

Crustal architecture and evolution of the Himalaya–Karakoram–Tibet Orogen: introduction



RAJESH SHARMA¹, IGOR M. VILLA^{2*} & SANTOSH KUMAR³

¹*Wadia Institute of Himalayan Geology, Dehradun 248 001, India*

²*Institut für Geologie, Baltzerstrasse 3, 3012 Bern, Switzerland, and Centro Universitario Datazioni e Archeometria, Università di Milano Bicocca, 20126 Milano, Italy*

³*Department of Geology, Center of Advanced Study, Kumaun University, Nainital 263 002, India*

IMV, 0000-0002-8070-8142; SK, 0000-0002-6999-2170

*Correspondence: igor@geo.unibe.ch

The Himalaya–Karakoram–Tibet (HKT) system is composed of at least four major geological components. One very prominent component at the present day is the Phanerozoic collisional belt, with the highest (and arguably most photogenic) mountains on our planet. The prehistory of the Himalaya we see today includes widespread Cambro-Ordovician orogenic magmatism, which in turn reworked Precambrian continental crust (which, in itself, bears clear traces of Proterozoic orogenesis and vestiges of Late Archean magmatism). The integration of geochemical and geochronological databases with the petrological diversity of the various crustal domains constituting the HKT provides an increasingly coherent prototectonic framework. In combination with subsurface imaging, petrotectonics unravels the mixing of mantle and crustal inputs and provides a better understanding of crustal growth, lithospheric evolution and geodynamics, which can be applied to any orogen. The present-day HKT very prominently features circulating fluids, which supplement the role of shallow and deep thermal anomalies in shaping petrotectonics during and after continental collision.

Research is evolving, based on the work of past decades, which contributed greatly to our understanding of the evolutionary history and fundamental architecture of the HKT. Contemporary field research studies the role of various lithospheric components and their inheritance in the geodynamic and magmatic evolution of the HKT through time, and their links to global geological events. An apparently decoupled field of research is focused at the (sub-)micrometre scale, e.g. micro-structural geology, crystal chemistry, circulating fluids and their evolution, distribution, migration and interaction

mechanisms at the atomic scale. The challenge is bridging this scale gap in the realization that a 2000 km-long orogen can be understood only if the processes at the nanometre and micrometre scales are taken into account.

To address the problems pertaining to the geodynamic evolution of the HKT system, and of its past and present orogenesis, the present volume includes a broad selection of contributions, which use both field and laboratory approaches to multiple disciplines such as structural geology, tectonics, petrology, mineralogy, petrochronology, elemental and isotope geochemistry and geophysics. The focus of the contributions gradually moves from the active seismicity of the present day to the remnants of the Proterozoic orogen.

In the first paper, **Poretti *et al.* (2019)** present and analyse the seismic data collected during the Gorkha (25 April 2015) and Ghorthali zone (12 May 2015) earthquakes from the permanent GNSS station located at the Everest Pyramid Laboratory. The data recorded during a period of three days before and after the earthquakes quantify the displacement of the GNSS station from its original position.

Kumar *et al.* (2019) delineate the structure of the upper lithosphere using seismic data collected from 35 broadband seismic stations located across the HKT orogen. The results suggest a NE-dipping Moho, increasing in depth from *c.* 40 km beneath the frontal part of the Himalaya down to *c.* 70–80 km beneath the collision zone, then shallowing substantially beneath the Tarim basin. A broad low-velocity zone at mid-crustal depth beneath the Karakoram and western Tibetan plateau and along the Indus–Yarlung Suture Zone (the surface expression of the India–Eurasia collision) is recognized and

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interpreted to be due to partial melting and/or the presence of aqueous fluids.

Thakur *et al.* (2018) analyse and review the historical accounts of seismic events of different magnitudes and their spatial distribution within thin- and thick-skinned segments corresponding to the central and NW Himalaya, respectively, the boundary of which is recognized along the Ropar–Manali lineament fault zone. They correlate and explain possible reasons for palaeo-seismicity and infer that the occurrence of earthquakes in the central Himalaya is on the plate boundary fault, the Main Himalayan Thrust (MHT), whereas the wedge thrust earthquakes in the NW Himalaya originate on faults in the hanging wall of the MHT. The examination of seismotectonic components may explain the past occurrence of giant earthquakes in the central Himalaya. The lack of large seismic events in the NW Himalaya is probably due to oblique plate convergence.

Adlakha *et al.* (2018) quantify the exhumation in Arunachal Himalaya by means of fission track dating of the Higher Himalayan Crystallines synformal nappe; they constrain the rate of exhumation and long-term erosion regimes since the Miocene. The Apatite Fission Track (AFT) ages yield slow exhumation rates (a median of 0.4 mm a^{-1}) since the middle to late Miocene. The slow exhumation despite the high rainfall in the central Arunachal Himalaya implies an absence of focused erosion, and thus of climate-induced tectonic deformation. **Adlakha *et al.* (2018)** synthesize the structural and rainfall databases in order to define the overall orographic evolution of central Arunachal Himalaya.

Puniya *et al.* (2019) present new data on micro-structures, strain analysis and fission track ages of the rocks from the Almora klippe and Ramgarh thrust sheet along the Chalthi–Champawat–Pithoragarh traverse in the eastern Kumaun Lesser Himalaya. The klippe emplacement age and post-emplacement exhumation rates of the Almora klippe and Ramgarh thrust sheet have been constrained using apatite and zircon fission track ages. Since the Pliocene (*c.* 5 Ma) the exhumation rates have ranged between 0.47 and 0.95 mm a^{-1} ; the variations by a factor of two are related to local effects of thrusting and normal faulting.

Bose & Mukherjee (2019) describe the discovery and field and structural mapping of 31 back-thrust locations in a traverse along the Bhagirathi River section of Garhwal Lesser Himalaya, NW India. Based on observed outcrop-scale features, spatial distribution and tectonic settings they group the back-thrusts into four major groups. They also propose that the back-structures in the Inner Lesser Himalaya might have been generated by shearing related to the folded Berinag Thrust. The spectacular back-structures recorded proximal to the Main Central Thrust (MCT) zone can be very well correlated

with those found at the Delhi–Haridwar Ridge. The observations in the present investigation establish the back-structures to be inherently well developed in parts of the Lesser Himalaya.

Montemagni *et al.* (2018) investigate movements along the Vaikrita Thrust, the upper boundary of the MCT zone, in the Alaknanda Valley, Garhwal Himalaya, NW India. They use (micro)structural evidence, microchemical analyses and ^{39}Ar – ^{40}Ar ages of biotite and muscovite formed during protracted fault activity. They recognize the episodic growth and re-crystallization of multiple mica generations associated with the Vaikrita Thrust and explain the likely causes of the observed chemical changes in these phases. They propose that the Vaikrita Thrust was active at least from 9 to 6 Ma, very probably from as early as *c.* 15 Ma, at around 600°C . Its movement ceased before or around 6 Ma.

Imayama *et al.* (2018) examine the kinematic evolution of the High Himalayan Discontinuity (HHD) and the thermal evolution of the upper High Himalayan Crystalline Sequence (HHCS) from far eastern Nepal Himalaya. Petrological arguments demonstrate that the HHD is a metamorphic discontinuity dividing the HHCS into two separate massifs. Based on *P*–*T* pseudosection modelling of cordierite migmatite and U–Pb zircon and monazite dating from migmatites and gneisses, two separate, diachronous partial melting events are recognized in the upper and lower HHCS. The migmatites in the upper HHCS were formed by biotite dehydration melting at *c.* 800°C around 33–25 Ma. The HHD was active between *c.* 27 and 19 Ma, before the activation of the MCT. The inherited zircon ages indicate the derivation of upper HHCS from Neoproterozoic to Cambrian sediments, which were intruded by *c.* 500 Ma old granitoids.

Broska *et al.* (2019) report for the first time alkaline schorlitic tourmaline together with domains of myrmekitic quartz and tourmaline intergrowths from quartzo-feldspathic Puga gneisses of the Tso Morari Crystalline Complex (TMCC), Eastern Ladakh Himalaya. They recognize four tourmaline types formed during the high-pressure/ultra-high pressure (HP/UHP) peak conditions and subsequent decompression. The HP origin of tourmalines is indicated by its association with rare-earth element (REE)-rich apatite, which upon exhumation decomposed into newly formed apatite, monazite-(Ce) and xenotime-(Y). The excess of silica and the structural disorder suggest that the Si-oversaturated tourmaline was stable at HP/UHP conditions. The authors demonstrate that the tourmaline-bearing Puga gneisses of the TMCC probably shared similar metamorphic conditions during Tertiary collision of the Indian and Eurasian plates as the associated UHP eclogites.

Kingson *et al.* (2019) investigate the easternmost continuation of the Himalayan orogen, the Indo-

Myanmar arc ranges, and report for the first time Sr and Nd isotopic compositions of mafic rocks from the Manipur Ophiolite Complex (MOC). The observed Nd and Sr isotope ratios, high field strength element concentrations, and the light REE patterns of the studied lithological units suggest variations in the slab-derived fluids and in the degree of melting of the fluid-metasomatized mantle. The fluid metasomatism of the mantle wedge changed its characteristics both in time and space across the subduction zone.

Chauhan *et al.* (2019) report and investigate lazulite occurring in the vicinity of a highly tectonized zone of the MCT in the northeastern part of Kumaun Lesser Himalaya. They demonstrate the formation of this refractory mineral adjacent to the MCT. The studied lazulite is an intermediate solid solution near the magnesian lazulite end member. It was formed during Himalayan shearing and concurrent metamorphism associated with a low salinity C–O–H fluid. The authors also document that the lazulite can retain fluid inclusions despite intense deformation conditions such as those prevailing on the MCT.

Heri *et al.* (2019) address the chemical variability observed in Eocene dykes that cross-cut the Ladakh Batholith, west of Leh (India), with diverse orientations, formed during a period of 5 Ma. A visual examination of the REE concentrations qualitatively suggests the existence of genetic relationships between subgroups of these dykes, formed in the same tectonic setting. To rationalize the visual grouping, the authors develop a new statistical tool to assess the genesis of these dykes that quantifies relatedness and consanguinity from the REE patterns, which reflect minor differences in magma chamber processes. Consanguinity tests between the Ladakh dykes and dykes from geographically unrelated areas highlight that similar magma chamber processes were repeated several times in diverse localities.

Godin *et al.* (2018) relate the present-day megastructures observed along the orogen with the relics of the Precambrian basement ridges buried beneath the Indo-Gangetic Plain to the south of the Himalayan deformation front. They carried out analogue centrifuge modelling, which confirms that offsets along the deep-seated basement faults can affect the location, orientation and type of structures developed at various stages of orogenesis, and conclude that it is mechanically feasible for strain to propagate through a melt-weakened mid-crust. They propose that the inherited Indian basement faults affect the ramp-flat geometry of the basal MHT, partition the Himalayan range into distinct zones, localize east–west extension resulting in graben formation in Tibet, and ultimately contribute to lateral variability in tectonic evolution along orogenic strike.

Ogasawara *et al.* (2018) investigate the elemental and Rb–Sr–Sm–Nd isotopic record of Ordovician granites and granite gneisses from the Mansehra region, Pakistan, as well as U–Pb ages and Hf isotope signatures of zircon grains. The Mansehra rocks typically represent Lesser Himalayan peraluminous granites derived by partial melting of sedimentary protoliths. The detrital and inherited zircon ages and $\epsilon_{\text{Hf}}^{(t)}$ values, whole-rock $\epsilon_{\text{Nd}}^{(t)}$ values, two-stage Nd and Hf model ages, and high initial Sr_i of granites and gneisses all indicate recycling and melting of dominant Paleoproterozoic–Neoproterozoic heterogeneous crustal components to produce the Mansehra granites and gneisses. The age range of older crustal components involved in the genesis of Mansehra rocks is similar to those found in the lithological units of the Greater Himalayan belt.

Bikramaditya *et al.* (2018) describe the Subansiri metagranitoids in the eastern Himalaya. They infer a peraluminous (S-type) to calc-alkaline nature for the intrusives, based on geochemical features of minerals and whole rocks. Zircon U–Pb ages constrain Ordovician emplacement (*c.* 516–486 Ma). The granitoids were formed in the Indian passive margin by partial melting of major Proterozoic metasedimentary (continental) sources (2.2 to 1.5 Ga) as indicated by negative $\epsilon_{\text{Hf}}(t)$ values (–1.4 to –12.7) of zircon grains.

Sen *et al.* (2018) recognize two major types of granite gneisses, namely the Upper (UBG) and Lower (LBG) Bhatwari gneisses exposed in the Bhagirathi Valley of the Garhwal Himalaya, which represent Paleoproterozoic crystalline rocks of the Inner Lesser Himalayan Sequence. The UBG (1895 ± 22 Ma) have peraluminous (S-type) to calc-alkaline characteristics generated from granite sources in a volcanic-arc setting, whereas the LBG (1988 ± 12 Ma) exhibit metaluminous (I-type) alkaline characteristics formed by melting of a monzonite protolith in a rift environment. Based on diverse chemical and tectonic features of the LBG and UBG, they infer that the Bhatwari gneisses originated and evolved during arc growth-related magmatism within a time frame of 1940–1840 Ma spanning from arc to back-arc rift environments, during assembly of the Columbia supercontinent.

Pathak & Kumar (2019) deal with field petrography, phase petrology, geochemistry, zircon U–Pb chronology and Hf isotopic compositions of Proterozoic Bomdila granite gneiss (BGGn) from western Arunachal Pradesh, eastern Himalaya. The presence of two micas (bt-ms), and the compositions of biotite, muscovite, tourmaline and whole rocks suggest typical peraluminous (S-type) magmas. The formation of BGGn is attributed to dehydration melting of metasedimentary sources at middle–upper crustal depths in syn- to post-collisional tectonic environments. Petrogenetic modelling constrains the

evolution of BGGn parental rocks by a moderate degree of fractional differentiation ($F = 0.45$) involving a biotite–plagioclase–K-feldspar–muscovite–titanite–apatite assemblage. Zircon U–Pb ages of 1752 ± 23 Ma lie in the formation period of the Columbia supercontinent. The inherited zircon ages (up to 2.4 Ga), negative $\epsilon_{\text{Hf}}(t)$ values (-1.67 to -7.99) and three-stage Hf-model ages (up to 2.8 Ga) indicate reworking of Archean and Paleoproterozoic crustal components.

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