**Zeitschrift:** Eclogae Geologicae Helvetiae

**Herausgeber:** Schweizerische Geologische Gesellschaft

**Band:** 82 (1989)

**Heft:** 2

**Artikel:** The crystalline rocks of the Kaghan Valley (NE-Pakistan)

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**DOI:** https://doi.org/10.5169/seals-166393

Eclogae geol. Helv. 82/2: 629–653 (1989)

0012-9402/89/020629-25 $ 1.50 + 0.20/0


# The crystalline rocks of the Kaghan Valley (NE-Pakistan)

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## ABSTRACT

The results of a reconnaissance survey of the crystalline rocks of part of the Northwestern Himalaya are described. The northeastward continuation of the Hazara-Kashmir Syntaxis in the Kaghan Valley comprises three tectonic elements each having different stratigraphic, metamorphic and deformational features. The lower, Lesser Himalayan element is characterized by greenschist-facies, mostly pelitic, rocks of Precambrian age of the Salkhala Unit. An important discontinuity, the Mylonite Zone, is considered to be the continuation of the Main Central Thrust in Northeast Pakistan, and therefore to represent the base of the Higher Himalaya. This second tectonic element consists of a polyphase folded, amphibolite-facies metamorphosed basement and cover sequence. The Indus Suture, which carries the deep crustal, mafic-ultramafic basal complex of the Kohistan Sequence (the third, uppermost tectonic element), cuts the Higher Himalayan structures and represents greenschist facies, retrograde transformations in the hangingwall rocks. A preliminary reconstruction of the Himalayan tectonic evolution suggests that the first southwestwards-directed phase of nappe transport led to a thickening of the tectonic pile, and that thickening was followed by a northwest-southeast directed deformation, perhaps contemporaneous with the last movements along the Indus Suture. A large-scale interference pattern of the two superimposed phases led to the doming of the area and, as a consequence, resulted in tectonic uplift of relatively deep crustal levels of the Himalayan.

## ZUSAMMENFASSUNG

Diese Arbeit befasst sich mit der nordöstlichen Fortsetzung der Hazara-Kashmir Syntaxis im Kaghan Valley (Nord Pakistan). Der tektonische Stapel besteht aus drei Elementen mit unterschiedlichen stratigraphischen, strukturellen und metamorphen Eigenschaften. Das untere Element, die Salkhala Unit, besteht hauptsächlich aus Präkambrischen Peliten, die unter grünschieferfaziellen Bedingungen verformt wurden. Oberhalb einer wichtigen Diskontinuität, der Mylonite Zone, die dem Main Central Thrust in Nordost Pakistan entspricht, folgt das Higher Himalaya Kristallin, dessen gneissiges Grundgebirge und basaltisch-karbonatisch-pelitische Bedeckung in mehreren Phasen unter amphibolitfaziellen metamorphen Bedingungen gefaltet wurde. Das oberste Stockwerk besteht aus einer mafisch/ultramafischen basalen Serie der Kohistan Sequence, die entlang der Indus Suture auf den Higher Himalaya überschoben wurde. Diese Verformung äussert sich einerseits durch retrograde Veränderungen des granulitischen Gesteins, anderseits durch eine strukturellen Diskordanz bezüglich des Liegenden. Der Versuch, die tektonische Entwicklung zu rekonstruieren, beginnt mit einer ersten Phase, einem nach Südwesten gerichteten Deckentransport, gefolgt von einer NW-SO orientierten Verformungsphase. Diese zweite Phase sollte sich gleichzeitig mit den letzten Bewegungen entlang der Indus Suture entwickelt haben. Die geometrische Überlagerung der zwei tektonischen Phasen erzeugte eine domartige Aufwölbung des Gebietes und ermöglichte den Aufschluss der kristallinen Gesteine entlang der Achse von Hazara-Kashmir- und Nanga Parbat Syntaxis.

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## 1. Introduction

The astonishing linearity of the Himalayan chain is interrupted at its northwestern part by two structural re-entrants, the Syntaxes of Hazara-Kashmir and of Nanga Parbat. In this region, mostly belonging the Northeast Pakistan, the geological lineaments change orientation by more than 90 degrees, passing from a NW-SE trend into a NE-SW one (Fig. 1).

Previous work (Bossart et al. 1988) has shown that the finite geometry of the core of the Hazara-Kashmir Syntaxis is that of a dome structure, which allows a view to be made of the metamorphically deeper parts of the tectonic elements. The shallower, frontal slabs are missing and crop out more laterally in the Hazara and Kashmir areas. The Kaghan Valley, which is situated southeast of the Indus-Kohistan gorge, enables a study to be made of the northeast continuation of the Hazara-Kashmir structural re-entrant into the Nanga Parbat Syntaxis, crossing the Higher Himalayan crystalline and its suture with the Kohistan Sequence.

The aim of this work is to give a preliminary report of the geology, petrography and tectonics of the Himalayan crystalline rocks and the overthrust Kohistan Sequence, exposed in the Kaghan Valley of Northeast Pakistan.

## 2. Geologic Setting

Pioneers in the geological exploration of the Kaghan Valley were Lydekker (1882) and especially D.N. Wadia (1931, 1934). In more recent years, the lower part of the Kaghan Valley has been extensively mapped by several authors who maintained the principal subdivisions proposed by Wadia (1934). From south to north, the investigated area comprises the Tertiary foreland of molasse sediments (Subhimalaya), the thrust nappes which belong to the northern margin of the Indian plate (Lesser and Higher Himalaya), and their northern collision margin with the Kohistan Sequence (the Indus Suture; cf. Fig. 1).

The tectonically lowermost element, occupying the core of the Hazara-Kashmir Syntaxis, corresponds to the "Foreland" of Wadia (1934) or to the *Subhimalaya* of Gansser (1964). It is mainly represented by the Murree Formation, consisting of an intertidal cyclic sedimentation of sandstone grading into siltstone with intercalations of nummulitic limestone of Late Paleocene to Middle Eocene age (Bossart & Ottiger 1989). The axial zone of the Syntaxis is cored by the Paleocene carbonates and the Cambrian Abbottabad Formation exposed along the hinge of the Muzaffarabad Anticline.

To the north, the *Main Boundary Thrust,* locally called the Murree Thrust, borders the Subhimalaya. Geometrically the fault plane cuts in its footwall the steeply dipping beds of the Murree Formation, carrying northeast plunging Lesser Himalayan schists and gneisses on its hangingwall (Bossart et al. 1988).

The lowermost Lesser Himalayan tectonic unit, the *Panjal Unit,* corresponding to the "Autochthonous Folded Belt" of Wadia (1934), was shown to consist of four different imbricate slices (Panjal Imbricate Zone of Bossart et al. 1988). The lowermost one is formed by a tectonic mélange of Permian to Eocene rocks, whereas the remaining three represent an Upper Paleozoic to Lower Mesozoic stratigraphic sequence of

Carboniferous tilloides (Agglomeratic Slates), Permian Panjal Trap volcanics, and Triassic limestones. The metamorphic grade reached the greenschist facies. The imbricated slices represent a typical "duplex" configuration, with the Main Boundary Thrust as floor-thrust, and the Panjal Thrust (which divides the Salkhalas from the Panjals) as roof-thrust.

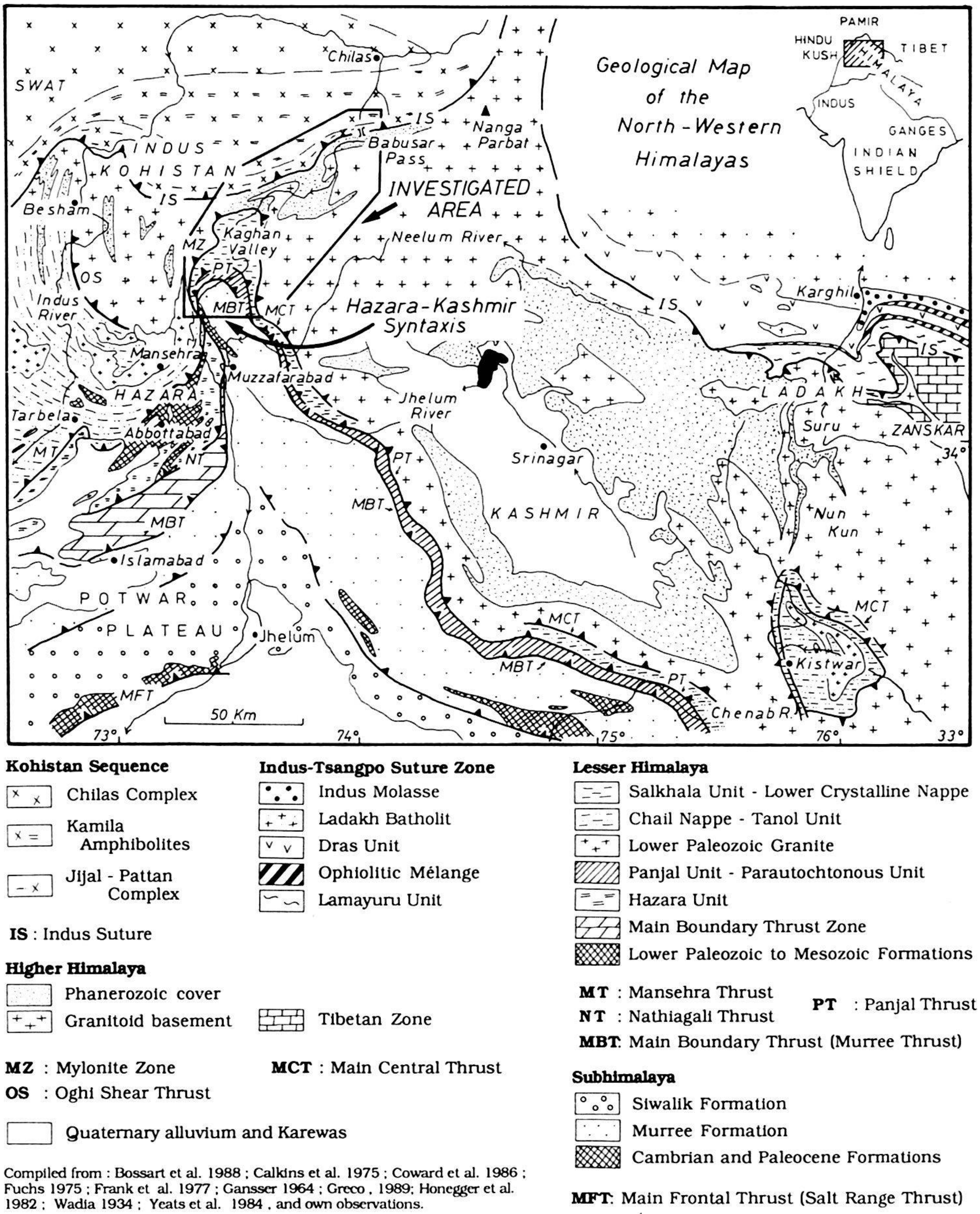


Fig. 1. Geological map of the Northwestern Himalaya showing the regional setting of the investigated area.

Above the Panjal Unit, a several kilometer wide, pelitic and carbonatic sequence, intruded by acid and basic rocks, has been considered to belong to the Precambrian Salkhala Series (Wadia 1934) or Salkhala Formation (Calkins et al. 1975). Bossart et al. (1988) grouped the entire, low- to medium metamorphic grade sequence into an uppermost Lesser Himalayan element called the *Salkhala Unit.*

Further north, in the upper part of the Kaghan Valley, Gansser (1979) recognized a well defined north-dipping thrust bringing high grade garnet-schists, calcschists and gneisses over the lesser metamorphic Salkhala schists. He suggested therefore that this thrust contact marked the northeastern end of the Lesser Himalayan Hazara-Kashmir Syntaxis, and that the overthrust rocks belong to a higher tectonic element. This *Higher Himalayan element* consists of at least two sheets or nappes of granitoid gneisses separated from the metacarbonates and metapelites by thick amphibolitic sheets. Further to the northeast, the element continues into the structural high of the Nanga Parbat Syntaxis where the crystalline granitoid basement is well exposed. Coward (1985) suggested that the rocks forming the Nanga Parbat Syntaxis are comparable with the $516 \pm 16$ my old Manshera Granite (Le Fort et al. 1980), and that they were intruded into Precambrian metasediments now seen as intergranite sheets some hundred meters thick.

The continuation of the suture between the Indian Plate and the Kohistan Island Arc has never been mapped with precision in the Kaghan Valley, but its approximate location in the Indus Kohistan area was indicated on maps. We propose calling this important thrust plane the "Indus-Yarlung Suture" (as suggested by Gansser in a verbal communication at the Himalaya-Karakorum Workshop in Nancy, France, February 1987), or more briefly, the *Indus Suture* in its western continuation in North Pakistan. We suggest therefore that the term "Main Mantle Thrust" (Tahirkheli et al. 1979) be abandoned, because rocks of the mantle are exposed only locally along this suture.

The uppermost tectonic element is formed by rocks of the *Kohistan Sequence* (Tahirkheli et al. 1979). These rocks have been interpreted as representative of a mature island arc, formed during a Late Mesozoic subduction of the Indian plate in the southern part of the Tethys, and obducted over the Indian Plate in Upper Cretaceous to Eocene time. This latter event produced polyphase folding and high pressure metamorphism in the magmatic rocks of the Kohistan arc basement complex (Bard et al. 1980, Coward et al. 1986). Consequently, medium to high metamorphic grade rocks as well as high pressure metamorphic sequences with their magmatic equivalent of the basal complex (Jijal-Pattan and Chilas Complex), accompanied by serpentine alteration, are exposed in the hangingwall of the Indus Suture.

Complex nappes of crystalline rocks have also been described in the Higher Himalaya of the Ladakh–Zanskar area (Fig. 1). The crystalline nappe complex is composed of granitoid gneisses and metasedimentary rocks with a medium to high grade metamorphism (Frank et al. 1977). The pre-Mesozoic basement consists of approximately 500 my old porphyric two-mica granites intruded into older metasedimentary paragneiss (Honegger et al. 1982). The Mesozoic metasediments are preserved in complex synclinal wedges and consist at their base of amphibolites representing the Panjal Trap volcanics, overlain by impure Triassic carbonates (Honegger et al. 1982).

Similarly, immediately south of the Kohistan Sequence in the Indus Valley (Besham area, Fig. 1), a basement, composed of Proterozoic group rocks intruded by Cambrian granitoids (TRELOAR et al. in press), is overlain unconformably by a cover sequence with carbonaceous Lower to Middle Paleozoic sediments (FLETCHER et al. 1986). The structural features of this area are characterized by ductile sheath-like folding and imbrication of basement with cover slices. A final backfolding event formed the small structural high of Besham, in which the deep-crustal rock sequence can now be seen (TRELOAR et al. in press).

## 3. The crystalline rocks of the upper Kaghan Valley

The object of the present investigation is a study of the structure and metamorphism of the crystalline rocks which are exposed in the upper Kaghan Valley and lie above the Panjal Imbricate Zone. The rocks comprise the uppermost Lesser Himalayan tectonic unit (the Salkhala Unit), a wide mylonitic discontinuity representing the Main Central Thrust in NE-Pakistan (the Mylonite Zone), the Higher Himalayan crystalline divisible in basement and cover rocks, the Indus Suture and a small portion of the Kohistan Sequence (Fig. 2).

### *3.1 The Salkhala Unit*

The Salkhala tectonic Unit lies directly above the Panjal Thrust. It is mainly composed of metapelitic schists with characteristic graphitic, quartzitic and carbonatic components (the Precambrian Salkhala Series of WADIA 1931). It is intruded by pegmatite dykes and by two mica augengneiss representing the deformed equivalent of the Lower Paleozoic granite (Manshera granite). The widespread basic dykes may have intruded during the Permian magmatic event which is suggested by the geochemical similarity with the Panjal volcanics (PAPRITZ & REY, this volume). The most common rock type is a fine-grained micaschist with alternating quartz-rich and mica-rich layers. This layering is best interpreted as relict sedimentary bedding. Despite the severe deformation, primary sedimentary structures such as cross bedding and current lamination are preserved in several quartzite horizons 3 km north of Kaghan village. These rocks are lithologically reminiscent of part of the Tanol Formation of Hazara and Kashmir (cf. FUCHS 1975).

In the Salkhala schists around Bimbal, weakly foliated, small bodies of granitic to alkali-granitic composition occur, showing a magmatic assemblage (K-feldspar, quartz, minor biotite and alkali-amphibole) overprinted by the growth of chlorite, white mica and stilpnomelane. The origin and the age of these bodies is uncertain.

This unit has been affected by Alpine metamorphism and deformation. As is discussed in more detail later (section 4.1), metabasic as well as metapelitic rocks have suffered a greenschist facies metamorphism, slightly increasing in grade towards the Mylonite Zone. The main deformational fabric is essentially syn-metamorphic: isoclinal folding produced a penetrative schistosity, accompanied by a strong mineral lineation (stretching- or X-lineation), which obliterated nearly all of the older structural features. A late-metamorphic crenulation cleavage folds the main schistosity.

Summarizing, the Salkhala Unit shows metamorphic and deformational features which differ from those of the Panjal Imbricate Zone, and from those in the overlying more ductile and more highly metamorphic Higher Himalayan Crystalline Unit. It has been suggested that the Salkhala Unit should be correlated with the Lower Crystalline Nappe of the Kistwar Window (Gansser, personal communication; Greco 1989), both of which tectonically belonging to the Lesser Himalaya and respresenting its stratigraphically oldest and structurally deepest units.

### *3.2 The Mylonite Zone*

An important zone of ductilely and strongly deformed rocks, first recognised by Bossart et al. (1988) west of Balakot, forms a very important structural and metamorphic discontinuity separating an underlying Salkhala Unit from an overlying Higher Himalayan Crystalline Unit. It is extremely well exposed in the Kaghan Valley at Darseri (4 km SW of Naran). Here the granitic, amphibolitic and metasedimentary rocks are extremely platy ("flagstones") with a well-marked regular planar banding showing, like all others in this zone, many of the characteristic features of true mylonites (very fine-grain size, quartz ribbon fabric with quartz sub-grains oriented obliquely across the ribbons, feldspar porphyroclasts with σ-structure and mica "fish"-structure). Elsewhere the mylonitic fabrics occur in granites, metapelites, marbles and metabasic rocks. In the Kaghan Valley the rocks above the Mylonite Zone are all in amphibolite facies whereas, in contrast, greenschist facies rocks lie beneath the zone. Within mylonitic metapelites syn- and post-metamorphic kyanite and garnet are stable, and in

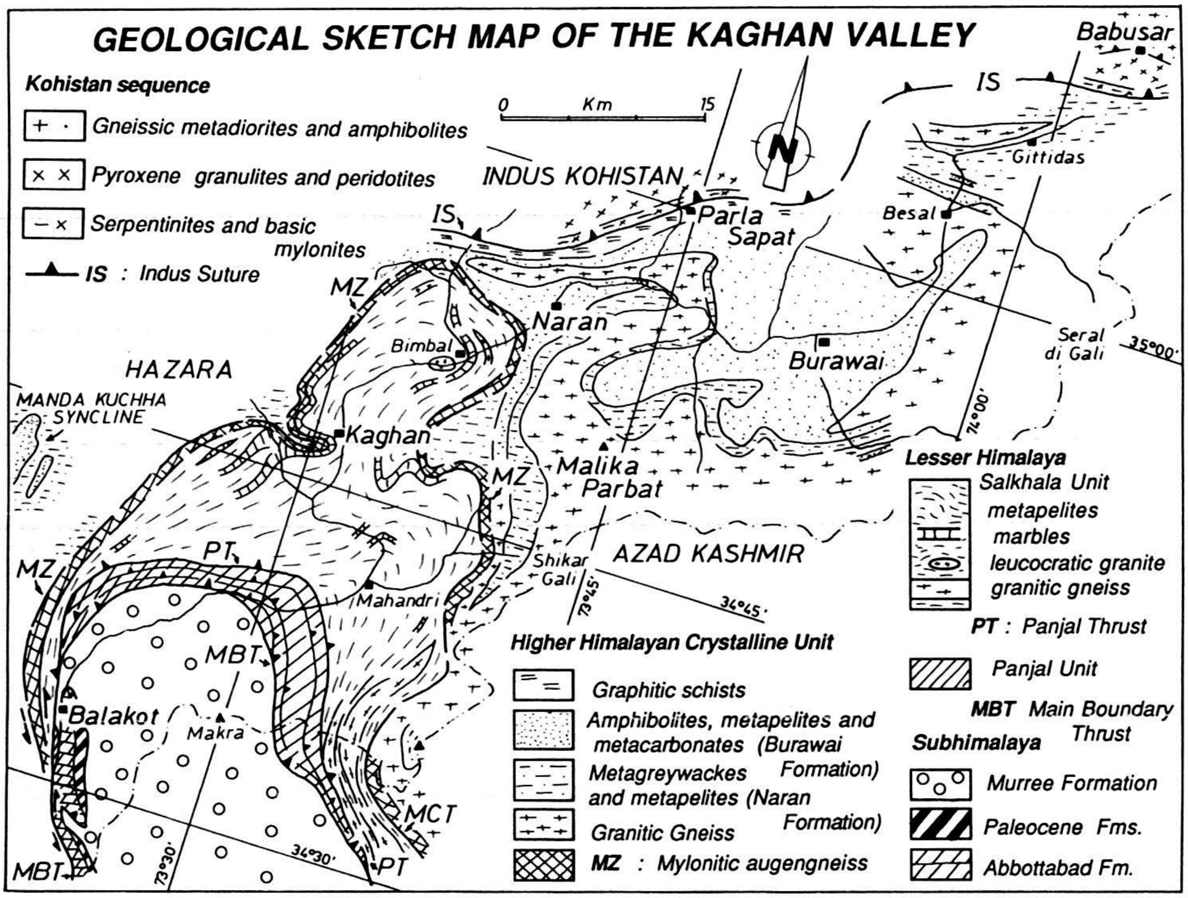


Fig. 2. Geological sketch map of the Kaghan Valley (compiled after Bossart et al. 1988 and new observations).

mylonitic amphibolites garnet and hornblende are stable. These observations suggest that mylonitisation occurred in an upper greenschist to amphibolite facies regime.

In the eastern part of the Hazara-Kashmir Syntaxis, this tectonic contact consists of a 500 m thick pile of metapelitic mylonites containing garnet, staurolite and fibrolitic sillimanite (GRECO 1989). In this area the Mylonite Zone shows strong similarities with the rocks of the Main Central Thrust Zone of the Kistwar Window (cf. STÄUBLI 1989) and of the Nepal Himalayas (cf. BOUCHEZ & PÊCHER 1981). It seems clear that the Mylonite Zone represents an important movement plane at the base of the Higher Himalayan crystalline, and it is probably correlated with the Main Central Thrust seen elsewhere in the Himalayas.

The westward continuation of the Mylonite Zone has been mapped in the tributary valleys of Kaghan where outcrops of granite-derived mylonites are found. In the western part of the Syntaxis, the Mylonite Zone changes from a moderately inclined ductile shear zone into a subvertical left-handed strike slip shear zone, giving rise to strong deformation in the Panjal Unit and also a slight deflection of the cleavage in the Subhimalayan Murree Formation (BOSSART et al. 1988). This shear deformation along the western limb of the Hazara-Kashmir Syntaxis seems to vary from being synchronous with, to later than, the northeast-southwest directed thrusting structures. Westwards in northern Hazara, the Oghi Thrust (COWARD et al. 1986) divides the Tanol Unit from the crystalline rocks (see Fig. 1) being, at least in part of its development, later than the southwesterly directed structures (TRELOAR et al. in press). The Oghi Thrust appears to be the tectonic equivalent of the Mylonite Zone and therefore of the Main Central Thrust.

### *3.3 The Higher Himalayan Crystalline Unit*

The rocks forming the Higher Himalayan element are bounded below by the Mylonite Zone and above by the Indus Suture bringing rocks of the Kohistan Sequence to lie above this unit. The Higher Himalayan Crystalline Unit can be separated into two main divisions which will be referred to as "basement" and "cover". Both have certain structural and metamorphic features in common as a result of having undergone the same deformational events and amphibolite facies recrystallisation during the Himalayan mountain building process. However, a number of distinguishing features have been retained. In the Kaghan Valley the subdivisions of the unit are particularly well displayed in the Saiful Muluk synform, the region north of the Malika Parbat, and in the mountains and valleys around Burawai (Figs. 2 and 3).

#### The basement

The basement rocks consist of two major components. The first (1 in Fig. 3) is made up predominantly of feldspathic granitoids intruded into psammitic, pelitic and calcareous metasediments with overall features similar to those of the Salkhala Units, although often extensively transformed into paragneisses by intense recrystallisation and local melting (Fig. 4A). The various lithological types alternate and wedge out laterally in a rather incoherent manner, and individual marker layers cannot normally be traced over long distances. Although some of these discontinuities are undoubtedly the

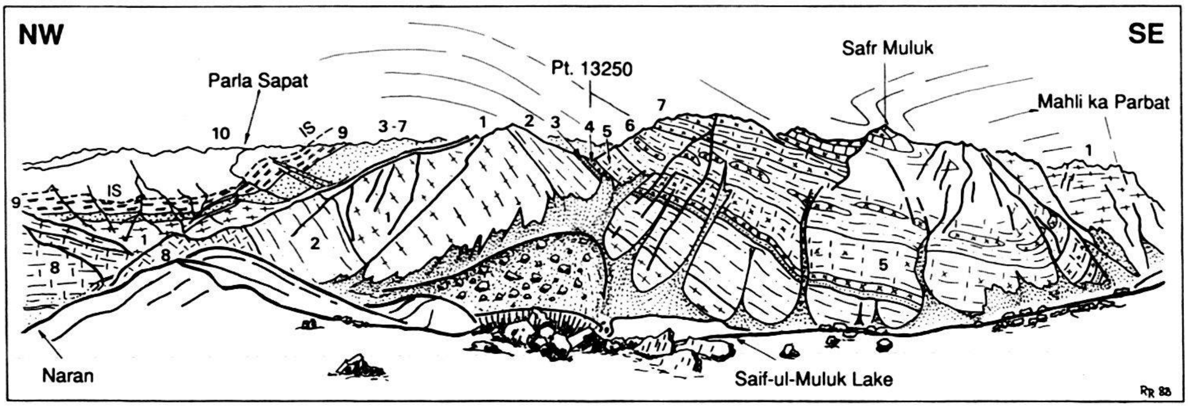


Fig. 3. View of the Higher Himalayan Crystalline Unit and of the Kohistan Sequence in the upper Kaghan Valley (compare with Fig. 2). Explanation: 1 to 2 = Precambrian to Lower Paleozoic basement; 1 = granitic gneisses of the basement; 2 = metagreywackes-metapelites of the basement (Naran Formation); 3 to 8 = Upper Paleozoic to Lower Mesozoic cover (Burawai Formation); 3 = quartzites and phlogopite marbles; 4 = garnet amphibolites; 5 = mica-bearing marbles alternating with garnet micaschists; 6 = carbonatic micaschists, diopside marbles, garnet-staurolite-kyanite micaschists and lenses of garnet amphibolites; 7 = amphibolite sheets and metacarbonates; 8 = carbonatic schists; 9 = graphitic schists with serpentinite lenses (footwall of the Indus Suture); 10 = Kohistan Sequence; IS = Indus Suture.

result of tectonic deformation and magmatic disruption, much of the variation appears to be a primary feature of the original sediments. The granitic bodies show features which can be best attributed to emplacement by plutonic intrusion (homogeneity of mineralogy over quite large areas, sudden changes of rock types showing well defined intrusive contact relationships, xenoliths and enclaves of both metasedimentary and cognate types) and are probably correlable with the Cambrian Manshera Granite (cf. Coward 1985). However, practically all these granitoids have been transformed into two-mica, K-feldspar porphyroblastic augen gneisses having Alpine kyanite and garnet. Segregations of the gneissic components into lenticular leucocratic parts surrounded by melanocratic selvages are often common (Fig. 4B). Associated with the granitoids are aplitic and pegmatitic dykes which are often found in a highly deformed folded and boudinaged state and are cross cut by schistosity fabrics. Undeformed tourmaline pegmatites are locally present discordantly cross-cutting Alpine fabrics (Fig. 4C). Discordant but deformed basic dykes as dolerites and schistose garnet-amphibolite sheets are sometimes abundant and appear to represent the hypabyssal equivalents (feeder dykes) of the metabasaltic rocks of the cover (see Papritz & Rey this volume). Primary mineralogical features and ophitic textures are observed and all the transitional stages towards completely overprinted Alpine metamorphic equivalents have been seen. Structurally and petrographically similar mafic dykes cutting Precambrian to Middle Palaeozoic rocks are known from the Ladakh and Zanskar regions (Honegger et al. 1982; Gaetani et al. 1986) which are chemically compatible with the Permian Panjal Traps (Honegger, personal communication).

The second component of the basement is a group of distinctive predominantly garnet and albite bearing semipelitic metasediments which will be provisionally termed the *Naran Formation* on account of the well exposed sections about 4 km east of Naran (north of Ghunla, 2 in Fig. 3). These metasediments are generally very well bedded and at many localities graded bedding is common. Small-scale cross bedding occurs in the upper parts of graded beds (Dora Nar river section, south of Burawai). Although deformation and the abundance of tectonic folds has made it impossible to unequivocally identify bottom structures of sedimentary origin, it does seem that the overall greywacke-like composition and grading signify deposition in a turbidite environment. Although the sediments are intruded by amphibolitic dykes, they do not usually show extensive in-situ gneissification. In fact, they are often characterised by sets of en-echelon quartz veins suggesting a period of pre-Himalayan deformation in a rather low grade (greenschist or lower) metamorphic environment. However, the relationships of these metasediments to the gneissic basement component is not absolutely clear. Preliminary mapping shows that the metasediments form an extensive, but not everywhere complete, sheet between the gneissic basement and the cover sediments (Fig. 2). This relationship, together with the difference in degree of gneissification and frequency of granitic bodies, is suggestive that the semi-pelitic metasediments represent a pre-Permian (Lower Palaeozoic?) succession deposited unconformably on a basement complex of metamorphic Precambrian and plutonic Cambrian rocks. It is also suggested

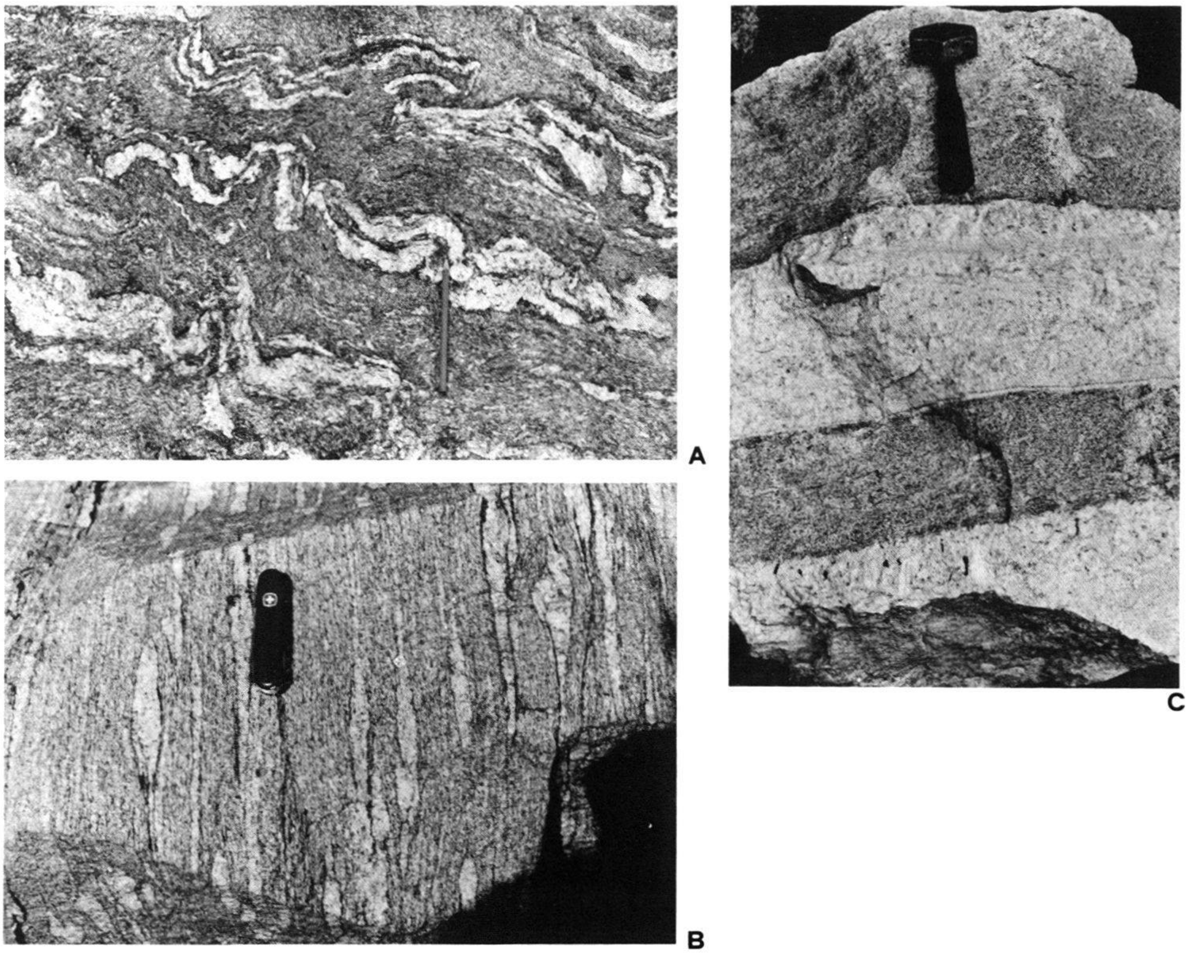


Fig. 4. Different types of basement gneiss of the Higher Himalayan crystalline: A = polyphase folded aplitic veins in (Precambrian ?) paragneiss; B = coarse-grained, quartzofeldspathic granitoid gneiss (Cambrian ?) representing stretched segregations of leucocratic lenses with melanocratic selvages resulting from Alpine recrystallisation; C = undeformed tourmaline pegmatite (post-Alpine ?) cross cutting the foliation of a fine-grained gneiss.

that the Naran Formation is an equivalent of the well known Lower to Middle Palaeozoic sediments of the Suru and Padam regions of Ladakh (Gaetani et al. 1986, Frank et al. 1987). These rocks form the base of the stratigraphic sequence above the Cambrian and older gneisses and granites, representing a Late Pan African episode (Gaetani et al. 1986, Garzanti et al. 1986), and therefore were deposited before the opening of the Neo-Tethys. For these reasons we group the Naran Formation within the basement, also because it lies below the clearly, regionally recognizable contact with the marbles and amphibolites of the lower part of the Alpine cover sequence (Burawai Formation).

The basement rocks form a series of sheets piled one on another. The geometrical features of these sheets are more suggestive of recumbent folds than overthrusts (cf. the Lepontine nappes of the Swiss Alps). The basement gneiss forms the high mountains making up the ridge south of the Kaghan Valley: a first "sheet" crosses the valley 10 km east of Naran and builds the lower part of its northern flank. Since these gneisses are not exposed in the valley north of Bimbal, we suppose that they close as a hinge of a large northward-closing recumbent anticline. A second "sheet" is exposed between Burawai and Besal, carrying its cover rocks over the metasediments of the underlying nappe. A third "sheet" lies above Gittidas.

## The cover sequence

The metamorphic rocks forming the "cover", provisionally termed *Burawai Formation* (3 to 8 in Fig. 3) after their excellent development around this village, show very marked differences in lithology from the metasediments classified as "basement". The succession begins with several widespread and often thick sheets of rather homogeneous oligoclase- and garnet-bearing amphibolite clearly representing metamorphosed basic igneous rocks, probably of extrusive origin (4 in Fig. 3). The petrographic, geochemical and overall geological features of this basic rock suite and its relationships with the metagreywacke of the basement are strongly suggestive that the rocks correlate with the well known Panjal Traps of Indian Kashmir (also seen farther south in the Kaghan Valley in the tectonic units which lie under the Panjal Thrust) and their metamorphic equivalents in the Suru and Padam regions of Ladakh. Honegger et al. 1982, Gaetani et al. 1986). The basal amphibolites are overlain by marbles and calcareous mica-schists also containing concordant and discordant sheets of amphibolite (5 to 7 in Fig. 3). The pelitic rocks are often porphyroblastic and contain mineral assemblages indicative of upper amphibolite facies (garnet, staurolite, kyanite), and the calcareous rocks commonly contain diopsidic pyroxene. Lithologically these rocks resemble the Bündnerschiefer of the central Lepontine zone of the Swiss Alps. In contrast to the sediments of the basement, the cover succesion is extremely coherent in that individual lithological units are regionally persistent and some can be traced widely throughout the region. Although the details of this succession await further investigation we note that the structurally highest (and perhaps stratigraphically youngest) units, exposed around Burawai, show clear evidence of synsedimentary extenson faulting, with grabenfaulted lower beds being truncated by erosional surfaces and overlain by unfaulted strata (Fig. 5). In this region there are well-developed amphibolite sheets with metamorphosed vesicles and traces of pillow forms on which carbonate

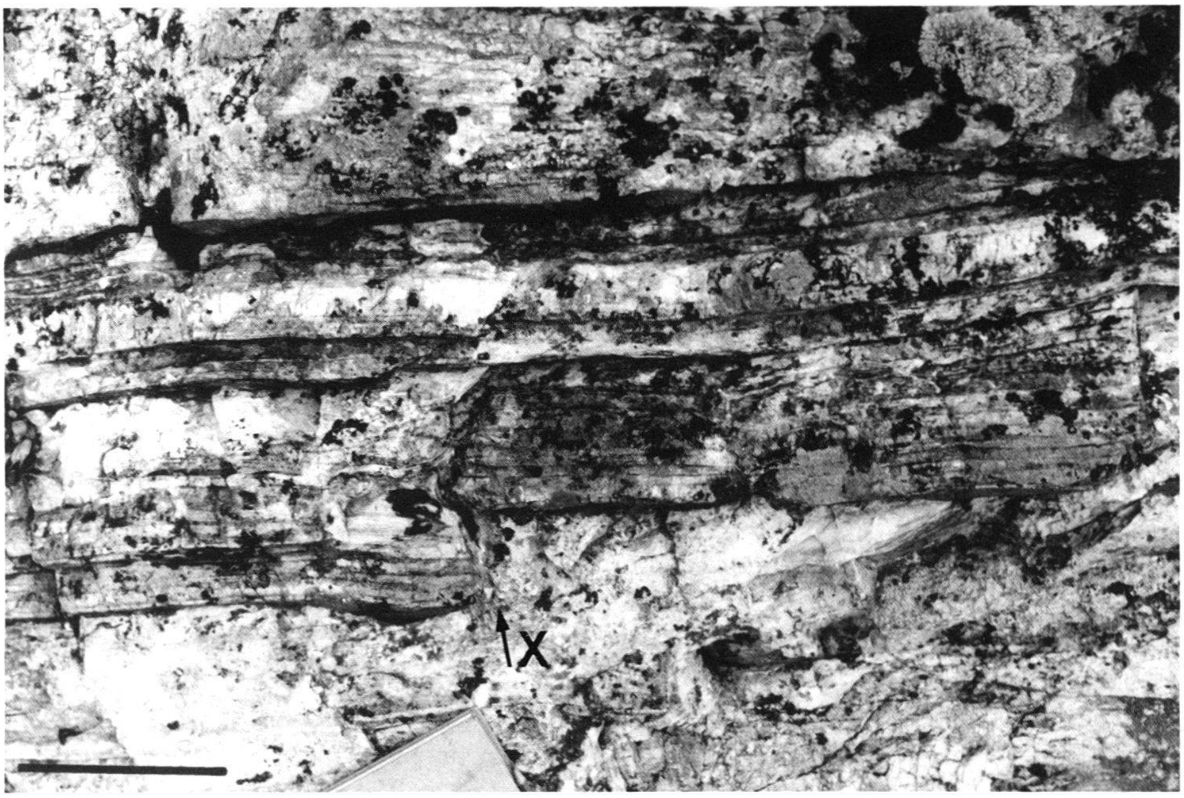


Fig. 5. Synsedimentary extensional fault (X) in the carbonaceous rocks associated with the basaltic flows of the Burawai Formation; explanation see text. Scale bar: 20 cm.

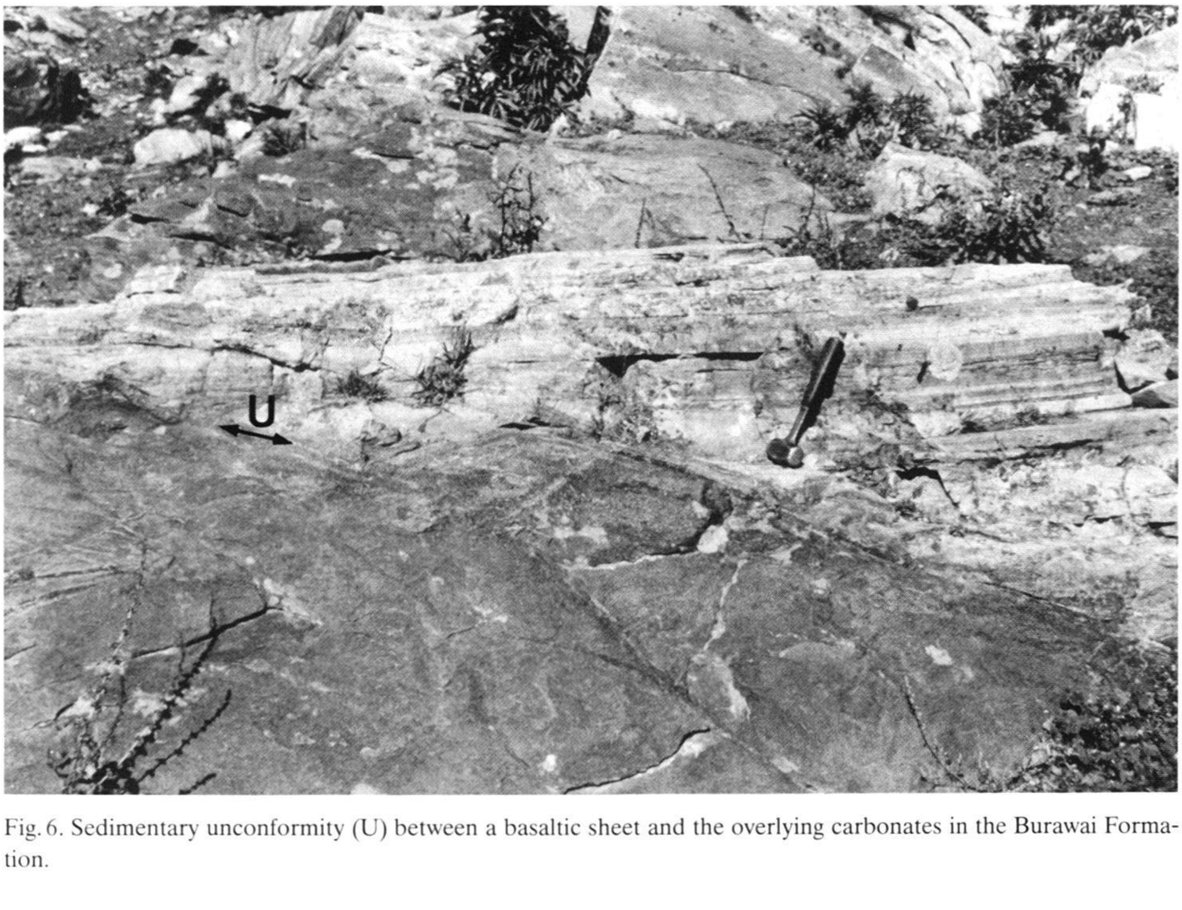


Fig. 6. Sedimentary unconformity (U) between a basaltic sheet and the overlying carbonates in the Burawai Formation.

and cherty sediments appear to have been unconformably deposited (Fig. 6). In the sediments all the original clastic grain fabrics have been destroyed by recrystallisation. Although no organic traces have yet been discovered, there seems no reason to consider such finds out of the question because fossils have been described in rocks of similar sedimentary and metamorphic facies in the Swiss Pennine Alps (cf. HIGGINS 1964). Decisive evidence that these rocks of Mesozoic age is, as yet, not available, but the lithological similarities with dated rocks in Ladakh are very striking.

Although basic extrusives and intrusives are very abundant, acid igneous material is rare in the Burawai Formation. Some acid sheets appear to originate by localised partial melting, and north of Naran, small swarms of dykes discordantly intruded the carbonatic mica schists (8 in Fig. 3).

### *3.4 The Indus Suture*

The suture separating the Higher Himalayan crystalline rocks from the overlying mafic rocks of the Kohistan Sequence runs along the northern flank of the upper Kaghan Valley. In its footwall, strongly deformed, dark graphitic, staurolite- and garnet-bearing phyllitic schists were mainly found (9 in Fig. 3). Within these schists, rare garnet amphibolites are intercalated towards the lower, gradational contact with the carbonatic micaschists of the cover, whereas towards the Indus Suture over 100 m long serpentinite slices are exposed. In the hangingwall of the suture, the retrograde metamorphism of the mafic – ultramafic rocks increases towards the thrust plane and the first hundred meters of the Kohistan Sequence consist of serpentinite rocks and clinozoisite-amphibolite rock with only textural relics of the original granulites.

The moderate north to northwest dipping Indus Suture was followed from Kaghan through the valley north of Bimbal to the village of Parla Sapat. Here the thrust plane, carrying serpentinites, clearly cuts the sleeply dipping schistosity of the underlying garnet phyllites (Fig. 7). Towards the east the Suture flattens, and its position was inferred from Landsat images. North of the Babusar Pass direct observations could again be made of the thrust plane which dipped at a moderate angle to the north. Its footwall is made of metagreywackes and metapelites of the Higher Himalaya, and the hangingwall shows well-preserved blastomylonitic, amphibolitic rocks of the Kohistan Sequence. These observations show that the Indus Suture cuts through different levels of both the Higher Himalaya and the Kohistan Sequence.

### *3.5 The Kohistan Sequence*

In the Kaghan Valley rocks of the Kohistan Sequence are thrust over gneisses and schists of the Higher Himalaya along the Indus Suture. Apart from the mineral transformations related to local shear strains along the Suture, which are limited to a band of 50–100 m in thickness, the rocks of the Kohistan Sequence are fresh, belonging to a granulitic complex very similar to the one of Chilas (QUASIM JAN et al. 1984 and COWARD et al. 1986). The main rock types are: two pyroxene – plagioclase granulites, pyroxenites and peridotites. Cumulitic textures were observed in some localities. Pyroxene- and garnet-bearing rocks (eclogites) with limited transformation into albite- and amphibole-bearing assemblages, were observed in blocks in the Parla Sapat Valley.


Fig. 7. The Indus Suture (IS) at Parla Sapat: serpentinites of the Kohistan sequence overlie discordantly the steeper dipping garnet and kyanite bearing phyllites of the Higher Himalaya.

In the Babusar Pass area a detailed examination was made of a section 5 kilometers north of the Indus Suture. The Kohistan Sequence shows the same kinds of metamorphic and structural transformations observed along the Indus Suture in the Kaghan Valley. In addition, well developed basic blastomylonites are widespread. The granulites, pyroxenites and peridotites are localised in a band, several hundred meters thick, which is strongly transformed close to the Suture. To the north, the rest of the sequence is composed of metadiorites and metagabbros (amphibole-, chlorite-, epidote-bearing gneissic rocks), intruded by basic dykes, hornblende pegmatitic veins, and aplitic veins, all showing metamorphic transformations. This sequence is cut by several northward dipping blastomylonitic bands, with a northeast directed mineral lineation of stretching type (X-lineation).

## 4. Metamorphism and deformation

Each of the three main tectonic units, the Salkhala, the Crystalline Unit and the Kohistan Sequence, shows a different tectono-metamorphic evolution.

### *4.1 The Salkhala Unit*

The greenschist facies metamorphism in the Salkhala Unit appears to predate the development of the penetrative schistosity. In a few thin sections garnet growth appears to have occurred before the development of the penetrative schistosity and contemporaneous with the development of an older, strongly folded and partially obliterated foliation.

All these microstructural features, considered of Alpine age (Greco 1989), are rare and the main features in the garnet-bearing micaschists have been developed during the main, synthrusting deformational phase. The Salkhala schists characteristically contain three planar surfaces: the firstphase, penetrative schistosity is formed by greenschist facies recrystallised minerals and cuts the original lithological banding at low angle. Because of the tight to isoclinal fold geometry, only a low angle discordance is found along fold limbs. These two planar surfaces (banding and schistosity) are frequently deformed in mm-scale, asymmetric, open folds and are cut by an axial plane crenulation cleavage. This later cleavage has formed by dissolution of the previously-grown minerals in zones of shear strain (second-phase fold limbs) rather than by mica recrystallisation. The occurrence of the second deformational phase should therefore postdate the peak metamorphic conditions in the Salkhala Unit. Especially in the upper parts of the unit, prograde metamorphism in biotite-garnet subfacies has outlived the first, pervasive deformation, whereas in the lower parts the obiquitous paragenesis chlorite + biotite (± garnet) is the syntectonic representative.

The significance of the frequently observed pre-greenschist mineral assemblages in the metabasic rocks is not completely certain. Samples from the Jhelum and Neelum Valleys show relics of augite, ilmenite and of gabbroic textures, strongly suggesting a magmatic origin of these rocks. In figure 8A, the augitic pyroxene is replaced and pseudomorphed by a green amphibole which grew before the development of the penetrative schistosity. Finally the main greenschist assemblage (hornblende, albite, chlorite, epidote, sphene) is related to the formation of the schistosity. It is therefore plausible, according to the field and to the petrographic evidence, that these basic rocks belong to the Panjal magmatic event, and should be compared with the doleritic dykes intruded into the basement of the Higher Himalayan crystalline. Although in the upper levels of the unit these mineral assemblages remained stable, in the lower part synkinematic retrograde effects (breakdown of hornblende to chlorite and actinolite) have been observed and appear to be related to movements along the Panjal Thrust (Greco 1989).

### *4.2 The Higher Himalayan Crystalline Unit*

This unit is characterised by a prevailing amphibolite grade metamorphism overprinted on basement and cover rocks and by the presence of several phases of deformation involving at least two major events. Although the geological features of the basement rocks suggest that one or more pre-Alpine deformation is present, no small scale structures, such as folds, schistosity or lineation could be definitely attributed to such early events. However, the clear recognition of such features would never be an easy matter in view of the intensity of the deformations and metamorphism associated with the Alpine mountain building. In tectonically similar units within the central Swiss Alps pre-Alpine structural features are either unknown or have only be ascertained after very extensive detailed mapping.

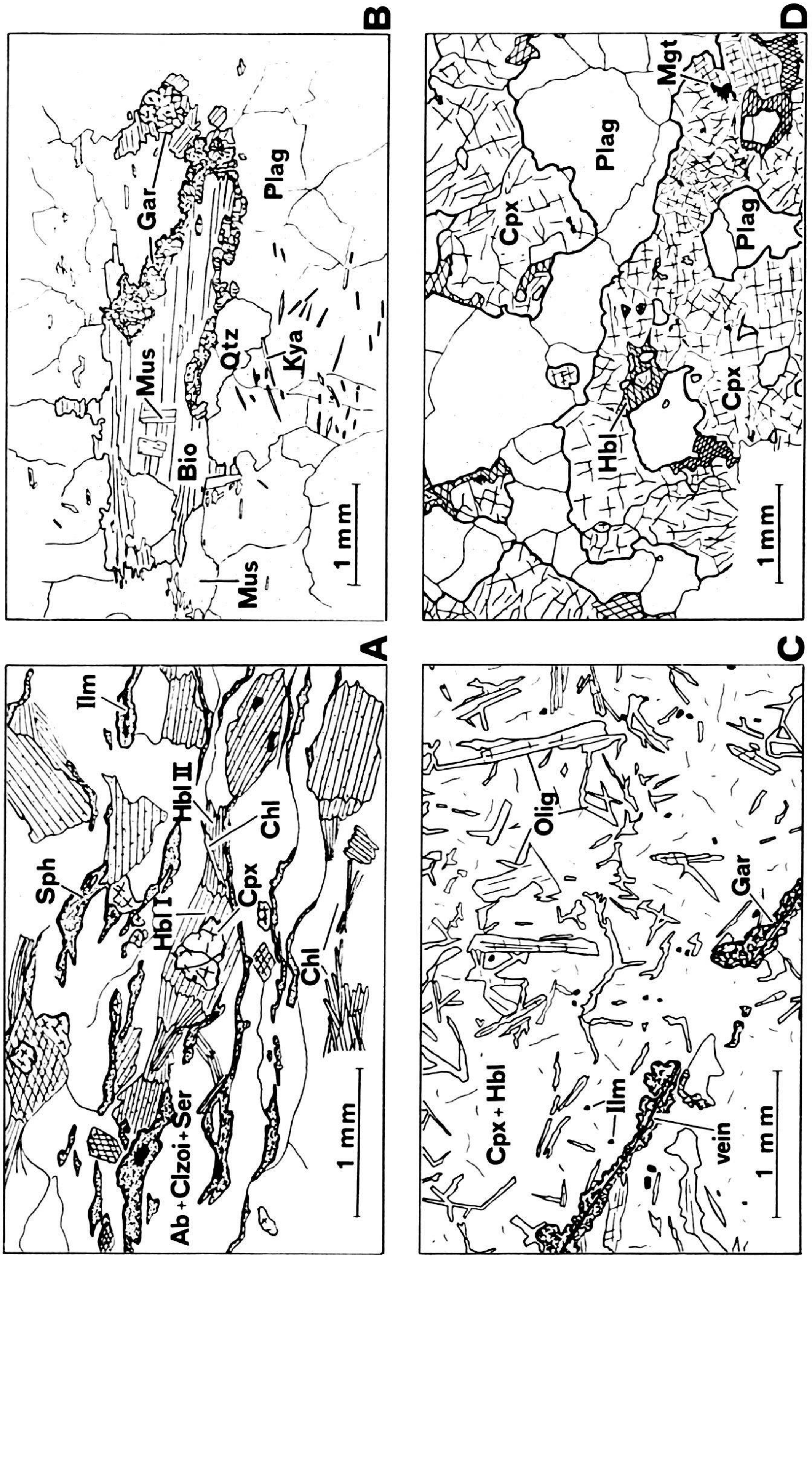


Fig. 8. Mineral assemblages in different rock units of the Kaghan Valley (for detailed explanations see text): A = amphibolite dyke in the upper Salkhala Units; B = granitoid gneiss of the Higher Himalayan basement; C = doleritic dyke in the Higher Himalayan basement; D = pyroxene granulite of the Kohistan sequence.

Planar fabrics can be found in all rocks of this unit. In rocks of sedimentary origin, mineral banding appears to represent the traces of original bedding units. However, these original sedimentary features can sometimes be seen to be cut by secondary banding structure (foliation) induced by metamorphic reconstructions accompanying the deformation. Practically all rocks show a schistosity formed by the sub-parallel orientation of the surfaces of platy crystals (micas) or prismatic forms of acicular crystals (hornblende), and this structure is either parallel to the axial surfaces of isoclinal or tight folds or forms convergent or divergent forms geometrically related to the fold forms. Schistosity is also a feature of most of the deformed granitic plutonic rocks of the basement, and the relationships between the shapes of xenoliths and the planar fabric indicate that the schistosity represents the flattening plane (XY) of the finite strain ellipsoid. Planar schistosity is usually accompanied by a co-planar linear orientation of mineral grains as a finite maximum stretching direction (X-direction, Fig. 9).

An intersection lineation is developed where lithological surfaces are cross-cut by schistosity (Fig. 9). This structure, always aligned parallel to the axes of tight to isoclinal folds, is often accompanied by fold rodding and quartz rod structure, and is parallel to the axes of major first folds in the basement and cover rocks. The fold axes and associated intersection lineations generally lie very close to the X-stretching direction on the schistosity (Fig. 9), a feature which is best explained by the rotation of fold axes towards the stretching direction as a result of high strain.

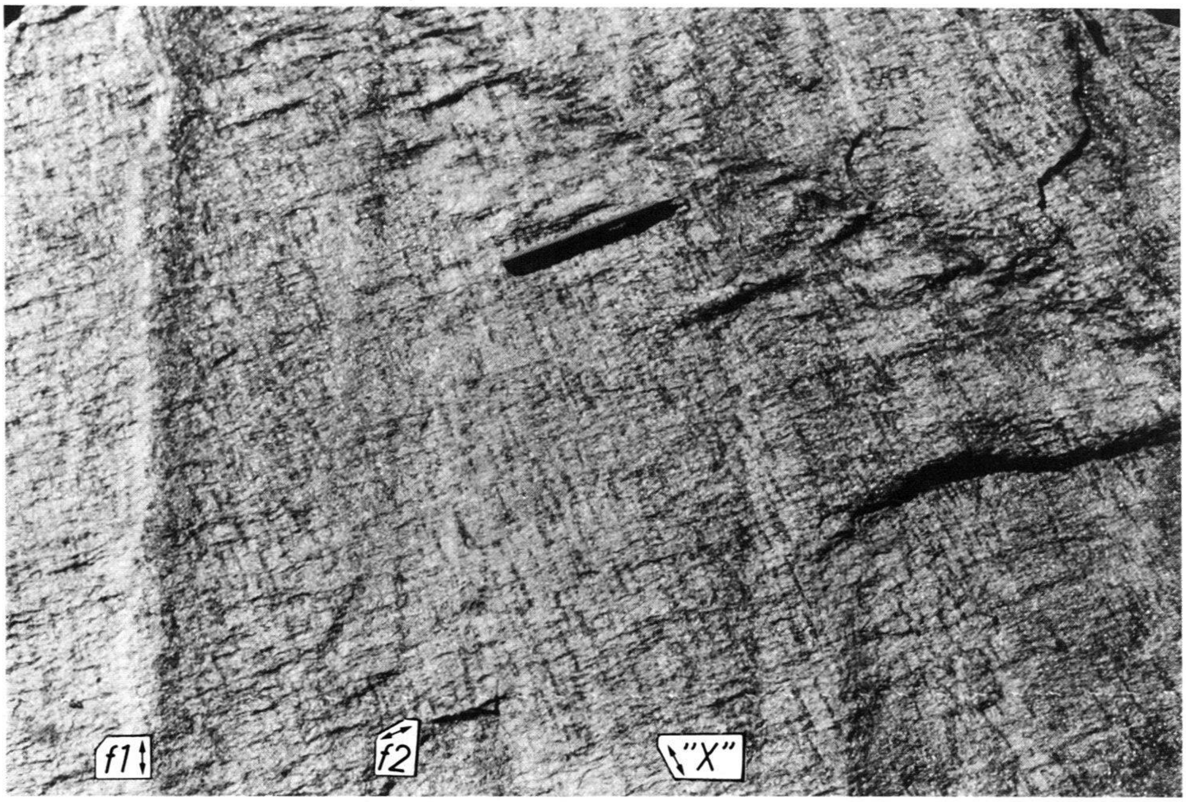


Fig. 9. Three lineations are visible on the schistosity plane of a semipelitic schist (Naran Formation): f1 = intersection lineation between schistosity and bedding trace; "X" = mineral lineation ("stretching"-direction); f2 = axis of small scale crenulation folds of the schistosity.

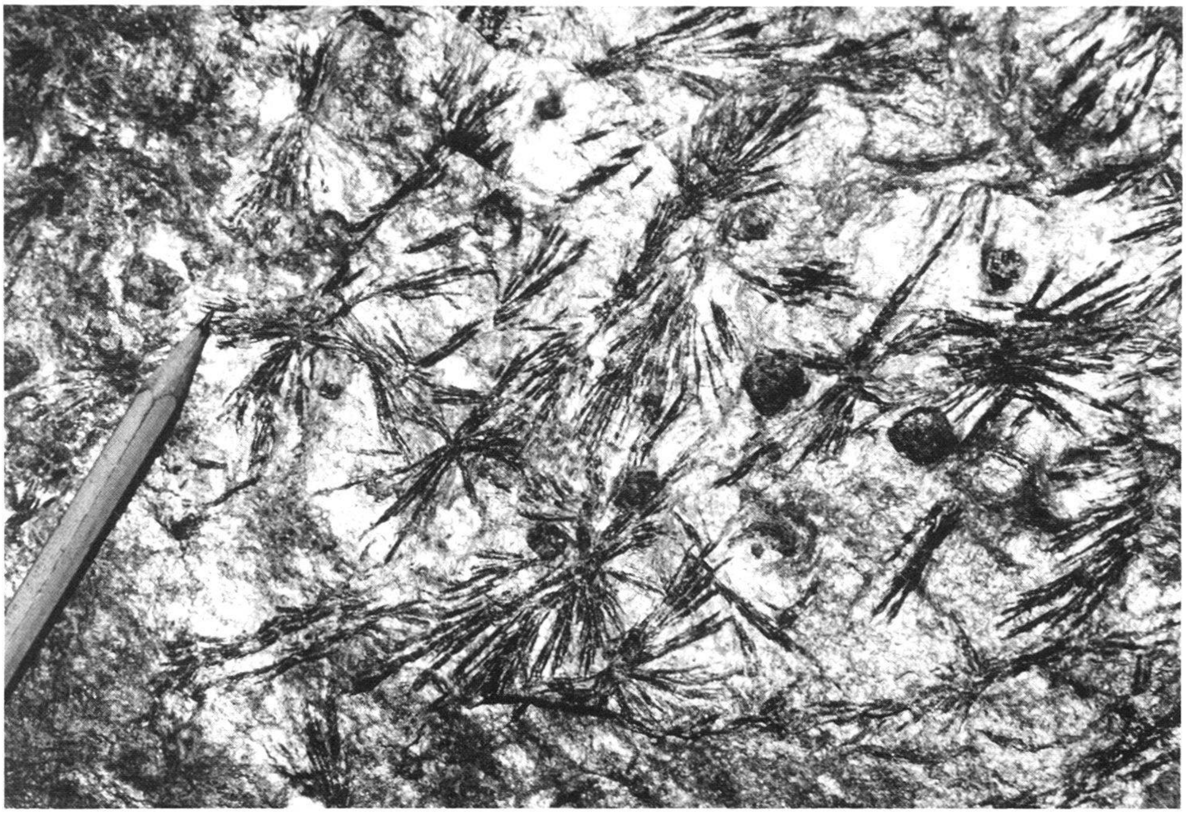

Fig. 10. Garnet – hornblende "Garbenschiefer" belonging to the Higher Himalayan (Mesozoic?) cover sequence.

The main schistosity is generally overprinted by crenulation folds and by the formation of a crenulation cleavage. The platy and prismatic minerals of the main schistosity are bent, broken or recrystallised into straight polygonal arc sectors. Large scale folds of second deformational phase with axial planes dipping southeast trend in a northeast-southwest direction and are related to the development of the crenulation cleavage. These second phase folds superpose the folds of the first phase, giving rise to interference patterns (Types 1 and 2, Ramsay 1967). At Naran competent layers which were stretched and boudinaged during the first major deformation show boudins which are pressed together, and which locally override each other or are folded.

The amphibolite grade overprint in the granitic basement is indicated by the growth of kyanite needles in plagioclase sites and by magmatic biotites rimmed by garnet (Fig. 8B).

In the metagreywackes of the Naran Formation and in the metapelites of the Burawai Formation, the characteristic kyanite-garnet-staurolite-biotite assemblage appears to have developed syn- to postkynematic with respect to the penetrative foliation and to the first folding event. Crystallisation outlasted this deformation and locally radiating bundles of primatic minerals form "garbenschiefer" fabrics (Fig. 10). The second phase crenulation cleavage is accompanied by local non-pervasive greenschist grade mineral growth. In the carbonate rocks, diopside with biotite or phlogopite and oligoclase are frequently observed.

The metabasic rocks of both basement and cover are present as dykes and thick sheets and have petrographic features which indicate a common origin and a similar metamorphic evolution. The protolithic relics are best preserved in the dykes within the basement (Fig. 8C), presumably because of the low level of fluid availability during the metamorphism. Relic igneous fabrics are typical of those seen in basalts and fine grained gabbros. The primary assemblages (calcium-plagioclase, augite, ilmenite, ± olivine) are progressively transformed into an amphibolite assemblages, with the development of garnet, green hornblende, ± diopside, oligoclase, biotite, clinozoisite, sphene in medium to coarsely foliated rocks. This metamorphic assemblage, which is in accordance with that seen in the metapelites of the cover, develops syn- to postkinematically with respect to the penetrative foliation, and is deformed by the subsequent crenulation.

In conclusion, the amphibolite facies metamorphic conditions in the Higher Himalayan rocks were attained during the first deformational phase of Alpine age. All traces of a pre-kinematic metamorphism have been completely obliterated. Metamorphic conditions remained high after this phase with a pressure-dominated character (kyanite) and a strong post-kinematic blasthesis. Greenschist facies conditions characterized the late deformational phase of refolding.

### *4.3 The Kohistan Sequence*

The Kohistan Sequence is characterized by a granulitic facies assemblage with more or less pronounced greenschist re-equilibration along the Indus Suture.

The granulite-facies minerals and textures are best preserved in the Parla Sapat area, and are represented by basic to intermediate granulites, associated with pyroxenites and peridotitic bodies. The granulites are composed of clinopyroxene, Ca-plagioclase, ± hornblende, ± quartz, ± ilmenite (Fig. 8D), which show transformations into greenschist-facies minerals such as clinozoisite (from plagioclase), tremolite-actinolite, amphiboles, chlorite and ± albite (from pyroxene). The peridotites and pyroxenites, locally displaying cumulitic textures, are composed of clinopyroxene, ± hypersthene, ± olivine, ± magnetite, rare hornblende and green spinel. The greenschist-facies re-equilibration gives rise to the growth of serpentine, Mg-chlorite, tremolite, magnetite and ± carbonate.

In the Babusar area the peridotites and pyroxenites display the same primary assemblages and metamorphic transformations as in the Parla Sapat area. The dioritic gneisses are characterized, together with the mylonitic horizons, by the presence of a green-blue amphibole. The mylonites associated with the Indus Suture appears to have been formed under greenschist facies conditions and show a typical matrix of albite, actinolite, epidote and sphene. The same minerals are also present, as individuals or in groups, in layers wrapped by the mylonitic foliation. Therefore these "blasts" were formed during the same greenschist facies event, being subsequently deformed and preserved as "clasts".

## 5. Large scale structural trend

In each tectonic unit we made measurements of the penetrative foliation with the stretching lineation and of the crenulation cleavage with the axis of related folding. These data have been summarized in the structural map of the whole area (Fig. 11).

The main planar features (bedding, thrust planes and penetrative schistosity) form a well defined loop around the Hazara-Kashmir Syntaxis, being folded by the later phase structures as is visible in the synform north of the Malika Parbat (Saiful Muluk) and in the domal antiform of the lower tectonic elements of the Hazara-Kashmir Syntaxis. These foliations tend to become parallel to the Indus Suture in the northwest as well as to the Mylonite Zone and to the Panjal Thrust in the south. In contrast, the planar features of the Murree Formation are cut by the Main Boundary Thrust (BOSSART et al. 1988).

The stretching lineations, which developed on the first phase schistosity planes, have a fairly constantly oriented trend, although the directions alternately plunge between northeast and southwest, because of the later doming of the structural pile.

In a simple shear regime the stretching lineation is related to the direction of tectonic transport in the shear system and, where the shear strains are high, the two are subparallel. This has been verified in the Panjal Imbricate Zone, where the transport direction inferred by the thrust geometry is subparallel to the stretching lineations determined in deformed volcanic rocks (BOSSART et al. 1988). Furthermore quartz textures and other mesoscopic structures like C–S fabrics asymmetric folds and rotated porphyroclasts observed in the Salkhala Unit as well as in the Higher Himalayan crystalline support this evidence, showing the southwestward thrusting of the hangingwall

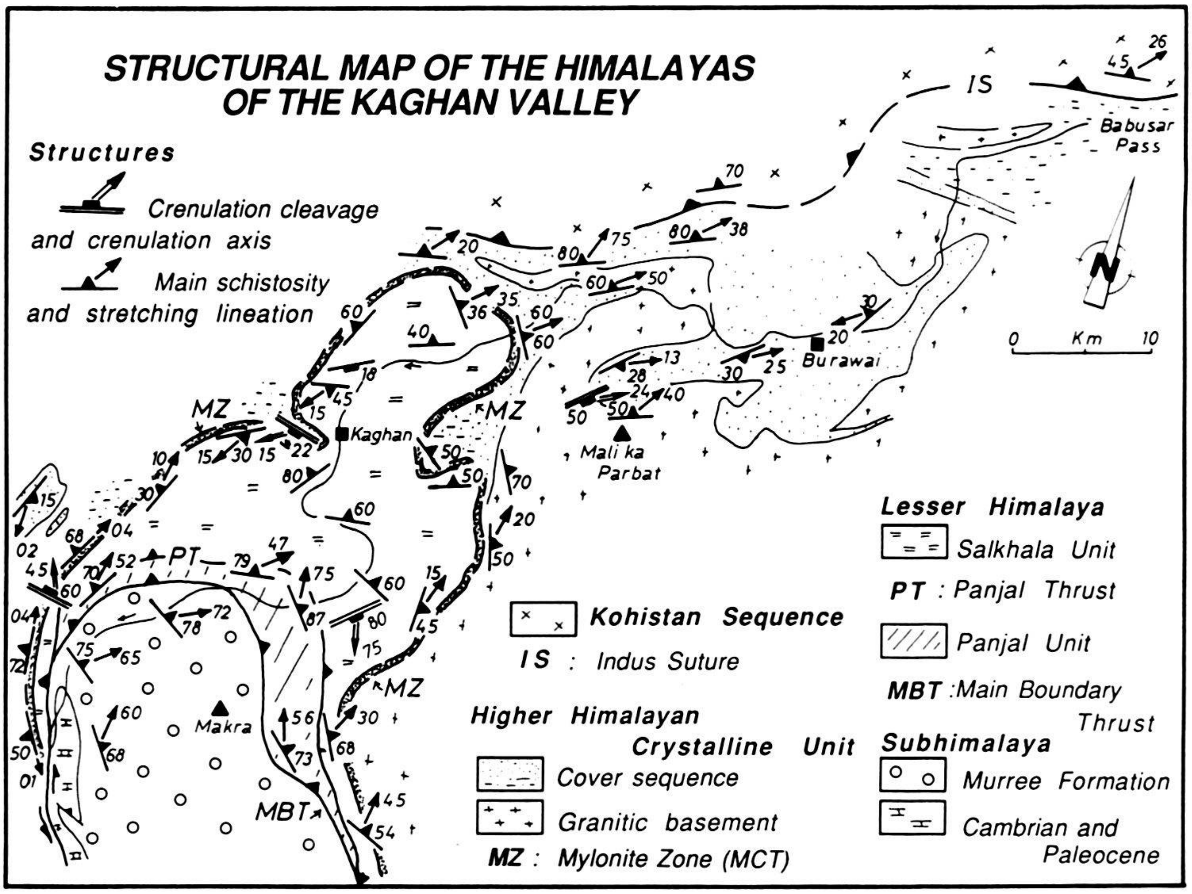


Fig. 11. Synoptic structural map of the Kaghan Valley showing regional trends of the measurements made in the area.

over the footwall (Fig. 12: shear sense on the stretching lineations). The geometry of the asymmetric folds and minor thrust planes in the Murree formation are also coherent with these observations.

The shear senses on the stretching lineations shown in Fig. 12 are coherent with those apparent from the regional set up. Except west of Balakot, where the Mylonite Zone turn into a north-south oriented, left-handed, subvertical discontinuity with subhorizontal lineations, the stretching lineations are approximately constant and northeast-southwest oriented from the Subhimalaya to the Kohistan Sequence at Babusar. In addition, in the Higher Himalayan crystalline, the shear sense remains constant despite the polyphase folding: identical shear senses have been observed on both limbs of the recumbent anticline of basement gneiss north of Naran, suggesting that the lineation has been formed during a shear regime acting at the same time or a little later than the development of the isoclinal folds.

A second phase of deformation produced the refolding of the previously described structures and developed a crenulation cleavage in all the rock units. As shown by the geometrical analysis of the Saiful Muluk synform (Fig. 12), the crenulation fold axes are subparallel to the first-phase stretching lineations. The steeply southeastwards dipping, second-phase fold axial plane, which could be continuously traced southwards

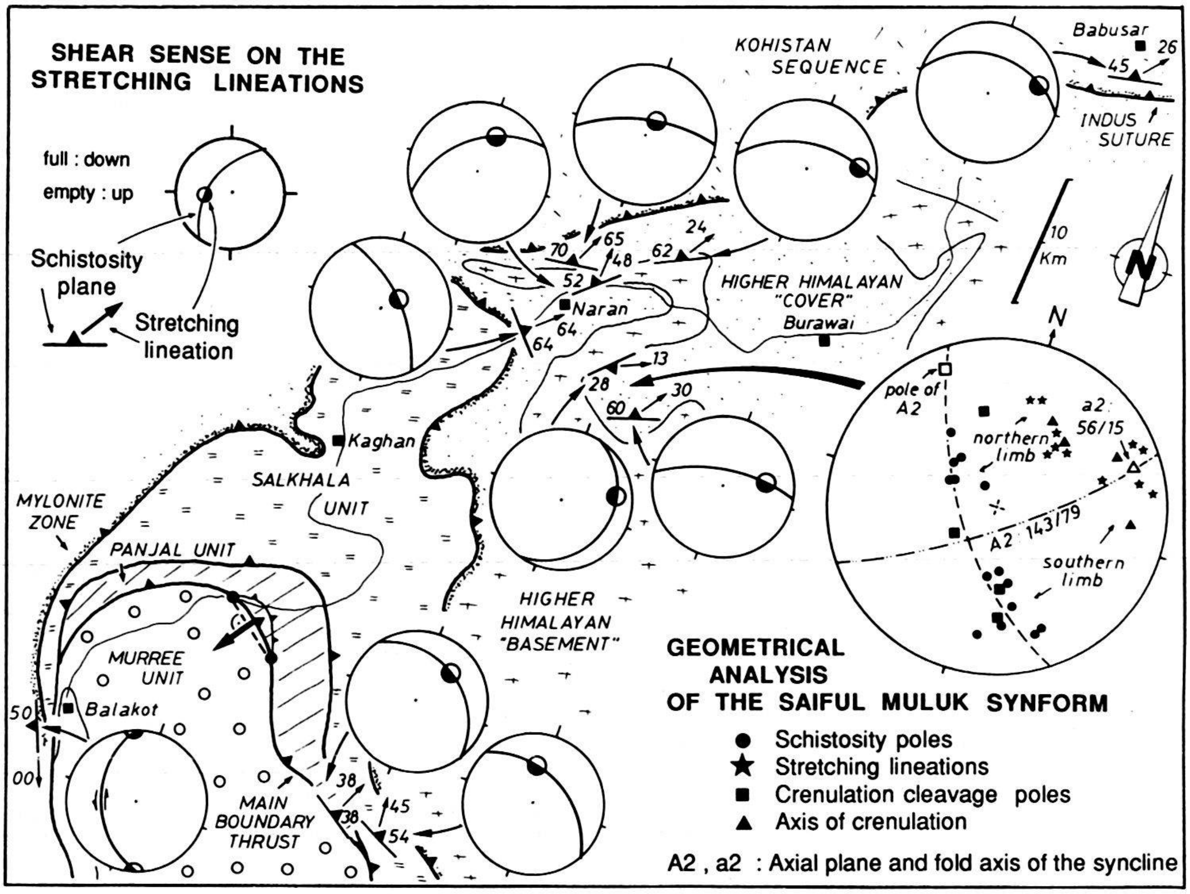


Fig. 12. Stereographic projections indicating geometrical relationships in the Saiful Muluk synform and the shear senses observed along stretching lineations in the whole area.

into the Lesser Himalayan units, is also subparallel in trend to the Indus Suture of the northern Kaghan Valley. In the western limb of the Syntaxis, these second phase structures clearly superimpose the mylonitic foliation (Bossart et al. 1988).

The orientation of the stretching lineation was measured in the Kohistan Sequence at Babusar as well as in the Himalayan units. The directions correlate rather well with those reported from Kashmir and Ladakh Himalaya but are subperpendicular to those reported by Coward et al. (1986) in the Astor and Indus Valleys. Bossart et al. (1988) suggested that these changing orientations are related to an anticlockwise rotation of the tectonic transport direction. This opinion is supported by the northeast plunging lineations measured in the amphibolitic rocks of the Kohistan Sequence at the Babusar village and in the Himalayan Units, lineations which also belong to a first phase of nappe transport. A second phase, clearly superimposed in the Higher Himalayan Unit, forms northeast to southwest oriented folds. These structures probably relate to the later northwest to southeast transport of the Indus Kohistan plate over the Higher Himalaya and produced the final northeast to southwest orientation of the Indus Suture serpentinites in the Kaghan Valley. The differently oriented lineations of the Kaghan, the Indus and the Astor Valleys could simply belong to different tectonic phases (in the Kaghan Valley the earlier, northeast to southwest directed one occurred in amphibolitic facies regime whereas the northwest to southeast one during a later greenschist facies metamorphism), the superposition of which caused the doming of the Hazara-Kashmir and Nanga Parbat Syntaxes. As an alternative interpretation the doming itself might have caused the reorientation of the structures in the Astor and Indus Valley.

## 6. Tectonic Evolution

Summarizing, in the whole area we have five tectonic units (1 to 5) with different composition and tectono-metamorphic evolution.

1. In the Kaghan Valley and at Babusar the Kohistan Sequence represents granulite grade, deep crustal rocks, which have been exhumed without major metamorphic readjustement except along the Indus Suture. Here, the associated shear deformation occurred under amphibolite to greenschist facies conditions.

2. Below, the Higher Himalayan Crystalline Unit is composed of upper crustal, granitic basement unconformably covered by a Phanerozoic metasedimentary sequence. Both basement and cover are together involved in the same kyanite-staurolite grade metamorphism of Alpine age, which overprinted the first-phase penetrative deformation associated with the nappe transport. A later deformational phase involved minor greenschist mineral readjustments. At the base of this unit a strong shear zone developed which shows distinct mylonitic features of amphibolite to upper greenschist facies conditions and marks the boundary with the Lesser Himalayan units.

3. The uppermost Lesser Himalayan unit, the Salkhala Unit is mainly composed of the Precambrian Salkhala schists (perhaps associated with the Upper Precambrian Tanol quartzites), intruded by Cambrian granites. This rock sequence has been subject to Alpine deformation in low metamorphic grade conditions. This ductile deformation developed in association with the main metamorphic mineral growth.

4. The lowermost Lesser Himalayan tectonic element in the Kaghan Valley is the Panjal Imbricate Zone representing a characteristic, imbricated Carboniferous to

Triassic stratigraphic sequence (the Panjal Unit) followed at the base by a tectonic mélange of Permian to Eocene rocks (Mélange Zone). The lower greenschist facies mineral assemblages are associated with a deformation of lesser ductile style with respect to those seen in the Salkhala Unit.

5. The Subhimalaya is mainly represented by the Murree Formation and is characterized by a very low (stilpnomelane-albite) metamorphic grade. Dissolution- and slaty-cleavage developed with the deformation and folding of the strata (Muzaffarabad anticline), and these planar fabrics have been cut by the movements along the Main Boundary Thrust.

The interpretation of the structural features (Fig. 13) as well as the metamorphic development of the area lead us to propose a model for the tectonic evolution.

The tectonic history of the Kaghan Valley begins with a first development of isoclinal to tight folds in each tectonic element. Such structures are found as the major recumbent fold nappes of the Higher Himalaya as well as small-scale folds and thrusts in the Lesser Himalaya, where the Salkhala Unit shows more ductile tectonic style compared to the imbricate fault structures seen in the Panjal Unit. The building of the Muzzafarabad anticline, with the Lower Cambrian strata in its core, represent a first phase in the Subhimalayas. These structures are not necessarily contemporaneous, but are the first to develop in each tectonic unit.

The well-established northeast to southwest directed thrust movements probably occurred together with the initiation of the folding and continued later deforming these structures. The main fold nappe features were cut by the Indus Suture between Besal and Gittidas. The Mylonite Zone also crosscuts these nappes because in its hangingwall different rocks units are found. The overlapping of the mylonitization on the first phase structures is particularly clear in the western limb of the Syntaxis, the associated deformation producing the curved bend of the Panjal imbricate structures. The Muzaffarabad anticline and the Murree sediments are clearly cut by the Main Boundary Thrust in the lower Kaghan Valley (Bossart et al. 1988), indicating that movements on the most frontal thrust plane took place after the first deformational phase. The most likely explanation for these geometric features is that the deformation developed first in the higher tectonic units and propagated towards the Subhimalaya. The north-south trend of the Mylonite Zone near Balakot, is accounted for by rotation of the initially formed northeast-southwest thrust during the later southeasterly directed overthrusts.

A second regionally identified phase of folds is superimposed on both isoclinal folds and thrusts. It is possible to follow these structures through the different tectonic elements (Fig. 13) suggesting their contemporaneous development. The crenulation cleavage remains fairly constantly oriented cutting the previously formed penetrative schistosity and mylonitic foliation. Regionally this deformation can be correlated with the northeast-southwest oriented structures which develop from Besham to the Hazara area (Fig. 1; Coward & Butler 1985; Coward et al. 1986; Bossart et al. 1988). In the Kaghan Valley it is clear that this second set of structures is superimposed on the older set, producing an anticlockwise rotation of the earlier thrust lineations.

The last tectonic event led to a doming of the earlier structures, the bowing up of the Murree Formation into the core of the "half-window" Hazara-Kashmir Syntaxis, and the domal arrangement of the dark phyllitic schists in the Salkhalas south of Bimbal (cf. Gansser 1979). "Basins" and regionally important synformal depressions have

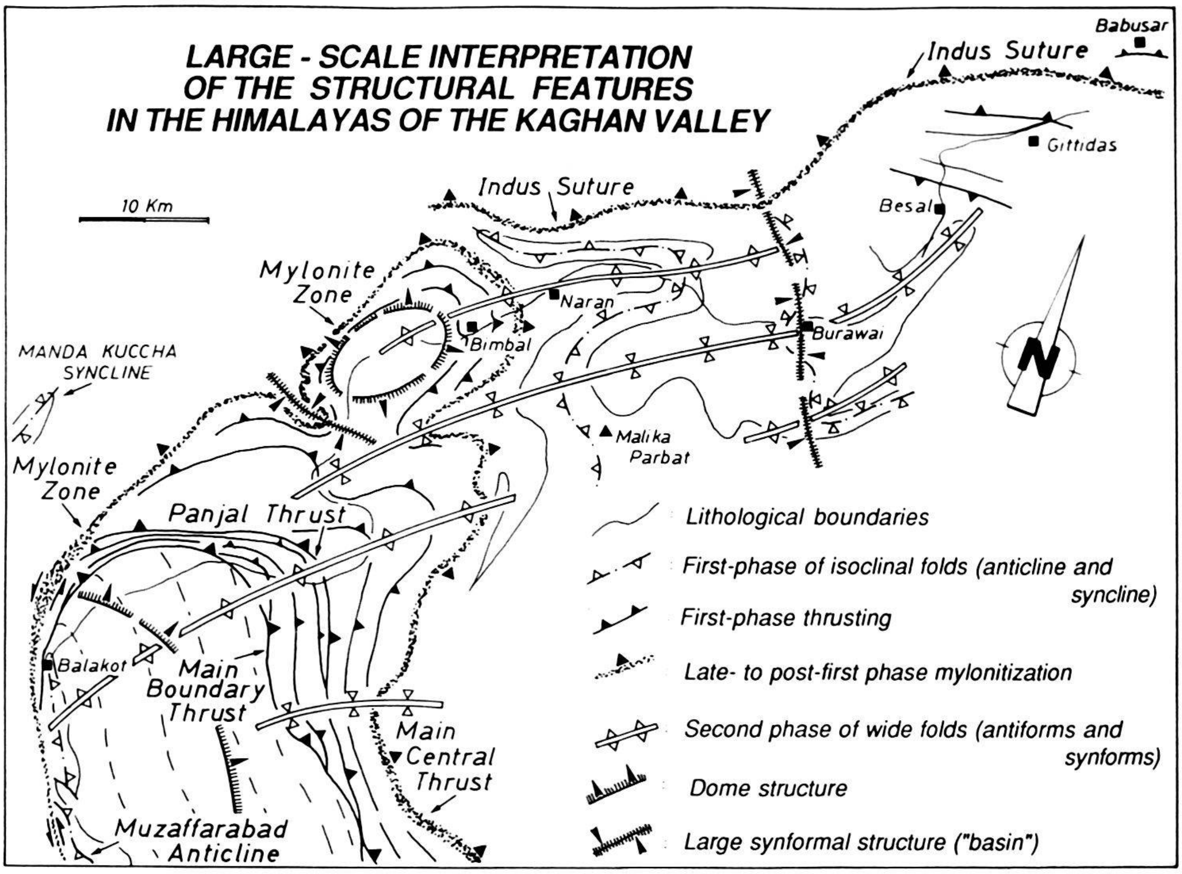


Fig. 13. Interpretation of the structural features in the Kaghan Valley.

been observed between the domes. These depressions cause the flexure of the Mylonite Zone around Kaghan village while a major axial depression has led to the extensive area of surface outcrop of the Paleomesozoic cover in the Burawai area.

In the Sub- and Lesser Himalaya we could not recognize discrete small-scale tectonic features related to the doming (minor folds, schistosity or shear structures). The domes are recognized only by the flexuring of the preexisting thrust planes, foliations and lineations. Consequently, it is suggested that the domes in the Subhimalayan and Lesser Himalayan units do not belong to a discrete third deformation but are the product of the non-coaxial interference pattern of type 1 (→2) (Ramsay 1967) of the two previous phases.

In the Higher Himalaya, the extreme ductility of the rocks caused the rotation of the first fold axes into a direction subparallel to that of the transport direction, and the superimposed second deformation could have produced a coaxial interference pattern of type 3 (Ramsay 1967). Furthermore, the observed weakly developed crenulation folding with axes perpendicular to the stretching mineral lineation (Fig. 9) could be genetically related to the wide synform depression of Burawai. In the Higher Himalayan Crystalline Unit the later development of the wide synforms of Burawai and perhaps of the doming in the Gittidas area is complex and more investigations need to be carried out to resolve the structural geometry.

## Acknowledgments

The authors are grateful to A. Gansser, P. Bossart and K. Honnegger for helpful discussions, to G. Früh-Green for correcting the manuscript, to U. Gerber for the photographs and to the two reviewers M. Coward, H. Masson and A. Steck. We wish also to thank the Federal Institute of Technology of Zurich for the received financial support (grants Nr. 0.330.060.22/9 and 0.330.084.48/4).

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Manuscript received 4 December 1988
Revision accepted 28 March 1989