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Magmatism in the Kohistan–Ladakh Paleo-arc: Building Continental Crust During the India–Eurasia Convergence

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1.1. Introduction

Petrological models of continental crust formation widely argue for a magmatic derivation from the mantle in magmatic arc settings. The geochemistry and production rate of arc magmas are linked to the geodynamic evolution of subduction zones. The thermal structure of the subduction zone, the flux of volatile released by the down-going slab, the crustal thickness of the arc and the nature of sediments entering the subduction zone are regarded as important parameters in controlling the geochemical characteristics of arc magmas (Ringwood 1974; Plank and Langmuir 1988, 1998; Grove et al. 2012). Furthermore, the tempo of arc magmatism, or magma addition rate, is thought to be linked to external forcing, notably changes in plate

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motion and subduction rate or to interconnected tectonic and magmatic processes within the arc crust (Paterson and Ducea 2015). Hence, long-term geochronological and geochemical records covering the lifetime of magmatic activity in arcs provide important constraints on evolving subduction processes during convergence and at the onset of collision in orogenic systems. The Kohistan–Ladakh paleo-arc is one of the best preserved and exposed arc sections worldwide (for recent reviews see Burg 2011; Petterson 2019). The plutonic and volcanic units cover $\sim$130 Ma of magmatic activity from 150 to 20 Ma. This time-span encompasses the evolution from an initial intra-oceanic subduction to partial melting of the thickened arc crust following the collision between the arc and the Indian and Eurasian continents. The Kohistan arc magmas represent a nearly complete record that provides insights into the processes of convergence and collision prior to and at the onset of the Himalayan Orogeny. This record provides insights into the debated tectonic models of arc formation in the Neotethys domain.

In addition to providing information on the orogenic processes, well-preserved arc sections are keys to understanding the formation of the continental crust. Arc magmatism along active margins represents the principal locus of production of new continental crust. Post-Archean continental growth predominantly results from accretion of the crustal section of island arcs during orogenic collisions, with an additional contribution from the intrusion of mantle-derived magmas in continental arcs (Taylor and White 1965; Rudnick 1995). Yet, melting of the metasomatized mantle wedge in subduction zones yields predominantly basaltic magmas, when estimates of the continental crust bulk composition are andesitic (Rudnick and Gao 2003). This paradox requires a mechanism removing mafic materials or adding silicic materials to the crust. In addition, the poorly understood and debated compositional stratification of the continental crust with a basaltic lower crust and a granitic upper crust requires a mechanism of differentiation within the arc crust. To address the formation and evolution of continental crust, it is consequently essential to characterize the compositional architecture of crustal arc sections, to document the mechanisms controlling magma differentiation in the crust and to establish the processes controlling mass addition or removal from the evolving crust. The Kohistan–Ladakh plutonic and volcanic units form a nearly complete crustal section from upper-mantle to lower-crustal ultra-mafic rocks through mid-crustal batholiths and to the volcanic cover, a nearly unique occurrence in the geological record (Jagoutz et al. 2009, 2011; Jagoutz 2010). This preserved crustal section (Figure 1.1) offers an exceptional opportunity to document the locus and mechanisms of differentiation in arc crustal sections.

The objectives of this chapter are to review the general geological, petrological and geochemical characteristics of the Kohistan–Ladakh rocks and discuss the implications for the Himalayan Orogeny, as well as for the production of continental crust through arc magmatism. Among arising questions concerned by this review are (i) the duration of magmatic arc construction; (ii) are there one or several arcs? and (iii) the timing of arc accretion to India and Asia, and insights for tectonic reconstructions of India–Asia convergence models (see Volume 1 – Chapter 1). This chapter summarizes the possible reconstructions based on recent data.

1.2. Geological setting of the Kohistan–Ladakh arc

The Kohistan–Ladakh arc forms a coherent tectonic block within the Himalayan belt, although the Kohistan and Ladakh sections are separated by the Nanga Parbat syntaxis (Figures 1.1 and 1.2).

It is considered to be part of the Trans-Himalayan plutonic complex, a 2,500 km linear suite of plutonic units extending from Pakistan in the west to Tibet in the east (Honegger et al. 1982; Bard 1983; Rolland et al. 2000). The Kohistan–Ladakh arc is delimited to the north by the Shyok (or Karakoram–Kohistan) suture and to the south by the Indus Suture (Figure 1.1). Eastward, the Shyok suture is dissected by the Karakoram fault and gives place to the Tsangpo suture delimitating India and the Eurasian margin (Figure 1.1). To the south, the Indus Suture marks the limit with the Indian plate. The suture contains ophiolitic sequences and ultra-high pressure rocks remnants of a subduction zone (Figure 1.2).

The Kohistan–Ladakh paleo-island arc developed during the Mesozoic in the equatorial area of the Neotethys Ocean, south of Asia and was wedged between the Indian and Asian plates during the Himalayan Orogeny (Bard 1983; Khan et al. 2009; Burg 2011; Bouilhol et al. 2013; Martin et al. 2020). U–Pb zircon ages indicate that the magmatic activity in the KLA started approximately 150 Ma and lasted until 20 Ma, with two main episodes of subduction-related magmatism (120–80 Ma and 80–40 Ma) (Figure 1.3) (for recent age compilations see Bouilhol et al. (2013), Burg and Bouilhol (2019) and Jagoutz et al. (2019)). North of the Shyok suture, a second subduction system was active simultaneously on the Eurasian continental margin and resulted in the formation of the Karakoram Batholith with U–Pb zircon ages ranging from 120 to 40 Ma (e.g. Debon et al. 1987).

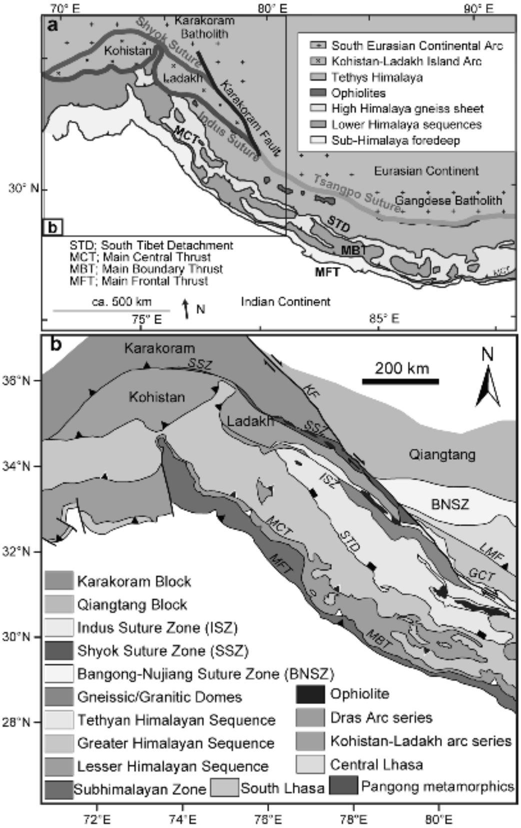

Figure 1.1. *(a) Location of Kohistan–Ladakh and ophiolites in the Himalayan Belt. (b) Simplified geological map of the western Himalayan orogen (modified after Parsons et al. 2020). Tectonic structures: ATF=Altyn Tagh Fault; BNSZ=Bangong–Nujiang Suture Zone; GCT=Great Counter Thrust; ISZ=Indus Suture Zone; JSZ=Jinsha Suture Zone; KF=Karakoram Fault; KSZ=Kunlun Suture Zone; LMF=Luobadui–Milashan Fault; MCT=Main Central Thrust; MFT=Main Frontal Thrust; SSZ=Shyok Suture Zone; STD=South Tibetan Detachment. (a) Location of Kohistan–Ladakh and ophiolites in the Himalayan Belt. (b) Simplified geological map of the western Himalayan orogen (modified after Parsons et al. 2020). Tectonic structures: ATF=Altyn Tagh Fault; BNSZ=Bangong–Nujiang Suture Zone; GCT=Great Counter Thrust; ISZ=Indus Suture Zone; JSZ=Jinsha Suture Zone; KF=Karakoram Fault; KSZ=Kunlun Suture Zone; LMF=Luobadui–Milashan Fault; MCT=Main Central Thrust; MFT=Main Frontal Thrust; SSZ=Shyok Suture Zone; STD=South Tibetan Detachment. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

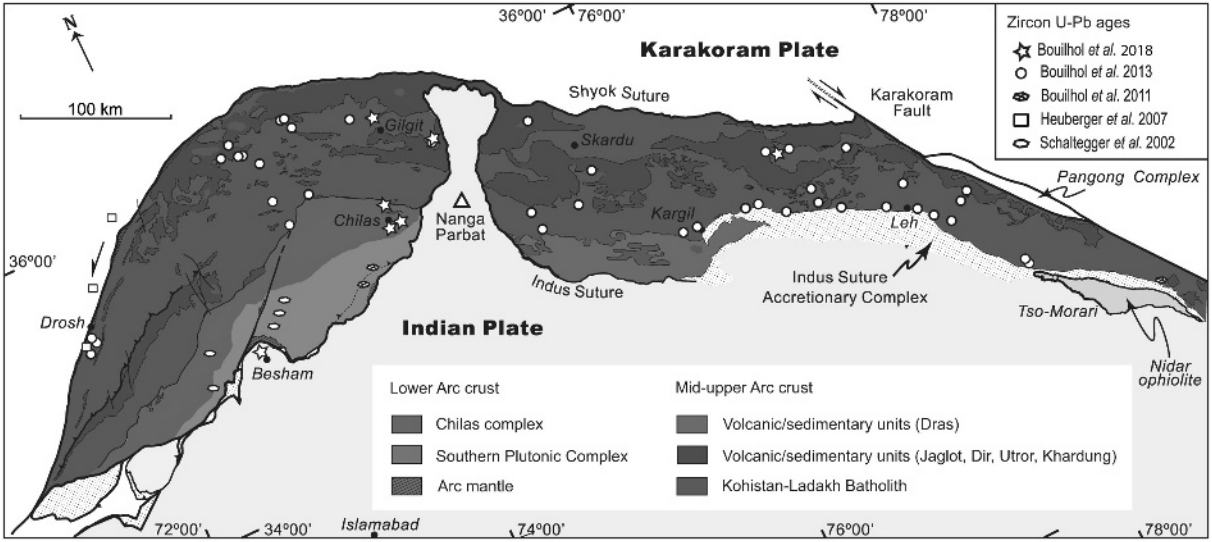

Figure 1.2. *Geological map of the Kohistan–Ladakh arc (modified from Jagoutz et al. 2019). Symbols indicate samples for which whole-rock geochemistry and zircon U–Pb ages were obtained, for a synthesis (see Jagoutz and Behn 2013). For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

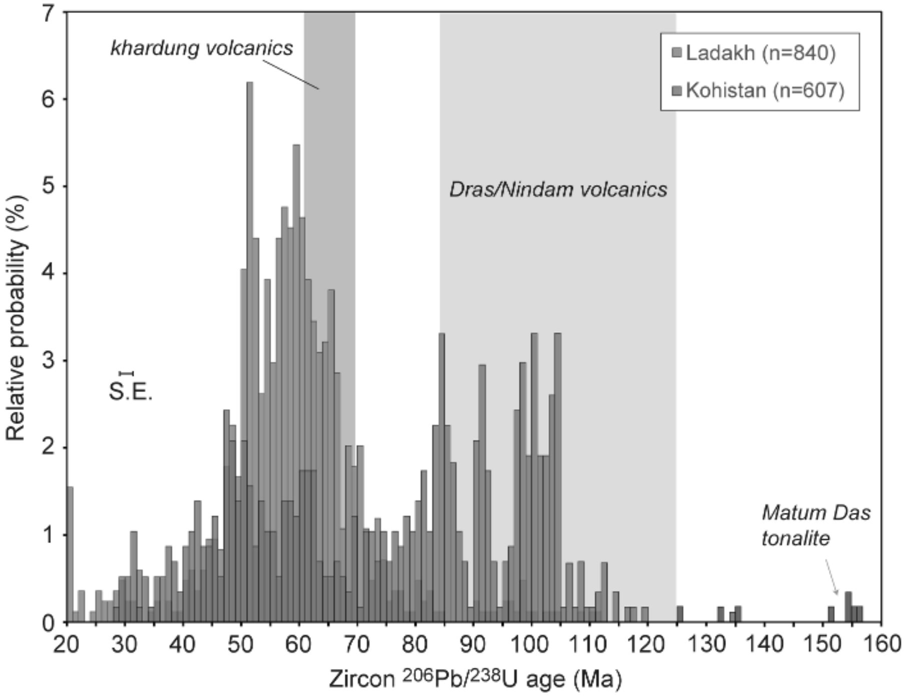

Figure 1.3. *Relative distribution of U–Pb Zircon ages from the Kohistan and Ladakh plutonic sections of the Kohistan–Ladakh arc (data are from Bouilhol et al. 2011, 2013; Bosch et al. 2011; Heuberger et al. 2007; Jagoutz et al. 2019; Ravikant et al. 2009; Schaltegger et al. 2002; Upadhyay et al. 2008). The shaded areas show the U–Pb Zircon age ranges for the Khardung volcanics, north Ladakh (Lakhan et al. 2020) and volcaniclastic Nindam formation, south Ladakh (Walsh et al. 2019). The latter is believed to represent the distal turbidities from the Dras arc. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

East from the Karakoram fault, the Karakoram Batholith gives place to the Gangdese Batholith. Timing of the collision of the arc(s) system(s) with the Eurasian and Indian continents is still contentious. Closure of the Shyok suture has been inferred to either predate or postdate the collision between KLA and India (Petterson and Windley 1985; Khan et al. 2009; Bouilhol et al. 2013; Walsh et al. 2019; Martin et al. 2020). In addition, it is debated whether part of the Ladakh sector of the arc developed on a continental or oceanic basement (e.g. Rolland et al. 2000; Burg 2011). These points are discussed further below.

1.3. Main geological contacts

1.3.1. *The Shyok Suture Zone*

The Shyok Suture Zone separates the Kohistan–Ladakh block from the Karakoram margin of Eurasia (Coward et al. 1986; Pudsey 1986; Rolland et al. 2000). The latter records Paleozoic (Ordovician)–Mesozoic sedimentation (Gaetani 1997; Rolland et al. 2002) on a >651 Ma Precambrian basement (Rolland et al. 2006b). Several phases of magmatism are recorded since the Upper Triassic to the Miocene (Rolland et al. 2001, 2006b; Heuberger et al. 2007; Ravikant et al. 2009; St-Onge et al. 2010; Phillips et al. 2013; Borneman et al. 2015; Kumar et al. 2017), Lower to Upper Jurassic and Lower to Upper Cretaceous phases of deformation (Gaetani et al. 1990), and middle Cretaceous to Cenozoic metamorphic events (Rolland et al. 2006a; Searle and Hacker 2019). To the East, the Qiangtang block might represent a lateral equivalent of the Karakoram across the Karakoram Fault, and the Bangong suture is considered equivalent to the Shyok suture (Phillips et al. 2004; Baxter et al. 2009; Robinson 2009; Rolland et al. 2009; Borneman et al. 2015). While the Bangong suture is generally considered to be Cretaceous in age, the Shyok suture closure age is more controversial. Geologic, metamorphic and stratigraphic data from the Shyok suture and adjacent Karakoram block support a middle Cretaceous accretion of the Kohistan–Ladakh arc (Rex et al. 1988; Treloar et al. 1989; Rolland et al. 2000; Palin et al. 2012; Borneman et al. 2015; Kumar et al. 2017), whereas geochemical and paleomagnetic data from the Kohistan–Ladakh arc are possibly indicative of a collision with India at ca. 50 Ma and a later collision with Karakoram at ca. 40 Ma (Bouilhol et al. 2013; Martin et al. 2020). However, age relationships provided by Borneman et al. (2015) are clearly indicative of a minimum Late Cretaceous age for the Shyok Suture. These authors showed that the youngest population of detrital zircons obtained in the overlying Saltoro molasse rocks is ∼92 Ma and obtained a U/Pb zircon date for a dike that cuts the basal molasse outcrops (∼85 Ma), which clearly rules out the possibility of an Eocene collision between Kohistan–Ladakh and Eurasia.

The eastward correlation of the Kohistan–Ladakh and Dras arc remnants with Tibetan units is also controversial, because a clear lateral continuation is hindered by the offset of the Karakoram Fault (Figure 1.1). Although built on a basement of distinct nature, these arc remnants are commonly correlated with those of the Lhasa block, which consists of a Precambrian basement overlain and intruded by Paleozoic to Cenozoic strata and magmatic rocks (Dürr 1996; Zhu et al. 2009). This correlation is based on the similar age, structural position and geochemistry of the Upper Cretaceous–Cenozoic batholiths from both arcs (Gangdese, Ladakh, Kohistan; Raz and Honegger 1989; Rolland et al. 2000; Weinberg et al. 2000; Ji et al. 2009). Alternative connections were proposed between intra-oceanic arc remnants located south of Lhasa (Zedong arc; Aitchison et al. 2000, 2007; McDermid et al. 2002) and either the Kohistan–Ladakh arc (Parsons et al. 2020), the Dras arc (e.g. Walsh et al. 2021) or the Spong arc (e.g. Hébert et al. 2012).

1.3.2. *The Indus Suture Zone*

The Indus Suture Zone in NW Ladakh is composed of igneous, metamorphic and sedimentary units (Figure 1.2). Here, a blueschist facies suture is exhibited (Honegger et al. 1982). Exposed north of the suture zone are the intrusive and volcanic units of the Kohistan–Ladakh arc. South of the suture, the Indus Group overlies the middle Cretaceous to lower Eocene Tar Group, which consists of the Aptian–Albian Khalsi Limestone (Garzanti and Van Haver 1988; Searle et al. 1990; Clift et al. 2000; Green et al. 2008; Henderson et al. 2010). The Tar Group is generally considered as the forearc basin of the Kohistan–Ladakh arc (Garzanti and Van Haver 1988; Searle et al. 1990; Green et al. 2008; Henderson et al. 2010). The Upper Jurassic to Paleocene Dras intraoceanic arc is tectonically juxtaposed against the Ladakh Batholith, the Tar Group and the Indus Group, to the north, and thrust over the Indian passive margin, to the south. The western part of the Dras arc is dominated by mafic to intermediate volcanic rocks, which transition eastwards into the deep-water volcaniclastic rocks of the Aptian to Paleocene Nindam Formation (Honegger et al. 1982; Dietrich et al. 1983; Reuber 1989; Clift et al. 2000; Bhat et al. 2019; Walsh et al. 2021). Exposed south of the suture zone is the Permian to lower Eocene Zanskar Supergroup of the Tethyan Himalaya (northern Indian margin), which is thrusted by the Jurassic to Upper Cretaceous Spongtang supra-subduction zone ophiolite (e.g. Reuber et al. 1987; Corfield and Searle 2000; Mahéo et al. 2004).

1.4. Reconstruction of the arc structure and evolution

The Kohistan–Ladakh paleo-arc is composed of several major plutonic-volcanic sections (Figure 1.2). The zonality of magmatic sections shows a progressive evolution from lower crustal cumulates in Kohistan towards mid-crustal plutons in both central Kohistan and in Ladakh, and more superficial intrusives and volcanic complexes on the northern side of Kohistan–Ladakh, along the Shyok suture.

The Kohistan sequence makes up the most complete arc section and is thus presented in detail in this article. The Kohistan section is formed by three major units from south to north: the Southern Plutonic Complex, the Chilas Complex and the Gilgit Complex (Figure 1.2). Detailed descriptions of these complexes can be found in Tahirkheli (1979), Jan and Howie (1980), Bard (1983), Petterson and Windley (1985), Burg et al. (1998), Petterson and Treloar (2004), Yoshino and Okudaira (2004), Jagoutz et al. (2006), Garrido et al. (2007), Jagoutz et al. (2007), Dhuime et al. (2007), Bouilhol et al. (2009), Dhuime et al. (2009), Jagoutz (2010), Burg (2011) and Petterson (2019). The inferred crustal thicknesses of the Kohistan arc (∼54–55 km) is significantly more than any currently active intra-oceanic arc, which have a crustal thickness of about 35 km. The Ladakh section is regarded as a lateral equivalent of the Gilgit Complex and represents an inferred crustal thickness of ∼30 km.

1.4.1. *Southern Plutonic Complex*

The Southern Plutonic Complex represents the lower arc crust and mantle transition, mainly formed of ultramafic rocks exposed in the Jijal area along the Indus River (Figure 1.2; Jan and Howie 1980; Miller et al. 1991). At its base (Jijal and Sapat sections), it comprises ultramafic to mafic rocks composed predominantly of clinopyroxene-rich lithologies (pyroxenite, wherlite and websterite) with subordinate harzburgite, dunite and garnet-gabbros. Amphibole becomes more important up section. Despite the granulite grade metamorphism, original igneous textures and structures are prevalent. The upper section of the complex (Kamila or Southern Amphibolite) consists of a 15–35 km thick pile of sheet-like intrusions composed of gabbros and diorites with subordinate tonalities, granites and trondhjemites. The Southern Plutonic Complex is characterized by originally horizontal sheet-like and lens-like intrusions. The mineral assemblages indicate pressures ranging from 1.5–1.8 GPa at the base of the complex to 0.7 GPa at the top. Zircon

U–Pb ages on zircons indicate that the complex was formed from ~118 to 85 Ma (Schaltegger et al. 2002; Dhuime et al. 2007; Bosch et al. 2011).

1.4.2. *Chilas Complex*

The mid-crustal Chilas Complex is mainly composed of gabbro(-norite) associated with mafic–ultramafic intrusions and minor diorites (Jagoutz et al. 2006, 2007). Tabular bodies of ultramafic rocks are sparce and are dominated by dunite with minor websterite and pyroxenite. Amphibole is generally absent or appears as a late magmatic phase. The mineral assemblage records formation pressures of ~7 kbar (Jagoutz et al. 2007). The Chilas Complex formed at ~85 Ma (Schaltegger et al. 2002). It is believed to have formed during intra-arc extension and to represent a relatively dry fractionation sequence distinct from the wet differentiation sequence recorded by the Southern Plutonic and Gilgit Complex (Jagoutz et al. 2011).

1.4.3. *Gilgit Complex and Kohistan Batholith*

The Gilgit Complex represents the mid- to upper arc crust, and is dominated by the calc-alkaline Kohistan Batholith, which makes up the northern two-thirds of the Kohistan block, and is equivalent to most of the Ladakh side. The volcanic units range from basalt to rhyolite (Petterson and Treloar 2004), while mafic basaltic to andesitic compositions predominate, alternating with marine volcanic breccia and limestones representing a marginal basin arc environment, like in northern Ladakh (Rolland et al. 2000).

The Kohistan Batholith range in compositions from rare gabbro through diorite, tonalite, granodiorite and granite. Amphibole is present in most batholith rocks, when pyroxene is rare. The batholith comprises numerous individual plutons, stocks, sheets and dykes ranging in size from a few meters to 5–15 km in diameter. Many plutons are compositionally heterogeneous at outcrop scale (Petterson and Windley 1985). Diorite dykes are common in the deeper part of the batholith in the south, when aplite-pegmatite to leucogranite sheets are abundantly close to the Nanga Parbat syntaxis (Petterson and Windley 1985; Jagoutz and Schmidt 2012). Emplacement pressure estimates based on amphibole barometry increase from < 2 kbar in the NW to ~8 kbar in the SE and are influenced by the presence of the Nanga Parbat syntaxis

(Jagoutz 2014). U–Pb zircon ages indicate that the magmatic activity began at least ca. 112 Ma and lasted ca. 28 Ma, with the bulk of the batholith emplaced between 85 and 40 Ma (Jagoutz et al. 2009; Bouilhol et al. 2013).

1.4.4. *Ladakh Batholith*

The Ladakh Batholith is composed of calc-alkaline intrusions with compositions varying from noritic gabbro to granite (Honegger et al. 1982; Debon et al. 1987; Ahmad and Islam 1998; Rolland et al. 2000; Weinberg and Dunlap 2000; Singh et al. 2007; White et al. 2011). Vast hornblende-biotite granodiorite occurs as the main rock type with regional strike of NW-SE and steep dips towards north. Remnants of dioritic and gabbroic bodies intruded by the granodiorite are seen in the southern parts while ascending to Khardung La. Aplitic veins intruding the main mass are common, while numerous dolerite dikes cut across the granodioritic mass and show chilled contact. Light colored exposures of granite and leucogranite are also observed locally. The Ladakh Batholith is largely undeformed. A diffuse deformation zone with an intense penetrative ductile shear fabric has nevertheless been observed by Weinberg and Dunlap (2000) within the NNW-trending dextral Thanglaso Shear Zone north of Leh. Biotite-rich enclaves that are possible remnants of biotite schist are found in alternation with marble in the central part of the batholith (Rolland et al. 2000), and may be remnants of volcano-sedimentary series. Based on different geochronometers, the batholith dates back to as early as 102±2 Ma (Schärer et al. 1984) with the most recent magmatic activity to approximately 46 Ma (Figure 1.3) (Honegger et al. 1982; Weinberg and Dunlap 2000; White et al. 2011). Emplacement pressure estimates based on amphibole barometry increase from 2 kbar in the north to ∼7 kbar in the south (Singh et al. 2007; Reubi and Müntener 2022).

To the north, the Ladakh Batholith shows unconformable relationships with the younger (Cenozoic) Khardung Volcanics, which are mainly rhyolite, andesite, agglomerate, gravelly sandstone and conglomerate intercalations (Rolland et al. 2000; Lakhan et al. 2020). To the southwest, the batholith emplaced into an unmetamorphosed thick pile of basic and acid volcanics (Dras Volcanics). To the southeast, it is covered by a vast alluvium of the Indus River.

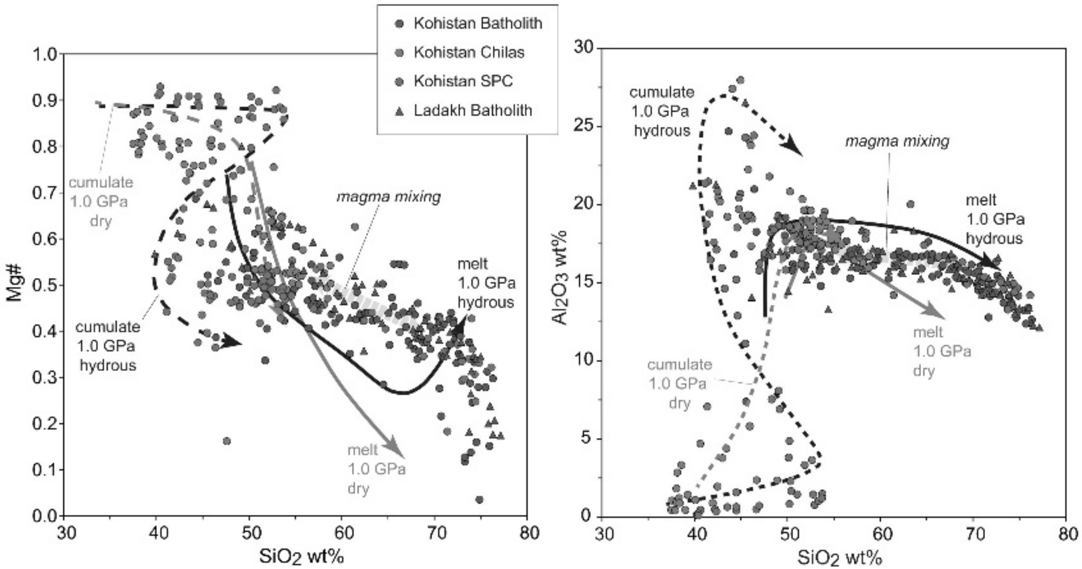

Figure 1.4. *Harker diagrams illustrating the different fractionation trends for the plutonic rocks from the Southern Plutonic (SPC), Chilas and Batholith complexes in Kohistan and the Ladakh Batholith. The black arrow represents the compositional evolution of the melts from hydrous fractional crystallization experiments at 1.0 GPa (data from Ulmer et al. 2018), when the dashed black arrow represents the evolution of the cumulates in these experiments. The gray arrow shows the melt evolution and the gray dashed arrow the cumulate evolution in anhydrous fractional crystallization experiments at 1.0 GPa (data from Villiger et al. 2004). The dashed yellow double arrow shows an arbitrary mixing trends producing the andesitic magmas through mixing between the mafic and silicic magmas produced by high-pressure hydrous fractional crystallization. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

1.5. Geochemistry and magmatic evolution of Kohistan–Ladakh magmas

According to their texture and geochemistry, plutonic rocks can be divided into two broad types; plutonic rocks with near melt chemical compositions and cumulates formed by the accumulation of mineral with some remaining melt. The plutonic rocks from the Southern Plutonic Complex mostly represent cumulate compositions, when the plutonic rocks from the Kohistan–Ladakh Batholith are, for the majority, representative of melt compositions (Figures 1.4 and 1.5) (Jagoutz et al. 2011; Jagoutz 2014).

The melt representative plutonic rocks follow a calc-alkaline fractionation trend, and incompatible trace elements are enriched compared to average mid-ocean ridge basalts (MORB) and depleted in high field strength elements (HFSE) compared to large ion lithophile elements (LILE), as typical for subduction zone magmatism. Based on their geochemistry, the melt representative plutonic rocks can be divided into two differentiation series: those from the Chilas Complex are characterized by a more drastic increase in incompatible elements (e.g. K_2O) over a given silica-enrichment compared to the Kohistan–Ladakh Batholith rocks (Figure 1.6) (Jagoutz et al. 2011). A comparison with melt compositions obtained experimentally demonstrates that these series results from distinct high-pressure fractionation trends, a relatively dry fractionation sequence of olivine–clinopyroxene–orthopyroxene–plagioclase–amphibole in the Chilas case, and a hydrous sequence of olivine–pyroxenes–garnet–Fe/Ti–oxide–amphibole–plagioclase for the Kohistan–Ladakh Batholith (Figure 1.4) (Jagoutz et al. 2011).

Furthermore, the Southern Plutonic Complex cumulates are mineralogically and geochemically similar to the cumulates produced experimentally by the fractional crystallization of hydrous mafic melts at high pressure, when the Chilas cumulates are equivalent to cumulates of dry high-pressure experiments (Figure 1.4) (Müntener and Ulmer 2018; Jagoutz et al. 2019).

These observations support the inference that the Chilas magmas were produced by decompression-melting during intra-arc extension and represent a relatively dry fractionation sequence distinct from the predominant wet differentiation sequence recorded by the Southern Plutonic Complex and the

Kohistan–Ladakh Batholith (Jagoutz et al. 2011). In addition, this indicates that the cumulates from Southern Plutonic Complex are complementary to the differentiated magmas from the batholith. Overall, the Kohistan magmatic arc section demonstrates that the bulk of differentiation that produced the silicic magma ubiquitous at mid- to upper-crust depths occurred predominantly by fractional crystallization in the lower crust ($\geq$ 30 km) (Figure 1.5). The geochemistry of batholith rocks requires nevertheless that a lesser amount of differentiation occurred as these magmas were ascending through the mid- to upper-crust (Reubi and Müntener 2022).

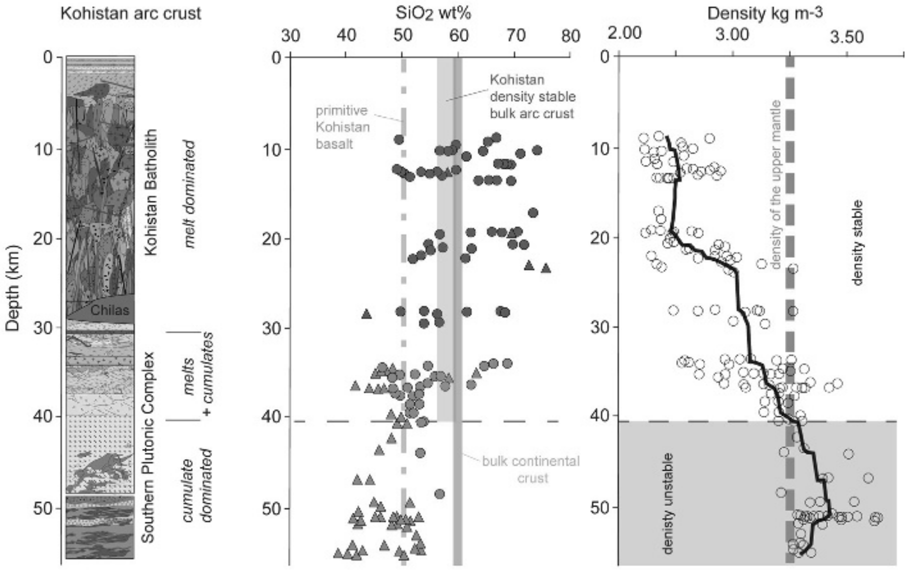

Figure 1.5. *Variation of bulk-rock SiO_2 contents and melt or cumulate density versus intrusion depth inferred from amphibole barometry pressure [modified from Jagoutz and Behn (2013)] and Jagoutz (2014). Triangles indicate plutonic rocks with near liquid chemical composition, and circles indicate cumulate rocks. The gray dashed line indicates the average composition of Kohistan primitive arc volcanics (after Jagoutz 2010). The light red box represents the volumetrically pondered average composition estimated for the density stable section of the Kohistan arc crust (after Jagoutz and Schmidt 2012). The orange line shows the compositional estimate for the bulk continental crust from Rudnick and Gao (2003). The details for the melt/cumulate density calculation can be found in Jagoutz and Behn (2013). For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

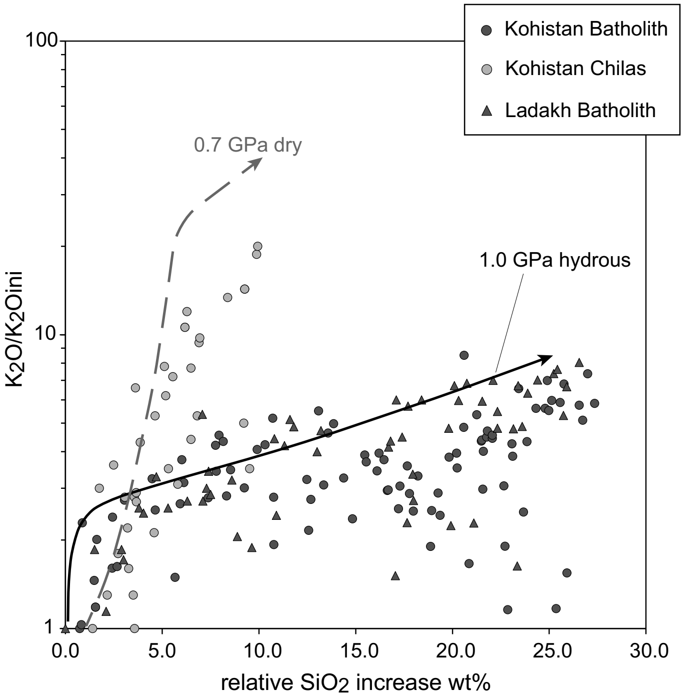

Figure 1.6. *Compositional evolution of the Chilas and Kohistan–Ladakh rocks representative of melt compositions compared to experimental melts from hydrous and anhydrous high-pressure fractional crystallization [experimental data from Villiger et al. (2004) and Ulmer et al. (2018). All data are normalized to the K_2O and SiO_2 contents in the least differentiated magmas/melt in each series. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

1.5.1. *Inferences for juvenile continental crust construction*

The Kohistan–Ladakh nearly complete crustal arc section provides unprecedented insights into the possible mechanisms that yield an andesitic (~60 wt% SiO_2) continental crust in oceanic arcs. In Kohistan, like in most arcs, primitive hydrous basalts produced by melting of the metasomatized mantle wedge have a broadly basaltic composition with approximately 50 wt% SiO_2 (Jagoutz 2014; Reubi and Müntener 2022). Crystallization of these compositions in the lower crust (at pressures of 1.5–0.7 GPa) produces, on one hand, garnet- and/or amphibole-rich cumulates that have a density exceeding the density of upper mantle peridotites, and, on the other hand, less dense silicate rich melts (Figure 1.5). Foundering of the silicate-poor and gravitationally unstable cumulates in the mantle leaves by mass balance a silicate-enriched crust. (Jagoutz and Schmidt 2012) estimated the average composition of the density stable crustal section in Kohistan to have an andesitic composition similar to the bulk continental crust estimates with SiO_2 of 56.6–59.3 wt% (Figure 1.5). Foundering of lower island-arc crust appears as a plausible mechanism to produce andesitic crust from primitive basaltic melts (Jagoutz and Behn 2013). The Kohistan–Ladakh arc is thus an example of how the continental crust can be derived from mantle melting in subduction zones, and argues for a progressive construction of continental crust through geological times.

In addition, the Kohistan–Ladakh magmatic section illustrates how magmatic differentiation can yield a chemically stratified crust with a predominately mafic lower crust and a differentiated but essentially bimodal upper crust. Interestingly, andesitic magmas with a composition similar to the bulk continental crust are rare in the density stable part of the section (Figure 1.5). This warrants caution against models arguing for derivation of the continental crust by primary magmatic processes (e.g. Kelemen 1995; Hacker et al. 2011) and rather indicates the importance of mass balance between the upper and lower crusts (Reubi and Müntener 2022).

1.5.2. *Isotopic composition, inferences on the mantle source and crustal assimilation, and implications for the timing of collisions*

The isotopic compositions of the Kohistan–Ladakh arc rocks results to εSr (–4 to –6) εHf (11.4–12.5), εNd (4.8–5.0), $^{208/204}$Pb (38–39), $^{207/204}$Pb (15–16) and $^{206/204}$Pb (18–19) (Khan et al. 1997; Rolland 2002; Jagoutz and Schmidt 2012; Bouilhol et al. 2013; Jagoutz et al. 2019), which is more evolved than modern pacific intra-oceanic arcs. These isotopic compositions fall within the range of DUPAL anomaly, which led Khan et al. (1997) to propose the derivation from mantle in the South Indian Ocean, where this anomaly is present. However, this evolved isotopic composition could also represent the involvement of a crustal component such as a continental basement or $<10\%$ of pelagic sediments (Rolland 2002; Bouilhol et al. 2013; Jagoutz et al. 2019). The depleted mantle component of the source is considered to be paleo-Tethyan MORB-type mantle (Khan et al. 1997) with isotopic signatures similar to the present-day Indian MORB-type mantle (Mahoney et al. 1998). Hf isotopes and U–Pb ages from single zircons, as well as bulk-rock Nd isotopes show a steady evolution to isotopically enriched compositions (decreasing εHf and εNd values) from 154 Ma to 50 Ma (Figure 1.7).

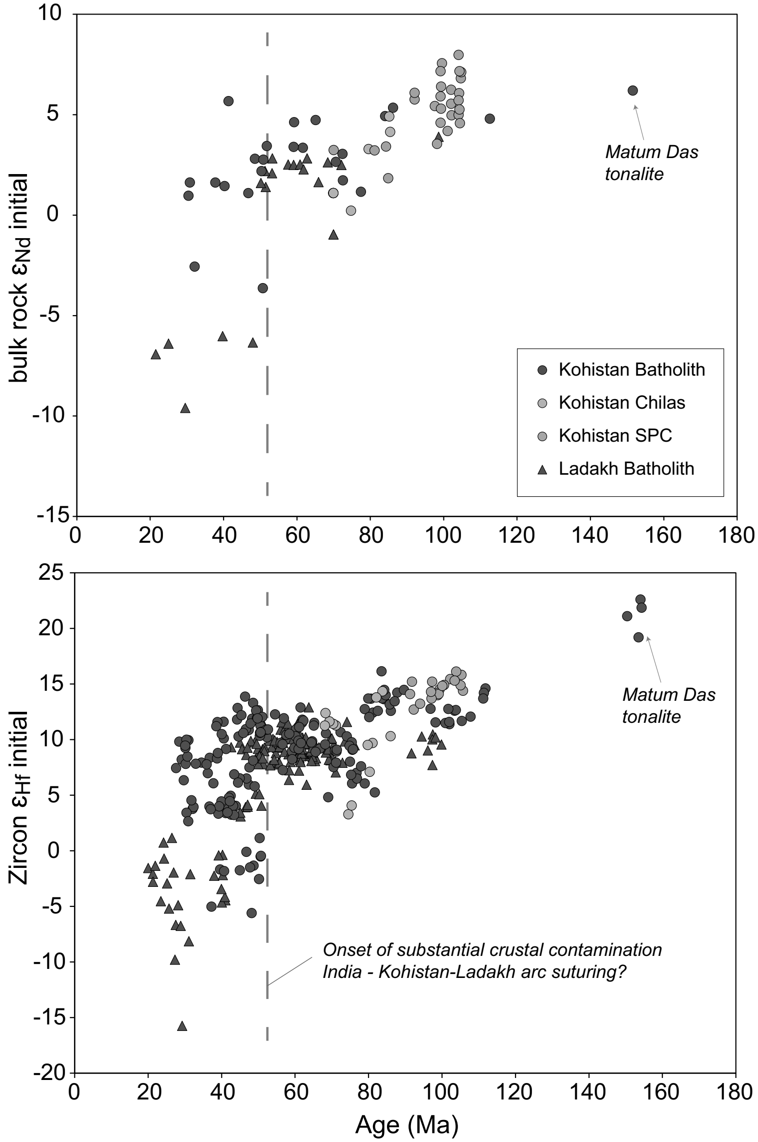

Figure 1.7. *Hf isotopes from single zircons and bulk-rock Nd isotopic compositions as a function of U–Pb zircon ages of plutonic rocks from the Kohistan–Ladakh arc (data are from Schaltegger et al. 2002; Heuberger et al. 2007; Bouilhol et al. 2011, 2013; Jagoutz et al. 2019). For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

This temporal trend is concomitant with bulk-rock increases in εSr, $^{208/204}$Pb, $^{207/204}$Pb and $^{206/204}$Pb (Jagoutz et al. 2019), suggesting an increasing influence of the sediment component issued from the subducting slab. The implications of that still need to be assessed and could indicate either an increase in the volume of the subducted sediments, an increase in the subduction flux, an increasing influence of terrigenous sediments or changes in the thermal state of the slab. Marked shifts to negative εHf and εNd values translating substantial crustal contamination of the arc magma source are only recorded after 50 Ma (Figure 1.7). These data argue for the collision between India and the Kohistan–Ladakh arc at 50Ma (Bouilhol et al. 2013).

Based on an apparent diachronic record of the shift to substantial crustal contamination between the south and the north of the Ladakh Batholith, Bouilhol et al. (2013) further suggested that the collision between the arc and India occurred first at 50 Ma along the Indus suture and that the final collision with Eurasia along the Shyok occurred at 40 Ma.

1.6. Tectonic reconstructions of Kohistan–Ladakh arc evolution

Based on the work and discussions of Andjić et al. (2022), tectonic reconstructions are proposed for the Kohistan–Ladakh arc, which is here assumed to be continuous with the Dras arc (KLD arc). Two hypotheses can be proposed (Figures 1.8 and 1.9): either (1) a south-dipping intra-oceanic subduction zone (scenario 1) or (ii) a north-dipping intra-oceanic subduction zone (scenario 2).

1.6.1. *Scenario 1: south-dipping subduction zone*

Arc continent accretion along the Shyok suture zone occurred either during the middle Cretaceous (e.g. Rolland 2002; Borneman et al. 2015) or the Eocene (e.g. Bouilhol et al. 2013; Martin et al. 2020). A Cretaceous age for the Shyok suture is in agreement with the inferred lateral correlation between the Shyok and the Cretaceous Bangong suture in Tibet. In this scenario, these sutures were formed by the southward subduction of an ocean that was bounded to the south by the Kohistan–Ladakh–Dras arc in continuity with the Lhasa Terrane (Gangdese Batholith) (scenario 1 in Figure 1.8). A subduction onset in the Jurassic is also argued for beneath the Lhasa Terrane (e.g. Zhu et al. 2009).

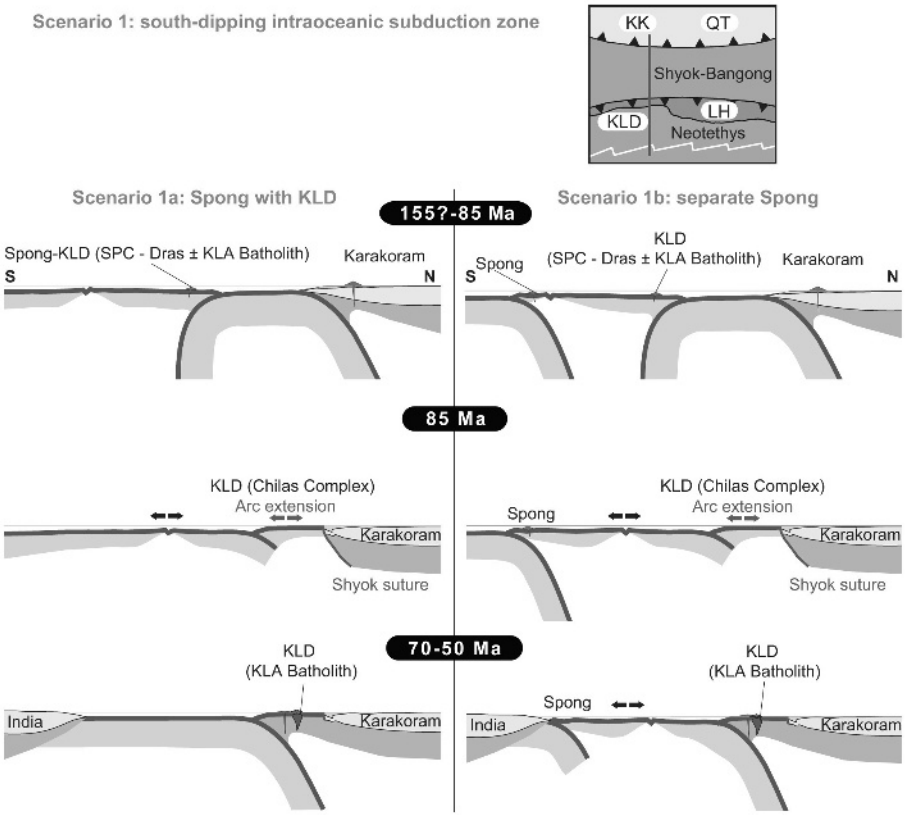

Figure 1.8. *Proposed scenario for Mesozoic tectonic evolution of the Kohistan–Ladakh–Dras (KLD) arc (after Andjić et al. 2022, modified). Scenario 1: the Kohistan–Ladakh–Dras arc formed along a south-dipping intra-oceanic subduction zone and was laterally continuous with the Lhasa Terrane (LH) to the east. The Spong arc may or may not be part of the same convergent margin as the Kohistan–Ladakh–Dras arc. 180–160 Ma=Early to Late Jurassic; 140 Ma=Early Cretaceous; 125 Ma=Early Cretaceous; 100–80 Ma=Late Cretaceous. KK=Karakoram; LH=Lhasa; SDLK=Spong–Dras–Ladakh–Kohistan; QT=Qiangtang. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

Tectonic accretion of the Kohistan–Ladakh–Dras arc to Eurasia during the Early Cretaceous is evidenced by a magmatic lull in those arcs and in the Karakoram margin (ca. 140–120 Ma) (Searle et al. 1989; Heuberger et al. 2007; Borneman et al. 2015; Searle and Hacker 2019). A possible re-start of magmatic activity was then triggered by the onset of northward subduction in the mid-cretaceous, evolving by roll-back towards intra- and back-arc basins (Rolland et al. 2000; Rolland 2002; Robertson and Collins 2002). Initiation of a southward intra-oceanic subduction along the KLD arc and away from the northern margin of India is supported by the accretion of Upper Permian seamounts to the Spong arc in post-Campanian times (Reuber et al. 1987; Corfield and Searle 1999).

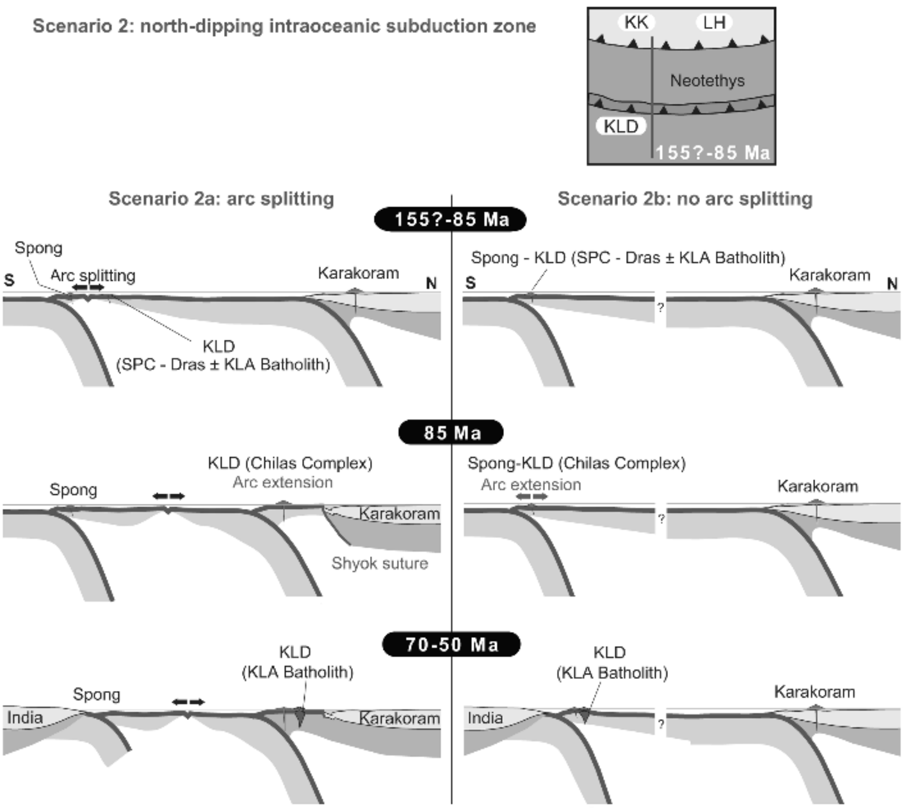

Figure 1.9. *Proposed scenario for Mesozoic tectonic evolution of the Kohistan–Ladakh–Dras (KLD) arc (after Andjić et al. 2022, modified). Scenario 2: the Kohistan–Ladakh–Dras formed along a north-dipping intra-oceanic subduction zone. Subduction initiation may have occurred as early as the Early Jurassic along a Neotethyan mid-ocean ridge. Pre-Late Jurassic accretion of Lhasa to Eurasia is assumed in scenario 2. 180–160 Ma=Early to Late Jurassic; 140 Ma=Early Cretaceous; 125 Ma=Early Cretaceous; 100–80 Ma=Late Cretaceous. KK=Karakoram; LH=Lhasa; SDLK=Spong–Dras–Ladakh–Kohistan; QT=Qiangtang. For a color version of this figure, see www.iste.co.uk/cattin/himalaya2.zip*

1.6.2. *Scenario 2: north-dipping subduction zone*

A simpler scenario of north-dipping subduction zones with accretion of an intra-oceanic KLD arc to the Karakoram during the Early Cretaceous may also agree with a Cretaceous age for the Shyok suture. In this scenario, the KLD arc drifted northward from a position within the Neotethys and the Lhasa Terrain had previously accreted to Eurasia (scenario 2a in Figure 1.9).

The observation that Lhasa-type and Eurasia-type zircons were transported to the Kohistan–Ladakh–Dras arc by the middle Cretaceous (Andjić et al. 2022) supports this scenario. It would require, however, a correlation of the Lhasa and Karakoram Terranes (e.g. Yang et al. 2017; Robinson 2009). Alternatively, a post-Cretaceous accretion of the KLD arc to the Karakoram Terrane along the Shyok suture would imply that the KLD arc remained in an intra-oceanic arc position until the Paleocene (e.g. Jagoutz et al. 2019; Bouilhol et al. 2013) (Figure 1.9, scenario 2b). The absence of a continent or a continental fragment in the vicinity of the KLD subduction zone makes, however, this scenario the least likely solution, because Lhasa- and Eurasia-type zircons were found together in the KLD arc by the middle Cretaceous by Andjić et al. (2022). Furthermore, the inferred Paleocene latitude of the KLD arc, a key argument to support an intra-oceanic position, is based on a single paleomagnetic pole, and is thus still ill-defined.

1.7. Conclusion

The Kohistan–Ladakh arc represents the better-preserved and most complete crustal arc section on Earth. Obduction of the arc onto the Indian margin to the south led to the uplift of the lower crustal section of the arc, while accretion to the Asian margin to the north exhibits a tectonic melange of diverse marginal arc units. This whole geological object provides valuable information on the processes of differentiation of a magmatic intra-oceanic arc and for the creation of juvenile continental crust. In addition, the Kohistan–Ladakh and Dras arcs witness the pre-collisional stages of India–Asia convergence, a necessary input for any precise reconstruction of the Himalayan orogeny (see Volume 1 – Chapter 1).

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