Educational Material

Script to Tectonics

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West-Himalaya: Island arc / continent collision

Closure of the Tethys Ocean and subsequent 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 Complex 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 Complex 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
Permian magmatic ages of granite-gneiss and tholeiitic metabasalts found on the northern edge of the Indian continent were produced during rifting that led to break-up of Pangea. This magmatism was pervasive, which suggests that India was the upper passive margin of the asymmetric extensional system. Like 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 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 anticlockwise rotation, which is still on-going. 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 formation of the Himalayas started in the early Cretaceous, when the Indian continent started drifting northward, opening the Indian Ocean behind, to the south, while closing the Tethys Ocean to the north. At that time, the intra-oceanic Kohistan arc formed over a subduction zone that dipped beneath the arc to the north.

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 at 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 north-western Himalaya (at 62-60 Ma) until Early Eocene (ca. 50 Ma) in the eastern Himalaya. The convergence rate became markedly slower after 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**

The backbone of the Karakoram Range is made up of Mid-Cretaceous to Late Cenozoic (120-55 Ma) tonalites, diorites and granodiorites with a calc-alkaline signature. 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. This interpretation is supported by strong stratigraphic similarities of the screening rocks. 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; 10 kbar). 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. Little is known about the thickness of the Karakoram plate. 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 as either 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 a series of late brittle faults that have faulted away the original suture. Undeformed subalkaline plutons of Eocene age are found on both sides of the Karakoram-Kohistan Suture. The 75 Ma age of an undeformed dyke cutting foliated rocks was taken as additional key to infer that this Suture was closed in the Late-Cretaceous, sometime between 100 and 85 Ma. However, calc-alkaline magmatism continued until at least 35 Ma in the Kohistan Arc and some Karakoram granitoids are as young as about 20 Ma. Paleomagnetic, structural, metamorphic and geochemical arguments rather indicate that, like early interpretations suggested, closure of the Karakoram–Kohistan Suture postdates collision of the Kohistan arc with India. In any case, 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 Kohistan sequence separates a structurally coherent section of an island arc terrane, comprising of a 30 to 40 km thick section of metamorphosed, plutonic, volcanic and sedimentary rocks. Six main rock assemblages from north to south, i.e. downward sequence, are present.

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Upper crust

Upper crustal sequences pertain to two geographically distinct domains.

Northern side of the island arc
Just south of the Karakoram-Kohistan Suture, they 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 form 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 to 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 Complex, 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 in Paleocene times in an extensional, restricted basin. Associated volcanic and volcanoclastic series are calc-alkaline basalts, basaltic andesites and andesites, emphasising an arc environment.

**Plutonic crust**

**Kohistan Batholith**

Kohistan Batholith is a name that gathers intrusive calc-alkaline granitoids. The oldest plutonic ages are at ca 155 Ma and arc magmatism was a steady process until ca. 50 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. This evolution is interpreted as the result of arc thickening and lower arc melting following suturing to Asia.

**Gabbronorites**

A massive body of locally layered gabbrororites 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 details, 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 6-8 kbar. A Sm-Nd internal isochron yields an age of c. 70 Ma, consistent with the conventional zircon U-Pb age of 85 Ma.

**Meta-gabbros to tonalities**

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

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 peridotites represent the sub-arc mantle. 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 depth > 50 km although early metamorphic pressures may have increased. The granulitic gabbros have later re-equilibrated at >700°C and 15 ± 4 kbar, which are pressure conditions similar to those calculated from the underlying ultramafic rocks. Sm-Nd isochrons at c. 95 Ma date cooling.

This succession is interpreted as a whole as calc-alkaline plutons intrusive into an oceanic crust and overlain by the calc-alkaline lavas and associated sediments. Accordingly, the interpretation is an intra-oceanic arc that developed during the Cretaceous somewhere in Tethys, a situation reminiscent of, but more evolved than the calc-alkaline lavas found in the Oman ophiolites.

Arc splitting

The calc-alkaline Chilas norites and noritic gabbros were first interpreted as having crystallised in the sub-arc magma chamber. Later geochemical analyses suggested that it was generated by intra-arc rifting and subsequent mantle diapirism. The latter interpretation is consistent with the gabbro-norites having intruded volcanic and sedimentary components of the arc. Petro-structural observation supportively suggests that the ultramafic-mafic-anorthosite associations occurring as a string of lenses over the >300km length of the gabbro-norite represent apices of intra-arc mantle diapirs that served as porous flow conduits to feed the gabbro-norite.

The Chilas suite of mantle diapirs points to splitting of the Kohistan arc, with initial rifting taking place at the island arc like it is documented in modern island systems (e.g. Rocas Verdes in Southern Chile). Potential analogues 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.
The UMA outcrops point to mantle diapirism as a key mechanism in opening back-arc basins between a volcanic and a remnant 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 can be subducted if the crust of the arc is as much as 8 to 10 km thick for granitic or basaltic magmatism, respectively. The question raised here is how long should an arc be active to thicken to the point that buoyancy would hinder subduction when the arc enters a trench. 10 Ma are sufficient for fast magma producing arcs, and the upper boundary is around 40 Ma 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.

![Diagram showing the relationship between the age of a volcanic arc, the rate of arc magmatism (pro km length) and buoyancy](image_url)

**Metamorphic record**

The Kohistan Arc and India were assembled during closure of Tethys, which produced thrusting along the Indus Suture. Within the Suture, a discontinuous but up to 20 km wide zone of imbricated ophiolites, greenschists and blueschists is locally referred to as “mélange unit”. It is a dominantly fore-arc related metasedimentary and metavolcanic assemblage obducted onto the Indian plate. In the footwall, the geology of the northern margin of the Indian plate is remarkably uniform. However, 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 imbricated within the suture between India and the Kohistan Arc yielded $^{40}\text{Ar} - ^{39}\text{Ar}$ 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 prism system.

**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 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 Ma after initial collision was therefore broad below the island arcs.
Exercise

Taking a convergence rate of 4.5 cm/yr and assuming that the leading edge of India was 100 km deep 10 Myr after 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 Complex strain localisation 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 subduction of the Tethys oceanic lithosphere below the Kohistan Arc Complex.
A major syncline (the Jaglot syncline) appears to involve the whole upper crust of Kohistan. However, steepening of the Indus Suture and the Kohistan sequence may be due to passive back-tilting produced by movements on the younger thrusts as they move up ramps to the south, or possibly to northwards back-thrusting on a southward dipping thrust.

**Indian Plate**
The uppermost rocks below the suture zone is a low-grade metamorphic sequence considered to represent Tethys sediments.

**Compressional structures**
The northern margin of the Indian plate consists of low- to high-grade calcareous schists, minor marbles and amphibolites and basement gneisses that have been stacked into a series of thrust units. Early high-grade fabrics and related folds indicate southward thrusting. Shear-sense indicators parallel to roughly N-S trending stretching lineations in amphibolite facies rocks of the Indian plate mostly express the south-directed, obduction related deformation. Post-metamorphic southward imbrication of rocks belonging to 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-Eocene thrust directions generated complex, refolded thrust patterns, large slab folding 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 later 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.

![Section across the Indus Suture with normal-faulting structures](image)

**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 the MBT began significant movement at about 11 Ma.

The Salt Range and Potwar Plateau are the external and most recent expression of Himalayan shortening. Seismic reflection data reveal that a thin-skinned fold-and-thrust belt detached upon thick early-Cambrian evaporites (mostly halite) 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 within Neogene shales. Restored section and forward modelling suggest movement concentrated on the frontal thrust (from 10 to 5 Ma and since 2 Ma) alternating with distributed deformation along forward and backthrusts throughout the section between 5 and 2 Ma.

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 analogue modelling of the southern Ural collision. The history can be summarised in 5 steps:
- 1. The leading edge of the Indian continental margin entered into the trench at 60-55 Ma. Owing to its buoyancy, 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. Because the fore-arc represents a relatively cold oceanic lithosphere, its subduction contributes to achieving low temperature gradients in the 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 this event is dated by the peak ultrahigh-pressure conditions 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 would explain eclogites and blueschists of the Indus Suture, including those found within the Indian continent. Uplift of the continental slice is accommodated by two major fault systems: a normal fault system along the upper slice boundary and a thrusting system at the base. The upper normal fault system would correspond to the normal faulting reactivation of the Indus Suture. As a result of both early thrusting and superimposed normal faulting, blocks of different origins and metamorphic grades are juxtaposed. The basal thrust system may include thrusts known further south (e.g. the Panjal Thrust) to be contemporaneous with extension within the suture. As such, the normal movements along the Indus suture are accommodation features of buoyancy-driven uplift during a bulk convergence. On the basis of geochronological data, exhumation back to greenschist facies was achieved at about 40 Ma.

- 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 would correspond to large domes between the suture and the Dargai ophiolitic klippe. This klippe would represent a tectonic outlier of the oceanic lithosphere on which the Kohistan arc was installed.

**Tectonic evolution of the West Himalaya**

The tectonic models describing the Western Himalayas and Tethys suturing in Pakistan involves two 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 kilometres apart and geochemical data demonstrate a Karakoram continental basement while Kohistan was installed on an oceanic lithosphere. The magmatic history of Karakoram suggests that the Karakoram-Kohistan Suture (KKS) subduction zone choked by ca 95 Ma. The lack of evidence for subduction of a large oceanic slab has been argument to infer that the KKS represents a closed back-arc basin.

![Diagram of tectonic evolution in the West Himalaya](image-url)
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.

**Continental arc–island arc docking: Karakoram–Kohistan**

Dominantly mid-Cretaceous calc-alkaline magmatism in the Karakoram Batholith marks northward subduction of the northern Tethys Ocean beneath Asia. Subsequent accretion of the Kohistan Complex to Asia along the KKS has been variously placed between 102 and 75 Ma, or after the 65-55 Ma Kohistan/Asia collision. Geochronological and multi-isotopic studies of magmatic rocks from the Kohistan / Ladakh Arc define collision with India at 50.2±1.5 Ma and collision between the assembled India/Arc and Eurasia, along the KKS and its eastern Shyok continuation, at 40.4±1.3 Ma.

Tectonic and magmatic activity existed until ca 30 Ma on the Kohistan side of the suture, offering a time gap sufficient to close a possible remnant oceanic basin, which comprised at least the Karakoram forearc. 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. Several hypotheses are allowed for the fate of the KKS slab. 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 exhumation of high-pressure rocks and prominent evidence for top-to-the-north sense of shear. Since both are lacking in the KKS, the slab has likely faded through thermal dissipation.

**Arc rifting: Slab rollback**

The Chilas suite of mantle diapirs and the the magmatic structures of the Chilas gabbronorite and associated plutonic rocks document a bulk south-dipping extensional system. These observations come in complement to geochemical and petrological arguments, all pointing to splitting of the Kohistan arc at about 85 Ma, with initial rifting taking place at the island arc, along its length. Contemporaneous alkaline plutonism in Karakoram suggests that the whole system was then extensional. Opening of the subsequent back-arc basins should 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 Complex.

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 = 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 Ma ago. Slab rollback and subsequent widespread extension in the hanging wall plate can also have favoured exhumation of the blueschists in the accretionary wedge of the Indus Suture, between 90 and 80 Ma, and triggered cessation of the subduction beneath Karakoram, which became kinematically unnecessary.

**Single Subduction**

The 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, abundant and calc-alkaline batholith while India approached the arc by the consumption of the intervening ocean. Contemporaneous rollback may have been active until 55–50 Ma to allow space for extrusion of ultra-high pressure crustal slivers of the Indian leading edge within the trench region.

If the arc-trench gap depends on the dip angle of subduction, then northward shift of the magmatic front from the Southern-Amphibolites to the Kohistan Batholith can be due to 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 fast convergence rate. Analogue modelling 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 recorded by deeply subducted parts of the Indian continent.

**Arc–Continent Collision: Kohistan–India**
Subsequent closure of the Tethys ocean took place 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. Arc magmatism was still active, generated from the main Tethys slab or/and from the oceanic forearc. The subducting Indian plate acted as a ramp along which the Kohistan arc and fore-arc were obducted southward over India. Once the Indian continental margin had been driven into the trench, its buoyancy inhibited significant underthrusting of continental lithosphere. Thrust slices towards the continent, synthetic with the early subduction, developed while sediment and slices of oceanic crust were driven onto the continental margin.

![Diagram](image)

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 expenses 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 with till Eocene sedimentation were likely inverted at that time. Apatite fission track ages indicate that suturing and basin closure were achieved by ca 15 Ma along both the KKS and the Indus Suture.
Conclusion
The Northwest Himalaya is a mountain range resulting from collision between an island arc and a continent. Kohistan geology establishes the existence of a fossil, obducted island arc which grew during the Mesozoic on the northern side of Neo-Tethys, while the southern side was subducting northward below the arc. The magmatic history shows that magmatic arcs are the main areas where new continental crust is created. The life of such an arc is limited and unstable, punctuated by important changes in tectonic settings and magmatic production and location. An important part of the Kohistan history involves arc-transverse rifting in the Late Cretaceous as arc-building process at a mature stage.

Early continental subduction refers to obduction and progressively increased horizontal stresses until compression was strong enough to trigger full collision and close all oceanic basins during Eocene–Miocene times. The arc was trapped and accreted between India and Asia in the early Eocene. Cessation of calc-alkaline magmatism in Kohistan signs the waning stages of this full collision while high-stress continental collision begins.

The Himalayan range represents a foreland thrust belt, currently active at its southern limit in the Salt Range where the basal thrust is still moving, resulting from arc-continent collision several hundred kilometres to the north.

Question
Is arc magmatism a steady-state growth process?

Recommended Literature


