Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 92 (1999)

Heft: 2

Artikel: The NE-directed Shikar Beh Nappe : a major structure of the Higher Himalaya

Autor: Steck, Albrecht / Epard, Jean-Luc / Robyr, Martin

DOI: https://doi.org/10.5169/seals-168665

0012-9402/99/020239-12 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1999

Eclogae geol. Helv. 92 (1999) 239–250

The NE-directed Shikar Beh Nappe: A major structure of the Higher Himalaya

ALBRECHT STECK, JEAN-LUC EPARD & MARTIN ROBYR

Key words: Himalayan tectonics, nappe tectonics, fold interference patterns, synorogenic extension

ABSTRACT

The structure of the Himalaya is dominated by two belts of SW-verging folds and thrusts. The North Himalayan nappes occur in the Tethys Himalaya to the north and the intracontinental Main Central and Main Boundary Thrust are located in the Higher Himalaya to the south. These SW-directed thrusts have been formed by underthrusting of the North Indian margin below Asia. The SW-verging nappe structures of the Himalayan chain, are in a later stage of the Himalayan orogeny, overprinted by NE-verging, back folds or counter thrusts, mainly developed along the Indus Suture. New investigations in the Lahul and Spiti regions of the Higher Himalaya show that the SW-verging structures of the MCT are overprinting a stack of older NE-directed intracontinental thrusts. Such NE-directed thrust structures may be followed over a distance of about 200 km along strike. Thin-skinned thrusts of a higher tectonic level are exposed in the low grade metamorphic zone of upper Spiti. Farther to the west, in the Kullu and Miyar Valley sections, the brittle imbricate thrust structures of the higher tectonic level grade with depth into a zone of NE-verging similar folds. The very ductile amphibolite to granulite facies rocks of the High Himalayan Crystalline zone grade into a NE-directed ductile thrust zone. The NE-verging Shikar Beh nappe stack represents an example of the transition from brittle to ductile conditions and has been formed by a SW-directed intracontinental underthrusting and accretion of Proterozoic to Mesozoic sediments of the North Indian margin. It is suggested that formation of the NE-directed Shikar Beh nappe has been favored by the presence of reactivated older SW-dipping listric normal faults, originally oriented parallel to the extensional border fault of the North Indian margin. The heating of the subducted sediments is responsible for the regional Barrovian type metamorphism, typical of the metamorphic High Himalayan Crystalline Zone. P-T estimates indicate a geothermal gradient of 25 °C/km and according to published geochronological data, peak thermal conditions where reached between 40 and 20 Ma. The transition from NE-verging folds on a high tectonic level to a mylonitic NE-directed thrust zone in a deep tectonic level may be observed in the NE-directed Miyar Valley Thrust Zone, located on the southern limb of the High Himalayan Crystalline dome structure of the Zanskar region. In the later stages of collision, this metamorphic zone was influenced by the SW-directed extrusion of the Crystalline nappe, with the extrusion limited by the Main Central Thrust at the base and the Zanskar Shear Zone and Dutung-Thaktote fault zone at the top. In the Chenab Valley south of Udaipur, SW-verging folds of the Crystalline nappe are responsible for the later overturning of originally NE-verging folds of the Shikar Beh Nappe resulting in its present SW-facing orientation.

ZUSAMMENFASSUNG

Die Struktur des Himalaya wird von zwei SW-vergenten Deckenstapeln dominiert, die Nordhimalayadecken im Tethyshimalaya im Norden und die intrakontinentalen Zentrale und Hauptrand-Überschiebungen im Hochhimalaya im Süden. Diese SW-gerichteten Überschiebungen entstanden während der Unterschiebung des nordindischen Kontinentalrandes unter Asien. Die SW-gerichteten Deckenstrukturen der Himalayakette werden in einer späten Phase der himalayischen Gebirgsbildung von NE-vergenten Rückfalten überprägt, dies vorwiegend längs der Indussuturzone. Neue Untersuchungen in den Regionen von Lahul und Spiti der Himalayahauptkette zeigen, dass die SW-vergenten Strukturen der Zentralen Hauptüberschiebung einen älteren intrakontinentalen und NE-gerichteten Deckenstapel überprägen. Solche NE-gerichteten Deckenstrukturen können über eine Distanz von ungefähr 200 km im Himalayastreichen verfolgt werden. Diskrete Abscherflächen eines hohen tektonischen Stockwerkes sind in den schwachmetamorphen mesozoischen Sedimenten des oberen Spititales aufgeschlossen. Weiter im Westen, in den Tälern von Kullu (der Beas) und der Miyar, gehen die kataklastischen und diskreten Überschiebungen eines hohen tektonischen Stockwerkes fliessend und mit zunehmender Tiefe in eine Zone von NE-vergenten Scherfalten und in den extrem duktilen amphibolit- und granulitfaziellen Metamorphiten des Hoch-Himalayakristallins in eine NE-gerichtete duktile Überschiebungsscherzone über. Der NE-vergente Shikar Beh Deckenstapel bildet ein Beispiel eines solchen Überganges von spröden zu duktilen Bedingungen. Der Deckenstapel ist während der SW-gerichteten intrakontinentalen Unterschiebung und Akkretion von proterozoischen bis mesozoischen Sedimenten des nordindischen Kontinentalrandes entstanden. Wir nehmen an, dass die Bildung der NE-gerichteten Shikar Beh-Decke durch Reaktivation einer SW-einfallenden listrischen Abschiebung enstanden ist. Die Aufheizung der unterschobenen Sedimente ist für die Barrow-Typ Regionalmetamorphose des Hochhimalayakristallins verantwortlich. Druck-Temperatur-Abschätzungen ergeben einen metamorphen Temperaurgradienten von 25 °C/km. Gemäss publizierten geochronologischen Daten wurden höchste Metamorphosetemperaturen zwischen 40 und 20 Millionen Jahren erreicht. Der Übergang von NE-vergenten Falten in einem hohen tektonischen Stockwerk zu einer NE-gerichteten mylonitischen Überschiebungsscherzone in einem tiefen tektonischen Stockwerk kann in der NE-gerichteten Miyar Valley-Überschiebungszone, auf der Südflanke des Zanskarkristallindomes beobachtet werden. In einer späten Phase der Kollision wurde diese metamorphe Zone von der SW-gerichteten Extrusion der Kristallindecke überprägt, welche an ihrer Basis von der Zentralen Hauptüberschiebung und im Dach von der Zanskarscherzone und der Dutung-Thaktote Normalbruchzone begrenzt wird. Im Chenabtal südlich von Udaipur sind ursprünglich NE-vergente Falten der Shikar Beh-Decke durch die SW-vergenten Falten der Kristallindecke in ihre heutige SW-gerichtete Position rotiert worden.

Section des Sciences de la Terre, Université de Lausanne, BFSH 2, 1015 Lausanne, Suisse, e-mail: albrecht.steck@imp.unil.ch

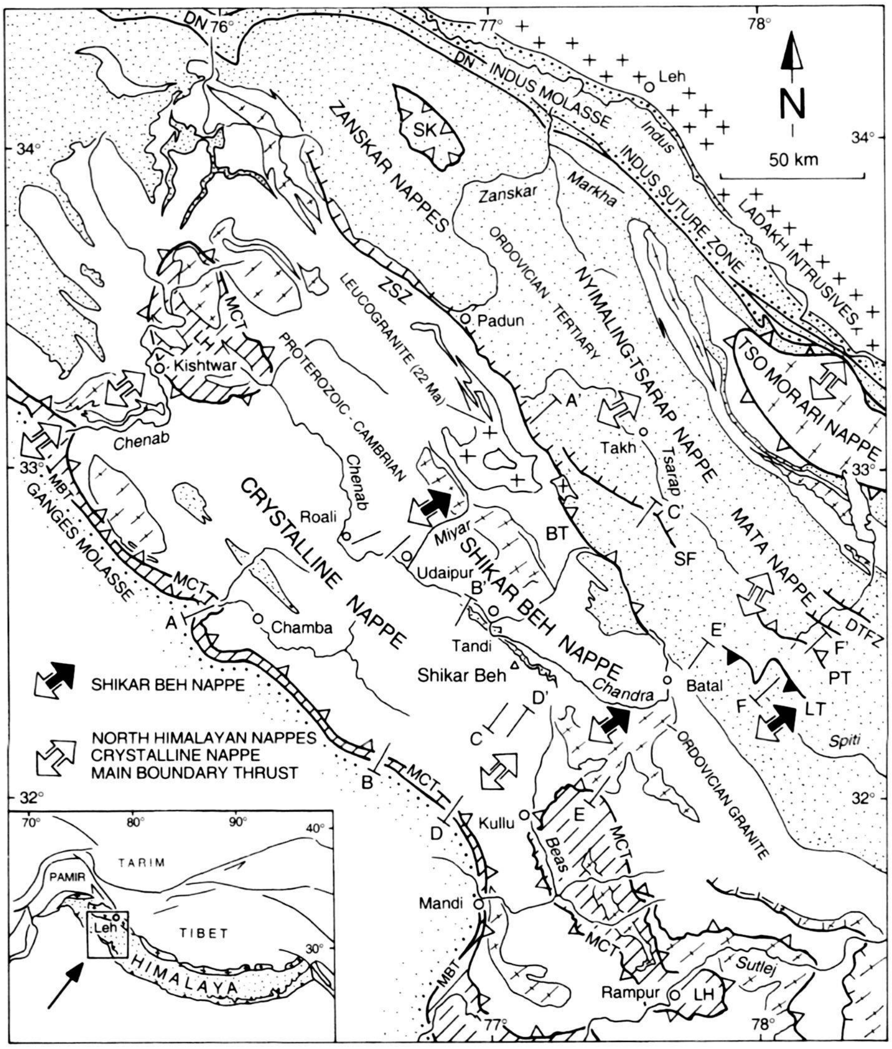


Fig. 1. Structural map of the NW-Himalaya. The main thrust directions, based on sample scale shear criterea, are indicated by arrows. BT = Baralacha La Thrust, DN = Dras-Nindam unit, DTFZ = Dutung-Thaktote Fault Zone, LH = Lesser Himalaya, LT = Lagudarsi La Thrust, MBT = Main Boundary Thrust, MCT = Main Central Thrust, SF = Sarchu Fault, SK = ophiolitic Spongtang Klippe, ZSZ = Zanskar Shear Zone. Three tectonic windows, the Tso Morari window below the Mata nappe and the Kishtwar and the Larji-Kullu-Rampur window below the MCT are shown.

Introduction

Two belts of SW-verging nappes are distinguished on the classical cross section through the Himalayan chain (Fig. 1). The North Himalayan nappes form a northern thrust belt deforming the sedimentary series of the Tethys Himalaya south of the Indus Suture. They formed by shearing off and accretion of the upper North Indian crust during its underthrusting below Asia. Farther to the South, the SW-verging Main Central and Main Boundary Thrusts are two intracontinental zones of thrusting located in the Higher Himalaya. These SW-verging nappe structures of the Himalayan chain developed during the later stages of the Himalayan orogeny and are overprinted by NE-facing, so-called back folds or counter thrusts, mainly developed along the Indus Suture (Heim & Gansser 1939, Frank 1973, 1977, Le Fort 1986). Some of these late folds (eg. the NE-verging Annapurna-Nilgiri antiform of Nepal) were attributed to the late orogenic South Tibetan detachment system (Caby et al. 1983, Colchen et al. 1986, Vannay & Hodges 1996). Another characteristic feature of the Himalayan range is fold structures with steep axial surfaces dipping either to the NE or to the SW. The interpretation of these bifacing structures is controversial. Frank et al. (1995) observed and documented on a detailed geological map of the Chamba and Kullu region such SW- and NE-facing folds with amplitudes of several thousand meters. Frank et al. (1995) interpret this fold geometry as the result of a simple SW-NE-oriented compression of the Higher Himalayan zone producing crustal thickening while simultaneously creating conjugate NE- and SW-verging folds. In this paper, such NE- and SW-verging fold structures are interpreted as fold interference patterns resulting from successive phases of folding.

Recent investigations in the Lahul and Spiti regions show that the SW-verging structures of the MCT overprint a stack of older NE-directed intracontinental thrusts (Fig. 2, Steck et al.

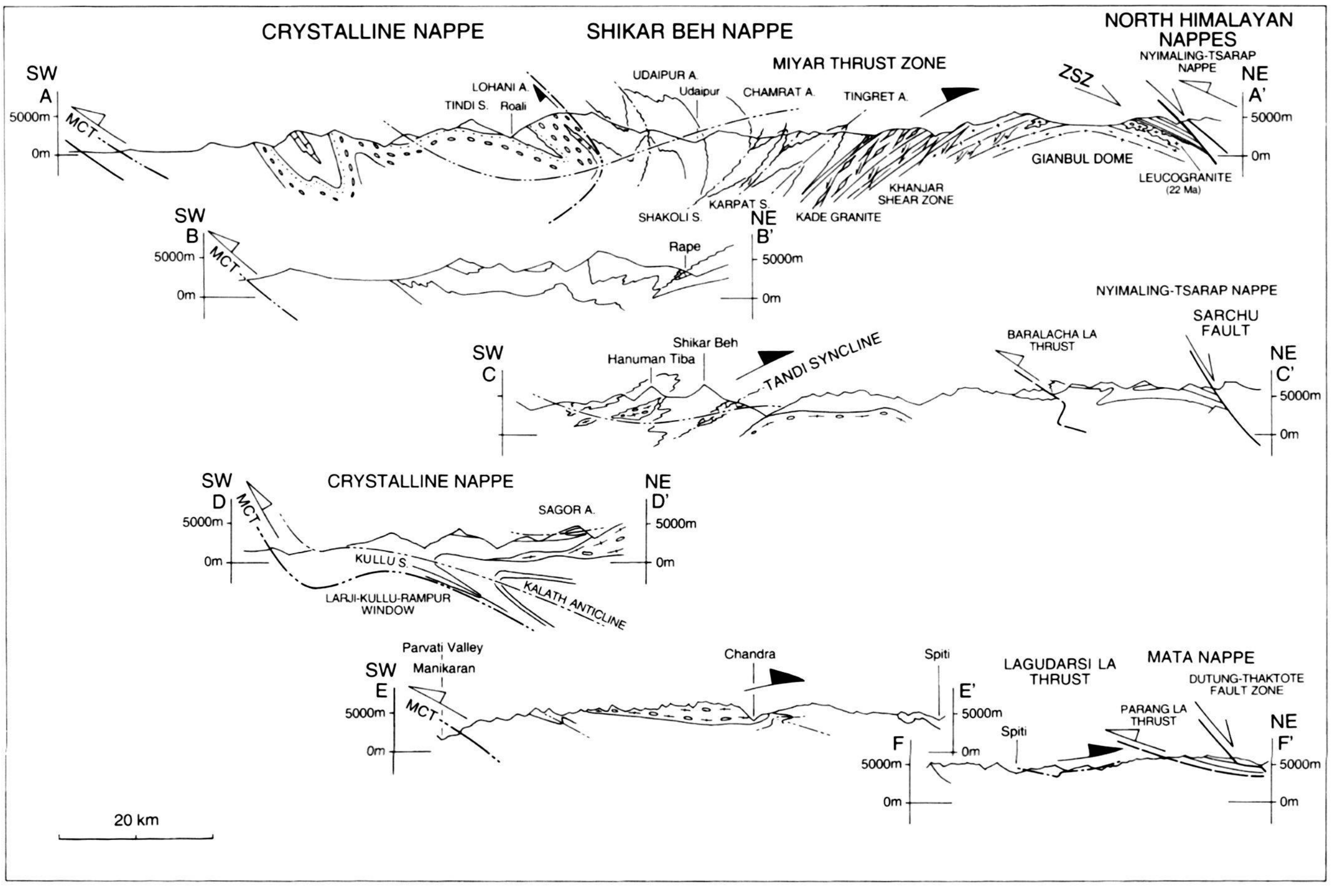


Fig. 2. Geological profiles through the region of Lahul, Kullu and Spiti, modified after Epard et al. (1995), Frank et al. (1995), Steck et al. (1998) and Wyss (1999).

1993, Vannay 1993, Epard et al. 1995, Vannay & Steck 1995). Such NE-directed thrust structures may be traced over a strike distance of about 200 km along the High Himalayan Crystalline Zone from the Spiti area to the lower Chenab valley (Fig. 1). To the east, in the upper Spiti Valley, the thin-skinned NE-directed Lagudarsi La thrust is exposed in the low grade metamorphic Kioto limestones (Steck et al. 1998). The thrust plane is folded by younger SW-verging folds in front of the SW-verging Mata nappe. Farther to the SW, in the Kun Zam La-Toss Valley transect (EE' on Fig. 2), Wyss et al. (1999) demonstrated that early NE-directed thrust structures are overprinted by the SW-verging folds and thrusts of the Nyimaling-Tsarap nappe to the north and by the so-called Crystalline nappe to the south. In the Rohtang La-Kullu Valley transect, the NE-verging older Tandi syncline is overprinted by younger SW-verging fold structures such as the Kalath fold, situated above the SW-directed MCT zone. In these regions, type 3 (Ramsay 1967) fold interference patterns have been formed by the succession of an undoubtedly older set of NE-verging folds overprinted by younger SW-verging folds. Epard et al. (1995) demonstrated that in the Kullu Valley transect the older NE-verging folds reached a higher degree of metamorphism than the younger retrograde SW-verging structures associated with the Crystalline nappe. The early NE-verging nappe of Spiti and Lahul has been named Shikar Beh nappe, after the highest mountain peak to the west of the Rohtang La (pass) (Steck et al. 1993, Vannay 1993). This nappe stack is responsible for crustal thickening and related amphibolite facies grade metamorphism of the Khoksar region (P = 6 ± 1kbar, T = 550 ± 50°C and a thermal gradient of ~25 °C/km, Epard et al. 1995). Throughout the region, the NE-verging folds and NE-directed thrusts of the Shikar Beh nappe are always older and deformed by the younger SW-directed frontal thrusts of the North Himalayan (Nyimaling-Tsarap and Mata) nappes (Steck et al. 1993, 1998, Wyss et al. 1999). The NE-verging Shikar Beh nappe was probably formed by reactivation of an older SW-dipping listric normal fault, representing a zone of intracontinental weakness along the North Indian margin (Steck et al. 1993).

Stratigraphy

The sedimentary rocks of the studied area belong to the Proterozoic to Cambrian Haimantas (Griesbach 1891, Frank et al.

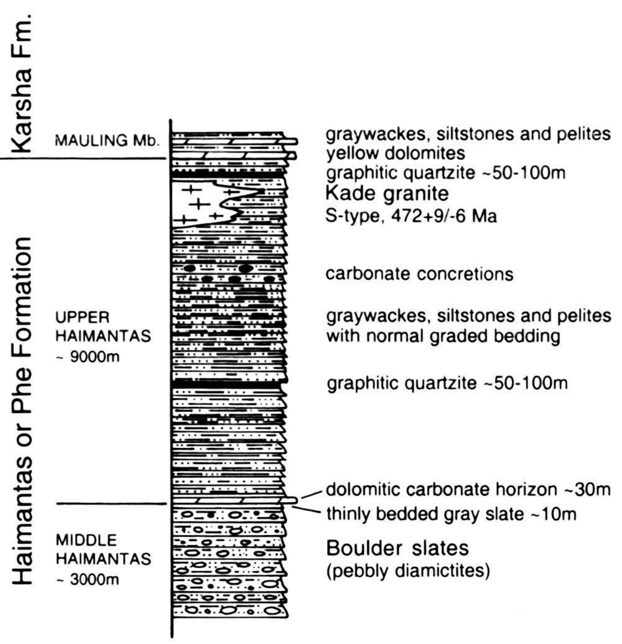


Fig. 3. Stratigraphic profile of the Proterozoic to Cambrian Haimantas or Phe Fm. of the Miyar-Chenab transect. The thickness of the Haimantas is estimated due to the scarcity of good stratigraphic horizons, the absence of datable fossils, and the important Tertiary deformation.

1995) or Phe formation (Nanda & Singh 1977). They consist of a sequence of detrital rocks, (graywackes, siltstones and pelites, Fig. 3). This monotonous series contains three marker units, which are from bottom to top: 1) a diamictite pebbly mudstone unit, 2) a dolomitic carbonates unit and, 3) at least two units of graphitic quartzites. In the Miyar Valley, these sedimentary rocks are intruded by the Ordovician Kade granite (472 + 9/–6 Ma, U-Pb monazite age, Pognante et al. 1990) which contains several lenses of basic rocks up to several hundred meters thick. The Kade granite is a porphyritic two mica granite gneiss with S-type geochemistry (Pognante et al. 1990).

The oldest rocks outcrop in the core of the anticline north of Tandi. It consists of a 3 km thick sequence of pebbly diamictites, frequently named "boulder slates", comprised of massive dark siltstone or fine-grained sandstone beds containing rather well rounded unsorted pebbles of white quartzite up to 10 cm in diameter. They form the core of the Lohani anticline in the lower Chenab Valley. This formation is correlated with the Manjir Conglomerate of Rattan (1973) by Frank et al. (1995). West of Lohani, along the road to Roali, there is an outcrop of well bedded fine-grained sandstone to siltstone. The beds are generally 5 to 10 cm thick and show very prominent graded bedding and are interpreted as distal turbidites. These rocks correspond perhaps to the "thinly bedded gray slate" of Rattan (1973), which are closely associated with the diamict bed mudstone. These sediments are considered as glaciomarine deposits and belong to the Middle Haimantas (Frank et al. 1995). Frequent angular millimeter-sized clasts in the mudstone matrix is consistent with the glaciomarine origin of these pebbly mudstones. A very similar formation of thinly bedded graded silts is observed near Urgos in the vicinity of the contact with the Kade granite.

The Middle Haimantas formation is overlain by dark carbonaceous (mainly dolomitic) pyritic beds forming a characteristic brown weathering horizon. It is a few tens of meters thick and is considered as the base of the Upper Haimantas formation (Frank et al. 1995). The rest of the 9 km thick Upper Haimantas is composed of a very monotonous detrital sequence of graywackes, siltstones and shales with common turbiditic structures, such as graded bedding, slump folds, load casts and oscillation (?) ripple marks. The bed thickness in this formation can vary from centimeters to two meters. At least two 10–50 m thick brown weathering graphitic quartzite beds have been mapped by Frank at al. (1995) for at least 40 km. This type of graphitic quartzite is also found in the high-grade metamorphic area of the Gumba Nala. One to 10 cm carbonaceous concretions of uncertain origin are abundant between Tamlu and Urgos. Their host rocks are associated with either the Upper Haimantas or as a lateral equivalent of the Middle Haimantas boulder slates (Frank et al. 1995).

Tertiary Himalayan structures

This paper presents new observations on NE- and SW-facing folds and NE-directed thrust structures (the Miyar Thrust Zone, MTZ); and a new interpretation of the structures in this area (Tab. 1). General cross sections from the Spiti to the Miyar Valley synthesize the present day knowledge of the structures related to the early NE-directed Shikar Beh nappe (Fig. 1, 2 and 4).

First schistosity S1, stretching lineation L1 and folds F1

An early schistosity (S1) associated with a NE-SW-oriented stretching lineation can be observed in the more ductile greenschist to amphibolite facies rocks of the upper Miyar Valley between Shakoli and Gumba Nala. It has also been locally observed in the Udaipur area. F1 fold structures associated with S1 are rare and small generally not exceeding a meter in size and therefore their amplitude is not sufficient to overturne the stratigraphic series. In most of the cases S1 is parallel to bedding, but locally the dip of S1 is steeper towards the south than bedding (Fig. 5). This bedding-schistosity relationship together with rare NE-verging F1 folds suggest that the formation of this first schistosity is related to NE-directed thrusting.

Second schistosity S1-2, stretching lineation L1-2 and folds F1-2

A main schistosity (S1-2), associated with a stretching lineation L1-2, forms the axial surface structure of the map-scale folds throughout the whole transect between Roali in the lower

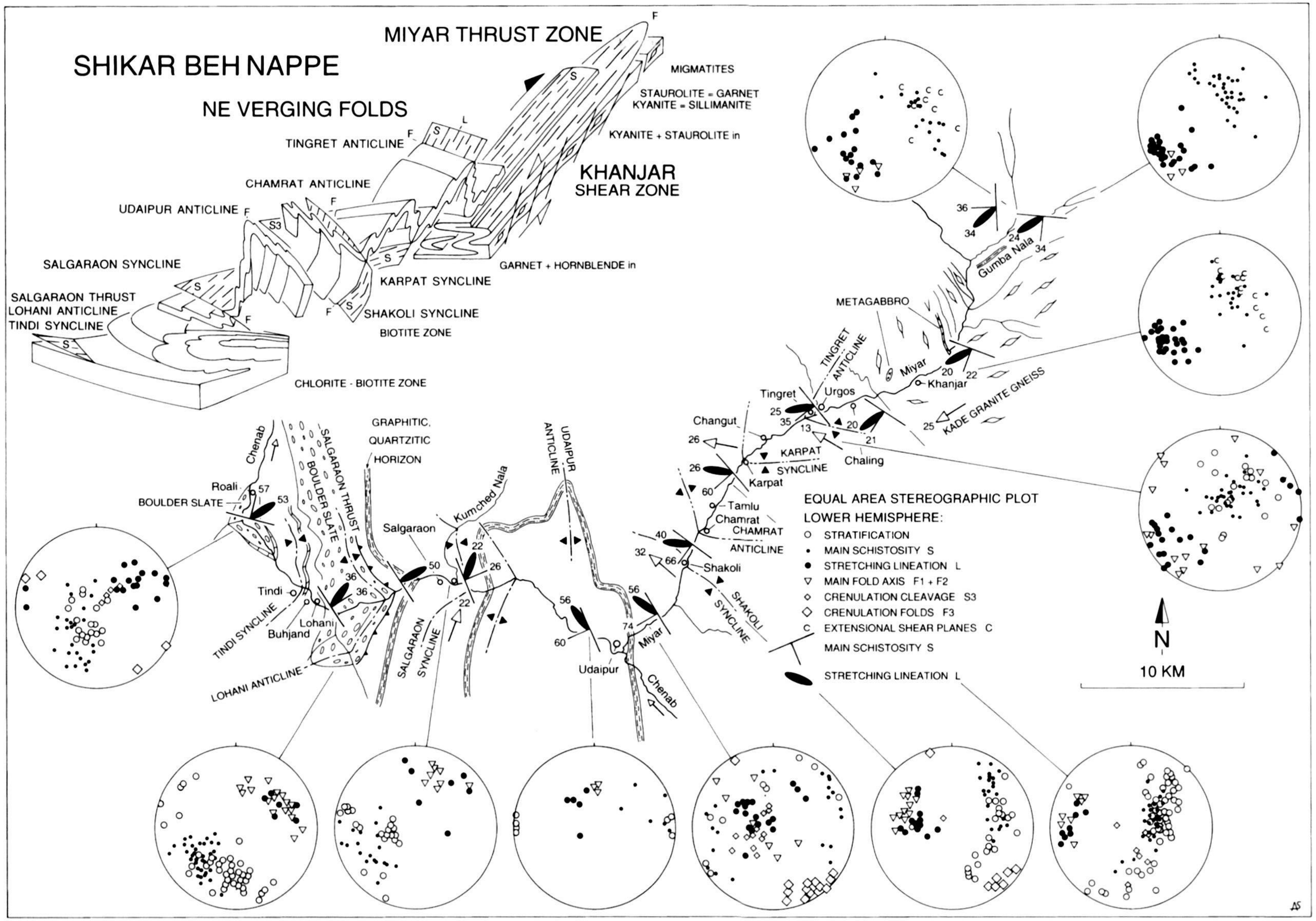
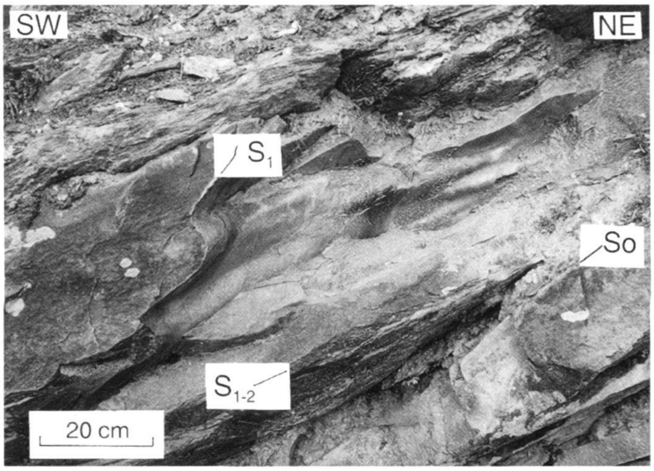


Fig. 4. Structural map of the lower Chenab and the Miyar Valley, partly after Frank et al. (1995). The inset suggests the NE-vergent folds and the NE-directed Miyar Thrust Zone of the NE-directed Shikar Beh Nappe which are reoriented in the present SW-facing position by the F3 Crystalline Nappe folding in the southern part of the section.

Tab. 1. Tertiary structures of the Miyar Valley transect

Main deformational phases	NE-directed thrusting and folding		SW-directed folding	SW-directed detachment	Leucogranite dykes
	D1	D1-2	D3	D4	
schistosity or crenulation cleavage	S1	S1-2	S3	S-C'	
stretching lineation	L1	L1-2			
folds	F1	F1-2	F3	F4	
Main structures	Shikar Beh Nappe Miyar Thrust Zone		Crystalline Nappe	Kanjar Shear Zone Gianbul dome (?)	Gumburanjun granite and dykes
Metamorphic grade	chlorite - sillimanite zones		chlorite - biotite zones	staurolite - sillimanite zones	
Time	Eocene		Miocene	Miocene	Miocene



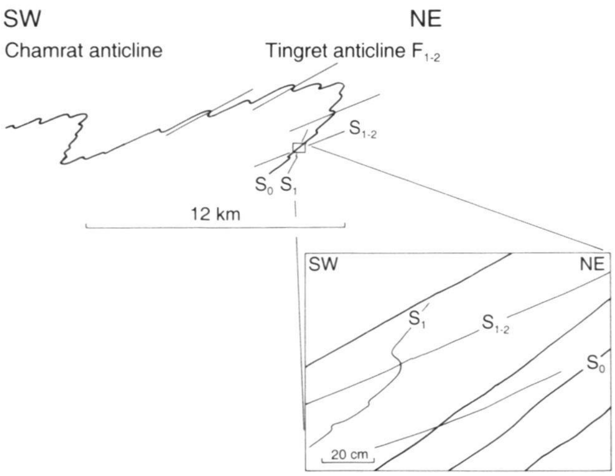


Fig. 5. S1-S1-2 and F1-2 interference pattern in the inverted northern limb of the Tingret anticline near Urgos. Note the NE-verging S1/So intersection and the L1 stretching lineation on the folded S1 schistosity surface.

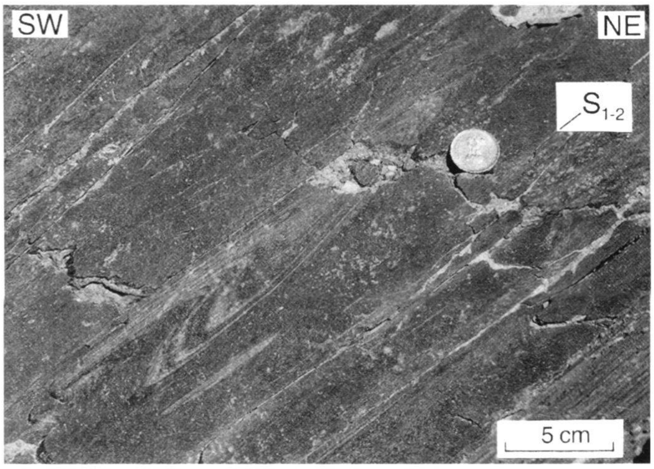


Fig. 6. F1-F1-2 fold interference pattern from the normal F2 fold limb between Shakoli and Chamrat.

Chenab Valley and the Gumba Nala in the upper Miyar Valley (Fig. 2, 4 and 5). This main schistosity overprints an older structure in the more northern metamorphic part of the section between Shakoli and Gumba Nala and therefore has to be considered as a second schistosity. However, in the southern part of the section, between Roali and Shakoli, no previous structure has been observed, with the exceptions of S1-relicts in the F1-2-antiform W of Udaipur. For this reason, the main schistosity, the stretching lineation and the main folds are designated by S1-2, L1-2 and F1-2 respectively. In the monotonous detrital Phe Formation, sedimentological criteria, such as graded bedding, load casts and ripple-marks were systematically used to determine the stratigraphic orientation and therefore the geometry and position of the main F1-2 fold structures. Open SW-facing folds of the lower Chenab Valley grade into upright folds near Udaipur and then into NE-verging folds in the Miyar Valley. These folds have an amplitude and wavelength of several kilometers (Fig. 2 and 4). As previously mentioned, F1 fold structures associated with the S1 old schistosity are rare and small generally not exceeding a meter in size. Therefore, their effect on the stratigraphic orientation is insignificant and F1-F1-2 fold interference patterns are rare

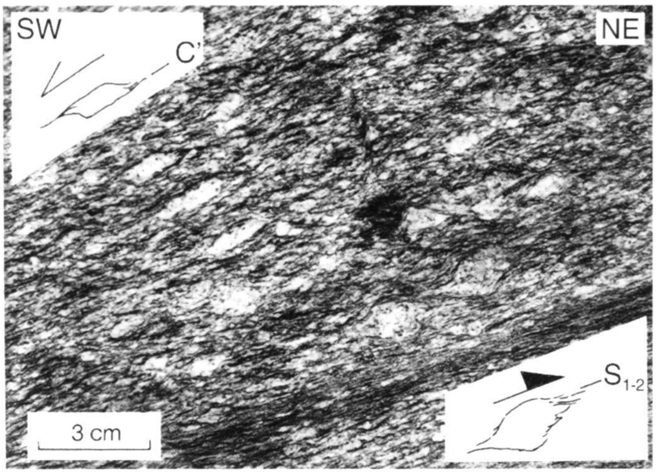


Fig. 7. The porphyritic Kade granite gneiss showing top-to-the NE shear sense criteria related to the main mylonitic schistosity S1-2 of the Miyar Thrust Zone (MTZ) and top-to-the SW C' shear bands related to the younger Khanjar (extensional) Shear Zone (KSZ).

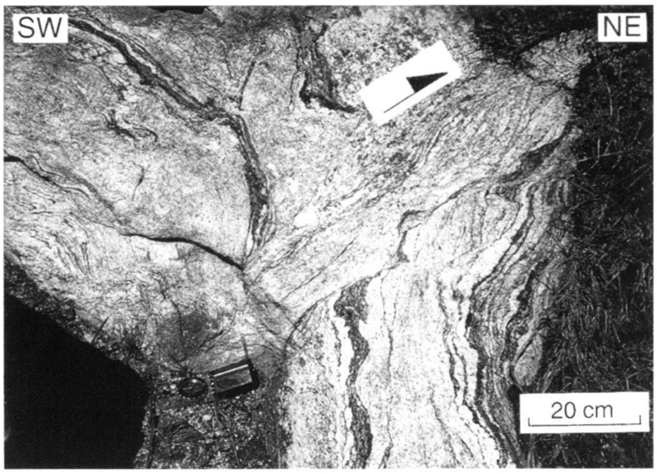


Fig. 8. Top-to-the NE shear structure of the Miyar Thrust Zone (MTZ) in the migmatites of the upper Gumba Nala.

(Fig. 6). This phenomenon can be explained by the homogeneous deformation of a mechanically homogeneous ductile series that does not produce F1 fold structures, whereas the main S1-2 and F1-2 structures were formed on a mechanically anisotropic medium caused by an oriented metamorphic recrystallisation fabric and the presence of the old S1 schistosity. This anisotropic medium favored the formation of flexure or buckling folds, which evolved in a later stage of deformation to similar folds. Voll (in Nabholz & Voll, 1963) described a similar situation in the Helvetic nappes of the Alps.

The NE-directed Salgaraon thrust and the Miyar Thrust Zone (MTZ) (D1-2)

The SW-facing Lohani anticline in the southern part of the section is characterized by a strong asymmetry in limb thickness. The northern, topographically higher limb is much thinner than its southern, topographically lower limb. This asymmetry is interpreted as the effect of a discrete thrust structure: the Salgaraon thrust. The originally NE-verging Lohani anticline was first thrusted towards the NE causing strong deformation and reduction of its overturned northern limb along the Salgaraon thrust. Then, this thrusted anticline was rotated to its present position by the S3-F3 SW-directed phase and the originally overturned reduced northern limb was uplifed to its present topographic position.

Young S-C' fabrics superimposed on the main schistosity (S1-2) are observed in an about 1 m thick and 60° NE-dipping shear zone in the Salgaraon thrust zone indicating that this important tectonic feature has been reactivated by SW-directed movement. The originally NE-directed Salgaraon thrust, at a high tectonic level, is interpreted as the brittle equivalent to a more ductile and deeper Miyar thrust zone, observed in the northern, more metamorphic part of the section. Both structures are characterised by NE-verging folds related to structures topping to the northeast.

The name of Miyar thrust was first used by Pognante et al. (1990) to describe a SW-dipping discrete thrust located in the upstream part of the Miyar Valley characterised by a gap in metamorphic grade between a relatively low grade metamorphic hanging wall and a relatively higher grade footwall. Our observations in the Miyar Valley do not confirm the existence of this metamorphic gap as suggested by Pognante et al. (1990). On the contrary, the metamorphic grade of the amphibolite facies metamorphic rocks change gradually over a distance of about 15 km along the Miyar river transect from the hornblende-plagioclase-in isograd near Urgos, through the staurolite and kyanite zones, to the staurolite-out and sillimanite-in isograds at the entrance of the Giumba Nala, suggesting a normal Barrovian-type metamorphism. Instead of a discrete and isolated structure as postulated by Pognante et al. (1990), there is strong evidence of a 20 km wide shear zone located in the southern limb of the High Himalayan Crystalline dome structure (the Gianbul Dome) as defined by Dèzes et al. (1999). We propose the name of Miyar Thrust Zone (MTZ) for this wide shear zone characterized by sheath folds, mylonitic structures and, well-developed top-to-the NE shear sense criteria (Fig. 7 and 8). The intensity of the deformation increases from south to north and is concomitant with a gradual increase in the metamorphic grade ranging from biotite, staurolite-kyanite up to the migmatite-sillimanite zone.

Dèzes (in press) suggests that our Miyar Thrust Zone could be connected with the Zanskar Shear Zone located in the Northern limb of the Gianbul dome. Both will be part of a unique NE-topping shear zone, later refolded by the Gianbul dome giving the present day situation with a north dipping

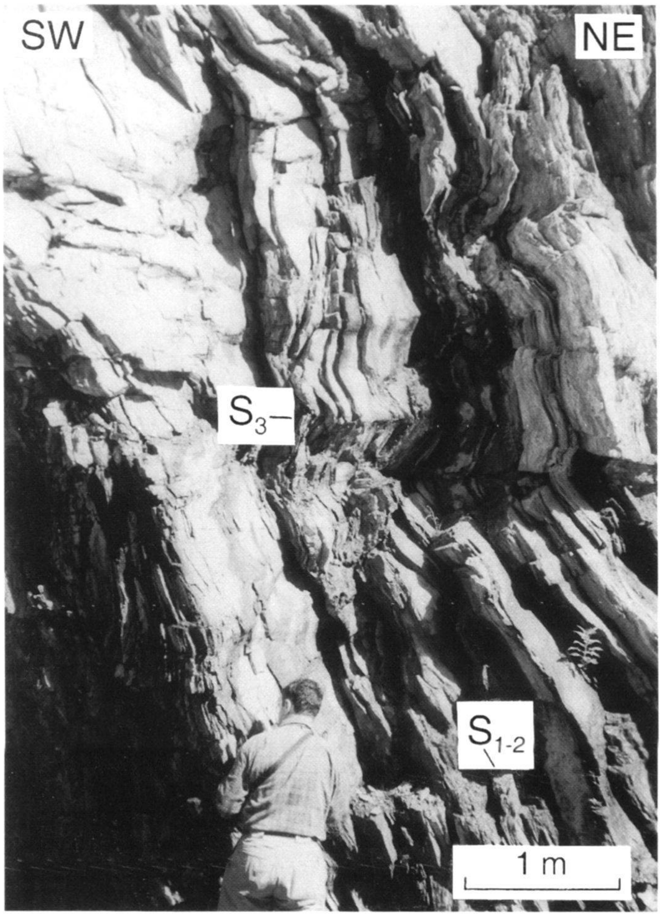


Fig. 9. F3 kink folds and spaced S3 crenulation cleavage in the vertical S1-2 schistosity. Miyar gorge between Udaipur and Shakoli.

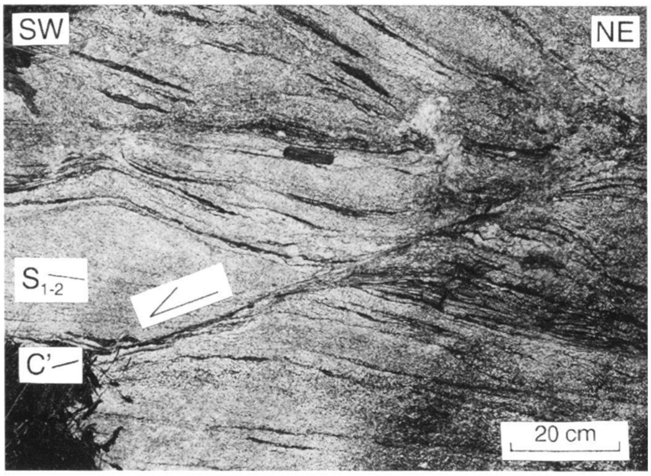


Fig. 10. Top-to-the SW extensional shear bands C' of the Khanjar Shear Zone (KSZ) in the sillimanite zone (migmatites) upper Gumba Nala.

Zanskar Shear Zone in the northern limb of the Gianbul dome and a south dipping Miyar Thrust Zone in the southern limb of the dome (Fig. 2). This "Zanskar-Miyar shear zone" would be produced by the extrusion of the crystalline nappe towards the SW contemporaneous with the MCT. We do not agree with this interpretation for the following reasons:

1. The spacing of the metamorphic isograds of the MTZ suggests a normal Barrovian thermal gradient, which may be related to the Shikar Beh nappe stack. In contrast, in the ZSZ the original distances between isograds have been strongly reduced by the extensional shear zone (Dèzes et al. 1999), indicating different deformational/metamorphic trajectories.
2. The Zanskar Shear Zone is interpreted by Dèzes (in press) as produced by the extrusion of the Crystalline Nappe towards the SW. If the Miyar Thrust Zone is the prolongation of ZSZ, it has to come back to the surface, south of the Miyar Valley and north of the MCT in the form of a top-to-the NE shear zone (or normal faults in the low grade metamorphic zone). There is no trace of this type of shear zone in the studied cross section between the Miyar Valley and Roali, and farther south, this type of structure has never been described. This will imply also that the Precambrian to Cambrian rocks of the Miyar-Roali area do not belong to the Crystalline Nappe but to a higher structural unit. The existence of this new tectonic unit is not supported at regional level by the map of Frank et al. (1995).
3. The top-to-the NE movement of the Miyar Thrust Zone are older than SW-verging structures we interpret as related to the Crystalline Nappe emplacement (S3-F3 structures, below). The movement of the Zanskar Shear Zone is interpreted by Dèzes (in press) as contemporaneous with Crystalline Nappe emplacement (Miocene), and therefore cannot be of the same age as the Miyar Thrust Zone (Eocene).

These kinematic and geometric inconsistences make the hypothesis of the prolongation of the Zanskar Shear Zone into the Miyar Thrust zone untenable.

Crenulation cleavage S3 and folds F3

The main F1-2 fold structures are folded by open F3 folds with a subhorizontal axial surface crenulation cleavage S3 (Fig. 9). F3 folds are abundant between Salgaraon and Karpat. Characteristic kink fold structures deform the axial surface of the Shakoli syncline. To the S of Shakoli, the F3 folding is responsible for the overturning towards the SW of the originally NE-verging folds.

At the regional scale of Lahul and the Kullu Valley, the F3 folds are related to the SW-verging Crystalline nappe and the MCT. The crenulation cleavage S3 evolved to a penetrative, narrow spaced structure in the MCT zone in the Parvaty Valley (Wyss et al. 1999). It represents the axial surface structure of the SW-verging Kalath anticline in the Kullu Valley (S2 in Epard et al. 1995). The NE-verging Tandi syncline is cross cut by a younger crenulation cleavage and folded by the associated SW verging folds (Sta2 in Steck et al. 1993, Vannay & Steck 1995). The geometric similarity of the fold interference patterns in the Tandi syncline, the SW-verging Kalath anticline and the SW-directed MCT zone is evident. Farther to the W, rocks in the lower Chenab and the Miyar Valley (this study) represent the upper part of the SW-directed Crystalline nappe located far away from the MCT. The structures related to the emplacement of the Crystalline nappe in this high tectonic level are obviously less well developed than in the lower part, close to the MCT. They are represented by the subhorizontal spaced third crenulation cleavage S3 associated kink folds ranging in size from cm to m. This third fold phase is responsible for the folding of the axial surface of the Shakoli syncline (Fig. 2 and 4). South of Shakoli, the F3 folding causes the overturning of the originally NE-verging folds towards the SW.

The Khanjar (extensional) Shear Zone (KSZ), the Gianbul dome structure (D4) and the Tertiary Leucogranites

In a late phase of deformation, the Miyar Thrust Zone is overprinted by the 15 km wide (~ 10 km thick) Khanjar extensional Shear Zone (KSZ). Synmetamorphic SW-dipping extensional shear bands (C') with top-to-the SW shear (C on the stereographic plots of Fig. 4) occur continuously in the whole kyanite-staurolite and sillimanite zones north of Chaling (Figs. 10 and 11). They are overprinting the older S1 and S1-2 schistosities of the Miyar Thrust Zone. Veins of anatectic melt are intruding the C' shear zones in the migmatites of the Gumba Nala area. The migmatitic extensional shear structures are crosscut by undeformed younger aplitic and pegmatitic leucogranite dikes (Fig. 11).

The Khanjar Shear Zone was developed on the southern limb of the Gianbul dome, a late dome structure of the eastern end of the high grade metamorphic zone of the Higher Himalayan range to the south of Zanskar (Dèzes et al. 1999). It is therefore closely associated in time and space to the migmatite and dome formation and could be related to a late vertical extrusion of ductile migmatites propelled upwards by buoyant forces.

In the Gianbul Valley, this young dome structure is folding the older Tertiary Gumburanjun leucogranite intrusion. Similar dome structures characterize the whole NE-SW-trending zone of Tertiary migmatites of the Higher Himalaya to the S of Zanskar (Kündig 1989). In the study area, Tertiary tourmaline-garnet-muscovite pegmatites and aplites (leucogranites) crosscut the high grade metamorphic rocks of the staurolite-kyanite, sillimanite and migmatite zones. Early dikes are deformed by the extensional cleavage of the Khanjar shear zone. Younger dikes are undeformed (Fig. 11).

The relative age of the D3 and D4 structures is unknown; they occur in different regions and tectonic levels. The SW-vergent F3 folds occur in the low grade greenschist facies rocks

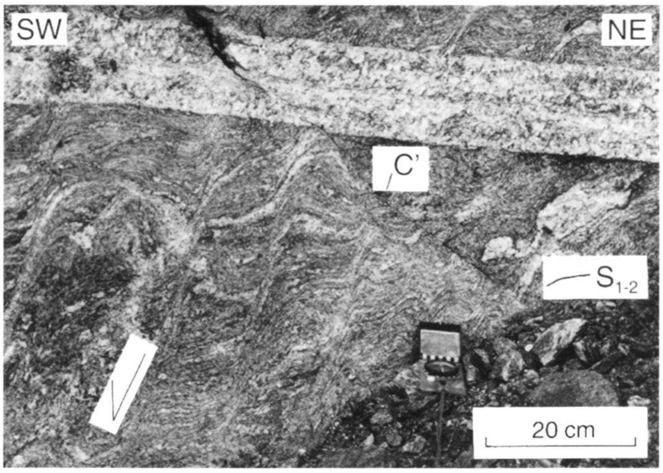


Fig. 11. Top-to-the SW extensional shear bands C' of the Khanjar Shear Zone (KSZ) in the upper Gumba Nala sillimanite zone (migmatites) crosscut by an undeformed muscovite-garnet-tourmaline pegmatite.

south of Karpat, whereas the rocks of Kanjar shear zone to the north of Chaling (Fig. 4) display amphibolite grade metamorphic facies. They may be of the same or different ages.

Modeling of the fold interference pattern

The refolding of F1-2 folds by open F3 folds produces a type 3 interference pattern (Ramsay 1967) that can be easily reproduced using the POLYPLI software (Perrin et al. 1993; Epard et al. 1997). The software is based on a heterogeneous simple shear model that can be applied several times in every user determined direction. This modeling does not pretend to reproduce the geometry of a geologic structure in every detail but intends to offer a geometric and kinematic analog of a specific situation that can be then compared to the actual geometry (Fig. 12).

The model of Figure 12 C has been obtained in 3 steps.

A) Sine wave type folds have been generated from originally horizontal beds using an heterogeneous simple shear on shear plane dipping of 20° towards the SW. It represents the early NE-vergent Shikar Beh nappe structure F1-2. Black lines represent the axial surfaces of these folds.
B) A moderate heterogeneous simple shear with shear plane dipping of 10° towards the NE is then superimposed. This phase represents the moderate shear towards the SW related to the Crystalline nappe emplacement. Black lines represent the refolded axial surfaces of the F folds.
C) Vertical shear on the NW-SE plane has been applied to reproduce the large wave length and open structure typical for a dome (i.e. Gianbul dome or Kullu-Rampur window) and their basin counterpart. In order to better visualize this deformation, it has been applied on two horizontal stippled lines of stage B).

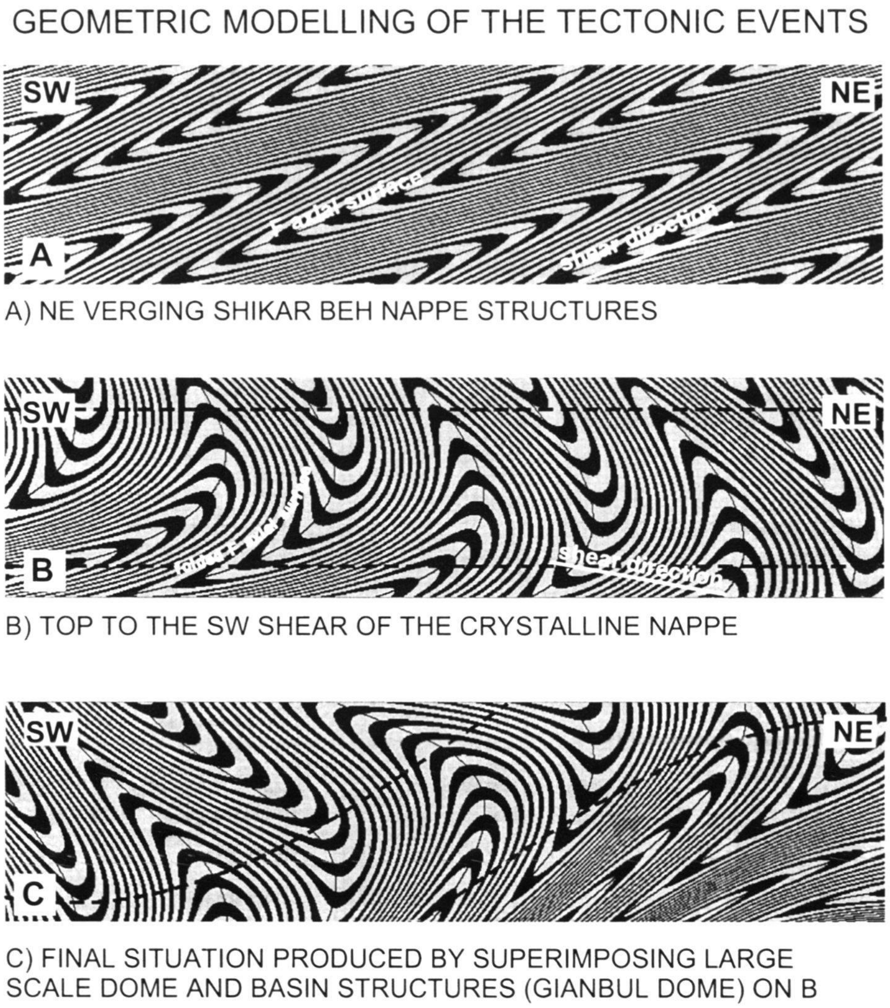


Fig. 12. Geometric modelling of the kinematic succession of tectonic events. A) NE-verging Shikar Beh nappe structures. B) superposition of A and a moderate top-to-the SW shear component during the Crystalline nappe emplacement. C) large scale open dome and basin structure possibly related to the Gianbul dome formation. See cross section A-A' (Fig. 2) for comparison.

The final picture Figure 12 C is in good agreement with the kinematic succession of folding observed in the Miyar valley and lower Chenab transect. The model geometry is very similar to the cross section of Figure 2 obtained independently from field observation. It demonstrates that moderate shear towards the SW is sufficient to reorient originally NE-vergent folds related to the Shikar Beh nappe and to generate this "doubly facing" structure alternatively interpreted as produced by one phase of NE-SW contraction. It demonstrates also that large scale hinges related to the F3 phase can be difficult to localize precisely in the field. That is probably why the regional effect of the F3 folding can go unnoticed unless a detailed structural analysis is performed.

Discussion and conclusions

The structure of the lower Chenab-Miyar Valley transect is characterized by the following tectonic events.

The first and older one includes the synmetamorphic Miyar Thrust Zone, the main folds (F1-2) and the Salgaraon thrust which are all part of the same tectonic event showing top-to-the NE movement. They represent an increase in deformation from rather open F1-2 folds in the Chenab Valley to the highly strained Miyar Thrust Zone in the upper Miyar valley. The metamorphic grade increases from the chlorite-biotite zone in the Chenab Valley to the sillimanite-migmatite zone and lower granulite facies (muscovite + quartz out) in the north. This early top-to-the NE event is correlated with the Shikar Beh nappe emplacement (phases D1 and D1-2).

The second event (phase D3) is characterized by open SW-verging F3 folds and an S3 crenulation cleavage producing a reorientation of the originally NE-verging F2 folds of the southern part of the section to presently SW-facing folds (phase D3). This reorientation can easily be obtained with a moderate top-to-the SW shear component. This event is related to the Crystalline nappe emplacement (SW thrusting and detachment of the Higher Himalayan rocks on the MCT and MBT). This event does not produce very prominent structures because the studied area corresponds to a high tectonic level with respect to the Crystalline nappe, located far away from the base of the nappe (MCT).

The successive and opposite verging F1-2 and F3 folding phases of the Higher Himalaya are responsible for the formation of spectacular NE-SW-facing fan shaped fold interference patterns. These structures are formed by two successive and opposite verging fold generations and they are not created during only one phase of NE-SW compression as proposed by Frank et al. (1973, 1977 and 1995). These fold interference patterns are also not "pop-up structures" which are typical of near surface thin skinned tectonics.

The third event is related to the late extension on the Khanjar extensional shear zone and late Gianbul dome uplift (phase D4). The Khanjar top-to-the SW shear zone is associated in time and space with the migmatization and leucogranite intrusions.

At a regional scale, the NE-verging Shikar Beh nappe can be traced over a distance of ~200 km, from the Zanskar range to the NW and the Spiti Valley to the SE (Steck et al. 1993, Epard et al. 1995, Steck et al. 1998 and Wyss et al. 1999) and therefore is a major structure of this part of the Himalaya. This nappe was formed during a SW-directed underthrusting and accretion of Proterozoic-Mesozoic sediments of the North Indian margin. It is suggested that the NE-directed Shikar Beh nappe formation was favored by the presence of reactivated older SW-dipping listric normal faults, originally oriented parallel to the extensional border fault of the North Indian margin. Therefore the High Himalayan Proterozoic to Mesozoic sequence with the Ordovician S-type granites formed, at the time of the opening of the Neotethys, intruding into the thinned continental border of the Indian plate. No older basement rocks are documented from this part of the Higher Himalaya, but do exist in the Lesser Himalaya and the Indian craton farther to the south (Frank et al. 1977 and 1995). This nappe emplacement produces Barrovian type metamorphism ranging from the chlorite zone in the lower Chenab Valley to the sillimanite zone in the Gumba Nala. At a regional scale it corresponds to the high grade Barrovian type metamorphism M1 of the High Himalayan Crystalline zone. According to Frank et al. (1977) and Dèzes et al. (1999), thermal peak conditions were reached between 40 and 25 Ma in the Kullu Valley and Zanskar region. The Shikar Beh nappe stack in the southern part of the Higher Himalaya and the Nyimaling-Tsarap and Zanskar nappes in its northern part are responsible for the early M1 metamorphic event.

The SW-directed extrusion of the Crystalline nappe, bounded by MCT at the base and the leucogranite intrusions and the Zanskar Shear Zone on top, indicates the Crystalline nappe is younger, and was emplaced between 25 and 20 Ma (Frank et al. 1973, 1977, Searle 1986, Herren 1987, Pognante et al. 1990 & Dèzes et al. 1999.). A synkinematic temperature dominated M2 metamorphism is related to this second Tertiary event. Finally, the geometry of the Crystalline nappe was modified by late syn-migmatitic dome structures.

Acknowledgments

Financial support by the Swiss National Science Foundation (grants 20-049512.96 and 20-52165.97) and the Herbette Foundation of the Faculty of Sciences of the University of Lausanne are gratefully acknowledged. Dan Marshall, Mike Cosca, Kip Hodges and Clarc Burchfiel are thanked for their constructive critical reading of the manuscript.

REFERENCES

Caby, R., Pêcher, A. & Le Fort, P. 1983: Le grand chevauchement central himalayen: nouvelles données sur le métamorphisme inverse à la base de la dalle du Tibet. Rev. Géol. Dyn. Géogr. Phys., Paris 24, 89–100.

Colchen, M., Le Fort, P. & Pêcher, A. 1986: Geological research in the Nepal Himalaya: Annapurna-Manaslu-Ganesh Himal, notice of the geological map on 1/200,000. Cent. natl. Rech. sci., Paris.

Dèzes, P. (in press): Tectonic and metamorphic evolution of the Central Himalayan domain in southeast Zanskar (Kashmir, India), Mém. Géol. (Lausanne).

Dèzes, P., Vannay, J.C., Steck, A., Bussy, F. & Cosca, M. 1999: Synorogenic extension; quantitative constraints on the age and throw of the Zanskar Shear Zone (NW Himalayas). Bull. Geol. Soc. Am. 111, 364–374.

Epard, J.-L., Steck, A., Vannay, J.-C. & Hunziker, J. 1995: Tertiary Himalayan structures and metamorphism in the Kulu Valley (Mandi-Khoksar transect of the Western Himalaya) – Shikar Beh Nappe and Crystalline Nappe. Schweiz. mineral. petrogr. Mitt. 75, 59–84.

Epard, J.-L., Masson, H., Perrin, M., Asis-Lopez, M. & Castella, J. 1997: Le logiciel POLYPLI: un support pour l'interprétation et la modélisation des terrains profonds. Doc. BRGM, 274, 33–36.

Frank, W., Hoinkes, G., Miller, C., Purtscheller, F., Richter, W. & Thöni, M. 1973: Relations between metamorphism and Orogeny in a Typical Section of the Indian Himalayas. Tscherm. Mineral. Petrogr. Mitt. 20, 303–332.

Frank, W., Thöni, M. & Purtscheller, F. 1977: Geology and petrography of Kulu-South Lahul area. Colloq. int. CNRS (Paris) 268, 147–160.

Frank, W., Grasemann, B., Guntli, P. & Miller, C. 1995: Geological Map of the Kishtwar-Chamba-Kulu Region (NW Himalayas, India). Jb. geol. Bundesanst. 138/2, 299–308.

Griesbach, C.L. 1891: Geology of the Central Himalaya. Mem. Geol. Surv. India (Calcutta) 23, 1–232.

Heim, A. & Gansser, A. 1939: Central Himalaya, geological observations of the Swiss expedition 1936. Mém. Soc. Helv. Sci. nat. 73, 1–245.

Herren, E. 1987: Northeast-southwest extension within the higher Himalayas (Ladakh, India). Geology 15, 409–413.

Kündig, R. 1989: Domal structures and High grade metamorphism in the Higher Himalayan Crystalline, Zanskar region, north-west Himalaya, India. J. metam. Geol. 7, 43–55.

Le Fort, P. 1986: Metamorphism and magmatism during the Himalayan collision. In: Coward, M.P. & Ries, A.C. (Eds): Collision tectonics. Geological Society Special Publication (London), 19, 152–172.

Nabholz, W.K. & Voll, G. 1963: Bau und Bewegung im gotthardmassivischen Mesozoikum bei Ilanz (Graubünden). Eclogae geol. Helv. 56, 755-808.

Nanda, M.M. & Singh, M.P. 1977: Stratigraphy and sedimentation of the Zanskar area, Ladakh and adjoining parts of the Lahul region of Himachal Pradesh. Himalayan Geol. (Dehra Dun) 6, 365–388.

Perrin, M., Cheaito, M., Bonijoly, D. & Turmeaux, T. 1993: Visualizing multifolded and multifaulted terrain geometry using computer graphics. Geoinformatics, 4(3), 189–198.

Pognante, U., Castelli, D., Benna, P., Genovese, G., Oberli, F., Meier, M. & Tonarini, S. 1990: The crystalline units of the High Himalayas in the Lahul-Zanskar region (northwest India): metamorphic-tectonic history and geochronology of the collided and imbricated Indian plate. Geol. Mag. 127, 191–116.

RAMSAY, J.G.: Folding and Fractering of rocks. McGraw-Hill, New York.
RATTAN, S.S. 1973: Stratigraphy and sedimentation of the Chamba area Western Himachal Pradesh. Himalayan Geol. 3, 231–248.
SEARLE, M.P. 1986: Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya. J. Struct. Geol. 8, 923–936.
STECK, A., SPRING, L., VANNAY, J.C., MASSON, H., BUCHER, H., STUTZ, E., MARCHANT, R. & TIÈCHE, J.-C. 1993: Geological transect across the North-western Himalaya Eastern Ladakh and Lahul (A model for the continental collision of India and Asia). Eclogae geol. Helv. 86, 219–263.
STECK, A., EPARD, J.-L., VANNAY, J.-C., HUNZIKER, J., GIRARD, M., MORARD, A. & ROBYR, M. (1998): Geological transect across the Tso Morari and Spiti areas: The nappe structures of the Tethys Himalaya. Eclogae geol. Helv. 91, 103–121.
VANNAY, J.C. 1993: Géologie des chaînes du Haut-Himalaya et du Pir Panjal au Haut Lahul (NW Himalaya, Inde): Paléogéographie et tectonique, Mém. Géol. (Lausanne) 16, 1–148.
VANNAY, J.C. & STECK, A. 1995: Tectonic evolution of the High Himalaya in Upper Lahul (NW Himalaya, India). Tectonics 14, 253–263.
WYSS, M., HERMANN, J. & STECK, A. 1999: Structural and metamorphic evolution of the northern Himachal Himalaya, NW India (Spiti-eastern Lahul-Parvati valley traverse). Eclogae geol. Helv. 92, 3–44.

Manuscript received January 15, 1999
Revision accepted July 28, 1999