From intra-oceanic convergence to post-collisionnal evolution: the India-Asia convergence in NW Himalaya, from Cretaceous to present

Y. Rolland

LGCA-LGIT, UPRES-A5025 CNRS - Université J. Fourier, Maison des Géosciences, BP 53, 38041 Grenoble, France
now at: Department of Geology, Australian National University, Canberra, A.C.T. 0200, Australia

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Abstract: The NW part of the Himalayan Orogen (Kohistan, Ladakh and Karakoram, in Pakistan and India) has been investigated to reconstruct the successive stages of convergence of two continents (India and Asia) over the past 110 Ma, from oceanic to post-collisional settings. The intra-oceanic stages of the convergence have been reconstructed from study of the preserved Tethyan Arc series of the Kohistan-Ladakh Terrane. Geochemical and lithological data indicate continuation of the Kohistan intra-oceanic arc in the west into an Andean arc on the Tibetan continental margin in the east. Adakitic and Nb-Ta-Ti rich lavas appear to be present, interlayered with basalts to andesites in the intra-oceanic arc series. Along with major, trace and isotopic (Sr, Nd and Pb) data of basalt to andesite lavas, adakitic magmatism suggests complex interactions between crustal melts and mantle. In the tectonic context of the Neo-Tethys Ocean at 110 Ma, the Kohistan-Ladakh Arc system may have formed following the subduction of the Neo-Tethys mid-oceanic ridge, similar to a model which has been proposed for the initiation of Oman ophiolite obduction. This ocean-ridge subduction could be triggered by the initiation of fast northward drift of India in the Middle Cretaceous period.

The post-collisional evolution comprises two stages: 1. A phase of crustal thickening by SW nappe stacking in a NE-SW shortening context, associated with Barrovian-type metamorphism (650°C, 10 kbar) between 60 and 37 Ma. 2. A phase of ongoing north-south shortening, characterised by tectonic partitioning between: a. An E-W band of domes that crosscuts the former structures, in a N-S shortening and vertical extrusion context, linked to HT granulite facies metamorphism (800°C, 6 kbar) and magmatism showing mantle affinities, formed during the last 20 Ma. This granulite grade metamorphism could be linked to advective heat input from the asthenosphere due to detachment of the Indian slab by 20 Ma. b. The Karakoram strike-slip fault, which accommodates the lateral extrusion of Tibet. Granulites exhumed within the fault zone suggest that it could be a lithospheric-scale fault, with a total dextral offset of approximately 300 km deduced from correlation between the Lhasa and Karakoram blocks.

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Introduction

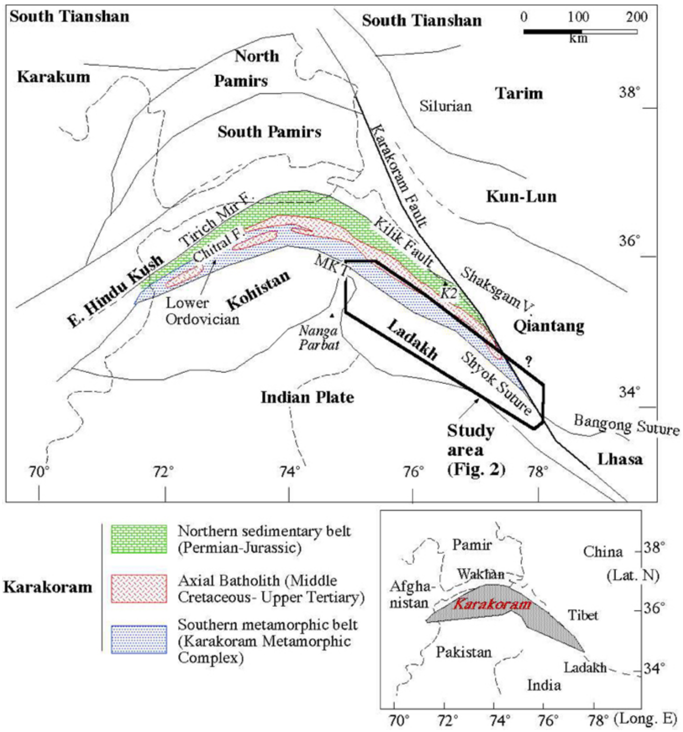
The Himalayan Orogen is one of the classic example of continent-continent collision (e.g., Argand, 1924; Dewey & Bird, 1970; Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1976), characterised by a high convergence rate of 5 $cm.yr^{-1}$ currently ongoing (Patriat & Achache, 1984; Klootwijk et al., 1992). The NW part of the orogen (NW Syntaxis) is made up of terranes formed during the intra-oceanic (Tethyan) stages of the India-Asia convergence (Ladakh and Kohistan terranes), as well as terranes largely deformed and metamorphosed during the Himalayan orogeny (Karakoram and Indian margins). For this reason, the NW Syntaxis is a key area to reconstruct the various steps of convergence of the Indian and Asian continents, since about 120 Ma.

In this paper, after a brief summary of observations and bibliography on the pre-Himalayan history of the NW Himalaya, followed by a review of our present understanding of the India-Asia convergence in NW Himalaya, we propose a tectonic reconstruction of India-Asia convergence for that part of the chain. This reconstruction is based on the compilation of structural, geochemical and metamorphic data from the area. The intra-oceanic phase of convergence is deduced mainly from the petro-geochemistry of the arc lavas (Rolland et al., 2000; 2002a); while the post-collisional phase is constrained by structural, metamorphic, magmatic and chronological data (Rolland, 2000; Rolland & Pêcher, 2001; Rolland et al., 2001, accepted; Mahéo et al., 2002).

Pre India-Asia convergence history (>110 Ma)

Several major fault zones north of the Himalayan Orogen bound tectonic blocks already sutured before the India-Asia convergence (Pozzi et al., 1972; Burg, 1983; Allègre et al., 1984; Sengör, 1984; Dewey et al., 1988; Matte et al., 1986). Most of these blocks are of small size, probably originating from the break-up of Gondwanaland in the Early Palaeozoic (Bond et al., 1984). They were progressively accreted from then on, contributing to the growth of the Asian (Laurasian) margin southwards (Allègre et al., 1984; Matte et al., 1996). In Early Palaeozoic, Altaids were accreted to the Siberian Platform (Burret, 1974; Burret et al., 1990), the Kunlun-Qinling blocks were accreted in the Silurian. Following the formation of the Siberian Craton, three successive cycles of accretion can be distinguished (Sengör, 1984; 1987; Sengör et al., 1993; Van der Voo, 1993, Klootwijk, 1996): (1) Variscan, (2) Cimmerian and (3) Alpine. The Variscan cycle is mainly concerned with the Tarim block in the Late Carboniferous-Permian (Sengör, 1987). The Cimmerian cycle corresponds to the break-up of the Cimmerian continent (CC) from the Gondwana margin, which began in the Late Permian and was complete during the Triassic (Sengör et al., 1988). At this stage, Panjal trap volcanism occurred in the northern part of the Indian margin (Honnegger et al., 1982), as well as in the Karakoram block (Rolland et al., accepted), possibly associated with the opening of the Neo-Tethys Ocean andthe separation of the Karakoram / Lhasa blocks from India. Following Sengör et al. (1988), the CC is complex. It extends in an E-W direction, comprising two parallel strips of continent separated by a small ocean, the Tangulla-Waser Ocean. The northern continental strip of the CC comprised the north Tibetan (or Qiantang) block in the west and the north China block in the east. The southern continental strip of the CC comprised the south Tibetan (or Lhasa) block in the west and the south China block in the east. The northward progression of the CC lead to the subduction of the Palaeo-Tethys Ocean along the southern margin of the Tarim block and to the formation of the Neo-Tethys Ocean between the CC and the Gondwana margin (Sengör, 1984). The closure of the Palaeo-Tethys Ocean and the suturation of the CC occurred between Middle Triassic and Early-Middle Cretaceous (Sengör, 1984; Van der Voo et al., 1999; Zanchi et al., 2000). The Qiantang Block was accordingly accreted along the Kilik suture during the Late Triassic (e.g., Matte et al., 1996; Fig. 1), while the Lhasa block was fully sutured along the Bangong suture in Lower-Middle Cretaceous after closure of the Tangulla-Waser Ocean (Besse et al., 1984; Sengör et al., 1988; Zanchi et al., 2000).

Figure 1. Schematic map of the Pamir-Karakoram-NW Himalaya syntaxis, with location of principal tectonic blocks and sutures



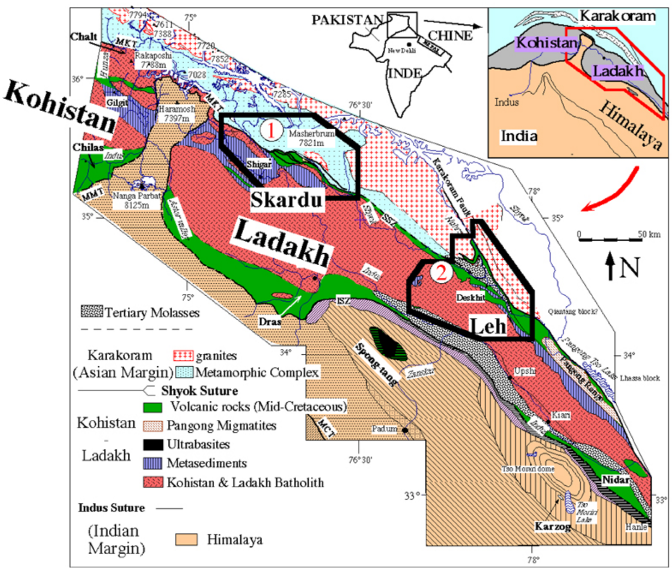
The main geological units of the Karakoram are shown. The location of the study area is indicated. MKT: Main Karakoram Thrust.

Our study in the SE Karakoram region of Skardu has shown that the south Karakoram Series are part of Cambro-Ordovician sequences overlying a Precambrian basement (Rolland et al., 2002b). Such successions have also been described by Le Fort et al. (1994) in SW Karakoram, and confirm continuity of the Karakoram block, with similar geological formations along its southern rim and on its northern part (Gaetani, 1996; Gaetani et al., 1996; Zanchi et al., 1997). Similar successions, comprising Cambro-Ordovician series overlying Cambrian gneisses, have also been described in the Lhasa block (Xu et al., 1985; Yin et al., 1988). These similarities suggest that the Karakoram may be an original part of Lhasa block later offset by the Karakoram Fault (Rolland et al., 2002b). The Early Cretaceous accretion of the Karakoram-Lhasa block was followed by that of the Kohistan-Ladakh Arc terranes in Late Cretaceous (Petterson & Windley, 1985). The India-Asia collision and Himalayan orogeny are therefore part of a long accretion history, originating in the Palaeozoic.

Review of our present understanding of the India-Asia convergence in NW Himalaya

The NW Syntaxis is made up of oceanic units (Kohistan-Ladakh) amalgamated between the Indian and Asian (Karakoram) continental margins. The Kohistan-Ladakh terrane is characterised by remnants of intra-oceanic arc magmatic rocks (Fig. 2) formed during Middle Cretaceous times. These magmatic rocks range in age from 110 to 90 Ma, based on radiometric data obtained both in Ladakh (Honegger et al., 1982; Schärer et al., 1984) and Kohistan (Treloar et al., 1989; Mikoshiba et al., 1999; Schältegger et al., 2000) and from palaeontological data (Desio, 1974; Tahirkeli, 1982; Dietrich et al., 1983; Pudsey, 1986; Reuber, 1989). These oceanic terranes are mainly remnants of arc-series reflecting intra-oceanic subduction of the Neo-Tethys. Different interpretations have been proposed for the polarity of subduction; north-dipping along the southern margin of the Asian continent (e.g., Tahirkeli et al., 1979; Bard et al., 1980; Honegger et al., 1982; Dietrich et al., 1983; Reuber, 1989; Khan et al., 1989; 1993; Petterson & Windley, 1991; Treloar et al., 1996), or south-dipping along the northern side of the Indian continent (Reynolds et al., 1983; Khan et al., 1997).

Figure 2. Geological sketch map of the NW Himalaya-Karakoram region

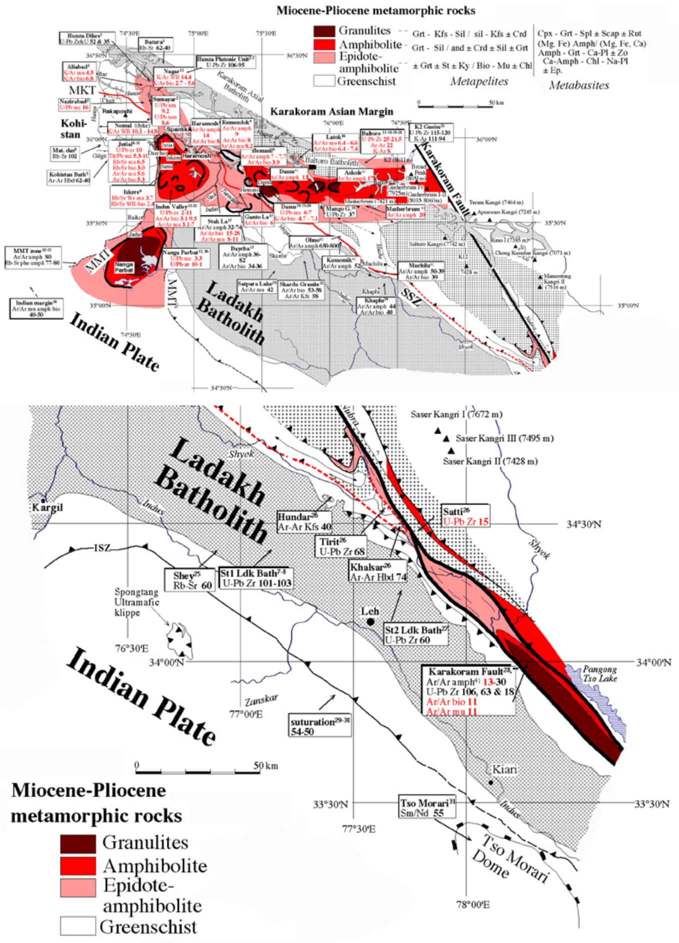


1, area investigated in Ladakh-Karakoram geological areas (Skardu, Pakistan); 2, area investigated in Ladakh and Karakoram Fault areas (Leh, NW India).

These terranes were subsequently accreted to the Asian margin during the Late Cretaceous (80 to 88 Ma, Petterson & Windley, 1985, Weinberg et al., 2000), along the Shyok (or Northern) Suture Zone (SSZ, Fig. 2), which separates them from the Karakoram margin of Asia, as summarised below. In Kohistan, this northern suture was reactivated along an out-of-sequence thrust: the Main Karakoram Thrust (MKT; Pudsey, 1986). Between 65 and 55 Ma, during the initial phase of the India–Asia continental collision, the Kohistan-Ladakh Arc was obducted onto the Indian margin along the Main Mantle Thrust (MMT, Tahirkheli et al., 1979), or Southern Suture, which is believed to be the western prolongation of the Indus-Tsangpo suture zone in Tibet. South of the MMT, southwards thrusting in the Indian margin gave rise to the Himalayan chain (e.g., Treloar and Rex, 1990). North of the Shyok suture, thickening of the Asian margin gave rise to the Karakoram Range. The central part of the Karakoram terrane is comprised of the NW-SE striking composite calc-alkaline Karakoram Batholith, emplaced between 120 and 88 Ma in response to northwards subduction of Tethyan oceanic crust (Debon et al., 1987; Searle et al, 1989). Between 80 and 37 Ma (M1 event), collision of the Karakoram terrane with the Kohistan-Ladakh terrane, and subsequently with India, has produced SW-directed nappe stacking and Barrovian-type metamorphism (Bertrand et al., 1988; Searle et al., 1989; Hanson, 1989; Allen & Chamberlain, 1991; Lemennicier et al., 1996; Rolland et al., 2001). This M1 event is characterised by NW-SE foliation and metamorphic isograds ranging from lower greenschist in the SW to amphibolite facies in the NE.

The Miocene to Pliocene evolution of the NW Syntaxis is characterised by intense deformation, metamorphism and magmatism, in particular in the Nanga Parbat-Haramosh (NPH) massif, in the Southern Karakoram margin and along the Karakoram Fault (Figs. 2-3).

Figure 3. Repartition of radiochronological ages with respect to metamorphic grade in the NW syntaxis (A, Pakistan side; B, Indian side)



Ages written in red are less than 25 Ma. Note the good correspondence between young ages and high grade metamorphism. Abbreviations used: ISZ: Indus Suture Zone; MMT: Main Mantle Thrust; MKT: Main Karakoram Thrust; amph: amphibole; and: andalusite; bio: biotite; Cord: cordierite; Ep: epidote; Grt: garnet; Scap: scapolite; Sil: sillimanite; Spl: spinel; Kfs: K-feldspar; mu: muscovite; mz: monazite; phe: phengite; pl: plagioclase; sp: sphene; St: staurolite; ura: uraninite; WR: whole-rock; xen: xenotime; Zo: zoisite; Zr: zircon. References cited: 1: Debon (1995); 2: Fraser et al. (2001); 3: Le Fort et al.. (1983), 4: Villa et al. (1996a); 5: Treloar et al. (1989); 6: Petterson & Windley (1985); 7: Honegger et al. (1982); 8: Schärer et al. (1984); 9: George et al. (1995); 10: Schneider et al. (1997); 11: Debon et al. (1987); 12: Zeitler & Williams (1988); 13: Zeitler et al. (1993); 14: Smith (1993); 15: Smith et al. (1992); 16: Schärer et al. (1990); 17: Villa et al. (1996b); 18: Parrish and Tirrul (1989); 19: Debon et al. (1986); 20: Searle et al. (1989); 21: Searle et al. (1990a); 22: Treloar et al. (1991); 23: Brookfield and Reynolds (1981); 24: Reynolds et al. (1983); 25:

Honegger (1983); 26: Weinberg et al. (2000); 27: Weinberg & Dunlap (2000); 28: Searle et al. (1998); 29: Garzanti and Van Haver (1988); 30: Searle et al. (1990b); 31: de Sigoyer et al. (2000); 32: Maluski and Matte (1984); 33: Anczkiewicz et al. (1998); 34: Treloar and Rex (1990); 35: Maluski and Schaëffer (1982); 36: Zeitler (1985); 37: Zeitler and Chamberlain (1991); 38-39: Smith et al. (1992, 1994); 40: Winslow et al. (1996); 41: Rolland (2000); 42: Rolland et al. (accepted).

The NPH massif is a N-S elongated structural window of Indian crust uplifted through its Kohistan-Ladakh cover. In this window, elevations are very high, locally over than 8000 m (Nanga Parbat), in contrast with the main part of the NW Himalayan chain. These elevations coincide precisely with young plutonic and high-grade rocks (10^{-1} Ma, U-Pb on zircon, Zeitler et al., 1993; Chamberlain and Zeitler, 1996, Schneider et al., 1997; 2001), suggesting very high uplift rates of up to 7 mm yr^{-1} (Zeitler et al., 1982; 1993). The NPH spur is regarded as a huge transverse anticline produced by shortening parallel to the strike of the belt, in response to deformation partitioning related to oblique India-Asia convergence (Seeber and Pêcher, 1998; Treloar et al., 1991).

In the Karakoram margin, the previously described M1 structures are crosscut by post-20 Ma (M2) structural, metamorphic and magmatic features. The NW-SE foliation is crosscut by the Mango Gusor granite dated at c. 37 Ma, and by the W-E striking, Baltoro granite dated at 21-25 Ma (U-Pb on zircon by Parrish and Tirrul, 1989; Schärer et al., 1990). M2 metamorphic peak temperature and subsequent doming coincided with granitic intrusions which have occurred all along the southern part of the Karakoram Terrane (e.g. Aliabad granite, 6.8 Ma, K-Ar on biotite, Le Fort et al., 1983, Sumayar granite, 9.2 Ma, U-Pb ages on uraninite, Fraser et al., 2001). This magmatism is K-rich and mantle derived (see a review of geochemical data in Mahéo et al., 2002). Magmatic advection has triggered migmatisation by mica dehydration melting reactions (Rolland et al., 2001). Subsequently, these softened mid-crustal-layers, in the core of an E-W trending fold structure, produced doming by local diapric amplifications. In the whole dome area, M2 is well documented with U-Pb monazite ages at 6-7 Ma in the Dassu Dome, and with cooling ages ranging from 10 to 3 Ma (see Rolland et al., 2001 for a review). Similarly to the NPH massif, these young metamorphic rocks suggest rapid uplift (3 mm.yr^{-1}) of the Karakoram massif. There are, however, several differences regarding the styles of metamorphism in these two zones (NPH and Karakoram). These differences are emphasised by the shape of the P-T paths, which is mainly adiabatic in the NPH massif and convex towards HT for the Karakoram. These differences in shape may relate to different tectonic causes for HT metamorphism.

East of the Karakoram terrane, the 1000-km long Karakoram Fault separates the Karakoram-Ladakh-Indian accreted terranes from the Lhasa-Qiantang blocks (Figs. 1-2). The Karakoram Fault is a dextral shear zone, trending 140°E. It reactivates former sutures between the tectonic blocs, branching in the NW into Pamir thrusts and strike-slip faults to and to the SE into the Shyok and Indus-Tsangpo sutures (e.g., Armijo & Tapponnier, 1989; Matte et al., 1996). The magnitudes of right lateral offset and slip rate and the duration of slip of the Karakoram strike-slip fault are debated. Peltzer & Tapponnier (1988) have estimated a large offset (1000 km), based on correlation of the Ladakh and Gangdese batholiths, and this has led to an estimate of elevated slip rates of 32 mm yr^{-1}, also suggested by the offset of topographical features (Liu et al., 1992; Liu, 1993). In contrast, Searle (1996) and Searle et al. (1999) have proposed a smaller offset estimate (120 km), from the correlation of the Baltoro and Tangtse granites and Shyok and Bangong Sutures in the central part of the fault. In the SE segment of the fault, Murphy et al. (2000) have estimated a post-13 Ma offset of 66 km of the Kailas Thrust. The Pangong Range, exhumed within the central part of the Karakoram Fault, provides several constraints on the time of strike-slip shearing. The Pangong Range is a 100 km long – 5 to 10 km wide massif, exhumed between two branches of the fault (Fig. 2; Rolland & Pêcher, 2001), and is comprised of two tectonic units: a central granulitic core and an amphibolitic rim. The presence of granulites exhumed within the fault zone suggests a high thermal gradient, interpreted as thermal advection within a lithosphere-scale fault (Rolland & Pêcher, 2001).

Further discussion on the magnitude of lateral offset of the fault, based on the exhumation history of the Pangong Range and on other geological evidence, is presented below.

Reconstruction of the India-Asia convergence in NW Himalaya (since 110 Ma)

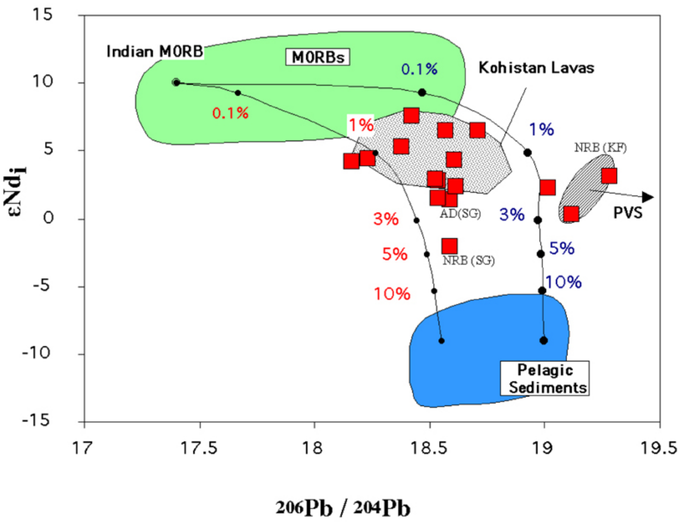
Intra-Oceanic evolution (110-80 Ma)

Different interpretations have been proposed concerning emplacement and polarity of subduction in the Neo-Tethys Ocean during the Mid-Cretaceous. The hypothesis of arc emplacement on the northern rim of the Indian plate, as a result of a south-dipping subduction, is mainly supported by Pb isotopic values for Kohistan lavas (Khan et al., 1997), which appear to plot within the range defined for the DUPAL anomaly. This has led these authors to propose that the arc was emplaced above the DUPAL mantle anomaly in the current South Indian Ocean (Hart, 1984).

Other explanations are plausible. Our geochemical study of Ladakh paleo-arc lavas in NE Pakistan and NW India (Fig. 2; summarised in Rolland et al., 2000; 2002a) suggests that similar Pb isotopic data in the lavas can be produced by intense interaction between slab melts and overlying mantle in the arc source region. These data are briefly summarised below. Lavas from the west Pakistan side of the Ladakh Arc can be separated mainly into two groups: (1) the Northern Group of back-arc tholeiites [$0.5<(La/Yb)_N<1.4$; $0.3<(Nb/La)_N<1.4$; $4<\varepsilon Nd<8$; $38.66<{}^{208}Pb/{}^{204}Pb<38.80$] and (2) the Southern Group of arc tholeiites [$1.8<(La/Yb)_N<3.9$; $0.1<(Nb/La)_N<0.6$; $5<\varepsilon Nd<6$; $38.40<{}^{208}Pb/{}^{204}Pb<38.66$]. Lavas from the Indian east side of the Ladakh Arc show a simple series of more evolved arc volcanics ranging from basalts to rhyolites [basalts and basaltic andesites: $2.5<(La/Yb)_N<5.7$; $0.4<(Nb/La)_N<0.5$; $1.8<\varepsilon Nd<5.5$; $38.70<{}^{208}Pb/{}^{204}Pb<38.80$]. These geochemical features are comparable to those for the Kohistan lavas, and provide support for correlating of Ladakh and Kohistan paleo-arc series. Ladakh Arc lavas have similarly high Pb isotopic ratios. In addition to these relatively classic arc lavas, an adakitic lava [$(La/Yb)_N=55.8$; $(Nb/La)_N=0.3$; $\varepsilon Nd=1.7$; ${}^{208}Pb/{}^{204}Pb=39.00$] and a Mg-poor, Nb-rich basalt [$(La/Yb)_N=4.6$; $(Nb/La)_N=1.3$; $\varepsilon Nd=-2$; ${}^{208}Pb/{}^{204}Pb=39.07$] are spatially associated with the tholeiitic arc lavas (Rolland et al., 2002a). Nb-rich lavas are also found interlayered within the mainly sedimentary Katzarah formation, further south [$3.4<(La/Yb)_N<9.8$; $1.4<(Nb/La)_N<2.1$; $3<\varepsilon Nd<5$], including radiogenic Pb lavas [$39.31<{}^{208}Pb/{}^{204}Pb<39.51$] and less radiogenic Pb lavas [$38.31<{}^{208}Pb/{}^{204}Pb<38.55$]. Adakitic and Nb-rich lava associations, within the basalt to andesite arc lavas, have recently been interpreted to result from slab-melting and subsequent interaction with the overlying mantle (e.g., Sajona et al., 1996). Such processes are also indicated by Pb isotopic ratios discussed below.

All the lavas from Kohistan (Khan et al., 1997) and Ladakh (Rolland et al., 2002a) display very high Pb, Sr and low Nd isotopic ratios, in the range of the DUPAL anomaly values. The occurrence of the DUPAL anomaly (e.g., Hart, 1984) is not as restricted as supposed by Khan et al. (1997), because this isotopic anomaly has been noticed in other areas of the SE Asia region (e.g., Tu et al., 1991). Comparable radiogenic Pb isotopic ratios can result from interaction of slab melts with the overlying mantle. All Kohistan and Ladakh lavas plot along a mixing curve between MORB and pelagic sediments end-members on the εNd vs. ${}^{206}Pb/{}^{204}Pb$ diagram (figure 4). Pb isotopic compositions of all the lavas, and in particular the radiogenic Nb-rich and adakitic lavas, suggest mixing between depleted mantle similar to the Indian MORB mantle and 0.1-5% of enriched components similar to pelagic sediments. Such inputs of slab components are more likely due to slab melting effects, also supported by the presence of adakitic and Nb-rich volcanism. For some Nb-rich lavas (Katzarah lavas), the initial isotopic features may be overprinted by effects of intense melting in the overlying mantle region, as suggested by their picritic composition. This might be due to their southern, possibly fore-arc, origin.

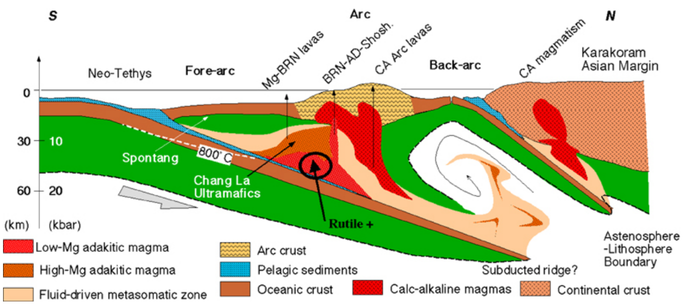
Figure 4. eNd vs. ${}^{206}Pb/{}^{204}Pb$ plot of the Ladakh lavas



The field of Kohistan lavas (Khan et al., 1997) is shown for comparison. AD: adakite; NRB: Nb-rich basalt; KF: Katzarah Formation; SG: Southern Group. The mixing curve is computed using compositions of least radiogenic values of the Indian MORB component (εNd = 10; $^{206}Pb/^{204}Pb$ = 17.31; Pb = 0.03 ppm; Nd = 0.8 ppm), and two extreme values of pelagic sediments (εNd = -9; $^{206}Pb/^{204}Pb$ = 18.56 & 19; Pb = 9 & 60 ppm; Nd = 30 ppm; Ben Othman et al., 1989). Note that even using a depleted MORB composition, small contributions of pelagic sediments can explain the radiogenic features of Ladakh and Kohistan lavas. This input is in the range 0.1-5%, being highest for Nb-rich basalt and adakite of the Southern Group, which are likely formed by slab-melt / mantle interactions. After Rolland et al. (2002a), modified.

Consequently, these geochemical data reflect intense mantle-slab melt interactions due to subducted crust melting. A reconstruction sketch of the arc is proposed on figure 5. Thermo-barometric conditions required in the case of slab melting are those prevailing in young (< 15-20 Ma) subducted crust (e.g., Martin, 1999). Nb-Ti-rich and adakitic lavas have been described in current volcanic arc settings where a young (< 5 Ma) oceanic crust is being subducted (e.g., Solomon Islands: Petterson et al., 1999; Mindanao island: Sajona et al., 1996; Cascade Range: Leeman et al., 1990).

Figure 5. Schematic cross-section of the Kohistan-Ladakh Arc, derived from geochemical data

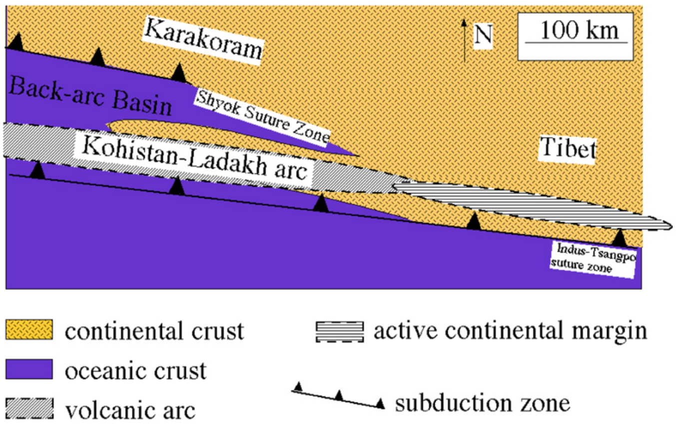


After Rolland et al. (2002a), modified.

Different interpretations have been proposed concerning the presence (Pudsey, 1986; Srimal, 1986; Coward et al., 1986; Srimal et al., 1987; Khan et al., 1994; 1996; Treloar et al., 1996; Rolland et al., 2000) or absence (Rai, 1982; 1983; Khan et al., 1997) of a back-arc basin along northern Kohistan-Ladakh series, mirroring discussion about the emplacement and polarity of subduction.

The geochemistry (summarised above) and lithology of the lavas clearly show that they were intra-oceanic in their Kohistan and western Ladakh parts, with both arc and back-arc marine environments. The lithology of the units described along the Shyok Suture Zone in Ladakh (Rolland et al., 2000) and in Kohistan (Pudsey, 1986) shows that two types of units (arc and back-arc) are present. The Southern Group units are mainly made of lava flows, interlayered with minor tuff and local bombs/lapilli layers. In contrast, the northern group units are made of transported blocks of lava in a tuff matrix, suggesting emplacement in a marginal basin. The geochemistry of the Southern Group lavas is typical of arc lavas, with enrichments in LREE, LILE and Nb-Ta depletions relatively to N-MORB concentrations, while that of Northern Group lavas, with compositions intermediate between N-MORB and arc lavas, is suggestive of a back-arc environment. To the east of the Ladakh terrane, the continental affinity of Indian Ladakh lavas and sediments show that the eastern part of the arc evolved to Andean series, possibly continental based, similar to southern Tibet (Coulon et al., 1986). This evolution from oceanic to continental settings suggest north-dipping subduction, oblique to the Asian margin (Fig. 6; Rolland et al., 2000).

Figure 6. Geometry of the Karakoram-Tibet Asian margin in Middle Cretaceous

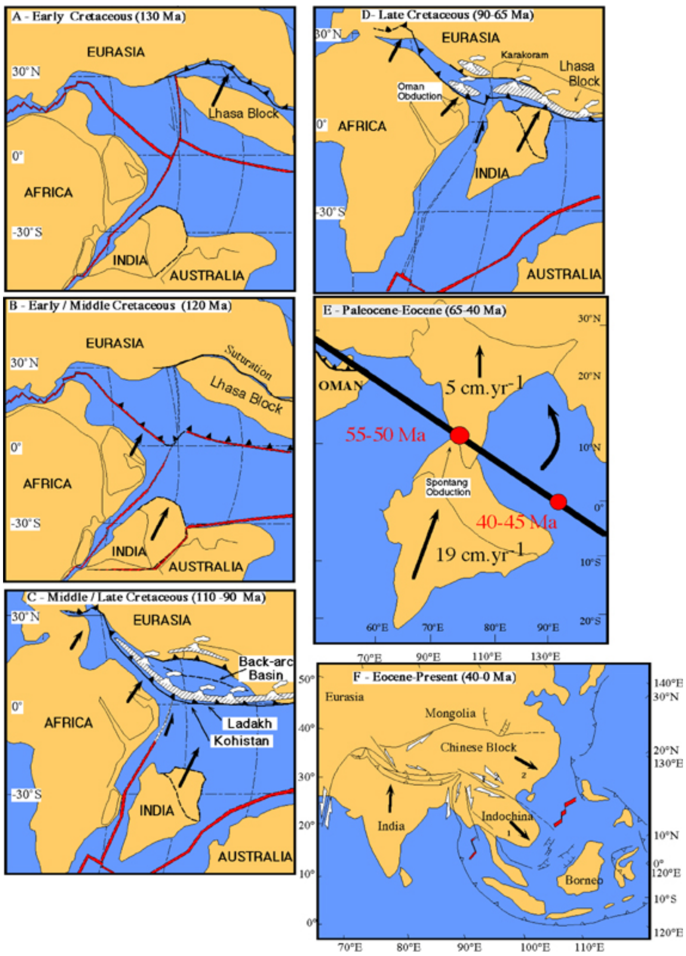


Geometry of the Karakoram-Tibet Asian margin in Middle Cretaceous, as inferred by geochemical and lithological data, after Rolland et al. (2000).

In the wider context of the Neo-Tethys Ocean in the Middle Cretaceous, the data presented above reflect the succession of two major tectonic events that may be combined to explain the subduction of such a young lithosphere (Fig. 7). Prior to arc formation rapid subduction of the Tangulla-Waser Ocean, north of the Karakoram-Lhasa block led to accretion of this block against the Asian margin during the Early Cretaceous (Fig. 7A, Besse et al., 1988). This accretion may have blocked the only free (Asian) boundary of the Tethyan system, where oceanic crust could be easily subducted. At this very critical moment, India and

Africa started their drift towards the north (rapid for India, up to 19 cm.yr^{-1} in Late Cretaceous-Early Tertiary; Patriat & Achache, 1984; Klootwijk et al., 1992). In this particular tectonic context, the Neo-Tethys oceanic ridge may have been the weakest plate boundary, where subduction could be more easily initiated (Fig. 7B), comparable to the model proposed for the initiation of the Oman obduction (Coleman, 1981; Boudier and Coleman, 1981; Pearce et al., 1981) with the formation of the Kohistan-Ladakh arc at 100-95 Ma (Fig. 7C; see Boudier et al., 1985 and Thomas et al., 1988 for Oman).

Figure 7. Tectonic reconstruction proposed for intra-oceanic stages of the India-Asia convergence



Double stripped lines and red colour represent mid-oceanic ridges, single bold lines (black) represent subduction zones and hatched domains to volcanic arc lineaments and arrows represent direction and norm of tectonic blocks motions from Patriat and Achache (1984). Approximate position of continents is from Scotese and Golonka (1992) and Van der Voo et al. (1999), and position of the Lhasa block is from Sengör and Natal'in (1996). The shape of India is according to Matte et al. (1997). The position of the Neotethys ridge is inferred from the relative position of Lhasa and India, and from the timing of emplacement of the Oman ophiolite (Coleman, 1981; Boudier and Coleman, 1981). A, Early/Middle Cretaceous: Accretion of the Lhasa block to the Eurasian margin. B, Middle Cretaceous: this accretion blocked the free boundary of the system while fast northward drift of India was initiated. In this context, the oceanic ridge may have been the weakest plate boundary, where subduction has been initiated. C, Middle/Late Cretaceous: formation of the Kohistan-Ladakh arc and back-arc. D, Late Cretaceous: back-arc closure and arc accretion along the Karakoram margin. E, India-Asia collision: the convergence is accommodated by lithospheric-scale partitioning between horizontal shortening (folding + thrusting) and strike-slip faulting (figure E after Tapponnier et al., 1986).

On the Karakoram margin, calc-alkaline magmatism, occurred contemporaneously with the formation of the Kohistan-Ladakh Arc. This magmatism, interpreted as supra-subductive (Debon et al., 1987; Crawford & Searle, 1992), implies existence of another subduction zone along the Karakoram Asian margin (Fig. 7C) responsible for formation of the Karakoram Batholith (Debon et al., 1987). This magmatism evolves from calc-alkaline to alkaline at ~ 88 Ma (Debon & Khan, 1996), which suggests deepening of the source-region and steepening of the Benioff plane directly preceding arc-continent accretion.

Arc-continent accretion (88-80 Ma)

Accretion of the Kohistan-Ladakh Arc to the Karakoram Asian margin occurred in the Late Cretaceous (Fig. 7D; Petterson & Windley, 1985; Weinberg et al., 2000). At this stage, there is only one subduction zone extending at least from the Middle East to the Tibet regions. Arc accretion may not have happened simultaneously due to the obliquity of the arc lineament with respect to the continental margin. It is dated at 75-65 Ma by plutonism developing along the Shyok Suture Zone, earlier in Kohistan (~ 75 Ma, Petterson & Windley, 1985), and later in eastern Ladakh (Tirit granite, 73.6-68 Ma; Weinberg & Dunlap, 2000; Weinberg et al., 2000). The stages that directly preceded, or accompanied, the accretion, are coeval with intense magmatism, with emplacement of granodiorite to granite plutons along the Kohistan-Ladakh Batholith. The volume of this later magmatism is far more important in Ladakh than in Kohistan. This late magmatism largely overprints the arc structure, being responsible for granulite-facies metamorphism in the central part of Ladakh (Raz & Honegger, 1989; Rolland et al., 2000) and amphibolite to epidote-amphibolite metamorphism along the northern suture (Hanson, 1989; Rolfo et al., 1997). Simultaneously with this metamorphism, different units of the paleo-arc series, belonging to arc and back-arc series, were stacked along southwest-vergent thrusts floored by serpentinites. The Karakoram and Kohistan-Ladakh terranes ultimately formed a completely accreted crustal section.

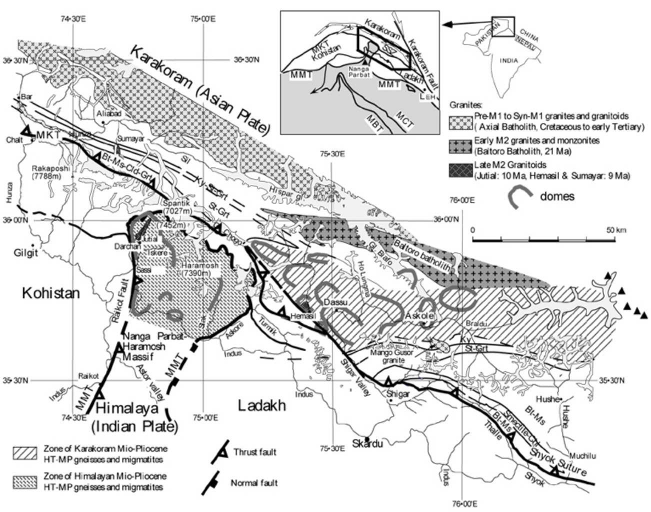
India-Asia collision (65-40 Ma)

The collision of India and Asia occurred between 65 and 55 Ma in NW Himalaya, for a detailed review of the data and references concerning the India-Asia collision, see Rowley (1996) and Searle et al. (1997; 1999). Magnetic studies have evidenced an abrupt decrease in convergence rate, from 18-19.5 cm.yr^{-1} to 4.5 cm.yr^{-1}, at ~ 50 Ma for Patriat & Achache (1984), 50-55 Ma for Klootwijk et al. (1992), and 57 ± 3 Ma for Acton (1999). These age estimates are interpreted to date the initiation of India - Asia collision. This drop in convergence rate coincides with a reduction in the spreading rate of SW and central Mid-Indian Ocean ridge at 56.1 – 50.3 Ma (Molnar & Tapponnier, 1975; Patriat & Achache, 1984; Patriat et al., 1985). The collision occurred initially in the NW and propagated to the SE (Fig. 7D; Bassoullet et al., 1981; Blondeau et al., 1986; Klootwijk et al., 1992; Guillot et al., 1999). This diachronous collision may be due to the initial shape of the Indian continent, colliding with NW-SE Asian margin (thick line on Fig. 7E). In a first stage, NW Indian continental crust was subducted to a minimum depth of 60 km, as indicated by eclogitic metamorphism documented in the Tso Morari area at ~ 55 Ma (P = 20 ± 2 kbar, T = 550 ± 50°C, Guillot et al., 1997; de Sigoyer et al., 1997; 2000). Subsequently, in the Palaeocene, the Kohistan-Ladakh sequences were obducted (in two stages) onto the Indian margin (Garzanti et al., 1987; Reuber et al., 1987); this is notably later than the obduction of the Oman ophiolite on the African realm (Latest Maestrichtian; Michard et al., 1984; Lippard et al., 1986; Goffé et al., 1988). In the meantime, and until 50 Ma, granitic magmatism still occurred in the Ladakh terrane (Weinberg & Dunlap, 2000). Locally, these last granitic melts bear a strong continental crust affinity (εNd = -7.5, Rolland et al., 2002a). This magmatic stage could thus correspond to partial melting of a continental crustal basement, or be due to melting of the paleo-arc siliceous sediments. The presence of such a contrasted metamorphic conditions between the HT-MP Kohistan-Ladakh terrane and the LT-HP subducted Indian slab is probably due to the efficient "thermal screen" provided by the thick sequence of ultramafic lithologies (i.e. the serpentinites) in between the two zones (e.g., Treloar, 1997). Such a contrast does not exist in eastern Himalaya (Lombardo & Rolfo, 2000), where eclogites have been totally transformed into granulites.

The earlier M1 structures found in the Karakoram area are NW-SE thrusts, schistosity and metamorphic isograds, oriented parallel to the Shyok Suture, and thus reflective of a stage of NE-SW shortening (Hanson, 1989; Allen & Chamberlain, 1991; Searle et al., 1999; Rolland et al., 2001). The M1 metamorphic grade increases towards the NE, reaching MP amphibolitic facies conditions (sillimanite zone, T = 650°C, P = 10 kbar) close to the contact with the axial batholith (Bertrand et al., 1988; Searle et al., 1989; Lemennicier et al., 1996). These structures are compatible with thickening of the Karakoram, with deep crustal levels thrusted over shallower ones.

Post-collisional evolution (40-0 Ma): Strain partitioning between lithospheric-scale shearing and folding

Figure 8. Geological and metamorphic sketch map of the S-Karakorum margin after Rolland et al. (2001)



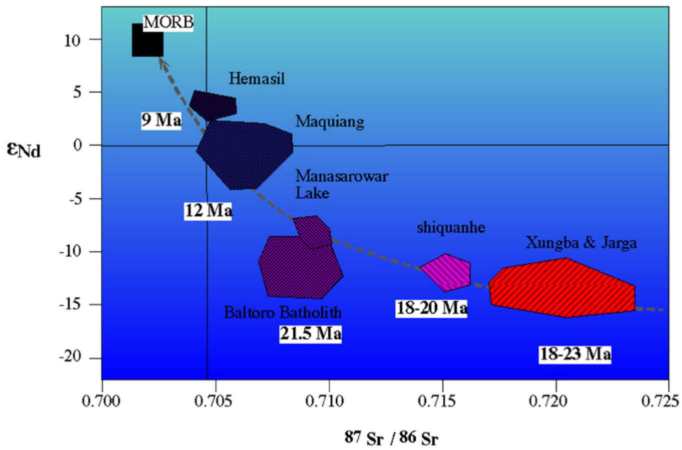
Main tectonic contacts are the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), the Main Mantle Thrust (MMT), the Shyok Suture Zone (SSZ), and the Main Karakorum Thrust (MKT). Full triangles are summits above 8000 meters.

Horizontal shortening

By 41 Ma, India was fully colliding with Asia on 2000 km length (Rowley, 1996), the collision propagating from

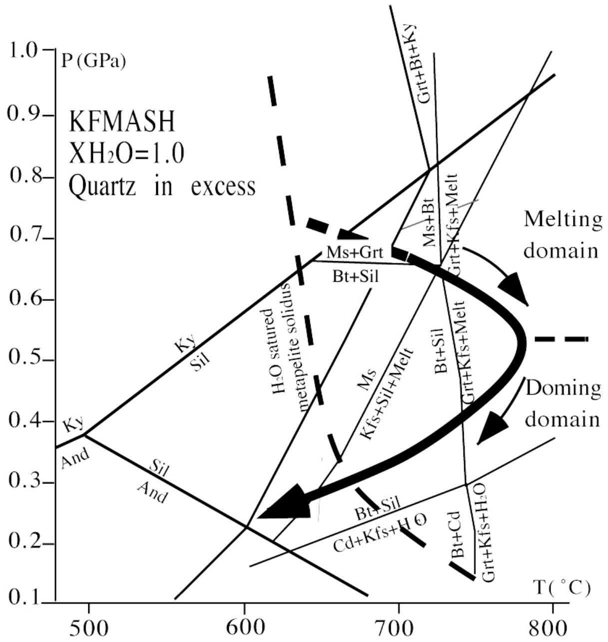
NW to SE. Between 57 and 41 Ma, the direction of India-Asia convergence had rotated from NNE-SSW to N-S (e.g., Guillot et al. 1999 and references therein). In the NW Syntaxis, this change in shortening direction is emphasised by the transition from M1 to M2 (Fig. 8). The Karakoram M1 structural pattern is crosscut by the 37 Ma Mango Gusar granite and by the 25-21 Baltoro granite intrusions (Parrish & Tirrul, 1989; Searle et al., 1989; Schärer et al., 1990). One of the most striking effect of the M2 event is the formation of migmatic domes, aligned E-W. It has been proposed for syntaxes areas (Namche Barwa), that thermal weakening following HT metamorphism in mid-crustal levels could have led to doming via fold amplification (Burg et al., 1997; Burg & Podladchikov, 1999). This heating is closely associated (spatially and temporally) to high-K mantle-derived plutons (see review in Mahéo et al., 2002). This mantle-derived magmatism is found all along the southern Tibetan margin (Turner et al., 1996; Miller et al., 1999). Compiled isotopic and age data from Mio-Pliocene magmatic rocks that were emplaced along the Tibet-Karakoram margin are presented on figure 9, which shows that mixed mantle-crust magmatism occurred since the intrusion of the Baltoro Granite at 21-25 Ma. In younging order, the magmatic intrusions are increasingly more mantle derived, suggesting less efficient mixing with the crustal component, with the youngest Hemasil Syenite, dated at 9 Ma (Ar-Ar Hornblende, Villa et al., 1996), bearing an isotopic signature close to that of MORBs (Lemennicier, 1996). The Hemasil Syenite is closely associated with the occurrence of high-temperature M2 metamorphism in the Dassu Dome area, peaking at 750-800°C and 6 kbar (Fig. 10; Rolland et al., 2001) and dated at 6-7 Ma (U-Pb on zircon, Smith, 1993). On figure 11, the P-T path for the Karakoram domes area (Askole-Dassu) is compared to the path for the High Himalayan Crystalline and the NPH Massif. The P-T path drawn for the domes area of the Karakoram indicates strong heating at only 6 kbar, while the exhumation rate was 3 $mm.yr^{-1}$. The P-T path of the Nanga Parbat granulites, in contrast, is characterised by nearly adiabatic decompression due to a very fast exhumation rate (7 $mm.yr^{-1}$, Zeitler et al., 1993). An additional source of heat must therefore be advocated for the Karakoram domes. The spatial and temporal relationships of metamorphic rocks and mantle-derived magmas in this zone suggests an efficient heat advection process from the mantle via magmas. Such relationships between HT metamorphism and mantle magmatism have been observed and interpreted, on the basis of numerical simulations, as the result of slab detachment processes by Davies & Blanckenburg (1995). For the NW Himalaya this hypothesis is supported by seismic data, which show an interruption of seismic activity at a depth of 170 km along the subducting Indian slab (Chatelain et al., 1981). A similar interpretation can be made from the tomographic data of Van der Voo et al. (1999), reinterpreted by Chemenda et al. (2000). The latter authors have experimentally simulated Indian slab detachment, at a state of convergence equivalent to 20-25 Ma.

Figure 9. εNdi vs. $^{87}Sr/^{86}Sr$ diagram showing isotopic composition of Miocene magmatic rocks from the Asian margin (Tibet + Karakoram)



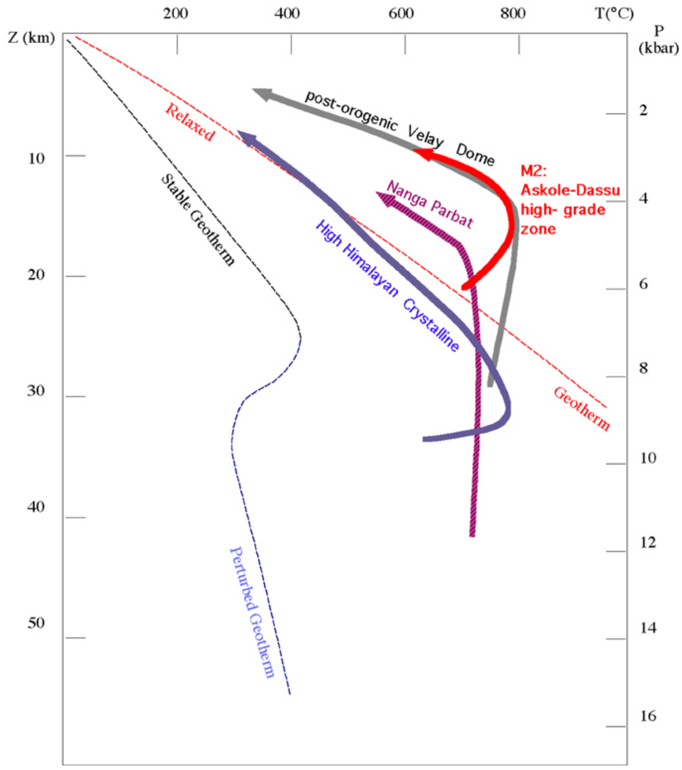
Data from Searle et al. (1992), Lemennicier (1996), Turner et al. (1996), Miller et al. (1999).

Figure 10. P-T path of M2 metamorphic event in Dassu and Askole domes



P-T path of M2 metamorphic event in Dassu and Askole domes (after Rolland et al., 2001).

Figure 11. Stable, perturbed and relaxed geotherms

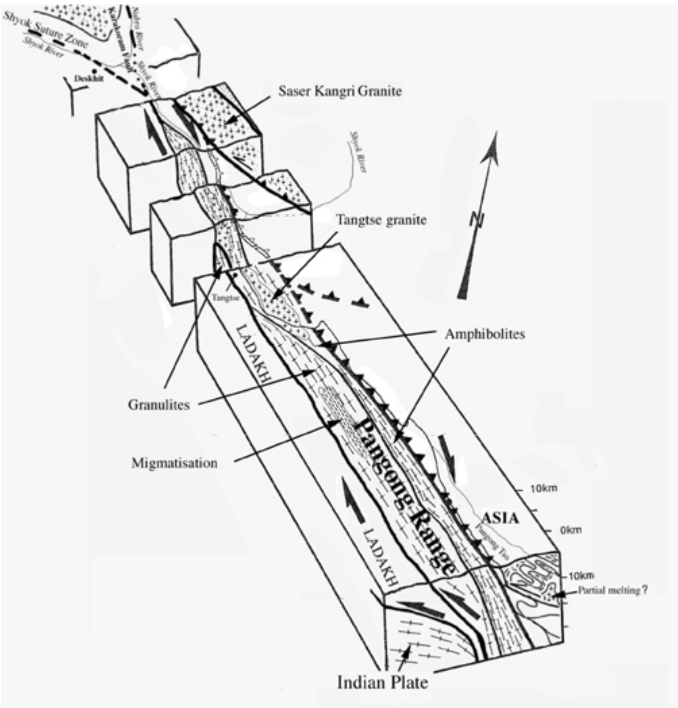


Stable, perturbed and relaxed geotherms compared to P-T paths obtained in the Karakoram (M2 Domes; Rolland et al., 2001), in the Nanga Parbat (Whittington et al., 1998), for the Miocene syn-stacking metamorphism in the High-Himalayan Crystalline (Guillot, 1999), and for the Hercynian post-orogenic metamorphism in the French Central Massif (Gardien et al., 1997).

Strike-slip shearing

Since c. 40 Ma, a considerable part of the convergence is accommodated by great strike-slip faults peripheral to the Himalayan Orogen, such as the Chaman, Altyn Tagh, Karakoram and Red River faults (Fig. 7E; Molnar & Tapponnier, 1975; Tapponnier & Molnar, 1977; Tapponnier et al., 1986; Peltzer & Tapponnier, 1988; Armijo et al., 1989). Time of metamorphism and uplift in the metamorphic core of the Pangong Range (Figs. 12 & 13), can be used to infer the depth and slip rate of the Karakoram fault. The Pangong Range was successively equilibrated in the granulite, amphibolite and greenschist facies. Granulite facies conditions of ~ 800°C were reached at relatively shallow depths (6 kbar, 18 km), and the subsequently estimated thermal gradient is high at upper crustal levels (45-55°C.km^{-1} at 5-20 km) within the fault zone (Rolland & Pêcher, 2001). These temperature conditions are more than 100°C above estimated temperatures obtained from crustal-scale shear heating modelling (Leloup et al., 1999). Additional heat input is thus required directly in the fault zone. It could be hypothesised that the full Lithosphere penetration of the shear zone, which divides two lithospheric blocks, allows efficient heat advection from the mantle, similar to the Red River and Altyn Tagh faults (Leloup et al., 1999; Wittingler et al., 1998).

Figure 12. Karakoram Fault structure



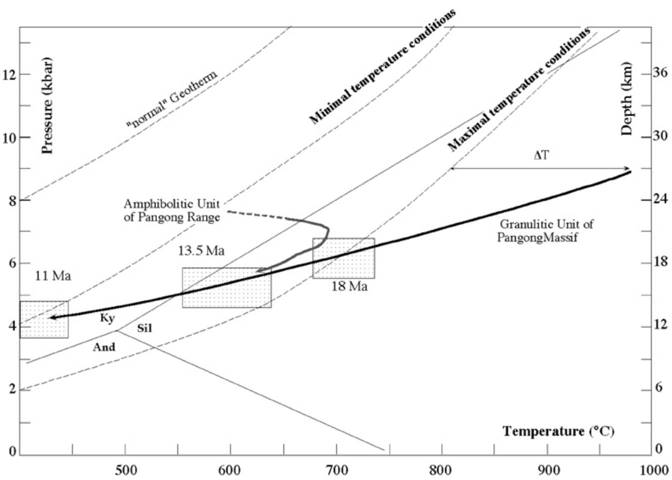
Schematic 3D interpretative view of the Karakoram Fault structure along Nubra, Shyok and Pangong Valleys.

The progress of the Pangong Range exhumation can be constrained by several geo-chronometers. From Ar-Ar analysis of the granulite facies rocks, the age of peak metamorphism is not well constrained yet, older than at least 32 Ma (Rolland, 2000). Ar-Ar dating of these rocks shows however a strong resetting of the Ar-amphibole chronometer at 18-13.5 Ma in the amphibolite facies. A similar age of 18 Ma has been obtained from the U-Pb zircon, on the Tangtse Granite emplaced at the contact between granulite and amphibolite units (Searle et al., 1998). Subsequent greenschist facies metamorphism is dated at 11.3-11.4 Ma from Ar-Ar dating on biotite and muscovite by Searle et al. (1998). The age and P-T estimates of the amphibolite facies, combined with closure temperature estimates reported in Villa (1998), suggest that the Pangong exhumed at a mean rate of 1 $mm.yr^{-1}$. A subsequent horizontal slip rate estimate of 1.7 $mm.yr^{-1}$ for the Pangong Range during its past 18 Ma exhumation can be derived from the 30°NW plunge of mineral lineations. The 300 km total slip of the Karakoram Fault, deduced from the lateral correlation of the Karakoram and Lhasa blocks (Rolland et al., 2002b), such slip rates imply:

(1) Initiation of the Karakoram Fault at the onset of the Karakoram-Lhasa block accretion to the Asian margin (at t > 130 Ma).

(2) If instead an age of 32-40 Ma is accepted for the initiation of the Karakoram Fault, faster slip rates of 7.5-10 $mm.yr^{-1}$ would be estimated. In that case, the slip rate estimates from the P-T-t path of the Pangong Range would be underestimated.

Figure 13. P-T-t path obtained in the Pangong Range (after Rolland and Pêcher, 2001)

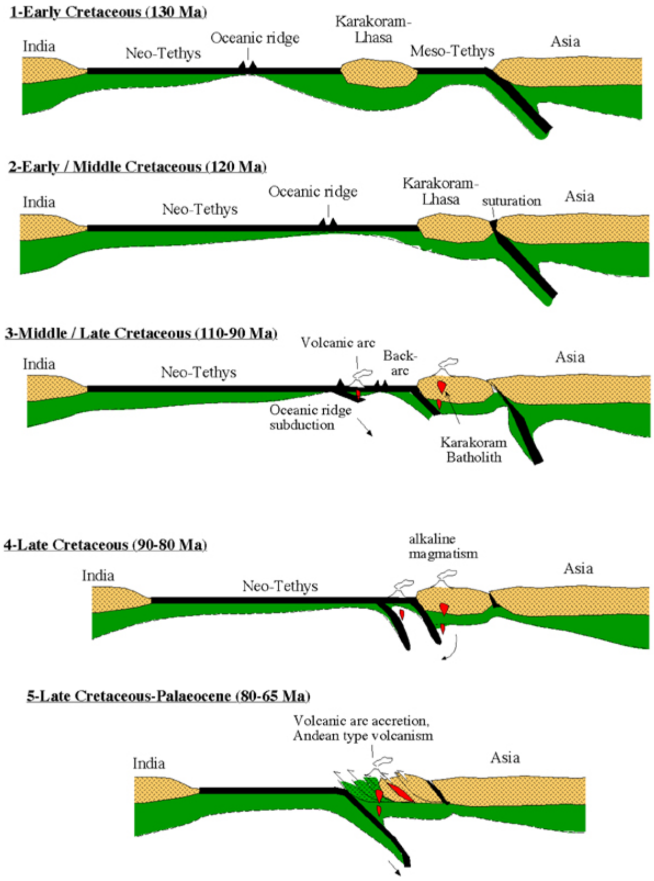


Minimal and Maximal PT conditions obtained for shear heating modelling by Leloup et al. (1999). U-Pb and Ar-Ar ages from Searle et al. (1998), and Rolland (2000).

Conclusions

In summary, investigations in the NW part of the Himalayan Orogen have provided structural, metamorphic, geochemical and geochronological data, which help to constrain the tectonic evolution of the area. These data suggest the following evolution (Fig. 14).

Figure 14. Tectonic reconstruction proposed for the India-Asia convergence



Tectonic reconstruction proposed for the India-Asia convergence in NW Himalaya since 110 Ma to 65 Ma, from the data compiled in this article.

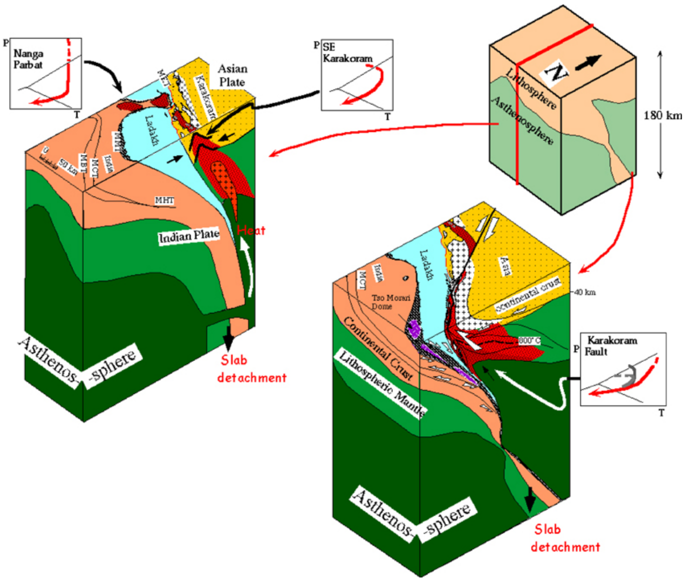
1. Accretion of the Lhasa – Karakoram block to the Asian margin in the Early-Middle Cretaceous (1 a-b, Fig. 14). This accretion blocked the only free boundary of the Tethyan Ocean, with India commencing its convergence with Asia (2, Fig. 14).

2. Formation of an unique volcanic arc / back-arc above a N-dipping subduction zone, to the south of the Asian Karakoram margin. Arc volcanism was likely produced by interactions between slab melts and mantle after subduction of the Neo-Tethyan mid-oceanic ridge (3, Fig. 14). This arc was immature and intra-oceanic in the west, evolving to mature and possibly continental-based, as the Tibetan active margin to the east. This lateral evolution, which is supported by the evolution of sediments from marine in the west to clastic, continent-derived in the east suggest a subduction oblique to the Asian margin.

3. The Ladakh back-arc domain was subducted under the southern rim of Asia (3, Fig. 14). Evolution of subduction-derived magmatism from calc-alkaline to alkaline compositions in Asia suggests steepening of the slab by 88 Ma (4, Fig. 14).

4. Accretion of Ladakh-Kohistan Arc to the Asian rim occurred in the range 88-80 Ma (5, Fig. 14). South-vergent thrusts were cross-cut by calc-alkaline plutons and overlain by Andean-type volcanic rocks.

Figure 15. 3D sketch of post-collisional evolution in NW Himalaya orogen



A, horizontal shortening, and crustal-scale folding, within the Karakoram margin. B, Lithosphere-scale shearing. PT path obtained in the Nanga Parbat from Whittington et al. (1998), in the Karakoram margin from Rolland et al. (2001), and in the Karakoram Fault from Rolland & Pêcher (2001).

5. Subsequent collision of India with the Asian margin produced a lithosphere-scale partitioning between zones affected by horizontal shortening (A in Fig. 15) and zones of strike-slip deformation (B in Fig. 15). In both cases HT metamorphism has been observed due to advection processes within crustal-scale folds or lithosphere-scale faults, respectively. The evolution of magmatic rocks towards mantle composition over the past 20 Ma, suggests melting of the continental lithosphere following Indian slab detachment process.

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