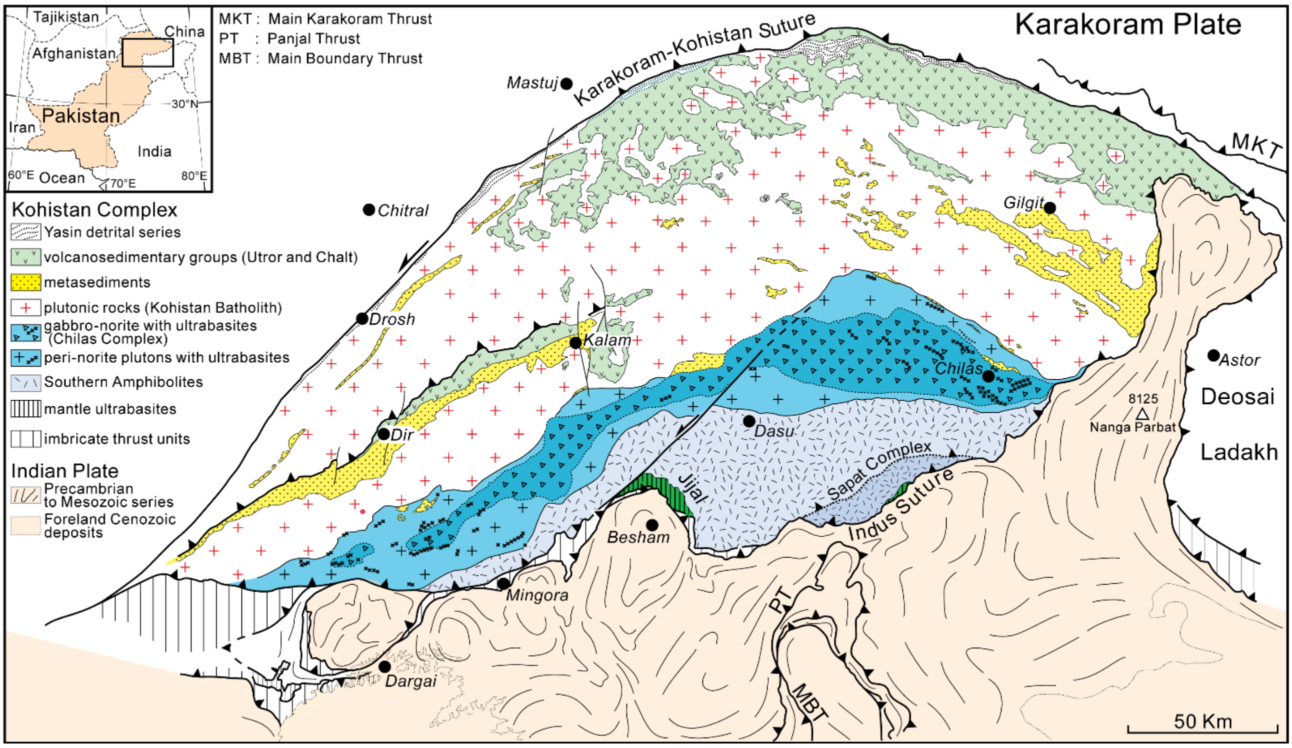
West-Himalaya: Island arc/continent collision

The closure of the Tethys Ocean and the subsequent, long-lasting collision of India with Asia produced the Himalayan mountain chain. The West Himalaya, in northern Pakistan, consists of three tectonic units:

- Farthest north, the Asian plate contains the late Cretaceous-Miocene Karakoram batholith.
- Farthest south, the Indian plate contains deformed and metamorphosed shelf and platform sediments covering a Precambrian basement. Early Eocene granites and alkaline, Carboniferous-Permian magmatic rocks intruded the whole. Tertiary molasse-type sediments were deposited in a huge foreland basin.
- Between the Indian and Asian plates, the Kohistan Terrane is bounded to the north, against the Karakoram batholith of Asia, by the Karakoram-Kohistan Suture, and to the south, against India, by the Indus Suture. The latter is also named the Main Mantle Thrust for the mantle peridotites squeezed in the contact zone.



The Kohistan Terrane correlates eastwards with the Ladakh arc-batholith in Northwestern India and the continental Karakoram Batholith correlates with the Transhimalaya Plutonic belt in Southern Tibet, where the Yalu Tsangpo suture is the eastern continuation of the Indus Suture. The Kohistan-Ladakh Complex was formed as an island arc somewhere within the Tethys Ocean in Mesozoic times, thrust southward onto the Indian margin to become ultimately squeezed between the converging Indian and Asian plates. The western Himalayas are therefore an example of arc-continent collision. Arc-continent collisional systems are relatively rare because they usually represent an intermediate step in the closure of an ocean and so are relatively short-lived (as obduction systems, see Oman). In effect, most volcanic-arc settings are unstable. Many arcs often split, subduction zones may flip in polarity from one side of an arc to the other, and a subduction zone may abandon the arc, jumping to a new locality and a new orientation. Thus, even though subduction zones define the locus of generation for new sialic (i.e. continental) material, the arcs rarely survive intact; they move relative to continents and continental growth takes place as a result of accretion tectonics involving arc-continent collisions. For example, Taiwan manifests the active accretion of a volcanic arc onto the east margin of Eurasia. The Banda Arc colliding with Timor and New Guinea also represents present-day arc-continent collision.

Paleomagnetic and kinematic data

The role of India in the plate tectonic system ruled the tectonic history of the Himalayas.

Ocean spreading – Tethys

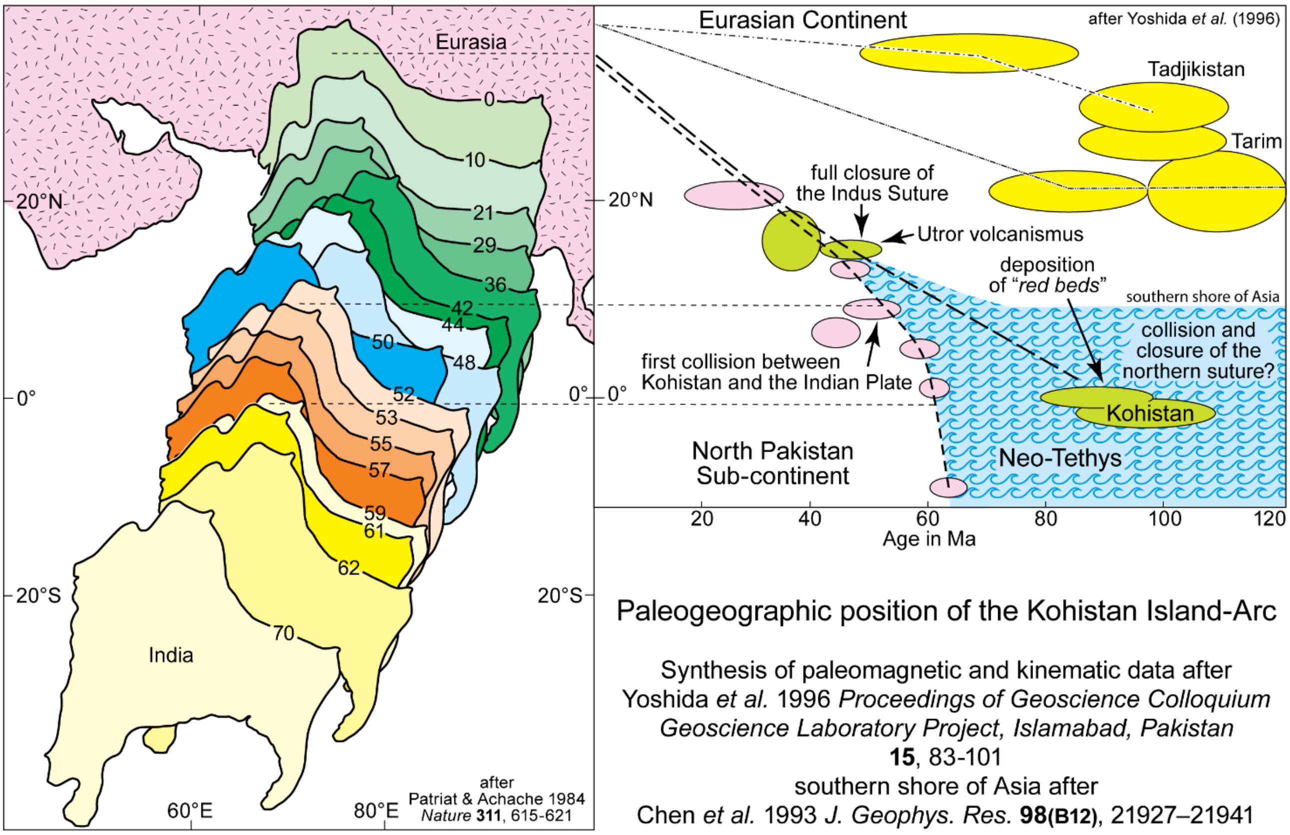
Rifting that led to the break-up of Pangea produced Permian granite-gneiss and tholeiitic metabasalts found on the northern edge the Indian continent. This magmatism was pervasive, which suggests that India was the upper passive margin of the asymmetric extensional system. As in Arabia, Late Permian marine submersion marks the beginning of thermal subsidence; deepening marine conditions followed in Early Triassic times. Later Mesozoic, carbonate-dominated and pelagic sequences record the subsidence/sea level history and paleogeography of this Indian-side Tethyan passive margin.

Closing Tethys

The more or less equatorial spreading that had dominated Tethys until the Late Jurassic (155-140 Ma) changed into the development of southwestward propagating spreading ridges that carved-up Gondwana (rifting of the Argo-Burma terrane from NW Australia and separation of Madagascar/India from Africa). At about 140 Ma, India stopped rotating clockwise and started its still on-going anticlockwise rotation. The coeval, northward motion of India started at that time and seems to have been through a no-latitudinal-convergence stage between 100 and 80 Ma.

Intra-oceanic subduction

Arc magmatism may have started in the Mid to late Jurassic, in temporal coincidence with a fundamental change in plate motions but the events leading to the collision of India with Asia, and the later formation of the Himalayas, started in the Early Cretaceous. At that time, the Indian continent started drifting northward, opening the Indian Ocean behind, to the south, while closing the Tethys Ocean to the north. The intra-oceanic Kohistan arc formed during this closure over a subduction zone that dipped to the north, beneath the arc.



Paleogeographic position of the Kohistan Island-Arc

Synthesis of paleomagnetic and kinematic data after Yoshida *et al.* 1996 *Proceedings of Geoscience Colloquium Geoscience Laboratory Project, Islamabad, Pakistan* **15**, 83-101
southern shore of Asia after Chen *et al.* 1993 *J. Geophys. Res.* **98(B12)**, 21927–21941

The paleogeographic position of the Kohistan island arc is uncertain. Existing data constrain its Late Cretaceous position (100-80Ma) in the equatorial zone and close to the Karakoram margin of the

Eurasian continent. At the same time, the Tajikistan and Tarim basins of Eurasia were more than 2000 km to the north of the Karakoram and Kohistan blocks while India was still in the southern hemisphere.
Paleomagnetic data and apparent polar wander paths for the Indian plate indicate that the northward movement of the Indian continent was rapid until around 58 Ma. This age dates the onset of tectonic interaction between India and Asia.

Closure of the Tethys Ocean

Lithostratigraphic and geochronological/structural information from both sides of the Kohistan Arc date closure of the Tethys Ocean at 65-60 Ma. To the east, obduction and subsequent interaction between India and Asia is dated at >50 Ma in the Ladakh Himalaya and about 65 Ma in the Central Himalayas. To the south-southwest, in the Waziristan– Kurram regions, obduction started also at ca. 65 Ma. Paleomagnetic reconstructions place collision between India and Asia at equatorial latitudes, with progressive suturing from Paleocene in the northwestern Himalaya (at 62-60 Ma) until Early Eocene (ca. 50 Ma) in the eastern Himalaya. The convergence rate became markedly slower after the initial collision. Late Paleocene–middle Eocene (65-45 Ma) sandstones of the foreland flexural basin on India contain ophiolitic and volcanic clasts supporting obduction/collision by this time.
There is no paleolatitude difference between India and the Kohistan Arc in middle Eocene times (ca. 45 Ma), which points to complete suturing along the Indus Suture at that time.

Karakoram paleo-active Margin of Eurasia

Mid-Cretaceous to Early Cenozoic (120-55 Ma) tonalites, diorites, and granodiorites with a calc-alkaline signature make the backbone of the Karakoram Range. These granitoids constitute the composite Karakoram Batholith that has intruded Paleozoic to Triassic sediments of Asian-plate affinity and their Proterozoic basement. The generation of this Andean-type south-Asian margin requires at least one major, northward-dipping subduction zone within the Karakoram-Kohistan Suture.

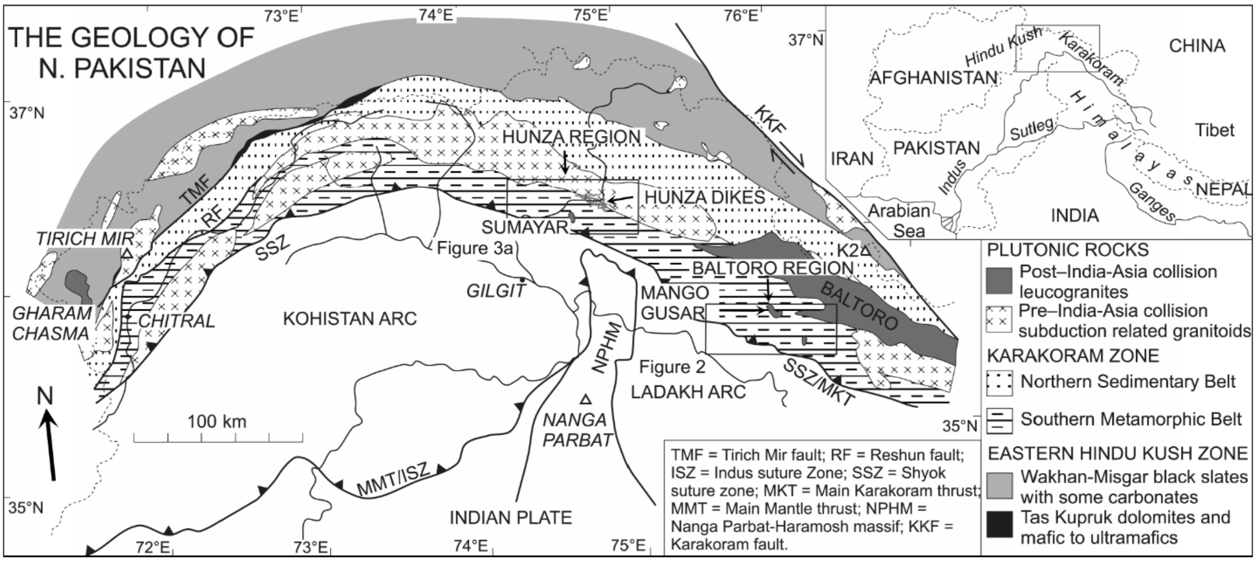


Figure 1. Location map showing the position of the Hunza Valley and Baltoro regions in relation to the rest of the Karakoram (after Searle, 1991; Hildebrand et al., 1998, 2001). Inset shows the figure in relation to Asia.

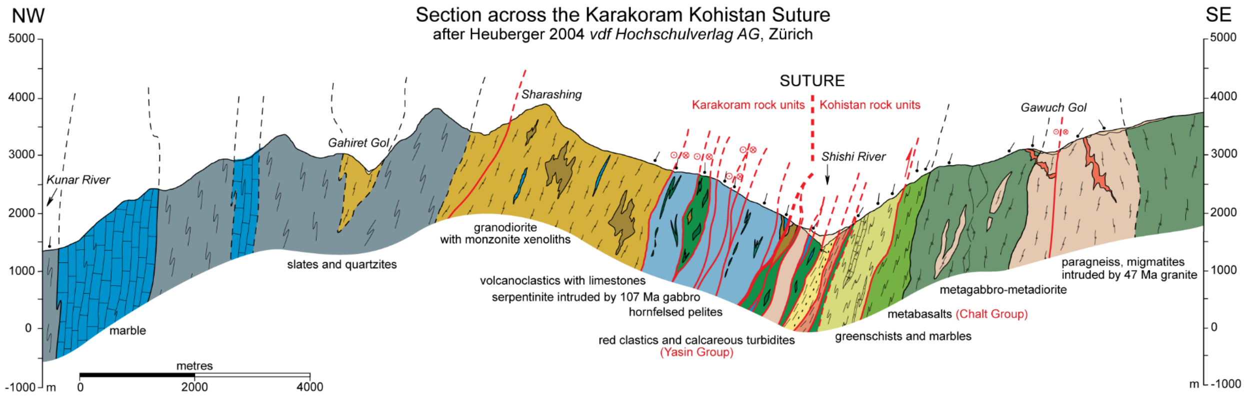
from Fraser *et al.* 2001 *Geol. Soc. Am. Bull.* **113(11)** 1443-1455

Similarities in setting, age, and chemistry suggest that the Karakoram Batholith is the western continuation of the Transhimalaya Batholith, in southern Tibet. Strong stratigraphic similarities of the screening rocks support this interpretation. The ensuing correlation suggests ~ 150 km dextral movement along the Karakoram wrench fault, the eastern boundary of the Karakoram terrane. To the south of the Karakoram Batholith, a belt of young (20-3 Ma) low-pressure high-temperature

metamorphic rocks and related migmatitic domes has overprinted a Cenozoic (65-35 Ma) tectonic and metamorphic event, which timely corresponds to the onset of the India-Asia collision. The lowest, southernmost part of the structural pile, above the Karakoram-Kohistan suture, is comprised of low grade, Cambro-Ordovician turbidites, and limestones. The south- to southwest-directed Main Karakoram Thrust separates these lower-greenschist facies rocks from paragneiss in which metamorphism grades upwards into amphibolite facies conditions (staurolite-garnet then kyanite-garnet zones). Upper amphibolite facies conditions are reached at the contact with the Batholith (sillimanite zone, 650–700°C; 1 GPa). At the peak of this phase of crustal thickening, partial melting of crustal rocks resulted in leucogranite magmatism at 40-35 Ma. The youngest (< 21 Ma) metamorphic event is attributed to heat advection from both mantle and lower crustal magmas into the thickened Karakoram crust.
The present-day thickness of the Karakoram plate is little known. The most accessible information places the Moho at about 50 km depth.

Karakoram-Kohistan Suture

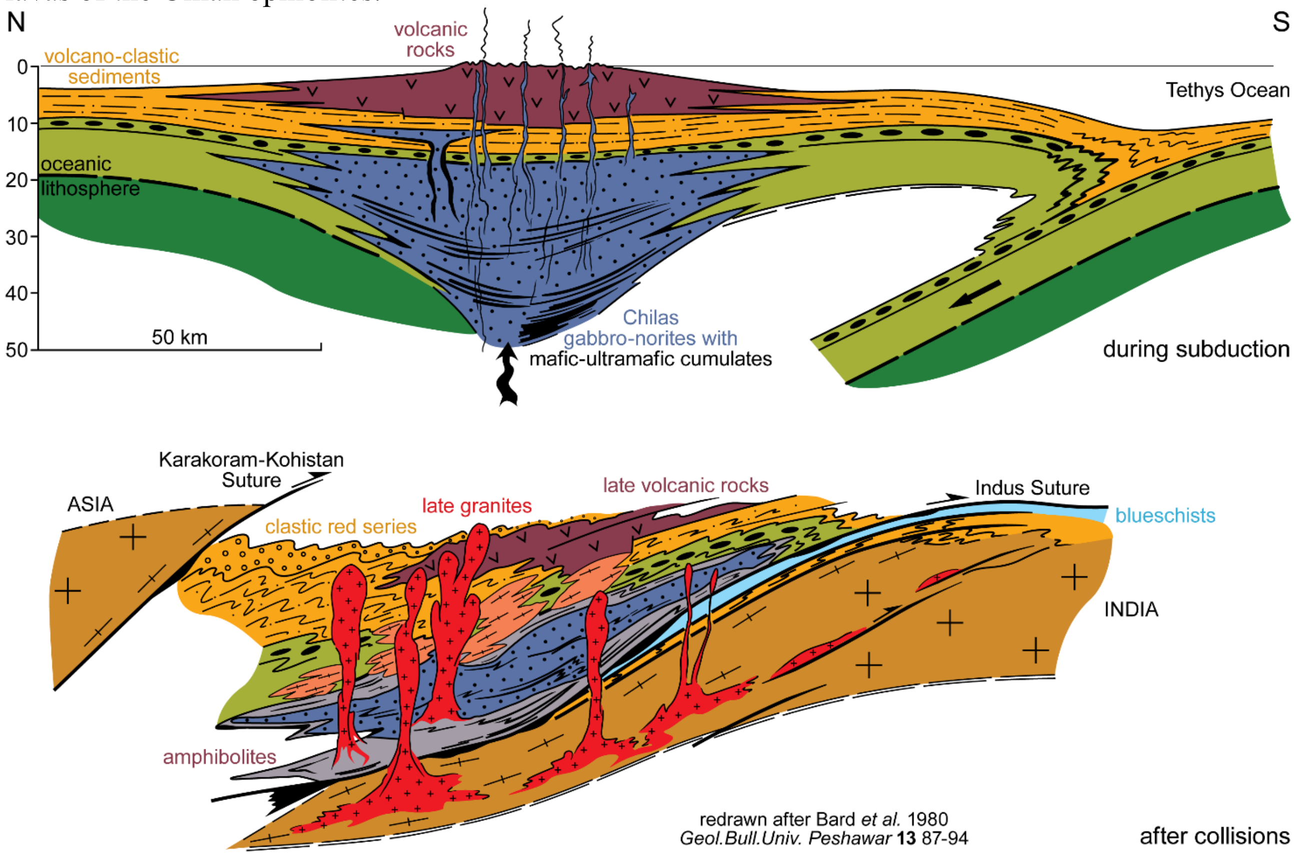
The Karakoram-Kohistan Suture consists of imbricate volcanic and volcanoclastic greenstones, red shales, limestones, slates, and serpentinites. Like for its eastern continuation, the Shyok Suture in India, it is interpreted either as the site of subduction of a wide Tethys Ocean or as a marginal basin along the southern margin of Asia. North- and south-vergent structures are found on both sides and within the suture. Imbrication is due to series of late brittle faults that have faulted away the original suture.



Undeformed subalkaline plutons of Eocene age exist on both sides of the Karakoram-Kohistan Suture. Foliated granitoids of the Kohistan Arc were dated ca 102 Ma (Rb-Sr whole rock isochrones). The 75 Ma K-Ar hornblende age of an undeformed dyke cutting foliated pillows of the Kohistan Arc was taken as an additional key to inferring that the Karakoram-Kohistan Suture was closed in the Late-Cretaceous, sometime between 100 and 85 Ma. However, the age of the dyke is an unconfirmed "personal communication" to the authors who published it while calc-alkaline magmatism continued until at least 35 Ma in the Kohistan Arc. Besides, some Karakoram granitoids are as young as about 20 Ma. The foliation of the Rb-Sr-dated granitoids may be a magmatic fabric. These observations place uncertainty on geological constraints of the Karakoram-Kohistan suturing since magmatism and deformation were heterogeneous and diachronous in the sampled area.
Paleomagnetic, structural, metamorphic, and geochemical arguments rather indicate that, as early interpretations suggested, closure of the Karakoram–Kohistan Suture occurred at about 40 Ma after the ca 50 Ma collision of the Kohistan Arc with India. In any case, the same fission track apatite ages on both sides of this suture show that no or imperceptible vertical differential movement has taken place along this fault zone since the late Miocene (11–13 Ma).

The Kohistan Island Arc

The 30 to 40 km thick section of the Kohistan Terrane includes locally metamorphosed, plutonic, volcanic, and sedimentary rocks. This rock association is interpreted as calc-alkaline plutons intrusive into an oceanic lithosphere and overlain by calc-alkaline lavas and associated sediments. Accordingly, the interpretation is an intra-oceanic arc that developed during the Cretaceous somewhere in the Tethys Ocean, a situation reminiscent of, but more evolved than the calc-alkaline lavas of the Oman ophiolites.



Six main rock assemblages from north to south, i.e. downward sequence, are present.

Upper crust

Upper crustal sequences pertain to two geographically distinct domains.

Northern side of the island arc

Just south of the Karakoram-Kohistan Suture, upper-crustal rocks consist of interlayered volcanoclastic sediments, volcanites, and rather immature turbidites deposited in a deep-water environment.

Sediments (so-called Yasin Group) are shales, graywackes and volcanoclastic rocks from a probable back-arc basin of Cretaceous age. They grade upward into fine-grained shales and tuffs and contain limestones with an Albian-Aptian fauna (ca. 100-120 Ma).

Volcanites (Chalt Volcanites) are calc-alkaline andesites to rhyolites succeeding in andesitic lavas, tuffs, and agglomerates of Early Cretaceous age. Exceptionally well-preserved pillow lavas are primitive island-arc-type, tholeiitic lavas that possibly represent part of an ophiolite assemblage obducted during the Kohistan-Asian collision. The size of this oceanic back-arc basin (with respect to the Kohistan) is conjectural.

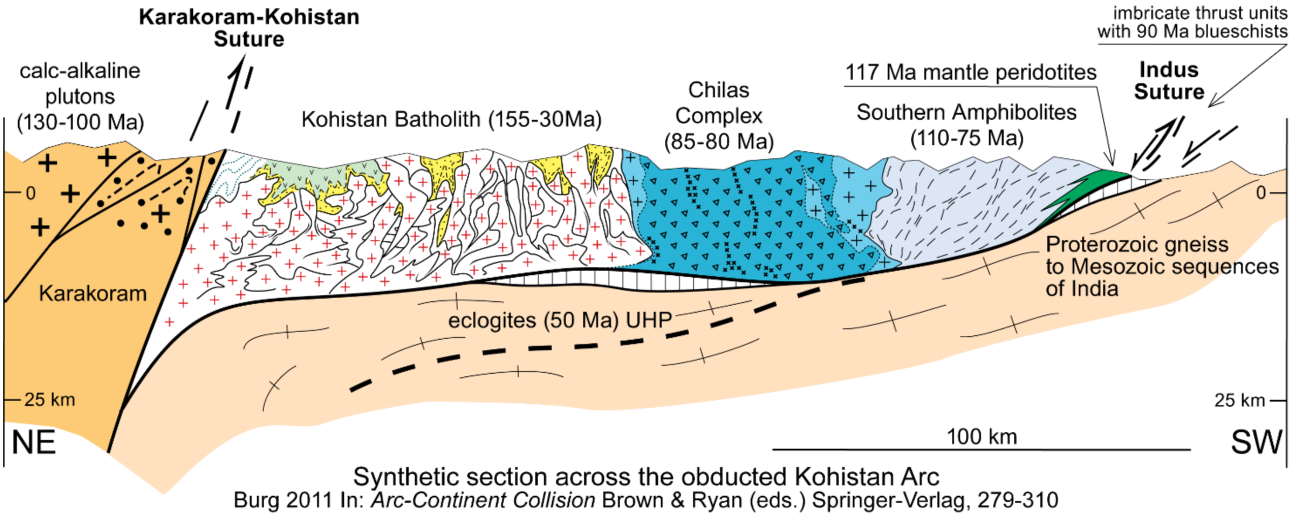
Basins within the island arc

To the Southwest and within the Kohistan Terrane, a metasedimentary sequence of deep marine origin (Dir, and Kalam Groups overlain by the calc-alkaline Utror volcanites) yielded late Paleocene (60-55 Ma) fossils in upper-level limestones. Depositional models point to rapid subsidence of an extensional, restricted basin in Paleocene times. Associated volcanic and volcanoclastic series are calc-alkaline basalts, basaltic andesites, and andesites, emphasizing an arc environment.

Plutonic crust

Kohistan Batholith

Kohistan Batholith is a name that gathers calc-alkaline granitoids. The oldest plutonic ages (U-Pb zircons) are ca 155 Ma and arc magmatism was a steady process until ca 30 Ma. Early plutons have isotopic signatures characteristic of a mantle derivation. The isotopic signatures of younger plutons show evidence for an increasing crust to mantle ratio, with the latest magmas being entirely crust-derived. Interpretation of this evolution refer to arc thickening and lower arc melting following suturing to Asia.



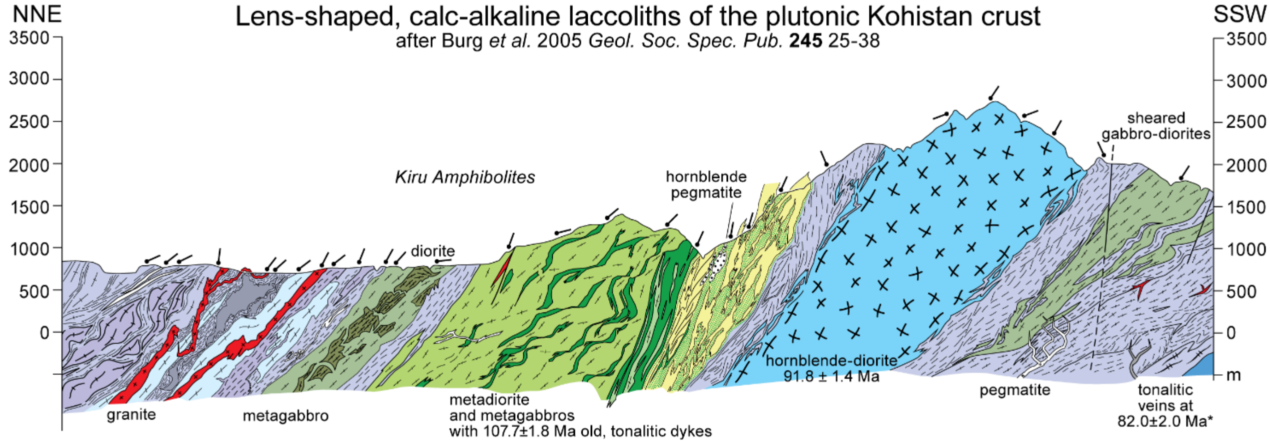
Synthetic section across the obducted Kohistan Arc
Burg 2011 In: *Arc-Continent Collision* Brown & Ryan (eds.) Springer-Verlag, 279-310

Gabbro-norites

A large body of locally layered gabbro-norite marks the axis of the arc. It is the more than 8 km thick and 300 km long Chilas Complex thought to be a layered magma chamber intruded into the arc in Cretaceous times. In detail, it is a stratiform complex of norites, noritic gabbros, and a string of lenses of diverse ultramafic-mafic-anorthosite (UMA) association.
The gabbro-norite cooled and equilibrated at 600-800°C and 0.6-0.8 GPa. A Sm-Nd internal isochron yields an age of ca 70 Ma, consistent with the conventional zircon U-Pb age of 85 Ma.

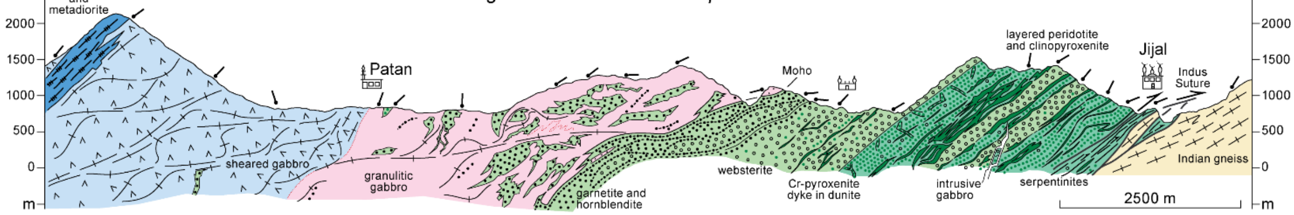
Meta- gabbros to tonalites

The Southern (so-called Kamila) Amphibolites form a thick pile of imbricated calc-alkaline laccoliths variably sheared in granulite to amphibolite facies conditions and dated between 110 and 75 Ma. Ar-Ar cooling ages on hornblendes cluster around 80 Ma.



<u>*Mantle*</u>

The so-called Jijal-Patan Complex is composed of more than 3 km thick ultramafic rocks overlain by garnet-plagioclase granulites. Garnet- and plagioclase-free peridotites and a few pyroxenites dominate the lowest section. The Jijal ultramafic rocks represent the sub-arc mantle at ca 120 Ma if a Sm-Nd isochron on clinopyroxenites dates their crystallization.



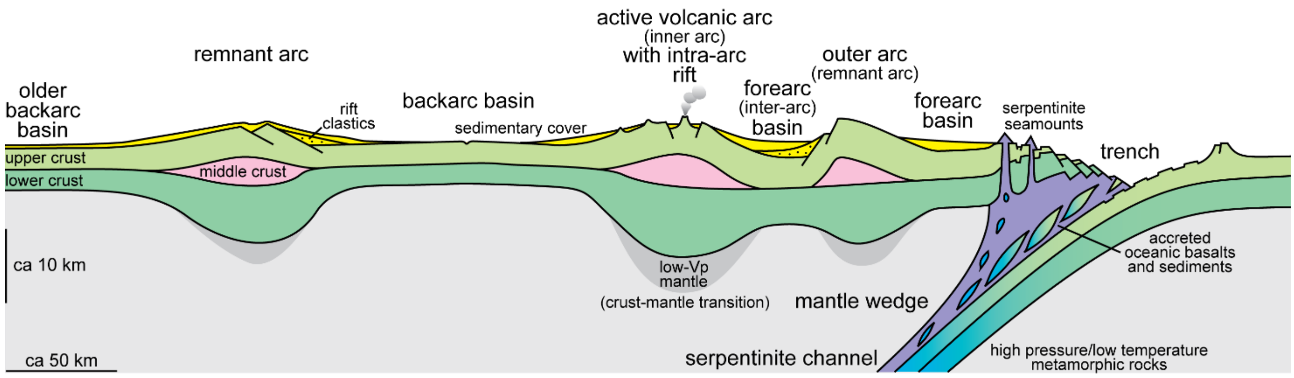
Section through the structurally deepest levels of the obducted Kohistan Arc
after Burg *et al.* 2005 *Geol. Soc. Spec. Pub.* **245** 25-38

The sharp contact between the ultramafic rocks and the overlying granulites, with well-preserved igneous structures, is the intrusive contact of lower crustal, calc-alkaline garnet-gabbros (the granulites) within mantle rocks. The contact is also the lower boundary of the arc crust, i.e. the arc-Moho. In the granulitic gabbro, metamorphic overprint essentially marks isobaric cooling within granulite facies conditions (starting T > 1150°C at early metamorphic pressures of 1.5-2 GPa). The granulitic gabbros have later re-equilibrated at >700°C and 1.5 $\pm$ 0.4 GPa, i.e depth equivalent > 50 km; these pressure conditions are similar to those calculated from the underlying ultramafic rocks. Sm-Nd isochrons at c. 95 Ma date cooling.

Arc splitting

The calc-alkaline Chilas norites and noritic gabbros were first interpreted as having crystallized in the sub-arc magma chamber. Petro-structural observation and geochemical analyses later suggested that the string of ultramafic-mafic-anorthosite associations occurring over the >300km length of the gabbro-norite represents apices of intra-arc mantle diapirs that served as porous flow conduits feeding the gabbro-norite. This interpretation is consistent with the gabbro-norites having intruded crustal components of the arc.

Structures in the Chilas suite of gabbros, norites, and mantle diapirs point to rifting splitting the Kohistan island arc, as it happens in modern subduction systems (e.g. Rocas Verdes in Southern Chili). Potential analogs of intra-oceanic arc rifting include Fiji and the Izu-Bonin-Marianas subduction, a 2500 km long arc system where the Pacific plate is subducting beneath the Philippine Sea plate.



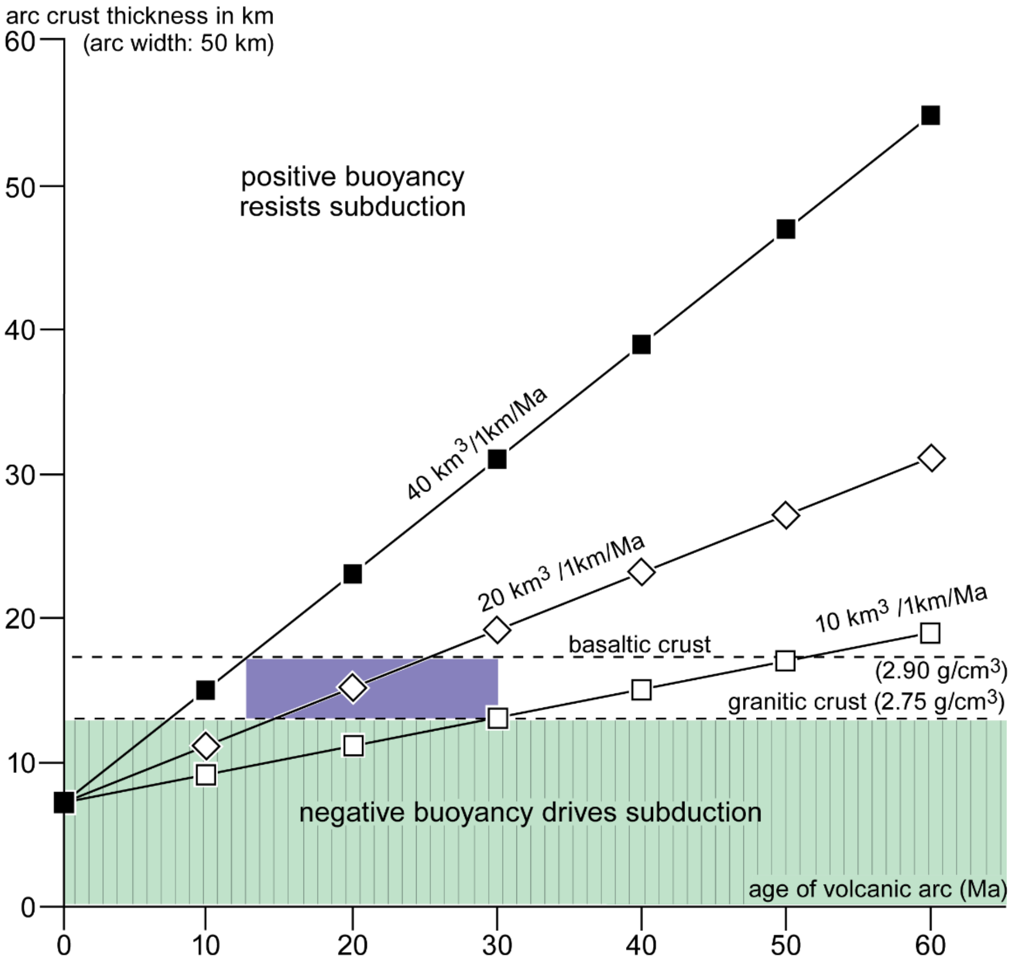
Generic section of an intra-oceanic subduction zone
after Ueda 2014 *Encyclopedia of Marine Geosciences* 8p. *doi:10.1007/978-94-007-6644-0_114-1*

The ultramafic-mafic-anorthosite outcrops point to mantle diapirism as a key mechanism in opening inter-arc basins between an active and a remnant volcanic arc, the latter perhaps now seen as rocks screening the Kohistan Batholith.

Obduction

Isostatic conditions

Simple isostatic calculations show that a 100 km thick oceanic lithosphere (7 km crust) with an intra-oceanic arc is negatively buoyant and thus can be subducted if the crust of the arc is as much as 8 km for basaltic to 10 km thick for granitic magmatism. The question is how long an arc should be active and thicken to the point that buoyancy would hinder subduction when it enters a trench. 10 Myr are sufficient for fast magmatic growth of arcs, and the upper boundary is around 40 Myr for slow magma production. The latter estimate is probably an upper limit since the calculation does not take into account the heating effect, which is thermal ”younging” of the lithosphere due to heat advection brought by plutons.



Relationship between the age of a volcanic arc,
the rate of arc magmatism (pro km length) and buoyancy
adapted from Cloos (1993) *Geol. Soc. Am. Bull.* **105(6)**, 715-737

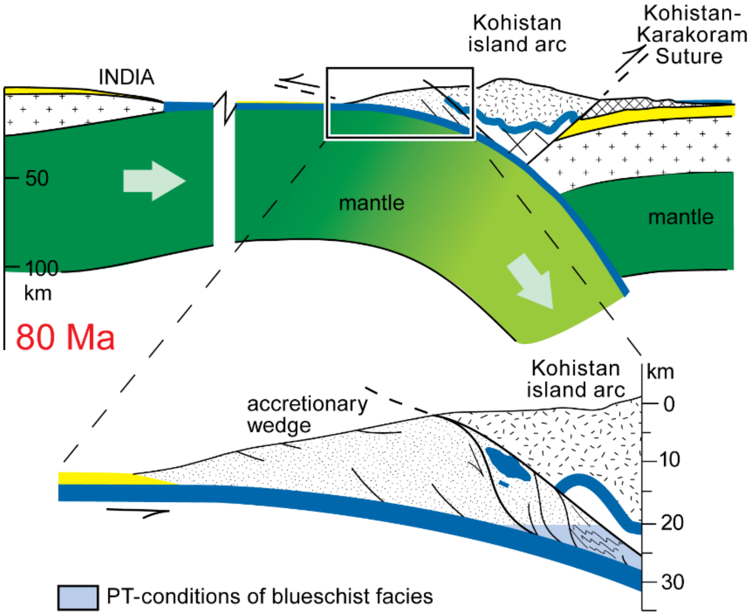
Metamorphic record

The Kohistan Arc and India were assembled during the closure of Tethys, which produced thrusting along the Indus Suture. Imbricated ophiolites, greenschists, and blueschists form a discontinuous but up to 20 km wide “mélange” within the suture zone, which is a dominantly forearc related metasedimentary and metavolcanic assemblage thrust onto the Indian plate. In the footwall, the geology of the northern margin of the Indian plate is remarkably uniform. Two high-pressure metamorphic events have accompanied the India-Kohistan convergence:

- blueschist facies metamorphism at ca. 80 Ma is linked to oceanic subduction,
- coesite-bearing eclogite facies metamorphism at ca. 50 Ma is linked to continental subduction.

Pre-collision events

Blueschists within the suture between India and the Kohistan Arc yielded ^{40}Ar-^{39}Ar and Rb-Sr phengite, and Na-amphibole ages at ca. 80 Ma and thus record a pre-collisional, Early/Late Cretaceous metamorphism during subduction of the Tethys oceanic lithosphere. Rapid exhumation and cooling of these high-pressure metamorphic rocks probably took place in an accretionary wedge.



Interpretation for blueschists in the Indus Suture
after Anczkiewicz *et al.* 2000 *Tectonophysics* **324** 111-134

Collision-related events

Coesite-bearing eclogites in Kaghan Valley, in the direct footwall of the Indus Suture, derive from Permian (245-275 Ma zircon ages), basaltic dykes intruded into the Indian continental margin during the break-up of Gondwana. Therefore, they are evidence that the leading edge of the Indian continent was deeply subducted (metamorphic pressures of 2.7 – 3.2 GPa, about 100km depth equivalence for lithostatic pressure) beneath the Kohistan Arc. U-Pb, Rb-Sr and Nd-Sm ages indicate that eclogite facies metamorphism happened at 50-45 Ma. This age is consistent with U-Pb zircon ages of coesite-bearing eclogites and gneisses of the Indian continent in the direct footwall of the Indus Suture beneath the Ladakh Arc, further west (Tso Morari region). Deep subduction of the northern margin of India about only 10 Myr after the initial collision was therefore broad below the island arcs.

From Kaneko *et al.* 2003
J. metamorphic Geol. **21(3)** 589-599

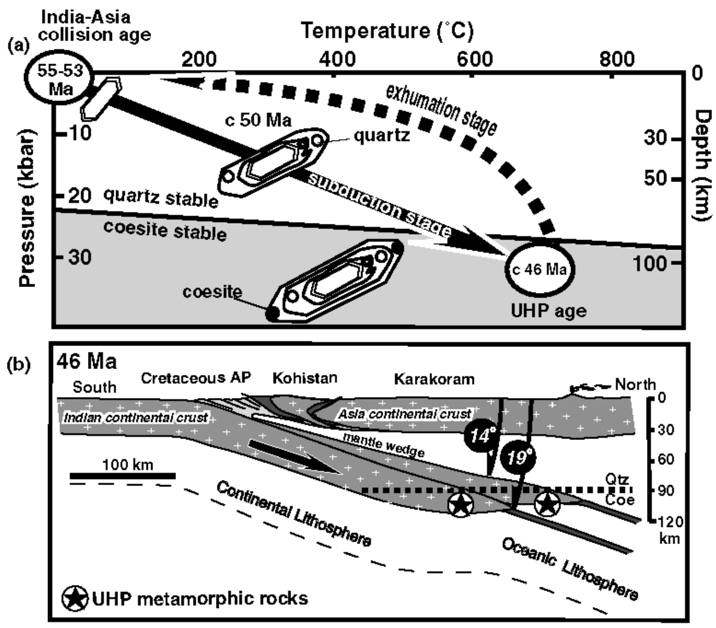


Fig. 10. (a) Schematic pressure-temperature-time paths for coesite-bearing Himalayan gneisses. SHRIMP analyses of different zircon domains allow the separation of the formational and metamorphic history of the Himalayan UHP rocks into three different stages: 253 170 Ma protolith age, 50.0 ± 1.0 Ma for the quartz-stable metamorphism stage, and 46.2 ± 0.7 Ma for the UHP metamorphism. Coesite-quartz reaction curve (Bohlen & Boettcher, 1982) is also shown. (b) Schematic cross-sectional diagram showing subduction of the northern part of the Indian continental crust, and formation of UHP rocks in the subducted slab at 46 Ma. The subduction rate of crustal rocks and the time integrated subduction angle are estimated as approximately 4.5 cm per year and 14 19°, respectively, since the initiation of the India Asia collision. AP = accretionary prism.

Exercise

Taking a convergence rate of 4.5 cm/a and assuming that the leading edge of India was 100 km deep 10 Ma after the initial collision, calculate the angle of subduction and compare with present-day subduction zones.

Much of the metamorphism of the Indian plate rocks in the footwall of the Indus Suture was along a Barrovian-type metamorphic gradient from chlorite to sillimanite grade. Peak metamorphism is dated at 45-50 Ma. The syn-metamorphic structures and fabrics in these rocks, therefore, should record an important part of the collisions and emplacement of the Kohistan Arc against this segment of the Indian plate. Ar/Ar mineral ages give cooling ages of hornblende at 38 Ma and muscovite cooling ages of 30 Ma.

Structures and Kinematics

Kohistan

In the lower levels of the Kohistan Terrane, strain localization took place continuously from magmatic emplacement to solid-state deformation during cooling of the gabbroic and dioritic plutons, between 100 and 83 Ma. The related shear strain probably represents arc-related deformation during the subduction of the Tethys oceanic lithosphere below the Kohistan Arc.
A major, nearly upright syncline (the Jaglot syncline) may have folded the Kohistan upper crust. Alternatively, steepening of the Indus Suture and the Kohistan sequence may be due to passive back tilting produced by extensional splitting of the arc, or movements on the younger thrusts as they move up ramps to the south, or possibly to northwards back thrusting on south-dipping thrusts.

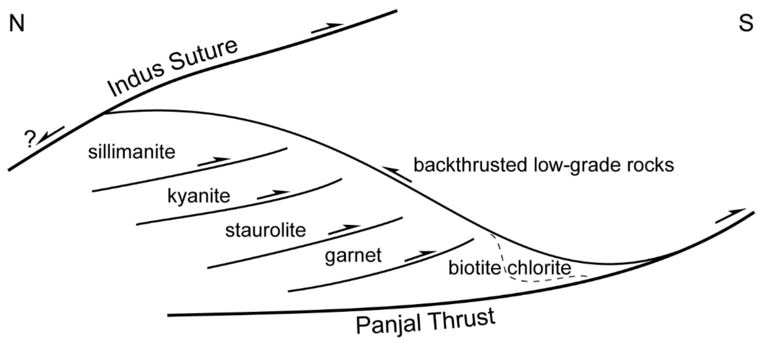
Indian Plate

The northern margin of the Indian plate consists of low- to high-grade calcareous schists, minor marbles and amphibolites considered to represent the Tethys oceanic crust and sediments, and basement gneisses that have been stacked into a series of thrust units.

Compressional structures

Oldest high-grade fabrics and related folds indicate southward thrusting. Shear-sense indicators parallel to roughly N-S trending stretching lineations in amphibolite facies rocks mostly express the south-directed, obduction related deformation.

Stacked metamorphic zones
by late thrusts in the footwall of the Indus Suture, in Pakistan
after Treloar *et al.* 1989 J. *metamorphic Geol* **7(1)** 111-125

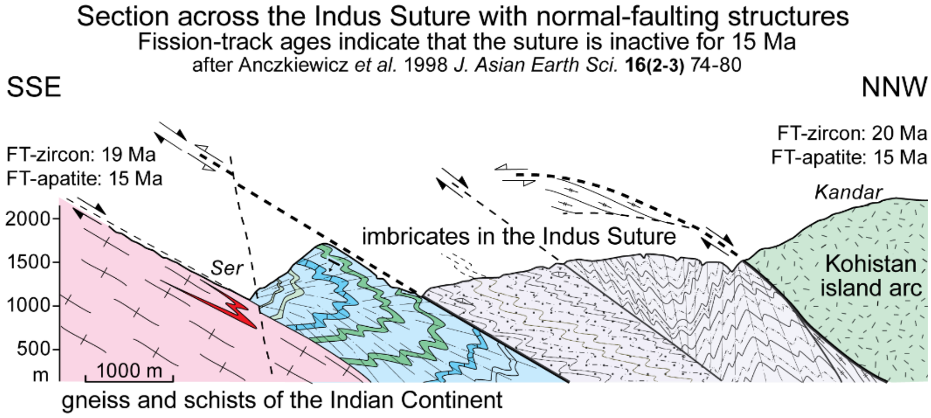


Southward imbrication of rocks of the northern edge of India produced sharp metamorphic discontinuities along ductile shear zones. The higher-grade rocks structurally overly the lower grades so that the metamorphic profile shows an overall tectonic inversion. This inverted metamorphic geometry is attributed to the sequential accretion of metamorphosed Indian plate rocks onto lower-grade rocks of the underthrusting parts of the plate.

The post-metamorphic post-Eocene thrust directions generated complex, refolded thrust patterns, large-scale folds, and rapid uplift with associated brittle faulting and seismic activity. No significant movement has taken place along the Indus Suture since 20 Ma, as indicated by similar fission-track ages on both sides of this Suture.

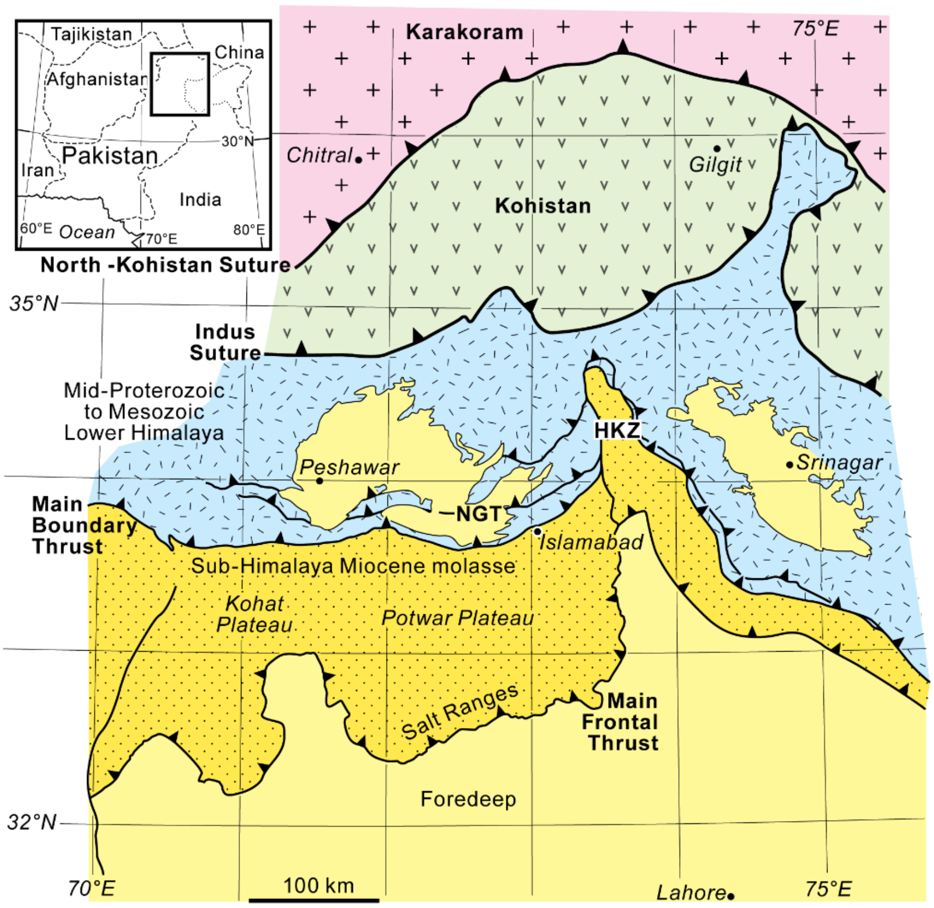
Extensional structures

Folds and shear bands give evidence for reactivation of the Indus Suture as a ductile-brittle normal fault. Mineral assemblages contained within both the thrust and extensional shear zones are consistent with both having operated synchronously during the amphibolite- to greenschist-facies transition. Amphibole Ar-Ar ages suggest that this was at 40-42 Ma. Normal faulting along the suture was still (or again) active between 29 and 15 Ma.



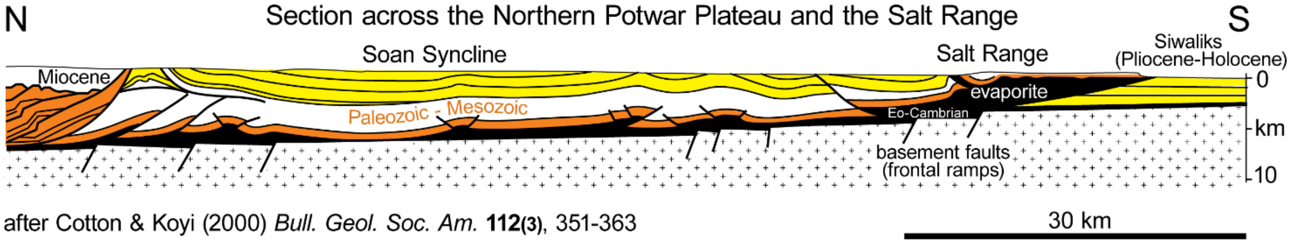
Recent compressional structures

Brittle reverse faults represent the latest faulting stage and show that shortening has outlasted normal faulting. In particular, recent folds and thrusts in the Indo-Gangetic foreland basin are parallel to the Main Boundary Thrust, the mountain front, and to the Main Frontal Thrust, about 100 km further south.



Thick, molasses-type deposits record the development of the Himalayan foredeep since 22 Ma. Enhanced subsidence rates throughout the foreland suggest that movement of the MBT became significant at about 11 Ma.

The Salt Range and Potwar Plateau are the external and recent expressions of Himalayan shortening. Seismic reflection data reveal that a thin-skinned fold-and-thrust belt detached upon thick early-Cambrian evaporites (mostly halite) and dominates thrusting across the foreland. The Main Frontal Thrust, carrying the Salt Range, represents the main décollement that steps upwards and becomes emergent to the south. The Potwar Plateau has been passively translated southward over the décollement level. A dextral wrench zone delimits the western limit of the Salt Range. It is attributed to the lateral boundary of the evaporites; the change in structural style on both sides of this fault zone reflects the lateral change in décollement rheology (weak friction over the evaporites versus stronger shear strength on the basement surface devoid of evaporite). Secondary décollements occur within Eocene evaporites and Neogene shales. The restored section and forward modeling suggest movement concentrated on the frontal thrust (from 10 to 5 Ma and since 2Ma) alternating with distributed deformation along forward and backthrusts throughout the section between 5 and 2 Ma.



after Cotton & Koyi (2000) *Bull. Geol. Soc. Am.* **112(3)**, 351-363

Thrusting and folding are still active in the region, as demonstrated by the 08.10.2005, Mw = 7.6 seismic event in the foreland thrust-and-fold belt, in front of Kohistan.

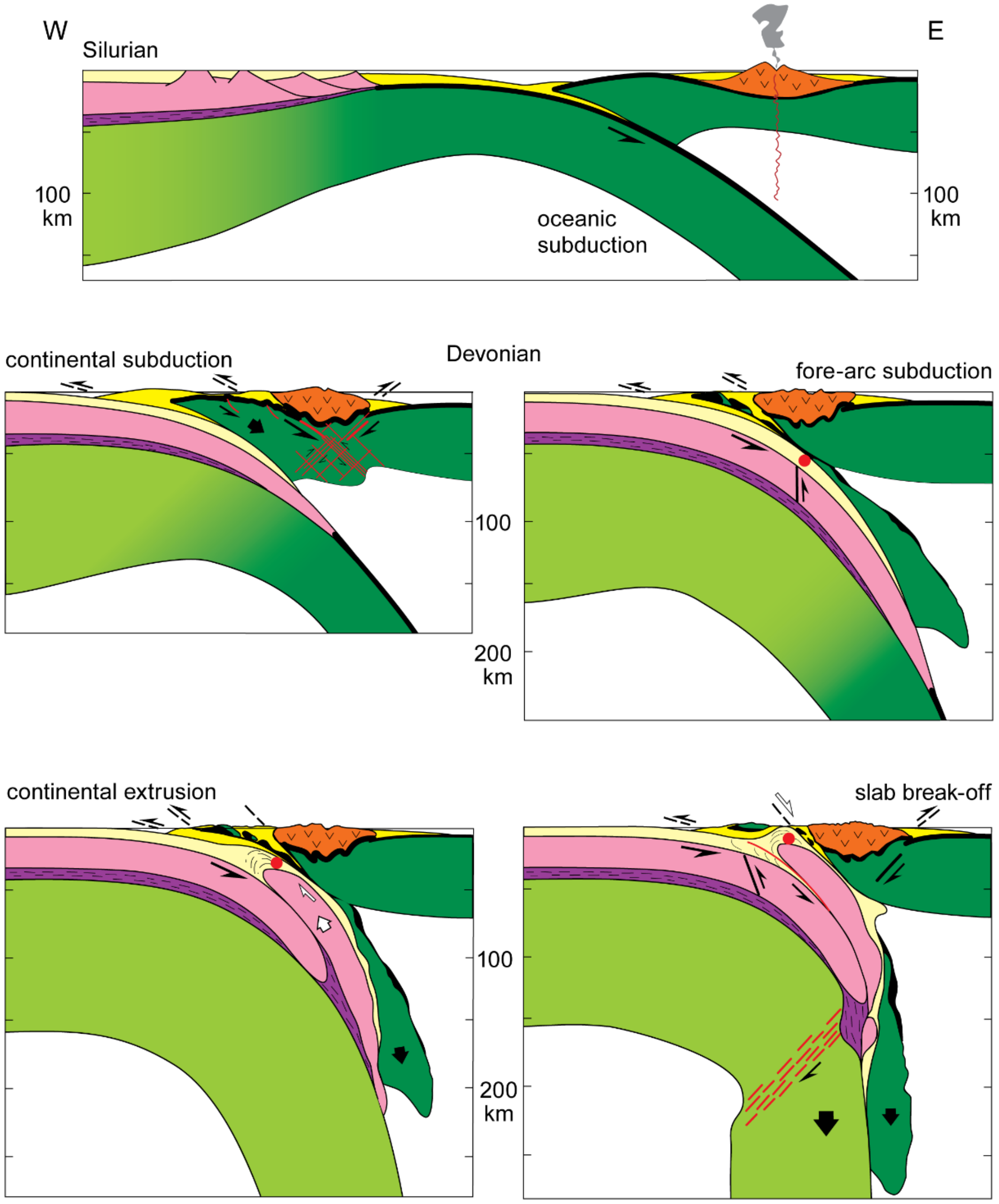
An exhumation problem?

The structural evolution of the arc-continent collision refers to analog modeling of the southern Ural collision. Five steps summarize the history:

- 1. The leading edge of the Indian continental margin entered into the trench at 60-55 Ma. Owing to its buoyancy, the subduction of an increasing amount of continental lithosphere progressively increased compressive stresses on the subduction plane and in the overriding plate. Continental subduction proceeds until the overriding plate yields along conjugate thrusts, in particular on both sides of the arc. The major, south verging thrust system would coincide with the Indus Suture and the conjugate, north-vergent system would occur along the Northern Suture where northward thrusts are reported**.** Deep subduction (100-150 km) of an old continent is a situation known today below the Banda arc.
- 2. Due to ongoing convergence, northward subduction involves both the Indian continental crust and a major part of the fore-arc region, which is clutched to the subducting continental lithosphere (Devonian stage in the model of Urals). Because the fore-arc represents a relatively cold oceanic lithosphere, its subduction contributes to achieving low-temperature gradients in the main subduction zone. It also screens the subducted continent from asthenospheric temperatures, thus permitting pressure and temperature conditions to form coesite-bearing eclogites.
- 3. The continental crust is subducted until increasing buoyancy forces reach its yield stress and failure produces a crustal-scale thrust away in front of the original suture. In Northwest Himalaya, the peak ultrahigh-pressure conditions date this event at about 45 Ma. The corresponding thrust is one of the many thrusts mapped to the south, in the Indian continent.
- 4. Upward expulsion of the subducted continental margin is due to its relatively negative buoyancy. The rising continental slice scrapes off previously subducted material including ophiolites, metaophiolites, and high-pressure / low-temperature rocks. This explains eclogites and blueschists of the Indus Suture, including those found within the Indian continent. Two major fault systems

accommodate uplift of the continental slice: a normal fault system along its upper boundary and a thrust system at the base. The upper normal fault system corresponds to the normal faulting reactivation of the Indus Suture. Both early thrusting and superimposed normal faulting juxtaposed blocks of different origins and metamorphic grades in the imbricated "mélange". The basal thrust system may include thrusts (e.g. the Panjal Thrust) known further south to be contemporaneous with normal faulting within the suture. As such, the normal movements along the Indus suture are accommodation features of buoyancy-driven uplift during a bulk convergence. Based on geochronological data, exhumation back to greenschist facies took place at about 40 Ma.

Analogue modelling of the southern Urals
after Chemenda *et al.* (1997) *Tectonophysics* **276**, 217-227



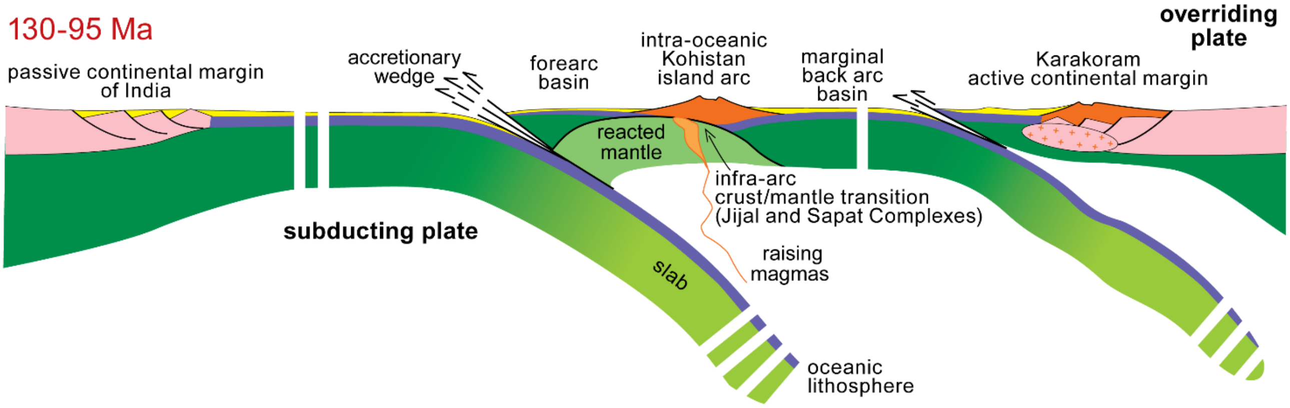
- 5. The expelled continental slice intruded the boundary between the overridden and the subducted plates, thus producing a wide antiformal area. Fission track dating indicates that rocks structurally belonging to the expelled continental slice cooled at ca. 20 Ma. In Pakistan, the antiformal area corresponds to large domes between the suture and the Dargai ophiolitic klippe. This klippe represents a tectonic outlier of the oceanic lithosphere on which the Kohistan Arc was transported.

Tectonic evolution of the West Himalaya

The tectonic models describing the Western Himalayas and Tethys suturing in Pakistan involve two subduction zones and two subsequent collisional events.

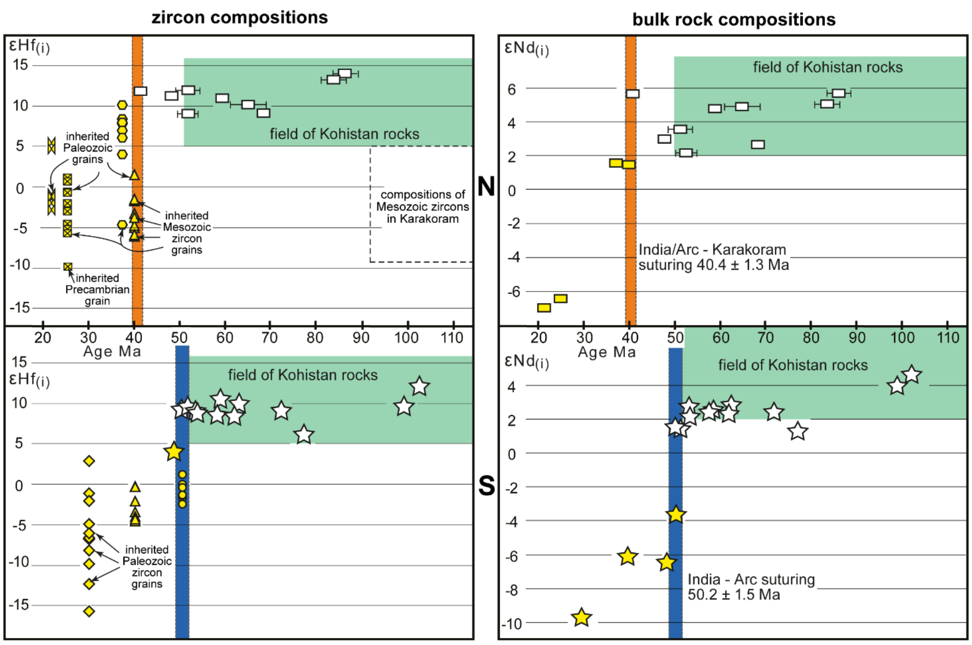
Double, north-dipping subduction

Double subduction during Early Cretaceous times (130–95 Ma) is required because arc-related magmatism of that age is established within both the Karakoram Eurasian margin and Kohistan. The simplest solution would plead that both were attached and represent the same arc. This is not sustainable because paleomagnetic data indicate that Karakoram and Kohistan were then thousands of kilometers apart and geochemical data demonstrate a Karakoram continental basement while Kohistan has grown on an oceanic lithosphere.



Continental arc–island arc docking: Karakoram–Kohistan

Dominantly mid-Cretaceous calc-alkaline magmatism in the Karakoram Batholith marks northward subduction beneath the continental magmatic arc of Asia until it choked by ca 95 Ma. The lack of evidence for a large oceanic slab has been an argument to infer that the Karakoram-Kohistan-Suture represents a narrow back-arc basin. Tectonic and magmatic activity existed until ca 30-20 Ma on both sides of the suture, offering a time gap sufficient to close a possible remnant oceanic basin. By comparison with modern continental forearcs, the width of this basin could have been anything from a 50 km wide straight to a more than 500 km wide sea. The discussion leaves open the question of linking cessation of convergence/subduction and full closure of the basin along the collision zone of the Karakoram forearc with the Kohistan back-arc.

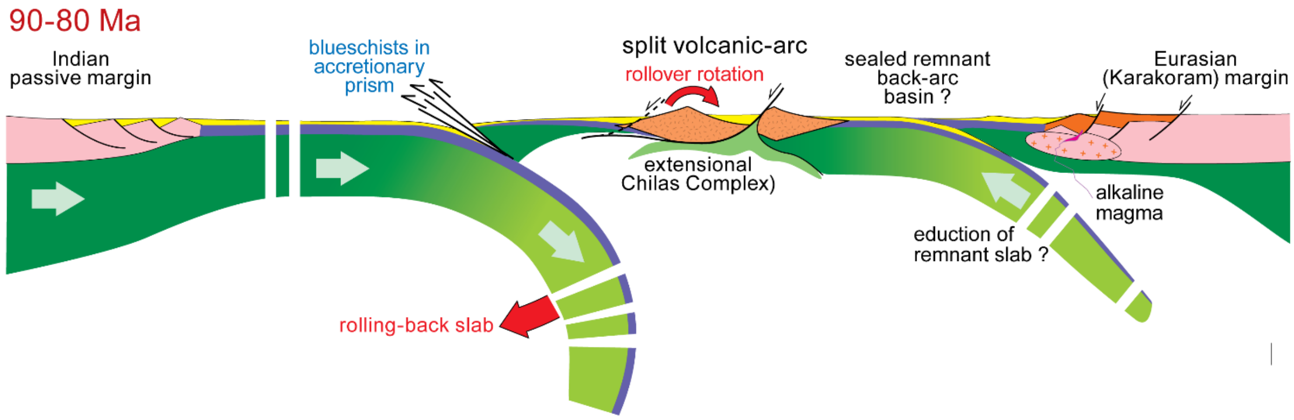


from Bouilhol *et al.* 2013 *Earth Planet.Sc.Lett.* **366** 163-175

Accretion of the Kohistan island arc to Asia has been variously dated between 102 and 45 Ma. Geochronological and multi-isotopic studies of magmatic rocks from the Kohistan/Ladakh Arc system define collision with India at 50.2±1.5 Ma and collision between the assembled India/Arc and Eurasia, along the Karakoram-Kohistan Suture and its eastern Shyok continuation, at 40.4±1.3 Ma.
Several hypotheses are allowed for the fate of the slab beneath the Karakoram, if any. Breakoff would trigger important magmatism and strong isostatic rebound of both plates. There is no evidence for either sign. Thermal absorption and/or eduction (reversed subduction) are possible. In the latter case, one would expect the exhumation of high-pressure rocks and prominent evidence for a top-to-the-north sense of shear. Since both are lacking in the Karakoram-Kohistan-Suture, the slab has likely faded through thermal dissipation.

Arc rifting: Slab rollback

The Chilas suite of mantle diapirs and the magmatic structures of the Chilas gabbro-norite and associated plutonic rocks document a bulk south-dipping extensional system. These observations come in complement to geochemical and petrological arguments, all pointing to the splitting of the Kohistan arc at about 85 Ma, with rifting taking place at the island arc, along its length. Contemporaneous alkaline plutonism in the Karakoram suggests that the whole system was then extensional. Opening of the subsequent back- or inter-arc basins may have separated a volcanic and a remnant arc, the latter now seen perhaps as rocks screening the Kohistan Batholith. The general north-dipping attitude of the Southern Amphibolites (the low crustal metagabbros and metadiorites) and their partial exhumation (regionally distributed $^{39}Ar/^{40}Ar$ cooling/unroofing ages at 83–80 Ma) may be attributed to extensional tilting. This (gravitational collapse?) event marks the end of magmatic activity in the southern part of the Kohistan arc Terrane.

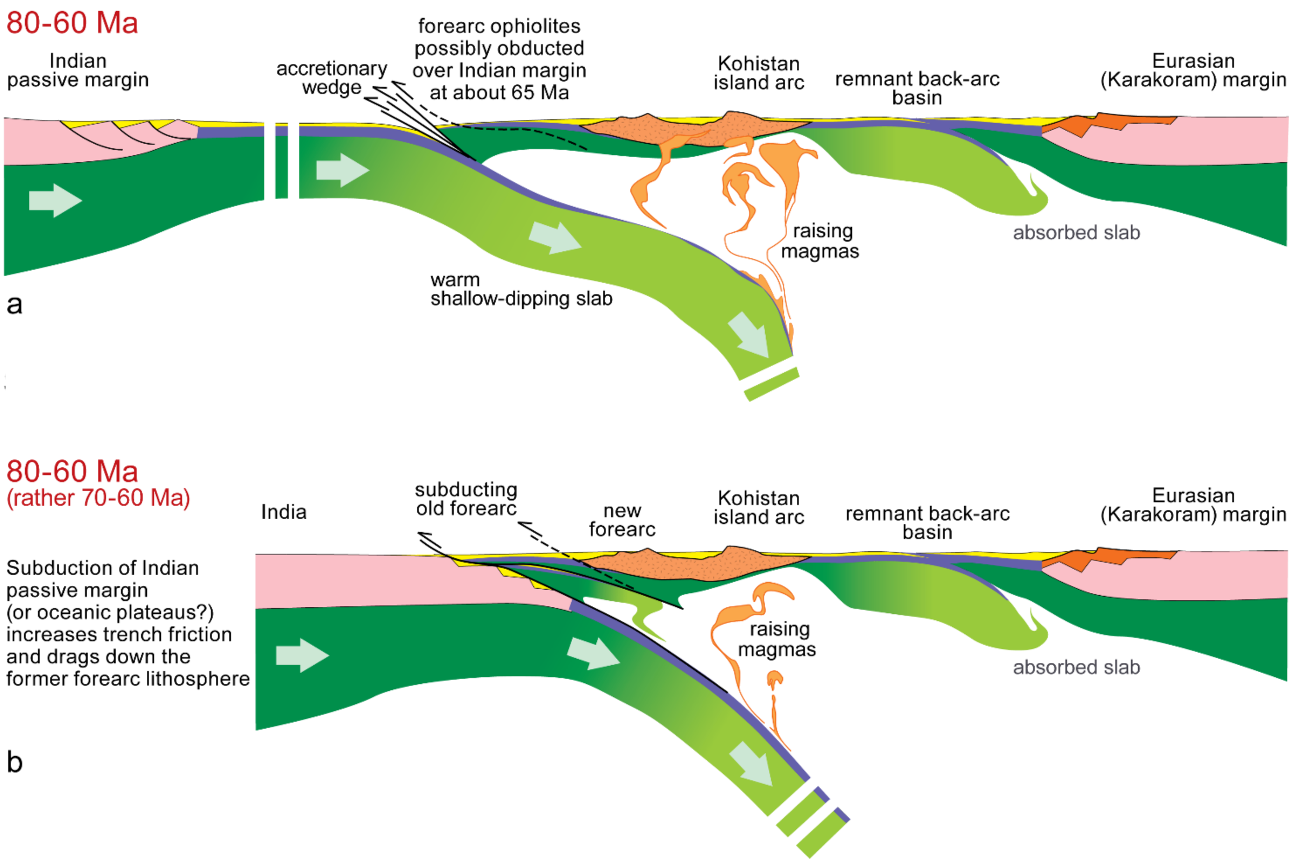


The crustal thickness of Kohistan was ca 50 km sometime around 100 Ma (depth equivalence of metamorphic pressure of granulite facies gabbros) and was reduced, at least locally, to 20–25 km during extension (petrological pressure 0.6-0.8 GPa. = depth of emplacement of the Chilas peridotites and gabbro-norite). In view of modern references such as the Lau Basin behind the Tonga Trench and the Mariana Trough and Trench, rifting apart Kohistan is tentatively linked to rollback. Rollback of the Tethys oceanic slab may have started as early as 105 Myr ago. Slab rollback and subsequent widespread extension in the hanging wall plate can also have favored exhumation of the blueschists in the accretionary wedge of the Indus Suture, between 90 and 80 Ma, and triggered cessation of the subduction beneath the Karakoram, which became kinematically unnecessary.

Single Subduction

A large amount of convergence and the fast rate at which India drifted over late-Cretaceous–Paleocene times are obvious indicators for ocean subduction south of the Kohistan arc, generating the post-80 Ma calc-alkaline batholith while India approached the arc by consumption of the intervening Tethys lithosphere.

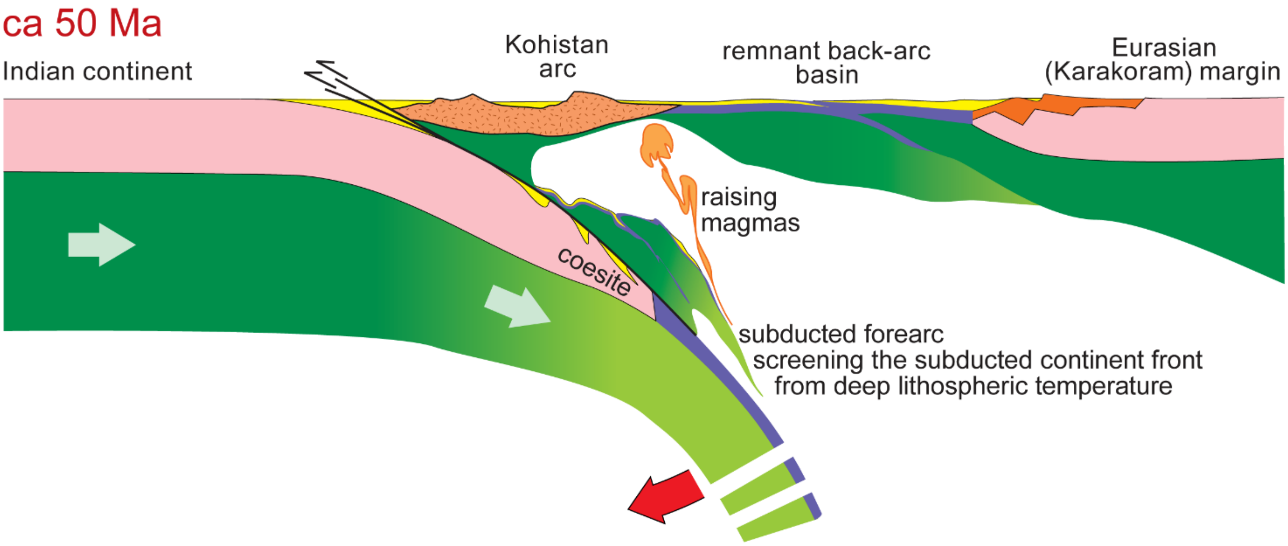
If the arc-trench gap depends on the dip angle of subduction, then the northward shift of the magmatic front from the Southern Amphibolites to the Kohistan Batholith can be due to the flattening of the slab. An important mechanism for flat-slab subduction is buoyancy. Either young Tethys lithosphere became subducted, marking the approach and entry of the oceanic ridge into the trench, or a submarine plateau made the flat portion of the subducted Tethys plate. Another mechanism for a shallow angle of descent is trench rollback due to the fast convergence rate.



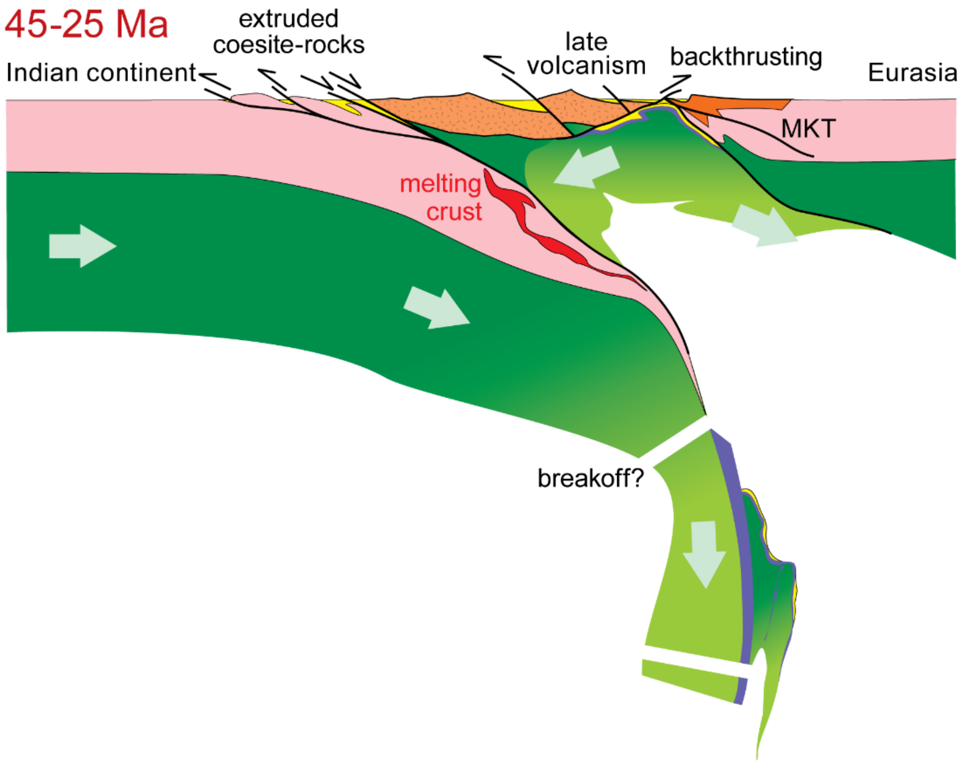
Analog modeling of intra-oceanic subduction systems offers an additional explanation for the temporal and spatial variation of magmatic activity: The magmatic front may have moved with the trench while the forearc was subducted. Forearc subduction would explain the scarce evidence for it and the accretionary wedge, the absence of large ophiolite nappes along with the relatively cold temperatures (thermal screening from the mantle) recorded by deeply subducted parts of the Indian continent.

Arc–Continent Collision: Kohistan–India

Collision processes started at about 65-55 Ma. At ca 55 Ma, tectonic interaction between the continental parts of India and Eurasia began, and frontal parts of the Indian continent were subducted down to the coesite stability field before 45 Ma. Contemporaneous rollback may have been active to allow space for extrusion within the trench region of ultra-high pressure crustal slivers of the Indian leading edge. Arc magmatism was still active in Kohistan, generated from the main Tethys slab or/and from the oceanic forearc. The subduction zone acted as a ramp along which the Kohistan arc and relicts of the fore-arc were obducted southward over India. Thrusts synthetic with the earlier subduction developed and placed sediment and slices of oceanic crust onto the continental margin.



The buoyancy of the Indian continental margin driven into the trench inhibited significant underthrusting of the continental lithosphere. Southward thrusting in the Indian continent was coeval with the reactivation of the Indus Suture as a ductile-brittle normal fault, numerous drag folds, and shear sense criteria indicating top-to-the-north normal movement. These structures are attributed to buoyancy-driven upward extrusion of the deeply subducted continental rocks thrust over the incoming tail of the Indian Continent. This is an important part of the Himalayan deformations that will further develop with syn- and post-metamorphic thrust imbrication at the expense of the Indian continent, with cooling through 500°C between 40 and 35 Ma.



Collision: Closure of all Basins

Increased horizontal stresses in the thickening collisional system lead to its total closure until locking of the sutures in Eocene–Miocene times. Within-arc and back-arc basins hosting as late as Eocene sedimentation were inverted at that time. Apatite fission-track ages indicate that suturing and basin closure were achieved by ca 15 Ma along both the Karakoram-Kohistan and the Indus Suture.

Conclusion

The geology of Northwest Himalaya documents a fossil, obducted intra-oceanic arc, Kohistan, which grew during the Mesozoic on the northern side of (Neo-)Tethys, while the southern side of this ocean was subducting northward below the arc. The magmatic history shows that such arcs create new continental-type crust. An important part of the Kohistan history involves arc-transverse rifting in the Late Cretaceous as an arc-building process at a mature stage. The life of intra-oceanic arc is correspondingly limited and unstable, punctuated by important changes in tectonic settings and magmatic production and location.

Early continental subduction refers to obduction and progressive increase of horizontal stresses until compression is strong enough to trigger full collision and closes all basins between intra-oceanic arcs and a continent. Cessation of calc-alkaline magmatism in Kohistan signs the waning stages of this full collision while high-stress continental collision begins. In the northwest Himalaya, this happened during Eocene–Miocene times when the Kohistan Arc was trapped and accreted between India and Asia.

A foreland thrust belt is currently active at the southern fringe of the Himalayan range. The Salt Range, where the basal thrust is still moving, results from arc-continent collision several tens of kilometers to the north.

Question

Is arc magmatism a steady-state growth process?

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