Introduction to Himalayan tectonics: a modern synthesis

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The Himalaya resulted from collision of the Indian plate with Asia and are well known as the highest, youngest and one of the best studied continental collision orogenic belts. They are frequently used as the type example of a continental collision orogenic belt in studies of older Phanerozoic orogenic belts. The beauty of the Himalaya is that, on a broad scale they form a relatively simple orogenic belt. The major structural divisions, the Indus–(Yarlung Tsangpo) suture zone, the Tethyan Himalaya sedimentary units, Greater Himalaya Sequence (GHS) metamorphic rocks, the Lesser Himalaya fold-and-thrust belt and the Sub-Himalaya Siwalik molasse basin are present along the entire 2000 km length of the Himalaya (Figs 1 & 2). Likewise, the major structures, the Indus–Yarlung Tsangpo suture with north-vergent backthrusts, the South Tibetan Detachment (STD) low-angle normal fault, locally called the Zanskar Shear zone in the west, the Main Central Thrust (MCT) zone and the Main Boundary Thrust are all mapped along the entire length of the mountain belt between the western (Nanga Parbat) and eastern (Namche Barwa) syntaxes. Klippen of low-grade or unmetamorphosed sedimentary rocks lie above the GHS high-grade rocks in places (e.g. Chamba klippe in India; Lingshi klippe in Bhutan), and far-travelled klippen of GHS rocks occur in places south of the main MCT and GHS rocks (e.g. Darjeeling klippe).

In broad terms the timing of major events shows little variation along the entire mountain range, with Late Cretaceous–Paleocene obduction of ophiolites onto the passive margin of India, Late Paleocene ultra-high-pressure (UHP) metamorphism at Kaghan (northern Pakistan) and Tso Morari (India), Early Eocene final marine sedimentation prior to the closure of Neo-Tethys, and Late Eocene to Early Miocene regional Barrovian-type metamorphism along the GHS (Fig. 3). Peak kyanite grade metamorphism (Late Eocene–Oligocene) pre-dates the regional higher-temperature, lower-pressure sillimanite ± cordierite-grade event, which was accompanied by widespread migmatization and mid-crustal melting during the Oligocene–Mid-Miocene. The age of the abundant leucogranite sills and dykes along the top of the GHS, beneath the STD, is concomitant with the sillimanite-grade metamorphic event. The GHS metamorphism is all part of one continuum of crustal thickening and shortening, increasing pressure and temperature following a standard clockwise Pressure-Temperature-Time (*PTt*) path. Decompression melting peaked with widespread partial melting and formation of migmatites and leucogranites along the highest peaks of the Himalaya. Structural mapping and timing constraints suggest the large-scale southward extrusion of a partially melted layer of mid-crustal rocks (sillimanite grade gneisses and leucogranites) bounded by the STD ductile shear zone with right-way-up metamorphic isograds above, and the MCT ductile shear zone with inverted metamorphic isograds below, during the Oligocene–Early Miocene. This corresponds to the channel flow (or channel tunnelling) model that is now widely accepted for the GHS ductile structures. Brittle folding and thrusting processes characterize the Lesser Himalaya, structurally below the ductile MCT, and corresponds to the critical taper model. The most recent comprehensive reviews of the structure, metamorphism and tectonic evolution of the Himalaya are given by Kohn (2014), Searle (2015) and Goscombe et al. (2018).

The relatively straightforward structural and metamorphic geometry, and timing constraints along the main Himalayan range are, however, complicated in the two syntaxis regions, the Nanga Parbat–Haramosh syntaxis in the NW (Pakistan), and the Namche Barwa syntaxis (SE Tibet) in the NE. In both these regions, a younger high-temperature metamorphic overprint on the standard Late Eocene–Miocene Himalayan events is apparent with high-grade sillimanite + cordierite crustal melting occurring in the deep basement, as young as Pliocene or even Pleistocene in age. This young metamorphism may be indicative of active metamorphism
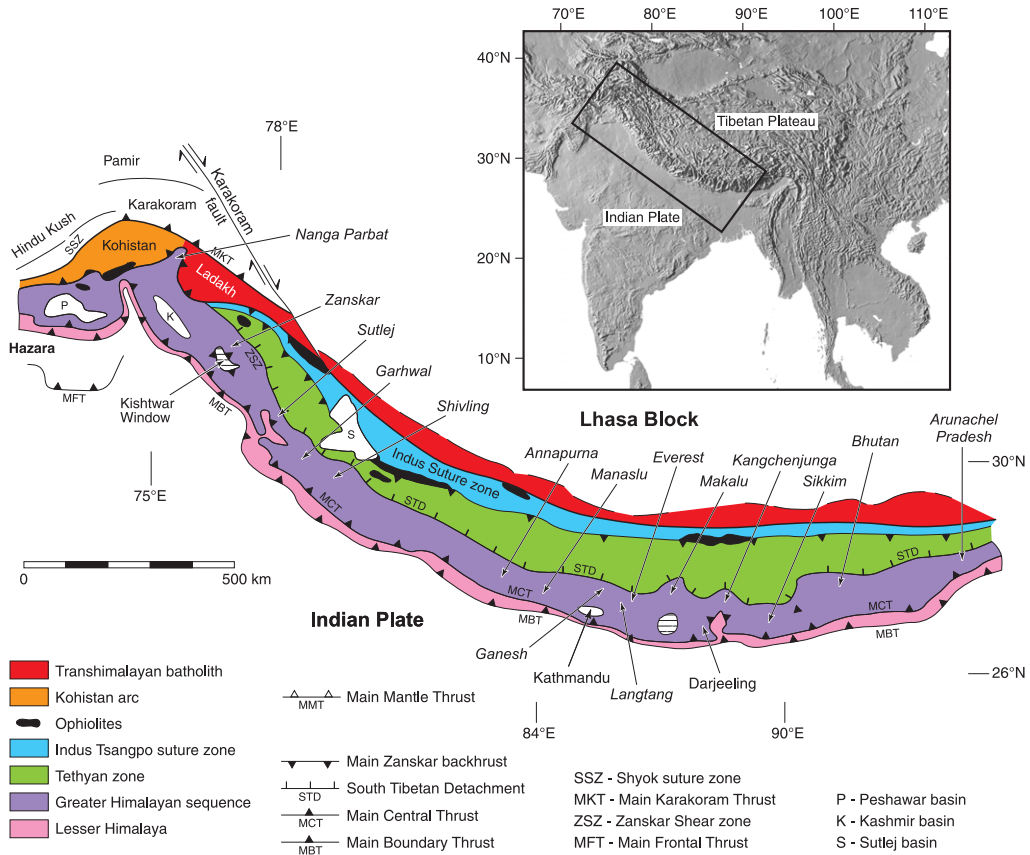
Fig. 1. Geological map of the Himalaya.

that is occurring at depth beneath the Himalaya today in rocks that have not yet been exhumed by thrusting, exhumation and erosion. The relatively straightforward tectonic picture along the main Himalayan range is also complicated in the Pakistan sector, west of Nanga Parbat, where the high-grade kyanite and sillimanite metamorphism has recently been dated as Ordovician, not Himalayan in age (Palin et al. 2018). In Zanskar there is also debate over the timing of the obduction of the Spontang ophiolite onto the Zanskar passive margin sequence, and the relative importance of pre-India–Asia collision folding and thrusting related to the final stages of the obduction, and post- India–Asia collision shortening and thickening.

History of research

The Himalaya have always been at the forefront of geodetic studies. The Great Trigonometrical Survey, started in 1802 under its founder William Lambton

and his successor George Everest, mapped out the Himalayan ranges for the first time. Amongst the many great achievements of the Survey, these surveyors accurately determined the heights of most of the highest peaks of the Himalaya and Karakoram, and measured gravity anomalies that led to the development of the theory of isostasy. Richard Oldham joined the Survey of India in 1879 and made the first detailed observation of a large Himalayan earthquake, the Great Assam earthquake of 1879 (Oldham 1917). Oldham first identified on seismograms the arrivals of primary (P-waves), secondary (S-waves) and tertiary surface waves, previously predicted by mathematical theory. The earliest geological and geographical explorations of the Himalaya were made in the late 1800s and early 1900s. In 1907 Colonel S.G. Burrard, Superintendent of the Trigonometrical Survey, and H.H. Hayden, Superintendent of the Geological Survey of India, published four volumes of their classic work *A Sketch of the Geography and Geology of the Himalaya Mountains and Tibet*. During the late 1800s geologists like
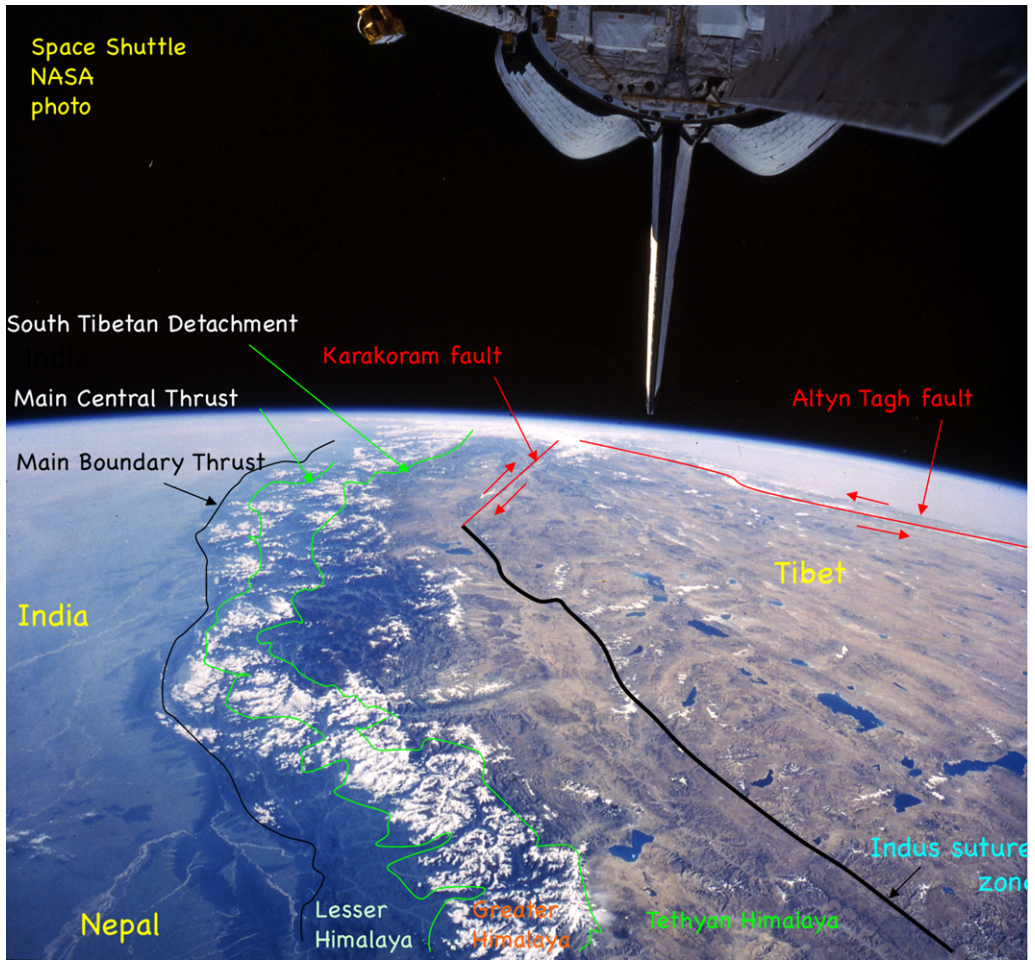
Fig. 2. Photograph taken from the Space Shuttle looking west along the Himalaya with the outline of the major structural divisions and major faults of the Himalaya. Photo courtesy of NASA.

Medlicott, Middlemiss and Oldham made significant discoveries in the western Himalaya, and Mallet and von Loczy first discovered the inverted metamorphic gradient in the Darjeeling klippe.

The next breakthrough was the publication of Arnold Heim and Augusto Gansser's *Central Himalaya: Observations from the Swiss Expedition of 1936* (Heim & Gansser 1939), and Augusto Gansser's classic *Geology of the Himalaya*, published in 1964. Heim and Gansser discovered the remnant ophiolites of SW Tibet in the Kiogar–Amlang-la Range, laid the foundations for the stratigraphy of the Indian plate and confirmed the inverted nature of metamorphism along the Main Central Thrust. Other great pioneering geologists were D.N. Wadia, who mapped large tracts of the NW Frontier region, J.B. Auden and K.S. Valdiya, who worked

along the central Indian Himalaya, Ardito Desio, who led the first successful ascent of K2 and mapped a large tract of the Baltoro Karakoram in 1955, and Rashid Khan Tahirkheli, a heroic Pakistani geologist who mapped large parts of remote Kohistan during the 1970s. This work was continued by the studies of Qasim Jan and Asif Khan and their students from the University of Peshawar. A regional map of the Central Karakoram Mountains covering the Hunza, Hispar, Biafo and Baltoro glacier region at the scale of 1:250,000 was published by Searle (1991) and a large compilation geological map of North Pakistan at scale of 1:650 000 was published by Searle & Khan (1996).

Some of the most important early geological mapping in the Indian Himalaya was carried out by K.S. Valdiya and his colleagues from Kumaon
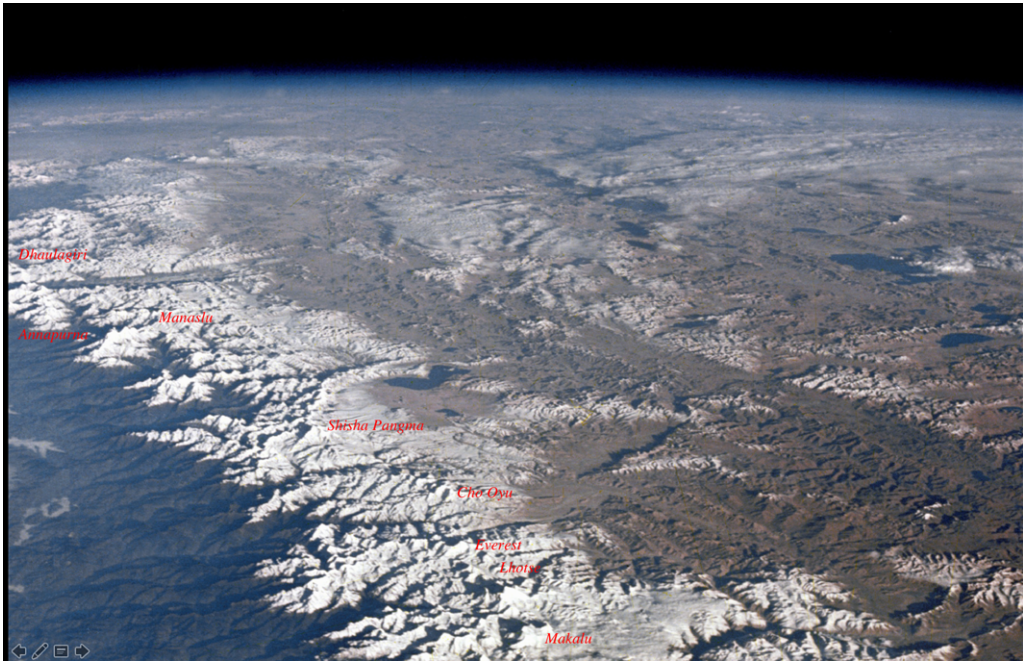
Fig. 3. Photograph of the central Himalaya in Nepal and plateau of Tibet showing the major high peaks, courtesy of NASA.

University, working mainly in the Garhwal–Kumaon Himalaya, and Vikram Thakur and colleagues from the Wadia Institute of Himalayan Geology, Dehra Dun, working mainly in Himachal Pradesh, Lahoul–Spiti and Ladakh. More advances were made by the field studies of A.K. Jain and Sandeep Singh and their students from the Indian Institute of Technology, Roorkee, and Talat Ahmad and colleagues from the universities of Kashmir and Delhi (Jamia Islamia University). With the opening of Ladakh to foreigners in 1979–80 geologists from Italy, Switzerland, France and the UK were also active in the Indian Himalaya throughout the 1980s and 1990s. In many respects this was the golden age of Himalayan research when vast tracts of geologically unknown mountain ranges were mapped and studied for the first time. Emphasis gradually shifted during the 1990s and 2000s from standard sedimentology, stratigraphy, palaeontology and structural mapping to more detailed metamorphic, thermobarometric and geochronological studies of the Himalaya.

In Nepal, the great pioneers of geological mapping include the Swiss Toni Hagen, who over 20 years trekked across large tracts of the country (Hagen 1960), Pierre Bordet in the Thakkhola and Nvi-Shang regions (Bordet et al. 1971, 1975) and in the Makalu region (Bordet 1961), and Michel Colchen, Patrick LeFort and Arnaud Pêcher in the Manaslu region (Colchen et al. 1986). Climbers contributed greatly to the early pioneering studies of Mount Everest. Noel Odell was a geologist–mountaineer on the 1924 British Everest expedition and was the last person to see Mallory and Irvine heading up the NNE ridge towards the summit. Odell made many original geological observations on their journey from Darjeeling and Sikkim to the Tibetan side of Everest, and collected many samples. Lawrence Wager made an invaluable collection of rock samples from the north side of Mount Everest during the 1933 British Expedition led by Hugh Ruttledge. Waters et al. (2018) published a detailed metamorphic–thermobarometric analysis of the Wager samples in 2018, more than 80 years after he collected them. A detailed geological map of the Mount Everest region in Nepal and South Tibet at scale of 1:100 000 was published by Searle (2003), reprinted in 2007 with the addition of the Makalu and Barun glacier region.

In Tibet, the great Swedish explorer Sven Hedin made four expeditions to Central Asia spanning 1893–1935, especially the Trans-Himalayan ranges of southern Tibet, and left an astonishingly large collection of rock samples (Hedin 1909, 1917). With the opening of Tibet to foreigners in the late 1970s and early 1980s, several groups, both Chinese and foreigners, began the huge task of mapping the vast plateau region. A Royal Society expedition

traversed the plateau from Lhasa to Golmud and published the first reconnaissance studies (Chengfa et al. 1988; Shackleton et al. 1988). A large group of French researchers led by Paul Tapponnier made more detailed studies, particularly of the active fault systems over c. 20 years of geological research across much of the plateau. Large-scale geophysical experiments, notably the four phases of the American- and Chinese-funded INDEPTH seismic profile, coupled with magnetotelluric and heat flow studies, spanned more than 20 years of work, and determined the large-scale structure of the lower crust and mantle across the Tibetan Plateau from the northern flank of the Himalaya north to the Kun Lun.

During the 1980s Western geologists started to map and describe the geology of the Himalaya in much more detail. The opening of the Ladakh–Zanskar region to foreigners during the late 1970s opened up this fascinating and remote region to geological research. Sporadic, but ongoing, political problems in Kashmir affected access to some critical areas in the western Himalaya. The first Himalaya–Karakoram–Tibet (HKT) Workshop meeting was convened by Mike Searle at the University of Leicester in 1985, and brought together for the first time a wide range of Asian, European and American geologists. The first talk in the first HKT conference was given by the 'father of Himalayan geology', Augusto Gansser. The meeting was so successful that it was decided to hold an annual HKT meeting, alternating between the Himalayan countries in Pakistan, India, Nepal and China, and Europe or further afield in Canada, the USA, Japan and Hong Kong. HKT meetings were held in Kathmandu in 1994 and 2012, in Peshawar, Pakistan in 1998, in Gangtok, Sikkim in 2002, in Leh, Ladakh in 2008, and in Dehra Dun, India in 2015. These HKT conferences continue to this day and the community is thriving (Fig. 4). The seventh HKT meeting held in Oxford University in April 1992 (convened by Mike Searle and Peter Treloar) led to GSL Special Publication 74, *Himalayan Tectonics*, published in 1993 (Treloar & Searle 1993).
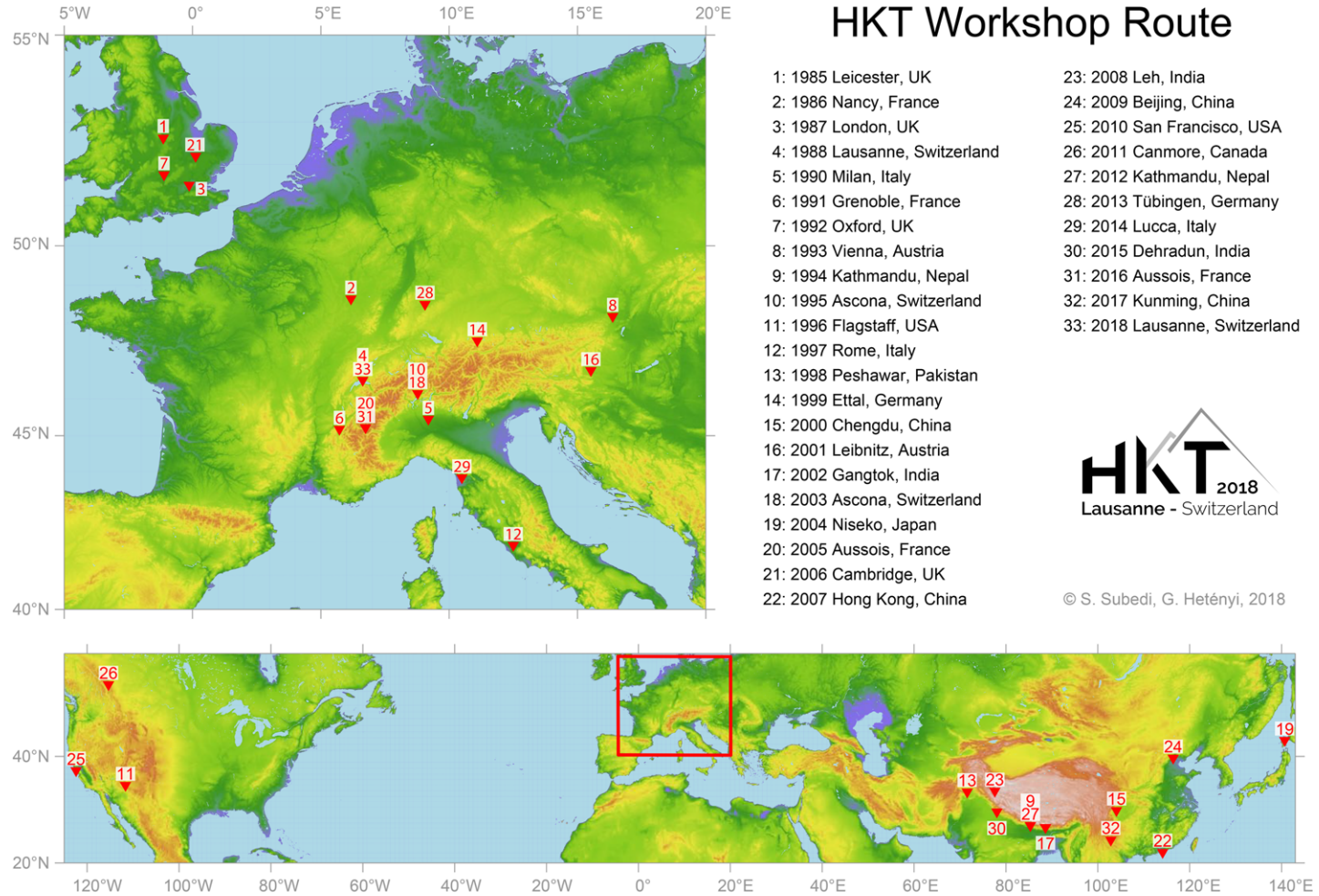
Containing 39 papers over some 600 pages, this volume continues to be widely cited today. Most of the ensuing science has been published in peer-reviewed scientific journals. However, a number of thematic volumes have been published that deal with specific aspects of the Himalaya. These include: GSL Special Publication 170, *Tectonics of the Nanga Parbat Syntaxis and Western Himalaya* (2000, edited by Asif Khan, Peter Treloar, Mike Searle and Qasim Jan), *The Tectonic Evolution of Asia* (1996, edited by An Yin and Mark Harrison), *Himalaya and Tibet* (1999, GSA Special Paper 328, edited by Allison Macfarlane, Rasoul Sorkhabi and Jay Quade), *Channel Flow, Ductile Extrusion and Exhumation in Continental Collision zones* (2006, GSL Special Publication 268, edited by Rick Law, Mike Searle and Laurent Godin). The most recent contributions are *Tectonics of the Himalaya* (2015, GSL Special Publication 412, edited by S. Mukherjee, R. Carosi, P. van der Beek, B. Mukherjee and D. Robinson) and *Crustal Architecture and evolution of the Himalaya–Karakoram–Tibet Orogen* (2018 GSL Special Publication 481, edited by R. Sharma, I. Villa and S. Kumar).

Tectonic processes and outstanding problems–Himalaya–Karakoram–Tibet

During the last 30 years, the annual HKT Workshop meetings have provided a catalyst for research targeted towards solving problems associated with continental collision processes. Some of the critical aspects that continue to be debated as more and more data are generated include the following:

(1) *Palaeogeography of India and the northward drift of the Indian plate*. Following the break-up of the Gondwana continental blocks, the northward drift of India since c. 140 Ma has been documented through palaeomagnetic studies. An abrupt slowing down of the Indian plate at c. 50 Ma at equatorial latitudes is generally thought to be coincident with the initial collision of India with Asia. Palaeogeographic reconstructions differ on the extent of Indian crust and whether an 'extra' ocean is required – the so-called 'Greater Indian Basin' (van Hinsbergen et al. 2012). As no oceanic rocks or ophiolites are known along the MCT zone, this model has been rejected by field geologists. Greater India was one contiguous plate and rock units can be matched across from Lesser–Greater–Tethyan Himalaya to the passive continental margin.

(2) *Proterozoic–Paleozoic evolution of the Indian plate and importance of the Cambrian–Ordovician Bhimpedian orogeny*. Important Cambrian and Ordovician metamorphic and magmatic units have been known along the Lesser Himalaya and klippen such as the Kathmandu klippe for a long time. Recently, kyanite and sillimanite grade gneisses below the Main Mantle Thrust in Pakistan have been dated as Ordovician (Palin et al. 2018), and the relative lack of a Himalayan overprinting has been a surprising result. Future lines of research may be able to distinguish the extent of the Paleozoic orogenic influence in Himalayan rocks overprinted by Cenozoic metamorphism and deformation.

HKT Workshop Route

1: 1985 Leicester, UK
2: 1986 Nancy, France
3: 1987 London, UK
4: 1988 Lausanne, Switzerland
5: 1990 Milan, Italy
6: 1991 Grenoble, France
7: 1992 Oxford, UK
8: 1993 Vienna, Austria
9: 1994 Kathmandu, Nepal
10: 1995 Ascona, Switzerland
11: 1996 Flagstaff, USA
12: 1997 Rome, Italy
13: 1998 Peshawar, Pakistan
14: 1999 Ettal, Germany
15: 2000 Chengdu, China
16: 2001 Leibnitz, Austria
17: 2002 Gangtok, India
18: 2003 Ascona, Switzerland
19: 2004 Niseko, Japan
20: 2005 Aussois, France
21: 2006 Cambridge, UK
22: 2007 Hong Kong, China

23: 2008 Leh, India
24: 2009 Beijing, China
25: 2010 San Francisco, USA
26: 2011 Canmore, Canada
27: 2012 Kathmandu, Nepal
28: 2013 Tübingen, Germany
29: 2014 Lucca, Italy
30: 2015 Dehradun, India
31: 2016 Aussois, France
32: 2017 Kunming, China
33: 2018 Lausanne, Switzerland

HKT 2018
Lausanne - Switzerland

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Fig. 4. Locations of all the Himalaya–Karakoram–Tibet (HKT) Workshop meetings and conferences; map courtesy of S. Subedi and G. Hetényi (with permission).

(3) *Timing of India–Asia collision along the Indus(–Yarlung Tsangpo) suture zone*. The precise timing of India–Asia collision has been hotly debated for at least the last 30 years, with proposed ages ranging from *c.* 65 Ma to as young as 37 Ma. Much depends on exactly how one defines 'collision'. Is it the first meeting of Indian continental crust with Asia, or is it the final disappearance of the Tethyan ocean that once separated the two plates? Various geological factors have been used to define the age of collision including palaeomagnetism (slow-down of northward drift of India), the age of UHP rocks along the northern margin of India (Kaghan and Tso Morari eclogites), the final marine sediments within the suture zone, the earliest clasts derived from Asia (Ladakh–Gangdese granites) in the Indus suture molasse deposits, the ending of calc-alkaline magmatism and volcanism along the south Asian margin (Ladakh–Gangdese batholith). UHP eclogites cannot be used to constrain collision as they are known from areas where continental collision has not yet occurred (e.g. Oman, Papua, New Guinea). In these examples subduction of the leading edge of the previously passive continental margin was the final stage of ophiolite obduction processes, not related to continent–continent collision (Searle & Treloar 2010). The most accurate timing of India–Asia collision is the precise foraminifera zonation of the final marine sediments along the suture zone, which are planktonic foraminifera zone P7-8 in Waziristan, Ladakh and South Tibet, at 50.5 Ma (Green *et al.* 2008). However, this age records the last marine sedimentation within the suture zone, not necessarily the first meeting of Indian and Asian crust.

(4) *Evolution of the Kohistan island arc and the Shyok suture zone*. The Kohistan–Dras island arc was a large, late Jurassic–Cretaceous intra-oceanic island arc sequence that lay between the Indian and Asian plates (Jagoutz & Schmidt 2012). The entire 20 + km-thick sequence has been tilted to the north and accreted onto the Asian plate along the Shyok suture zone, and obducted south onto the Indian plate along the Main Mantle Thrust (MMT). The arc itself has multiple basalt–andesite–rhyolite volcanic phases spanning the Cretaceous to Early Eocene, overlying a mid-crustal amphibolite and lower crust garnet–granulite sequence (Jijal complex), intruded by the Chilas complex gabbro norites. The entire island arc sequence has been intruded by multiple granodiorite–granite intrusions related to the Trans-Himalayan (Ladakh–Gangdese) batholith. Debate continues as to whether the Shyok suture closed first accreting the arc onto Asia, or whether the Shyok and Indus sutures closed simultaneously during early collision. The geology of the Indus suture in Ladakh and south Tibet is well mapped, but the Shyok suture in Pakistan to the north remains enigmatic and poorly known.

(5) *Timing of ophiolite obduction onto the Indian plate*. By definition, ophiolite obduction must have occurred prior to continent–continent collision. Since ophiolites generally form the structurally highest thrust sheet, separated from the continental margin by intermediate thrust slices of passive margin slope to basin facies sedimentary rocks that originally lay between the continental margin and the ophiolite, they were the first to be removed by erosion. Only exceptional structural features (out-of-sequence or breakback thrusts) have preserved large ophiolitic thrust sheets, such as the Spontang ophiolite, in Zanskar (Searle *et al.* 1997). A major phase of crustal shortening and thickening occurred prior to deposition of Paleocene–Eocene shallow marine sedimentary rocks around Spontang, a deformation phase that has been ascribed to ophiolite obduction, rather than India–Asia collision. Determining the timing of upper crustal folding and thrusting along the Tethyan Himalaya is an important goal for future work.

(6) *Timing of metamorphism along and across the GHS*. Following the India–Asia collision crustal thickening along the Indian plate resulted in burial and metamorphism of the Indian plate rocks. Protoliths of GHS metamorphic rocks can be correlated across to unmetamorphosed sedimentary and volcanic (Permian Panjal Trap) rocks in the Tethyan zone to the north, and to Proterozoic and Paleozoic age rocks in the Lesser Himalaya to the south. GHS rocks have protolith ages ranging from Proterozoic (Haimanta Series) through Paleozoic to Jurassic. U–Pb ages of kyanite grade rocks are generally in the range *c.* 45–30 Ma, and sillimanite grade rocks range from *c.* 30 to *c.* 11 Ma (see reviews in Kohn 2014 and Searle 2015). The youngest ages are recorded from the two syntaxis regions, Nanga Parbat in the west and Namche Barwa in the east, with ages of crustal melting as young as Pliocene–Pleistocene (3–1 Ma) in the Nanga Parbat core. More detailed geochronology, linking accessory phase dating to specific

metamorphic periods and *PT* conditions would tie down the thermal history in greater detail.

(7) *PTt paths of rocks across the GHS*. One of the major advances in the last 20 years has been the ability to match U–Pb ages on accessory minerals such as zircon, monazite, allanite and rutile to points on the pressure-temperature path of rocks. This has resulted in numerous studies relating *PTt* paths to prograde burial and retrograde exhumation paths across the GHS. Isochemical phase diagram (pseudosection) modelling using large datasets such as THERMOCALC has been extremely useful for interpretation of pressure–temperature data, but must be used with caution. At the outset, it must be determined whether the minerals used are in equilibrium and whether the 'age' obtained from an accessory mineral is actually related to the metamorphic reaction in question. Linking *PTt* paths with microstructures gives an extra dimension with *PTtD* (deformation) paths. Determining prograde and retrograde *PTtD* paths across major structures and being able to put a precise age on specific parts of the path has undoubtedly revolutionized our understanding of timescales of metamorphism. It is apparent now, for example that, in places rocks showing younger prograde burial *PTt* paths lie structurally beneath rocks showing older *PTt* paths, conforming to the general southward propagation of metamorphism across the GHS with time, following the regional structures. As older metamorphic slices in the north were being exhumed, younger metamorphic rocks in the south were being buried. Future research is needed to determine whether cryptic shear zones within the GHS are real structures, or whether they are metamorphic isograds. The High Himalayan Detachment (Goscombe *et al.* 2006, 2018), for example, may be either a ductile shear zone or the sillimanite + K-feldspar isograd marking the first appearance of migmatite melt and leucogranite sills (and possibly the base of the extruding channel). Only field-based mapping combined with well-constrained *PTtD* paths along the upper GHS will be able to accurately correlate many of these cryptic structures along-strike.

(8) *Nature and timing of motion along the South Tibetan Detachment low-angle normal fault*. One of the major new advances in Himalayan (and other) orogenic processes has been the recognition and detailed mapping of large-scale, low-angle normal faults such as the South Tibetan Detachment, which runs for over 2000 km along-strike. The STD bounds the upper (northern) extent of the GHS metamorphic rocks and consists of a thick ductile shear zone to brittle detachment which separates high-grade gneisses, migmatites and leucogranites below from unmetamorphosed sedimentary rocks above, frequently with a large *PT* jump across it. Minimum offsets on the STD are in excess of 100 km along the Everest profile, and this structure was instrumental in the recognition of the 'channel flow' hypothesis, whereby a thick slab of partially molten middle crust (upper GHS), was extruded southward during the Early Miocene (Searle *et al.* 2006). U–Pb dating of concordant leucogranite sills and discordant cross-cutting leucogranite dykes has tied down the timing of shearing along the STD to *c.* 23–15.4 Ma (Cottle *et al.* 2015).

(9) *Origin and evolution of inverted metamorphism along the Main Central Thrust*. The inverted metamorphic sequence along the base of the GHS is present along the entire >2000 km length of the orogen. The increase in pressure and temperature up-structural section from unmetamorphosed rocks of the Lesser Himalaya through low-grade metamorphic rocks, through staurolite, kyanite, sillimanite gneisses and the first appearance of partial melt in migmatites defines an inverted metamorphic sequence. The amounts of southward thrusting of GHS rocks are difficult to quantify but are thought to be similar to the minimum offsets along the STD zone at the top of the GHS. Models to explain inverted metamorphism include thrusting a hot slab over a cold slab (LeFort 1975), shear heating along the MCT (England *et al.* 1992) and the post-metamorphic folding of earlier formed metamorphic isograds (Searle & Rex 1989). Field mapping of metamorphic isograds in the NW Indian Himalaya showed that right-way-up metamorphic isograds along the STD ductile shear zone (Zanskar shear zone) could be linked to inverted metamorphic isograds along the MCT ductile shear zone below (Kishtwar Window). This folded isograd geometry was the origin of the channel flow model (Searle & Rex 1989; Searle *et al.* 2008).

(10) *Crustal melting and channel flow processes in the GHS*. Partial melting of the crust first appears with kyanite-bearing migmatites that have been found in many parts of the GHS. The higher volume melts are related to the muscovite dehydration melt reaction with sillimanite + muscovite breaking down

to sillimanite + K-feldspar + melt. These melts form a thick network of *in situ* migmatites, foliation-parallel sills with cross-cutting, interconnecting dykes and larger leucogranite massifs, now known to be giant sills rather than intrusive diapirs. Himalayan leucogranites have varying amounts of garnet, tourmaline and muscovite, whilst later leucogranites may contain cordierite and even andalusite as magmatic phases (Searle *et al.* 2010*a*; Streule *et al.* 2010*a*; Visona *et al.* 2012). The leucogranites all appear in the upper GHS and are structurally truncated by the overlying STD. The larger leucogranite bodies are the Shivling–Bhagirathi mountains in India, the Manaslu, Everest–Nuptse–Makalu and Kangchenjunga massifs in Nepal, Shisha Pangma leucogranite in South Tibet, and several peaks along the upper GHS in Bhutan (Chomolhari, Masang Kang, Kula Khangri, etc.). It is a surprising fact that peak temperatures associated with melting occur in the upper part of the middle crust, never in the lower crust. This unusual structural setting can only be related to the high heat-producing elements concentrated along the NeoProterozoic black shales of the Haimanta Sequence (Cheka Sequence in Bhutan), rocks thought to be protoliths of the sillimanite gneisses and migmatites. The 'channel flow' model of southward extrusion of the partially molten mid-crust layer in the upper GHS, bounded by the STD low-angle normal fault above and the south-directed ductile shear zones along the upper MCT below (e.g. Godin *et al.* 2006; Searle *et al.* 2006), was derived from detailed structural mapping, combined with metamorphic petrology, thermobarometry and geochronology.

(11) *Critical taper fold-and-thrust processes along the Lesser Himalaya*. Below the ductile MCT zone, rocks of the Lesser Himalaya contain brittle fold and thrust structures, typical of shallow-level fold-and-thrust belts. The controversies between channel flow and critical taper are contrived (Webb *et al.* 2011; He *et al.* 2015). Channel flow refers to the ductile extrusion of hot migmatites and leucogranites during the Early Miocene along the GHS; critical taper models refer to brittle folding and thrusting along the Lesser Himalaya and Main Boundary thrust from about 11 Ma ago to the present (Searle *et al.* 2017). Folding of the Lesser Himalaya formed a series of klippen (e.g. Kathmandu klippe) that are stranded remnants of GHS rocks above the Lesser Himalayan duplexes.

(12) *Timing of thrusting along the Main Boundary Thrust and infill of the Siwalik foreland basin*. Ductile channel flow processes along the GHS ceased at around 13–11 Ma when thrusting propagated southwards to the Lesser Himalaya. During this time, a flexural foreland basin developed along the southern margin of the Himalaya owing to loading by the Himalayan thrust sheets and warping of the Indian plate as it underthrust the Lesser Himalaya. The Siwalik basin was infilled with sediments eroded off the rising Himalaya to the north. Dating of these sediments using detrital zircon ages, and provenance studies have shown that maximum periods of sediment accumulation in the foreland basin correspond to periods of increased rock uplift and exhumation along the Himalaya. The Siwalik-type sediments continue SW into the Indus basin and offshore Indus Fan, and also to the SE along the Ganges River to the Bhramaputra basin and Bengal Fan, where these sediments reach a thickness of over 20 km offshore the Ganges Delta.

(13) *Active thrusting and earthquakes along the Main Himalayan Thrust*. Historic and recent earthquakes, particularly the 25 April 2015 magnitude 7.8 Gorkha earthquake in Nepal, have provided invaluable data on the mechanics and scale of active thrust faults. With the advances in GPS and InSAR technology, these have revealed remarkable detail on the rupture scale, timing and magnitude of slip, and uplift mechanism (Elliott *et al.* 2016). Forensic studies on older historic earthquakes such as the magnitude 8.1 Bihar earthquake of 1934, the largest known along the Himalayan belt, can also benefit from comparisons with the better known recent earthquakes (Bilham 2004).

In addition to Himalayan tectonic processes, important processes along the Asian plate in the Karakoram, Pamir and Tibetan plateau region include:

(14) *Timing of granite magmatism, calc-alkaline volcanism along the Gangdese granite batholith*. The southern margin of the Asian plate is marked by a linear granite batholith – the Ladakh–Gangdese batholith composed of calc-alkaline I-type granitoids with andesitic volcanics (Linzizong volcanics). These Andean-type granitic rocks are related to the subduction of Tethyan oceanic lithosphere northwards beneath Tibet. U–Pb zircon ages span from Late Jurassic through to Eocene time (Chung *et al.* 2005), and their ending is thought to be soon after continent–continent collision which closed off the

oceanic subduction source. Small-volume, post-collision adakites are sourced from melting of a garnet-bearing lower crust eclogite or amphibolite and occur across the Tibetan plateau. At least four very large porphyry copper (and gold) deposits occur within the Gangdese batholith in south Tibet, but it remains unclear if they are related to calc-alkaline subduction-related Gangdese plutonism, or the younger Miocene lower crust-derived adakites.

(15) *Timing of crustal thickening and uplift of the Tibetan Plateau.* The crustal structure and timing of uplift of the Tibetan plateau has been the source of much controversy. Some older studies presumed that the plateau uplifted as recently as 7–8 Ma based on highly convoluted reasoning and far-field effects (e.g. climate and vegetation changes in Tibet and India and changes in global ocean chemistry, etc.; Molnar *et al.* 1993). Others proposed much older uplift, even pre-collisional based on U–Pb age data from metamorphic and magmatic rocks in the Karakoram and parts of more deeply exhumed Tibetan crust (Searle *et al.* 2010*b*, 2011). It seems quite likely that southern Tibet had a topography similar to that of the present-day Andes before the collision of India, with increased and enhanced post-collision uplift concomitant with regional kyanite- and sillimanite-grade metamorphism extending back to at least 65 Ma. Certainly, erosion rates on the Tibetan plateau have been extremely low, since fission track ages extend back to at least 49 Ma. These data suggest a rather passive uplift of the Tibetan plateau rather than any homogeneous shortening that would have produced regional Cenozoic metamorphism across Tibet.

(16) *Extent of underthrusting of lower Indian crust northwards beneath the Tibetan plateau.* Two end-member models to explain the double crustal thickness beneath the Tibetan plateau are wholescale underthrusting of the Indian plate beneath the whole of the plateau as first suggested by Argand (1924), and post-collisional homogeneous crustal shortening and thickening, as first suggested by Dewey and Burke (1973). It seems apparent that the Himalaya has absorbed at least 500 km shortening in upper crustal rocks (Proterozoic and younger). The equivalent lower crust Archean rocks that underlay these prior to collision have been underthrust north, at least half-way across the plateau (Searle *et al.* 2011). This model is supported by several deep crustal geophysical

experiments (e.g. INDEPTH, HiCLIMB) that suggest that the southern half of the plateau is underlain by cold lithospheric mantle and only the northern part of the plateau along the Kunlun has a hot asthenospheric mantle with strong east–west mantle anisotropy. This region also correlates with the youngest shoshonitic mantle-derived volcanics. Future studies might constrain mantle structure in more detail and tomographic studies might be able to delineate old, subducted slabs in the deep mantle beneath the plateau.

(17) *Timing of regional metamorphism along the southern Karakoram and Pamir gneiss domes.* The southern margin of the Asian plate in the west lies along the Karakoram Mountains of north Pakistan, and far north Ladakh. Regional mapping along the Baltoro and Hushe regions, combined with structural, metamorphic and U–Pb geochronology, has constrained the southern Karakoram metamorphic complex as being mainly post-collisional kyanite- and sillimanite-bearing gneisses, migmatites and leucogranites (Searle *et al.* 2010*b*). Earlier, pre-collision high-temperature, low-pressure andalusite–sillimanite metamorphism in the Hunza valley region is related more to the I-type granite batholiths along the southern margin of Asia. These regional metamorphic rocks support a post-collisional thickening event north of the suture zone, but similar rocks are not seen in Tibet, although it is possible that they remain buried and have not yet been exhumed. U–Pb ages constrain the ages of metamorphism in both the southern Karakoram and the central Pamir gneiss domes as Eocene to middle Miocene, a similar time span to that known along the Indian plate Himalaya south of the suture zone.

(18) *Geological offsets and timing of slip along the major strike-slip faults of Tibet* (e.g. Karakoram, Altyn Tagh, Kun Lun, Xianshuihe, Jiale faults). Another important tectonic model originally proposed by Molnar & Tapponnier (1975) was the eastward extrusion of Tibetan crust, bounded by large-scale strike-slip faults, notably the dextral Karakoram and Jiale faults along the SW and SE, and the sinistral Altyn Tagh and Kun Lun faults along the north. Initially the geological offsets along these bounding strike-slip faults was thought to be very large (500–1000 km; Tapponnier *et al.* 1982). Subsequent detailed field structural mapping combined with U–Pb geochronology, particularly along the Karakoram fault, determined that finite

geological offsets were much lower (120–35 km; Searle *et al.* 2010*b*), and initiation of shearing was younger than the youngest dated leucogranites (<13 Ma; Phillips *et al.* 2004). Strike-slip faulting cannot explain the uplift of the plateau, and it would appear that, despite some of these faults being extremely active (e.g. Xianshui-he fault), their total offsets are limited. More detailed mapping combined with geochronology studies is needed along many of the other active strike-slip faults on and around the margins of Tibet.

(19) *Relationship between Tibetan plateau uplift and the Indian monsoon.* The link between topographic uplift of the Tibetan Plateau, Northern Hemisphere or global climate change, and initiation of the Indian monsoon has been the source of much research and speculation. The rise of the plateau certainly must have deflected the west to east air flow of the jet stream (Molnar *et al.* 1993). The rise of the Himalaya certainly formed an abrupt back-stop to the northerly flowing Indian summer monsoon winds. Timing of uplift of the plateau and timing of uplift of the Himalaya are therefore crucial to our understanding of climate changes across Asia.

(20) *How does the Himalaya–Karakoram–Tibet orogen compare with other continent–continent collision mountain ranges back in time*? Comparisons of the HKT orogen have been made with the Proterozoic Trans-Hudson orogen of Northern Canada (St-Onge *et al.* 2006), the Paleozoic Caledonian orogen (Streule *et al.* 2010*b*) and the Variscan orogeny (Maierova *et al.* 2015), with varying results. There do appear to be some unique features of the Himalaya and it could be argued that the HKT orogeny is unique in many aspects.

Himalayan Tectonics–A Modern Synthesis

The justification for the current volume in some ways goes back to the success of the 1993 *Himalayan Tectonics* volume, which provided a remarkably broad ranging set of papers that covered the full range of geography and science that the Himalaya provide us with. These papers have been and continue to be widely cited. With the possible exception of Yin & Harrison (1996), no subsequent volume has attempted this. Twenty-five years after publication of the 1993 book, it seemed an appropriate moment to provide a wide-ranging update of what we now know about the Himalaya–Tibet–Karakoram region. Rather than doing this as a conference volume,

the method employed was to invite leading scientists to write review papers in their own fields that together will provide a coherent framework on which future research can be based. We are grateful to our friends and colleagues who agreed to participate in this project and trust that 25 years down the road this volume will appear as significant as the 1993 book.

The present volume comprises a set of papers on the Himalaya, Kohistan arc, Tibet, the Karakoram and Pamir ranges that represent a review of our current understanding of the geology and processes that formed the mountain ranges we see today. The first paper by **Searle (2018)** reviews the geological evidence for the timing of subduction initiation, arc formation, ophiolite obduction and final closure of NeoTethys along the Indus suture zone and Ladakh Himalaya in particular. There is a complex series of events involved here that document India–Asia plate convergence, pre-collision ophiolite emplacement, UHP metamorphism and 'collision' between India and Asia. It is easy to confuse features that relate to pre-collisional events with those that actually relate to the collision itself. The age of India–Asia depends on how one defines collision, but the generally accepted age, based on final marine fossiliferous sediments within the suture zone and along the north Indian plate margin, is *c.* 50 Ma. **Myrow et al. (2018)** describe the restoration of the Himalaya using the Neoproterozoic and Paleozoic stratigraphy along the Lesser Himalaya and Tethyan Himalaya. They develop a stratigraphy for the Indian Plate rocks with a Paleo-Proterozoic basement >1.6 Ga, overlain by a sequence of Neo-Proterozoic sediments <1.1 Ga old. These are blanketed by Cambrian and younger sediments. Understanding this stratigraphy is key to unravelling field geology along the arc.

Two complementary papers explore the geology and evolution of the Kohistan arc in the Pakistan Himalaya. **Petterson (2018)** reviews the geological history of all units forming the Kohistan island arc, one of the largest and best exposed arcs in the geological record. Kohistan exposes a *c.* 40–50 km structural profile through this late Jurassic–Cretaceous intra-oceanic arc from deep garnet granulites and peridotites at the base through gabbros and amphibolites to classic calc-alkaline granites and volcanics at the top. Pettersen provides an up-to-date stratigraphy and time line for the forearc region. **Jagoutz et al. (2018)** present a comprehensive set of U–Pb, Hf, Nd and Sr isotopic data along the Kohistan–Ladakh arc spanning some 120 myr of geological history. They document a long-term magmatic evolution that shows a continuously increasing contribution of an enriched component derived from the subducted slab into the depleted sub-arc mantle.

Along the Himalaya the geology of the currently exposed Indian plate includes: continental shelf–slope–basin rocks at the leading edge of the plate margin, a slice of which was subducted to UHP depths of more than 100 km, as exposed in the Kaghan, Stak (Pakistan) and Tso Morari (India) eclogite belts; the Neoproterozoic to Cenozoic Tethyan sedimentary upper crust; North Himalayan domes; the Greater Himalayan metamorphic sequence; and Lesser Himalayan thrust sheets. O'Brien (2018) reviews the geology, thermobarometry and timing of the coesite-bearing UHP eclogites in both the Kaghan and Tso Morari regions. The UHP rocks are distinctly different from the granulitized eclogites of deep levels of the GHS as seen in the Ama Drime massif, north Sikkim, NW Bhutan and the Namche Barwa syntaxis. These rocks represent deep crustal Proterozoic rocks that have been subducted beneath south Tibet and undergone Oligocene–Miocene UHP metamorphism during crustal thickening. Butler (2018) reviews the geology of the Nanga Parbat syntaxis in northern Pakistan. He argues that feedback mechanisms implied in the tectonic aneurism models may have been over-emphasized and that patterns of ductile flow within the syntaxes are consistent with orogeny-wide gravitational flow. Treloar et al. (2019) review the geology of the Pakistan Himalaya south of the Kohistan arc and Main Mantle Thrust. Here, kyanite- and sillimanite-grade gneisses previously thought to be the result of Himalayan age metamorphism, now reveal an important Ordovician peak thermal event (Bhimpedian orogeny), constrained by U–Pb dating of monazites, with a weaker Himalayan overprint. These rocks are clearly different from the main Himalayan GHS gneisses of Late Eocene to Mid-Miocene age, with their migmatites and leucogranites as exposed along the Zanskar Himalaya and further east to Garhwal, Nepal, Sikkim and Bhutan. They do, however, correlate with rocks along the Lesser Himalaya and Kathmandu klippe which also have Cambrian–Ordovician metamorphism and S-type granites.

A number of papers deal with the Nepalese sector of the Himalaya. Dyck et al. (2018) describe the protolith stratigraphy of the Langtang GHS based on detrital zircon dating of the high-grade gneisses and compare the Proterozoic–Paleozoic protolith stratigraphy in the Langtang Himalaya with that of the Annapurna region to the west and the Everest region to the east. They argue that, within the context of the Northern Indian sedimentary successions, the Lesser, Greater and Tethyan Himalayan successions are structurally rather than lithologically defined. Carosi et al. (2018) describe the structure and metamorphism of the central western Nepal region with emphasis on the High Himalayan Discontinuity, a cryptic tectono-metamorphic boundary lying above the Main Central thrust. Most data support a model for GHS metamorphism of in-sequence shearing affected by minor later out-of-sequence thrusts. Waters (2019) provides a comprehensive and detailed review of the metamorphism of the Nepal Himalaya, in terms of pressure–temperature conditions, phase diagram (pseudosection) modelling, ductile strain and timing. The first part of his paper reviews the techniques used to constrain the metamorphic evolution of orogenic belts. The second part of the paper documents different PTt paths in the GHS below and above the 'High Himalayan Discontinuity' (Goscombe et al. 2006, 2018) that divides the GHS into an upper zone capable of ductile flow and a lower zone characterized by inverted metamorphic gradients and downward decreasing metamorphic ages. Kellett et al. (2018) review the structures and metamorphism of the South Tibetan Detachment system in Nepal and South Tibet and discuss the various tectonic models including gravitational collapse, wedge extrusion, channel flow and duplexing. The STD appears to be an enigmatic and possibly unique structure, a low-angle normal fault that caps the southward extruding ductile middle crust (GHS). Jessup et al. (2019) distinguish two type of gneiss domes along the northern Himalaya. The North Himalayan gneiss domes formed by warping of the GHS metamorphic rocks after metamorphism and are cored by granite and gneiss. The type 2 domes formed in response to orogen-parallel extension during the Late Miocene. They present a new terminology to classify the domes which helps elucidate their significance.

The Siwalik foreland basin along the southern boundary of the Lesser Himalaya preserves an erosional history of the uplift and exhumation of the Himalaya since collision. Garzanti (2019) summarizes the stratigraphic, petrological and mineralogical evidence from the foreland basin sequence. The onset of India–Asia collision is pinned down to middle Paleocene (60–58.5 Ma) time with the first provenance of Asia plate material interbedded with Indian plate continental rise rocks. The final marine sedimentary rocks within the suture zone and along the north Indian plate margin are c. 50.5 Ma. Thus, the timing of India–Asia collision could be bracketed between these two ages. The abrupt appearance of metamorphic fragments derived from the uplifted GHS appears at c. 23 Ma.

A comprehensive review of historical seismicity along the Himalaya is provided by Bilham (2019). He assesses the risk and slip potential of different segments of the Himalaya and concludes that more than half the region has the potential to host a great earthquake ($M_w \geq 8.0$). This is particularly worrying given the magnitude of destruction and loss of life (>9000 dead, 22 000 injured) that occurred during the 25 April 2015 M_w 7.8 Gorkha earthquake. This

earthquake occurred at midday on a Saturday when schools were closed and most people were outdoors; if it had happened at night or during school time, the death toll would have been far greater. He argues that the death toll of a major nocturnal earthquake could exceed 100 000 owing to increased population and the vulnerability of present-day construction methods. **Priestley *et al.* (2019)** review all the geophysical data that allow an interpretation of the deep structure of the Himalaya, including seismic, gravity and modelling. They argue that, although the gross crustal structure of much of the Himalaya is becoming better known, understanding of the internal structure is still sketchy.

The Asian margin of the India–Asia collision zone comprises the Gangdese granite belt along the southern margin of the Lhasa Block, and the northern terranes of the Qiangtang and Kunlun. These central Tibet terranes continue west into the Karakoram Mountains and Pamir ranges. **Metcalf & Kapp (2019)** present results of mapping more than 200 km of the Yarlung Suture zone using detrital zircon U–Pb ages and petrography. Their model has the Zedong arc representing the southward migration of the Gangdese arc as it was emplaced onto a forearc ophiolite complex along the southern margin of Asia. **Zhu *et al.* (2018)** review the magmatism along the Gangdese batholith of south Tibet since 120 Ma using a very large dataset of 290 U–Pb zircon ages that span *c.* 210 – *c.* 10 Ma. The majority of the ages are from the main calc-alkaline granite–granodiorite Gangdese rocks, but an important minority are from the small volume felsic adakites that were erupted at *c.* 16 Ma. The age of the Linzizong calc-alkaline volcanics is now refined to *c.* 60–52 Ma.

The geology of the Karakoram and Pamir, the eastern extension of the northern Lhasa and Qiangtang terranes, is very different from the geology of central Tibet. Much of the latter is composed of sedimentary rocks and granites with few metamorphic deep crust rocks, whereas large tracts of the southern Karakoram and central Pamirs are dominated by kyanite- and sillimanite-grade regional metamorphic rocks. **Searle & Hacker (2018)** review the structure and metamorphic evolution of the Karakoram and Pamir. The ages of peak metamorphism appear close to mirror images of the Oligocene–Miocene ages from the Greater Himalaya, suggesting post-collision crustal thickening spread both south (Himalaya) and north (Karakoram, Pamir) of the suture zone. These Cenozoic metamorphic rocks are not exposed across central or eastern Tibet, but could be present in parts of the deep crust of the plateau region, unexposed thus far by erosion–exhumation processes. **He *et al.* (2018)** integrate new geological mapping along the Muskol metamorphic dome in the Central Pamir with detrital zircon geochronology

and petrography. They describe Triassic rocks unconformably overlain by Cretaceous strata that are similar to the southern Qiangtang terrane and Bangong suture zone. Oligocene conglomerates interbedded with siltstones record a juvenile magmatism at *c.* 32 Ma. Finally, **Clift & Webb (2018)** review the history of the Asian monsoon in South Asia. They describe a strengthening of rainfall at *c.* 24 Ma, with a peak wet period at *c.* 15 Ma in the middle Miocene and a drying at *c.* 8 Ma. Neither of these ages correlates with the timing of uplift of the Tibetan plateau, or with the retreat of shallow marine seas from central Asia. The rise of the Himalaya during the Miocene provided an abrupt tectonic barrier to the northerly summer monsoon wind and rainfall, a situation that continues to this day.

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