna and Ganga faults in the past 15,000 years. Similar young cross faults have been described in far eastern Nepal and Sikkim. The NE- to NNE-striking Kosi (E. Nepal) and Gish (Sikkim) faults cut Sub-Himalayan units and offset the range front. Microseismicity is consistent with strike-slip kinematics (Mukul et al., 2018). In western Nepal, the Western Nepal Fault System cuts obliquely across the range and while this structure cuts Quaternary deposits and the MFT, the angle of obliquity is much lower and it has been considered to be somewhat of a continuation or step-over of the Karakoram Fault (Silver et al., 2015). Recent work has recognized a cross fault in the Greater Himalayan sequence in the Khumbu region of eastern Nepal, the Benkar Fault Zone (Hubbard, 2017; Seifert, 2019). In that zone, non-penetrative shear planes exhibit fabric consistent with right-lateral, normal displacement along a 3-10 km-wide, NE-striking zone. Preliminary $^{40}Ar/^{39}Ar$ ages on muscovite are consistent with post ~12 Ma displacement. The presence of cross faults in the Greater Himalayan and the Sub-Himalayan zones suggests that cross-faults have either played a role in the convergent processes of the Himalaya for an extended period of time, but at different crustal levels at different times or that cross faults penetrate multiple crustal levels. Further mapping of these structures and further geochronologic work will help constrain our understanding of the connection of these structures to the major thrust systems which will in turn, help us to understand whether the origin of these structures relates to a tear fault process or is more closely connected to extension in Tibet, or some other process.

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Megamountains, megarivers and megafloods: Understanding the interactions of Earth-surface processes and tectonics in the Eastern Himalaya

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The Tsangpo gorge region of the far eastern Himalaya is a spectacular geologic feature of the Earth's crust, where erosion of the Yarlung-Siang-Brahmaputra river has sliced a narrow gorge between two >7 km Himalayan peaks in a zone of extremely localized rapid erosion and rock uplift. It has been argued that this area represents some of the best evidence for a localized positive feedback between erosion and deformation on Earth. We test this hypothesis by using detrital geochronology and thermochronology of modern river sediments and Cenozoic foreland basin deposits to establish the relative timing of river capture and the onset of rapid erosion/exhumation. Results rule out 3-4 Ma river capture or Quaternary climate change as triggers for rapid exhumation, and instead point to a tectonic driver for extreme rock uplift rates.

We investigate the mechanisms by which fluvial erosion keeps pace with rock uplift in different climate regimes by investigating the history, hydraulics, and geomorphic impact of outburst floods through the Tsangpo gorge. Evidence for valley blockage by glacial and landslide dams suggests that catastrophic outburst floods may have been common throughout the Quaternary. We integrate geochronology (radiocarbon and single-grain luminescence dating) and provenance studies (Bayesian inversion of detrital zircon U-Pb data) of single-event slackwater flood deposits from historical dam-break outburst floods and ancient glacial megafloods preserved downstream of the gorge with numerical simulations of flood hydraulics. Our findings highlight the potential for outburst floods to promote not only different amounts, but also different patterns of bedrock erosion than meteoric floods, with implications for the role of prehistoric megafloods in the topographic evolution of the eastern Himalaya.

Tourmalines from the Mansehra Granitic Complex, NW Pakistan: A major element and boron isotope study

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The Mansehra Granitic Complex (MGC) is one of the major plutonic complexes in the lesser Himalayas of Pakistan, intruded into the Precambrian Tanawal Formation. The MGC is composed of multiple intrusions of peraluminous and calc-alkaline granites with both porphyritic and foliated texture. Tourmaline is an important ferromagnesian mineral in the Mansehra granite, present as both mineral clusters and disseminated accessory grains in the groundmass of the granite. It exists as individual ferromagnesian mineral or coexists with biotite. It also forms a major mineral in pegmatite within the granite. The major element composition and boron isotope ratios of tourmaline have been determined as a petrogenetic indicator and to help evaluate the fluid/magma source and fluid-rock interactions.

Tourmaline chemical and boron isotope compositions were determined in-situ by electron microprobe and secondary ion mass spectrometry, respectively, on samples from different intrusions of the MGC: 1) Two-mica undeformed Mansehra Granite (TMMG), 2) Granitic orthogneisses (GOGns), 3) Pegmatite and 4) Tourmaline-rich orthogneisses (TOGns). In thin section, tourmaline displays fine to medium-grained, anhedral to euhedral crystals varying in color from green-yellowish green, khaki, greenish blue to orange-brown. The crystals are mostly fractured and display both optical and chemical zoning. The latter shows a decrease in Al and increase in Na, Fe, Mg, and Ca from core to rim. The majority of tourmalines from MGC belongs to the alkali and x-vacancy groups and have intermediate schorlitic to foititic composition, less commonly dravitic composition with variable alumina content. The Fe (Fe^{2+}/Fe^{2+}+Mg) contents in foliated granite and GOGns are lower than in the undeformed TMMG and in TOGns, while tourmaline from pegmatites have the highest Fe concentrations. The compositional variability of tourmalines in the MGC is controlled by the $FeMg_{-1}$, Al X_{vac} $(R^{2+}Na)_{-1}$, and Al O $(R^{2+}OH)_{-1}$ exchange vectors, where R^{2+} denotes divalent cations and Xvac denotes the X-site vacancy.

The total range of tourmaline B-isotope composition in the MGC (as $\delta^{11}B$) is from -8.2 to -13.6 ‰, and most samples are relatively homogenous. The pegmatite and GOGns tourmaline has relatively high values with -8.2 to -9.8 ‰ and -9.0 to -10.0 ‰, respectively, while the TOGns yielded intermediate values from -10.6 to -12.5 ‰ and the TMMG tourmaline is slightly lower, from -12.4 to -13.6 ‰. The $\delta^{11}B$ values from TOGns and TMMG tourmaline are well within the typical range for S-type granites worldwide, supporting a magmatic origin for boron. The textural characteristics of mineral replacement and higher $\delta^{11}B$ values of tourmaline in pegmatite and GOGns may reflect post magmatic processes of deformation and hydrothermal alteration of the Mansehra granite.

Keywords: Mansehra granite, tourmaline, mineral chemistry, boron isotope, magmatic source.

The Low-Temperature Thermo-Tectonic Evolution of the Eurasian Margin

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Low-temperature thermochronology has long been used to explore the tectono-thermal evolution of major orogenic systems such as the Eurasian Margin. Extensive application of thermochronology to major faults, and topographic structures have allowed researchers to distinguish different periods of cooling and investigate the relationships between erosion, deformation, and topography.

In recent years, the density and distribution of low-temperature thermochronological data such as zircon (U-Th-Sm)/He, apatite fission track, and apatite (U-Th-Sm)/He data along the major topographic structures of the Pamir, Tibet, and Tianshan has become great enough that it is possible to explore trends in cooling ages, topography, and the tectonic evolution of the Eurasian continent. In this contribution, we compile thousands of published basement zircon (U-Th-Sm)/He, apatite fission track, and apatite (U-Th-Sm)/He ages from the Pamir, Tibet, and the Tianshan and explore the thermo-tectonic evolution of Eurasia at a regional scale. Integrating the thermochronology with the available plate reconstructions, modern climate records, prevailing stress-regime and gravity measurements provides insights into the relationships between these different but interconnected tectonic and topographic features.

First order inferences show a clear southward younging trend of thermochronological ages, with notable discrete steps in age related to microcontinent boundaries. High modern topographic regions in the Tianshan, show similar ages to those found in the Pamir and southern Tibet, suggesting limited, but not wholesale propagation of stress from the India-Eurasia collision into the Eurasian interior. Further, there are distinct regions such as the Borohoro and Bodga Mountains in the eastern Tianshan and south-eastern Tibet that highlight a different tectonic relationship to the prevailing trend. Preserving younger and older ages, respectively, when compared to their surrounding thermochronological data.

The comparison between modern annual precipitation rates and cooling ages show a weak relationship between ages and rates of precipitation, suggesting a climactic control on erosion. Geophysical databases such as the world stress map and the Bouguer Gravity Anomaly data show that the main structural boundaries such as the ones between Tibet and Tarim and the Pamir and the South Tianshan are characterized by thrust faulting, relatively lower BGA values and young, late Cenozoic thermochronological ages. Whereas the areas that preserve older, early Cenozoic-Cretaceous ages are dominated by strike-slip, normal faulting stress regimes, and relatively higher BGA values, outside regional heterogeneity such as the south Tibetan rifting.

Despite the regional coverage there are still regions, such as the western Qiangtang and Kunlun Mountains, which would benefit from further low-temperature thermochronological study. However, this study is able to provide a representative temporal and spatial framework for the thermo-tectonic history of the Pamir, Tibet, and Tianshan throughout the Mesozoic and Cenozoic.

A developing glacier-surge-dammed lake in Pakistan, and other recent mass movement dammed rivers

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For the past two years a surge has been underway of Shishper Glacier in a valley that is a major tributary of the Hunza River. In 2019, the surge reached the terminus, which has advanced, and by spring 2019 the engorged distal lobe of the glacier has dammed another tributary, which now has formed a lake—we call it Shishper Lake. The lake has grown in recent weeks, and like all glacier-dammed lakes, it is unstable. How it will drain, and how rapidly, is unclear. This event will be compared to others in the Himalaya-Karakoram region that have involved ice avalanches and landslides in the past decade. Some of these events were monsoon triggered, others eathquake triggered. Some avalanches completely crossed over rivers but did not dam them, and other avalanches and landslides dammed their rivers briefly—hours or days. Some burst out violently, and others drained slowly enough that no major consequences ensued. We will present some details on the dynamical behavior of the Shishper Glacier and other mass movement dammed lakes and present some ideas on why some mass movements dam their rivers, and others don't.

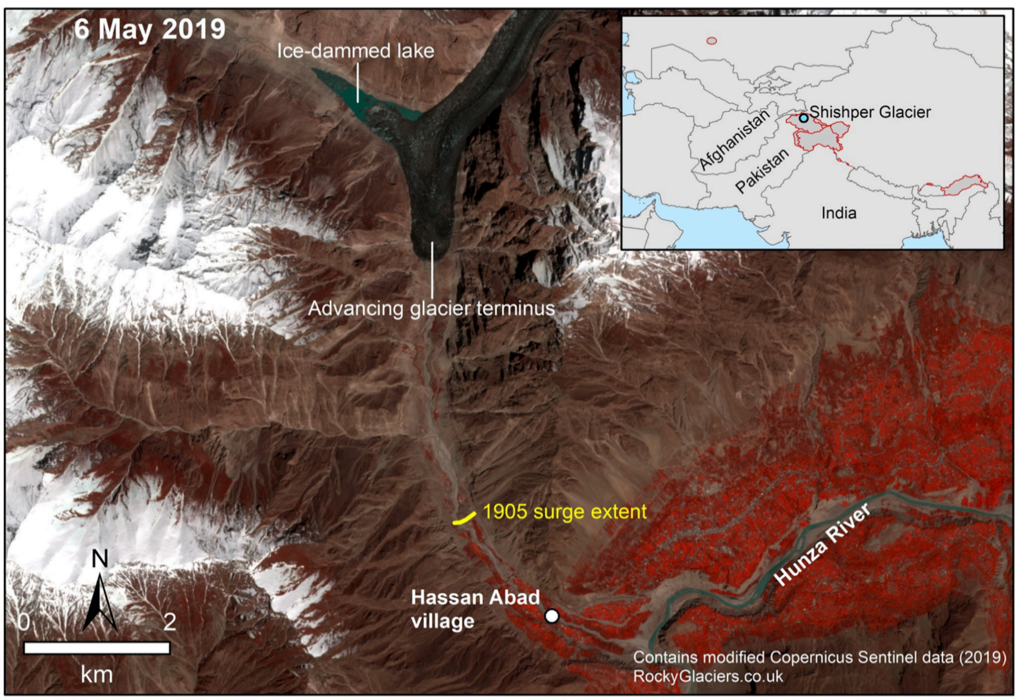

Figure 1. Tongue of Shishper Glacier and the lake growing behind the ice dam.

More information: Bhambri, R. Hewitt, K. Kawishwar, P. and Pratap, B. 2017. Surge-type and surge-modified glaciers in the Karakoram. Scientific Reports. 7(1), p15391. NASA Earth Observatory, 2019: https://earthobservatory.nasa.gov/images/145038/surging-glacier-creates-a-new-lake. C. Scott Watson's website: http://www.rockyglaciers.co.uk/understand/shishper.html

Landslide potential and glacial lake outburst flood hazards in the Makalu-Barun area (Nepal) accentuated by lithological variability

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A landslide in 2017 triggered a small glacial lake outburst flood (GLOF), transitioned to a debris flow, dammed the Barun River at its confluence with the Arun River, created a brief impoundment, which then burst, causing a flood and debris flow near Langmale Eastern Nepal (Byers et al. 2018). The hazard sequence initiated by a landslide originating from the Main Everest-Makalu Granite and Barun Gneiss bedrock (cf, mapping by Streule et al.), moraines derived from them, and glacier ice. Although this sequence caused relatively minor damage and no human deaths, the potential for a tremendous disaster is signaled by proximity of the Langmale event to the Upper Barun and Lower Barun lakes, which exist in a sequence where a relatively small landslide or ice avalanche into Upper Barun Lake could cascade into Lower Barun Lake and trigger a giant GLOF. Fortunately, the Langmale event was small and downstream of those lakes.

Petrography of field samples of the Langmale landslide/GLOF/debris flow/landslide dam reveal granite, leucogranite, and gneiss, consistent with available geologic mapping (Streule et al.). The three major formations of the Upper Barun Valley are the Barun Gneiss, the Main Everest-Makalu Granite, and the Makalu Leucogranite. The large mineralogical and geomechanical contrast of these rocks might make bedrock failures and landslides more likely and can create deposits having large variations of grain sizes, thus tending to make space-filling and relatively impervious landslides and debris capable of impounding rivers.

Carina Ahlqvist plans to undertake further sampling in spring 2019 up to the summit of Makalu. Sample petrography will improve understanding of landslide hazards and the geology and tectonics of the Makalu massif.

Acknowledgement: We thank NASA's Interdisciplinary Science Program for support.

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Preservation of the early Oligocene Barrovian-type metamorphism caused the fluid-present melting along Bhagirathi River in the Uttaraganti area, NW India

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The Himalaya orogen was formed by collision between the India-Asia Continents during Eocene. Metamorphism in the Himalayan mid-crust after the collision was generally classified as the Barrovian-type metamorphism (kyanite zone) accompanied by crust thickening in the Late Eocene-Oligocene and the high temperature–type metamorphism (mainly sillimanite zone) in the Early-Middle Miocene caused the widespread anatexis (e.g., Searle et al., 2003). Recent discoveries of kyanite and sillimanite bearing migmatite from Eocene to Oligocene from Nepal (Imayama et al., 2012, Carosi et al., 2016) imply that the Himalayan crust could suffer regional partial melting even before the Early Miocene. Understanding the early partial melting is important because it could promote the flow in the thickened crust and greatly influence the early evolution of the Himalayan crust. In this study, we investigated schist and orthogneiss in the Main Central Thrust (MCT) zone and kyanite-bearing migmatites in the High Himalayan Crystalline (HHC) along Bhagirathi river in the Uttaraganti area, NW India based on geothermobarometry and zircon U-Pb SHRIMP ages. Main mineral assemblage of the HHC is Grt + Bt + Ms + Qtz + Ky ±Sil + Ru ± Ilm. Metamorphic P-T conditions estimated using geothermobarometers indicate that metamorphic grade across the MCT rapidly increases upwards from the MCT zone (ca. 500 °C, 6-8 kbar) to lower HHC (680-690 °C, 13-14 kbar), and then metamorphic grade basically decreases towards the upper HHC (560-590 °C). The P-T condition at thermal peak for lower HHC inferred from pseudosection including XFe and Grs isopleths of garnet core is T = c. 670-740 °C and P = c. 9.0-12.0 kbar. Residual pressures of quartz inclusions in garnet is estimated using the Raman spectrometer, and it gave 13.3-15.0 kbar preserving peak P. The pseudosection P-T condition for middle HHC reveals the P-T condition (T= 690-760 °C, P= 8.1-10.8 kbar) at thermal peak, whereas residual pressures yields the peak P of 11.0-12.5 kbar. Considering the P-T conditions, absent of peritectic K-feldspar, and existence of muscovite in these samples, it is likely that the partially melted kyanite-bearing migmatites were formed by fluid-present muscovite melting. Zircons in kyanite-bearing migmatites in the HHC are divided into detrital core and metamorphic overgrowth rim based on cathodoluminescence image. The detrital cores yield the 207Pb/206Pb age range of 631-3206 Ma, whereas the metamorphic rims yield the 206Pb/238U ages of 32.0 ± 0.1 Ma (sample in lower HHC) and 34.3 ± 1.3 Ma (sample in middle HHC). These results indicate that the HHC in the study area preserves regionally early Oligocene Barrovian-type metamorphism caused the fluid-present melting.

Inherited terrane properties explain enigmatic post-collisional Himalayan-Tibetan evolution

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The Himalayan-Tibetan (H-T) orogen evolved to produce enigmatic features which deviate from our expectations of continent-continent collisional orogenesis of uniform continents. In the uniform case, deformation of the crust and underlying continental lithospheric mantle (CLM) is expected to initiate near the suture, and propagate outwards into both the retro- and pro-continent, leading to crustal thickening, heating, and possibly removal of the retro-CLM as a single piece[1,2] resulting in a single magmatic event.

In contrast, the Himalayan-Tibetan orogen, in which Tibet comprises a number of terranes accreted prior to terminal continent-continent collision, evolved enigmatically with crustal deformation and magmatism migrating in seemingly erratic ways across the Tibetan plateau. The following complexities of the Himalayan-Tibetan system requiring explanation are summarized from[3-5] (and references therein).

1) Gangdese arc magmatic flare up ~51 Ma.
2) Tso Morari UHP exhumation.
3) Eo-Himalayan metamorphism and continuing south Lhasa terrane magmatism to ~38 Ma.
4) Early northward motion of the Indus-Yarlung suture and the Lhasa terrane.
5) Early (50–45 Ma) crustal shortening and thickening and magmatism in central Tibet, notably far from the Indus-Yarlung suture.
6) Outward growth of the Tibetan plateau from the Qiangtang terrane.
7) 27-21 Ma southward migration/jump of magmatism from Qiangtang to Lhasa terranes.
8) Widespread south Lhasa terrane 20-10 Ma small volume magmatism.
9) Recent (since 18 Ma) magmatism in northern Tibet and contemporaneous high-temperature, lower-crustal metamorphism, and crustal shortening and thickening.
10) Seismic interpretations indicating northward underthrusting Indian lithosphere beneath the western H-T orogen, and accumulated thick mantle lithosphere beneath Lhasa terrane and India in the central H-T orogen.
11) Recent, 3 Ma, Qiangtang and northern Tibetan crustal magmatism with entrained hot xenoliths.
12) 15 Ma onset of east-west extension in the Himalaya and Tibetan plateau.

We show using 2D thermo-mechanical mantle-scale geodynamical models that diverse styles of CLM deformation and delamination can evolve self-consistently as emergent phases in the model evolution. These phases are controlled by the inherited properties of the accreted terrane CLM (strength and density), where deformation initially localizes in the weakest and densest terranes. These phases of CLM deformation in turn provide novel explanations for many of the above noted complexities. Furthermore, these models also provide a number of testable predictions.

The broad implication of these models is that all highly deformed, large orogens containing previously accreted terranes are expected to evolve in idiosyncratic ways.

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Discovery of a widespread mantle component of 3He in thermal springs of the Lhasa Block and Tethyan Himalaya, eastern Tibet, and of the Lhasa Block, western Tibet: Evidence for roll-back of the Indian lithospheric mantle south of the Yarlung suture zone, and incipient mantle melting beneath the eastern and western Lhasa block

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Our Sino-US collaborative study of Xizang thermal springs and their noble gases has thus far sampled >150 separate springs for $^3He/^4He$ analyses, from 80–93°E and 28–35°N. In contrast to previous work focused on geothermal fields in the Yangbajain-Gulu rift, we sampled springs far beyond the Neogene rift systems, south into the Tethyan Himalaya, and north into the Qiangtang.

Observations of mantle contributions to ^3He at Earth's surface require incipiently melting mantle to release ^3He into the crust faster than the ^3He signal can be overwhelmed by radiogenic production of ^4He. Crustal helium (dominated by radiogenic ^4He) has a canonical $^3He/^4He$ ratio of $0.02•R_A$ (R_A = atmospheric $^3He/^4He$ ratio), whereas upper-mantle helium (enriched in primordial ^3He) has a canonical value of $8•R_A$. Any $^3He/^4He$ ratio > $0.1•R_A$ (after correction for air contamination, then denoted R_C) is accepted to have an unequivocal mantle component.

Cratonic Indian mantle far below its melting temperature cannot be a source of ^3He, so mantle-sourced ^3He in Tibet must come from hotter Tibetan mantle or asthenosphere. Many seismologists place the "mantle suture" (northern limit of Indian lithosphere at the Moho, equivalently southern limit of Tibetan/Asian mantle at the Moho) at 31–33°N, parallel to the Himalayan arc. However, previously studied springs within the Yangbajain-Gulu rift zone have $R_C/R_A \geq 0.1$ as far south as 30°N, just 90 km north of the Yarlung Zangbo suture (YZS), suggesting that either the mantle suture is south of 30°N, or that a tear in the subducting Indian plate permits linear asthenospheric upwelling and transfer of ^3He into the Yangbajain-Gulu rift.

Our new data show a simple linear upwelling is not an adequate explanation, because we measure unequivocal mantle contributions of ^3He far outside the rift zone, e.g. within the Gangdese batholith in Lhasa City. We also extend the "mantle-helium domain" with $R_C/R_A \geq 0.1$ much further south, to a southern limit that trends ESE from 50 km north of the YZS in the PumQu-Xainza graben to 100 km *south* of the YZS in the Cona-Sangri graben. In eastern Tibet (88°–93°E) our 38 springs with $R_C/R_A \geq 0.1$, spanning $2•10^5$ km^2 of eastern Tibet from north of the Banggong-Nujiang suture to south of the YZS, demonstrate that the India-Asia mantle suture must be in places *south* of the YZS, and that even if Indian *crust* is underthrust north of the YZS its subjacent lithospheric *mantle* has rolled back or delaminated.

In western Tibet (77–82°E) the extent of the mantle-helium domain is similar to that in eastern Tibet, in that our 10 springs with $R_C/R_A \geq 0.1$ are found from north of the Banggong-Nujiang suture south to the YZS or (further west) to the Karakoram Fault, and no springs with $R_C/R_A \geq 0.1$ are found further south. In contrast, in Central Tibet (82–88°E) the boundary between 8 springs with $R_C/R_A \geq 0.1$ and 19 springs with $R_C/R_A \leq 0.1$ follows the seismologists' mantle suture at 31–33°N.

Our new results, combined with our re-interpretations of seismic common-conversion point receiver-function images, suggest a tri-partite segmentation of the Indian mantle lid that underthrusts Tibet only to the Karakoram Fault in Western Tibet, almost to the Bangong-Nujiang suture in Central Tibet, and not even to the Yarlung Zangbo suture in Eastern Tibet.

Tectonic Evolution of the Pamirs and North-western Tibetan margin (West Kunlun) as determined from the sedimentary record of Aertashi and Kekeya, Western Tarim Basin, China

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The Pamir and West Kunlun Mountain ranges of Northern Tibet, located in Central Asia at the western end of the India-Asia collisional system, is the location of some of the Earths most spectacular and dramatic mountains. The Pamir orogen is an example of an active intracontinental collisional zone and the focus of much debate regards the timing of indentation of the Pamir and lithospheric model responsible for the formation of the orogen.

The Pamir orogeny has a complex geological history and comprise of numerous amalgamated terranes, which have distinct petrographic and thermochronological characteristics. The terranes have amalgamated as a result of collisions during Paleozoic, Mesozoic, the subsequent closure of the Tethys and the Cenozoic Indian-Eurasian collision. The sedimentary sequences located on the southern margin of the Tarim Basin and north of the Pamir and West Kunlun orogenies were deposited from the Jurassic to present. The sedimentary sequences have recorded a near continuous record of the changes in depositional palaeo-environment providing a record of these collisional processes and geological evolution of the hinterland regions.

Two sedimentary sections were studied concentrating on the Cenozoic sedimentation to provide a comparison between the detrital archive recording the geological evolution of the Pamir at Aertashi, located on the Eastern Pamir, and the sediment sequence derived from the West Kunlun northern margin of Tibet, at Kekeya, over the equivalent period.

Stratigraphically the sections are comparative, recording predominantly low energy redbeds in the lower section. A dramatic change in depositional environment occurs in the upper sections and transition to the high energy Xiyu conglomerates, occurring at 15 Ma at Aertashi and 27 Ma at Kekeya. The Xiyu conglomerates are postulated to represent a phase of uplift and the initiation of a thrust belt formed on the eastern margin of the Pamir with the Qimugen structural wedge at Aertashi. This dramatic change in lithology from the deposition of low energy redbeds to conglomerates is marked structurally by changes in bedding and an 'on-lap' relationship signifying syn-orogenic uplift. The thrust belt of the eastern Pamir margin is suggested to young northwards in a transpressional setting.

The precise timing of the crustal evolution of the Pamir indentation and timing of uplift and exhumation is much debated. The tectonic model responsible for the formation of the orogen is also poorly understood with several models currently debated.

Applying a number of techniques to the Aertashi and kekeya sedimentary sections; concentrating on the understudied Xiyu conglomerates we show using detrital ages from U-Pb zircon, apatite fission track (AFT), zircon fission track (ZFT), U-Pb apatite, U-Pb Rutile and Sm-Nd bulk rock analysis. These results will be discussed in terms of comparative provenance analysis, timing of metamorphism, exhumation and tectonic evolution of the east Pamir and NW margin of Tibet in the West Kunlun region.

Exhumation History of Bhumichula Plateau, Western Nepal

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[1]*University of Arizona*

The Greater Himalaya generally has extreme topography with local relief >3000 m. However, in western Nepal, several outlying areas of Greater Himalayan rocks have anomalously low relief at moderate to high elevations. One such area is the Bhumichula plateau, located on the northern limb of the synformal Dadeldhura klippe, an erosional outlier of Greater Himalayan high-grade metamorphic rocks structurally above the Main Central thrust. The plateau extends over ~250 km^2 with an internal relief of ~300-400 m, and flanking relief of up to ~4000 m. This study aims to constrain the exhumation history of the plateau and its flanks in the Dadeldhura klippe to examine the enigmatic presence of this low relief area in the context of regional tectonics. Our samples extend upstream onto Bhumichula plateau along steep elevation transects and cover the entire breadth of the Dadeldhura synform, allowing assessment of the role played by structural uplift on the synform flanks, as well as headward fluvial erosion. We applied zircon-He (ZHe) and apatite fission track (AFT) low-temperature thermochronology to samples from the plateau and the flanks of the Dadeldhura klippe to attain a comprehensive regional cooling history. Our ZHe ages from the klippe are ~14-11 Ma, possibly reflecting exhumation and cooling due to emplacement of the Main Central thrust sheet and or the underlying Ramgarh thrust sheet. Preliminary AFT ages on the surface of Bhumichula plateau at elevations >4000 m are 7-9 Ma whereas ages on the flanks of the klippe at lower elevations are ~11 Ma. We suggest that late Miocene ages on the flanks of the klippe reflect exhumation due to uplift of the Dadeldhura klippe during emplacement of the Ramgarh thrust sheet. On the other hand, late Miocene ages on the plateau surface could reflect exhumation and paleodrainage incision due to formation of the Lesser Himalayan duplex.

NSF-Tectonics, EAR-1763432

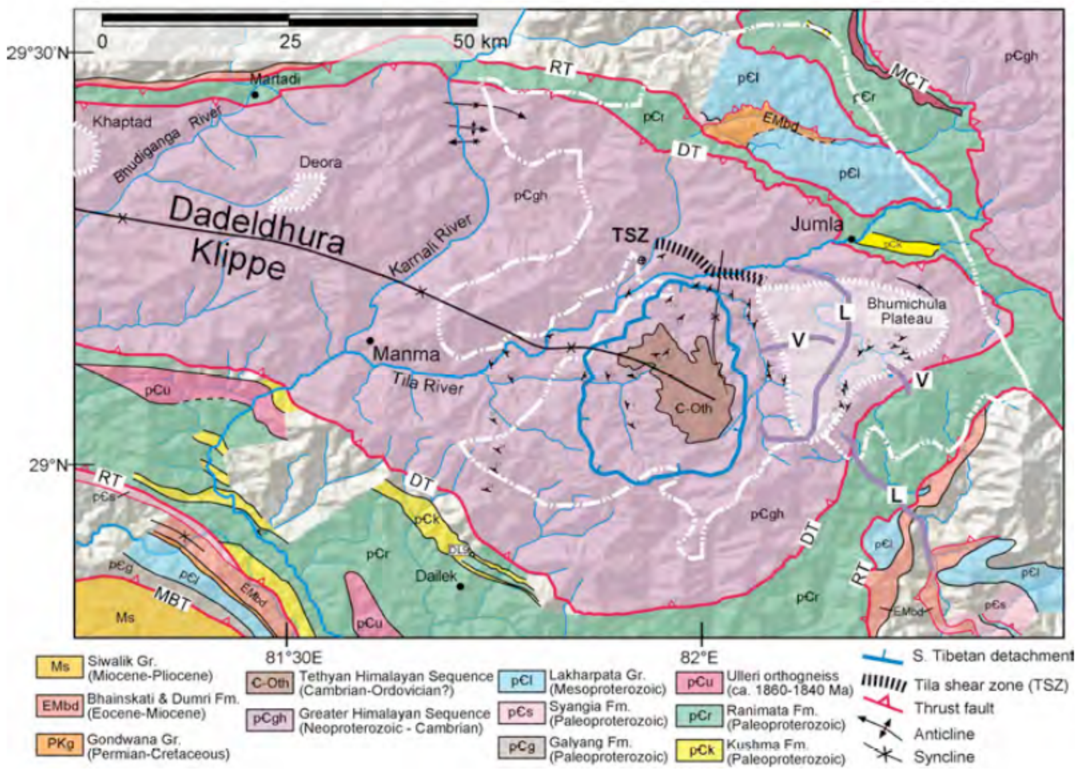

Figure 1. Geological map of the Dadeldhura klippe in western Nepal. Bhumichula plateau lies on the northern limb of the synformal klippe (DeCelles et al., in review)

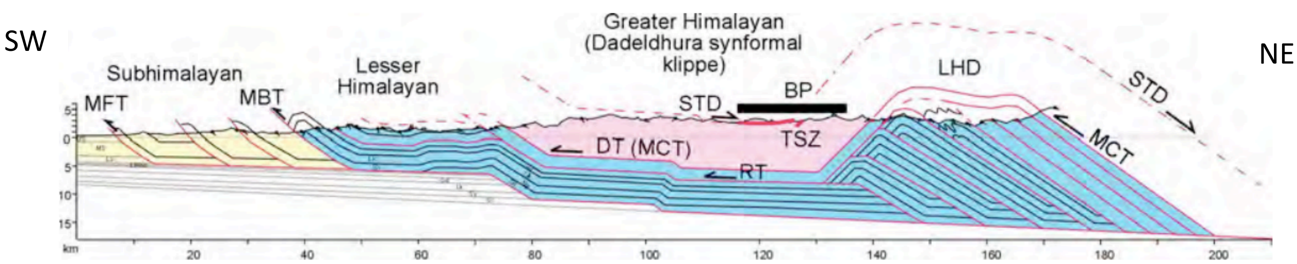

Figure 2. Preliminary cross-section of the Dadeldhura klippe in western Nepal (DeCelles et al., in review). Black bar represents span of Bhumichula plateau. MFT- Main Frontal thrust; MBT- Main Boundary thrust; DT- Dadeldhura (Main Central) thrust; RT- Ramgarh thrust; STD- South Tibetan detachment; TSZ- Tila shear zone; LHD- Lesser Himalayan duplex.

Detrital zircon provenance analysis of trench basin strata along the India-Asia suture in southern Tibet suggest that the Lhasa River is antecedent and transported sediment from the central Lhasa Terrane to the trench in Late Cretaceous time

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During Late Cretaceous time, Rongmawa Formation trench basin strata were deposited in the subduction zone that consumed Neo-Tethyan oceanic lithosphere along the southern margin of the proto-Tibetan Plateau. We conducted detrital zircon (DZ) U-Pb geochronology on six trench basin samples (n = 1,716) collected near Dênggar, Tibet (~500 km west of Lhasa city) to assess the provenance of these rocks and reconstruct Late Cretaceous sediment transport pathways. Provenance analysis consisted of qualitative comparisons, multi-dimensional scaling, and non-negative matrix factorization to extract source spectra. All trench basin samples contain DZ ages that point to a unique source around Lhasa city, north of the Late Cretaceous Gangdese magmatic arc. This signal is only rarely observed in forearc strata, suggesting that the transport pathway to the trench largely bypassed the forearc basin. The modern Lhasa River catchment contains the requisite sources and its main trunk transects the Gangdese magmatic arc, joining with the Yarlung River at a barbed junction at the India-Asia suture. At this location, forearc assembages are not preserved, which could either reflect pre-Late Cretaceous subduction erosion or later modification during India-Asia collision. We interpret that the Lhasa River is an ancient feature that transported sediment to the subduction zone in Late Cretaceous time and persisted during India-Asia collision. The Ancestral Lhasa River was likely analogous to the modern Fuji River, which crosses magmatic arc highlands in southern Japan and feeds the Nankai Trough by connecting to a submarine canyon and a continuous, >400-km-long, trench-parallel submarine channel.

Two rapid uplifting in the northern margin of Tibet from sedimentary records

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The tectonic revolution of Tibet is recorded by the sedimentary strata of basins along the northern margin of the plateau. Based on the combined interpretation of drilling wells, field outcrops and reflected seismic profile, the oldest strata filled in the Cenozoic basins in the northern margin of Tibet is the Xiliugou Formation (58~51Ma) in the Lanzhou Basin, while the oldest strata in Qaidam Basin and Xining Basin are Lulehe Formation (55.8?~43.8Ma) and Qijiazhuan Formation (55~50Ma), respectively. The oldest strata in the Guide-Xunhua Basin, Linxia basin, and Jiuquan Basin are Xining Group (~52~21Ma), Tala Formation (29~21.4Ma) and Huoshaogou Formation (40.5~33Ma), respectively.

Since 55Ma lateral contiguous alluvial fan and fan delta deposited in the front of the Altyn Mountains and the northern Qaidam Basin. The sediments of Dahonggou section in Yongdeng Basin is of orange-red mudstones and massive sandstones interlayered with fine conglomerates. And the Lanzhou and Xiejia sections in Xining Basin are of purple-red or maroon mudstones interlayered with yellow-green argillaceous plaster. They are the river-salty lake sedimentary systems with the sources from the Western Qinling Mountains. Although the simultaneous sedimentary strata have not been revealed in the Jiuquan Basin, the molasses may develop in the front of the northern Qilian Mountains. The alluvial fan and fan-delta developed in the northwestern Qaidam Basin should be response of the rapid uplifting of Tibet due to the collision between the Indian and Eurasian Plates.

During the Eocene to the Middle Miocene (Before 8Ma), the East Kunlun-Qinling Mountains, Qilian Mountains and their branch mountains had been uplifted. The Qaidam Basin, Lanzhou-Xining Basin, Guide-Xunhua Basin and Jiuquan Basin which filled by the river and salty lake sediments, continued to expand. The deposition range of the Qaidam Basin expanded rapidly and fan-delta sedimentary system started to appear in the front of the middle Kunlun Mountains. Whereas, since 20~14Ma, the Daban Mountain, Laji Mountain and Jishi Mountain that separated the Xining, Lanzhou, Linxia and Guide-Xunhua Basins, began to gradually uplift, and the alluvial fan-braided river sediments started depositing in the mountain front of the Jiuquan, Linxia and Xining Basins. Especially, the thick conglomerates and glutenites of Guidemen Formation which belonged to alluvial fan-gravel braided river, deposited in the Guide-Xunhua Basin. The Tibetan Plateau was mainly in a relatively stable adjustment stage.

Since the Late Miocene (after 8~5Ma), large-scale alluvial fan and fan-delta have deposited in the northern, southern and southwestern margins of the Qaidam Basin. And the Guide-Xunhua Basin, the Ganjia conglomerates formation consisting of large set of gray boulder rocks interlayered with lenticular pebbly sandstones and sandstones developed, and a thick conglomerate strata named the Jishi Formation, consisting of blue-gray glutenites interlayered with brown-yellow mudstones and sandy mudstones formed in the Linxia Basin. In the Jiuquan Basin, a thick sandy-muddy gravel layer named the Yumen-Jiuquan Formation was also deposited. All the above conglomerates formations belonging to alluvial fan-gravel braided river systems mainly reflect the sedimentary response of the tectonic uplift of the Laji, Jishi and northern Qilian Mountains and indicate another rapid uplift event of the Tibetan Plateau since 8~5Ma.

Paleozoic metamorphism in the Himalaya? Potential implications of new garnet Lu-Hf geochronology

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The Himalayan orogen initiated ~55 myr ago reflecting the onset of continental collision between India and Eurasia. It has been widely examined as the modern analogue for large, hot orogens. Much of the work that has defined current structure and evolution of Himalayan orogen has relied on various analytical techniques to gain insight into metamorphic, deformational, and anatectic processes. Many of these techniques are based, at least in part, on the major and/or trace element compositions measured in metamorphic garnets and accessory geochronometers, such as monazite and zircon. These data are often used to inform the pressure-temperature (P-T) conditions specimens were subjected to and interpret the timing of chronometer growth with respect to derived P-T paths.

Recent work in the Kanchenjunga region of far eastern Nepal used monazite petrochronology and interpreted prograde vs. retrograde growth based on trace elements along with pressure-temperature-time (P-T-t) paths (derived mainly from garnet major element chemistry) to infer the existence of five "cryptic" discontinuities. New results of Lu-Hf garnet geochronology, conducted to test the interpreted timing of prograde metamorphism in specimens from different inferred thrust sheets, however, yield surprising dates of 291.3 ± 0.7 Ma and 293.3 ± 0.5 Ma. These Paleozoic ages indicate that at least some of the garnet material in the Kanchenjunga region is relict and formed long before the initiation of Himalayan orogen. This implies that P-T-t paths built with chemical information from such grains may not accurately reflect the conditions and relative timing of garnet growth as previously interpreted. The ca. 290 Ma ages obtained from the garnet in two independent, spatially separated specimens overlaps directly with initial rifting and the opening of the Neotethys ocean.

Apatite fission track data reveal the Mid-Miocene re-activity of the Baiganhu Fault, part of the Altyn Tagh Fault

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The Altyn Tagh fault (ATF) is a large-scale bounding fault in the Northeastern Tibetan Plateau (NETP), which plays a key role in the Cenozoic evolution of the whole Tibetan Plateau (TP). As a branch of the ATF, the Baiganhu fault is bound to play an important role in the Cenozoic development of its adjacent region. The Baiganhu fault is the boundary between the East and West Qimen Tagh Mountains. In this study, we collected three granite samples in the Qimen Tagh Mountains near the Baiganhu fault for which apatite fission track lengths and ages were obtained. HeFTy modeling shows that a rapid cooling event occurred since ~14-8 Ma, which means that the preexisting Baiganhu fault has been re-activated since the middle Miocene. Combined with previous studies, the Qimen Tagh Mountains experienced the two-stage evolution history, at ~40-30 Ma and since ~14-8 Ma. The central part of the East Qimen Tagh Mountains experienced the first stage uplift, while the West Qimen Tagh Mountains and two end-sides of the East Qimen Tagh Mountains possibly experienced the second stage uplift. This Cenozoic two-stage evolution has impacted not only the Qimen Tagh Mountains, but also the whole NETP.

Two-mica granite as a complement to crystal accumulation: Insights from the Eocene Lhunze pluton-subvolcanic complex, South Tibet

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The link between volcanic and plutonic rocks remains an elusive issue in Earth sciences **(**Bachmann, and Bergantz, 2004**).** The Lhunze area (SE Tibet), in the eastern Himalaya, uniquely juxtaposes both Cenozoic granitic plutons and sub-volcanic rocks in the Tethyan Himalayan Sequence. In this study, the potential petrogenetic connection between crystal-rich two-mica granite (TMG) and crystal-poor subvolcanic leucogranite porphyry (SLP) from the Lhunze area is investigated using petrology, geochronology, and geochemistry. Igneous layering and feldspar comb structure in the TMG indicates mineral segregation and accumulation. Monazite U-Th-Pb ages imply the TMG crystallized in the Mid-Eocene at 44-43 Ma, consistent with previous zircon U-Pb isotopic data (Aikman et al., 2008; Zeng et al., 2011, 2015). Monazite in the SLP also records a U-Th-Pb age of 44 Ma, suggesting contemporaneous emplacement with the TMG. SiO_2 concentrations increase from intermediate (69 wt%) in the TMG to highly silicic (74 wt%) in the SLP. REE patterns, Ba and Zr concentrations, and Zr/Hf ratios are consistent with a model in which a parent magma differentiated into a TMG cumulate and a SLP melt extract. Sr contents of monazite in both the TMG and SLP indicate that crystal fractionation dominated melt evolution. Whole rock and in situ apatite Nd isotope compositions of SLP are slightly less radiogenic than TMG, indicating the SLP likely assimilated more Precambrian country rocks during its intrusion. We interpret the TMG and SLP to reflect fractional crystallization of a single magma mush, such that crystals accumulated to form the TMG, while the complementary melt segregated to form the SLP. These data predict magma stratification within the crust, with increasingly silicic melts at shallower levels (Deering, 2011). More broadly, Eocene Neo-Tethyan slab breakoff could have increased mantle heat flow and triggered the generation and extraction of large volumes of silicic melt. Complementary melt extraction and crystal fractionation might have been the dominant process for forming the Himalayan upper continental crust during the Eocene.

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A structural model for the South Tibetan detachment system in northwestern Bhutan

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One of the most enigmatic aspects of Himalayan structural architecture is the generally north-dipping, north-vergent South Tibetan Detachment system (STDS), which separates migmatitic, mid-crustal rocks of the Greater Himalayan (GH) package from overlying, low-grade to unmetamorphosed, upper-crustal sedimentary rocks of the Tethyan Himalayan (TH) package. Since its recognition, the STDS has become a key focus of Himalayan research, primarily for the kinematic challenge that it presents, requiring north-vergent displacement during construction of an overall south-vergent contractional orogenic belt. A critical prerequisite for interpreting the genesis of the STDS is an understanding of the structural and metamorphic field gradients that are the cumulative result of shearing, and the implications of these gradients for the style, offset magnitude, and structural evolution of this detachment system. Here, we present data that illuminate trends in peak and deformation temperature, quartz crystallographic fabric development, thin section-scale finite strain magnitude, and kinematics along a transect across the STDS in northwestern Bhutan. These data facilitate definition of the boundaries and internal architecture of the STDS, allow estimation of offset magnitude, and are integrated with published geochronology to produce a detailed model of the structural evolution of the shear zone.

We divide the STDS into distinct lower and upper structural levels. The lower level consists of the uppermost ~2 km of GH rocks, with the base defined by the onset of top-to-NW shear-sense indicators and an upward-increasing gradient in quartz fabric intensity. Integrating kinematic vorticity numbers with published pressure data defines ~6-13 km of apparent structural thinning (86-93% shortening) accommodated via ≥30-76 km of simple shear-dominant (W_m = 0.74-0.88), top-to-NW displacement. Peak metamorphic temperatures within the lower level of the STDS zone are ~650-750 °C. The upper level of the STDS zone consists of the lowermost ~4.5 km of TH rocks, which accommodated ≥21 km of top-to-NW displacement via an upward decrease in pure shear-dominant (W_m = 0.00-0.45), transport-parallel lengthening (from 44% to 2%). Two intervals of telescoped, upright isotherms are observed in the upper level of the STDS zone, and define ~160-260 °C/km field gradients. The lower of the two intervals exhibits an upward decrease in peak metamorphic temperature from ~700 °C to ~450 °C over a structural thickness of ~1.5 km. Above this, temperatures increase abruptly upward from ~450 °C to ~620 °C, which we interpret as the result of post-STDS thrust repetition. The upper interval of telescoped isotherms exhibits an upward decrease from ~620 °C to ~320 °C over a structural thickness of 1.1 km. Telescoped isotherms are located entirely above the highly-thinned lower level of the STDS zone, and therefore are spatially decoupled from strain magnitude. We interpret this decoupling as a consequence of progressive elevation of isotherms during distributed intrusion of granite sills that spanned the duration of shearing. The top of the STDS zone is defined by an abrupt upward decrease in finite strain. Above the STDS zone, peak temperatures decrease gradually upward from ~320 °C to ~250 °C through a 7 km-thick section of overlying TH rocks, defining a field gradient of ~13 °C/km.

Previous work has demonstrated that prograde monazite growth in GH rocks occurred between ~26 and ~21 Ma, with peak metamorphism and partial melting interpreted at ~22-23 Ma, bracketing the earliest possible timing of shearing on the STDS. Published geochronology also shows that initial shearing was accompanied by retrograde growth of monazite in GH rocks from ~19 to ~15 Ma, and intrusion and solid-state deformation of granite sills throughout the STDS zone, which crystallized between ~24 and ~16 Ma. TH rocks in the upper level of the STDS zone cooled through ~425 °C by ~11 Ma, potentially bracketing the final stages of shearing.

Late Jurassic ophiolite obduction and the Lhasa-Qiangtang collision in central Tibet

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When the Bangong-Nujiang suture ophiolite was obducted and the Lhasa and Qiangtang terranes collided in central Tibet remain topics of great debate. We investigated subaerial to shallow marine strata (Dongqiao Formation) that sit unconformably on ophiolites in the Bangong-Nujiang suture zone. Based on foraminiferal and coral studies, the Dongqiao Formation was deposited during the Oxfordian and Kimmerigian (Late Jurassic time). Provenance analysis of sandstones including sandstone composition, geochemistry of detrital spinels, and detrital U-Pb age populations suggest that the Dongqiao Formation was sourced from the Bangong-Nujiang ophiolites, with a forearc supra-subduction zone signal, together from sedimentary and metamorphic rocks of Lhasa terrane affinity. We propose that Bangong-Nujiang suture ophiolites were obducted onto the Lhasa terrane, or a micro-continent of Lhasa terrane affinity, during Late Jurassic time.

Early Eocene syn-orogenic magmatism, metamorphism and tectonic event in Gangdese Belt (southern Tibet) inferred from *P-T-t* and kinematic constraints: Implications for Indo-Asian collision

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The collision between the Indian and Eurasian continents is considered to be one of the major tectonic events of Cenozoic time. However, the collision timing and processes are still in hot debate. In this contribution, we present a new geological map together with cross-sections. We combine field relations, petrology, structural geology, geochronology and phase equilibria modeling to interpret the tectonic evolution of the southern Tibet. These investigations reveal that the Nymo intrusive complex was formed at c. 50-47 Ma, dominated by diorite pluton. Meanwhile, the overlying Jurassic Bima volcano-sedimentary sequence underwent Early Eocene (50-47 Ma) high temperature (HT) amphibolite facies metamorphism. Petrology and phase equilibria modeling of garnet-biotite schists reveal that these rocks have mineral assemblages of melt + plagioclase + garnet + biotite + magnetite + ilmenite + sillimanite formed under conditions of 5.3–7.5 kbar and 700–800 °C. Kinematic analysis suggests that the northern margin of the intrusive complex is constrained by top-to-the-S/SE shearing, with syn-tectonic veins aged from 49 to 47 Ma. Combining with available data, we contend that the Early Eocene Nymo intrusive complex represents part of the c. 50 Ma magmatic 'flare-up', whose magma chamber triggered the HT amphibolite facies metamorphism. Meanwhile, due to the continuing Indo-Asian collision, a top-to-the-S/SE shearing occurred. The synchroneity of magma emplacement, HT metamorphism and S/SE-directed thrusting in the Gangdese Belt roughly coincides with the main collision between the Indian and the Asian continents. In addition, the collision indeed triggered the crustal thickening of the Lhasa terrane.

Evidence for the Breakup of the Indian Plate and Rise of the Shillong Plateau

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There is remarkable simplicity in the structure of the foreland basin of the Himalayan fold and thrust belt. However, this simplicity breaks down east of 90º E, as we encounter the upto 2 km tall Shillong Plateau. We use a combination of modern geodetic velocities and river steepness indices to show active convergence of the Shillong Plateau with the Indian plate and the Indo-Burman Wedge. By constructing a regional block model, we estimate the modern convergence rate at 6-8 mm/yr which may be partitioned among the Dauki Thrust, Dapsi Thrust, as well as faults along the northern extent of the Shillong Plateau, bordering the Brahmaputra Basin. Using objective model and parameter selection we estimate a dip of ~28º for the Dauki Thrust and show that the fault is locked and accumulating strain currently. Comparisons of modern convergence rates with millennial to quaternary (and longer) exhumation trends of the upper plate indicate that not all the inter-block convergence can be explained by shortening of the plateau. This leads us to hypothesize that the Indian oceanic plate, south of the Dauki Thrust may be subducting beneath the Shillong Plateau.

Correlating Tibet and the Pamirs: New constraints from detrital zircon age distributions

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We present zircon age distributions for metamorphic rocks exposed north of the Karakoram Fault between Pangong Lake and Sumur (Nubra Valley), spanning 100 km along strike. We used LAICP mass spectrometry to measure uranium and lead isotope ratios for around 240 grains from each of five samples. One sample had a narrow age distribution of 125 to 156 Ma, suggesting an igneous protolith, possibly related to the Qiangtang Arc. The remaining samples were metapelites with maximum depositional ages between 413 and 506 Ma. Close to Lake Pangong, our detrital zircon age distributions are similar to those found nearby in the western Qiangtang terrane of Tibet. This supports the hypothesis that the mid-crust of the Qiangtang terrane is exhumed by the Angmong normal fault system, which connects the Karakoram Fault and Longmu Co Fault. Moving northwest along strike, the age distributions are similar. However, we cannot show whether this correlation continues into the South Pamir or Central Pamir terrane, because the reported zircon spectra of these terranes are not distinct. Our data are consistent with the model of relatively young (age less than 1.4 Ga) crust fragments with a common history on the Gondwanan margin. The age of the youngest zircons observed in these fragments increases steadily from around 350 Ma in the west (Central Pamir terrane) to around 500 Ma in the east (Qiangtang and Lhasa terranes). This may be related to the diachronous opening of the Palaeo-Tethys, or may simply indicate greater exhumation in the east.

Seismological constraints on the density, thickness and temperature of the lithospheric mantle in southwestern Tibet

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We constrain the lithospheric mantle in southwest Tibet to be cold, thick, and dense by considering seismological observations, isostasy, and gravity anomalies. First, virtual deep seismic sounding (VDSS) indicates that the thickness of the crust increases from 50 ± 4 km beneath the Himalaya to 70 ± 4 km in the Lhasa terrane. This implies a ‘residual topography’ (difference between true elevation and the isostatic elevation of the crust) of -2.5 ± 1.5 km. Taking into account deviations from isostasy, the lithospheric mantle must be dense enough to depress the surface by 1 to 5 km. Our joint inversion of fundamental-mode Rayleigh wave dispersion and receiver functions suggests that the vertically-polarised shear wave speed (V_{sv}) is 4.6 ± 0.1 km s^{-1} at depths of 120 to 300 km. From the shear speed profile, we estimate the geotherm, which is on average 200 °C below the 1350 °C adiabat, and suggest that the base of the lithosphere is at a depth of 290 ± 30 km. To match the negative buoyancy, the lithospheric must be denser, on average, than ‘normal’ fertile adiabatic mantle, which rules out a depleted (harzburgite) composition. This is surprising, given that the origin of this lithosphere is thought to be the depleted, cratonic Indian slab. We conclude that either the Indian slab is not currently in place beneath southwestern Tibet, or that its composition has changed to increase its average density. Our constraints of high density and fast seismic propagation favour a lithospheric mantle composition containing eclogite, but we cannot rule out cold mantle with a lherzolite composition.

History of subduction erosion and accretion recorded in the Yarlung Suture Zone, southern Tibet

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The history of pre-Cretaceous subduction accretion and erosion along the Yarlung Suture Zone remains poorly constrained. We present new geological mapping along ~200 km of the suture zone, 4881 detrital zircon U–Pb ages, and sandstone petrography for the subduction complex and Tethyan Himalayan strata. We provide the first documentation of the ~158 Ma marine Xiazha Formation, which contains volcanic clasts of intermediate to felsic volcanic rocks and ooids with both calcareous and volcanic cores. Based on our new data and synthesis of published data, we present a model in which the Zedong arc represents the southwards migration of the Gangdese arc onto a forearc ophiolite that was generated proximal to the southern Asian margin during Neotethyan slab rollback at 160–150 Ma. This contrasts with previous suggestions that the Zedong arc, Yarlung ophiolites and subduction complex rocks developed above an intra-oceanic subduction zone thousands of kilometers south of Asia. Although Gangdese arc magmatism began in the Middle Triassic, the only forearc units preserved are 160 Ma until collision between the Xigaze forearc basin and Tethyan Himalaya at ~59 Ma. This suggests that almost all pre-Cretaceous forearc assemblages have been removed by subduction erosion at the trench.

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Kinematics and time constraints of the South Tibetan Detachment System: new data on the exhumation of the belt

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The South Tibetan Detachment System (STDS) is a system of regional ductile-to-brittle top-to-the E and NE normal shear zone and faults developed for more than 2000 km along the Himalaya strike .
STDS separating the lower medium to high-grade metamorphic rocks of the GHS from the overlying THS has a complex architecture. Along many sections of the belt it is characterized by a lower ductile shear zone, affecting the upper part of the high-grade-metamorphic rocks of the GHS and the amphibolites facies rocks at the bottom of the THS (lower THS) (i.e. Checka Formation, Haimanta Group, Everest Series) and by an upper brittle fault, above which the very-low-grade to non metamorphic rocks of the THS (upper THS) crop out. A primary role of the STDS, acting coevally with the lower Main Central Thrust with opposite kinematics, has been attributed in the exhumation of the metamorphic core of the belt (Godin et alii, 2006 for a review).

Multidisciplinary studies have been conducted along several sections of the belt, spanning from NW to Central and Eastern Himalaya, integrating field-based, microstructural, petrographic and geochronological studies.

The ductile shear zone is always very-well developed in the study sections and it affects both tectonic units, i.e. THS and GHS. Due to the carbonate-rich nature of THS and GHS rocks along many of our study transects, identifying and mapping the STDS has not been a simple task ,
Ductile deformation is always heterogeneous, leading to the development of high- to low-temperature mylonites associated to a mylonitic foliation striking parallel to the STDS and dipping at low-angle to the N and NE and all kinematic indicators confirm a top-to-the N and NE sense of shear.

Vorticity of flow (Wk), estimated by different vorticity gauges, highlighted a non-coaxial deformation regime, with a main pure shear component, acting during the STDS activity both in high- and medium-temperature and low-temperatures mylonites. In addition a condensed metamorphic field gradient has been clearly detected through deformation mechanism and microstructures pointing out a component of shortening perpendicular to the shear zone responsible for the telescoping of the metamorphic isograds at the base of the THS.

Ductile shearing has been constrained in mylonites deformed in the STDS by in situ monazite datings and Ar-Ar geochronology. Our results point out that the ductile activity of the STDS is not coeval with the shearing along the lower Main Central Thrust zone, at least along the study sections, but started after the activation of the older Higher Himalayan Discontinuity in the GHS (Montomoli et al., 2015; Carosi et al., 2018). The STDS could have been active in different pulses during the exhumation of the GHS, so the exhumation of the unit driven by the activity of the two opposite shear zone, i.e, STDS and MCT, should be deeply revisited.

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Salient-recess transition structures in the Himalaya: Insights from the Gish Transverse Zone in the Darjiling-Sikkim Indian Himalaya

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The Himalayan orogenic belt is wedge-shaped in cross-section and arcuate in map view at 100s of km scale. However, the Himalayan arc is sinuous at 10s of km scale. This sinuosity is expressed as salients and recesses. Salients are convex whereas recesses are concave to the Himalayan foreland. The Nahan salient is bordered by the Dehradun recess to its east and the Kangra recess to its west. These salients and recesses have been well studied in the NW Himalaya. In the Eastern Himalaya, the Dharan salient and the Gorubathan recess have been studied more recently. The Gish Transverse zone (GTZ) has been identified as the transition structure between the Dharan salient and Gorubathan recess in the Darjiling-Sikkim Himalaya and has been mapped over an aerial distance of ~50 km as a ~1.5 to 2 km wide, NNE–SSW trending, near vertical to west-dipping, sinistral strike-slip fault zone that extends from the mountain front northward to the Indo-Tibet-Bhutan border near the Yadong-Gulu rift.

The GTZ was identified as an emergent tear fault characterized by fault gouge anastomosing around islands of less deformed rocks and cohesive cataclasite indicating near-surface brittle or elastico-frictional deformation. The GTZ thickness varies along its strike. We measured a maximum GTZ thickness of ~2 km in the Munsiari thrust sheet in a geomorphic saddle near Labha town. A spaced cleavage sub-parallel to the trend of the GTZ is seen developed in the islands of less deformed rocks in the GTZ. The orientation of the cleavage is broadly similar from south to north across the thrust sheets of the Himalayan belt. In the Ramgarh sheet near the mountain front, the mean orientation of cleavage is 009°/74°E. In the Munsiari thrust sheet the mean orientation of the cleavage is 013°/88°E and 011°/83°E near the Indo-Tibetan border and the Labha town, respectively. Valleys and saddles at water divides are typical geomorphologic expressions of the GTZ. Stream Length Index (SL) indices computed along some of the river valleys that intersect the GTZ are anomalously low compared to those computed outside the fault zone irrespective of the lithology and the thrust sheet.

The kinematics of deformation west and east of the GTZ varies immensely. The Dharan salient west of the GTZ is characterized by multiple thrusts in the footwall of the folded Main Boundary thrust that deform and expose the Siwalik section. In the Gorubathan recess east of the GTZ, the Siwalik section is not exposed and the major structural mountain front is defined by the Ramgarh thrust. The Main Boundary thrust is blind but neotectonically active as the overlying Quaternary fans have been warped near the surface trace of the fault. Global Positioning System based geodetic measurements reveal that the frontal part of the Himalayan décollement (Main Himalayan thrust) is locked in both Dharan salient and Gorubathan recess. However, higher convergence (∼7 mm/yr) is observed in the recess than the salient (∼3.5 mm/yr between 27 and 27.5 ºN north of the locked region indication differences in kinematics even over decadal time scales.

The salient-recess transition zones, therefore, have an important role in the evolution of the Himalayan orogenic belt. The detailed geometry, kinematics, landscape development of these transverse faults and their role in sculpting the Himalayan mountain front remains largely unknown. Therefore, that there is a strong need to study the Himalayan transverse zones in more detail and connect them to the adjacent salient-recess pairs to develop a better understanding of the deformation kinematics, geometry, landscape evolution, segmentation of the Himalayan arc and consequently the Himalayan seismic hazard.

Mineralogy, geochemistry and genesis of Fe-Cu deposits in Damal Nisar, SW Chitral, NW Kohistan Arc, Pakistan

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Iron-copper deposits occur in the Damal Nisar area of southwestern Chitral, NW Pakistan. Field, petrographic and geochemical data were integrated to characterize these deposits and decipher the nature and origin of their ore forming fluids. More than a dozen, small to medium-size, lens-shaped massive ore bodies occur in the area hosted in the metamorphosed Aptian-Albian volcanic and sedimentary (mainly marble) rocks of the Gawuch Formation. The Gawuch Formation has been intruded along most of its thickness by Mirkani granitoids (diorite, quartz-diorite, granodiorite and granite). Both the Gawuch volcanic rocks and the intruded Mirkani granitoids dominantly display arc-related, calc-alkaline geochemical characters.

The ore minerals in these bodies include oxides of iron (magnetite and hematite) as major phases while malachite and occasionally bornite and pyrite constitute minor constituents. Whereas garnet, pyroxene and olivine constitute the prograde phases, epidote, calcite, chlorite, serpentine and amphibole seem to be part of retrograde assemblage. The presence and mode of occurrence of calcite, clay minerals, sericite and chlorite indicate pre-ore alteration of the Mirkani granitoids. On the other hand, the formation of hematite, limonite and malachite suggests post-ore alteration.

The magnetite in the samples was investigated by in situ LA-ICP-MS analysis at Stockholm University. The grains demonstrate variable concentrations of Ti, V, Cr, Ca, Co, Ni, Sc, Zn, Cu, Mo, Sn, and Ga with Ti,V and Mn being the most abundant trace elements yielding concentrations up to 1.3, 0.4 and 2.52 wt.% respectively. Trace elements systematics (e.g., Cr vs. Ni, Ni/Cr vs. and V_2O_5 vs. TiO_2) and petrographic data coupled with field observations imply that the low-TiO_2 magnetite grains that form the bulk of the Fe-ores, show a calcic-magnetite-skarn association. The time-space evolution of the magmatic-metasomatic processes in Damal Nisar mineralization district demonstrates that the island arc-related magma which originated the Mirkani granitoids (KIA), have been the ore forming hydrothermal source for these skarn deposits.

However, few of the magnetite samples exhibit relatively higher concentration of TiO_2 (>1wt.%) which could be attributed to relatively high temperature magmatic hydrothermal fluids (c. 500 to 700^0C) from the Mirkani source or may have been the inherited grains of the volcanics belonging to Gawuch Formation. The Damal Nisar Fe-Cu deposits are exhibiting mineralogical assemblages as well as hydrothermal characteristics consistent with those of typical Fe-skarn deposits occurring worldwide.

The Raka Conglomerate: A wedge-top record at the onset of India-Asia collision, southern Tibet

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The Raka Conglomerate is siliciclastic sedimentary succession located along the central part of the Yarlung suture zone, southern Tibet. The dominant lithofacies are clast-supported, massive to imbricated pebble-boulder conglomerate interbedded with red massive, mottled mudstones and siltstones. These lithofacies are consistent with deposition in an alluvial-fan environment dominated by debris flows and sheetfloods. The Raka Conglomerate was deposited in a contractional setting, as evidenced by growth strata, which require deposition in the footwall of a south-vergent thrust fault. Today, strata are cut by north-vergent thrust faults of the Great Counter Thrust system.

Within a measured section, significant detrital zircon U-Pb age components include 85-125 Ma and 145-155 Ma, with minor Triassic and Precambrian ages. The youngest age component yields maximum depositional ages (MDAs) from ~85-94 Ma. Samples collected outside of the measured section have similar age peaks, but yield younger MDAs of ~58 Ma and 72-80 Ma. We interpret these age populations to be sourced from the southern Lhasa terrane. Based on the youngest age component and structural relationships with the Yarlung ophiolite and Xigaze forearc basin, this sedimentary succession is Late Cretaceous to early Cenozoic in age, with the youngest sediments deposited during the initial stages of continental collision. We interpret the succession to represent the wedge-top equivalent of the nearby Sangdanlin foredeep. Based on the similarity of facies, structural position, and detrital zircon age spectra, the Raka Conglomerate may be correlative to the Liuqu Conglomerate.

Primary surface faulting of the 1697 and the 1950 great earthquakes along the eastern Himalayan Frontal Thrust

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Ongoing convergence across the Himalayan décollement is responsible for generating megathrust earthquakes. These inescapable seismic threats pose serious risk to the inhabitants as well as to the infrastructure of the foothill regions. The paleoseismic record in this highly vulnerable mountain chain often generates conflicting conclusions amongst experts on the rupture length and the magnitude of these seismic events. On the other end, historical archives suggest dozens of earthquakes along the Himalayan arc whose geological evidences are lacking, posing the question whether these events ruptured the surface or remain blind (like 2015 Gorkha earthquake) and act as catalysts in generating future great earthquakes. However, if these documented earthquakes broke the front, then enigma still exists about their rupture extent and magnitude. In order to find answers in the eastern Himalaya, we excavated a 26 m long, 8 m wide and 9 m deep trench across a ~15m high fault scarp at Himebasti (27.54˚ N, 94.36˚ E). Twenty-one radiocarbon samples were collected to constrain the faulting event in the trench that shows age arrays from 43000 BP to 1960 CE. In addition, two OSL (Optically Stimulated Luminescence) samples were used to bracket the event, giving ages of 273±20 and 1737±367 years. While gathering additional evidences for the surface faulting event, we collected three wood log samples emplaced in the youngest terrace along the Subansiri River near the trench site. These drifted wood logs gave consistent radiocarbon ages between 1650 and 1890 CE, suggesting damming of the Subansiri River due to an earthquake and subsequent outburst of the river that led to flooding, and emplacement of the wood logs. On summation of these results and when compared to the historical record, we conclude that the area has been devastated by two earthquakes: One in the 17th and one in the 20th century, producing a minimum observed vertical separation of ~6.8 m with a dip-slip displacement of 15.32 ± 4.69 m in total. We correlate the penultimate event at this site with the 1697 CE Sadiya earthquake also documented in historical notes, which was followed by the well-known most recent event in 1950 CE. By using intensity prediction equations (IPE), we constrain the 1697 CE Sadiya earthquake at a magnitude between 7.4 and 8.1 with a minimum estimated rupture length of ~100 km. The present study suggests that the eastern Himalayan Frontal thrust has been ruptured to the surface by two great earthquakes at close time interval of ~253 years.

Active Fault System of the Lesser Himalaya of Nepal with special reference to the Badi Gad Fault

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Lesser Himalaya is a fold-and-thrust belt of the Himalaya. In Nepal Himalaya, several active faults are identified and mapped by many researchers in the past. The Badi Gad Fault is a well-known but less studied active fault of the Himalaya. In the present study, an attempt was made to assess the Badi Gad Fault and to map its extension precisely in the region. For this purpose, a detailed geological map and geological cross-sections were prepared from Ridi to Shantipur area of western Nepal in 1:25,000 scales. During the field work, several geological as well as geomorphic evidences of the existence of fault were observed. Some of the important evidences are also found under the aerial photo observation and thin section studies under the polarizing microscope. The evidences include the presence of several shear zones, slickenside, clustering of large and several landslides along the certain region, river course diversion, terrace tilting, recent fault scarps, development of several spring lines etc. The discharge of aquifers through the fault zone has triggered the occurrences of several landslides in one hand and depletion of groundwater resources in the upper reaches of the hills on the other hand. The fault has caused landslide damming floods recently. This region of Nepal has a long seismic gap and the presence of this fault can be considered as the potential source for future earthquake.

The Jajarkot Nappe in the west and the Kahun Klippe in the east of the Badi Gad Fault are the two well-known thrust sheets in the region. The Harewa Khola Thrust adjacent to the Badi Gad Fault is found out-of -sequence in nature as it is dipping towards south unlike to the other major thrusts of the Himalaya. The tectonic development of these thrust sheets and faults are poorly understood.

Present research has aimed to map both the Badi Gad Fault and the Harewa Khola Thrust along with the thrust boundary of the Jajarkot Nappe precisely and to link these geological structures with the tectonics of the Himalaya. The thrust zone has also considered a potential area to prospect the gemstones in the region.

Key words: *Badi Gad Fault, Harewa Khola Thrust, Jajarkot Nappe, Kahun Klippe, Nepal Himalaya*

The role of lateral rheology contrasts in the temporal evolution of mountain ranges: insights from South-East Tibet

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Controversy surrounds the rheology of the continental lithosphere and how this controls the evolution and behavior of mountain ranges. In this study we investigate the role of lateral strength contrasts using numerical modelling and recently published results from stable-isotope palaeoaltimetry. Stable-isotope palaeoaltimetry provides the constraints on vertical motions required to distinguish between competing models for lithosphere rheology in south-east Tibet. Such results suggest that parts of south-east Tibet have been at or near their present-day elevations since the late Eocene, meaning that uplift rates are likely to be lower than has previously been suggested based on river incision. We use numerical modelling of the temporal evolution of a gravity-driven fluid to investigate the effect of lateral rheology contrasts on the shape and evolution of mountain ranges. We find that lateral rheology contrasts, analogous to the contrast between the relatively undeforming Sichuan Basin and Central Lowlands of Myanmar and the rapidly deforming south-eastern margin of Tibet, result in deformation that mirrors the main features of the present-day topography, GPS velocity field and earthquake-derived strain rate in SE Tibet, without the need for the low-viscosity, lower-crustal channel which has previously been proposed. The first-order similarity between this simple model and key features of the deformation and topography of SE Tibet suggest that lateral rheology contrasts play a fundamental role in determining the shape and temporal evolution of topography. In addition, our modelling suggests that sediments deposited at or near the surface may be transported hundreds of kilometres, an effect which is important in interpreting.
palaeoaltimetric results.

Little Geodetic Evidence for Localized Indian Subduction in the Pamir-Hindu Kush of Central Asia

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Geodetically derived velocities from Central Asia show that Northern Afghanistan, the Tajik Pamir, and northwestern Pakistan all move northward with comparable large velocities toward Eurasia. Steep velocity gradients, hence high strain rates, occur only across the Main Pamir Fault zone and with lesser magnitude between the northernmost Hindu Kush and the south and southeast margins of the Tajik Depression. Localized shortening is not apparent on any active India-Hindu Kush crustal boundary; hence, crustal convergence between India and Eurasia in Central Asia is absorbed primarily on the northern and western margins of the Pamir. This concentrated strain on the Pamir margins is consistent with one, geometrically complex, interface between subducting Asian lithosphere and the Pamir. That interface might curve westward such that the Hindu Kush seismic zone is a continuation of the Pamir seismic zone, or alternatively, Hindu Kush earthquakes might occur in convectively unstable mantle lithosphere mechanically detached from surface faults.

Rapid subsidence in Kathmandu Valley measured by GPS and InSAR

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GPS and InSAR measurement of vertical change in Kathmandu Valley, Nepal show regions with greater than 10 cm/yr downward movement. This is inferred to be from subsidence related to groundwater withdrawal from this sedimentary aquifer. GPS data come from one continuous station operating since 2013 and five campaign sites measured 2-4 times over 2015-2017. These show vertical rates varying from 3 to nearly 13 cm/yr downward in different areas. Sentinel-1 InSAR time series from an 18 month period in 2016-2018 show range increase (line-of-sight movement away from the satellite) of up to ~15 cm/yr in a region of northwest Kathmandu and 0-10 cm/yr in other areas. Similar rates and locations from both ascending and descending satellite tracks implies that these observed motions are indeed due to subsidence. A bedrock-anchored continuous GPS station just outside of Kathmandu records little vertical change, showing that the valley subsidence is non-tectonic. The mapped InSAR displacements show a complex pattern of differing subsidence rates, indicating a complex interplay of subsurface geology, river infiltration, valley-margin recharge, and pumping. These very rapid subsidence rates pose a serious long-term threat to Kathmandu's aquifer capacity in this valley with >2.5 million residents.

Sedimentary facies analysis of the Siwalik Group along Muksar Khola section to decipher the evolution of the fluvial system in eastern Nepal Himalaya

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The Siwalik in the Muksar Khola section of the Eastern Nepal Himalaya consists of Neogene Sediments derived from the erosion of the Himalaya. These sediments can be divided according to three fold classification of the Siwalik i.e. Upper, Middle and the Lower Siwalik. Difference in the exhumation history of Himalaya from west to east (Yin, 2006; Ojha et al., 2009) should also have made difference in the fluvial environment and its timing from west to east. In this study we focused on recognizing the fluvial environment on the basis of facies analysis. We recognized five facies associations (FA1 to FA5). They are interpreted as the deposits of fine grain meandering river (FA1), debris flow dominated braided river (FA2), flood flow dominated meandering river (FA3), sandy meandering river (FA4), and debris flow dominated gravelly braided river (FA5).

Braided river system has been identified in the Lower Siwalik (FA2) and Upper Siwalik (FA5). According to the paleomagnetic time frame by Ojha et al., (2009), change in the braided river system (FA5) occurred at ca. 3.5 Ma. This change may be related to the late Miocene/early Pliocene Himalaya exhumation. Whereas the occurrence of the braided river system in Lower Siwalik (FA2) indicates sudden rise in the level and velocity of water which last for short time probably an evidence of flooding. Since Ojha et al., (2009) magnetostratigraphy does not cover this section, we estimated a rough age of ca. 10.6 Ma using his oldest sedimentation rate and thickness from columnar section of present study. Various researcher point out the episodic Himalaya exhumation and its relation to the intensification of monsoon. In the present study area the record of mid Miocene (~15-10 Ma) sediment is not good, this flood event must be related to the mid Miocene monsoon intensification. This intensification of monsoon should have developed a large catchment area in the eastern Nepal Himalaya, due to which domination of flood was observed in the meandering river system till ca. 5.7 Ma.

In contrast to the Siwalik section in the central and western Nepal Himalaya, Middle Siwalik in the present study area is deposited by meandering river system. Based on the lithofacies and architectural element of Lower and Upper Siwalik, these sediments were more probably deposited by more than a single river system.

Keywords: Miocene; Siwalik; Facies; Fluvial; Muksar

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GLOF and Hydropower Development in Nepal in the Context of Global Warming

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Nepal has more than 6000 rivers and streams, most of them snow- and ice-fed. These water resources of Nepal are regarded as one of the principal opportunities for future economic development of the country. A worldwide consensus is that climate change is rapidly advancing. Climate change is pervasive and is a major factor to be weighed in development of Nepal. Climate change is especially profound in the Nepal Himalaya because of its impact on water resources, biodiversity, and consequences for the economic growth (hydropower development) and human safety in the region.

Driven by global climate change, the increased regional trend of glacial retreat and the variability of temperature and precipitation have direct impacts on water resource and hydropower development. As many of the larger glaciers have thinned and retreated in the Himalayas, hundreds of new glacial lakes holding millions of cubic meters of water have formed or grown, creating new or increased hazards of glacial lake outburst floods (GLOFs). Although studies concerned with the basic science of glacial lake growth and formation are gradually improving our knowledge of their state and dynamics, the trigger processes and dynamics of GLOFs and Himalayan-specific, cost-effective, sustainable risk-reduction methods remain poorly understood. The devastating April 25, 2015 earthquake and major aftershocks added a new uncertainty because of increased landslide risks, which could play into higher chances of a GLOF. A deficient understanding of how to assess and mitigate GLOF hazards thus prevails, leaving the risks to downstream populations and costly infrastructure (million's dollar Hydropower) poorly quantified and next steps uncertain.

The purpose of this study is twofold: 1) to share the lesson learned from GLOF occurred from Gongatongshacuo on 5 July, 2016 and flooded in BhoteKoshi/Sunkoshi river that has severely damaged the hydropower, agricultural land and other infrastructures, such as bridges, schools etc., and severely affected the socio-economic life of the people of downstream areas, and 2) is to make the assessment of the safety of downstream area including hydropowers from one of the fastest growing and dangerous glacier lake in Marshyangdi watershed namely Thulagi glacier lake or Dona lake

This study will highlight the new systematic, cost-effective approach to reduce the GLOF risk by developing the hydropower projects from the glacier lakes for the economic development of Nepal. If this approach successfully applied in Thulagi lake it can be replicated throughout Nepal as well as in countries throughout the high-mountain regions of the world that face similar threats and challenges related to new glacial lake formation.

Key words: Global-warming, Glaciers, GLOF, Hydropower, and Downstream Impacts

Is Accelerated East-West Extension of the Tibetan Plateau Driven by Underthrusting of the Indian Plate? A Study of the Tangra Yumco Rift, South-Central Tibet

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This project will test the India underthrusting hypothesis through field mapping, apatite fission track, (U-Th)/He thermochronology, and thermokinematic modeling of the Tangra Yumco (TYC) rift, a ~350 km long, north-south striking rift in south-central Tibet. Researchers interpret initiation of east-west extension in Tibet to have occurred synchronously across the plateau during Miocene time, preceding extension acceleration by ~5-10 Myr. The underthrusting hypothesis links acceleration of rifts to the northward propagation of the subducting Indian plate, but this model has not been widely tested. This poster presents a research plan to test this hypothesis across one of the longest and most central rifts on the plateau, in which three key research questions will be addressed; (1) What is the structural geometry of the Tangra Yumco rift and how does it change along strike? This question will be addressed through geologic mapping and construction of structural cross sections. (2) Did acceleration of east-west extension propagate northward at a rate plausibly matching the rate of underthrusting of India? This question will be addressed by sampling for apatite fission track and (U-Th)/He thermochronology along the north-south length of the TYC rift. (3) What are the time-temperature histories of footwall rocks in the Tangra Yumco rift, and what can they tell us about extensional history? This question will be addressed through thermokinematic modeling in Pecube. Results from this study will contribute to the research community's understanding of Tibetan tectonics, and may deliver broad implications regarding the significance of Tibetan rifting within the wider framework of the India-Asia collision. Since Tibet is often cited as a primary example of synconvergent extension, this research may also inform how analogous structures are interpreted in different geologic settings (e.g. metamorphic core complexes in the Western US).

Abrupt cooling and surface uplift at ~3.6 Ma in the Northeastern Tibetan Plateau indicated by clumped isotopes in Plio-Pleistocene lacustrine carbonates from the Qinghai Lake, China

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The Indo-Eurasian collision was followed by widespread deformation and surface uplift over regions located more than 1500 km north of the collision zone. One of them is the Northeastearn Tibetan Plateau (NETP) margin, currently at ~4000 m.a.s.l. The paleoelevation history of the Tibetan Plateau is unresolved, but studies suggest that portions of the plateau may have been uplifted in a stepwise or pulsed manner, and that this would have caused significant changes in Asian climate. For example, recent climate models suggest changes in atmospheric circulation and precipitation patterns in Central Asia could have been controlled by Late Cenozoic growth of the NETP.

We are investigating the paleoelevation history of the NETP during the Plio-Pleistocene using oxygen and carbon stable isotopes and clumped-isotope thermometry of lacustrine authigenic carbonates collected from the Yilang sediment core, retrieved from the southern margin of the Qinghai Lake. The Yilang core age model based on magnetostratigraphy suggests the following Qinghai Lake basin evolution: from 5.1-4.6 Ma, sediments were of eolian origin (Loess); at 4.6 Ma, lake began to form; from 4.6-3.6 Ma, a deep lacustrine environment developed; from 3.6-2.1 Ma, the system transitioned to a shallow lacustrine depositional environment. Correlation between the magnetostratigraphic age model and seismic profiles show that normal faulting, growth strata and an angular unconformity occurred in the basin at 3.6 Ma. Concurrently, several other basins on the margins of the NETP experienced thrust faulting, coarsening, angular unconformities and growth strata.

We collected >1000 core samples spanning 5.1 to 2.0 Ma and analyzed oxygen and carbon stable isotope analyses of 788 authigenic carbonates (micrite). Results show that mean values increased by 2.3‰ ($\delta^{13}C_c$) and 1.5‰ ($\delta^{18}O_c$) at ~3.75 Ma, and subsequently decreased by 2.7‰ ($\delta^{13}C_c$) and 3.6‰ ($\delta^{18}O_c$) at ~3.5 Ma. We analyzed 21 selected samples using carbonate clumped isotope thermometry to obtain temperature of carbonate formation (Δ_{47}T), i.e. temperature of the water in which they formed. Based on Δ_{47}T, we calculated air mean annual air paleotemperatures ($MAAT_{air}$) using transfer functions based on empirical data. Using Δ_{47}T and $\delta^{18}O_c$, we calculated the $\delta^{18}O_{lw}$ of lake water in which carbonates formed. From 4.3-3.8 Ma (n=5), mean Δ_{47}T=17.5˚C, T_{air}=10.1˚C; $\delta^{18}O_{lw}$=-3.9‰. From 3.7-3.5 Ma (n=6), mean Δ_{47}T=22.4˚C, T_{air}=15.5˚C; $\delta^{18}O_{lw}$=-3.5‰. From 3.45-2.06 Ma (n=10), mean Δ_{47}T=12.1˚C, T_{air}=3.0˚C; $\delta^{18}O_{lw}$=-7.0‰. Modern Qinghai Lake surface water mean summer temperature (T_{lwmod}) is 13.5˚C; modern mean annual air temperature ($MAAT_{airmod}$) is 1.45˚C; and modern $\delta^{18}O$ of lake water ($\delta^{18}O_{lwmod}$) is 1.8‰.

Based on this set of evidence, we hypothesize that an episode of regional surface uplift occurred in the NETP at ~3.6 Ma. A comparison between the period prior to 3.75 Ma and posterior to 3.5 Ma show a concurrent decrease of Δ_{47}T, $\delta^{18}O_{lw}$ and $MAAT_{air}$ in the Qinghai Lake region. This suggests that: (1) Lake inflow waters became more negative given that meteoric water is typically more depleted at higher elevations; and (2) Temperatures became lower as elevation increased. If we take the simple approach of using a global average temperature-elevation gradient ("lapse-rate") of -5.5˚C/km, we estimate an increase in elevation of 1.29 km. However, we acknowledge the uncertainties involved in this estimate since we are assuming all temperature changes are related to elevation gain and estimates strongly rely on our choice of temperature lapse-rate. The lithospheric processes that could explain such an abrupt elevation increase remain a matter of further investigation, but two main possibilities are proposed: lithospheric delamination or lower crustal flow.

Stalagmite Growth Perturbations from the Kumaun Himalaya: Potential Earthquake Recorders

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The timing of the large earthquakes in the Himalayan region have always been a great interest of researchers and is much debatable. In this talk we presents why we consider the cave studies, although a proven method for paleo-climate investigations, provide some interesting insights into the earthquake occurrences. The central sector of the Himalaya, which includes Kumaun and Garhwal provinces of India, is well-known for its prolonged seismic silence the chronology of great earthquakes. We explored three limestone caves, located in the Pithoragarh and Nainital District in Kumaun Himalaya. Here we describe the chronological constraints on deformational events that are registered on the stalagmites within these caves. All three caves exhibited deformed stalagmites, but the chronological constraints on deformational events are exclusively based on dates obtained from samples collected from the Dharamjali Cave. As stalagmites grow upward from the cave floor, receiving water droplets of dissolved calcium carbonate from the roof, any change in the orientation or alignment with the roof is likely to affect their vertical growth axis pattern. The changes in the orientation of the growth axis and breakage of stalagmites as potential proxies for seismic events. The growth anomalies in stalagmites include abrupt tilting or rotation of growth axes, growth termination, and breakage followed by re-growth. The speleothems usually act as closed system with respect to U-series isotopes and are ideal to establish the absolute chronology. The U-Th age data from three specimens allow us to constrain the intervals of growth anomalies, and these were dated at 4273±410 years BP (2673–1853 BCE), 2782±79 years BP (851–693 BCE), 2498±117 years BP (605–371 BCE), 1503±245 years BP (262–752 CE), 1346±101 years BP (563–765 CE), and 687 ±147 years BP (1176–1470 CE). The dates may correspond to the timings of major/great earthquakes in the region and the youngest event (1176–1470 AD) shows chronological correspondence with either one of the great medieval earthquakes (1050–1250 and 1259–1433 AD) evident from trench excavations across the Himalayan Frontal Thrust

Keywords: Stalagmites, Speleoseismology, Earthquake recurrence, Central Indian Himalaya, Seismic gap

Structural analysis of the Benkar Fault Zone, a cross structure in the Higher Himalaya of the Khumbu region, eastern Nepal

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The Himalaya are dominated by laterally continuous, range-parallel thrust faults and less frequent extensional structures such as the South Tibetan Detachment system. Recent discovery of range-perpendicular strike-slip and extensional fault zones (cross structures) in the Himalaya has raised questions regarding the significance of these structures in the collisional process. We have analyzed a newly-recognized cross structure in the Khumbu region of eastern Nepal, the Benkar Fault Zone. Structural mapping, petrographic observation, and analytical evidence reveals a 2-11 km-wide zone of consistently NE-striking, SE-dipping foliation from the villages of Phakding to Gorak Shep along the Dudh Kosi valley. Quartz crystallographic fabric orientation suggests crystal plastic deformation, however, deformation within this zone is predominantly restricted to foliation-parallel, nonpenetrative, anastomosing sillimanite- and mica-bearing shear zones that wrap around poorly deformed quartz and feldspar enclaves. Kinematics of these shear zones from thin sections and outcrop observations are consistent with normal, right-lateral oblique slip and some local zones of purely extensional displacement. Offset in newly collected $^{40}Ar/^{39}Ar$ ages on muscovite across the Benkar Fault Zone are consistent with this interpretation. Outcrop observations show evidence for isolated brittle-ductile deformation, suggesting short-lived brittle events that punctuated a history of predominantly plastic deformation. Benkar Fault Zone fabric crosscuts older, thrust-related foliation and suggests that deformation within the zone postdates peak metamorphism and occurred while rocks were on the retrograde path. $^{40}Ar/^{39}Ar$ ages on muscovite constraints the timing of deformation to be younger than ~12 Ma. The Benkar Fault Zone could be an expression of a large-scale tear fault, a lateral ramp, seismic partitioning, strain partitioning due to oblique convergence, or extension due to orogenic collapse. The current data best supports the interpretation of a tear fault within the Greater Himalayan sequence associated with differential displacement along a structurally deeper thrust.

The Greater Himalayan thrust belt: Insight into the assembly of the exhumed Himalayan metamorphic core, Modi Khola valley, central Nepal.

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Multiple strike-parallel discontinuities have now been identified within the exhumed Himalayan metamorphic core (HMC) across the Himalaya. These discontinuities are generally interpreted to reflect thrust sense movement, however, there has been disagreement on the movement direction of adjacent blocks across one such structure in the Modi Khola region of central Nepal. Different workers have contrastingly argued that the Bhanuwa Fault accommodated either top-to-the-north or top-to-the-south displacement across it. The lack of agreement on the nature of the fault has hampered efforts to understand the kinematics of the region and potentially correlate it with structures at similar structural levels observed elsewhere along the Himalaya.

This study takes an integrated approach towards characterizing discontinuities in the Modi Khola valley that includes phase equilibria modelling, Quartz-in-Garnet (QuIG) barometry, Lu-Hf garnet geochronology and Th-Pb monazite petrochronology. This new dataset confirms the existence of multiple structural breaks within the HMC in the Modi Khola valley that coincide with previously recognized features including, from north to south, the Sinuwa Thrust, the Bhanuwa Fault and the Main Central thrust (MCT). Lu-Hf garnet ages and peak pressure estimates obtained from the rocks across the Sinuwa Thrust yield similar prograde ages of ca. 35 Ma and peak pressures of ~ 11.0 - 11.5 kbar. The ages obtained from monazite and trace element analysis of garnet and monazite also indicate that the rocks record similar evidence of partial melting, which may have initiated as early as ca. 28 Ma followed by cooling and exhumation between ca. 24 and 15 Ma. In contrast, rocks structurally below the Bhanuwa Fault, while they record similar garnet growth at ca. 35 Ma with peak pressures of ~11.5 kbar, experienced melting and cooling after ca. 21 Ma, indicating that prograde metamorphism in the footwall of the Bhanuwa Fault was partially coeval with the exhumation of hanging wall rocks. Interestingly, published $^{40}Ar/^{39}Ar$ cooling ages across the Bhanuwa Fault indicate cooling and exhumation of hanging wall rocks ca. 18 - 16 Ma, compared to ca. 12 - 10 Ma for those in the footwall, implying normal sense motion across the structure later during mid-late Miocene. Finally, garnet Lu-Hf and monazite geochronology from the rocks in the footwall of MCT indicate prograde metamorphism ca. 17 - 13 Ma with peak pressures of ~ 7 kbar, coeval with the cooling and exhumation of rocks from the hanging wall. This down-structural section migration of prograde metamorphism, anatexis, cooling and exhumation is consistent with models of progressive underplating and in-sequence thrusting during the development of the Himalayan mid-crust. Furthermore, the break in cooling ages between two adjacent rock packages across the Bhanuwa Fault is consistent with late stage normal-sense reactivation of the Bhanuwa Fault, perhaps tied to the foreland propagation of strain during mid-late Miocene.

This new integrated data set, combined with similar data from other transects along the Himalaya, shows that the final assembly of the HMC was a result of progressive deformation and juxtaposition of multiple ductile thrust sheets, which is broadly consistent with the results of the published geometric predictions from thermo-mechanical models of the Himalaya. We refer to this as the Greater Himalayan thrust belt.

Effects of Gondwanan Rifting on the Himalayan metamorphism and tectonics

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Several continental slivers rifted off the northern leading edge of the Indian plate and sequentially collided with the Asian margin – the India-Asia collision in Paleocene being the last and the strongest of this series of collisions. Thus the rocks at the tethyan margin of the Indian plate underwent prolonged extension followed by a collision related tectonism starting between 50 and 60 million years.
Recent detailed high definition seismic profiling of rifted margins indicate almost universal existence of crustal or lithospheric scale boudins in rifted margins in all parts of the world. While the upper crust is highly boudinaged, a thinned and sheared lower crust fills the inter-boudin areas which are also areas of high thermal anomaly.

The Himalayan Mountain, south of the Indus suture, consists of three parallel high grade metamorphic belts separated by unmetamorphosed or lowly metamorphosed sedimentary sequences. These are, from north to south: Tso Morari Crystallines-Tehyan belt – The Central Crystallines – the Inner Lesser Himalayas – the Lesser Himalayan Crystallines – the Outer lesser Himalayan.
Himalayan Metamorphism, like many other orogenic metamorphic belts, is characterized by multiple episodes of metamorphism and concomitant episodes of deformation. The early F1 fold is of reclined to recumbent geometry with a regional axial plane foliation. The second generation folds are raised on these foliations and with axial trace parallel to the strike of the Himalayas. The major thrusts and associates shear zones are all parallel to the regional foliation and are syntectonic with the F1 folding. From textural evidence it is apparent that the migmatisation, development of gneissic foliation, major progressive Barrovian metamorphism are all pre to syntectonic with F1 Two major episode of granitic magmatism is associated with the Himalayan crystalline belts which are an early Eocene-Oligocene (50 -40 Ma) phase and a later Miocene phase (c. 20 ma)

Some of the characteristics of Himalayan metamorphism are: a. presence of inverted metamorphism along the southern margin of the central and lesser Himalayan crystalline belts. b.. While the southern bounding fault of the crystallines are in the nature of a thrust, the northern boundary are ocean-ward dipping normal faults.

The present model proposes that concomitant with the rifting of the Gondwanan fragments, The passive Indian margin experienced prolonged extension resulting in the development of normal fault bounded lithospheric scale continental boudins The boudin necks experienced extreme extension, thinning, were sites of high thermal anomaly and were filled with ductile and sheared middle to lower crustal rocks. The early high grade metamorphism, formation of Himalayan foliation, migmatisation and the formation of the earlier anatectic granites and adakites took place in these boudin necks . The extensional phase came to end with the India-Asia collision at around 55 ma. The collision localized intense deformation at the boudin necks which were filled with hot and ductile material. Overturned folding of the rocks already metamorphosed during the extensional stage produced the inverted metamorphic sequences of the central crystalline and of the lesser Himalayan crystalline belts. This phase of deformation and thrusting caused crustal thickening, superposition of hot and thinned crust and rapid exhumation of the thickened crust resulting in the second phase of metamorphism characterized by isobaric cooling. The present model is supported by field, isotopic and PTt data and does not require the mechanism of channel flow or of allochthonous nappes to explain Himalayan metamorphism and tectonics.

Cataclastic strain from external thrust sheets in fold-thrust belts: Insights from the frontal Indian Himalaya

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Crustal evolution studies in fold-thrust belt (FTB) settings like the Himalayan orogenic belt includes kinematic analysis of deformation. Pure strain is recognized as an important component of the total displacement vector that characterizes the deformation especially in internal and transitional thrust sheets where strain is computed from strain markers or grain shape preferred orientation. It is generally assumed that external thrust sheets are strain free. We first describe a methodology to compute cataclastic strain from external thrust sheets using the Bootstrapped Modified Normalized Fry Method in rocks that have undergone cataclastic flow under elastico-frictional conditions. We then validate the method in two different structural settings in the frontal Himalaya. In the frontal imbricate zone of the Dharan salient we measure the highest strain ratios from a central imbricate thrust (T3) and find that strain ratios (Rf) systematically decreases away from the fault zones within individual thrusts. Modelling of our results using StrainSim 3.6.1 indicates that there was significant vertical flattening in the fault zones while layer parallel shortening related strain dominated the thrust sheets. Also, fault parallel shear decreased away from the fault zones. In contrast, vertical flattening was largely absent in the fault zone associated with the Main Frontal thrust and the MFT sheet in the Mohand Range of the Dehradun recess. Here the strain distribution pattern was consistent with a trishear fault propagation monocline which is our preferred model for the structure of the MFT sheet in the recess. Maximum finite strain was measured close to the MFT fault zone. Minimum strain was obtained near the fault propagation monoclinal hinge while intermediate strain values were measured in the NE-dipping limb of the monocline. Modelling of these results using StrainSim 3.6.1 suggests that fault parallel shear decreased away from the MFT fault zone like in the thrust sheets in the Dharan salient. Bedding parallel shear was observed in the dipping northern limb of the fault propagation monocline suggesting that fault propagation folding was accomplished by flexural slip folding. We contend that our methodology can be used effectively to quantify and study the pure strain part of the total displacement vector in external thrust sheets from fold-thrust belts worldwide.

Preliminary paleoseismic data along the Himalayan Frontal Thrust fault at the Haldwani site, Uttarakhand, India

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The trench site of Haldwani in the state of Uttarakhand, India is located along a segment of the Himalayan Frontal Thrust fault (HFT) that likely falls within the bounds of the Central Seismic Gap (CSG) that extends from north-central India into Nepal. The CSG has been defined as the section of the HFT that lies between the areas affected by the 1905 Kangra and the 1934 Nepal-Bihar earthquakes, which has not experienced a great (Mw≥8.0) earthquake for more than a century. The CSG is a region of high seismic potential and threatens impending great earthquakes. There is a scarcity of historical documentation for medieval earthquakes on the HFT; however, limited historical anecdotes are recorded in Newari, Sanskrit and Nepali chronicles. This lack of historical information has prompted paleoseismologists to conduct research aimed at determining the timing of past earthquakes at several sites along the HFT. The current study centers on the site of Haldwani, which lies ~170 kilometers (km) southeast of Haridwar and 66 km northwest of the Nepal border. Excavation of an exploratory paleoseismic trench across the fault scarp northwest of Haldwani in November 2018 provided evidence of previous, large-magnitude ruptures at the site. The trench was 25 m long, ~3.5 m wide, and up to 4 m in height, and was excavated along a northeast to southwest striking, ~18-m-high fault scarp. The north and south walls of the trench were cleaned, gridded in 1 m sections, and logged. Fourteen stratigraphic units were identified and differentiated by grain size, color, and lithology, including colluvium, gravel, silt, and finer silty clay layers that were defined into depositional facies. Deformational features in unlithified fluvial terrace sediments observed in the trench appear unique when compared to previous paleoseimological sites along the HFT. Two fault strands were identified, generally striking northeast to southwest. Faulting occurred in fluvial channels in a gravel deposit (upper fault) with a dip of 47° and across finer, silty sediments (lower fault) with a dip of 32°. Gravel clasts along the upper fault plane are aligned along the strand. In all, fourteen detrital charcoal samples were collected and submitted for radiocarbon analyses. Samples were collected in fluvial units involved in faulting and fold deformation. Additional samples were collected from the overbank sediments that cap the lower and upper faulting events. Furthermore, two radiocarbon samples were collected at the Haldwani Quarry located to the east of the trench site, where two fluvial terraces are backtilted by faulting. The terrace deformation and resultant incision is inferred to be controlled by seismic activity and not by fluvial processes. Results of radiocarbon analyses will provide evidence for the timing of rupture and terrace deformation. A great earthquake at Haldwani would pose a regional threat to infrastructure and to millions of people that reside in adjacent areas of the Indo-Gangetic plain.

Early Mesozoic volcanic rocks on both side of the Yarlung-Tsangpo Suture: implications for early evolution of the Neo-Tethys

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The Early Mesozoic volcanic rocks of both sides of the Yarlung-Tsangpo Suture Zone record the most information of the early evolution of the Neo-Tethys. On the basis of field investigations, several sections of volcanic rocks related to Neo-Tethyan evolution in Gangdese belt and Tethyan-Himalaya were selected for comprehensive studies on petrology, geochemistry, Sr-Nd isotopes, zircon U-Pb dating and Lu-Hf isotopes in this paper, with the aim of revealing their formation age, petrogenesis and tectonic implications. Intergrated studies suggest that the Mesozoic volcanic rocks on both side of the Yarlung-Tsangpo Suture have experienced a long evolution history. The Middle Triassic (226 Ma) OIB-type basalts in Langjiexue area is related to the initial break-up between Tethyan-Himalaya and Lhasa terrane, which indicating that the opening of the Neo-Tethyan Ocean started before middle Triassic. Since Late Triassic (~226 Ma), initiation of subduction may happened at the sites of transform faults or rejuvenated pre-existing subduction zones. In combination with the Early Jurassic high-Mg andesites in Quxu area and highly fractionated I-type rhyolites in Mailonggang area, and the distribution of the Mesozoic magmatic rocks in the southern Lhasa terrane, we speculate the rollback of the subducting Neo-Tethyan Ocean was the prime reason for the Early Jurassic tectono-magmatic evolution in the southern Lhasa terrane. This process facilitated a rapid linear upwelling of the asthenospheric mantle beneath the southern Lhasa terrane and ultimately led to the large-scale magmatic flare-ups. Furthermore, events associated with slab rollback likely played an important role in crustal growth in the southern Lhasa terrane.

The Alichur dome, South Pamir, western India–Asia collisional zone: detailing the Neogene Shakhdara–Alichur syn-collisional gneiss-dome complex and connection to lithospheric processes

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Neogene, syn-collisional extensional exhumation of Asian lower–middle crust produced the Shakhdara–Alichur gneiss-dome complex in the South Pamir. The <1 km-thick, mylonitic–brittle, top-to-NNE, normal-sense Alichur sense shear zone (ASZ) bounds the 125 × 25 km Alichur dome to the north; the Shakhdara dome is bounded by the <4 km-thick, mylonitic–brittle, top-to-SSE South Pamir normal-sense shear zone (SPSZ) to the south, and the dextral Gunt wrench zone to its north. The Alichur dome comprises Cretaceous granitoids/gneisses cross-cut by early Miocene leucogranites, its hanging wall non/weakly-metamorphic rocks. The 22–17 Ma Alichur-dome-injection-complex leucogranites transition from foliation-parallel, cm–m-thick sheets within the ASZ into discordant intrusions that may comprise half of the volume of the dome core. Secondary fluid inclusions in mylonites and mylonitization-temperature constraints imply Alichur-dome exhumation from 10–15 km depth. Thermochronologic dates bracket footwall cooling between ~410–130 °C from ~16–4 Ma; tectonic cooling/exhumation rates (~42 °C/Myr, ~1.1 km/Myr) contrast with erosion-dominated rates in the hanging wall (~2 °C/Myr, <0.1 km/Myr). Dome-scale boudinage, oblique divergence of the ASZ and SPSZ hanging walls, and dextral wrenching reflect minor ~E–W material flow out of orogen. We attribute broadly southward-younging exhumation across the Central–South Pamir between ~20–4 Ma to: (i) Mostly northward, foreland-directed flow of hot crust into a cold foreland during the growth of the Pamir orocline; and (ii) Contrasting effects of basal shear related to underthrusting Indian lithosphere, enhancing extension in the underthrust South Pamir and inhibiting extension in the non-underthrust Central Pamir.

Is Himalayan leucogranite a product by in situ partial melting of the Greater Himalayan Crystalline?

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Leucogranite is widely distributed in the Himalayan orogen. It is commonly accepted that this kind of rock was originated by in situ partial melting of the Greater Himalayan Crystalline (GHC) when it underwent high-grade metamorphism during the Cenozoic Himalayan orogenesis. Therefore, the leucogranite and associated migmatite could be used to constrain the exhumation history of the GHC. However, the evidence is emerging that their petrogenetic relationship may not be well constrained. A detailed study, integrating petrographic, geochronological, mineralogical, and geochemical analyses, was carried out on the leucosome and the leucogranite in Nyalam, southern Tibet. Monazite U–(Th)–Pb dating from this study and literatures indicates that the anatexis of the GHC took place during late Eocene to Miocene (40–14 Ma), while the emplacement of leucogranite lasted with a little narrower age range from 27 to 14 Ma. It is indicated that there are marked differences between the leucosome and leucogranite in terms of their field geology, mineralogy and geochemical compositions, suggesting that they may have different petrogenesis. The leucosome mostly occurred as pocket or interlayered with melanosome in stromatic metatexite. The plagioclase is oligoclase and biotite is Fe-rich, with whole-rock having high K_2O content (4.8–7.4 wt.%), K_2O/Na_2O ratio (1.35–2.97), positive Eu anomaly (Eu/Eu* =0.93–2.61), and low rare metal (Li, Be, Cs, Sn, and Ta) content, indicating its origination from muscovite dehydration melting of the GHC. However, the leucogranite intrudes in the GHC, and occurs as small pluton along the South Tibetan Detachment System (STDS). In contrast to leucosome, the plagioclase and biotite from leucogranite are albite and siderophyllite, respectively. In geochemistry, the leucogranite has relatively low K_2O (4.3–4.7%) and K_2O/Na_2O ratios (1.04–1.24), high rare metal concentrations, with significant negative Eu anomaly (Eu/Eu* = 0.47–0.70), indicating its origination of highly fractional crystallization. It is proposed that the leucogranite originated from a magma produced in the deeper GHC at peak-metamorphism of the Himalayan orogenesis, and the intensive fractional crystallization occurred due to a long-distance of upwards migration of magma along the STDS, with exhumation of the GHC. During these processes, the high-grade metamorphosed GHC was partial melted, and resulted in the formation of leucosome within migmatite. Therefore, the leucosome is not equal to the leucogranite in origination, and they should be considered separately for their implications to the Himalayan orogenesis.

Defining the age of eclogite-facies metamorphism in the central Himalaya

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Rare garnet-bearing mafic rocks occurring in the Greater Himalayan Sequence (GHS) of northwest Bhutan are interpreted as retrogressed eclogite, based upon textural information that includes the presence of clinopyroxene ± amphibole symplectite after omphacite (Grujic et al., 2011). Depleted heavy rare earth (HREE) concentrations and suppressed Eu* anomalies in zircon from these rocks have encouraged interpretations that eclogite-facies metamorphism peaked between ~16–14 Ma, with subsequent rapid exhumation at initially high temperatures. Similar interpretations of a young (≤20 Ma) age of HP metamorphism have been proposed for eclogite from other localities in the central Himalaya (Ama Drime massif: Wang et al., 2017; Arun Valley: Corrie et al., 2010). Yet garnet Lu/Hf dates of *c.* 36 Ma reported by Kellett et al., (2014) suggest the prograde history of mafic rocks in the Ama Drime region spans a much longer time period. Zircon LA–ICPMS U/Pb dates of 16–14 Ma from the same rocks are correlated with a late granulite-facies overprint (Kellett et al., 2014).

We measured U/Pb dates and trace element concentrations in zircon from three float samples of mafic rock collected in the valley draining the Jichu Drake massif in the Jomolhari region of northwest Bhutan. Zircon cores and rims were analyzed by split stream LA–ICPMS at the UC Santa Barbara geochronology facility. Two of the samples are coarse granulitized eclogite containing garnet (partially replaced by hornblende + plagioclase ± orthopyroxene symplectite) and clinopyroxene + plagioclase symplectite interpreted as replacing former omphacite. Both samples yield a tight cluster of slightly discordant to concordant dates between 19–17 Ma. The majority of analyses exhibit depleted rare earth and particularly HREE concentrations, and relatively suppressed Eu* anomalies. A third sample of coarse, weakly retrogressed garnet amphibolite yields older concordant to slightly discordant zircon core and rim analyses ranging from 28–22 Ma, with only a couple of spots younger than 20 Ma. These data are consistent with previously reported 38–18 Ma U/Th–Pb zircon and monazite analyses from metapelites in this region (Regis et al., 2014, 2016).

Our results show that mafic rocks in the GHS of northwestern Bhutan contain a broadly similar chronology to other localities throughout the central Himalaya. Metapelitic rocks, and the weakly retrogressed amphibolite examined here, yield many zircon and monazite dates between *c.* 38 Ma to 20 Ma, accompanying prograde amphibolite to eclogite-facies metamorphism. The timing of peak conditions is still unknown, but must predate regional emplacement of plagioclase-bearing leucogranite dykes, which are younger than *c.* 21 Ma (e.g. Kellett et al., 2009; Cooper et al., 2015; Montomoli et al., 2016). The two granulitized eclogite rocks examined here contain abundant zircon that essentially defines a single age population of *c.* 17 Ma, with no signal of an earlier history. Rather than supporting a young age of peak eclogite conditions, this narrow date range in retrogressed rocks favors efficient scavenging and re-growth of zircon during exhumation, possibly by fluid ingress accompanying anatexis in surrounding felsic and pelitic rocks of the GHS.

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Episodic supply of high-temperature metamorphic mineral-concentrated sands to the Bengal Fan

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The Bengal Fan is the largest submarine fan in the world. It has developed as a direct result of the collision between India and Asia plates, reflecting the orogeny of the Himalayas. International Ocean Discovery Program Expedition 354 (IDOP Exp. 354), which focused on clarifying the relationship between climate change and Himalayan weathering and erosion, obtained a complete sequence of fan deposits from the Oligocene to the present (France-Lanord et al. 2015). Yoshida et al. (2016) reported the general trend of change in the heavy mineral assemblage from the Early Miocene to the present day. In this study, details regarding detrital garnet, spinel, and amphibole chemistries, and the existence of high-temperature metamorphic-mineral-concentrated sand in the Bengal Fan sediments are the focus. The heavy-mineral fractions were isolated from the core samples, which range in age from the earliest Miocene to the present, and their chemical composition was analyzed using an electron microprobe.

As a result, the sediments drilled at U1451A&B site in Exp. 354 were found to consist of mica and quartz-rich sand, silt, and clay. Most sand layers in the lower Miocene contain tourmaline, apatite, rutile, and amphibole grains with relatively Mg-rich almandine garnets that are correlated with the metamorphic garnets in the High Himalayan Crystalline complex. However, several sand layers contain sodic amphibole and chromian spinels, which show very low TiO_2 content (< 0.05 wt%), suggestive of a depleted ultramafic rock origin. In the Middle Miocene sequence, most of the sand layers contain Mg-rich almandine garnet and amphiboles; however, several sand layers contain sodic amphibole and chromian spinels with almandine garnet. Pliocene and Pleistocene sands frequently include pyroxene, olivine, sodic amphibole, and chromian spinels.

In addition, the sand and sandstone samples, which include large amounts of high-temperature metamorphic minerals, i.e., staurolite and chloritoid, are found. These samples are dispersed to several horizons, at least seven, out of the 55 studied horizons from the Lower Miocene to the Upper Holocene. The content of these high-temperature minerals reaches 7–17% of the entire collection of heavy mineral grains that are isolated by heavy liquid. In other horizons, high-temperature metamorphic minerals are generally included as a very minor constituent, under 2% of the entire set of heavy mineral grains.

The sand layers containing both sodic amphibole and chromian spinels were possibly derived from the ophiolite zone in the Yarlung Tsangpo suture zone. These heavy minerals might be carried by some "preceding valley" cutting a major Himalayan structure, or rivers reaching the suture zone on account of river capturing/switching, i.e., the modern Brahmaputra river. Through the Gangs river, which carried the most of detritus from central and western Himalayas, the ancient Brahmaputra river could episodically supply the detritus from the suture zone. The relative richness of the sodic amphibole and chromian spinels in the Pliocene and Pleistocene sands is considered to be caused by strong uplift around the Eastern Himalayan syntaxes. Sporadic occurrence of sands with concentrations of high-temperature metamorphic minerals were probably shed by episodic supply and the corresponding slope failure in the High Himalayan Crystalline Complex, located relatively close to the sedimentary basin, i.e., somewhere in the central Himalayas. In addition, the incomplete mixing process of the sediment shed by different rivers and hinterland around the Ganges delta, which is thought to be source area of the sediments in the Bengal Fan, is also a possible explanation for this episodic record of various compositions in the Bengal Fan sediments.

Recurrence Interval of Large Earthquakes in the Eastern Himalaya

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The on-going convergence between India and Eurasia plates poses a huge seismic hazard on the Himalayan foreland, which is one of the most densely populated areas in the world. However, little is known about the Himalayan earthquakes in the 18th century and before. The timing and magnitudes of paleo-earthquakes and their return periods are poorly constrained in the Himalaya. This research aims to reconstruct the seismic history of an exposed surface rupture recently identified along the Himalayan front in eastern Bhutan to develop accurate hazard evaluations and determine the seismic risk in the region.

The large coseismic surface rupture was observed along an individual fault. Striking 95°, and dipping about 20° to the north, the fault places Late Miocene Lower Siwalik siltstone[1] on top of the Holocene river terraces with a throw of about 6 m. The huge offset may have been caused by a very large earthquake (M>8), or by a sequence of large earthquakes. Based on the ages of the known large historic earthquakes in the eastern Himalaya[2,3], we hypothesize that the surface rupture in eastern Bhutan was caused by at least one of the large earthquakes, either the 1714 Bhutan earthquake or a medieval earthquake of ~1255 AD or ~1100 AD.

Four dating techniques have been applied to accurately and precisely constrain the timing of the paleo-earthquakes. To avoid the limitation caused by one dating method, radiocarbon (C-14) dating[4] and conventional optically stimulated luminescence (OSL) thermochronology[5] are used together to determine the burial age of the youngest displaced river terrace layer yielding the maximum ages of the paleo-earthquakes. To overcome the drawbacks of indirect dating method caused by lack of the oldest undisturbed layer yielding the minimum age and to obtain the direct ages of the seismic events we applied another two OSL methods. Multi-OSL-thermochronometry of feldspar[6] is used to date fault gouge produced during the paleoseismic movement. High precision rock surface dating[7] is applied to the pebbles exposed along the thrust and the layer boundaries.

Based on the timing of the paleo-earthquake and the newly constrained surface rupture length(s), the most likely magnitude(s) of the earthquake(s) will be calculated applying the empirical scaling methods[2,8,9]. Finally, the recurrence interval of major Himalayan earthquakes will be calculated. The results will contribute not only to seismic hazard evaluation in the area but to the debate about a potential for subduction-type mega-earthquakes in the Himalaya in general. If the surface rupture in eastern Bhutan was caused by either ~1255 AD or ~1100 AD event, the location of the study area would extend its surface rupture length to ~1000 km, making it a likely M9 earthquake[8]. Such mega-earthquakes have not yet been found in the Himalaya[10], or any other continental setting.

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