Eclogites and other high-pressure rocks in the Himalaya: a review

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Abstract: Himalayan high-pressure metamorphic rocks are restricted to three environments: the suture zone; close to the suture zone; and (mostly) far (>100 km) from the suture zone. In the NW Himalaya and South Tibet, Cretaceous-age blueschists (glaucophane-, lawsonite- or carpholite-bearing schists) formed in the accretionary wedge of the subducting Neo-Tethys. Microdiamond and associated phases from suture-zone ophiolites (Luo-busa and Nidar) are, however, unrelated to Himalayan subduction–collision processes. Deeply subducted and rapidly exhumed Indian Plate basement and cover rocks directly adjacent to the suture zone enclose eclogites of Eocene age, some coesite-bearing (Kaghan/Neelum and Tso Morari), formed from Permian Panjal Trap, continental-type, basaltic magmatic rocks. Eclogites with a granulite-facies overprint, yielding Oligocene–Miocene ages, occur in the anatectic cordierite ± sillimanite-grade Indian Plate mostly significantly south of the suture zone (Kharta/Ama Drime/Arun, north Sikkim and NW Bhutan) but also directly at the suture zone at Namche Barwa. The sequence carpholite-, coesite-, kyanite- and cordierite-bearing rocks of these different units demonstrates the transition from oceanic subduction to continental collision via continental subduction. The granulitized eclogites in anatectic gneisses preserve evidence of former thick crust as in other wide hot orogens, such as the European Variscides.

High-pressure metamorphic rocks such as blueschists (glaucophane ± lawsonite-bearing rocks), eclogites and high-pressure granulites are the products of major geodynamic processes such as subduction, collision and crustal thickening. More important, however, is the fact that metabasic blueschists, eclogites and high-pressure granulites often undergo much less deformation and recrystallization during exhumation to the present-day surface than their host rocks and thus provide crucial preserved evidence for these processes in the form of their metamorphic pressure–temperature histories. Extensive, more complete, information over the timing and extremes of metamorphic conditions for a region reduce significantly the uncertainties in thermomechanical models designed to reconstruct geodynamic processes, and thus allow a much more reliable prediction of how ongoing collision belts could respond and develop. Blueschists form in environments where temperature (T) conditions are relatively low but pressures (P) are relatively high (i.e. high dP/dT) – a situation typical for the upper levels of subduction zones, especially in accretionary prisms. The finding of blueschists in orogenic belts, especially when they are associated with ophiolites, is thus a key indicator of the location of former suture zones (i.e. plate boundaries). Eclogites also form at high pressures but require minimum pressures higher than those reached in normal continental crust such that plagioclase is no longer stable. In contrast to blueschists, eclogite can form at a wide range of temperatures and thus, if not completely retrogressed, can yield evidence of high pressures reached through the processes in crustal thickening as well as subduction. A third group of high-pressure rocks, high-pressure granulite, is another indicator of extreme metamorphic conditions, conditions compatible with thickening or even short-lived subduction of the continental crust. Intensive investigation of orogenic belts in the last 30 years, aided by improvements in microanalysis methods such as micro-Raman spectroscopy, has allowed us to identify minerals such as coesite and microdiamond in rocks of subduction–collision orogens: minerals formed at mantle depths of 100 km or more (e.g. Schertl & O’Brien 2013). All of these rock types, blueschist, eclogite and high-pressure granulite, as well as rocks containing coesite and diamond occur within the Himalaya. How have they helped us to understand this orogeny?

The discovery of coesite in Kaghan Valley (Pakistan) eclogite (O’Brien et al. 1999, 2001) required

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existing tectonometamorphic models for the Indian Plate, essentially based on crustal thickening, to be significantly modified to include an early (Eocene) deep-crustal subduction and exhumation within the same, already short, timescale. Likewise, the discovery of granulitized eclogites in low-pressure–high-temperature gneisses, far from the initial subduction zone and with a Miocene metamorphic age (Lombardo & Rolfo 2000), has also caused a major rethink of collision models. Even more spectacular were finds of microdiamond and other ultrahigh-pressure minerals in remnants of Tethyan oceanic lithosphere trapped between the Indian and Asian plates (Robinson et al. 2004). Does this discovery require a further modification of existing tectonic models?

In this review of the high-pressure rocks of the Himalaya, the large-scale features and subdivision of the orogen will be summarized and the distribution of particular high-pressure rocks with respect to this subdivision outlined. Subsequently, the key geological, petrographical, petrological and geochronological features of the individual high-pressure locations will be presented. The final section will attempt to integrate knowledge gained from the high-pressure rocks with that from the vastly more abundant host series to allow a coherent tectonometamorphic model for the evolution of this spectacular orogenic belt to emerge.

Geological overview and simplified subdivision of the Himalaya

The closure of the Neo-Tethys Ocean and collision between the Indian and Asian plates and intervening arc terranes, starting in Eocene times and continuing to the present day, has produced the world’s highest and most spectacular mountain chain, the Himalaya, as well as the largest area of high elevation, the Tibetan Plateau (Argand 1924; see the review by Searle 2015). On the Indian Plate, south of the suture zone, 10 peaks over 8000 m are located in the Himalaya, whereas four further 8000 m peaks are found at the margin of Asia north of the suture in the Karakoram. Fossiliferous marine sediments and segments of former ocean crust are found thousands of metres above sea level and far from any ocean. How can we explain this? In trying to reconstruct the Himalayan orogenic process as a whole from the metamorphic rocks presently exposed, it is necessary to separate the individual metamorphic stages and their respective environments.

The Himalayan–Tibetan orogen can be most easily subdivided into a number of roughly parallel belts, running for over 2500 km along strike of the collision zone, separated by major faults and thrusts (Fig. 1) (Gansser 1964; Hodges 2000; Yin & Harrison 2000). These are, from north to south, the Trans-Himalayan Batholith, the Indus–Tsangpo

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**Fig. 1.** Simplified geology of the Himalaya showing the main subdivisions, boundaries and positions of the main locations discussed in the text. Boundaries (apart from the intrusive granites) are all tectonic.
Northward subduction of Neo-Tethys resulted in the development of an Andean-type, calc-alkaline magmatic arc of Upper Cretaceous–Eocene age, the Trans-Himalayan Batholith, running from Afghanistan to Burma (Honegger *et al.* 1982; Schärer *et al.* 1984; Wen *et al.* 2008). In the Lhasa terrane of Tibet this magmatism defines the Gangdese Belt, whereas further west, in India and Pakistan, identical mainly dioritic, tonalitic and granitic bodies have intruded the Kohistan–Ladakh island arc to produce the Ladakh (Honegger *et al.* 1982; Weinberg & Dunlap 2000) and Kohistan (Peterson & Windley 1985) batholiths. A last peak of magmatic activity at around 50 Ma and only very minor subsequent intrusion to around 46 Ma (Upadhyay *et al.* 2008; Wen *et al.* 2008) reflect the transition from oceanic to continental subduction as the Neo-Tethys Ocean closed completely.

The suture zone itself, roughly marking the course of two of the major rivers draining the southern Tibetan Plateau, is appropriately called the Indus–(Yarlung)–Tsangpo Suture Zone (ITSZ). It is well exposed in Ladakh (Fig. 2) where a series of deformed thrust sheets (Garzanti *et al.* 1987; Searle *et al.* 1990; Henderson *et al.* 2010) brings together shelf and slope rocks of the Indian Plate (Lamayuru Group), rocks of the oceanic realm (ophiolitic mélangé, volcanic and volcaniclastic rocks of the Dras intra-oceanic arc) and rocks of the Asian margin (slope, shelf and shallow-marine sediments of the Tar and Jurutse groups). In the same area the youngest marine sediments (nummulitic limestone, 50.5 Ma: Green *et al.* 2008) and the exposed Ladakh granodiorite are directly overlain by terrigenous, fluviatile conglomerates (containing cobbles from the batholith) and sandstones of the Indus Molasse (Frank *et al.* 1977; Brookfield & Andrews-Speed 1984). In many places along the suture zone, large outcrops of ultramafic–mafic ophiolite sequences, interpreted as back-arc basin oceanic crust of Jurassic–Cretaceous age, are a more obvious reminder that the suture zone marks the site of a former ocean (Bédard *et al.* 2009).

South of the ITSZ are rocks of the Indian Plate, imbricated, stacked and metamorphosed to different degrees, and separated by a series of...

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**Fig. 2.** Aerial view showing the excellent exposure of the ITSZ along the Zanskar River, Ladakh (view to the NNE from above Chilling). The Indus Valley and Ladakh Batholith in the background. Distance from the viewpoint to Indus is 17 km.
roughly north-dipping thrusts and faults. In simple terms, the margin of the Indian Plate comprised Archean and Early Proterozoic gneisses, Lower and Mid-Proterozoic metasediments, and Neo-proterozoic–Lower Paleozoic series covered by further Paleozoic–Cenozoic sedimentary series, with local basaltic (especially noteworthy being the Permian-Triassic Panjal traps) and granitic (Lower Proterozoic c. 1850 Ma and Cambro–Ordovician c. 480–500 Ma) magmatic events (e.g. Gansser 1964; DeCelles et al. 2001; Kohn et al. 2010; Gehrels et al. 2011). The continental crust entering the orogen has first undergone high-grade metamorphism, forms the present-day high topography and is known as the Higher (or Greater) Himalaya Crystalline Nappes (HHC). Crust incorporated into the thrust stack later, now tectonically below the HHC, is associated with lower topography, shows a dominantly lower grade of metamorphism (even in tectonic windows 100 km or more from the orogenic front) and is generally known as the Lesser Himalaya (LH). Emplacement of the hot HHC on the incoming LH along the ductile shear zone known as the Main Central Thrust (MCT) is associated with an inversion of metamorphic isograds: that is, prograde metamorphism structurally upwards in the LH, retrograde metamorphism downwards in the HHC (LeFort 1975; Stephenson et al. 2000).

For much of the arc of the Himalaya, Cambrian–Eocene marine sequences are absent at the ITSZ. These units, called Tethys Himalaya (TH), have become detached from the underlying Proterozoic basement as the Indian Plate was subducted, and thus, although strongly folded and imbricated, underwent mostly only very-low- to low-grade (up to greenschist-facies) metamorphism and preserve stratigraphic information as well as fossils (Gaetani & Garzanti 1991). The boundary with the underlying HHC later acted as a normal fault, the South Tibetan Detachment (STD), allowing exhumation of the HHC in an overall still compressional orogenic environment, Tectonically below the LH, separated by the Main Boundary Thrust, erosion products of the Himalaya are represented by Cenozoic marine and continental sedimentary rocks, deposited in the foreland basin to the south of the orogen, forming the Sub-Himalaya (Burbank et al. 1996). These rocks have been deformed and thrust southwards along the Main Frontal Thrust onto the Indian Craton over the youngest foreland basin sediments. Detailed study of the temporal evolution in detrital components in the Sub-Himalaya (e.g. Najman 2006) has allowed an insight into the erosion of the ITSZ and the pattern of exhumation of the HHC and LH.

High-pressure metamorphic rocks occur in a number of locations within the Himalayan belt but are restricted to three specific structural–tectonic environments, namely: the ITSZ; deeply subducted and quickly exhumed Indian Plate (HHC) close to the suture zone; and high-grade Indian Plate (HHC) in nappes south of the Tethyan Series far (>100 km) from the suture zone. In the NW Himalaya of India and Pakistan, Cretaceous blueschists and associated rocks (glaucophane- and/or lawsonite- and/or carpholite-bearing schists) are reported from the accretionary wedge marking the subduction of Tethys beneath the Kohistan–Ladakh oceanic island arc. Further east, in the Sangsang region of south central Tibet, comparable blueschists formed in the subduction complex south of the continental arc along the Asian Plate margin. Ophiolites within the suture zone locally contain ultrahigh-pressure indicators (e.g. at Luobusa in Tibet and Nidar in Ladakh). The metamorphosed continental margin of the Indian Plate is evidenced close to this suture zone in the Upper Kaghan valleys of Pakistan and the Tso Morari area of Ladakh in India in the form of eclogites, some of which are coesite-bearing. In both cases, these eclogites formed from dykes, sills and flows of bimodal magmatic rocks located within granitic, pelitic and carbonate series of Paleo-proterozoic and Mesozoic age, thus indicating subduction of both the basement and cover units. Other ultrahigh-pressure rocks close to the suture zone indicating Indian Plate subduction are found at Stak (Nanga Parbat syntaxis, Pakistan), in the Lopu Range (south central Tibet) and in the Namche Barwa syntaxis
(SE Tibet). A separate group of eclogites, strongly overprinted by granulite-facies assemblages, occur within the ortho- and paragneiss series of the Higher Himalayan Crystalline Nappes in the Kharta/Ama Drime area of Tibet and across the nearby border in NE Nepal, as well as in northern Sikkim and in NW Bhutan (i.e. significantly south of the suture zone).

**Himalayan high-pressure rocks**

**High-pressure rocks in the ITSZ**

The ITSZ comprises a complex mixture of rocks from the margins of both the Indian and Asian plates (i.e. shelf, trench, slope and accretionary prism environments), as well as segments of the Neo-Tethys oceanic crust and remnants of intra-oceanic arc volcanic rocks. The majority of high-pressure rocks of the ITSZ occur as blueschists within the ophiolitic mélange of the former accretionary prism, such as in the well-known Shangla (Pakistan) and Sapi–Shergol (Ladakh) locations (Honegger et al. 1989). Another unit in the ITSZ yielding evidence for high- and ultrahigh-pressure processes is the ophiolite itself. East of the Himalaya, in NE India (Nagaland) and Burma, the margin of the Indian Plate is also marked with a lawsonite–blueschist- and eclogite-bearing ophiolite belt similar to the ITSZ (Ghose & Singh 1980; Chatterjee & Ghose 2010; Ao & Bhowmik 2014; Bhowmik & Ao 2015). This eastern margin of the Indian Plate is not the subject of this review but these studies are listed for completeness.

**Blueschists in the ophiolitic mélange: Shangla (Pakistan).** Blueschists in Pakistan are readily accessible at Shangla where serpentinites, metabasaltic blueschists and piemontite schists are visible beside the Besham–Khwazakhela road either side of the pass (Shams 1972; Desio 1977). The rocks of this ophiolitic mélange exhibit assemblages of the blueschist and green schists facies. Blue amphiboles recorded from here are crossite and riebeckite, as well as the facies-indicator glaucophane, which occurs with phengite, albite, garnet, chlorite and rutile/titanite (Shams 1980; Jan 1985). Metamorphic conditions (Fig. 3) of around 0.7 GPa at 400°C (Guiraud 1982; Jan 1985) are compatible with the proposed subduction-zone environment. Glaucophane and phengite in the metabasites yield a c. 80 Ma age (Rb–Sr, K–Ar, 39Ar/40Ar methods) for peak metamorphism, and the lack of an Eocene high-pressure overprint indicates a shallow depth, passive hanging-wall position prior to Indian Plate subduction (Desio & Shams 1980; Maluski & Matte 1984; Anczkiewicz et al. 2000).

**Ladakh (India).** In Ladakh, blueschist-bearing sequences occur in thrust slices of the palaeo-accretionary prism ‘ophiolitic mélange’ unit at Puga, Urtsi, Hinju, Sapi–Shergol and Zildat, situated between the Indian Plate Lamyauru nappes in the south and the nappes of the intra-oceanic Nindam–Naktui–Dras Arc in the north (Virdi et al. 1977; Honegger et al. 1989; Groppo et al. 2016) (see Fig. 1). This unit comprises basic and ultrabasic rocks, as well as volcanoclastic sequences, cherts and minor carbonates (Frank et al. 1977; Honegger et al. 1989; Mahéo et al. 2006). In the largest body at Sapi Shergol, schistose metabasic rocks contain glaucophane, lawsonite, omphacite/aegirine–augite, phengite, minor chlorite and titanite, whereas silicic metasediments are glaucophane–phengite schists with or without garnet and lawsonite, and carbonate-rich rocks are lawsonite–glaucophane–calcite schists with minor phengite and/or prehnite (Groppo et al. 2016). In all cases secondary veins are albite-rich. Applying the thermodynamic pseudosection approach, a cold subduction environment for lawsonite–blueschist development peaking at 1.9 GPa and 470°C, and also exhumation along the same cold subduction path in order to preserve lawsonite, has been proposed (Fig. 3) (Groppo et al. 2016). As in Pakistan, the age of blueschist metamorphism (c. 100 Ma K–Ar: Honegger et al. 1989; 114–121 Ma 40Ar/39Ar phengite: Genser 2016) predates ocean closure and continent–continent collision.

**Sangsang (Tibet).** Apart from the blueschists in Pakistan and India, there are also reports of rocks of similar character and age in the suture zone, north of Everest, at Sangsang in southern Tibet (Xiao & Gao 1984). Here, thrust-bounded units of ophiolite and ophiolitic mélange with blueschist-facies (≤540°C) metabasic and metasedimentary rocks as part of the ITSZ have been described (Borneman et al. 2014). A geochronological
investigation suggested a protolith age of c. 111 Ma (U–Pb zircon) and 65 Ma for high-pressure metamorphism ($^{40}$Ar/$^{39}$Ar amphibole) in a metavolcanic rock (Borneman et al. 2014). The ophiolite itself, as in many other cases in the ITSZ, is Early Cretaceous in age (130–120 Ma: Xia et al. 2008).

**Ultrahigh-pressure indicators in serpentinites (India and Tibet).** Unusual ultrahigh-pressure minerals have been identified within serpentinized peridotites of the ITSZ ophiolite (Fig. 1) at Nidar, Ladakh (Das et al. 2015, 2017) and Luobusa, Tibet (Robinson et al. 2004; Yang et al. 2007). In both cases microdiamond occurs, as well as other phases (wadsleyite, clinopyroxene, moissanite and coesite) requiring pressures corresponding to mantle depths of 140 km or more. These serpentinized peridotites represent altered segments of deep mantle that has upwelled during seafloor spreading and ocean-crust formation. The ultrahigh-pressure minerals in these rocks, although occurring spatially related to accretionary prism blueschists and eclogites of subducted crustal origin, do not yield information about the Himalayan subduction–collision process. Instead, they are unusual relict phases preserving evidence of unrelated deep-mantle processes. Modern microanalytical tools have made these phases accessible to study and recent summaries have emphasized how common these relics are in other ophiolites worldwide (Zhang et al. 2016).

**High-pressure rocks: Indian Plate close to the suture**

**Tso Morari (India).** The first reliable record of eclogites in the Himalaya, and their interpretation as metamorphosed Panjal Trap lavas and dykes (corona dolerite microstructure), was from the Tso Morari
(Figs 1 & 4) area of Ladakh (Berthelsen 1953) but an even earlier report from Haydon (1904) had already noted garnet in the southern Tso Morari basic dykes. This finding lay largely forgotten until the 1990s when renewed investigation, spurred on by the reports of eclogite in the Kaghan Valley of Pakistan (Pognante & Spencer 1991), also began to unearth a high-pressure history for Indian Plate rocks in Ladakh (de Sigoyer et al. 1997; Guillot et al. 1997). Subsequently, several groups have published detailed petrographical, petrological and geochronological reports on the Tso Morari eclogites, although a surprisingly large number of these (e.g. de Sigoyer et al. 1997; Sachan et al. 1999; O’Brien & Sachan 2000; Mukherjee & Sachan 2001; Mukherjee et al. 2003; Sachan et al. 2004; Konrad-Schmolke et al. 2008; Singh et al. 2013; St-Onge et al. 2013; Palin et al. 2014, 2017; Chatterjee & Jugoutz 2015; Wilke et al. 2015; Jonnalagadda et al. 2017b) are for the same outcrop (Fig. 5a) already figured in Berthelsen (1953, p. 367, fig. 13).

Geologically, the crystalline rocks of the Tso Morari gneiss dome form a c. 100 km-long, 50 km-wide, NW–SE-orientated body (Fig. 4) emerging from below the ITSZ, along the Zildat detachment fault (Fig. 5b), at the NE boundary and dipping below the Tethyan Himalaya of Zanskar to the SW (Steck et al. 1998; Epard & Steck 2008). The dominant rocks of the dome are variably deformed augen-gneisses derived from Cambro-Ordovician (479 ± 2 Ma) porphyritic S-type granite – the Puga Gneiss of the Tso Morari nappe (Fig. 6a, b) (Girard & Bussy 1999). Locally, such as at Polokongka La, the granite is hardly deformed but mylonitized variants are identical in age (Steck et al. 1998; Girard & Bussy 1999). The granites were intruded into clastic and carbonate sediments of late Proterozoic–Cambrian age and the whole sequence was intruded by basic dykes, geochemically characterized as subalkaline, within-plate basaltic rocks attributed to the Permian Panjal traps which today form folded and stretched layers and boudins (Rao & Rai 2006; Jonnalagadda et al. 2017a). Eclogite-facies relicts occur within this unit. Structurally overlying nappe units, the Tetraogal (Permian and younger shelf deposits with bimodal volcanic rocks) and Mata–Nyimaling–Tsarap (Late Proterozoic–Mesozoic clastic and carbonate metasediments intruded by the Ordovician I-type Rupshu granite) nappes, and intervening serpentinites, metagabbros, chromites and metabasalts of the Karzok ophiolites, show no eclogite-facies relicts and are mostly of amphibolite to greenschist grade (Steck et al. 1998; Epard & Steck 2008).

In the Tso Morari nappe, high-pressure indicators such as glaucophane + jadeite, garnet + omphacite + coesite and talc + kyanite occur in metapelites, metapelite and boudins, respectively (Guillot et al. 1997; de Sigoyer et al. 1997; Sachan et al. 2004). The bulk chemistry of the metasediments controls the peak parageneses: Fe-rich metapelites contain Grt + Jd + Ctd + Pg + Gln + Zo + Chl ± Bt, Mg-rich
types (whiteschists) Ky + Mg-Chl + Tlc + Grt and intermediate types Sta + Ky + Bt + Chl (all with Phe + Qz + Rt), whereas meta-sandstones contain Phe (up to 3.57 Si per formula unit (p.f.u.)) + Chl + Grt + Pg + Zo (Guillot et al. 1997; Epard & Steck 2008). These samples yielded $P-T$ conditions of $2.0 \pm 0.2$ GPa and $550 \pm 50^\circ$C for the eclogite-facies peak, 1.8–1.3 GPa at the same temperature for an eclogite–blueschist overprint, a subsequent heating at normal crustal depths (i.e. amphibolite facies) and finally partial retrogression to green schist-facies (c. 0.5 GPa at 500°C) conditions (Guillot et al. 1997).

The best-preserved eclogites (Fig. 6c) contain Grt + Omp + Phe + Coe/Qtz + Rt ± Ky ± Mgs but show multiple reaction stages as for the metasediments (de Sigoyer et al. 1997; Mukherjee & Sachan 2001; Mukherjee et al. 2003; Wilke et al. 2015). A key feature is inclusion-rich (quartz, rutile, calcic and sodic-calcic amphibole, paragonite,

Fig. 5. Field relationships in the Tso Morari area near Puga. (a) Eclogite boudins in Puga gneiss (intensively studied eclogites: see the text). The geologist ringed in the left foreground is for scale. View looking north. (b) Puga gneiss plunging below the ophiolitic mélange and ophiolite of the ITSZ along the Ribil–Zildat Fault near Puga (view looking north from 3 km south of Puga). The width of view is c. 5 km.
aegirine-rich omphacite, dolomite, clinzoisite, and apatite) garnet cores (Fig. 7a) overgrown by inclusion-poor garnet with much higher Mg content (O’Brien & Sachan 2000; St-Onge et al. 2013; Wilke et al. 2015) with a very sharp boundary between the two zones hardly affected by diffusive reequilibration. Coesite (Fig. 7b) occurs exclusively in the Mg-rich overgrowth (Wilke et al. 2015). Major and trace element (e.g. REE) patterns of these garnets allowed the combined thermodynamic and trace element modelling of fractionated garnet growth first at low-temperature eclogite facies and then ultrahigh-pressure conditions, thus substantiating the absence of coesite in the garnet core and its restriction to Mg-rich garnet rims (Konrad-Schmolke et al. 2008).

The matrix to the garnet (Fig. 7c) shows the patchy development of multiple steps along the exhumation path. Important features are: the presence of glaucophane as an early retrograde phase that is itself then mostly consumed by later sodic–calcic and/or calcic amphiboles (de Sigoyer et al. 1997); phengite as a peak phase; paragonite in garnet core or as a secondary reaction product (de Sigoyer et al. 1997; Wilke et al. 2015); and matrix magnesite as cores to later dolomite and calcite (Mukherjee et al. 2003; Wilke et al. 2015). Additionally, a renewed heating phase to produce ilmenite and paragasite further complicates the petrographical story (de Sigoyer et al. 1997; St-Onge et al. 2013).

The first geothermobarometric results for the eclogites presented >2.0 ± 3 GPa and 550 ± 50°C for the peak (Fig. 8) (de Sigoyer et al. 1997), but O’Brien et al. (2001) utilized the same data to deduce coesite stability-field conditions: a prediction soon fulfilled with the discovery of coesite (Mukherjee & Sachan 2001). Subsequent studies incorporating coesite presence yielded $P$–$T$ conditions of 2.7–2.8 GPa and 640–650°C (e.g. St-Onge et al. 2013), although workers considering the magnesite–dolomite relationship proposed even higher (>4.5 GPa) pressures (Mukherjee et al. 2003; Wilke et al. 2015). The complex growth and post-peak reaction history, resulting in multiple generations of key phases in different microstructures, makes geothermobarometry by both conventional and thermodynamic pseudo-section approaches difficult (Singh et al. 2013; Chatterjee & Jagoutz 2015; Jonnalagadda et al. 2017b).
Nevertheless, matrix glaucophane cores to sodic–calcic amphibole indicate c. 550°C at pressures <1.7 GPa, whereas the later amphibolite stage at around 1.0 GPa and 650–700°C clearly requires a heating episode (de Sigoyer et al. 1997; Wilke et al. 2015; Jonnalagadda et al. 2017).

Initial geochronological studies of the Tso Morari high-pressure–ultrahigh-pressure rocks presented ages of 55 ± 12 Ma (Lu–Hf Grt–Omp–WR metapsammitic) and 55 ± 7 Ma (Sm–Nd Grt–Gla–WR metapelitic) and 55 ± 17 Ma (U–Pb Aln) for the eclogite stage; 48 ± 2 Ma (40Ar/39Ar Phe) and 45 ± 4 Ma (Rb–Sr Phe–Ap–Rt) in metapelites interpreted as the amphibolite-facies overprint; and mica 40Ar/39Ar ages of around 30 Ma in deformed metapelites interpreted as final cooling (de Sigoyer et al. 2000). Despite the large analytical errors, a spectacular initial exhumation rate of >5 mm a⁻¹ was proposed (de Sigoyer et al. 2000, 2004). However, diffusion modelling to determine the timescale allowing preservation of the sharp compositional step between the inner and outer garnet domains indicated even higher rates (23–45 mm a⁻¹) which, when fitted to the existing ages, would require <3 myr (from 45 to 48) (Fig. 9) for the whole eclogite to greenschist history (O’Brien & Sachan 2000; Massonne & O’Brien 2003). Some workers (e.g. Leech et al. 2007) continued to propose 55–45 Ma to encompass the eclogite to amphibolite evolution despite the limitations from preserved garnet zoning but subsequent zircon geochronology (Donaldson et al. 2013; St-Onge et al. 2013) has added strong support to the <50 Ma age for the eclogite stage. A further constraint on the thermal evolution is given by zircon and fission-track ages, indicating exhumation to about 10–15 km depth by 45–40 Ma (Schlup et al. 2003). Taking into account the c. 50 Ma age for the end of marine sedimentation in the ITSZ, this is certainly a phenomenal example of exhumation occurring as fast as subduction (e.g. Rubatto & Hermann 2001).

Kaghan and Neelum valleys (Pakistan). In Pakistan, Indian Plate rocks commonly attributed to the HHC (Fig. 10) in most places abut directly the mafic–ultramafic root of the tilted Kohistan Arc (along what is known as the Main Mantle Thrust or MMT) with locally only small slivers of ITSZ rocks in-between. Unlike the arid, high plateau of the Tso Morari with its eclogite-bearing ortho-augengneiss, the dissected (by glacial valleys) former plateau (e.g. van der Beek et al. 2009) of the upper Kaghan and Neelum valleys is far more varied both in terms of vegetation and geology (Figs 10 & 11a). Here a Proterozoic basement comprising pelitic and psammitic metasediments and granitic orthogneisses is overlain by a Late Paleozoic to Mesozoic carbonate-rich (calc-schist, dolomitic marble, diopside marble, mica schist and quartzite) cover sequence containing abundant lenses and bodies of metabasite and felsic intrusive rocks.
Structurally, the area comprises a stack of isoclinally folded thrust sheets, folded again by east–west-trending open folds to give the present structure (Greco & Spencer 1993; Kaneko et al. 2003; Treloar et al. 2003). Eclogites and amphibolitized eclogites occur as dykes, sills and boudins (Fig. 11b–e) in basement orthogneisses, as well as in cover unit paragneisses, as well as in cover unit paragneisses and marbles (Pognante & Spencer 1991; Fontan et al. 2000; Lombardo et al. 2001; O’Brien et al. 2001; Kaneko et al. 2003; Wilke et al. 2010a). As in Tso Morari, geochemically, the metabasites are subalkaline–alkaline tholeitic basaltic rocks of within-plate type (Papritz & Rey 1989; Spencer et al. 1995; Wilke et al. 2010a; Rehman et al. 2014, 2016) and belong to the Permian Panjal Trap bimodal basaltic–rhyolitic sequence, as also indicated by zircon ages (Rehman et al. 2016).

Most eclogites occur in the uppermost nappe unit near Gittidas, Besal, Jalkad and south of Burawai at Joranar. Equivalent metabasites in the lowermost nappe unit, easily accessible at lake Saif-ul-Muluk, and between Naran and Burawai, are coronitic dolerites still preserving magmatic textures (Fontan et al. 2000; Wilke et al. 2010a). The eclogites occur in several varieties (Fig. 12): coarse-grained and skarn-like (first mapped by Chaudhry & Ghazanfar 1987); extremely fine-grained (garnet <0.1 mm); layered epidote-/clinozoisite-rich; medium-grained with relic magmatic texture (Fig. 13c); and well preserved (Fig. 13a, b) containing coesite ± glaucophane ± magnesite/dolomite (Wilke et al. 2010a, b). Coesite occurs as partially altered inclusions predominantly in fresh omphacite (rarely also in garnet and zircon) in eclogites from close to the MMT near Gittidas and Lulusar (O’Brien et al. 2001; Kaneko et al. 2003; Wilke et al. 2010a). These rocks also contain secondary sodic–calcic amphiboles cored by glaucophane (Lombardo et al. 2000; Wilke et al. 2010a) (Fig. 13a, b). The dominant metabasites are amphibolitized (Fig. 13d), matching the grade of the Grt + Ky ± Sta-bearing metapelites and Grt + Cpx-bearing impure marbles (Greco & Spencer 1993; Rehman et al. 2007) but tell-tale large

Fig. 8. Summary of pressure–temperature estimates for Tso Morari eclogites. Data are from Guillot et al. (1997) (G + 97), de Sigoyer et al. (1997) (dS + 97), Mukherjee et al. (2003) (M + 03), St-Onge et al. (2013) (S + 13), Chatterjee & Jagoutz (2015) (CJ15), Wilke et al. (2015) (W + 15) and Palin et al. (2017). Coe = Qz: Bohlen & Boettcher (1982); Ab = Jd + Qz: Holland (1980); diamond = graphite: Bundy 1980. Depth is calculated for a density of 2850 kg m$^{-3}$. 

(Chaudhry & Ghazanfar 1987; Greco et al. 1989).
amphibole porphyroblasts enclosing garnet relicts testify to the more complex earlier history. Later deformation related to the exhumation of the high-grade units is reflected by a pervasive north-directed extensional shearing, at high structural levels, close to the MMT (Burg et al. 1996; Treloar et al. 2003). This latter stage is well evidenced by folds involving albite porphyroblasts (often several centimetres in length) representing a pervasive greenschist-facies overprint in pelitic, granitic and basic rocks.

The metamorphic conditions (Fig. 14) for the formation of the Kaghan eclogite, derived from equilibria for the Grt + Omp + Phe + Coe/Qtz + Rt peak assemblage, scatter around 2.5–3.2 GPa and 700 ± 70°C (Lombardo et al. 2000; O’Brien et al. 2001; Parrish et al. 2006; Wilke et al. 2010a). Retrograde resetting combined with patchy growth zoning makes the choice of equilibrium mineral composition difficult. The post-peak growth of glaucophane requires cooling to 580–630°C (at 1.0–1.7 GPa) during the initial exhumation (Wilke et al. 2010a). The subsequent amphibolite-facies overprint, the metamorphism dominant in the surrounding Grt + Ky-bearing gneisses (Treloar 1995) and reflected as Cpx + Pl ± Amph symplectites consuming omphacite, multiple varieties of green to brown calcic amphibole in different microstructural sites and ilmenite ± titanite replacing rutile indicates heating to 650–720°C (at 1.0–1.2 GPa) for this stage (Lombardo et al. 2000; Kaneko et al. 2003; Parrish et al. 2006; Wilke et al. 2010a). The growth of albite

Fig. 9. Summary depth–time plot showing rapid exhumation of the Tso Morari eclogites. Geochronological data are from de Sigoyer et al. (2000) (dS + 00), Schlup et al. (2003) (Sch + 03), Donaldson et al. (2013) (D + 13) and St-Onge et al. (2013) (St + 13). Diffusion modelling of garnet from O’Brien & Sachan (2000) (O + S 00). Depth is calculated for a density of 2850 kg m⁻³. FT, fission track.

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porphyroblasts over the amphibolite-facies assemblages and the related folding at greenschist facies (400–500°C) marks the last major overprint.

The first multi-method geochronological study of Kaghan eclogites deduced 49 ± 6 Ma for the eclogite-facies stage (Sm–Nd, garnet–clinopyroxene) with 43 ± 1 Ma (Rb–Sr, phengite) and 39–40 Ma (U–Pb, rutile) interpreted as recording rapid cooling (Tonarini et al. 1993). Subsequent studies defined the eclogite-facies stage as closer to 47 Ma by the dating of zircon from eclogite (46.4 ± 0.1 Ma: Parrish et al. 2006; 44 ± 3 Ma: Spencer & Gebauer 1996; 48 ± 3 and 47 ± 1 Ma: Rehman et al. 2016) and gneisses (46.2 ± 0.7 Ma: Kaneko et al. 2003; 47.4 ± 0.3 and 47.3 ± 0.4 Ma: Wilke et al. 2010b). Zircon analysis also revealed Permian ages for many grains from both basaltic and rhyolitic protoliths, thus supporting the correlation with Panjal Trap volcanic rocks (Kaneko et al. 2003; Wilke et al. 2010b; Rehman et al. 2013). The metamorphic age of c. 47 Ma is substantiated by 40Ar/39Ar ages of phengite and amphibole (Wilke et al. 2010b), and U–Pb ages of titanite and centimetre-sized rutile (Treloar et al. 2003; Parrish et al. 2006; Wilke et al. 2010b). Several studies report amphibole 40Ar/39Ar ages of 39–42 Ma (Chamberlain et al. 1991; Smith et al. 1994; Hubbard et al. 1995), indicating that continental subduction was soon over. As in the Tso Morari eclogites, cooling to greenschist-facies conditions and below was rapid (Fig. 15), as deduced from mica 40Ar/39Ar ages in gneisses and also apatite fission-track ages as old as 24.5 ± 3.7 close to the MMT near Gittidas (Wilke et al. 2010b; Wilke et al. 2012).

Stak (Pakistan). Northeast of the Kaghan Valley, where the Indus cuts through the Nanga Parbat–Haramosh Massif, eclogite and high-pressure granulite have been described within rapidly exhuming Indian Plate rocks directly at the contact with the Kohistan Arc at the Stak location (LeFort et al. 1997). Mafic rocks occur as small lenses and boudins within the felsic gneisses forming part of the Paleozoic and Mesozoic cover to basement gneisses, just as in the upper HHG further west. Although eclogite garnet and omphacite compositions and zoning are comparable to that of certain Kaghan eclogites (Lanari et al. 2013; Kouketsu et al. 2016), the rocks lack low-temperature retrograde glaucophane and/or barroisite, and instead contain abundant

Fig. 10. Simplified geology of the Kaghan and Neelum valleys showing eclogite locations (data are from Greco & Spencer 1993; Fontan et al. 2000; Lombardo et al. 2000).
high-temperature secondary brown hornblende. This difference is reflected in deduced $P$–$T$ conditions (Fig. 14) of 2.5 GPa and 750°C for the peak eclogite stage followed by exhumation through the high-pressure granulite and amphibolite field (Cpx + Pl symplectites and amphiboles) at 0.9–1.6 GPa at 650–700°C (Lanari et al. 2013). Geochemically, the metabasites appear in their major and trace element, as well as isotope patterns very similar to Panjal Trap and Kaghan eclogitized Panjal Trap basalts (Kouketsu et al. 2017). The eclogites contain small (<0.05 mm), irregularly shaped zircons, devoid of oscillatory zoning, some of which yielded a sensitive high-resolution ion microprobe (SHRIMP) U–Pb lower intercept age of 32.0 ± 2.6 Ma, whereas other analyses, typically also showing significantly higher Th/U, yielded $^{206}$Pb/$^{238}$U ages of 93–158 Ma (Kouketsu et al. 2016). Due to the small size of zircons, some ages represent a mix of younger and older domains in grains but clearly a Mesozoic protolith and Cenozoic metamorphic overgrowth are present. The relationship between the c. 32 Ma age and the eclogite-facies stage is not clear. It is possible that symplectitic replacement of eclogite-facies
omphacite led to zircon overgrowth but, regardless of the zircon growth process, it is clear that this segment of the HHC stayed longer at high-grade conditions than the nearby Kaghan crustal segment. Further high-pressure mafic granulites (1.0 GPa and 700°C), probably belonging to the 1.6 Ga dyke swarm in the basement (Treloar et al. 2000), were described from within the kyanite-bearing gneisses of the HHC further north in the Stak Valley (Pog- nante et al. 1993). A correlation between these granulites and the granulitized eclogites in the Eastern Himalaya (Namche Barwa, Ama Drime, Bhutan) remains speculative.

In the suture zone of southern Tibet, in the Lopu Range roughly north of Kathmandu (Fig. 1), Indian Plate rocks that experienced Eocene age high-pressure metamorphism are exposed. As elsewhere in the Central Himalaya, ophiolite and molasse of the ITSZ occur between the Gangdese Arc and low-grade Phanerozoic TH rocks but a top-to-the-north normal-sense shear zone exposes high-pressure metasediments in its footwall within this sequence (Laskowski et al. 2016). Petrological and geochronological investigations reveal conditions of >1.4 GPa and ≤600°C for the metamorphism of various Phe + Chl ± Sta ± Grt-bearing

Fig. 12. Kaghan metabasites in the field: (a) Fe-rich cumulate type; (b) banded epidote-rich type; (c) freshest coesite + phengite type showing amphibole porphyroblasts; (d) amphibolitized eclogite with characteristic amphibole porphyroblasts; (e) corona dolerite; and (f) corona gabbro.
metasediments, an age of $40.4 \pm 1.4$ (Lu–Hf Grt–WR) for garnet, and $^{40}\text{Ar}/^{39}\text{Ar}$ phengite ages of between 34 and 39 Ma (Laskowski et al. 2016). Detrital zircon age spectra from these rocks indicate a correlation with Tethyan sequences (Laskowski et al. 2017) and thus, as in Tso Morari and the Kaghan/Neelum valleys, continental India and its sedimentary cover were both subducted and metamorphosed at the start of the orogeny with at least a small fragment quickly returned to shallow levels, thus preserving the petrological evidence.

Namche Barwa (Tibet). At the easternmost end of the main Himalayan arc, centred around the peaks of Namche Barwa and Gyala Peri (7782 and 7151 m, respectively) in Tibet (Fig. 16), an anticlinal dome of HHC protrudes through the Asian margin, comprising Gangdese Belt granites intruded into Phanerozoic sediments and their basement, very much like the situation of Nanga Parbat protruding through the Kohistan Arc far to the west in Pakistan (Burg et al. 1998). A narrow strip of ophiolitic mafic and felsic rocks, thought to be equivalent to those of the ITSZ, separates these continental units and is associated with metasediments (quartzites, metapelites, calc-silicate rocks), attributed to the TH, that are also strongly deformed (Zhang et al. 1992; Geng et al. 2006). The crystalline rocks of the Namche Barwa core are predominantly anatectic gneisses with local garnet-rich felsic and mafic granulites, and a discrete unit containing marble and calc-silicate marble: both Proterozoic and Paleozoic components have been identified (Zhang et al. 1992).

Although widespread sillimanite- and/or cordierite- and/or spinel-bearing assemblages are found in the anatectic gneisses, a central zone (Fig. 16) contains kyanite-bearing rocks evidencing a former high-pressure granulate-facies stage in the assemblage Grt + Ky + Rt + Qz + ternary feldspar, for which conditions of 1.7–1.8 GPa and 890°C...
(Fig. 17) were estimated (Liu & Zhong 1997). Subsequent studies deduced similar temperatures but fractionally lower pressures for this stage: for example, 1.4–1.5 GPa at 800°C (Ding et al. 2001) and 1.5–1.6 GPa at 850°C (Guilmette et al. 2011; Zhang et al. 2015). The dominant migmatitic, low-pressure granulite-facies stage at 0.4–0.6 GPa and 750–850°C (Booth et al. 2009; Zhang et al. 2015) occurred from 10 Ma down to 3 Ma according to zircon, monazite and titanite ages (Ding et al. 2001; Booth et al. 2009), whereas the maximum age for the high-pressure stage from metamorphic zircon indicates at least 24 Ma (Xu et al. 2010) but possibly up to 40 Ma (Ding et al. 2001; Zhang et al. 2015). The distinct spread of zircon ages has been suggested to indicate a long period of high-temperature metamorphism (from 40 to 8–10 Ma: Zhang et al. 2015), which was followed by rapid exhumation (>10 mm a⁻¹) and cooling (>100°C/Ma) over the last c. 3–5 myr as deduced by mica ⁴₀Ar/³⁹Ar, zircon (U–Th)–He, and apatite and zircon-fission track ages (Burg et al. 1998; Malloy 2004).

**High-pressure rocks: Indian Plate far from the suture**

In the same year that coesite eclogite was discovered in the Kaghan Valley, Lombardo et al. (1998) reported for the first time eclogites from the Eastern Himalaya with petrographic and petrological details published soon after (Lombardo & Rolfo 2000). These newly discovered eclogites, strongly granulitized but recognizable as former higher-pressure rocks, were found east of the Everest–Makalu region, in the fault-bounded Ama Drime Range, close to the Phung Chu River (Arun River when it crosses into Nepal) and near the village of Kharta. Subsequent studies in the same region, just south across the border into Nepal (Cottle et al. 2009; Corrie et al. 2016), in north Sikkim (Rolfo et al. 2008) and in NW Bhutan (Warren et al. 2011, 2012; Regis et al. 2014), also resulted in new finds of relict eclogites (Fig. 18).

In Tibet, the metabasic rocks occur as boudined dykes and lenses, decimetre to metre sized,
within granitic orthogneisses (Kfs + Pl + Qz + Bt) and sillimanite-bearing paragneisses (Grt + Sil + Bt; Bt + Sil + Ged + Crd) in the western (Kharta area, Belung and Tanghyu valleys: Lombardo & Rolfo 2000; Groppo et al. 2007) northern (Li et al. 2003) and eastern (Y.H. Wang et al. 2017) parts of the Ama Drime Range. Geochemically, the Ama Drime metabasites are olivine tholeiitic basalts and exhibit chondrite-normalized heavy rare earth element (REE) patterns with flat heavy REE (HREE) and slightly enriched REE (LREE) (Lombardo et al. 2016; Y.H. Wang et al. 2017). The equivalent rocks in Bhutan, also occurring in granulite-facies (Crd-, Sil- and Opx-bearing) paragneisses, show comparable geochemical features (Chakungal et al. 2010; Warren et al. 2012). Zircon U–Pb discordia upper intercepts at 971 ± 8 Ma (Liu et al. 2007: note also the 1122 ± 100 Ma from the same authors) and 970 ± 40 Ma (Cottle et al. 2009), together with the spot age of 1017.5 ± 9.6 Ma (Y.H. Wang et al. 2017), are suggested to date the metabasite protolith: the c. 1800 Ma zircon spot ages reported by Lombardo et al. (2016) match protolith ages of host gneisses (e.g. Cottle et al. 2009). These rocks are thus of continental, rift-related origin but, in contrast to the Panjal Trap basalts of the NW Himalayan eclogites, of Proterozoic rather than Permo-Triassic age.

Detailed petrographical descriptions and photomicrographs in the literature concerning the Eastern Himalaya granulitized eclogites note especially a
fine-grained symplectitic intergrowth of Jd-poor clinopyroxene and plagioclase (oligoclase), interpreted as a replacement of former omphacite (Lombardo & Rolfo 2000; Liu et al. 2007; Cottle et al. 2009; Warren et al. 2011). Matrix omphacite has not been found but exists as rare inclusions in garnet and zircon (Y.H. Wang et al. 2017). The symplectites locally contain isolated amphibole or orthopyroxene but commonly these domains are surrounded by massive amphibole. Garnet is dominantly Alm–Gr–Prp in the ratio 3:2:1, unzoned, in some samples rich in inclusions (Qtz + Rt), and commonly with reactions at rims that produced orthopyroxene + plagioclase (andesine). In more heavily overprinted samples, garnet sits in moats of secondary plagioclase and thus eclogite peak compositions have probably been lost. Former phengite has been replaced by orientated biotite in plagioclase (Lombardo & Rolfo 2000; Groppo et al. 2007; Y.H. Wang et al. 2017) and ilmenite (later also titanite) has replaced most of the rutile in the matrix.

The first study investigating the conditions of metamorphism in these complex, multiply-overprinted rocks (Groppo et al. 2007) deduced an initial (M1) eclogite facies (i.e. plagioclase-free, Grt + Omp assemblage) stage at >1.5 GPa and >580°C; a peak high-pressure granulite (M2) overprint (Cpx + Pl symplectites replacing Omp) at 0.8–1.0 GPa and >750°C; a subsequent lower-pressure granulitic (M3) stage (coronas of Opx + Pl around Grt) at 0.4 GPa and 750°C; and, finally, amphibolite facies (M4) cooling to 700°C (Fig. 17). More recent works propose even higher pressures of 2 GPa at correspondingly higher temperatures of 710 ± 50°C (Corrie et al. 2016; Y.H. Wang et al. 2017).

Geochronological studies of the granulitized eclogites, their host gneisses and structures linked to their exhumation have been undertaken by several groups. Zircon U–Pb ages of 13.9 ± 1.2, 14.9 ± 0.7 (Y.H. Wang et al. 2017), 17.6 ± 0.3 (Li et al. 2003), 13–14 ± 1 (Lombardo et al. 2016) and 15.3 ± 0.3–14.4 ± 0.3 Ma (Grujic et al. 2011) have been interpreted as the age of metamorphism in the metabasites. Lu–Hf dating of garnet (20.7 ± 0.4 Ma) from equivalent granulitized eclogites from the Arun River valley in Nepal (Corrie et al. 2016) appears to substantiate this young (Miocene-age) eclogite-facies metamorphism. However, garnet Lu–Hf ages of 37.5 ± 0.8, 36 ± 1.9 and 33.9 ± 0.8 Ma from Ama Drime metabasite samples, yielding additionally U–Pb zircon ages of 13–15 Ma, strongly suggest an Eocene age for eclogite-facies metamorphism and a Miocene age for the granulite-facies overprint (Kellett et al. 2014). Ages of monazites in gneisses hosting the granulitized eclogites record well the high-temperature stage (11–15 Ma: Cottle et al.
Fig. 17. Summary pressure–temperature estimates for Namche Barwa and other Eastern Himalaya high-pressure rocks. Data are from: Liu & Zhong (1997) (LZ97), Groppo et al. (2007) (G + 07), Liu et al. (2007) (L + 07), Guilmette et al. (2011) (G + 11), Zhang et al. (2015) (Z + 15) and J.M. Wang et al. (2017) (W + 17). Ab = Jd + Qz from Holland (1980). Depth is calculated for a density of 2850 kg m$^{-3}$.

Fig. 18. Simplified geological map of showing the location of the Eastern Himalayan granulitized eclogites (based on Grujic et al. 2011).
Discussion

In older Phanerozoic eclogite-bearing, subduction–collision orogens, such as the Caledonides and Variscides in Europe, the mountains have been deeply eroded, the crust and lithosphere has returned to a stable thickness, and dynamic tectonic and metamorphic processes are no longer active. In contrast, the Himalayan region, and other equivalent Cenozoic orogens such as the European Alps, are still undergoing active shortening as reflected in the frequency and magnitude of earthquakes, are typified by high mountains and relief contrast, and have overthickened crust reaching 70 km or more. Looking at the present-day structure (Fig. 19, stage 4) of the Himalayan–Tibetan region as visualized by large-scale geophysical programmes (e.g. INDEPTH: Zhao & Nelson 1993; Nelson et al. 1996; and HIMPROBE: Jain et al. 2012; Caldwell et al. 2013), thickened continental crust is certainly an important feature: a continental crust that is at eclogite- and high-pressure granulite-facies conditions today. However, this large-scale structure is a product of collision processes that have been taking place for 50 myr and are still ongoing. Can we use this present-day information to explain the high-pressure rocks at the surface today?

The ages and associated rocks of these different high-pressure units within the Himalaya nicely demonstrate the general tectonic history of this subduction–collision orogen: that is, the transition from oceanic subduction to continental collision via a short-lived deep-continent subduction stage (Fig. 19). The presence of lawsonite-bearing blueschists (Groppò et al. 2016) and carpholite-bearing metasediments (Oberhänslī 2013) indicate low-temperature (i.e. ‘cold’) subduction but also an exhumation regime that also remained cool or was sufficiently fast to enable transport to shallow crustal levels. This type of tectonometamorphic regime is typical of Pacific-type convergent margins (see the review by Tsujimori & Ernst 2014), although extensive carpholite-bearing series exist in the European Alps and along the Mesozoic collision belt in Turkey (Oberhänslī 2013). This environment represents the stage of subduction of Neo-Tethys under the Asia margin, and the processes taking place in ocean crust-derived volcanosedimentary units within the accretionary prism. The Cretaceous age of blueschist minerals ties in well to the age of ophiolite formation and obduction (Bédard et al. 2009). The blueschists are in a piggyback position, tectonically above major intracrustal thrusts, and with hot anatetic crustal rock sequences to the north and south. In older collision orogens, where only eroded deeper crustal levels are exposed, it is unlikely that this upper tectonic level would have survived, and perhaps only serpentinized peridotites hint at the former presence of a suture zone.

As the last of the oceanic crust was subducted, the initial continental margin was also deeply subducted (Fig. 19, stage 2). The record of this stage is marked by the eclogites in the Kaghan/Neelum valleys in Pakistan and the Tso Morari area of the NW Himalaya (de Sigoyer et al. 1997; O’Brien et al. 2001). The distribution of eclogites in the Proterozoic basement, and Paleozoic metasediments and granitic orthogneisses indicate that the whole of the Indian Plate crust was subducted, thus contrasting with the tectonic separation of basement (involved in intracrustal stacking and emplacement below the Asia margin) and Tethyan cover (deformed but remaining south of the suture) in the central part of the orogeny. The Lopu area is a minor exception to this pattern that requires further investigation. Coesite in the Kaghan and Tso Morari eclogites and gneisses strongly suggests crustal subduction depths of at least 90 km but geochronological data support only a very short time for both the subduction and the majority of the exhumation: that is, exhumation occurred at subduction rates of several centimetres per year (Massonne & O’Brien 2003; Wilke et al. 2010b). The presence of glaucophane post-dating the metamorphic pressure peak in both areas supports exhumation at lower temperatures, as expected for rocks moving upwards between the mantle wedge and the down-going slab. Continental crust is significantly less dense than the mantle, even if partially transformed to high-pressure minerals, thus buoyancy forces would lead to intracrustal shear-zone development with the consequence that detached crustal slivers would force their way back up the subduction channel, at least to typical (i.e. c. 30 km) crustal depths (Chemenda et al. 2000; O’Brien 2001; Treloar et al. 2003). The presence of these ultrahigh-pressure eclogite units now directly adjacent to the ITSZ strongly supports exhumation in the subduction channel (as well as a steep angle of subduction). In the Kaghan area, the HHC is not a single coherent unit but a series of at least three nappes with coesite eclogite structurally uppermost and basic magmatic rocks only partially altered to corona dolerite in the lowest nappe. Again, support for subduction-channel stacking of the same crustal unit that had reached different depths. The location of ultrahigh-pressure eclogites and the rate of subduction and exhumation may seem spectacular but is perfectly compatible with the results of
thermomechanical modelling of subducted crust assuming suitable input parameters (e.g. Warren et al. 2008; Beaumont et al. 2009).

Although the majority of petrological studies of the Kaghan and Tso Morari coesite eclogites concluded a hairpin-like $P$–$T$ path indicating the initial exhumation as near isothermal or accompanied by cooling (de Sigoyer et al. 2000; O’Brien et al. 2001; Mukherjee et al. 2003; Wilke et al. 2010a, b, 2015; St-Onge et al. 2013; Palin et al. 2014, 2017), alternative interpretations do exist. The work of Chatterjee & Jagoutz (2015), in contrast to all previous studies, proposed exhumation of the Tso Morari eclogite by diapiric ascent through the overlying mantle wedge, and also interprets the high-temperature overprint at amphibolite facies proposed by most authors, to have been at significantly higher pressures of the eclogite facies. However, first-order observations such as core–rim compositions of inclusion and matrix omphacite, the absence of lawsonite, the presence of coesite exclusively in the Mg-rich zones of overgrowth garnet, exhumation

Fig. 19. Schematic cross-sections (not to scale) of the NW Himalaya for four critical time periods emphasizing the environments for characteristic metamorphic rocks (loosely based on Jain et al. 2012). At stage 4, the flow of anatexic crust with granulitized eclogites is shown as arrows.
initially producing glaucophane, and the modelling of trace-element and inclusion patterns in garnet (e.g. de Sigoyer et al. 1997; Konrad-Schmolke et al. 2008; Wilke et al. 2015) do not support this alternative. Once all these problems are resolved the $P$–$T$ path for diapiric exhumation through the mantle disappears and a deep, fast subduction and fast exhumation history, including a marked heating at around 1.0 GPa, emerges: a path directly comparable, also in its timing, to that of the coesite eclogite of the Kaghan Valley, Pakistan.

It is fortunate that the section of Indian Plate containing the Kaghan and Tso Morari eclogites reached shallow levels such that they were located in the hanging wall to the subsequent low-angle emplacement of Indian Plate crust below Asia. What would have happened to rocks that stayed deeper? The Stak eclogite resembles closely the Kaghan eclogites but has suffered a greater degree of overprint, indicating that it was not so well protected from thermal effects during and after exhumation (Lanari et al. 2013). Metamorphic zircons in this rock are also significantly younger than those of the Kaghan eclogite (32 Ma compared to 47 Ma: Kouketsu et al. 2016). Is this a reflection of more zircon being produced during the sympletite breakdown of omphacite in the Stak sample as opposed to ultrahigh-pressure metamorphic zircon being sampled in fresh Kaghan eclogite, or is there a real difference in the age of eclogite formation? The same question has to be asked of the eclogites and high-pressure rocks in the Eastern Himalaya (Ama Drime/Sikkim/Bhutan/Namche Barwa). A critical question to ask is whether these rocks were metamorphosed early in the orogeny, stayed at depth for 20–30 myr, heated during crustal relaxation and partial exhumation to granulite facies, then were extruded in migmatite-rich units to shallow structural levels? Such a model is consistent with the geochronological results of Kellett et al. (2014), whereby Lu–Hf ages of garnet (Eocene) are clearly separated from those of zircon (Miocene) in the same rock. The linking of zircon growth to exact stages in the metamorphic history is a difficult but critical aspect of interpreting such high-grade terranes and is, for good reason, still a major research area (e.g. Harley et al. 2007; Rubatto 2017). Interestingly, in metasediments of the Eastern Himalaya, monazite ages document several other stages in Oligocene–Miocene times making them unusually more informative, geochronologically, than the metabasites despite their weaker petrographical memory and further supporting an extended high-grade metamorphic evolution (Chakraborty et al. 2016; J.M. Wang et al. 2017).

The detailed models designed to reconstruct the crustal architecture of the Himalaya and its metamorphic evolution (e.g. Beaumont et al. 2001, 2004, 2006; Jamieson et al. 2004) based on the large-scale features deduced from the geophysical studies show several features that could help to answer these questions. Once the short-lived subduction and exhumation of the Indian continental margin was over, continued convergence of India and Asia led to the subduction of India Plate material below Asia, the development of a foreland-propagating series of shallow-angle thrusts leading to a widening of the orogen, and thickening of the lithosphere (to produce kyanite-grade rocks) both to the north and the south of the suture zone (Fig. 19, stage 3). In a crust now dominated by stacked slivers of upper-crustal material with respective upper-crustal radioactive heat production, heating produced sillimanite-grade gneisses overprinting earlier kyanite-bearing assemblages. The high-grade rocks would be partially molten, weak and thus liable to flow if squeezed enough. This type of process was invoked to explain the extrusion of anatectic, sillimanite-grade HHC below a detachment roof (Searle & Rex 1989; Beaumont et al. 2004, 2006; Searle et al. 2006) (Fig. 19, stage 4) but others (e.g. Kohn 2008, 2014) still question whether a steady-state critical taper rather than channel flow better explains the thermal pattern. The important point is that the stacked and thickened crust of the past, as that of today, was at eclogite-facies pressures at its base. However, as temperature increased, melting occurred and rock masses started to flow to be emplaced at shallower levels, initiated by the ‘indentor’ effect of incoming Indian lithosphere (Warren et al. 2008); it is highly likely that the dominant metasedimentary gneisses would be unable to retain mineralogical evidence of the high-pressure stage apart from minor kyanite relics. In contrast, metabasites in migmatite terranes commonly allow insight into their past history even when multiply overprinted (e.g. Scott et al. 2013).

The discovery of granulitized eclogites within migmatitic gneiss complexes is well known from other orogens. For example, in the Moldanubian Zone of the European Variscides, numerous metabasites with eclogite-facies omphacite and garnet relics partially overprinted by granulite-facies (augitic clinopyroxene, orthopyroxene, spinel or even Fe-rich olivine) assemblages are enclosed by anatectic cordierite + sillimanite-bearing metapelites (O’Brien & Vrana 1995; O’Brien 1997; Scott et al. 2013). In contrast to the Himalayan granulitized eclogites, Variscan examples are closely associated with serpentinitized spinel peridotite, thus yielding strong evidence for a tectonic interleaving of metabasite-peridotite and sedimentary units (i.e. of crust and mantle). Regardless of whether the Kharta/Ama Drime, Sikkim or NW Bhutan granulitized eclogite locations are considered, there are no mantle slices and no convincing evidence that metabasic rocks have been tectonically emplaced into the HHC.
para- and orthogneisses. A logical interpretation of this situation is that the eclogitization and granulitization of the metabasites was in situ: that is, that these particular nappe units of the Higher Himalaya also experienced eclogite-facies conditions as a whole. In contrast to the Tso Morari and Kaghan areas of the HHC directly adjacent to the suture zone, these rocks were not so deeply subducted and lack a rapid exhumation to cold, shallow levels; instead, staying longer at depth, undergoing significant heating and being exhumed as anatetic bodies to become emplaced over other Indian Plate units that were never at eclogite-facies conditions. Results from modelling of the Himalayan-type crustal collision (e.g. Beaumont et al. 2004, 2006; Jamieson et al. 2007) predicts a long duration for high-grade metamorphism before rocks become extruded. These models incorporated erosion at a mountain front to aid extrusion but the wide, hot crustal belt in the Himalaya and southern Tibet also fits the characteristics of modelled Grenville Orogen crust (Jamieson et al. 2007) which shows breakouts of hot, deep levels into shallow, cooler levels independent of surface erosion. It is clear from the increasing data from the field (e.g. Goscombe et al. 2006; Carosi et al. 2010; Chakungal et al. 2010; Grujic et al. 2011; Warren et al. 2011, 2012; Montomoli et al. 2015) that the HHC is not a single coherent slab but different units, with different histories, separated by ductile shear zones. This allows a more reasonable explanation for the granulitized eclogites yielding Miocene ages; namely, that these rocks were a deeper, eclogite-facies part of the crustal stack that became extruded in the Miocene. It has been speculated that the reason for the extrusion of an anatetic, deeper part of the thickened Himalayan nappe stack is the incorporation of the orogen of a cold, rigid ‘plunger’ of Indian Plate material at this time (‘hard’ India–Asia collision): a period also associated with marked slowing of the India–Asia convergence (Warren et al. 2008; Molnar & Stock 2009; Grujic et al. 2011; van Hinsbergen et al. 2012). The cluster of ages, dominantly from zircon and monazite, is most likely to have been due to the widespread granulite-facies overprint which led to the breakdown of former higher-pressure phases: that is, the end of the stay in the lower part of the thickened crust is documented by datable minerals in the metabasite, and not the start and duration of the thickened-crust episode. In detail, however, monazite ages in the metapelites indicate a long period of residence at high temperatures (or, less likely, multiple metamorphic episodes), whereas the metabasites, although rich in information petrologically, unusually have a poorer geochronological memory (Cottle et al. 2009; Grujic et al. 2011; Warren et al. 2011, 2012; Chakraborty et al. 2016; J.M. Wang et al. 2017). The extrusion of granulitized eclogites and their emplacement on lower-grade units all within the HHC may be the best example of all for channel flow.

Summary and conclusions

Despite the predominance of petrological studies in the Himalaya on metasedimentary rocks, it is perhaps once again the minor metabasic rocks that have a reliable memory of the full extent of the metamorphic development and, by extrapolation, thus also the tectonic history of Earth’s most spectacular mountain belt. The minor lawsonite-, glauco- phane- and even carpholite-bearing rocks testify to the cold subduction environment predating collision. Despite predominant amphibolite- and even greenschist-facies assemblages in Indian Plate basement–cover sequences in the Kaghan/Neelum valleys and Tso Morari, it is the minor preserved eclogite cores to mafic boudins, especially those containing coesite, that elucidate the full extent of the deep, rapid subduction and equally rapid exhumation of the leading edge of India as Neo-Tethys was finally consumed. In addition, despite sillimanite ± cordierite ± spinel formation, along with copious melt, in HHC metasediments and orthogneisses in the Eastern Himalaya, once again it is the resilience of the metabasites to complete resetting that allows the picture of an early eclogite-facies stage to emerge. This last eclogite stage is perfectly consistent with the geophysical evidence of an overthickened crust still present today. With collision still ongoing after 50 myr, it would not be surprising if further pulses of extrusion from deep levels occur—taking a closer look at older, deeply eroded orogens such as the Variscan, Caledonian, Grenville or Trans-Hudson might yield some indicators as to how this will look (Johannson & Moller 1986; Massonne & O’Brien 2003; Jamieson et al. 2010; St-Onge et al. 2006).

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References

Anczkiewicz, R., Burg, J.P., Villa, I.M. & Meier, M. 2000. Late Cretaceous blueschist metamorphism in the Indus
CORRIE, S.L., KOHN, M.J. & VERVOORT, J.D. 2016. Young eclogite from the Greater Himalayan Sequence, Arun Valley, eastern Nepal: P–T–t path and tectonic implications. *Earth and Planetary Science Letters*, 289, 406–416.

COTTLE, J.M., JESSUP, M.J. ET AL. 2009. Geochronology of granulitized eclogite from the Ama Drime Massif: implications for the tectonic evolution of the South Tibetan Himalaya. *Tectonics*, 28, TC1002, https://doi.org/10.1029/2006TC002256.

DAS, S., MUKHERJEE, B.K., BASU, A.R. & SEN, K., JR., 2015. Peridotitic minerals of the Nidir Ophiolite in the NW Himalaya: sourced from the depth of the mantle transition zone and above. In: MUKHERJEE, S., CAROSI, R., VAN DER BEEK, P.A., MUKHERJEE, B.K. & ROBINSON, D.M. (eds) *Tectonics of the Himalaya*. Geological Society, London, Special Publications, 412, 271–286, https://doi.org/10.1144/SP412.12.

DAS, S., BASU, A.R. & MUKHERJEE, B.K. 2017. In situ peridotitic diamond in Indus ophiolite sourced from hydrocarbon fluids in the mantle transition zone. *Geology*, 45, 755–758, https://doi.org/10.1130/G39100.1.

DECELLES, P.G., ROBINSON, D.M., QUADE, J., OHA, T.P., GARZONI, C., COPELAND, P. & UPRETI, B.N. 2001. Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. *Tectonics*, 20, 487–509.

DE SOGOYER, J., GUILLOT, S., LARDEAUX, J.M. & MASCLE, G. 1997. Glaucophane-bearing eclogites in the Tso Morari dome (eastern Ladakh, NW Himalaya). *European Journal of Mineralogy*, 9, 1073–1083.

DE SOGOYER, J., CHAVAGNAC, V. ET AL. 2000. Dating the Indian continental subduction and collisional thickening in the northwest Himalaya: multichronology of the Tso Morari eclogites. *Geology*, 28, 487–490.

DE SOGOYER, J., GUILLOT, S. & DICK, P. 2004. Exhumation processes of the high-pressure low-temperature Tso Morari dome in a convergent context (eastern Ladakh, NW Himalaya). *Tectonics*, 23, TC3003.

DESIO, A. 1977. The occurrence of blueschists between the middle Indus and the Swat valleys as an evidence of subduction (North Pakistan). *Atti della Accademia Nazionale dei Lincei. Classe di Scienze Fisiche, Matematiche e Naturali. Rendiconti, Serie 8*, 62, n.s., 565–661. Accademia Nazionale dei Lincei.

DESIO, A. & SHAMS, F.A. 1980. The age of blueschists and the Indus Kohistan Suture line, N.W. Pakistan. *Proceedings of the Italian Academy of Sciences*, 68, 74–79.

DING, L., ZHONG, D., YIN, A., KAPP, P. & HARRISON, T.M. 2001. Cenozoic structural and metamorphic evolution of the eastern Himalayan syncline (Namche Barwa). *Earth and Planetary Science Letters*, 192, 423–438.

DiPIETRO, J. & POUGE, K.R. 2004. Tectonostratigraphic subdivisions in the Himalaya: a view from the west. *Tectonics*, 23, TC5001, https://doi.org/10.1029/2003TC001554.

DONALDSON, G.D., WEBB, A.A.G., MENOLD, C.A., KYLANDER-CLARK, A.R.C. & HACKER, B.R. 2013. Petrochronology of Himalyan ultrahigh-pressure eclogite. *Geology*, 41, 835–838.

EPARD, J.-L. & STECK, A. 2008. Structural development of the Tso Morari ultra-high pressure nappe of the Ladakh Himalaya. *Tectonophysics*, 451, 242–264.

FONTAN, D., SCHOPPE, M., HUNZIKER, C.J., MARTINOTTI, G. & VERKAEREN, J. 2000. Metamorphic evolution, 40Ar–39Ar chronology and tectonic model for the Neehum valley, Azad Kashmir, NE Pakistan. In: KHAN, M.A., TRELOAR, P.J., SEARLE, M.P. & JAN, M.Q. (eds) *Tectonics of the Nanga Parbat Synaxis and the Western Himalaya*. Geological Society, London, Special Publications, 170, 431–453, https://doi.org/10.1144/GSL.SP.2000.170.01.23.

FRANK, W., GANSSER, A. & TROMMERSDORF, V. 1977. Geologic observations in the Ladakh area (Himalayas): a preliminary report. *Schweizerische Mineralogische und Petrographische Mitteilungen*, 57, 89–113.

GAETANI, M. & GARZANTI, E. 1991. Multi-cyclic history of the northern India continental margin (Northwestern Himalaya). *AAPG Bulletin*, 75, 1427–1446.

GANSSER, A. 1964. *Geology of the Himalayas*. Wiley-Interscience, New York.

GARZANTI, E., BAUD, A. & MASCLE, G. 1987. Sedimentary record of the northward flight of India and its collision with Eurasia (Ladak Himalaya, India). *Geodinamica Acta*, 1, 297–312.

GEHRELS, G., KAPP, P. ET AL. 2011. Detrital zircon geochronology of pre-Tertiary strata in the Tibetan-Himalayan orogen. *Tectonics*, 30, TC5016, https://doi.org/10.1029/2011TC002868.

GENG, Q.R., PAN, G.T. ET AL. 2006. The Eastern Himalayan Syntaxis: major tectonic domains, ophiolitic melanges and geologic evolution. *Journal of Asian Earth Sciences*, 27, 265–285.

GENSER, J. 2016. Ar/Ar ages from the Shergol blueschist unit, Indus suture zone, Ladakh: preservation of early stages of subduction of the Neotethys. Paper 2838 presented at the 35th International Geological Congress, 27 August–4 September 2016, Cape Town, South Africa.

GHOSE, N.C. & SINGH, R.N. 1980. Occurrence of blueschist facies in the ophiolite belt of Naga Hills, east of Kiphire, N.E. India. *Geologische Rundschau*, 69, 41–43.

GIRARD, M. & BUSSY, F. 1999. Late Pan-African magmatism in the Himalaya: new geochronological and geochemical data from the Ordovician Tso Morari metagranites (Ladakh, NW India). *Schweizerische Mineralogische und Petrographische Mitteilungen*, 79, 399–418.

GOSCOMBE, B., GRAY, D. & HAND, M. 2006. Crustal architecture of the Himalayan metamorphic front in eastern Nepal. *Gondwana Research*, 10, 232–255.

GRECO, A. & SPENCER, D.A. 1993. A section through the Indian Plate, Kaghan Valley, NW Himalaya, Pakistan. In: TRELOAR, P.J. & SEARLE, M.P. (eds) *Himalayan Tectonics*. Geological Society, London, Special Publications, 74, 221–236, https://doi.org/10.1144/GSL.SP.1993.074.01.16.

GRECO, A., MARTINOTTI, G., PAPRITZ, K., RAMSAY, J.G. & REY, R. 1989. The crystalline rocks of the Kaghan Valley (NE-Pakistan). *Eclogae Geologicae Helvetiae*, 82, 629–653.

GREEN, O.R., SEARLE, M.P., CORFIELD, R.I. & CORFIELD, R.M. 2008. Cretaceous–Tertiary carbonate platform evolution and the age of the India–Asia collision along the Ladakh Himalaya (northwest India). *Journal of Geology*, 116, 331–353.
Groppe, C., Lombardo, B., Rolfo, F. & Pertusati, P. 2007. Clockwise exhumation path of granulitized eclogites from the Ama Drime range (Eastern Himalayas). Journal of Metamorphic Geology, 25, 51–75.

Gropp, C., Rolfo, F., Sachan, H.K. & Rai, S.K. 2016. Petrology of blueschist from the western Himalaya (Ladakh, NW India): exploring the complex behavior of a lawsonite-bearing system in a palaeo-accretionary setting. Lithos, 252–253, 41–56.

Guiraud, M. 1982. Géothermobarométrie du faciès vert à glaucophane. Modélisation et applications (Afghani stan, Pakistan, Corse, Bohême) [Géothermobarometry of the greenschist facies with glaucophane. Modelling and applications (Afghanistan, Pakistan, Corsica, Bohemia)]. PhD thesis, Montpellier University, Montpellier, France.

Guillet, S., de Sigoyer, J., Lardeaux, J.M. & Mascle, G. 1997. Eclogitic metasediments from the Tso Morari area (Ladakh, Himalaya): evidence for continental subduction during India–Asia convergence. Contributions to Mineralogy and Petrology, 128, 197–212.

Guilmette, C., Indares, A. & Hebert, R. 2011. High-pressure anatexic paragneisses from the Namche Barwa, Eastern Himalayan Synclise: textural evidence for partial melting, phase equilibria modeling and tectonic implications. Lithos, 124, 66–81.

Haddad, M.Q. 1985. High-P rocks along the suture zones around Indo-Pakistan plate and phase chemistry of blueschists from eastern Ladakh. Geological Bulletin of the University of Peshawar, 18, 1–40.

Jonnalagadda, M.K., Karmalkar, N.R. & Duraibswami, R.A. 2017a. Geochemistry of eclogites of the Tso Morari complex, Ladakh, NW Himalayas: insights into trace element behavior during subduction and exhumation. Geoscience Frontiers, 2017, 1–17.

Kellel, D.A., Coutand, I., Cottle, J. & Mukul, M. 2013. The South Tibetan detachment system facilitates ultra-rapid cooling of granulite-facies rocks in Sikkim Himalaya. Tectonics, 32, 252–270, https://doi.org/10.1002/2012TC003551.

Kellel, D.A., Cottle, J.M. & Smir, M. 2014. Eocene deep crust at Ama Drime, Tibet: early evolution of the Himalayan orogeny. Lithosphere, 6, 220–229.

Khan, M.A., Jan, M.Q., Qazi, M.S., Khan, M.A., Shah, Y. & Sajjad, A. 1995. Geology of the drainage divide between Kohistan and Kaghan, N. Pakistan. Geological Bulletin University of Peshawar, 28, 65–77.

Kohn, M.J. 2008. P–T–t data from central Nepal support critical taper and repudiate largescale channel flow of the Greater Himalayan Sequence. Geological Society of America Bulletin, 120, 259–273.
Kohl, M.J. 2014. Himalayan metamorphism and its tectonic implications. Annual Reviews in Earth and Planetary Science, 42, 381–419.

Kohl, M.J., Paul, S.K. & Corrie, S.L. 2010. The lower Lesser Himalayan Sequence: a Paleoproterozoic arc on the northern margin of the Indian Plate. Geological Society of America Bulletin, 122, 325–335.

Konrad-Schmolke, M., O'Brien, P.J., De Capitani, C. & Carswell, D.A. 2008. Garnet growth at high- and ultra-high pressure conditions and the effect of element fractionation on mineral modes and compositions. Lithos, 103, 309–332.

Kouke, Y., Hattori, K. & Guillot, S. 2017. Protolith of the Stak eclogite in the northwestern Himalaya. Lithos, 240–243, 155–166.

Kouketsu, Y., Hattori, K. & Guillot, S. 2017. Protolith of the Stak eclogite in the northwestern Himalaya. Italian Journal of Geosciences, 136, 64–72.

Lanari, P., Riel, N., Guillot, S., Vidal, O., Schwartz, S., Pecher, A. & Hattori, K.H. 2013. Deciphering high-pressure metamorphism in collisional context using microprobe mapping methods: application to the Stak eclogitic massif (northwest Himalaya). Geology, 41, 111–114.

Laskowski, A.K., Kapp, P., Vervoort, J.D. & Ding, L. 2016. High-pressure Tethyan Himalaya rocks along the India–Asia suture zone in southern Tibet. Lithosphere, 8, 574–582.

Laskowski, A.K., Kapp, P., Ding, L., Campbell, C. & Liu, X.H. 2017. Tectonic evolution of the Yarlung suture zone, Lopu Range region, southern Tibet. Tectonics, 36, 108–136. https://doi.org/10.1002/2016TC004334

Leech, M.L., Singh, S. & Jan, A.K. 2007. Continuous metamorphic zircon growth and interpretation of U–Pb SHRIMP dating: an example from the western Himalaya. International Geology Review, 49, 313–328.

LeFort, P. 1975. Himalayas: the collided range. Present knowledge of the continental arc. American Journal of Science, 275A, 1–44.

LeFort, P., Guillot, S. & Pecher, A. 1997. HP metamorphic belt along the Indus suture zone of NW Himalaya: new discoveries and significance. Comptes Rendus de l’Académie des Sciences [Proceedings of the Academy of Science], Series IIa, Earth and Planetary Sciences, 325, 773–778.

Li, D., Liao, Q. et al. 2003. SHRIMP U–Pb zircon geochronology of granulites at Rimana (southern Tibet) in the central segment of the Himalayan orogen. Chinese Science Bulletin, 48, 2647–2650.

Liao, J.G. 1971. P–T stabilities of lawsonite, wairakite, lawsonite, and related minerals in the system CaAl2Si2O7–SiO2–H2O. Journal of Petrology, 12, 379–411.

Liu, Y. & Zhong, D. 1997. Petrology of high-pressure granulites from the eastern Himalayan syntaxis. Journal of Metamorphic Geology, 15, 451–466.

Liu, Y., Siebel, W., Massonne, H-J. & Xiao, X. 2007. Geochronological and petrological constraints for tectonic evolution of the central Greater Himalayan Sequence in the Kharta area, southern Tibet. Journal of Geology, 115, 215–230.

Lombardo, B. & Rolfo, F. 2000. Two contrasting eclogite types in the Himalayas: implications for the Himalayan orogeny. Journal of Geodynamics, 30, 57–60.

Lombardo, B., Pertusati, P., Rolfo, F. & Visona, D. 1998. First report of eclogites from the Eastern Himalaya: implications for the Himalayan orogeny. Memorie di Scienze Geologiche, 50, 67–68.

Lombardo, B., Rolfo, F. & Compagnoni, R. 2000. Glauco- phane and barroisite eclogites from the Upper Kaghan nappe: implications for the metamorphic history of the NW Himalaya. In: Khan, M.A., Treloar, P.J., Searle, M.P. & Jan, M.Q. (eds) Tectonics of the Nanga Parbat Synaxis and the Western Himalaya. Geological Society, London, Special Publications, 170, 411–430, https://doi.org/10.1144/GSL.SP.2000.170.01.22

Lombardo, B., Rolfo, F. & McClelland, W.C. 2016. A review of the first eclogites discovered in the Eastern Himalaya. European Journal of Mineralogy, 28, 1099–1109.

Maheo, G., Fayoux, C., Guillot, S., Garzanti, E., Capez, P. & Masclle, G. 2006. Geochemistry of ophiolitic rocks and blueschists from the Sapi-Shergol mélangé (Ladakh, NW Himalaya, India): implication for the timing and closure of the Neo-Tethys Ocean. Journal of Asian Earth Sciences, 26, 695–707.

Mally, M. 2004. Rapid erosion at the Tsangpo knickpoint and exhumation of southeastern Tibet. MS thesis, Lehig University, Bethesda, PA, USA.

Maluski, H. & Matte, P. 1984. Ages of tectonometamorphism in NW Pakistan. Tectonics, 3, 1–18.

Massonne, H-J. & O’Brien, P.J. 2003. The Bohemian Massif and the NW Himalayas. In: Carswell, D.A. & Compagnoni, R. (eds) Ultrahigh Pressure Metamorphism. EMU Notes in Mineralogy, 5, European Mineralogical Union, Budapest, 145–187.

Molnar, P. & Stock, J.M. 2009. Slowing of India’s convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics. Tectonics, 28, TC3001, https://doi.org/10.1029/2008TC002271

Montomoli, C., Carosi, R. & Iaccarino, S. 2015. Tectono-metamorphic discontinuities in the Greater Himalayan Sequence: a local or a regional feature? In: Mukherjee, S., Carosi, R., Van der Beek, P.A., Mukherjee, B.K. & Robinson, D.M. (eds) Tectonics of the Himalaya. Geological Society, London, Special Publications, 412, 25–41, https://doi.org/10.1144/SP412.3

Motttram, C.M., Warren, C.J., Regis, D., Roberts, N.M.W., Harris, N.B.W., Argles, T.W. & Parrish, R.R. 2014. Developing an inverted Barrovian sequence: insights from monazite petrochronology. Earth and Planetary Science Letters, 403, 418–431.

Mukherjee, B.K. & Sachan, H.K. 2001. Discovery of coesite from Indian Himalaya: a record of ultra-high pressure metamorphism in Indian continental crust. Current Science, 81, 1358–1361.

Mukherjee, B.K., Sachan, H.K., Ogasawara, Y., Muko, A. & Yoshoka, N. 2003. Carbonate-bearing UHPM rocks from the Tso-Morari region, Ladakh, India: petrological implications. International Geology Review, 45, 49–69.

Naian, Y. 2006. The detrital record of orogenesis: a review of approaches and techniques used in the Himalayan sedimentary basins. Earth Science Reviews, 74, 1–72.

Nelson, K.D., Zhao, W. et al. 1996. Partially molten middle crust beneath southern Tibet: synthesis of Project INDEPTH results. Science, 274, 1684–1688.
ECLOGITES IN THE HIMALAYA 211

OBERHANSLI, R. 2013. High-pressure–low-temperature evolution in the Indus-Tsangpo Suture along the Kohistan Arc (Kaghan Valley, NE Pakistan). *Episodes*, 36, 87–93.

O’BRIEN, P.J. 1997. Granulite facies overprints of eclogites: short-lived events deduced from diffusion modeling. *In: Qian, X., You, Z., Jahn, B.-M. & Halls, H.C.* (eds) *Precambrian Geology and Metamorphic Petrology: Proceedings of the 30th International Geological Congress, Volume 17, Part II*. VSP, Utrecht, The Netherlands, 157–171.

O’BRIEN, P.J. 2001. Subduction followed by collision: alpine and Himalayan examples. *Physics of the Earth and Planetary Interiors*, 127, 277–291.

O’BRIEN, P.J. & SACHAN, H.K. 2000. Diffusion modelling in garnet from Tso Morari eclogites and implications for exhumation models. *Earth Science Frontiers*, 7, 25–27.

O’BRIEN, P.J. & VRÁNA, S. 1995. Eclogites with a short-lived granulite facies overprint in the Moldanubian Zone, Czech Republic: petrology, geochemistry and diffusion modelling of garnet zonings. *Geologische Rundscha*, 84, 473–488.

O’BRIEN, P.J., ZOTOV, N., LAW, R., KHAN, M.A. & JAN, M.Q. 1999. Coesite in eclogite from the upper Kaghan Valley, Pakistan: a first record and implications. *Terra Nostra*, 99, 109–111.

O’BRIEN, P.J., ZOTOV, N., LAW, R., KHAN, M.A. & JAN, M.Q. 2001. Coesite in Himalayan eclogite and implications for models of India–Asia collision. *Geology*, 29, 435–438.

PALIN, R.M., ST-ONGE, M.R., WATERS, D.J., SEARLE, M.P. & DYCK, B. 2014. Phase equilibria modelling of retrograde amphibole and clinozoisite in mafic eclogite from the Tso Morari massif, northwest India: constraining the $P$–$T$–$M(\text{H}_2\text{O})$ conditions of exhumation. *Journal of Metamorphic Geology*, 32, 675–693.

PALIN, R.M., REUBER, G.S., WHITE, R.W., KAUS, B.J.P. & WELLER, O.M. 2017. Subduction metamorphism in the Himalayan ultrahigh-pressure Tso Morari massif: an integrated geodynamic and petrological modelling approach. *Earth and Planetary Science Letters*, 467, 108–119.

PAPRITZ, K. & REY, R. 1989. Evidence of the occurrence of Permian Panjal Trap basalts in the Lesser- and Higher-Himalayas of the western syntaxis area, NE Pakistan. *Eclogae Geologicae Helvetiae*, 82, 603–627.

PARRISH, R.R. & HODGES, K.V. 1996. Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequences, Nepalese Himalaya. *Geological Society of America Bulletin*, 108, 904–911.

PARRISH, R.R., GUGCH, S.J., SEARLE, M.P., & WATERS, D.J. 2006. Plate velocity exhumation of ultrahigh-pressure eclogites in the Pakistan Himalaya. *Geology*, 34, 989–992.

PETTERSON, M.G. & WINDLEY, B.F. 1985. Rb–Sr dating of the Kohistan arc-batholith in the Trans-Himalaya of north Pakistan, and tectonic implications. *Earth and Planetary Science Letters*, 74, 45–57.

POGNANTE, U. & SPENCER, D.A. 1991. First report of eclogites from the Himalayan belt, Kagan valley (northern Pakistan). *European Journal of Mineralogy*, 3, 613–618.

POGNANTE, U., BENNA, P. & LE FORT, P. 1993. High pressure metamorphism in the High Himalayan Crystallines of the Stak valley, northeastern Nanga Parbat-Haramosh syntaxis, Pakistan Himalaya. *In: Treado, P.J. & Searle, M.P.* (eds) *Himalayan Tectonics*. Geological Society, London, Special Publications, 74, 161–172, https://doi.org/10.1144/GSL.SP.1993.074.01.12

RAO, R. & RAJ, H. 2006. Signatures of rift environment in the production of garnet amphibolites and eclogites from Tso Morari region, Ladakh, India: a geochemical study. *Gondwana Research*, 9, 512–523.

REGIS, D., WARREN, C.J., YOUNG, D. & ROBERTS, N.M.W. 2014. Tectono-metamorphic evolution of the Jomolhari massif: variations in timing of syn-collisional metamorphism across western Bhutan. *Lithos*, 190–191, 449–466.

REHMAN, H.U., YAMAMOTO, H., KANEKO, Y., KANSA, A.B., MURATA, M. & OZAWA, H. 2007. Thermobaric structure of the Himalayan metamorphic belt in Kaghan Valley, Pakistan. *Journal of Asian Earth Sciences*, 29, 390–406.

REHMAN, H.U., KOBAYASHI, K. ET AL. 2013. Ion microprobe U–Th–Pb geochronology and study of micro-inclusions in zircon from the Himalayan high and ultrahigh-pressure eclogites, Kaghan Valley of Pakistan. *Journal of Asian Earth Sciences*, 63, 179–196.

REHMAN, H.U., TANAKA, R. ET AL. 2014. Oxygen isotopes in Indian Plate eclogites (Kaghan Valley, Pakistan): negative delta O-18 values from a high latitude protolith reset by Himalayan metamorphism. *Lithos*, 208, 471–483.

REHMAN, H.U., LEE, H.Y., CHUNG, S.L., KHAN, T., O’BRIEN, P.J. & YAMAMOTO, H. 2016. Source and mode of the Permian Panjal Trap magnatism: evidence from zircon U–Pb and Hf isotopes and trace element data from the Himalayan ultrahigh-pressure rocks. *Lithos*, 260, 286–299.

RICHARDS, A., ARGLES, T., HARRIS, N., PARRISH, R., AHMAD, T., DARBYSHIRE, F., & DRAGANITIS, E. 2005. Himalayan architecture constrained by isotopic tracers from clastic sediments. *Earth and Planetary Science Letters*, 236, 773–796.

ROBINSON, P.T., BAI, W.J. ET AL. 2004. Ultra-high pressure minerals in the Luobusa Ophiolite, Tibet, and their tectonic implications. *In: Malpas, J., Fletcher, C.J.N., Ali, J.R. & Atchison, J.C.* (eds) *Aspects of the Tectonic Evolution of China*. Geological Society, London, Special Publications, 226, 247–271, https://doi.org/10.1144/GSL.SP.2004.226.01.14

ROLLFO, F., CAROSI, R., MONTOMOLI, C. & VISONÀ, D. 2008. Discovery of granulitized eclogite in North Sikkim expands the Eastern Himalaya high-pressure province. *In: Singh, S., Jahn, A.K. & Shrestha, B.* (eds) *The 23rd Himalayan–Karakoram–Tibet Workshop*, 8–11 August 2008, Leh, Ladakh, India: Extended Abstracts. *Himalayan Journal of Sciences*, 5, (7), 126–127.

RUBATTO, D. 2017. Zircon, the metamorphic mineral. *In: Kohl, M.J., English, M. & Lainai, P.* (eds) *Petrochronology: Methods and Applications*. Reviews in Mineralogy and Geochemistry, 83, 261–295.

RUBATTO, D. & HERMANN, J. 2001. Exhumation as fast as subduction? *Geology*, 29, 3–6.

SACHAN, H.K., BODNAR, R.J., ISLAM, R., SZABO, C. & LAW, R.D. 1999. Exhumation history of eclogites from the Tso-Morari crystalline complex in eastern Ladakh: mineralogical and fluid inclusion constraints. *Journal of the Geological Society of India*, 53, 181–190.
SACHAN, H.K., MUKHERJEE, B.K., OGASAWARA, Y., MARUYAMA, S., ISHIDA, H., MUKO, A. & YOSHOKA, N. 2004. Discovery of coesite from Indus Suture Zone (ISZ), Ladakh, India: evidence for deep subduction. *European Journal of Mineralogy*, 16, 235–240.

SCHRÄER, U., HAMET, J. & ALLEGRE, C.J. 1984. The Transhimalaya (Gangdese) plutonism in the Ladakh region: U–Pb and Rb–Sr study. *Earth and Planetary Science Letters*, 67, 27–339.

SCHERTZ, H.-P. & O’BRIEN, P.J. 2013. UHP-metamorphism: minerals and microstructures. *Elements*, 9, 261–266.

SCHLUP, M., CARTER, A., COSCA, M. & STECK, A. 2003. Exhumation history of eastern Ladakh revealed by $^{40}$Ar/$^{39}$Ar and fission-track ages: the Indus River–Tso Morari transect, NW Himalaya. *Journal of the Geological Society, London*, 160, 385–399, https://doi.org/10.1144/0167-64902-084

SCHMIDT, M.W. 1995. Lawsonite: upper stability and formation of higher density hydrous phases. *American Mineralogist*, 80, 1286–1459.

SCOTT, J.M., KONRAD-SCHMOLKE, M., O’BRIEN, P.J. & GUNDER, C. 2013. High-T, low-P formation of rare olivine-bearing symplectites in Variscan eclogite. *Journal of Petrology*, 54, 1375–1398.

SPENCER, D.A., TOLERINI, S. & POGNANTE, U. 1995. SHRIMP evidence for a Permian protolith age and a 44 Ma metamorphic age for the Himalayan eclogites (Upper Kaghan, Pakistan): implications for the subduction of Tethys and the subdivision terminology of the NW Himalaya. *In: MACFARLANE, A.M., SORKHABI, R.B. & QUADE, J.* (eds) *11th Himalaya–Kararakoram–Tibet Workshop, Flagstaff, Arizona, Abstracts*, 147–150.

SPENCER, D.A., TONARINI, S. & POGNANTE, U. 1995. Geochemical and Sr–Nd isotopic characterisation of Higher Himalayan eclogites (and associated metabasites). *European Journal of Mineralogy*, 7, 89–102.

SPENCER, C.J., DYCk, B., MOTTRAM, C.M., ROBERTS, N.M.W., YAO, W.H. & MARTIN, E.L. 2018. Deconvolving the pre-Himalayan Indian margin – Tales of crustal growth and destruction. *Geoscience Frontiers*, https://doi.org/10.1016/j.gsf.2018.02.001

STECK, A., EPARD, J.L., VANNAY, J.C., HUNZIKER, J., GIRARD, M., MORARD, A. & ROBYR, M. 1998. Geological transect across the Tso Morari and Spiti areas: the nappe structures of the Tethys Himalaya. *Eclogae Geologicae Helvetiae*, 91, 103–122.

STEPHENSON, B.J., WATERS, D.J. & SEARLE, M.P. 2000. Inverted metamorphism and the Main Central Thrust: field relations and thermobarometric constraints from the Kishtwar Window, NW India Himalaya. *Journal of Metamorphic Geology*, 18, 571–590.

ST-ONGE, M.R., SEARLE, M.P. & WODECKA, N. 2006. Trans-Hudson Orogen of North America and Himalaya–Kararakoram–Tibetan Orogen of Asia: structural and thermal characteristics of the lower and upper plates. *Tectonics*, 25, TC4006, https://doi.org/10.1029/2005TC001907

ST-ONGE, M.R., RAYNER, N., PALIN, R.M., SEARLE, M.P. & WATERs, D.J. 2013. Integrated pressure–temperature–time constraints for the Tso Morari dome (northwest India): implications for the burial and exhumation path of UHP units in the western Himalaya. *Journal of Metamorphic Geology*, 31, 469–504.

TONARINI, S., VILLA, I.M., OBERLI, F., MEER, M., SPENCER, D.A., POGNANTE, U. & RAMSAY, J.G. 1993. Eocene age of eclogite metamorphism in Pakistan Himalaya: implications for India–Eurasia collision. *Terra Nova*, 5, 13–20.

TRELLOAR, P.J. 1995. Pressure–temperature–time paths and the relationship between collision, deformation and metamorphism in the north-west Himalaya. *Geological Journal*, 30, 333–348.

TRELLOAR, P.J., GEORGE, M.T. & WHITTINGTON, A.G. 2000. Mafic sheets from Indian plate gneisses in the Nanga Parbat syntaxis: their significance in dating crustal growth and metamorphic and deformation events. *In: KHAN, M.A., TRELLOAR, P.J., SEARLE, M.P. & JAN, M.Q.* (eds) *Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya*. Geological Society, London, Special Publications, 170, 25–50, https://doi.org/10.1144/GSL.SP.2000.170.01.03

TRELLOAR, P.J., O’BRIEN, P.J., PARRISH, R.R. & KHAN, M.A. 2003. Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya. *Journal of the Geological Society, London*, 160, 367–376, https://doi.org/10.1144/0167-64902-075

TSUMORI, T. & ERNST, W.G. 2014. Lawsonite blueschists and lawsonite eclogites as proxies for palaeo-subduction zone processes: a review. *Journal of Metamorphic Geology*, 32, 437–454.

UPADIYAY, R., FRISCH, W. & SIEBEL, W. 2008. Tectonic implications of new U–Pb zircon ages of the Ladakh
batholith, Indus suture zone, northwest Himalaya, India. *Terra Nova*, **20**, 309–317.

van der Beek, P., Van Melle, J., Guillot, S., Pécher, A., Reiners, P.W., Nicoleau, S. & Latif, M. 2009. Eocene Tibetan Plateau remnants preserved in the northwestern Himalaya. *Nature Geoscience*, **2**, 364–368.

van Hinsbergen, D.J.J., Lippert, P.C., Dupont-Nivet, G., Mcquarrie, N., Doubrovin, P.V., Spakman, W. & Torsvik, T.H. 2012. Greater India Basin hypothesis and a two-stage Cenozoic collision between India and Asia. *Proceedings of the National Academy of Sciences of the United States of America*, **109**, 7659–7664.

Virdi, N.S., Thakur, V.C. & Kumar, S. 1977. Blueschist facies metamorphism from the Indus suture zone of Ladakh and its significance. *Himalayan Geology*, **7**, 479–482.

Wang, J.M., Wu, F.Y., Rubatto, D., Liu, S.R., Zhang, J.J., Liu, X.C. & Yang, L. 2017. Monazite behaviour during isothermal decompression in pelitic granulites: a case study from Dinggye, Tibetan Himalaya. *Contributions to Mineralogy and Petrology*, **172**, 81, https://doi.org/10.1007/s00410-017-1400-y

Wang, Y.H., Zhang, L.F., Zhang, J.J. & Wei, C.J. 2017. The youngest eclogite in central Himalaya: P–T path, U–Pb zircon age and its tectonic implication. *Gondwana Research*, **41**, 188–206, https://doi.org/10.1016/j.gr.2015.10.013

Warren, C.J., Beaumont, C. & Jamieson, R.A. 2008. Modelling tectonic styles and ultrahigh pressure (UHP) rock exhumation during the transition from oceanic subduction to continental collision. *Earth and Planetary Science Letters*, **267**, 129–145.

Warren, C.J., Grubic, D., Kellett, D.A., Cottle, J., Jamieson, R.A. & Ghalley, K.S. 2011. Probing the depths of the India–Asia collision: U–Th–Pb monazite chronology of granulites from NW Bhutan. *Tectonics*, **30**, TC2004, https://doi.org/10.1029/2010TC002738

Warren, C.J., Grubic, D., Cottle, J.M. & Rogers, N.W. 2012. Constraining cooling histories: rutile and titanite chronology and diffusion modelling in NW Bhutan. *Journal of Metamorphic Geology*, **30**, 113–130, https://doi.org/10.1111/j.1525-1341.2011.00958.x

Weinberg, R.F. & Dunlap, W.J. 2000. Growth and deformation of the Ladakh Batholith, Northwest Himalayas: implications for timing of continental collision and origin of calc-alkaline batholiths. *Journal of Geology*, **108**, 303–320.

Wen, D.R., Liu, D.Y. *et al*. 2008. Zircon SHRIMP U–Pb ages of the Gangdese Batholith and implications for Neotethyan subduction in southern Tibet. *Chemical Geology*, **252**, 191–201.

Wilke, F.D.H., O’Brien, P.J., Altenberger, U., Konrad-Schmolke, M. & Khan, M.A. 2010a. Multistage history in different eclogite types from the Pakistan Himalaya and implications for exhumation processes. *Lithos*, **114**, 70–85.

Wilke, F.D.H., O’Brien, P.J., Gerdes, A., Timmerman, M.J., Sudo, M. & Khan, M.A. 2010b. The multistage exhumation history of the Kaghan Valley UHP series, NW Himalaya, Pakistan from U–Pb and 40Ar/39Ar ages. *European Journal of Mineralogy*, **22**, 703–719.

Wilke, F.D.H., O’Brien, P.J., Sobel, E.R. & Stockli, D.F. 2012. Apatite fission track and (U–Th)/He ages from the Higher Himalayan Crystallines, Kaghan Valley, Pakistan: implications for an Eocene Plateau and Miocene to Pliocene exhumation. *Journal of Asian Earth Sciences*, **59**, 14–23.

Wilke, F.D.H., O’Brien, P.J., Schmidt, A. & Ziemann, M.A. 2015. Subduction, peak and multistage exhumation metamorphism: traces from one coesite-bearing eclogite, Tso Morari, western Himalaya. *Lithos*, **231**, 77–91.

Xia, B., Li, J.F. *et al*. 2008. SHRIMP U–Pb dating for diabase in Sangsang ophiolite, Xizang, China: geochronological constraint for development of eastern Tethys basin. *Geochimica*, **37**, 399–403.

Xiao, X. & Gao, Y.L. 1984. Tectonic evolution of the Tethys Himalayas of China. In: *Tectonics of Asia, Colloquium K.05, 27th International Geological Congress, 1984, Moscow*, Reports, **5**, 181–189.

Xu, W.C., Zhang, H.F., Parrish, R., Harris, N., Guo, L. & Yuan, H.L. 2010. Timing of granulite facies metamorphism in the eastern Himalayan syntaxis and its tectonic implications. *Tectonophysics*, **485**, 231–244.

Yang, J.S., Dobrzheskaya, L., Bai, W.J., Fang, Q.S., Robinson, P.T., Zhang, J. & Green, H.W., II. 2007. Diamond- and coesite-bearing chromitites from the Luobusa ophiolite, Tibet. *Geology*, **35**, 875–878, https://doi.org/10.1130/G32766A.1

Yin, A. & Harrison, T.M. 2000. Geologic evolution of the Himalayan–Tibetan Orogen. *Annual Reviews in Earth and Planetary Science*, **28**, 211–280.

Zhang, R.Y., Yang, J.S., Ernst, W.G., Jain, B.M., Izuka, Y. & Guo, G.L. 2016. Discovery of in situ super-reducing, ultrahigh-pressure phases in the Luobusa ophiolitic chromitites, Tibet: new insights into the deep upper mantle and mantle transition zone. *American Mineralogist*, **101**, 1285–1294.

Zhang, Z., Xiang, H., Dong, X., Ding, H. & He, Z. 2015. Long-lived high-temperature granulite-facies metamorphism in the Eastern Himalayan orogen, south Tibet. *Lithos*, **212–215**, 1–15.

Zhang, Z.G., Liu, Y.H., Qiao, T.W., Yang, H.X. & Xu, B.C. 1992. *Geology of the Namche Barwa Region*. Chinese Science Press, Beijing.

Zhao, W., Nelson, K.D. & Project INDEPTH. 1993. Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. *Nature*, **366**, 557–559.