The Kohistan Sequence: Crust and Mantle of an Obducted Island Arc.

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Abstract: The Kohistan sequence outcrops in the western part of the western Himalayan syntaxis. It is a thick pile (30-40 km) of metamorphosed magmatic, volcanic and sedimentary rocks. It is composed of six main units i.e. from bottom to top:

- the southern amphibolitic belt with basal ultramafics,
- the "pyroxene granulite" belt (10-15 km thick),
- the northern amphibolitic belt, intruded by various dioritic bodies,
- a metasedimentary oceanic series (Kalam series),
- a volcanic calc-alkaline series (Utror Volcanics), up to 6-8 km thick,
- an upper detrital series (Yasin group, Lower Cretaceous).

This sequence is interpreted as a complete cross-section of a mature island arc formed by subduction during Mesozoic in the southern part of the Neotethys and obducted onto the Indian plate in Upper Cretaceous times.

A) INTRODUCTION

The presence of oceanic sutures and ophiolitic rocks separating the Asian and Indian continents along the Himalayan belt is now widely accepted. Typical ophiolitic sequences and melanges have been well described in Afghanistan and Pakistan (Mattauer *et al.*, 1978; Asrarullah *et al.*, 1979) and in the Tsangpo and Ladakh areas (Gansser, 1964, 1980; Franke *et al.*, 1977).

However in the western syntaxis of the Himalaya (Kohistan and surrounding areas) the rocks belonging to the suture zone are not typical ophiolites but a thick complex sequence (40 km) of calcalkaline plutonic, volcanic and volcanosedimentary rocks, which have suffered low to high grade metamorphism: the Kohistan sequence. It has been proposed that this sequence represents the complete cross-section of an island arc obducted onto the Indian continent (Tahirkheli *et al.*, 1979). New field work and petrologic studies strongly support this hypothesis.

The aim of this paper is to describe in more detail the Kohistan sequence, to discuss the origin of the metamorphic, magmatic and metavolcanic rocks and to put forward the arguments favouring our interpretation of an obducted island arc.

B) – THE KOHISTAN SEQUENCE

The Kohistan sequence is particularly well developed in the western branch of the Himalayan syntaxis between 71°E (Kunar river) and 75°E (Nanga Parbat antiform). This sequence appears as a thick, more or less monoclinal slab dipping 30° to 60° NW and is bounded by two main thrusts: The low dipping "main mantle thrust" (MMT) separates the Kohistan sequence from the Indian plate. It has been strongly refolded in places (Nanga Parbat, Patan antiforms). The Main Karokorum thrust (MKT) or Northern Megashear (Tahirkheli and Jan, 1979) is generally verticalized and marks the boundary between the Kohistan sequence and the Asian continent (fig. 1).

The sequence may be well described along three main natural cross-sections: the Panjkora (Dir), Swat (Saidu-Bahrain-Utror) and Indus (Jijal-Chilas-Gilgit) valleys which cut the Kohistan Mountains in a more or less transverse direction.

Despite the intrusion of late to postkinematic bodies of dioritic to granitic roks, and tectonic complications due to some minor thrusts, six main lithologic series may be distinguished from bottom to top in the Kohistan sequence (fig. 2):

1 – a "Southern (or Lower) Amphibolitic belt" (Jan and Mian 1971; Jan, 1979) which shows in its lower part various ultramafic bodies such as those of the Jijal-Patan complex;

2 – a "Pyroxene Granulite belt" whose thickness (10-15 km) decreases progressively westwards and eastwards from the central Indus valley section;

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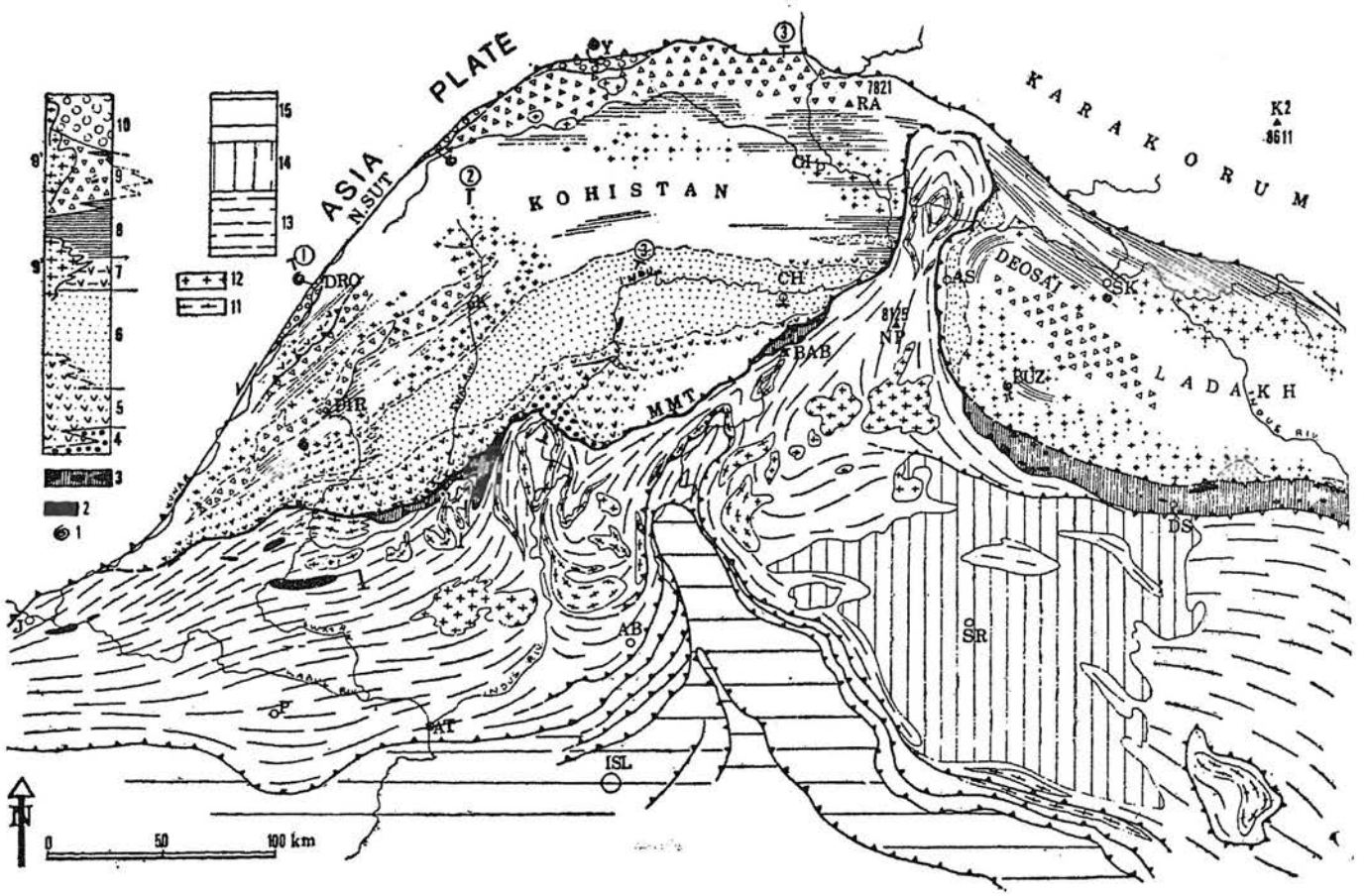

Fig. 1. Interpretative geological sketch map of the western Himalayan syntaxis.

Kohistan arc sequence : 1) Cretaceous fossils (Eocene in Dir) — 2) Ultramafic klippes — 3) Green schist belt, with local blue-schist slices (Shangla-Kargil)-Ophiolitic melanges, with peridotite blocks (including Dras volcanics) — 4) Jijal ultramafic complex — 5) Southern amphibolitic belt — 6) "Pyroxene Granulite" belt — 7) Northern Amphibolitic belt — 8) Kalam-like oceanic series — 9) Utror volcanic and volcanosedimentary equivalents — 9) Syn to post-kinematic dioritic and granodioritic intrusives — 10) Detrital upper series.

Indian Plate : 11) Orthogneiss (Paleozoic granites ?) — 12) Un-deformed granitoids — 13) Precambrian and Paleozoic series — 13) Upper Paleozoic to Triassic series of the Srinagar basin including Panjal Traps — 15) Foreland Cenozoic deposits (Murree form. etc .....)

AB : Abbottabad — AS : Astor — AT : Attock — BAB : Babusar pass — BUZ : Burzil pass — DRO : Drosh — Ds : Dras — GI : Gilgit — ISL : Islamabad — J : Jallalabad — K : Kalam — N. SUT : Northern Suture — MMT : Main "mantle" thrust (Southern suture) — NP : Nanga Parbat — P: Peshawar — SR: Srinagar — SK : Skardu.

3 – a "Northern (or Upper) Amphibolitic belt" intruded by various latekinematic diorites and granodiorites; this belt shows some meta-gabbros and pillowed metabasalts of possible ophiolitic origin;

4 – a "Metasedimentary Series" of black or green shales interbedded with metacherts and scarce calcomagnesian lenses (Kalam Series, Jan op. cit);

5 – a "Volcanic Series" (Utror volcanites) up to 6-8 km thick, with intraformational conglomerates, volcanic agglomerates, andesitic lava flows in the lower part and dacitic-rhyodacitic (even perhaps rhyolitic) lavas in the upper part. These volcanics belong to a calc-alkaline series similar to that of present mature island arcs; These two units are also intruded by the same various late to post-kinematic diorites, granodiorites and a few granitic rocks;

6 – "A detrital upper Series" of pink-violet shales, wackes and some volcanics which begins by polygenic conglomerates with pebbles of Utror Volcanics and dioritic rocks. Limestones interbedded in this series have given Lower Cretaceous fossils (Drosh-Yasin).

B.I. – The Southern Amphibolitic Belt

This thick Series (5-15 km) has been well described by Jan (1971-1979). It is mainly composed of massive or banded amphibolites.

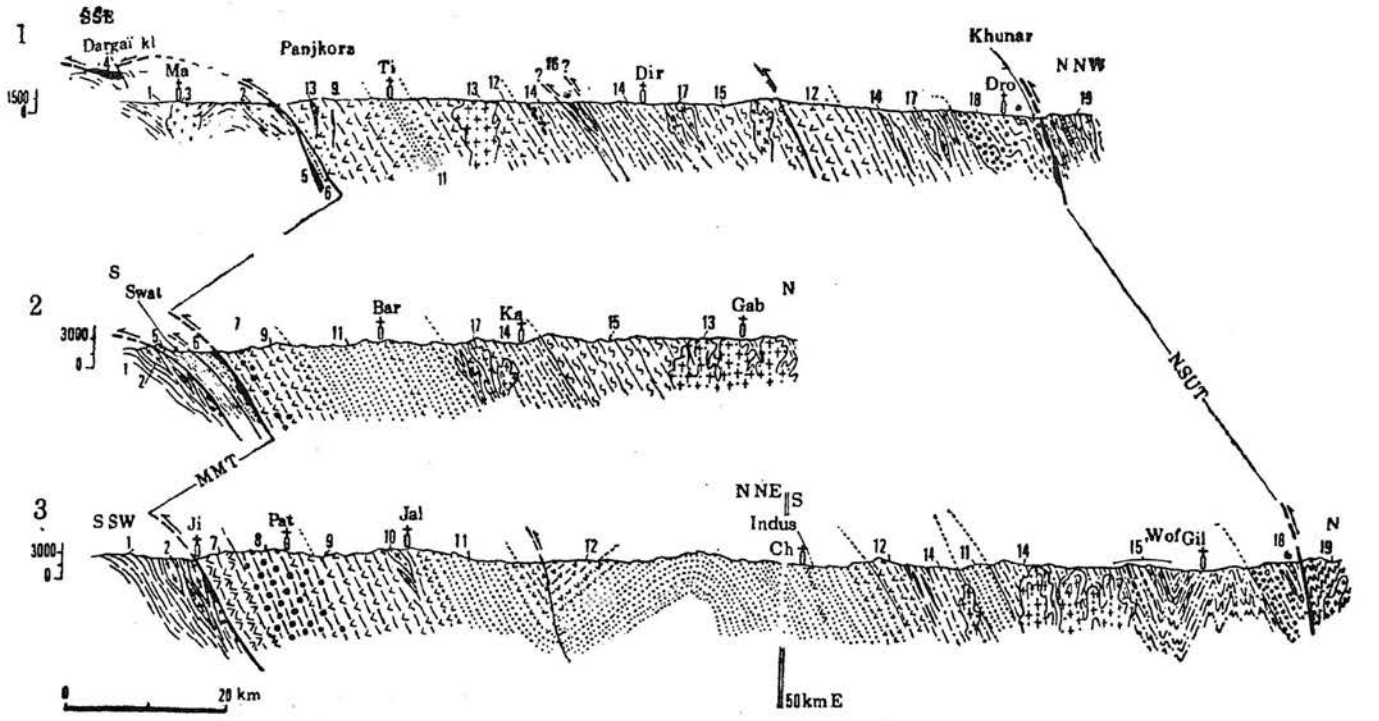

Fig. 2. The three main N-S Cross-Sections of Kohistan (see map fig. 1 for positions).

1) Buner (Paleozoic) metamorphic series (Indian plate) — 2) Orthogneiss (Paleozoic granites ?) — 3) Malakand-type granite (post-tectonic) — 4) Ultramafic Dargai klippe (mainly harzburgites and pyroxenites) — 5) Lower tectonic slice (greenschist) under MMT — 6) Upper tectonic slice (blueschist) with "tectonic melanges", under MMT — 7) Jijal ultramafic rocks (mainly diopsidites) — 8) garnet "anorthosites" — 9) Lower amphibolitic belt — 10) Garnet-phengite metadioritic rocks of Jalkot — 11) Layered noritic orthogneisses ("granulitic belt") — 12) Striped upper amphibolites — 13) Late to post-kinematic diorites and granodiorites — 14) Kalam type metagreywacke series with shales, cherts, marbles, and some "oceanic" gabbros and pillowed metabasalts — 15) calc-alkaline lava flows (mainly andesites and dacites) (Utror series) locally replaced by or grading into metasediments interbedded with lavas — 16) Dir Eocene fossiliferous (f) series — 17) late-kinematic heterogeneous quartz-diorites — 18) Drosh-Yasin red and green series with unconformable basal conglomerates, shales, and fossiliferous Aptian-Albian limestones (molastic series, early stage of obduction?) — 19) Asian plate formations: metamorphic sediments (with fossiliferous Paleozoic) intruded by Mesozoic granitic rocks. MMT: Main Mantle Thrust (southern suture of Kohistan): N-Sut: Northern suture of Kohistan or "Northern megashear".

Names of localities : *Cross Section n°1* : Ma = Malakand, Ti = Timurgara, Dro = Drosh — *Cross Section n°2*: Bar = Bahrain, Ka = Kalam, Gab = Gabral — *Cross Section n°3*: Pat = Patan, Ji = Jijal, Jal = Jalkot, Ch = Chilas, Gil = Gilgit.

The banded amphibolites are heterogeneous rocks showing alternating bands 1-10 cm thick of various felsitic rocks and fine grain amphibolites often isoclinally folded. Layering of these rocks has three possible origins: 1) Metamorphic differentiation along numerous shear zones almost parallel to the foliation. 2) veins and veinlets of early injections of leucocratic melts transposed into the foliation, 3) inherited layering of possible volcano-sedimentary origin (tuffs and tuffites).

The foliation is clearly composite ($S_1 + S_2$): it is cut by leucocratic dykes, which are in turn isoclinally folded and sheared, with garnet metablasts surrounded by the S_2 foliation. The P_2 fold axes have a N20 N30 direction. Some of the coarse grain amphibolites are clearly flaser-gabbros with sometimes original ophitic textures preserved.

The lower part of the Southern Amphibolite belt contains bodies of ultramafic rocks which are mainly diopside pyroxenites with minor hornblendites. The most characteristic outcrops are around Jijal-Patan; they consist of diopside ± garnet ± clinozoisite ± hornblende rocks (with lenses of garnetites), grading to gneissose layered garnet anorthosites cut across by garnet plagioclase veins folded isoclinally.

These anorthosites in turn grade upwards to massive garnet amphibolites, which include in places patches of inherited Cpx-Opx granulite-like rocks invaded by discordant feldspar-garnet-hornblende veinlets: the pyroxene granulite lenses seem to grade into hydrated equivalents ("retromorphosed granulites" or Jan's "degranulitized amphibolites").

The ultramafic Jijal-Patan rocks, as well as the

massive garnet amphibolites, show numerous blastomylonitic shear-zones, some of which have been formed prior to the emplacement of the garnet plagioclase veinlets.

The lower part of the Jijal complex is mainly composed of diopsidites with some dunitic layers containing Cr-Cpx and pods or layers of chromite and/or magnetite. A thick (several tens of meters) mylonitic shear zone marks the lowermost part of the Jijal complex near the major thrust (M.M.T. of Tahirkheli *et al.*, 1979) which separates the Kohistan sequence from the metamorphic sialic rocks of the Indian Plate. A blue-schist belt with tectonic melanges, harzburgites, serpentinites, glaucophanites, outcrops locally between these two main structural units (fig. 2 and Bard *et al.*, 1979)).

B.2. – The Pyroxene-Granulite Belt

This belt extends over 250 km from the Panjkora valley to the Nanga Parbat antiform, with a maximum thickness exceeding 15 km. The rocks are particularly well exposed along the Indus valley between Jalkot and Chilas. Similar rocks are also visible on the eastern limb of the Nanga Parbat antiform in the Twar-Astor-Deosai area. The Pyroxene granulite belt has been well studied by Jan (op. cit.) in the Swat valley: the "granulites" are mainly leuconoritic foliated rocks with hypersthene-rich and plagioclase-rich isoclinally folded dykes. Coarse grain, plagioclase-hornblende pegmatites cut the foliation of these "granulites". Later fractures and conjugate shear zones show uralitization of Cpx and Opx along their borders suggesting water transfer along these fractures.

The layering of the pyroxene granulites is sometimes well marked by an alternation of noritic to leuconoritic-anorthositic rocks. In some outcrops this layering is cut by the main foliation suggestion a cumulative pretectonic origin. Recent observations along the Indus road, East of Chilas, confirm this interpretation: In this less deformed part of the "granulite belt" are exposed cumulates with cross-bedding, graded bedding, and microslump structures and with inherited textures of adcumulates or heteradcumulates, similar to those described in other layered mafic complexes. Preliminary studies of these cumulates show that the dark layers are hypersthenites or metadunites (sometimes upwelled or injected into the neighbouring layered rocks), and metatroctolites. The latter show coronitic textures in response either to late magmatic or synmetamorphic solidus or retrogressive processes between olivine and the basic plagioclase of the matrix: Early olivine is rimmed by opaques, then Opx, which are in turn rimmed either by symplectite-like associations of Cpx plus green spinel or Mg-rich (pargasitic ?) pale green hornblende plus green spinel.

Most leucocratic layers of the cumulative complex are anorthositic in composition but some contain small amounts of quartz and K. feldspar. Biotite is common as a late crystallization product.

In the margins of the "granulite" metanoritic belt the rocks are enriched in brownish hornblende in apparent textural equilibrium with Opx (and Cpx). This suggests that some of the coarse-grained massive foliated amphibolites of the southern amphibolitic belt, with similar field aspects as the pyroxene granulites, are not "degranulitized" rocks in response to a late retrogressive wet metamorphism but early wet metabasites. Supply of water from neighbouring stripped amphibolites may be advocated to explain this feature during an early syntectonic and synmetamorphic event.

In the vicinity of the Jijal-Patan ultramafites and anorthosites, the "pyroxene granulites" show the development of quartz-zoisite garnet veinlets or patches in association with the amphibolization of the pyroxenes. These features are related to a second metamorphic over-print.

By local later shearing some parts of the layered metanoritic granulite complex have been transformed into mylonitic chlorite-actinolite bearing rocks (the so-called prasinites of Desio, 1974).

B.3. – The Northern Amphiboliet Belt

Despite the intrusion of various heterogeneous diorite or grano-diorite bodies, it appears clearly that the "granulites" lie below a complex of stripped (hornblende-epidote ± garnet ± biotite) amphibolites which have a tuffaceous or volcanic (basaltic) origin. These amphibolites, as well as the lower ones, show partial melting-like structures with progressive dismembering by dioritic mobilisates. This apparent migmatization, quite similar in aspect to that of the granitic anatectic zones, increases eastwards in the High Indus and Shyok valleys. It could explain the formation of some heterogeneous subautochtonous dioritic granodioritic bodies by basic palingenesis.

In the uppermost less metamorphic part of the Northern Amphibolite Belt pillowed metabasalts are still recognizible (South of Dir, road Gilgit-Chalt, South of Skardu). Coarse diallage-bearing gabbros and other mafites, quite similar to the classical euphotides and diabases from alpine ophiolites, are also present in places. Along the Indus, opposite the Astor valley, there is a recurrence of leuconoritic-dioritic gneissosse rocks similar in aspect to that of the Pyroxene-granulite belt.

B.4. – The Metasedimentary (Kalam-Type) Series

There is a progressive transition between the Northern Amphibolite belt and the overlying Metase-

dimentary Kalam-Dir series, which is mainly composed of black or green shales, metagreywackes, basaltic metatuffs and cherts. Some calc-silicate lenses and marbles are also present.

To the East (South of Gilgit and aruond Skardu) the series becomes thicker (> 2000 m) with graded bedded flysch intercalations, black shales and a great development of cherts in some places (South of Skardu). True sandstones and quartzites are lacking.

B.5. – The Utror Volcanics

This series is particularly well developed in Western Kohistan (Swat-Utror valley) where it reaches more than 6 km in thicknes. It is also well represented West and North of Gilgit (Yasin, Chatorkhand, Chalt-Rakaposhi area) and in the Deosai Plateau and Dras-Kargil series.

The Utror series is composed from bottom to top of:

- polygenic andesitic agglomerates and breccia,
- massive dark violet to pink (pigeonitic) andesites intruded by microquartzdiorites and gabbros,
- violet to grey latites or dacites with some rhyodacitic lava flows,
- scarce rhyolitic and/or ignimbritic rocks (near Gabral).

Though detail mapping of these rocks is lacking and though the uppermost part of the volcanic pile is invaded by numerous heterogeneous granodioritic or granitic late kinematic bodies, it seems that this association represents a partly aerial, volcanic complex similar to that of present mature island arcs. Local interbedding and lateral transition of 4 and 5 is probable.

B.6. – The Detrital Upper Series

This series with a maximum thickness of about 150 m forms the uppermost and northernmost part of the Kohistan sequence and lies at the boundary with the Asian continent along the Main Karakorum thrust. It is particularly characteristic, well developed and fossiliferous (Lower Cretaceous) in Drosh (Kunar valley), Harchin-Chumarkhan, and Yasin areas. Similar fossiliferous series outcrop in Shigar valley (North of Skardu) and Deosai plateau (Burji-la; Burzil pass), but with less clear relationships with the above mentioned arc series due to the abundance of late dioritic intrusives.

The upper detrital series generally begins with coarse polygenic conglomerates with pebbles of mainly Utror volcanics, some diorites, and minor cherts, schists or marbles, in a reddish or violet microconglomeratic matrix. This conglomerate lies unconformably on the Utror volcanic complex and/or dioritic intrusives.

The overlying series is composed of microconglomerates, wackes, pink-violet and green slates, in which are interbedded grey micritic fossiliferous limestones with Rudists and Orbitolina of Aptian-Albian age (Desio 1975, Rossi Roncheti 1965, Desio et al., 1977, Fourcade, pers. comm.). In the upper part of the series flows of green andestitic to basaltic lavas are interlayered.

C) – AGE OF THE KOHISTAN SEQUENCE

From the above stratigraphic and paleontologic observations it appears that most of the Kohistan sequence was built (at least in western Kohistan) before Albian times.

Eocene microfossils have been found around Dir but these outcrops could be part of a cover lying unconformably on the Kalam–Dir series and later squeezed below thrusts.

In the Deosai plateau Late Cretaceous limestones have been found (Desio 1978) in the so called "Dras Volcanics" but the structural relations between the different formations are not clear again.

There are so far very few reliable radiochronologic data on the Kohistan sequence itself. Most of the measurements concern late kinematic diorites and granites intruded in the sequence:

– Ages ranging between 37 and 56 my have been found on such rocks by Casnedi et al (1978) in the Yasin area by $^{40}Ar/^{36}Ar$ and $^{40}K/^{36}Ar$ isochrons. An age of 43 my has been found by Maluski on biotite of an intrusive diorite of the Indus valley East of Deosai by $^{39}Ar/^{40}Ar$ method.

The only ages measured on the Kohistan sequence itself are made in the Pyroxene-granulite belt around Barhain (Swat): an age of 67 my on a hornblende of a pegmatite cutting the foliation (Jan and Kempe 1973); an age of 80 my on zircons of the pyroxene granulite (U/Pb method, Neiser, pers. comm.).

In our mind these Upper Cretaceous events could represent the age of the metamorphism that occurred during the obduction of the Kohistan Sequence onto the Indian plate. It is in agreement with the age of glaucophane of the Shangla blueschist-melange belt dated by Maluski at 67 ± 2 my ($^{39}Ar/^{40}Ar$).

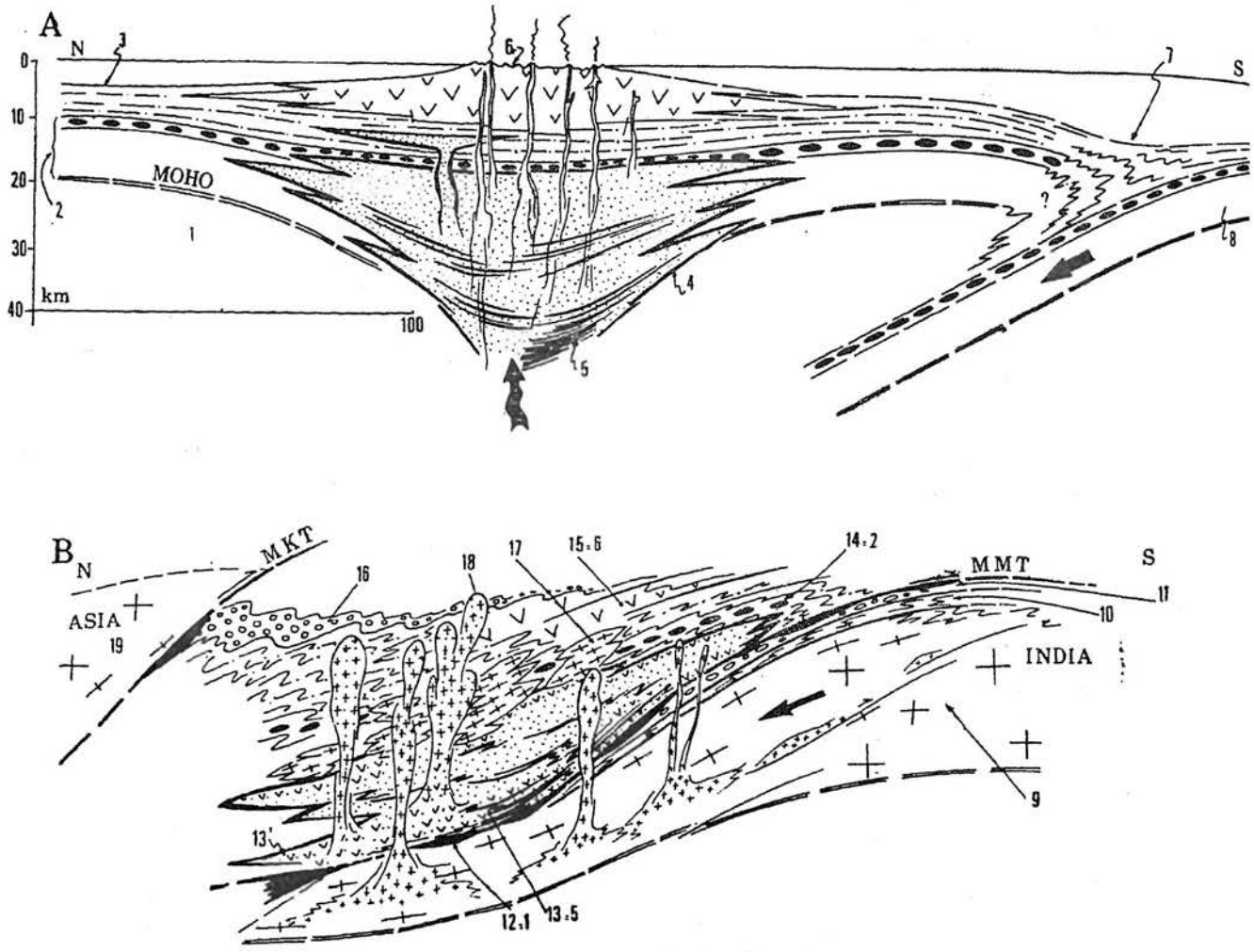

Fig. 3. Tentative model for the evolution of the Kohistan volcanic arc.

Stage A: Volcanic arc building stages during Mesozoic by northward intraoceanic subduction of the oceanic part of the Indian Plate (the continental part is still more south) — 1) upper mantle under arc system — 2) oceanic crust under arc (dots represent levels 1 and 2 of present oceanic crust models) — 3) volcano-sedimentary series — 4) Noritic layered intrusives as back bone of arc system with mafic ultramafiic cumulates (5) — 6) volcanic lava flows of the arc (mainly andesites and dacites) — 7) trench with possible early high-P metamorphism and deformation during subduction of oceanic crust (8).

Stage B: Tertiary early stage of collision with Asia, after late Cretaceous arc obduction on the continental part of the Indian Plate (9) — 10) Lower tectonic slice under MMT Suture — 11) Blueschist belt (upper tectonic slice under MMT suture) with "tectonic melanges" formed during obduction processes — 12) Mantle slices in MMT — 13) Jijal ultramafic complex — 13) Lower amphibolitic belt (including degranulitized metanorites) — 14) Basaltic or gabbroic metaophiolites in amphibolitic belts — 15) Utror volcanics and related rocks — 16) Upper detritic red series — 17) Syn to late-kinematic quartzdiorites — 18) Late to post-kinematic diorites or granodiorites — 19) Sialic metamorphics of Asian Plate (for n°12 to 15, equivalences refer to stage A).

D) – CONCLUSIONS – THE KOHISTAN SERIES : AN ISLAND ARC

As proposed by Tahirkheli et al. (1979) the Kohistan sequence could represent an old island arc. This arc was built during Mesozoic times and obducted on the Indian continental Plate at the end of the Cretaceous. This hypothesis is supported by the following arguments:

1 – Utror volcanies have petrologic and geochemical characters similar to those of present island arcs.

2 – The Kohistan thick pile (30-40 km) has neither characteristics of continental crust (lack of sialic sediments and intrusives) nor that of normal oceanic crust (much thicker and almost entirely calc-alkaline).

Oceanic like sediments and volcanics (metaflysch,

tuffs, cherts and pillow basalts) are only clearly represented in the upper part of the pile.

The most characteristic feature of the Kohistan sequence is the "Pyroxene granulite belt"; we have seen that this noritic complex shows conspicuous inherited magmatic layering with hypersthene-diopside or oliving rich cumulates suggesting that these rocks represent a huge calc-alkaline pluton emplaced under and/or through the previous oceanic crust. This pluton could be the source of the andesitic-dacitic magmas of the Utror volcanics.

Further geochemical and geochronological studies are of course necessary to confirm our hypothesis and particularly two main problems are not completely solved:

i – The Meaning of the Jijal Complex

Do these ultramafic rocks represent thick mata-cumulates at the bottom of the former oceanic crust, or more probably those of the calc-alkaline pluton?

ii – The Timing and Meaning of the High Grade Metamorphism

The syn to late-kinematic high pressure metamorphism (garnet ± zoisite ± rutile ± phengite paragenesis) which affects the lower part of the Kohistan sequence and increases downwards toward the MMT may be related reasonably to the obduction process and the blue schists. If so, what is the significance of the initial "granulitic" assemblages. Are they related to an early stage of obduction or to older stages of intraoceanic subduction?

These problems are of major interest because the Kohistan sequence is probably the first complete cross-section of an Island arc described so far, showing the deepest parts not accessible in present island arcs. The Kohistan sequence is thus a key to any correct model of the subduction and obduction processes and to give geological constraints to the geophysical models.

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