Geology, Structural Evolution and Metamorphic Zoning in the Kulu Valley (Himachal Himalayas, India) with Special Reference to the Reversed Metamorphism *)

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24 Figures and 1 Map (Taf. 13)

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*) This paper is a summary of the authors' thesis. The original manucsript (in German) is deposited at the Geological Institute of the University of Vienna.

Mitt. Ges. Geol. Bergbaustud. Österr.	24	S. 125–187	Wien, Okt. 1977

Content

1. SUMMARY

An area of about 1800 km^2 in the northwestern part of the Indian Himalayas (Himachal Pradesh, Kulu Valley) was investigated. A sketch of the lithologic-stratigraphic and tectonic situation and of the grade of metamorphism is given in the geological map.

From a tectonic-paleogeographic and a petrographic-petrogenetic point of view the investigated area can be subdivided in three major units :

1. An anchi- to epimetamorphic lower tectonic unit of quartzites, slates-phyllites, metabasites and carbonatic rocks (mainly stromatolite-bearing dolomites), which forms a tectonic window, the **Lārji-Kulu-Rampur-Window**. Apart from the stromatolites, the metasediments of this unit are barren of fossils. Most probably these rocks are of Proterozoic age. Considering the tectonic zonation of the Himalayas this rock series correspond to the Chail Nappes of the Lower Himalayas described by G. FUCHS (1967), forming a slightly inverted stratigraphic sequence with the oldest part, the Berinag series, at the top of the rock pile.
2. The upper tectonic unit, the **Crystalline Nappe**, overthrusted the above described rock series during Alpine orogeny, coming from north–northeast. Th Crystalline Nappe consists of a monotonous series of low- to high-grade metapelites with s-parallel intercalated layers of augengneisses and large discordant granitic bodies.
3. At the base of the Crystalline Nappe a very thin rock sequence with a special lithology has been observed on a regional scale. This „**Bajaura Nappe**“ is considered as a separate unit.

Considering tectonics and metamorphism the following can be summarized :

□ In the LKR-Window as in the Crystalline Nappe three different tectonic macrostructures have been observed, showing generally the same strike direction in both tectonic units :
a) Lineations and mineral elongations, oriented in NE-SW-direction (normal to the strike of the mountain chain); b) b-axes of different dimensions, oriented NW-SE (parallel to the mountain chain); c) Late small-scale crumping folds, oriented NW/WNW-SE/ESE. The relation of these tectonic structures to those in mesozoic rock series of neighbouring regions (Chamba; Tandi-Syncline) on the one hand and to the metamorphic evolution, especially within the Crystalline Nappe, on the other hand, suggests that all the observed tectonic elements have been formed in postmiddlemesozoic times.

□ The metamorphism is of Barrowian type : it may be characterized as an essentially synkinematic, progressive-coherent and alpidic event. A late, partially intensive diaphthoritic alteration of the mineral assemblages is restricted to locally reactiveted s-planes.

□ The inverted metamorphic sections in the upper Kulu Valley and in the Malāna–Parbati Valley are interpreted as the product of the very rapid thrusting of the higher metamorphic Crystalline Nappe over the cooler foreland of the Lower Himalayas combined with internal deformation of the transported mass, causing partly inverted metamorphic zones in an inverted temperature zone (FRANK, 1972) and partial contemperaneous, synmetamorphic folding of the ss-planes (Phojal-Kallath-macrofold). This very rapid overthrusting may be explained by the rapid convergence of India and Eurasia by means of plate-tectonic movements.

□ According to field observations the granitic rocks of the Crystalline Nappe have intruded in pre-metamorphic times; according to radiometric age determinations (FRANK, 1973/74) they belong to the Caledonian era.

RÉSUMÉ

Récemment une étude a été faite d'une région d'environ 1800 km^2 dans le nord-ouest de l'Himalaya (Région de Kulu, H.P.). La carte donne une impression de la variété des formations, de la situation tectonique et du stade de la métamorphose.

Suivant les données tectoniques et paléogéographiques d'une part, et les données petrographiques et petrogénétiques de l'autre, trois unités ont été determinées :

1. Une étage inférieure, composée de zones anchi-jusqu'a épimétamorphes, comprenant une suite de quartzites, schistes-phyllites, métabasites et carbonates (en général des dolomites

de stromatolites), qui doit être considérée comme une **fenêtre tectonique** = Fenêtre de Lārji-Kulu-Rampur. Les métasediments de cette unité sont, mis a part les stromatolites, dépourvus de fossiles. Leur âge protérozoique peut être considérée comme assuré. A l'intérieur de la construction tectonique en étages de l'orogéne les séries lithologiques de cette zone correspondent a celles des la nappe de Chail du bas Himalaya, décrite à base régionale par G. FUCHS (1967).

2. L'étage supérieure, **la nappe cristalline**, a charrié la zone 1. durant l'orogénesè alpidique (ère tertiaire), venant du N-NE, jusqu'aux abords méridionaux. Cette unité consiste en une série monotone, pauvre en carbonates, de métapelites épi-jusqu'à catazonaux, avec des couches d',,Augengneis" parallèles a la schistosité et des blocs de granite discordants.
3. A la base de la nappe cristalline a été séparée une unité très mince mais de propagation d' ordre régional, de lithologie particulière, sous le nom de „**nappe de Bajaura**".

Les résultats primordiaux de l' étude concernant la structure et la métamorphose sont les suivants :

□ Il faut différencier trois types structurales plus ou moins concourants dans la fenêtre LKR et dans la nappe cristalline : a) Linéation et élongation de minéraux, orientés NE-SW (perpendiculairement a la direction de la chaine); b) Axes-b parallèles a la chaine, de direction NW-SE; c) Gaufrage tardif, NW/WNW-SE/ESE.

La relation entre ces structures tectoniques et, d'une part, les structures des complexes lithologiques mésozoiques voisines (synclinaux de Tandi, Chamba), d'autre part la métamorphose, principalement dans la nappe cristalline, permet de déterminér un âge post-mésozoique de ces structures;

□ La métamorphose est du type Barrow; il s'agit d'un evénément principalement syncinématique, progressivement monophase et certainement alpidique. Une diaphtorèse tardive fut partiellement intensive mais n'a eu des résultats locaux.

□ Dans la vallée superieure du Kulu et dans la vallée de Parbati, résultant du charriage très rapide de la nappe cristalline fortement réchauffée par-dessus l'avant-pays (de température moins élevée) et, en même temps, de la déformation intensive de la masse transportée, a eu lieu la formation de zones de métamorphose inverse, grâce a une inversion de température (FRANK, 1972), en même temps que le plissement synmétamorphe des couches sédimentaires (mégapli de Phojal-Kallath). La cause d'un charriage tellement rapide est à chercher dans des mouvements de tectonique des plaques (mouvement du sous-continent indien vers le nord et collision avec l'Asie).

Les granites de la nappe cristalline ont, d'après les observations faites sur-les-champ, un âge d'intrusion antémétamorphe et selon les mesures d'âges absolues, auraient été formés durant le paléozoique inférieur.

RIASSUNTO

Il territorio in esame (Himalaya, Valle di Kulu) copre un'area di 1800 km^2 circa. Dal punto di vista petrografico-petrogenetico, come anche da quello tettonico e paleogeografico, la serie in questione può venir suddivisa in tre grandi unità :

1) L'unità anchi-epimetamorfica inferiore, rappresentata da quarziti, scisti filladici e rocce carbonatiche ricche di stromatoliti. Nel quadro tettonico regionale queste rocce sono in posizione di finestra tettonica, la **Finestra di Lārji-Kulu-Rampur**, appartenente all'unità Chail dell' Himalaya inferiore („Lower Himalayas", G. FUCHS, 1967). I metasedimenti affioranti in quest' area non sono fossiliferi (eccetto gli stromatoliti) e vengono considerati come rocce precambriche.
2) Unità superiore, o **Ricoprimento Cristallino**, sovrascorso con provenienza da N-NE, sulla serie inferiore nel corso dell'orogenesi Alpidica (era Terziaria). Sie tratta di una serie abbastanza monotona di rocce a diverso grado metamorfico, derivate da originari sedimenti argilloso-arenacei, frammiste con gneiss leucocratici e masse granitiche intrusive, particolarmente nel settore settentrionale del territorio in esame, laddove il metamorfismo ha agito più incisivamente.
3) **Zona di Bajaura**, considerata rappresentare, in base a criteri prevalentemente litologici, un' unità separata in posizione basale del ricoprimento cristallino.

Per quanto concerne l'assetto strutturale, si può osservare come nell' area in esame esistano tre elementi tettonici caratterizzati, in tutte e tre le unità, dall'avere più o meno la stessa orientazione : a) Lineazioni ed orientazioni di minerali, dirette NE-SW (assi trasversali); b) Pieghe a varie dimensioni con assi orientati approssimativamente NW-SE e vergenti a S-SW; c) Micropieghe, con assi orientati WNW-ESE e NW-SE. – Le lineazioni rappresentano l'elemento strutturale più antico, mentre le micropieghe si possono riferire alle ultime fasi tettoniche.

Ponendo in relazione sia gli elementi sopracitati con analoghe strutture segnalate in territori limitrofi, presenti in sedimenti paleo-mesozoici (sinclinale di Tandi e di Chamba) come anche quanto deducibile dalle osservazioni sui processi metamorfici, particolarmente per quanto riguarda il ricoprimento cristallino, si può ritenere l'assetto strutturale nella Valle di Kulu attribuibile all'attività tettonica di età Alpidica (post-giurassica, v. POWELL e CONAGHAN, 1973 a). Si ritiene che l'evento metamorfico verificatosi sia riconducibile al tipo barrowiano, caratterizzato come un evento sincinematico progressivo e continuo, di età Alpidica. Non sono stati trovati relitti di eventi metamorfici di età anteriore. – Il metamorfismo inverso osservato nella parte settentrionale del ricoprimento cristallino viene spiegato come dovuto ad un'inversione sincinematica dei gradienti di temperatura, fatto questo ovviamente verificatosi a causa del movimento estremamente rapido del cristallino sovrascorrente sul basamento meridionale meno metamorfosato, oltre che a deformazioni interne della massa trasportata. – Il movimento rapido verso N del subcontinente indiano durante l'era Terziaria rappresenta l'elemento fondamentale a cui riferire la successiva evoluzione metamorfica e tettogenetica-orogenetica dell'Himalaya.

Secondo i dati di campagna, l'età dei granitoidi del ricoprimento cristallino e premetamorfica; successive datazioni radiometriche hanno dimostrato che questi corpi intrusivi sono riferibili all' „evento caledonico" (FRANK, 1973/74).

ZUSAMMENFASSUNG

Es wurde ein Gebiet von ca. 1800 km^2 im Nordwest-Himalaya (Indien, Himachal Pradesh, Bereich Kulu) neu bearbeitet. Die geologische Karte (Originalmaßstab 1 : 63.440) bringt eine Übersicht über die Verteilung der Serien, tektonische Verhältnisse und die Zonierung und das Stadium der Metamorphose.

Nach tektonisch-paläogeographischen und petrographisch-petrogenetischen Gesichtspunkten wurden drei Einheiten unterschieden :

1. Ein anchi- bis epizonal metamorphes tieferes Stockwerk, bestehend aus einer Wechselfolge von Quarziten, Schiefern bis Phylliten mit lokal linsig oder gangförmig eingeschalteten Diabaskörpern und Karbonaten (im wesentlichen grobgebankte Dolomite, reich an Stromatolithen), das als tektonisches Fenster = Lārji-Kulu-Rampur-Fenster (FRANK et al., 1973) aufzufassen ist. Innerhalb des tektonischen Stockwerkbaues des Orogens entsprechen die Gesteinsserien dieser Zone den von G.FUCHS (1967) auf regionaler Basis beschriebenen Chail Nappes des Niederen Himalaya. Zur Frage des Sedimentationsalters der zum größten Teil (von den Stromatolithen abgesehen) fossilleeren (Meta-)Sedimente des Niederen Himalaya gibt es noch immer zwei grundsätzlich verschiedene Ansichten. Manche Autoren nehmen paläozoisches, andere proterozoisches Alter an. Wir vertreten für die Serien des Larji-Kulu-Rampur-Fensters proterozoisches Alter. Argumente dafür sind a) das massenhafte Auftreten von verschiedenen Algenstromatolithenarten aus der Gruppe *Collenia*, von denen die meisten für das Proterozoikum charakteristisch sind; b) das völlige Fehlen von anderen pflanzlichen und tierischen Fossilien; c) einige wenige radiometrische Altersdatierungen (Gesamtgesteinsalter von 1840 ± 70 Mio. J.; FRANK, 1973/74) aus Augengneisen, die als synsedimentäre Bildungen in eine mächtige Schieferserie dieser tektonischen Einheit zwischengeschaltet sind.

2. Das höhere Stockwerk, die **Kristallindecke**, hat die Serien des Niederen Himalaya im Laufe der alpidischen Orogenese, von N bis NE her kommend, teilweise bis an die südlichen Randzonen des Gebirges hin überfahren. Lithologisch besteht das Kristallin aus einer monotonen, sehr karbonatarmen Serie epi- bis katazonal metamorpher Metapelite und Metapsammite mit s-parallel eingeschalteten Augengneislagen und diskordanten Granitstöcken.
3. An der Basis der Kristallindecke wurde eine sehr geringmächtige, teils auskeilende, aber regional verbreitete Einheit besonderer Lithologie (Paraschiefer, Kalkmarmore, Mikroklinaugengneise) als **Bajaura Decke** abgetrennt.

Bezüglich **Gefügeinventar** wurden in allen drei untersuchten Einheiten drei ± gleich verlaufende, generell verbreitete lineare tektonische Gefügeelemente beobachtet : a) NE-SW verlaufende Lineationen und Mineralelongationen (B_1); b) gebirgsparallele b-Achsen (Biege- bis Biegescherfalten verschiedener Dimension), NW-SE orientiert (B_2); c) Feinfältelung, WNW/NW-ESE/SE verlaufend (B_3). Die Beziehung dieser tektonischen Strukturen zu solchen in sicher mesozoischen Gesteinskomplexen angrenzender Gebiete (Tandi-Synklinale im N, Chamba-Synklinale im NW) einerseits und zum Metamorphosegeschehen, insbesondere in der Kristallindecke, anderseits läßt für die Gesamtgefügeprägung postmittelmesozoisches Alter annehmen. In der relativen zeitlichen Abfolge der Strukturbildung sind die (besonders in der Kristallindecke ausgeprägten) Lineationen und Mineralelongationen als die ältesten und – in bezug auf die Metamorphose – jedenfalls sehr frühe Elemente (Bildung z.Z. des thermischen Höhepunktes der Metamorphose) anzusehen. Die gebirgsparallelen b-Achsen werden als syn- bis spätmetamorphe Bildungen angesehen. Großfalten wurden teilweise auch noch postmetamorph ausgestaltet. Die B_1-Strukturen sind in die B_2-Strukturen eingebaut. Ihre Entstehung ist materialkinetisch schwer zu interpretieren (diese „Querstrukturen" verlaufen normal zum Gebirgsstreichen). Vermutlich handelt es sich um echte a-Lineationen, die durch einen Mechanismus, der als „simple-shear" bezeichnet werden kann, während der beginnenden Abscherung und Südbewegung der Gesteinsserien ausgebildet wurden (vgl. MATTAUER, 1975). Die B_3-Strukturen werden als relativ späteste Bildungen in den schon metamorphosierten Gesteinen aufgefaßt (Auffahren der Kristallindecke auf den Niederen Himalaya).

Die **Metamorphose** gehört generell dem Barrow-Typus mit einem vermutlich leicht gesteigerten Temperaturgradienten an. Sie ist als progressiv-einphasiges, synkinematisches und jedenfalls alpidisches Ereignis aufzufassen. Reliktgefüge konnten, ebenfalls wie ältere Strukturelemente, nirgends – weder im Kristallin noch im Fensterbereich – sicher nachgewiesen werden. Die feldgeologisch eindeutig als prämetamorph erkennbaren Granite sind nach absoluten Altersdatierungen altpaläozoisch (FRANK, 1973/74). Diese in der Kristallindecke ausgedehnten Intrusivgesteinsareale legen den Schluß auf eine voralpidische Regionalmetamorphose (und eine damit zusammenhängende Gefügeprägung) nahe. Aus paläogeographischen Überlegungen wird jedoch eher wahrscheinlich, daß diese mit der Granitintrusion sicher verbundene Gesteinsumprägung auf relativ tiefere Krustenteile beschränkt blieb (Schmelzbildung) und als wesentlich „statisch-thermisches" Ereignis, ohne größere tektonisch-orogenetische Vorgänge zu betrachten ist. Im oberen Kulutal und im Parbatital kam es infolge sehr rascher Überschiebung des stärker aufgewärmten Kristallins über das kühlere Vorland, bei gleichzeitiger interner Deformation der transportierten Masse, zur Ausbildung echt inverser Metamorphosezonierung in Zusammenhang mit einer Temperaturinversion (FRANK, 1972) bei teilweise gleichzeitiger, synmetamorpher Verfaltung des Materiallagenbaues (Riesenliegendfalte von Phojal-Kallath). Der Grund für derartig rasche Überschiebungen ist in plattentektonischen Bewegungen, nämlich der vergleichsweise sehr raschen Norddrift des Indischen Subkontinents und seiner Kollision mit dem asiatischen Block während des Tertiärs, zu suchen.

Paläogeographisch gesehen entstanden die Metamorphite der Kristallindecke in einem, gegenüber der heutigen Position, weiter nördlich gelegenen Bereich der Pro- bzw. Urtethys. Der Sedimentationsraum für die Metasedimente des Niederen Himalaya hingegen ist weit im Süden, in einem dem Indischen Subkontinent (Teil des Gondwanalandes) nördlich vorgelagerten Schelfbereich zu suchen. Die weiteren paläogeographischen Beziehungen der beiden Großeinheiten, der Kristallindecke und des Niederen Himalaya, insbesondere ihre Ausdehnung nach S bzw. N, bleiben bis zur alpidischen Orogenese unbekannt. Für die geringmächtige Bajaura Decke wird auf Grund lithologischer Affinitäten ein den Sedimenten des Niederen Himalaya benachbarter Entstehungsraum (etwa als nördliche Grenzzone) eher angenommen als eine ursprüngliche nahe Beziehung zur Kristallindecke.

2. GENERAL INTRODUCTION

2.1. Topography and problem presentation

The field research for the present study was begun in the autumn of 1972 as part of the „Österreichische erdwissenschaftliche Himalayaexpedition 1972" (Austrian Geological Himalayan Expedition 1972) and continued and provisionally terminated in 1973 during a prolongation of this project (FRANK et al. 1973).

The area studied is in the Indian territory of Himachal Pradesh, near 77° eastern longitude and 32° northern latitude (Fig. 1). The Kulu Valley, a fertile, densely-populated high-mountain valley north of Simla, now also easily attainable thanks to good communication facilities, has long been one of the most important links between north and south in the north-western Himalayas: over the Rohtang Pass (4050 m) to South Lahaul and Spiti and then on past the Bara Lacha La to Ladakh, Kashmir and Tibet. The entire area south of the Rohtang Pass is affected by the summer monsoon.

The first goal of this study was to prepare a suitable geological map, as complete as possible, of the entire region, as nothing of the sort existed in 1972 for the immediate vicinity of Kulu. Detailed mapping did not appear to be of any use nor was it possible on the basis of the topographic maps and time available. Furthermore, apart from the description of lithological series, the degree of metamorphism and the structural set-up were to be studied on the basis of comparative sections. The materials used for mapping were the old Anglo-Indian „quarter inch" and „half inch" maps (1:126.720 respectively), sheets 53 $\frac{E}{NW}$, 52 $\frac{H}{SW}$, 52 $\frac{D}{SE}$, 53 $\frac{A}{NE}$, as well as the American edition 2-AMS-„India and Pakistan 1:250.000", sheets NI 43-16, NH 43-4.

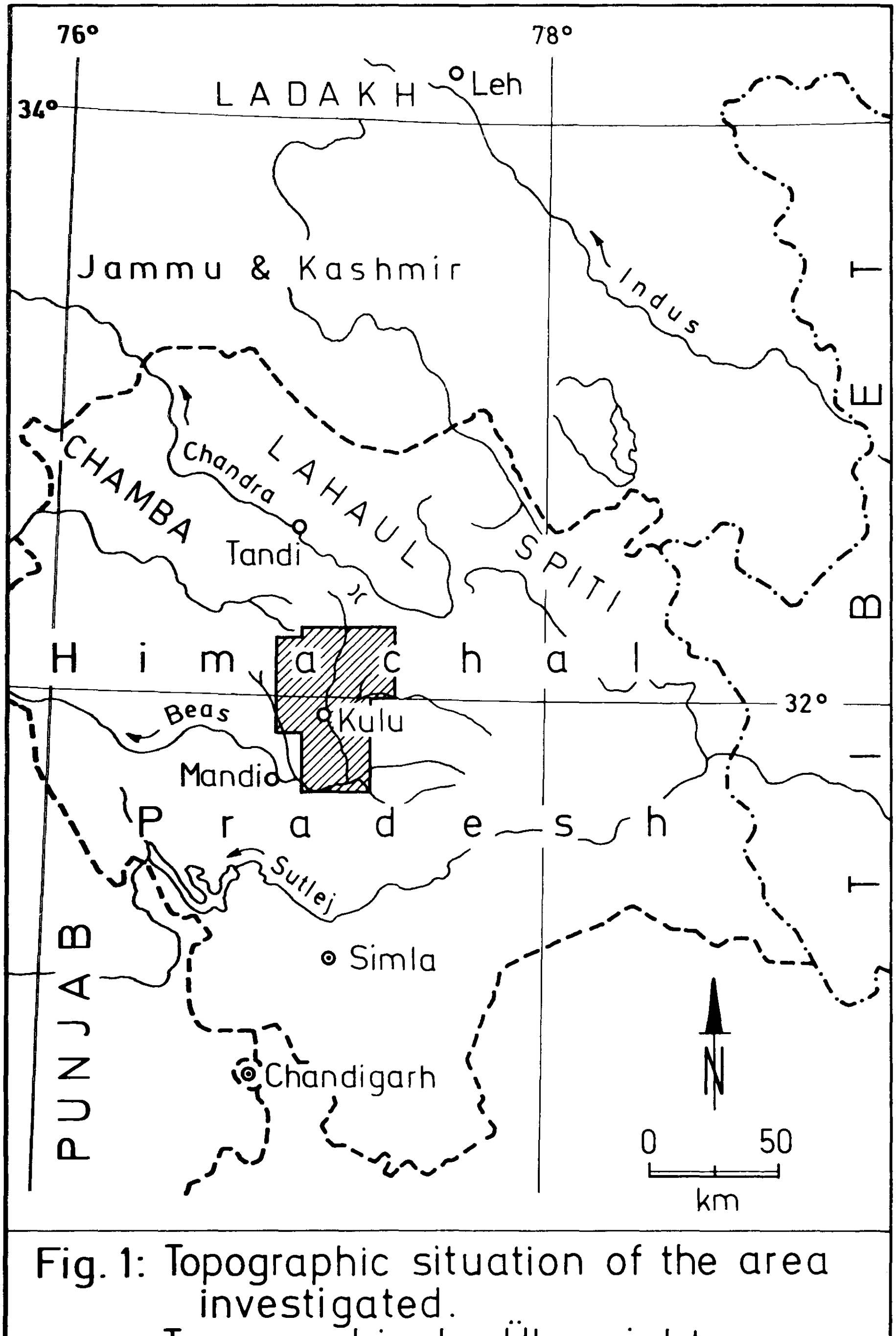


Fig. 1: Topographic situation of the area investigated.
Topographische Übersicht.

2.2 Regional Geological Outline

Approaching from the south (i.e. from the Indian plaine), one crosses the following zones in the Himalayas:

a) The **Subhimalayas** (or foothills, Siwaliks), the neogene-quarternary, slightly folded molasse-zone of the young orogen.

b) The (geographical-) geological unit of the **Lesser Himalayas** (Lower Himalayas), a zone of a complex tectonic structure, of non-metamorphic to slightly metamorphic sedimentary formations, mostly non-fossiliferous and often of still uncertain age. Details of the peleogeographic location of the southern Krol unit and the northerly Chail unit, differentiated on the basis of regionally recognizable variations in facies, are still interpreted in various ways. This zone was thrust over the Siwaliks along the Main Boundary Thrust.

c) The **Higher Himalayas** (for the most part forming the Great Himalayan Range): this zone overthrusted the Lesser Himalayas along the Main Central Thrust in a southerly direction in the form of a giant nappe; at present the low metamorphic underground, uncovered by erosion, frequently emerges in tectonic windows and half-windows beneath the medium- to high-grade metamorphics of the Crystalline Nappe.

d) The fossiliferous paleo-mesozoic sediments of the **Tibet** (Tethys) **Himalayas** form a normal stratigraphic sequence above the Crystalline Nappe.

e) The northernmost zone is formed by orogenic flysch sediments and ophiolites in the region of the **Indus** suture.

2.3 Earlier studies

The early geological investigation of the Himachal Himalayas was concentrated mainly on the central and northern sectors of this mountain-section (Mc MAHON, 1879; LYDEKKER, 1883; HAYDEN, 1904). The first references to the lithology and tectonics of the Kulu region were made by H. B. MEDLICOTT (1864). This scientist perceived – four decades before the breakthrough of the nappe theory in the Alps – the nappe-like structure of the crystalline mass above the carbonates of Larji; in the „gneisses" west of the Kulu Valley he saw a west-southwest directed recumbent syncline (?Phojal giant fold). AUDEN (1934, 1938) used the term „Lārji-window" for the tectonic window in the lower Kulu Valley. FUCHS (1967) was the first to present a rough picture of the lithology and the structural conditions between Pandoh and the Rohtang Pass. More recentely the Lārji-Kulu-Manali-Khoksar area has been studied, partly in detail, by the following authors: S.KUMAR (1971, unpubl.), MEHTA (1972, unpubl.; 1977), SINHA (1972, unpubl.; 1973), POWELL & CONAGHAN (1973 a), FRANK (1972, unpubl.; 1973/74), FRANK et al. (1973), PANDE & KUMAR (1974), SRIKANTIA & BHARGAVA (1974 b), KUMAR (1975).

3. DIFFERENTIATION OF THE SERIES; LITHOLOGY AND STRATIGRAPHY

3.1 Crystalline Nappe

The Crystalline Nappe has overthrust the formations of the Lesser Himalayas in the form of a gigantic nappe system in a south-southwesterly direction, in parts all the way to the southern boundary of the range. The crystalline is spread out towards the east and the west, in the same tectonic position, over the entire orogen (HAGEN 1959; GANSSER 1964; FRANK & FUCHS 1970; LE FORT 1975). Lithologically, this unit is composed of throughout metamorphosed para- and orthomaterial.

3.11 Meta-Sedimentary Rocks

The greater part of the metamorphics of the Crystalline Nappe can be derived from a thick series of clayey-sandy marine sediments. Deeper marine regions can be considered the most probable depositional environment; however, the rarely preserved sedimentary structures, such as oscillation ripple marks (Bubu Jot, K. 11441), can furnish evidence of a shallow-water deposition. On the other hand, organic remains or traces thereof have not been found, even in zones of weak metamorphism. The sedimentation age of these monotonous, flysch-like series is most probably precambrian (BERTHELSEN 1953; VALDIYA 1964 a,b; PANDE 1967); however, in the area under study a local participation of phanerozoic rocks is considered possible in the case of the low-grade metamorphic series of the Kali Hain Pass–Berlanga Pass–Bubu Jot region, which form the southeastern continuation of the Chamba syncline (see RATTAN 1973 and the present paper,p.164). In view of the comparatively small spectrum of lithological variation, it was decided to forego a detailed subdivision of the metapsammites and -pelites on the map. On the other hand, an attempt was made, although very schematically, to plot, as completely as possible, the lines of intersection between the s(s)-planes and the morphology, as this can be of importance for tectonic considerations.

L i t h o l o g y : Fine- to medium-grained, megascopically massive quartz-biotite-schists and biotite-quartzites are the most common rocks, especially in the area of Katrein. Rough layering is pronounced, frequently with thin layers of metapelitic material between the banks, reflecting the gradation of sand and clay. Pure quartzites (containing over 80 % quartz) are rare.

Schists, containing varying amounts of chlorite, muscovite, biotite and other components, originate from arenaceous-argillaceous sediments; in areas of higher metamorphism of the upper Kulu Valley and the Malāna–Parbati Valleys such material was transformed into mica-schists (binary schists; garnet-, staurolite-, kyanite-mica-schists); or, with increasing content of feldspar: gneissose mica-schists and paragneisses (biotite-plagioclase-gneisses) were formed.

The low-grade, usually light-green, well-layered metamorphics in the southwestern part of the Crystalline Nappe are shown on the map as meta-siltstones by means of an overlain symbol. Furthermore, graphitic schists and quartzites occur locally west of the Kulu Valley (Kali Hain Pass, Lag Nāl, Uhl Valley).

Meta-calcareous rocks: Within the monotonous metapelite series of the Crystalline Nappe, especially in the Katrein–Malana–Pulga area, we find calc-silicate rocks (Zoisite-schists to -quartzites; hornblende-„garbenschiefer"; para-amphibolites; hornblende-plagioclase-gneisses), in the form of s-parallel layers, lenses or schlieren. With a few exceptions (T 402), these metamorphics are interpreted, according of the conditions of their bedding and their mineralogy, as being derivates of sandy-clayey marls or partly of carbonate concretions.

3.12 Meta-Granites and Meta-Granitoids

Within the Crystalline Nappe two structural types of granitoid rocks can be differentiated:

a) discordant intrusive granites

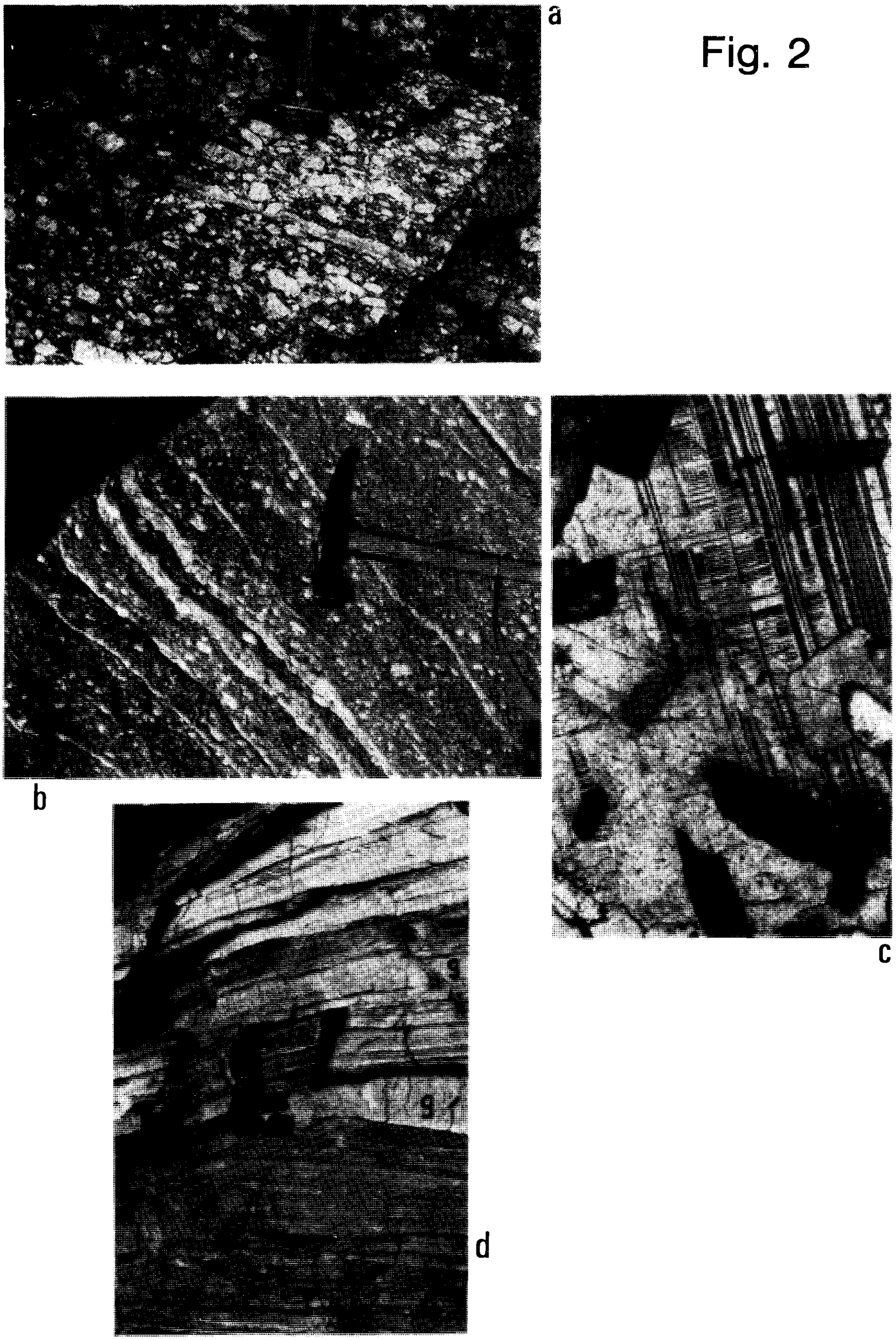
b) s-parallel augen-gneisses.

Ad a) Light-coloured, massive intrusive rocks are widespread in the northern Kulu Valley and in the Malāna–Parbati Valley (Deo Tibba, Hanumantibba). Mostly they are coarse-grained, garnet-bearing, binary granites of varying mica content. For the most part the boundary to the para-crystalline series is discordant. In some places fist-sized clumps of para-material with distinctly preserved sedimentary structures have been observed within the homogeneous granitic „groundmass" (south of Kālo Nao Nāla): the intrusive material may have partly melted the sorrounding rocks during emplacement in higher levels. Gneissification has affected the granite bodies in varying degrees; contact aureoles to the sorrounding metasediments have not been preserved; it is clear from the mineral content and the texture that the granites were emplaced b e f o r e the main metamorphism of the Crystalline Nappe took place.

Ad b) Augen-gneisses occur mainly in the northern Crystalline Nappe in the form of s-parallel layers, at most a few hundred meters thick. Their spatial relationship with the intrusive granites suggests a temporal connection as well; the formation of these granitic gneisses by s-parallel intrusion and later tectonic deformation is an acceptable theory. On the other hand, the thin augen-gneiss layers within the low-grade metamorphics of the southern crystalline (Kulu; northwest of Aut), which can nevertheless be observed over relatively large distances along the direction of their strike, are totally isolated. Tectonic imbrication of these layers is not an acceptable explanation. A synsedimentary, volcanogenetic formation of these rocks is most likely (tuffite-porphyry). The texture is often unmistakably volcanogenetic: centimeter-large idiomorphic to elongated feldspars swim in a fine-grained matrix, some of which can be, with the slight metamorphism in the south, interpreted clearly as metasedimentary material and often alternates with the pure metapelites (feldspar-free layers) in a cm-dm-rhythm (road-outcrops near Jhatingri, southeast of Guma). We consider the designation „migmatites" for the s-parallel inset augen-gneiss west of Kulu (MEHTA 1977, p.165) to be completely inappropriate. According to our investigations, the sorrounding para-crystalline rocks containing the Kulu augen-gneiss does not show any sign of a high-grade pre-alpidic metamorphism with the associated migmatization, just as no unambiguous textures of any earlier (pre-alpidic) metamorphism could be discovered in the entire para-crystalline (see p.164).

A similar genetic interpretation is assumed for certain outcrops in the zone of high-grade metamorphism of Manali, where very thin leucocratic layers alternate

Fig. 2



with para-gneisses and mica-schists (road south of Jagutsukh). However, in this case consideration may also be given – at least partly – to partial anatexis, mobilization and felspathization of para-material for the formation of the leucocratic „granitoid" layers, in view of the high degree of metamorpism. As synsedimentary formations, the meta-porphyrites in particular would be older than the thick intrusive granites (see p. 165 and p. 181).

In principle three structure types can be differentiated within the granitic gneiss (Fig. 2):

α) Porphyroid augen-gneisses; idiomorphic feldspars in a weakly-recrystallized matrix; widespread in the south.

β) Well-recrystallized augen-gneiss with markedly lensy-deformed feldspars; e.g. west of Katrein.

γ) Holo-leucocratic rocks, practically biotite-free, medium-grained augen- to flaser-gneiss; in the northern part of the crystalline mass.

3.2 The weakly metamorphic Lārji-Kulu-Rampur-Window (LKR-Window)

Lithology, structural conditions and above all the degree of metamorphism indicate that the area southeast of the Beas Valley is tectonically a lower unit which has been overthrust from north to northeast by the higher-metamorphic Crystalline Nappe. The gigantic tectonic bulge, named „Lārji-Kulu-Rampur-Window" (FRANK et al. 1973) after its outermost points, continues towards the southeast at least as far to the Sutlej River and must be assigned, in regional-tectonic terms, to the Chail Nappes of the Lesser Himalayas (FUCHS 1967).

Within the LKR-Window, f o u r stratigraphic units have been differentiated, according to the subdivision by G. FUCHS (1967) (see Fig. 3). Since there are no fossils (not counting the stromatolites), the differentiation of series can be made only on a lithological basis.

3.21 Shali-Group: The main component of this subdivision is a thickly bedded, fine-grained, blue-grey dolomite containing many stromatolites (which are often silicified). South of Aut, a thin layer of dark slates is intercalated in the dolomites (Shali slates; cf. FUCHS & FRANK 1970, p.42). At several points (southwest of Aut, south and east of Bajaura, south and north of Lārji) a breccia with a calcite matrix and pink and yellow dolomite components and more rarely with violet slate components was observed („concrete breccia"). The presence of algae-stromatolites on a large scale suggests shallow-water conditions for the deposition of the

Fig. 2: Granitic rocks of the Crystalline Nappe. a) Porphyroid augengneiss with large feldspar crystals (W of Kulu). b) Biotitegranitgegneiss with leucocratic tourmaline-rich layers (W of Katrein). c) Polysynthetically twinned plagioclase with strongly recrystallized clinozoisite (W of Katrein). d) Thin granitic layers (g) within high-grade metapelites; S of Jagutsukh.

Granitoide der Kristallindecke. a) Porphyroider Augengneis mit cm-großen Feldspäten, 2,5 km W Kulu; b) Biotitgranitgneis mit leukokraten turmalinreichen Lagen, K. 10048 W Katrein; c) Polysynthetisch verzwillingter Plagioklas mit grob rekristallisierter Fülle aus idiomorphem Klinozoisit (dunkel), aus dem Augengneistyp der Abb. 1b); d) Wechsellagerung von Paramaterial mit dm-mächtigen hellen granitoiden Lagen (g), 0,5 km S Jagutsukh.

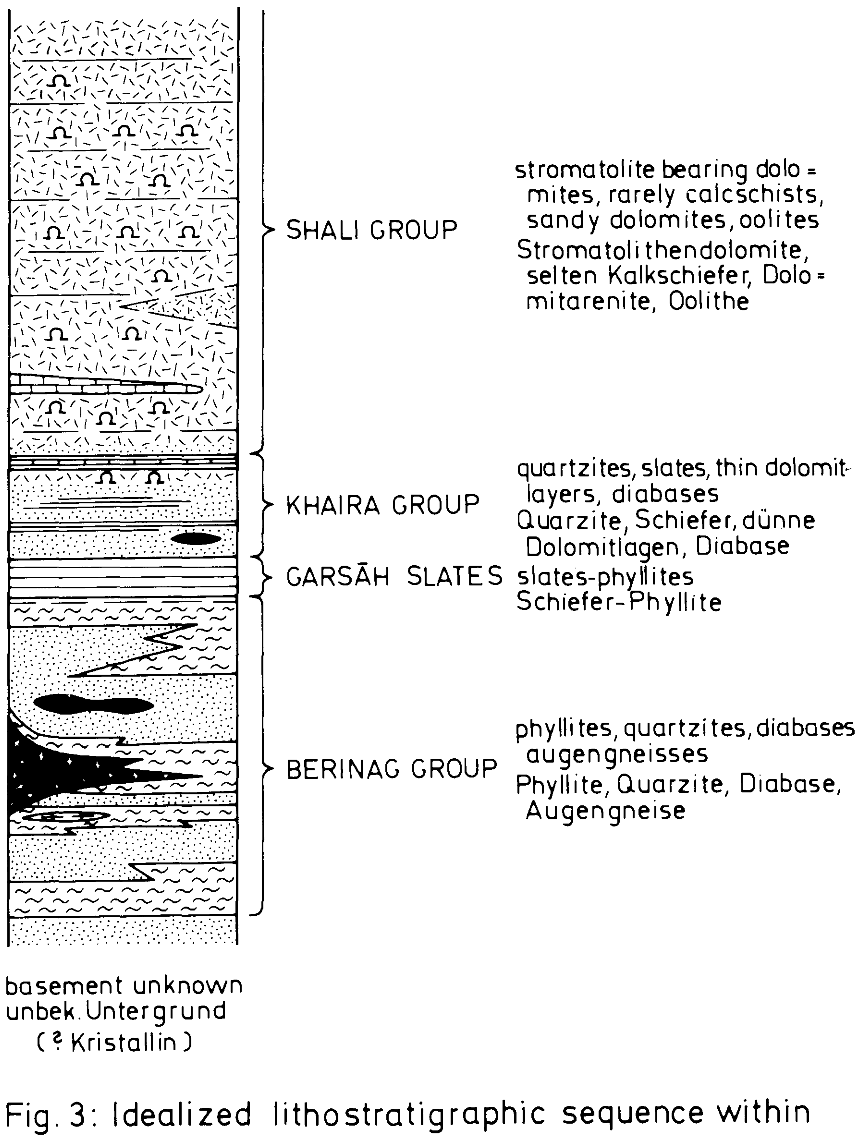
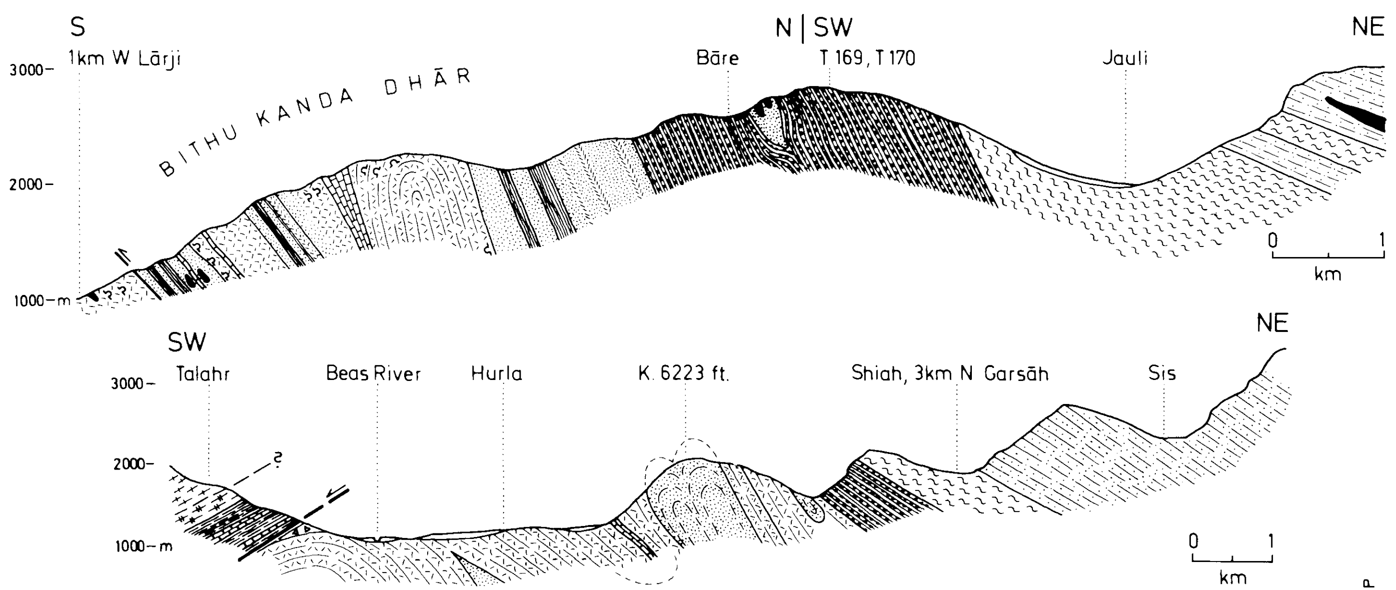


Fig. 3: Idealized lithostratigraphic sequence within the LKR-Window

Lithostratigraphische Abfolge im LKR-Fenster



Legend	
Metasedimentary rocks of the CRYSTALLINE NAPPE / Parakristallin der KRISTALLIN-DECKE	
Microclineaugengneisses / Alkalifeldspatgneise	BĀJAURA NAPPE / BĀJAURA DECKE
Dark schists / Dunkle Schiefer	BĀJAURA NAPPE / BĀJAURA DECKE
Dark calcschists / Dunkle Kalkschiefer	BĀJAURA NAPPE / BĀJAURA DECKE
Shali dolomite with stromatolites (up) / Shali-Dolomit m. Stromatolithen (oben)	SHALI GROUP
Sandy dolomites, oolites / Dolomitarenite, Oolithhorizonte	SHALI GROUP
Intraformational breccia / Intraformationelle Brekzie	SHALI GROUP
Pink calcschists / Kalkschiefer hellrosa	SHALI GROUP
Red spotted quartzites, local diabase lenses / Rotgetüpfelte Quarzite, lokal Diabaslinsen	KHAIRA GROUP
Thin laminated, variegated slates / Dünnblättrige, bunte Schiefer	KHAIRA GROUP
Rusty brown dol., partly with stromatolites / Rostig anwitternde, dkl. Dol.-bänke, tlw. m. Stromat.	KHAIRA GROUP
Calcschists / Kalkschiefer	KHAIRA GROUP
Biotite bearing slates-phyllites / Biotitführende Schiefer-Phyllite	GARSĀH SLATES
Mostly green, partly tuffitic phyllites / Meist grünliche, teilw. tuffitische Phyllite	BERINAG GROUP
Pure light quartzites, diabases / Reine, weiße Quarzite, lokal Diabaslinsen	BERINAG GROUP

Fig. 4: Lithologic and tectonic situation in the sw part of LKR-Window
Lagerungsverhältnisse im SW Teil des LKR-Fensters

Shali dolomite. According to a morphological camparision of growth forms (see VALDIYA 1969), the following stromatolite species of the *Collenia* group are present in the dolomites of the LKR-Window: *Collenia columnaris* FENTON & FENTON = *Masloviella columnaris* KOROLJUK 1960; *Collenia symmetrica* FENTON & FENTON. The presence of *Collenia baicalica* MASLOV is uncertain. SINHA (1972, in ASHGIREI et al. 1975, p.146) also mentions, from the area around Lārji, stromatolites of the group *Conophyton* and *Colonella* which, according to the Russian classification, would indicate lower to middle Riphean age.

3.22 Khaira-Group: This is a variegated alternation of redviolet, grey-green to dark slates with thin calcitic intercalations, thickly-layered, light-coloured quartzites which are speckled with haematite and dark, ferruginous dolomite containing stromatolites. Small diabase bodies are found locally in the slate series. In the area of transition to the Shali dolomites, dolomite-arenites and oolite horizons are to be found. Frequently occuring oscillation ripple marks, cross-bedding, stromatolites as well as frequent reddish colouring of the sediments are all indications of shallow-water deposition. Lithologically Khaira corresponds to the Nagthats of G.FUCHS (1967).

3.23 Garsāh slates: Above the Shali-Khaira-complex follows a 300–400 m thick series of very thin-laminated, brown to dark, strongly tectonized slates to phyllites. The Garsāh slates – named after an occurrence near the town of Garsāh in the lower Hurla Nal – resemble lithologically the Chandpurs (FUCHS & FRANK 1970) or the Simla slates and, according to their sedimentary character, were deposited in an area of little movement in deeper water. These sediments are considered to be a special facies at the top of the Berinag series.

3.24 Berinag-Group: The almost entirely clastic Berinags cover by far the largest part of the LKR-Window. The following lithology is characteristic:

a) Chloritic schists to phyllites, usually greenish, containing little biotite, rarely carbonate or with feldspar-rich („tuffitic") layers are common in the southwestern part of the window.

b) Pure, white, thickly bedded quartzites with ripples and cross-bedding in the northeastern part.

c) Lense-shaped meta-diabase bodies.

In the higher Sainj Valley (beyond the mapped area), a thick layer of augen-gneisses and volcanoclastics is intercalated within the schists.

Concerning the age of the meta-sediments of the LKR-Window, there are still two basically different opinions on the dating of these largely non-fossiliferous rock series of the Lesser Himalayas. One group of researchers suggests (partly with exception of Krol) Proterozoic age (HOLLAND 1908; MISRA & VALDIYA 1961; VALDIYA 1962 a, b, 1964, 1969; GANSSER 1964 b; FRANK in FRANK & FUCHS 1970; SINHA 1972, 1973; SRIKANTIA & BHARGAVA 1974 b; LE FORT 1975; MEHTA 1977), while others assume a Paleozoic age (WEST 1939; AUDEN 1948; FUCHS 1967; PANDE & SAXENA, 1968; – for the discussion of the biostratigraphy and paleogeography of the Lesser Himalayas see also the newly published paper by V. J. GUPTA 1977, in press). It is mainly to the credit of G. FUCHS (1967) that a lithostratigraphic scheme of the Lesser Himalayas on a regional basis was worked out. In this system the Berinags of the LKR-Window correspond lithologically to the „Chails“ (PILGRIM & WEST 1928) and the Khaira-Shali-Group to the Nagthat-Shali-(Krol-)sediments.

We suggest Proterozoic age for the meta-sediments of the LKR-Window. These partly parautochthonous and southwards overturned series are still, for the most part, in their primary sedimentary relationship with the Shali carbonates as the youngest sediments at the bottom and the Berinags as the oldest ones at the top of the rock pile. The stromatolites, found locally (SINHA 1972) as well as regionally and globally (VALDIYA 1969), were of use, in particular, for the subdivision of the Riphean in Siberia (KRYLOV 1960, 1963, 1967), although the stratigraphic value of these forms is doubted in some quarters. Moreover, we consider, that the lack of any other fossils in the thick Berinag-Shali series is the weightiest argument in favour of a pre-Phanerozoic sedimentation age.

The term Berinag (VALDIYA 1965) for the thick phyllite-quartzite series was preferred in the present case to that of „Chail“ because the Chails in their type locality are probably much mor closely related to the Crystalline Nappe than was formerly assumed and have a position similar to that of the green phyllites which, in the area in question, were mapped as part of the crystalline (but named „Chails“ by G. FUCHS 1967) in the southwestern Kulu Valley. It should be emphasized, however, that in general we accept FUCH's tectonic concept and the relative age-dating of his „Chail“ series below the Shali carbonates.

Direct proof for the Precambrian age of the Berinags was obtained by the radiometric age-dating of augen-gneisses which are intercalated s-parallel in the Berinag phyllites of the Sainj Valley: Rb/Sr whole rock age of 1840 ± 70 m.y. (FRANK 1973/74, p. 2).

3.3 Bajaura Nappe

At the base of the Crystalline Nappe we find regionally a not very thick unit of peculiar lithology which partially feathers out: muscovite-schists, some of which are strongly pigmented, dark, flaggy calc-schists and strongly tectonized microcline-augen-gneisses and porphyry-schists form, in various thicknesses, the petrographic content. Lithologically, the schists show relations to the overlying Crystalline Nappe; the ortho-gneiss, however, tends more towards the Berinags (augen-gneiss in the Berinag phyllites of the Sainj Valley).

The transition towards the Crystalline Nappe is always comformable. The degree of metamorphism of the Bajaura Nappe is comparable, say, to that of the basis of the Crystalline Nappe. The question whether the Bajaura Nappe is to be considered a separate tectonic unit or whether it merely represents a special lithofacies within the Crystalline Nappe is, quite apart from the paleogeographic implications, of special importance particularly with regard to the reversed metamorphism (see p.175). If the Bajaura Nappe has maintained the basal position in the Crystalline Nappe since pre-metamorphic times, then it is really part of the inverse metamorphic section and, as the zone of the weakest metamorphism, lies at the bottom of this rock pile. If one considers the inversed metamorphic sections in the Mālana–Parbati Valley to be the lower limb of a giant fold and thus – taking into account the Bajaura Nappe as well – as an inverted section, then an inversion of the entire basal crystalline mass, all the way to the periphery of the chain, would be implied. An inverse layering of the crystalline mass in the southern Kulu Valley is, however, rather improbable. For this reason, too, it seems more plausible to consider the Bajaura Nappe and the Crystalline Nappe separately.

On a regional scale the Bajaura unit shows certain similarities in lithology and in mineral facies to the Jutoghs (PILGRIM & WEST 1928) in the Simla area or to the „Lower Crystalline Nappe“ (FRANK & FUCHS 1970) in western Nepal. A possible parallelization of the Bajaura Nappe with „Chail 3“ (FUCHS & FRANK 1970), as suspected by FUCHS (oral comm., 1977), seems to be out of the question for purely lithological reasons.

4. PETROGRAPHY, MINERALOGY, CHEMISTRY

4.1 Crystalline Nappe

4.11 Meta-Pelitic and Meta-Psammitic Rocks

OPTICAL and CHEMICAL OBSERVATIONS in MINERALS: The principal differences in the texture and mineral content in the metasedimentary rocks of the Crystalline Nappe are the result of the change in the degree of metamorphism from south to north (see Fig. 19).

The majority of the microscopically studied mineral parageneses are quartz-rich, feldspar-poor schists with a varying content of phyllosilicates, often also garnet, less frequently alumosilicates, calc-silicates and accessory minerals. The following generalized parageneses are representative:

a) weakly metamorphic metapelites and metapsammites of the southern Crystalline Nappe: qz + chl + ms + bio + ab/olig + acc;

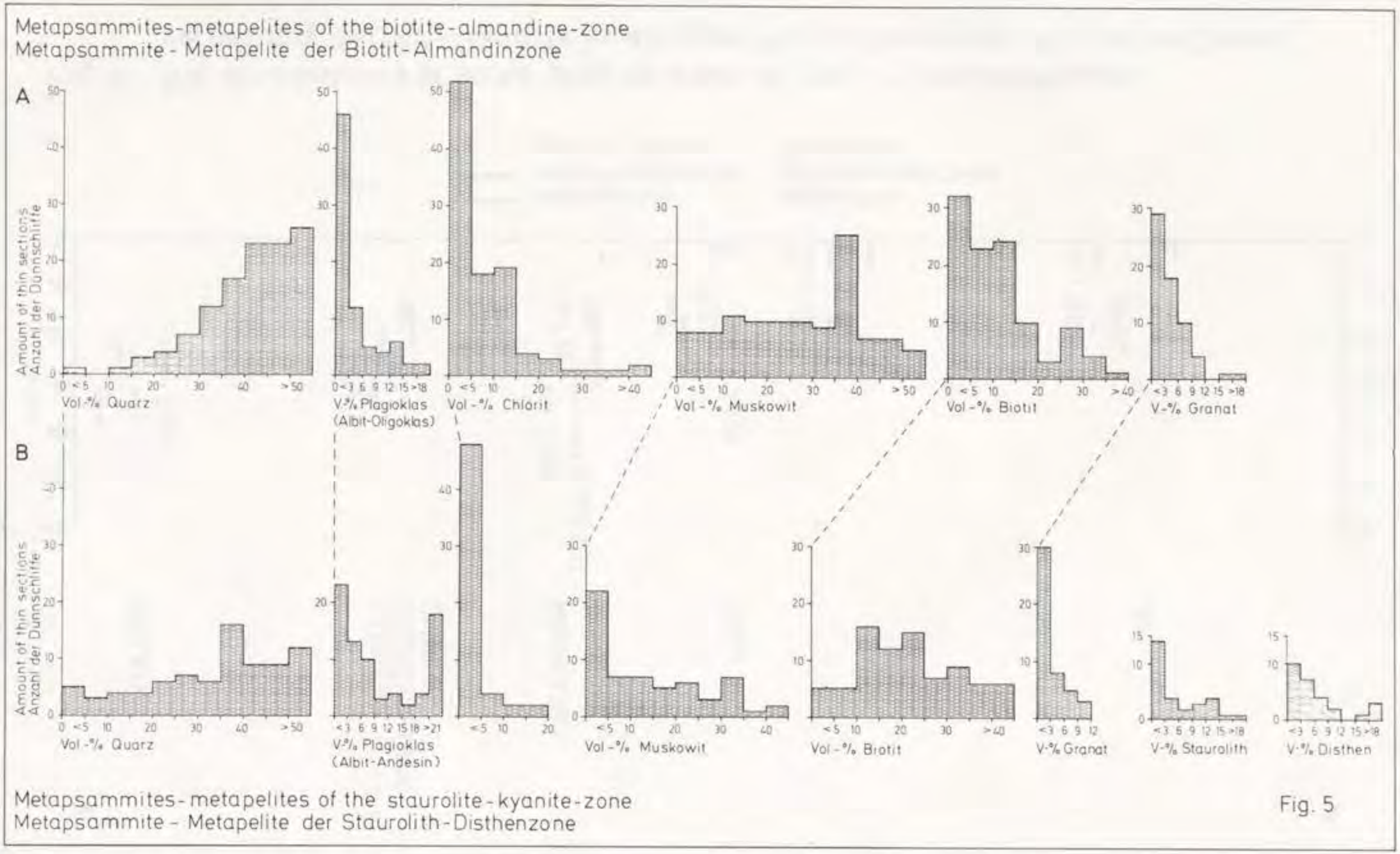
b) higher metamorphic metapsammites of the northern Crystalline Nappe: qz + bio ± plag ± ga + acc;

c) higher metamorphic metapelites of the northern Crystalline Nappe: qz + bio + ms + staur ± ga ± plag ± ky ± chl + acc.

Q u a r t z : With well over 20 vol-%, quartz forms the main component of most of the metasediments and, as a weathering-resistent mineral, is an indication of the relatively high degree of maturity of the original sediments. Especially within the metapsammites, poor in phyllosilicates, it shows well-developed, regular, homogeneous, granoblastic polygonal textures. Sometimes there appear textures (sample T 151) with pronounced differences in grain size,

Fig.5: The variation in the mineral assemblages of the metapsammites-metapelites of the Crystalline Nappe (200 thin sections from 188 rock samples); calcsilicate rocks are not shown here. The amounts of the minerals have been estimated using the diagrams by SHVETSOV (1954). Accessory minerals: tourmaline, clinozoisite-zoisite/epidote, orthite, zircon, apatite, sphene, rutile, graphitic material, opaque minerals (e.g.ilmenite).

Die Variation im Mineralbestand der Metapsammite-Metapelite der Kristallindecke (188 Proben, 200 Dünnschliffe); Kalksilikatgesteine sind nicht berücksichtigt. Der Mineralbestand wurde im Dünnschliff nach den Diagrammen von SHVETSOV (1954) geschätzt. Häufige Akzessorien sind: Turmalin, Klinozoisit-Zoisit/Epidot, Orthit, Zirkon, Apatit, Titanit, Rutil, Pigment, Opazit (Ilmenit).


Metapsammites-metapelites of the biotite-almandine-zone
Metapsammite - Metapelite der Biotit-Almandinzone
A
B
Amount of thin sections
Anzahl der Dünnschliffe
Vol-% Quarz
V-% Plagioklas
(Albit-Oligoklas)
Vol-% Chlorit
Vol-% Muskowit
Vol-% Biotit
V-% Granat
V-% Plagioklas
(Albit-Andesin)
V-% Staurolith
V-% Disthen
Metapsammites-metapelites of the staurolite-kyanite-zone
Metapsammite - Metapelite der Staurolith-Disthenzone
Fig. 5

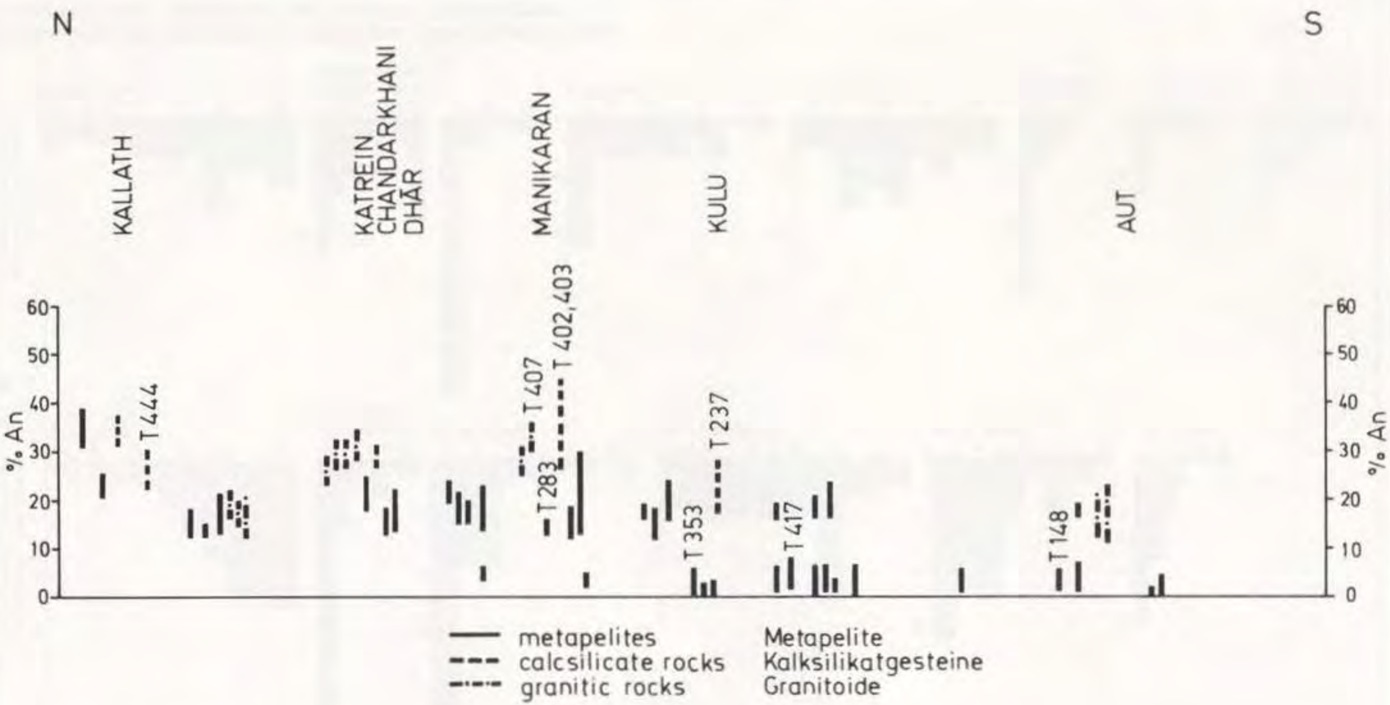


Fig. 6: The An-contents of some plagioclases of the Crystalline Nappe
Verteilung der An-Gehalte in einigen Plagioklasen der Kristallin-Decke

where isolated, large rounded pebbles occur within the fine-grained components, revealing differences in the size of the original detrital grains. Undulatory extincition and a slight heteroaxy were frequently observed.

Plagioclase: The markedly low content of feldspar is typical for the major part of the metasediments of the Crystalline Nappe. The whole rock analyses (Fig. 7) show analogous results in their comparatively low CaO-content. The plagioclases in the metasediments are never secondarily unmixed; preferred twinning is in accordance with the albite law, in the north a combined twinning in accordance with the albite/pericline law occurs more frequently.

The An-content in the metasediments rises to the andesine level in regions of medium-grade metamorphism (Fig. 6). A characteristic feature of the southern part of the Crystalline Nappe is, that even in the slightly metamorphic biotite-schists An-contents of around 20 % or over occur. Given a simultaneous low content of placioclase, this may seem surprising since the presence of oligoclase seemed, up to now, to be restricted to zones of higher metamorphism. It should be pointed out that, in all the still garnet-free metapelites studied here, plagioclase is the only Ca-bearing mineral. Measurements were carried out mainly with the universal stage, partly also with an automatic ARL-SEMQ Microprobe.

White mica: Thanks to the excellent orientation along the s-surfaces the micas generally attest their synkinematic growth. They reproduce even the finest folding in s-surfaces. Transverse muscovites as single occurrences are insignificant. In the fine-grained metasediments of the southern Crystalline Nappe muscovite often occurs as parallel intergrowths with chlorite and optically can not always be sharply separated from it. The few white micas from mica-schists near Kulu which were investigated with the EMP show a low content of phengite (T 353: 3 wt.% (FeO + MgO)). As a secondary alteration product of staurolite (T 12, T 347) and kyanite (T 462), sericitic muscovite II appears in the form of a microcrystalline heap.

Biotite: Biotite generally occurs as a major constituent in the Crystalline Nappe. Biotite-free parageneses are rare and in such cases the lack of biotite is certainly not due to the too low degree of metamorphism, as these biotite-free muscovite-chlorite-schists (T 118, T 139, T 147, T 160) or mica-schists (T 135, T 256) form only very thin layers within an otherwise biotite-rich complex. The chemical bulk composition of these biotite-free schists shows a fairly low content of alkalies.

In the slightly metamorphic schists of the south, one of the predominant microscopic features of the biotite is a dirty, olive-green, green-brown or light brown colour; in the more coarse-grained gneisses (also ortho-gneisses) and mica-schists in the north for the most part only dark-brown biotites were observed. Even if the characteristic colour of this mineral is dependent primarily on the chemistry (Ti and Fe III; see HAYAMA 1959) of the original rock, on the other hand the relationship and colour-change and change in the metamorphic grade is striking. Generally speaking, the biotites must be regarded as essentially synkinematically formed minerals, especially in view of their definite relation to the transverse structures (see p. 157). Phyllosilicates similar to biotite and having a wide chlorite edge were occasionally observed. Thin section analysis has not, however, been able to determine with certainty whether a retrograde transformation from biotite to chlorite II has taken place (T 91).

Chlorite: Finely acicular and flaky chlorite with anomalous, deep-violet to indigo, brown-green to blue-green, rarely chocolate-brown interference colours is widespread in the south. Parallel intergrowth with white mica is common in this area and in general chlorite occurs more frequently in muscovite-rich parageneses than in biotite-rich ones. Comparisons with optical classifications of other authors (WETZEL 1975) have shown that most chlorites in the mica-schists represent Fe-rich ripidolites (ALBEE 1962).

Towards the northern part of the Crystalline Nappe, the chlorite content of the metasediments definitely decreases in favour of biotite (and garnet); however, even the highly metamorphic staurolite-kyanite-porphyroblast-schists in the upper Kulu Valley still contain chlorite, sometimes even as a major constituent (T 471). These coarse-scaly, optically negative aggregates with weakly grey-green interference colours were analyzed with the EMP. They are rich in Mg and show the following proportion: Fe_{tot}: (Fe + Mg) = 0,42–0,47. According to the classification of HEY (1954) they lie in the boundary field between pycnochlorite and diabantite. Within the total parageneses chlorite represents a relatively late formation (transverse chlorite). In zones of diaphthoresis they are practically the only alteration product of garnet, rarely of hornblende.

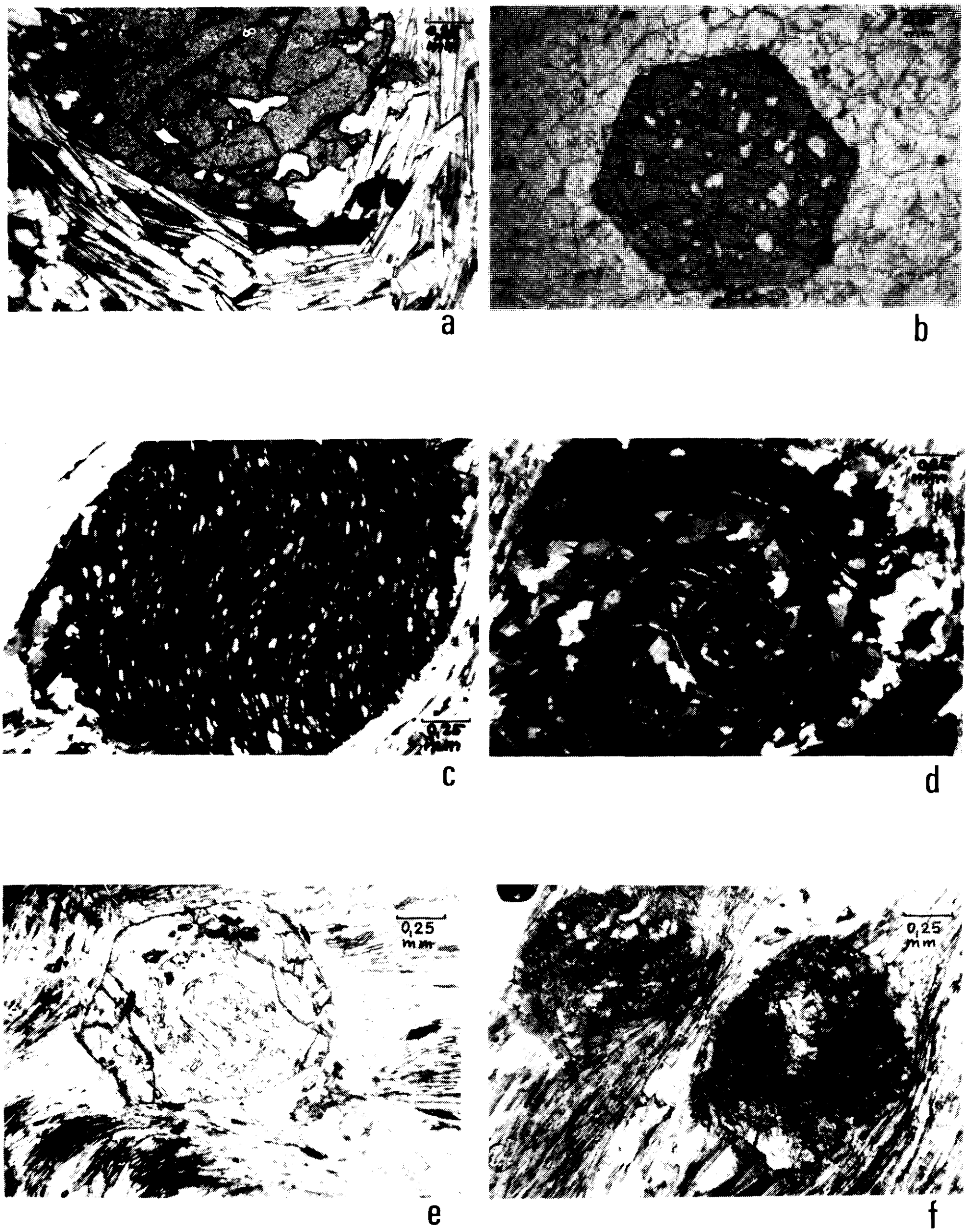


Fig. 7

G a r n e t : In most of the metapelites, garnet is present as a minor constituent. The slightly metamorphic biotite-chlorite-schists in the crest between the Beas and Uhl Valley contain no garnet.

The morphology of the garnets (Fig. 7) varies greatly within a small area and seems on the one hand to be a function of the paragenesis and of the intergranular mobility dependent on this, and on the other hand of the metamorphic grade and the duration of rock deformation. The following forms can be observed:

a) Idiomorphic rhombic dodecahedrons with unoriented quartz inclusions; found in quartzites and quartz-mica-schists (T 79, T 459).

b) Unoriented poikiloblasts („ghost-garnets") as amoeba-like intergrowth within the wavy groundmass in quartz-rich layers, partly with idiomorphic rims.

c) Idioblasts with strongly rotated internal texture and an inclusion-free edge (T 135).

d) Spherical xenoblasts, which are permeated by sigmoidally displaced inclusion lines (consisting mainly of elongated quartz) from the center to the rim (T 114); widespread in mica-schists.

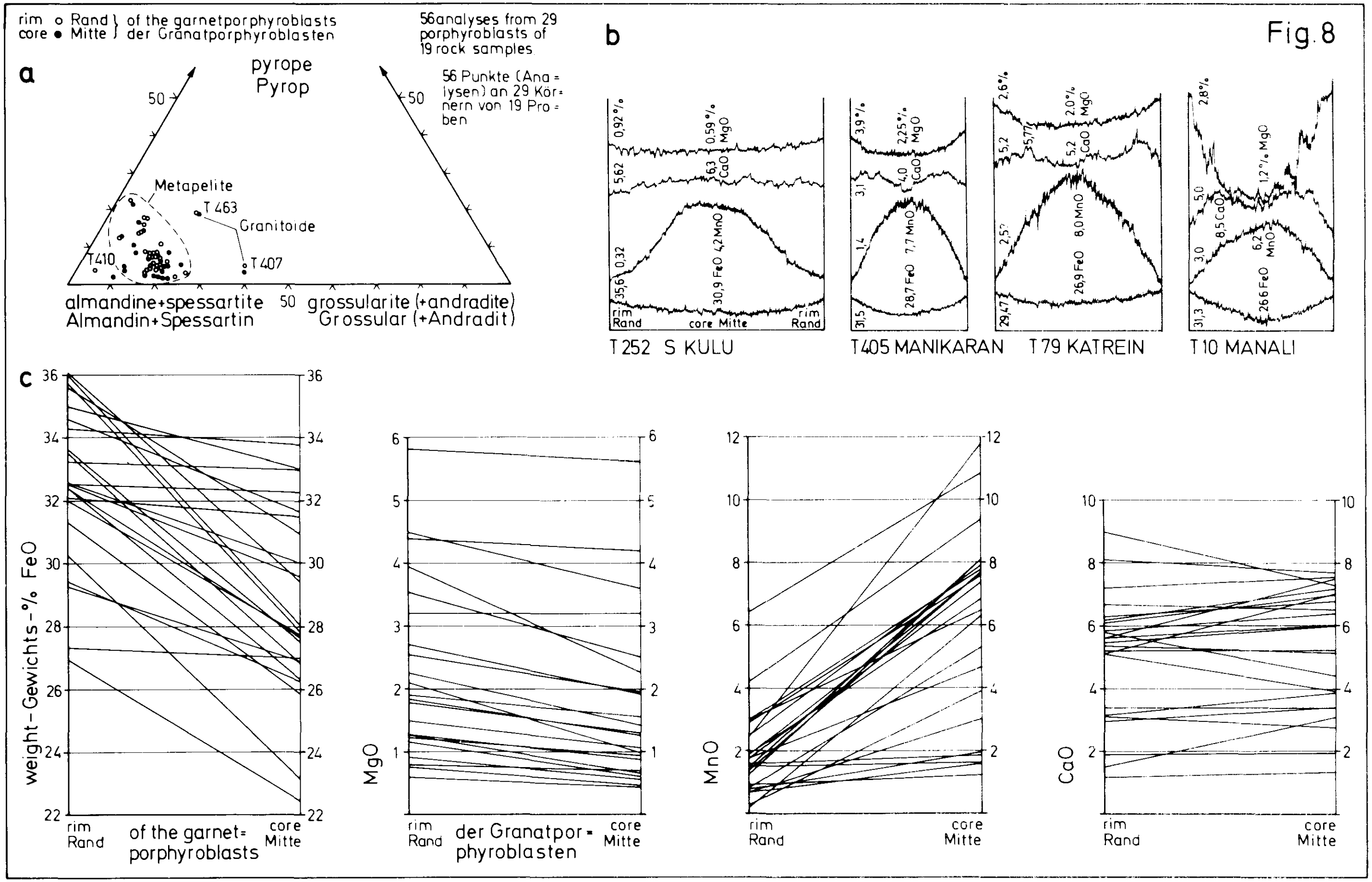
Widespread is the retrograde alteration of garnet to finely flaked chlorite II (pseudomorphs of chlorite after garnet) in the strongly tectonized basal part of the Crystalline Nappe.

Frequently occuring displacement of the internal texture shows that garnet blastasy in the most general sense is to be interpreted as a synkinematic process. Apart from the local variation in the behaviour of deformation, which is certainly very dependent on the material, the axes of rotation of the synkinematically rolled garnet xenoblasts from the Kulu mica-schists would appear to be conform with the chain-parallel B_2-axes (see p.159); in this sense the sigmoidal internal textures in garnet represent south- to southwest-facing micro-(shear-)-folds (see DE WIT 1976). This has been proved by serial observation of oriented thin sections. The rotation axes of such synkinematically formed garnet porphyroblasts were observed in three perpendicularily oriented thin sections of the same sample. Several such examples clearly show that the rotation axes of the garnets are oriented perpendicularily to the lineation of the deformation phase D_1 (see p.159), and they show therefore no closer genetic relationship to the transverse structures, formed synmetamorphically relative to the formation of biotite and disthene.

Garnets of 25 metapelitic rocks of the Crystalline Nappe were analyzed with the EMP. All the garnets thus examined are rich in almandine. Furthermore, most grains show a well-formed, continuous zonation (Fig. 8), in which the FeO- and MgO-contents increase from the center towards the rim of the porphyroblast, while the MnO-content decreases in the same direction. The CaO-content varies discontinuously or remains constant. All the analysed garnets, varying greatly in size, morphology and internal texture, show a very similar chemical composition.

Fig.7: Different shape of garnet. a) Cataclastically deformed porphyroblast without inclusions. b) Idioblast with non-oriented inclusions of quartz in a quartzite. c) Syncinematic „snowball-garnet" with oriented internal fabric of quartz. d) Syncinematically rolled porphyroblast. e) Porphyroblast with rotated internal fabric in the core and an idiomorphic rim. f) Alteration of garnet in chlorite (pseudomorphs).

Zur Granatmorphologie: a) Einschlußfreier, kataklastisch zerbrochener Granat (T 100, Chandarkhāni Dhār); b) Idioblast mit regellosen Quarzeinschlüssen aus einem Quarzit (T 79, W Katrein); c) Synkinematisch gebildeter Rundling mit verlegtem Quarzinterngefüge (T 114, NW Kulu); d) „Gerollter", synkinematisch gewachsener Xenoblast (T 371, Malāna Nāla W); e) Porphyroblast mit sigmoidal verlegtem Interngefüge im Kernbereich und idiomorphem, einschlußfreiem Rand (T 135, W Bajaura); f) Diaphthorese von Granat, das Umwandlungsprodukt ist ein feinschuppiger Chlorit (T 102, Chandarkhāni Dhār). Restgranat im Kern.


rim o Rand } of the garnetporphyroblasts
core • Mitte } der Granatporphyroblasten
56 analyses from 29 porphyroblasts of 19 rock samples
56 Punkte (Analysen) an 29 Körnern von 19 Proben
a
pyrope
Pyrop
50
Metapelite
T 463
Granitoide
T 407
T410
almandine+spessartite
Almandin+Spessartin
grossularite (+andradite)
Grossular (+Andradit)
b
0,92 %
0,59 % MgO
5,62
6,3 CaO
0,32
4,2 MnO
35,6
30,9 FeO
rim Rand
core Mitte
rim Rand
3,9 %
2,25 % MgO
3,1
4,0 CaO
1,4
7,7 MnO
31,5
28,7 FeO
2,6 %
2,0 % MgO
5,2
5,2 CaO
2,5
8,0 MnO
29,47
26,9 FeO
2,8 %
1,2 % MgO
5,0
8,5 CaO
3,0
6,2 MnO
31,3
26,6 FeO
T 252 S KULU
T405 MANIKARAN
T 79 KATREIN
T 10 MANALI
c
weight-Gewichts-% FeO
MgO
MnO
CaO
rim Rand
core Mitte
of the garnetporphyroblasts
der Granatporphyroblasten
Fig. 8

Figs. 8 b, c show the distribution of the four elements Fe, Mg, Mn, Ca.

In the slightly metamorphic area in the south garnet coexists mainly with chlorite and quartz (muscovite and biotite). It is therefore obvious to assume that the main reaction for the formation of garnet was a gradual decomposition of chlorite, as suggested by MIYASHIRO (1973, p. 217):

$$\text{chl} + \text{qz} \rightarrow \text{pyralspit. ga} + H_2O.$$

With increasing temperatures, more complex reactions (inclusion of biotite) are probably involved in the formation of this mineral.

S t a u r o l i t e : In the feldspar-poor mica-schists of the upper Kulu Valley, between Patlikuhl and Manali, staurolite appears in thin mica-schist layers as a major component. Microscopically the cm-long idioblasts often show a displaced internal fabric of quartz, ilmenite, epidote and graphitic material (T 346). Retrograde alteration, especially of cataclastically destroyed metacrysts into finely flaked sericite and sometimes chloritoid II (T 347) is restricted to special horizons.

K y a n i t e : Disthene is restricted, as is staurolite, to thin layers of the northern Crystalline Nappe. As a lithologic-tectonic datum horizon, „disthene-mica-schist-datum-horizon", a kyanite-bearing layer which, despite its relative thinness of a few meters, can be followed from Chandarkhani Dhar over the Malāna Nāla as far as to the upper Parbati Valley north of Pulga, which corresponds to a horizontal distance of over 10 km. This mineral shows a preferred NE-SW orientation (transverse structures; see p.157). Microscopically kyanite shows often poikiloblastic growth. We rarely find bent crystals, which are evidence of postcrystalline deformation.

A c c e s s o r y c o n s t i t u e n t s : The most common accessory mineral in the metasediments is tourmaline; this mineral sometimes occurs concentrated in schlieren (T 353, T 437: over 20 % tourmaline). Idiomorphic shape and zonation are typical of tourmaline. Sphene, clinozoisite/zoisite – epidote are found especially in calc-silicate rocks. Zircon, apatite and opaque ores (ilmenite) also occur; rutile is found more rarely.

C h e m i s t r y of the m e t a p e l i t e s : On the whole, the analyses of 30 metamorphic rocks from the para-crystalline (Fig. 9) correspond to the average bulk composition of metapelites (SHAW 1956). These metamorphics can be derived from marine clays and sandstones. A striking feature, however, is the relatively low content of CaO, which explains the low content of Ca-silicates (plagioclase, zoisite/epidote). The original sediments must have been very poor in carbonates, but rich in clastic material (source area of mainly crystalline rocks poor in limestones).

C a l c - s i l i c a t e r o c k s : Average parageneses of calc-silicate rocks contain: qz + amph + clzo/zo-ep + tit ± bio ± ga.

Amphiboles and zoisite-epidote-minerals appear in these marl-descendents as major and minor constituents.

Fig.8: Chemistry of garnets. a) The position of some garnets of the Crystalline Nappe within the system pyrope – almandine + spessartite – grossularite (+ andradite). b) Some examples for the variation in content of Fe, Mg, Ca and Mn in syncinematic garnet porphyroblasts (microprobe analyses). c) The change in the chemical composition from the core to the rim of syncinematic garnetporphyroblasts (transitional values are not shown here).

Chemie der Granate. a) Die Lage der untersuchten Granate aus der Kristallindecke im Dreieck Pyrop – Almandin + Spessartin – Grossular (+ Andradit). b) Einige repräsentative Beispiele für die Verteilung der Elemente Fe, Mg, Ca, Mn von synkinematisch gewachsenen Granatporphyroblasten (Elektronenmikrosondenprofile). c) Änderung der vier Elemente Fe, Mg, Ca, Mn, vom Rand zur Mitte in synkinematisch gebildeten Granatporphyroblasten (schematische Darstellung; Mikrosondenanalysen).

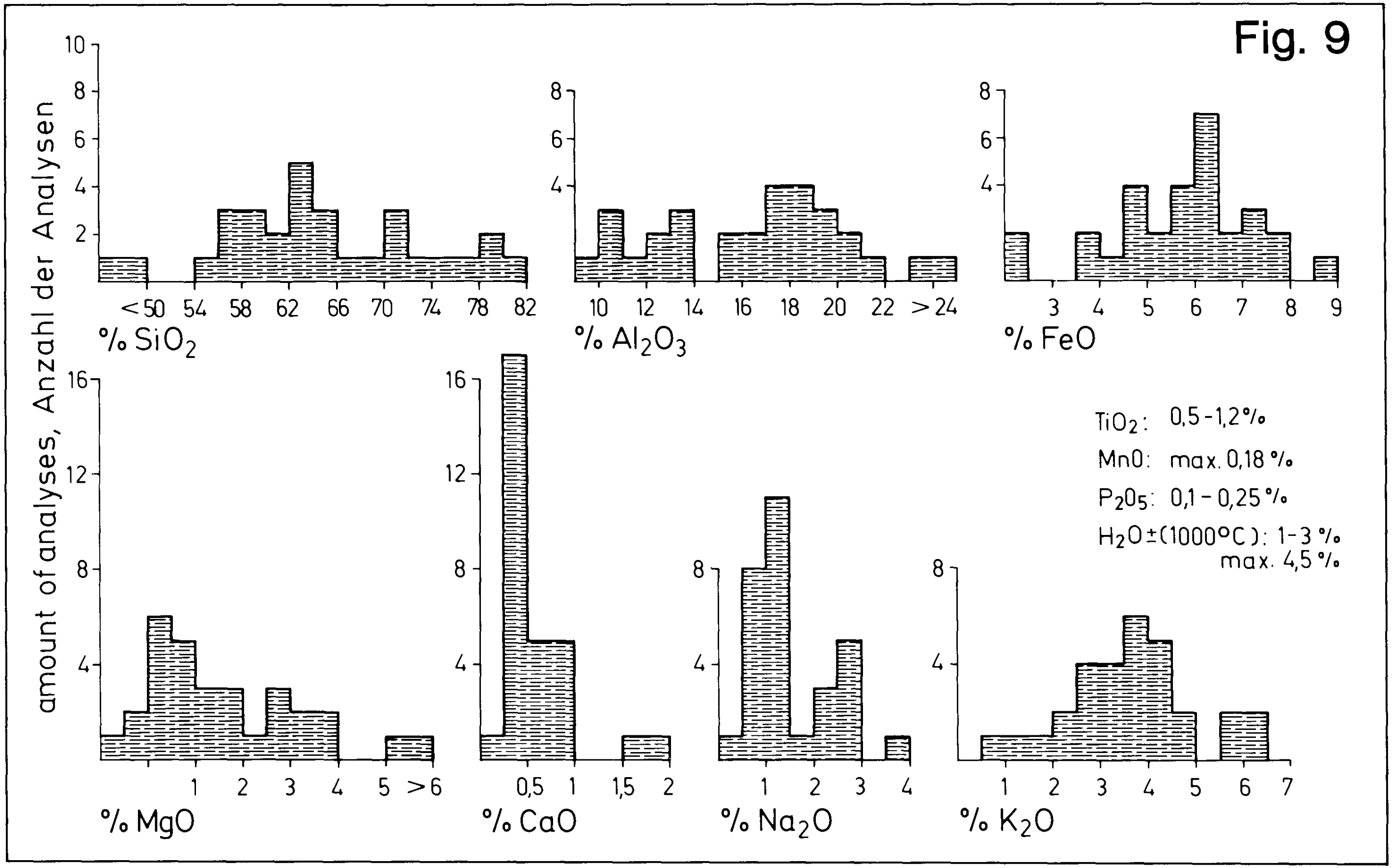

amount of analyses, Anzahl der Analysen
% SiO2
% Al2O3
% FeO
% MgO
% CaO
% Na2O
% K2O
TiO2: 0,5-1,2%
MnO: max. 0,18 %
P2O5: 0,1-0,25 %
H2O±(1000°C): 1-3 %
max. 4,5 %

Fig. 9

A m p h i b o l e s . On the basis of optical criteria (angle of extinction, colour), these minerals mostly belong to the Tschermakite group. In the Kulu area and in the basal parts of the inverse metamorphic series of the northeast we observed blue-green varieties (? Barroisites), while further north green, rarely brownish amphiboles are widespread. The occurrence of hornblende-blasts in the mica-schists of Kulu and Manikaran indicate a deficiency in potassium, since these minerals are found in such rocks only when the amount of potassium is unsufficient to create biotite out of the available quantities of magnesium and iron. The pleochroitic zoning of varying intensity which is frequently observed within a single grain is probably due to chemical variation within individual grains, as shown by WETZEL (1974, p.177). The mainly nematoblastic crystals show only incoherent orientation in s („garbenschiefer") in the mica-rich metapelites north of Kulu, in the quartz-rich calc-silicate-schists, on the other hand they show, in addition, strict linear orientation (T 88, T 457). Poikiloblasts with or without idiomorphic rims are widespread in quartzitic rocks, subidioblasts with displaced internal texture in mica-rich ones. An alteration at the edges of hornblende to chlorite, epidote, finegrained hornblende II and biotite was observed near Kulu and Manikaran. The presence of tremolite in the slightly metamorphic graphite-quartzites and -schists of the Kali Hain Pass area (T 461) indicates that there were small amounts of dolomite in the original sediment.

Z o i s i t e / c l i n o z o i s i t e and e p i d o t e occur especially in quartz-rich, biotitebearing schists with a very good orientation of the whole fabrics in the area of Katrein and east of it, epidote and dark brown orthite occur merely as a minor or accessory constituent and often in idiomorphic form. Zoned minerals with epidote as center and zoisite as rim are widespread. Within the calc-silicate layers a very striking material differentiation in a cm-scale was often observed; it probably represents fine sedimentary bedding structures with a strong metamorphic overprinting.

4.12 Meta-Granitoids

Granitoid rocks in thin section show a definitely magmatic, partly still unoriented fabric, which has been affected by metamorphism in various ways. The following paragenesis may typify the average mineral content:

plag + K-feldspar + bio + qz + ms + acc (ga, tourm, etc.).

P l a g i o c l a s e is usually polysynthetically twinned according to the albite/pericline law, the An-content lying mainly in the albite/oligoclase field and rising to a maximum of 40 % An in the biotite-rich granitoids in the north (T 407: 7,8 % CaO = 37 % An, EMP-measurement). In the augen-gneisses of the southern area plagioclase is always altered, showing numerous inclusions of sericitic muscovite and idiomorphic zoisite, coarsly recrystallized (synmetamorphic unmixing). In the north, on the other hand, we find apart from unmixed plagioclases also entirely „fresh" ones (obviously formed or recrystallized during Alpine metamorphism).

The idiomorphic, or augen-shaped deformed, large K - f e l d s p a r s consist entirely of microcline- perthites. Unmixing within K- and Na-(Ca-)feldspar has passed through all stages, from string-, vein- and patch-perthites including „chess-board-albitization". The augen-shaped potash-feldspars often show „hard lattice-like" texture in the outer parts, meanwhile in the „armoured" interior this „latticing" is only vaguely discernable. On the border surfaces between potash-feldspar and plagioclase formation of myrmekite was often observed.

The q u a r t z content is often over 20 vol-%. The porphyroid augen-gneisses of the south were possibly syngenetically contaminated by detrital quartz.

Fig.9: Variation of chemical composition of clastic metasediments of different metamorphic grade from the crystalline of Kulu area (30 rock analyses).

Variation in der chemischen Zusammensetzung von klastischen Regionalmetamorphiten verschiedenen Metamorphosegrades aus der Kristallindecke (30 Gesamtgesteinsanalysen) des Kulutales.

M i c a occurs in a coarse, platy form. The average content of dark brown biotite is somewhat higher than that of muscovite. Sagenitic textures in biotite are rare, chloritization of biotite was observed only in one single case (T 64).

Apart from garnet, the observed accessory constituents are tourmaline, zircon, apatite, rutile, orthite and opaque ores.

Chemistry of the Granitoids.

Table 1 shows the chemical bulk composition of seven granitic rocks from the Crystalline Nappe and the Bajaura Nappe. The variation is considerable, but does not permit of a grouping between intrusive granites and granitic gneisses.

	T 40	T 67	T 124	T 125	T 154	T 230	T 439
	massive	schistose	schistose	schistose	±massive	schistose	massive
				s t r u c t u r e			
SiO_2	73,34	69,50	74,89	68,91	75,05	70,97	69,60
TiO_2	0,13	0,29	0,23	0,45	0,16	0,57	0,40
Al_2O_3	14,90	15,23	12,65	15,86	14,88	13,91	16,03
FeO	1,16	2,33	2,21	3,51	0,92	3,28	3,35
MgO	0,27	1,10	0,28	0,78	0,27	0,74	0,87
CaO	0,68	2,60	0,12	0,42	0,34	1,48	1,28
MnO	0,06	0,07	0,01	0,07	0,02	0,05	0,05
Na_2O	3,40	2,99	1,49	1,77	3,48	2,49	2,74
K_2O	4,80	4,80	6,48	6,01	3,50	5,00	4,46
P_2O_5	0,33	0,10	0,06	0,13	0,17	0,19	0,14
$H_2O^{\pm}$	1,05	1,22	1,42	2,11	1,56	0,88	1,00
Total	100,12	100,23	99,84	100,09	100,35	99,56	99,92

Table 1 : Chemistry of the Granitoids; Zur Chemie der Granitoide
T 40 = Bhaga Valley; T 67 = W Katrein; T 124 und T 125 = W Bajaura;
T 154 = Aut NW; T 230 = W Kulu; T 439 = Deo Tibba.

4.2 Bajaura Nappe

The dark c a r b o n a t e s of this unit consist of coarsely recrystallized, almost pure calc-marble with well-developed twin lamellae. The phyllosilicate-rich layers of the q u a r t z - m u s c o v i t e - s c h i s t s are often of dark colour (Manikaran) and contain the following as major or accessory constituents : finely-needled chlorite, olive-green to brown biotite, rarely tiny garnets (T 161, T 162), calcite in lenses, albite, tourmaline and opacite. In the area of transition to the microcline-augen-gneisses we find rocks of mixed sedimentary and volcanic origin : „ p o r p h y r y - m a t e r i a l - s c h i s t s ". Here and there (T 128, T 162) they contain large feldspar insets within a finely-grained matrix of quartz, muscovite and chlorite. Some of the feldspars exhibit a typical lath-form (sanidine) and twinning according to the Karlsbad law. The presence of stilpnomelane is optically not ascertainable. An interesting feature is the large amount of ilmenite, usually with a microcrystalline reaction border of leucoxene (Fig. 10 c). The m i c r o c l i n e - a u g e n - g n e i s s from the type-locality west of Bajaura shows, in thin section, large, cataclastically destroyed microcline-perthites; the fissures in the microcline augen are filled with a fine-grained, idiomorphic quartz of mortar texture and finely-flaked white mica. Additional major constituents are polysynthetically twinned plagioclase, chlorite, olive-brown tourmaline and opaque ore. The horizontal as well as the vertical dissemination of the meta-volcanics in the Bajaura unit suggests that the synsedimentary magmatic activity was regionally widespread but of variable effect. The explanation for the intensive tectonization is to be found in the relative position of the thin Bajaura Nappe between two larger tectonic units moving towards each other.

4.3 Lārji-Kulu-Rampur-Window

The lithological groups differentiated below correspond to different stratigraphic levels:

a) Carbonates. Microscopically the dolomite of the Shali unit shows a fine-grained texture which is intergrown by spots of coarse-grained dolomite aggregates with twinning lamellae. The thin carbonate layers of the Khaira-Group consist of fine-grained calc-schists.

b) Quartzites. The quartzite of the Khaira-Shali unit contains well-rounded, egg-shaped, detrital quartz grains (sometimes also feldspar or tourmaline) of mm-size. The grains with strong undulatory extinction are embedded in a fine-grained matrix of quartz and white mica. They show a slight ss-parallel regulation and often a secundarily-grown edge. The more or less monomineralic Berinag quartzite is distinguished by a xenomorphic to sub-idiomorphic polygonal texture of quartz with a striking equal size of the grains.

c) Carbonate-quartzites, dolomite-arenites, meta-oolites. As transitional horizons between dolomite and quartzite, these rocks are widespread within the Khaira-Shali-Group. On average, the dolomite: quartz proportion is 1 : 1. The components usually consist of mm-large, well-rounded detrital quartz grains which are bound by a cement which consists mainly of recrystallized dolomite and some fine-grained quartz. The detrital quartz often shows BÖHM's lamellae and finely-needled, optically unidentifiable insets of high refraction (?zoisite, ?sillimanite); the quartz-detritus probably originates from metamorphic tectonites (erosion of a metamorphic region). Sometimes these grains have a concentric layering of dolomite and/or fine-grained quartz (meta-oolite; Fig. 10 a); more often, however, they show secondary growth edges of newly-formed quartz which is optically well separated from the detrital grain by a fine edge of small pores (Fig. 10 b). These rims of new-formed quartz II show also undulatory extinction. Intergranular, coarse-flaky chlorite rarely has been formed.

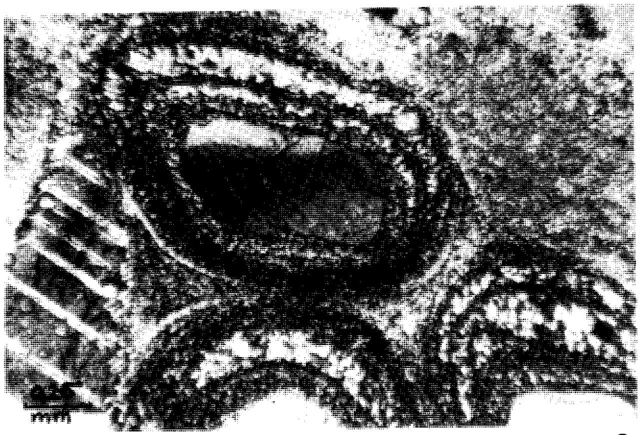
d) Schists – phyllites. The usually red-violet slates of the Khaira (Blaini) unit with a striking slaty cleavage show a microcrystalline quartz-rich mica-texture interbedded mainly with dolomitic carbonate of mm to cm thickness. Coarsely-flaked white mica is rare (T 217).

The homogeneous phyllites of the Garsāh unit contain, apart from quartz, golden yellow-brown to green-brown biotite, muscovite, chlorite, ore and carbonate.

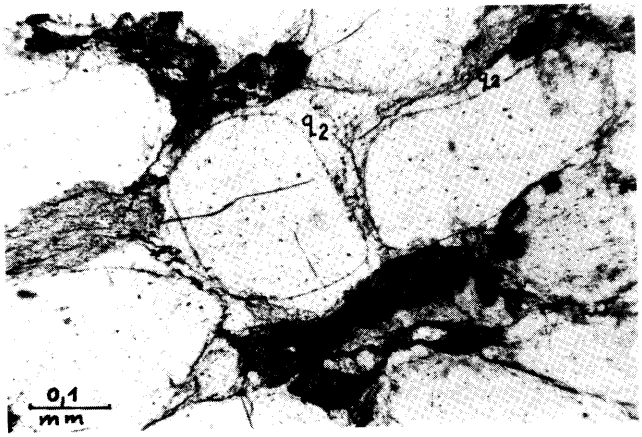
The mostly greenish slates–phyllites of the Berinag series consist mainly of quartz and chlorite; muscovite, biotite, feldspar, ore and carbonate are minor constituents, tourmaline and orthite accessories. The very assymetrical X-ray-diffractogram-reflexes of between 8° and 9° Θ must probably be viewed as narrow intergrowths of muscovite and biotite with incipient transformation of biotite (chloritization), as in the case of the microscopically observed biotite grains of the crystalline with smooth passage of the interference colours to a chlorite edge. The presence of kaolinite (T 312, T 313), a mineral which in view of the given metamorphic conditions should be unstable, is an indication of local, secondary alterations, which are most probably due to the thorough weathering taking place in this sub-tropical area. The layerwise enrichment of plagioclase and ilmenite with leucoxenic edges has parallels with the porphyry-material-schists of the Bajaura Nappe and is associated with a volcanic (tuffitic) contamination in the course of diabase formation.

Sixty samples of slates from various stratigraphic levels within the LKR-Window were studied by means of X-rays, particularily in view of the crystallinity of the newly-formed white micas. The (001)-reflexes (methods of measurement after KUBLER, 1966, 1968; WEBER, 1972) of the white micas in the X-ray diffractograms show fairly well to well recrystallized illites (see p.157).

e) Metabasites. The diabases of the Berinag and Khaira series which are inset as s-parallel lenses or as dikes have to a large extent altered their volcanic texture and primary mineral content. The polysynthetically twinned plagioclases are unmixed (zoisite-microlites),

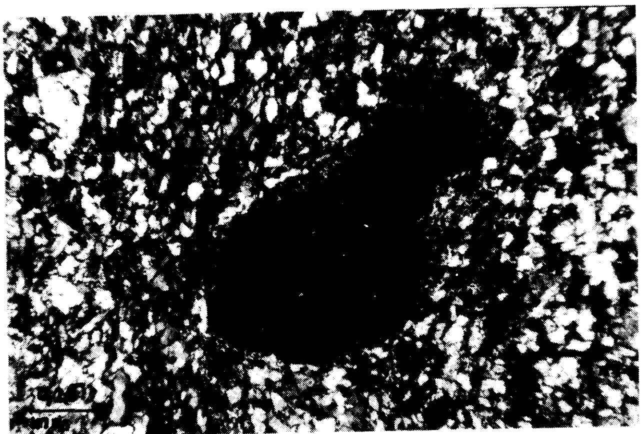


a



b

Fig. 10



c

amphibole and pyroxene have been transformed into chlorite II at the boundaries, ilmenite shows microcrystalline, leucoxenic reaction-edges. Newly-formed epidote/zoisite and stilpnomelane are common, whereas new quartz and biotite are less frequent. Carbonate occurs interstitially as a primarily-formed component. Whether the amphiboles are really magmatic minerals or, on the contrary, deuteric formations, i. e. post-magmatically formed at the expense of earlier-formed pyroxene, can not be determined for certain by microscopic studies.

4.4 Trace Elements (Rb/Sr-contents)

The Rb/Sr-content of over 200 rocks of varied tectonic-lithostratigraphic origin was determined by X-ray-fluorescence-analysis of powdered samples. Three groups were distinguished (Fig. 11).

a) Granitoids. (24 samples). The relatively small range of variation of the Rb/Sr-content indicates a certain homogeneity and genetic relationship within all the magmatites. The relationship of the Rb-content to the K-content (K-feldspar) is obvious : the potassium-richer microcline-augen-gneiss is also richer in Rb. The average Sr-content agrees well with that of „true low-calcium granites“ (granites of the continental plates; TUREKIAN & KULP, 1956).

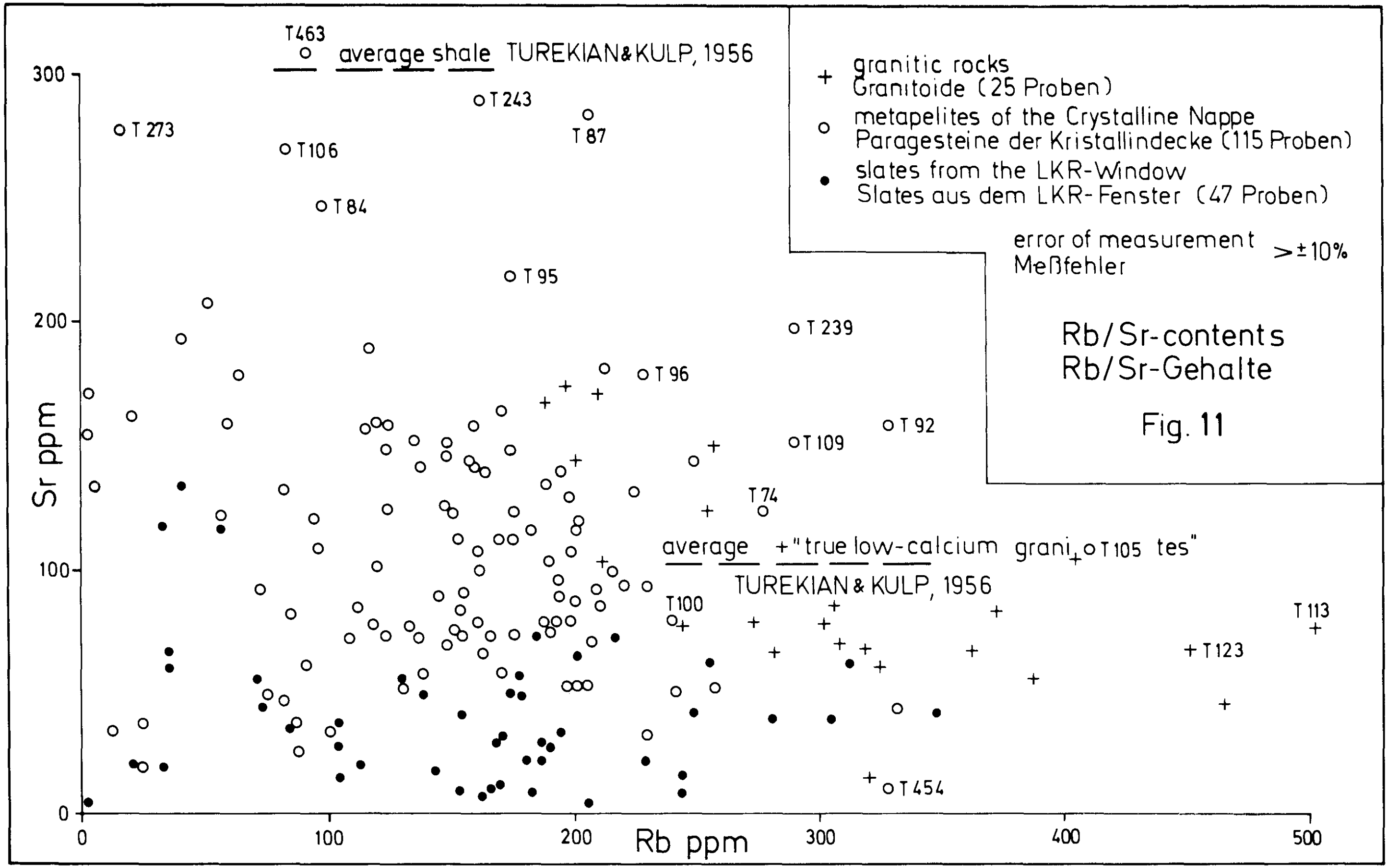
b) Metapelites of the Crystalline Nappe. Average content of 115 analysed samples : 110 ppm Sr, 151 ppm Rb. The majority of the „average rock types“ (quartz-rich schists) shows a very small range of variation in the trace-element-content, which is an indication of similar areas of origin and conditions of formation for these metamorphics. Where even a small amount of calc-silicate minerals is present, there is a sudden rise of the Sr-content (Ca-Sr-relationship). Moreover, the distribution of the Rb/Sr-content in the highly metamorphic metapelites shows no close relationship to the granitoids; accordingly, viewed regionally, they cannot be considered as „in-situ-anatexites“ or „migmatites“ (PANDE & KUMAR, 1974; cf. GRAUERT, 1969, p. 47).

c) The schists of the LKR-Window show a similar Rb-content, but a definitely lower Sr-content than the metapelites of the Crystalline Nappe. Average for 47 samples : 160 ppm Rb, 44 ppm Sr.

The Sr-content of all the para-crystalline rocks studied is very low and lies far below the average value of 300 ppm given by TUREKIAN & KULP (1956, p.292) for shales of marine origin.

Fig.10: a) Dolomite-arenite; well rounded quartz showing partly BÖHM's lamellae, partly with rims of fine-grained dolomite and quartz within a dolomitic matrix. b) Well rounded detritic quartz components with new formed quartz rims around a margin of small pores (Khaira). c) Idiomorphic ilmenite with a rim of leucoxene (Bajaura Nappe).

a) Dolomitarenit; gut gerundete Quarze mit BÖHM'scher Streifung und Schalenstruktur aus feinkörnigem Quarz und Dolomit in einer meist feinkörnigen dolomitischen Grundmasse (NE Larji). b) Gut gerundete Detritusquarze mit sekundärer Randbildung (q_2) um einen Porensaum (T 169, Khaira; W Bihāli). c) Idiomorpher Ilmenit mit Reaktionssaum aus Leukoxen aus einem quarzitischen Schiefer der Bajaura Decke (T 162, S Aut).


T463
average shale TUREKIAN & KULP, 1956
T 243
T 273
T 87
T 106
T 84
T 95
T 239
T 96
T 92
T 109
T 74
average + "true low-calcium granites" TUREKIAN & KULP, 1956
T 105
T100
T 113
T 123
T 454
Sr ppm
Rb ppm
0
100
200
300
400
500
+ granitic rocks
Granitoide (25 Proben)
○ metapelites of the Crystalline Nappe
Paragesteine der Kristallindecke (115 Proben)
● slates from the LKR-Window
Slates aus dem LKR-Fenster (47 Proben)
error of measurement
Meßfehler
> ± 10%
Rb/Sr-contents
Rb/Sr-Gehalte
Fig. 11

5. STRUCTURAL OUTLINE

5.1 Structure Elements

5.11 s(s)-Planes and the boundary Crystalline Nappe (+ Bajaura Nappe) – LKR-Window

The Crystalline Nappe overlies the slightly metamorphic series of the LKR-Window more or less conformably along the Main Central Thrust. Only alongside the southern edge is the bulging of the window in part discomformably cut off by the overlying unit. South of the window the crystalline mass forms a giant, flat syncline. The schistosity (s_1) is usually parallel to the sedimentary bedding (ss), which is recognizable even in areas of strongest metamorphism. Slaty cleavage is widespread within the meta-siltstones of the southwestern Crystalline Nappe and the slates of the LKR-Window.

Contrary to the mapping by G. FUCHS (1967, plate 12, 1 A), the metamorphics of the western flank of the Kulu Valley between Pandoh and Kulu are assigned to the Crystalline Nappe and not to the „Chails" = Berinags (see THÖNI, 1976, Fig. 15). The following arguments are decisive : a) As far as the lithology, structure and metamorphic grade are concerned, these metamorphics are more closely related to the crystalline mass than to the Berinags. b) No support could be found in the field for a tectonic contact in the position indicated by FUCHS. Sometimes the s-planes strike diagonally across the border postulated by FUCHS. c) Furthermore, the Bajaura unit, which is inset schuppen-like at the base of the Crystalline Nappe, forms a true border unit between the window and the Crystalline Nappe; the schists at the top of the Bajaura Nappe are thus definitely part of the crystalline mass.

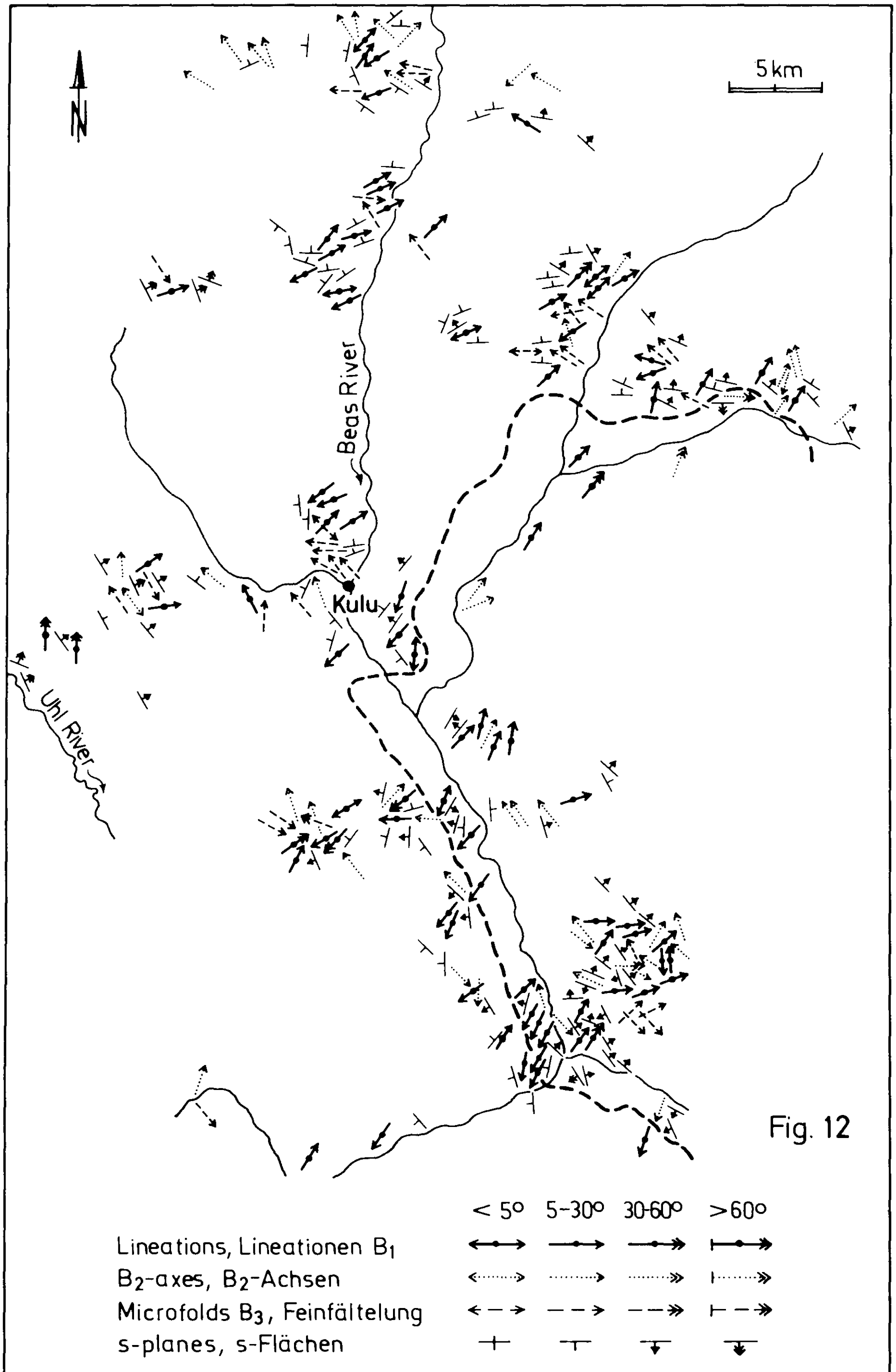
The presentation by SRIKANTIA & BHARGAVA (1974 b) and by MEHTA (1977) shows the spread of the tectonic window of Lārji more or less correctly.

Three main types of linear structures were differentiated : B_1, B_2 and B_3, which are related to three different, but temporally sometimes interfering deformation phases : D_1, D_2 and D_3.

5.12 Lineations, Mineral Elongations (B_1) and the problem of the formation of transverse structures (D_1)

This generation of structure elements is most evident in the Crystalline Nappe and is generally NE-SW-oriented, that is, p e r p e n d i c u l a r to the strike of the mountain chain. The temporal relationship of these structures to the main process of mineral growth can on the whole be described as a p a r a c r y s t a l l i n e event, especially with reference to biotite- and disthene-blastasy. It is assumed that several interfering factors must have been responsible for the formation of these structures, which are regionally widespread in a large exterior zone of the northwestern Himalayas and, on the other hand, are in some ways contradictory to the mechanics of orogenic movements.

Since the transverse structures of the deformation-type D_1 are generally elongation structures, oriented ± parallel to the direction of greatest narrowing of the



Structural sketch map of Kulu Valley Strukturkarte des Kulutales transported unit, and not bend- or bend-shear-folds (which are primarily due to lateral compression), one must assume that these structures are due mainly to a movement of material („flowing") in the direction of transport of the thrust mass. Material-movement on a submicroscopic scale leads to a definite lineation and lenghtwise orientation of the material (elongation), the causal factors for this material mobilization being a synkinematic rise of temperature (high plasticity of the transported material) and the elevated stress (pressure from all sides). On the other hand, it must be noted, that precisely in the southern part of the Crystalline Nappe, where such transverse structures are widespread, this degree of plasticity of material was hardly attained, because the degree of metamorphism was too low.

The inhomogeneity of the material may be the reason for the preferred development of these structures in areas with incompetent rock horizons.

The formation of the transverse structures by means of continous rotation of formerly chain-parallel b-axes (see SANDERSON 1973) is out of the question in this case because of the close relationship of these structures to the process of mineral growth, which, in terms of the main orogenetic movements, took place early. For the same reason, it is difficult to accept PLESSMANN's explanation (1961, p.323), which proposes a preferred formation of such B' ⊥ B-structures due to material surplus occuring in bend-folds during progressive narrowing, as the main formation of all larger bend-folds in the area studied is interpreted as being a relatively later act than the formation of B_1.

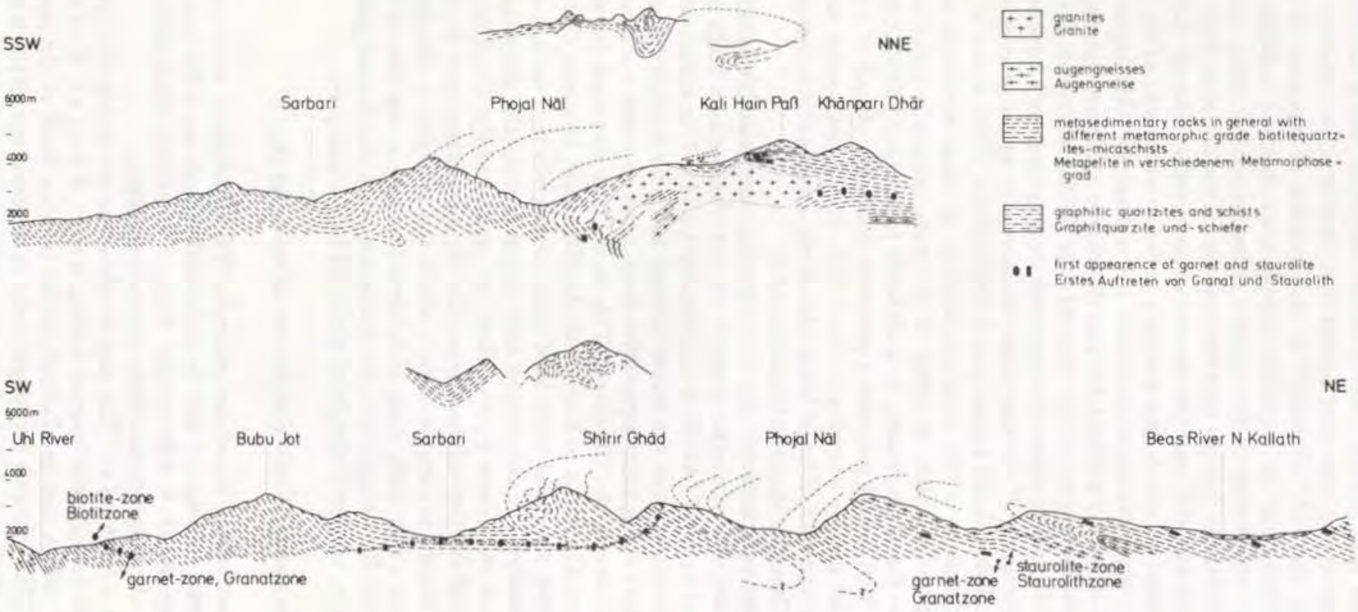
„Transverse structures" also occur in other orogenies (Western Alps, Norwegian Caledonides). Of particular interest are the observations made by MATTAUER (1975) and by MATTAUER & ETCHECOPAR (1977, in press), who describe very similar structures from the Massif Céntral and who interpret these „a-lineations" as a product of nappe-transportation from north to south – a situation quite similar to that one in the Himalayas. This model may also work for the B_1-structures in the crystalline mass of Kulu, with the difference, however, that in this case these transverse structures must have been formed in a very early stage of nappe movement. Analyses of the rotation axes of synkinematically grown garnet metacrysts have shown that these D_1-lineations are parallel to the (southward) direction of transport of the Crystalline Nappe. The D_1-elongations may be due to a process which is known as „simple shear", which was effective in the direction of transport during a very early stage of deformation, i. e., at the time of the décollement of the Crystalline Nappe and simultaneously with the thermal peak of alpidic metamorphism, but not during later phases of nappe transport.

5.13 Chain-parallel Folding in the cm- to km-range (B_2)

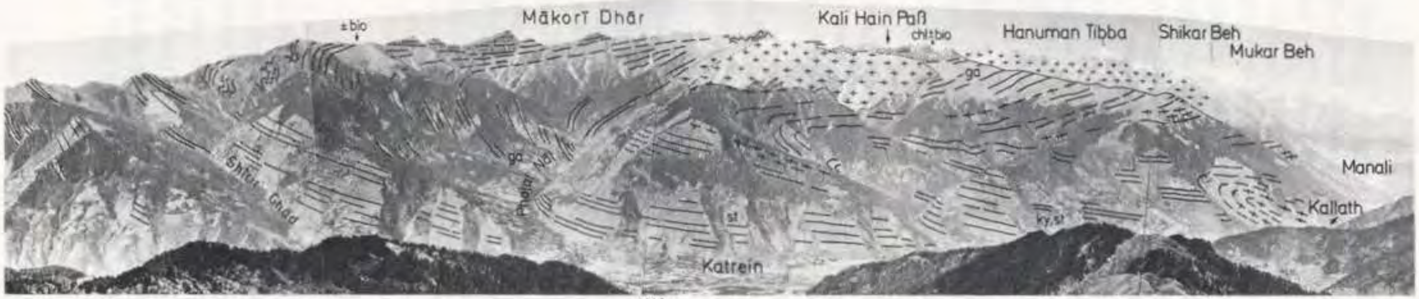
The dominating b-axes are generally NW-SE-oriented, most axes dipping NW. All observed foldings of this B_2 deformation type are S-SW-facing bend-(shear-) folds, from which it follows that there is a definite relationship to the relative direction of transportation of the Crystalline Nappe.

G i a n t f o l d s . The largest fold-structure within the Crystalline-Nappe, partly with complicated internal folding, is the „ P h o j a l - K a l l a t h - g i a n t - f o l d ", which can be observed on the western flank of the upper Beas Valley (Fig. 14). The fold-core is thought to be in the outcrops on the steep slopes southwest of Kallath, where light layers of granitic gneisses within the darker metasedi-

Fig. 13: Internal structure of the crystalline nappe on the western slopes of upper Kulu Valley
Internstruktur der Kristallindecke an der Westseite des oberen Kulutales



The Phojal-Kallath macrofold in the upper Kulu Valley
Die Phojal-Kallath-Großfalte im oberen Kulutal



W — N
K 11.617 ft
Chandarkhāni Dhār

granites / Granite — augengneisses / Augengneise — s-planes of metapelites / s-Flächen der Metapelite — graphitic quartzites and schists / Graphitschiefer und-quarzite

bio = biotite, Biotit — ga = garnet, Granat — st = staurolite, Staurolith — ky = kyanite, Disthen

Fig. 14

mentary rocks make the bending of the s(s)-planes easily recognizable; in the higher Phojal Nāl, especially between Neri and Kathi, the plunging of the back limb is well exposed in a 1000 m-scale. The schists on the southern flank of the Phojal Nāl, which dip steeply northwards, turn rapidly to flat bedding in the rear of the valley near the Mākorī Dhār, so that the top limb of the giant-fold seems sharply bent. In the upper Shīrir Gād complicated internal folding within the giant structure can be seen (FRANK 1975, oral inform.). The b-axis of the Phojal-Kallath-giant-fold dips slightly in WNW-NW-direction. The minimum distance from the core of the fold to its crest is estimated to be at least 15 km as the crow flies. However, the limits of this giant structure in the southwest, especially in the area west (Bubu Jot, Sarbari Nāla) and northwest (Achhari Dhār) of Kulu, have not yet been entirely clarified. A continuation of the Phojal-Kallath-giant-fold towards the (east-)southeast in the area of the sections of the inverted metamorphism of the Malāna-Parbati Valley can be discussed only in theoretical terms, as the crystalline rocks above the LKR-Window have been largely eroded and in those which remain no field observations of larger fold-structures have yet been made.

The secondary fold which overlies this giant fold and which is exposed in the darkly-pigmented graphitic schists in the Kali Hain Pass area can be explained by a northward compensatory movement (northward-trending downfold) in the rock pile overlying the giant recumbent fold.

In principle, all the smaller bend-folds observed within the crystalline rocks show the same orientation as the macrostructures.

Within the LKR-Window the massive narrowing of the series is documented not only by steep dipping, pressing and squeezing, but also by giant folding. The steeply-dipping Shali-dolomite-anticline north of Lārji is one of the most impressive structural elements (Fig. 15). Contrary to the representation by FRANK et al. (1973, p. 309), the stromatolites at Bithu Kanda Dhār are upright. The inversely-bedded stromatolites of Sainj Khād, southwest of Bihāli, probably reflect only a northerly edge-fold of the giant structure. Within the Khaira series one often finds disharmonic folding in a 10 to 100 m-scale (entrance to the Hurla Nāl; Bithu Kanda Dhār above Bare).

5.14 Small-scale Folding, Crenulation (B_3)

It was mainly mica-schist complexes, but not, however, more bend-resistent layers, which were affected by this deformation-phase D_3, in the form of fine crenulations. Superimpressed folds (west of Bajaura; southwest of Malāna) definitly assign this structure-type to a later deformation phase than D_2. B_3-axes usually bisect B_2-axes at a sharp angle and are oriented WNW to NW in the Crystalline Nappe; in parts of the LKR-Window they are also E-W-oriented. The diaphthoresis in the Crystalline Nappe (Cr_2) is associated with this late, locally intensive deformation of the fabrics.

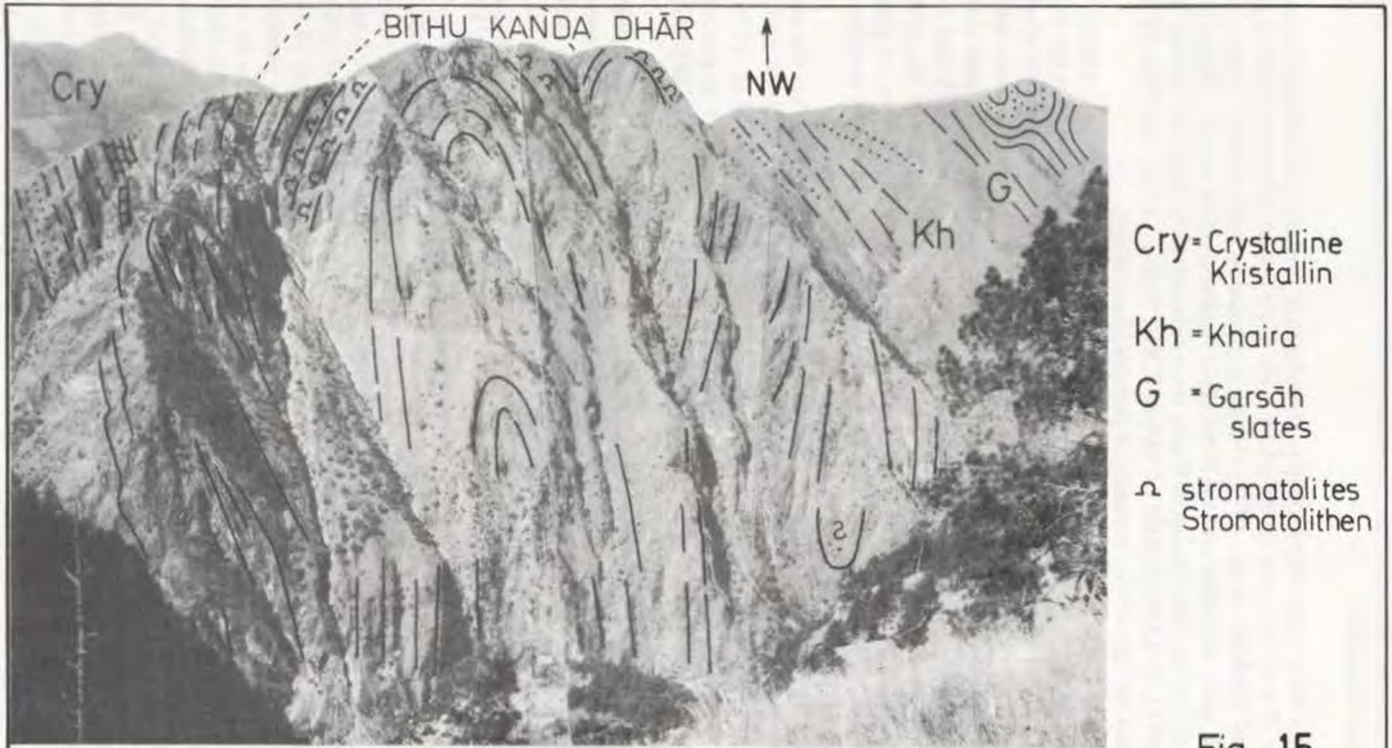


Fig. 15

The Shali-dolomite anticline N Lārji
Die Shali-Dolomitantiklinale N Lārji

5.2 The Structural Evolution and its relationship to the Metamorphism. ? „Old" Structure Elements

One of the most important factors in the temporal gradation of the macrostructures is the Carbonate Syncline of Tandi in the north of the mapped area (see FRANK et al. 1973). There is a primary sedimentary connection between this giant structure and the Crystalline Nappe and the former follows the regional chain-strike. The youngest fossils from this unit date from the Middle Jurassic (POWELL & CONAGHAN 1973 b; PICKETT et al. 1975; GUPTA 1974, 1975), so that the age of this structure is post-Middle-Jurassic.

Of more immediate importance for the dating of metamorphism and structural development, especially of the transverse lineations, in the Kulu Valley is the area of the Chamba Syncline: lying in the direct, striking continuation northwest of the weakly metamorphosed meta-siltstone series of the southwestern Kulu Valley, this fossiliferous permo-carboniferous rock sequence (with a triassic core; see RATTAN 1973; THAKUR & TANDON 1976) shows biotite growth and the typical formation of transverse structures in the form of an elongation of the pebbles in the metapsephites (FRANK 1975, oral inform.). The assumption of post-Triassic age for the formation of the B_1-structures and the associated metamorphism is thus acceptable for the Kulu Valley.

Many authors claim to recognize „old" = pre-alpidic structures within the crystalline mass (SAXENA & PANDE 1968; SAXENA 1975, p. 136; MEHTA 1977) or also within the metasediments of the LKR-Window (ASHGIREI et al. 1975). We do not consider that the results of field research so far warrant such an assumption, either for the Crystalline Nappe or for the window area (see also POWELL & CONAGHAN 1973 b).

The extensive pre-metamorphic granite areas within the Crystalline Nappe point to a pre-alpidic regional metamorphism and probably associated structural events. However, for paleogeographic reasons (see p.181) it can be assumed that this rock-transformation, which was surely connected with the granite intrusion, was limited to relatively low parts of the crust and must be considered mainly as a „static-thermal" event without any major tectonic-orogenetic movements (Fig. 24). Thus far, no structures have been located in the metamorphics investigated which are older than the macrostructures, which are definitely of Alpidic (Himalayan) age.

In this connection and especially in view of the question of a Hercynian event in the area of the Himalayas under investigation, the following additional points will be discussed, reference being made to the recently published study of MEHTA (1977). The whole rock age of the Mandi granite (southwestern part of the present map, Plate 1), which for the most part shows a similar tectonic position and, in part, also very similar petrography within the Crystalline Nappe to the granitoids of the northern Kulu Valley, is given by JÄGER et al. (1971) as 480 ± 90 m. y. The ages given by MEHTA (1977) for this granite differ, sometimes greatly, from those of the earlier authors; for example apart from one isochron of 545 ± 12 m. y. (Mandi granite; 3 points), he also presents an other one of 311 ± 6 m. y. (leucocratic Mandi granite; also 3 points). It would appear doubtful whether 3 points are sufficient to establish a conclusive and reliable isochron and to deduce a „Hercynian event" from it. The „Hercynian" muscovite Rb/Sr-ages could, in our opinion, represent merely ages which have been rejuvenated by the locally weak alpidic metamorphism. This is indicated by the Rb/Sr-data of W.FRANK (cf. FRANK et al. 1977, and many other still unpublished data) from coarse-grained pre-alpidic muscovites from the wider area under study, which have given very different values ranging between 425 and 207 m. y., although the rocks from which these minerals were separated can all be placed more or less exactly on one isochron (6 points) of an age of 495 ± 16 m. y. In this connection, the dating by FRANK of leucocratic types of the Mandi granite and of very similar rocks somewhat further east (Goda Goshaini, Kakri Gad, south of the Tirthar Valley), where in this case, too, 3 points would permit the calculation of a perfect isochron, is of great importance; however, their age of 443 ± 12 m. y. has for sure no geological meaning, since the coarse-grained muscovite (Rb^{87}/Rb^{86} = 3885,9; Sr^{87}/Sr^{86} = 28,774) of the Goda Goshaini granite has furnished an exceptionally reliable age of 489,5 ± 20 m. y., whereas the coarse-grained muscovite of an other sample from this isochron has given an age of only 299 ± 12 m. y. In view of these data, a local, hydrothermal, pre-alpidic influence seems possible, but we do not consider that a magmatic event of Hercynian age has by any means been reliably established.

Summarizing, the following picture emerges for the structural evolution in the area studied (see Fig. 16):

All three structural types, B_1, B_2 and B_3, are more or less similarily formed and oriented within the Crystalline Nappe as well as in the LKF Window and are all of Alpidic (Himalayan) age.

a) The formation of the transverse structures B_1 took place early; it must have coincided with the thermal peak of the metamorphism (biotite- and kyanite-blastasy). The transverse structures are incorporated in the macrofolds.

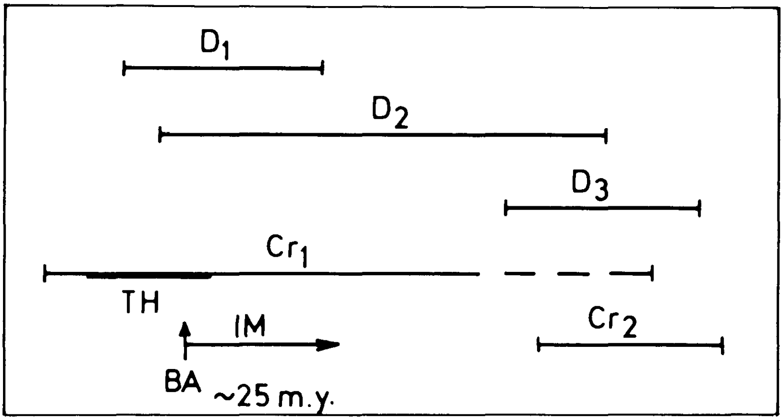


Fig. 16: Relation of deformation and crystallization. D_1, D_2, D_3 = phases of deformation; Cr_1 = main crystallization; Cr_2 = diaphthoresis; TH = thermal peak; BA = beginning of transport movements and thrusting; IM = evolution of inversed metamorphism.

Zeitliches Verhältnis von Gefügeprägung und Kristallisation. D_1, D_2, D_3 = Gefügeprägungsphasen. Cr_1 = Hauptkristallisation, Cr_2 = Diaphthorese. TH = Thermischer Höhepunkt. BA = Beginnende Abscherung. IM = Entwicklung der inversen Metamorphose.

b) The Phojal-Kallath-giant-fold was, *in nucleo*, also formed early; it is considered to be a partly transported nappe-fold. Its detailed interior development as well as the formation of the chain-parallel B_2-structures in general probably falls within the period of main narrowing and the incipient décollement of the crystalline mass and probably lasted a long time.

c) The approximately chain-parallel fine crenulation B_3 was formed in a late stage of tectonic activity (D_3); this reflects a late further narrowing of the series, which were already metamorphic (thrusting of the crystalline mass against the Lesser Himalayas).

From a regional point of view, the main tectonic-orogenetic movements in the southern Himalayas took place, roughly speaking, in the Paleogene–Neogene transition period (to the north, for example in Ladakh, one must reckon with definitely older – cretaceous-paleogene – movements). In the area of Simla, the lower miocene Dagshais, as the stratigraphically youngest series, are included in the nappe-structures (FUCHS 1967, p. 206). From this, it follows that the great, distant overthrusting movements are of post-Middle-Miocene age.

However, it was only in pliocene to pleistocene times that the Himalayas grew to a proper mountain chain.

6. METAMORPHISM

6.1 Lārji-Kulu-Rampur-Window

6.11 General remarks ; Texture

The variegated lithology of the LKR-Window may be assigned, on the basis of structural and textural criteria, to the anchi- to epizonal stage of metamorphism.

Sedimentary marks and structures, such as ripple marks, cross-bedding, grading and ooids were hardly altered by metamorphism. The silicification of the stromatolites must probably be considered as an early diagenetic process. Sometimes elongation and smoothing of carbonate layers or lenses can be observed. Within the slates newly-formed sericite is enriched in the form of silkily shining skins parallel to the surfaces of s(s).

Microscopically, the coarse detrital minerals are clearly distinguishable from the finely-grained, recrystallized or newly-formed intergranular material. Carbonate is recrystallized in various degrees.

6.12 Mineral growth, p-T conditions, Isograds

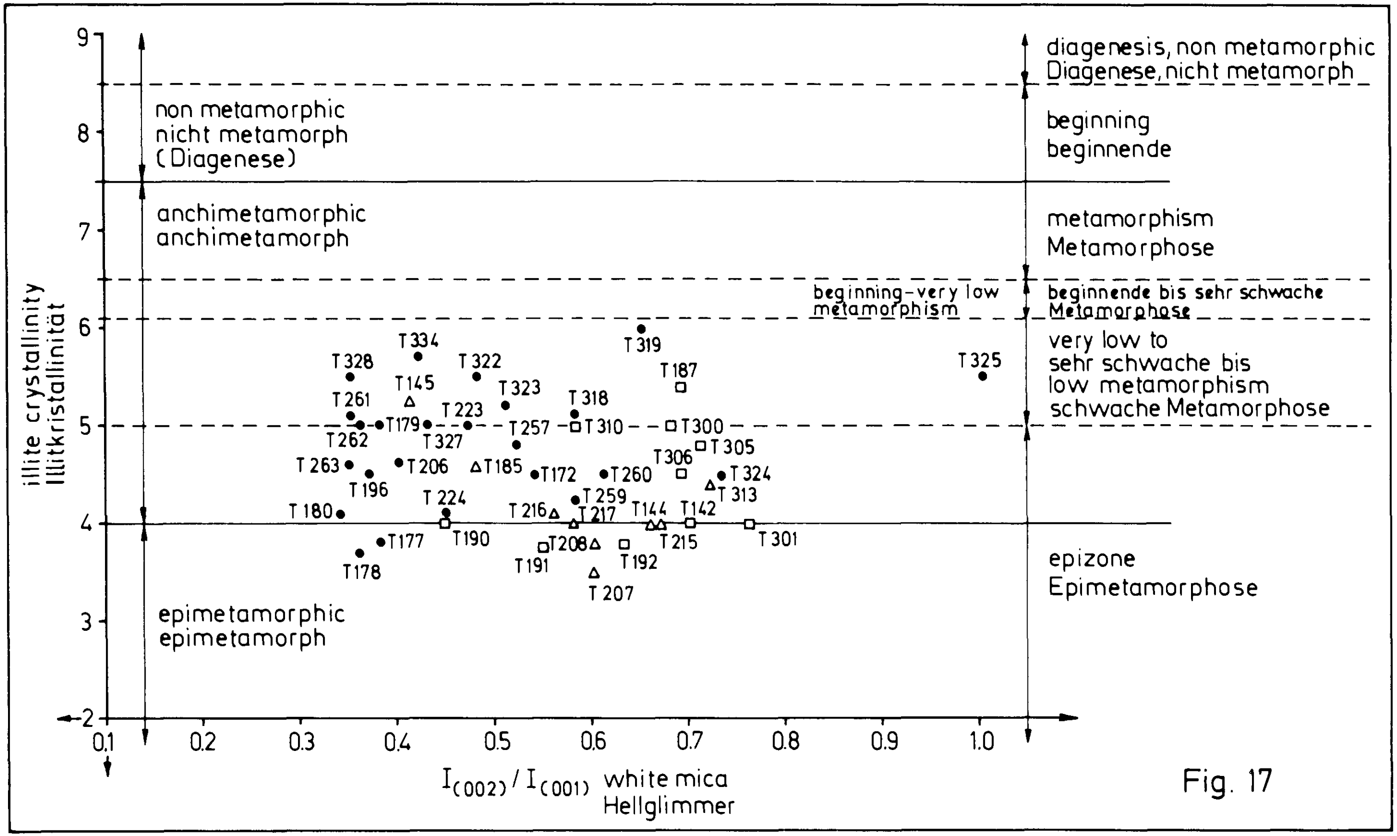
The appearence of new-formed zoisite and stilpnomelane in the metabasites can be considered as critical for the estimating of the metamorphic grade. Stilpnomelane is an indication of p-T conditions of the deep very-low-stage to beginning low-stage (WINKLER 1970). The upper limit of stability of stilpnomelane, according to NITSCH (1970) is 4 kb/445 $\pm$ 10° C or 7 kb/460 $\pm$ 10° C. These p-T conditions were not attained in the metabasites and meta-tuffites of the southern LKR-Window. Zoisite is an indication that the „zoisite-clinozoisite in" isograd has been reached and thus that the conditions of the very-low-stage have been exceeded. The Garsāh slates, with a phyllitic-crystalloblastic texture, show considerably intensive growth of biotite, whereas biotite occurs in only minor quantities in the chlorite-schists of the Berinags. This difference in mineral content is probably due alone to the chemical variation within the original sediments for these two rock types and not to any difference in the degree of metamorphism. On the other hand, the reaction for biotite-formation in the Garsāh-Berinag unit is unknown, and a direct comparison of stilpnomelane-bearing metabasites from the southern edge of the window and biotite-bearing slates/phyllites further north is by itself not sufficient to warrant the assumption of a higher degree of metamorphism in the northern part of the window. As (during metamorphism) newly-formed mineral content in the Berinag phyllites we observed: albite, muscovite, quartz (as rims around detrital grains) and zoisite, in addition to biotite and, predominantly, chlorite. Detrital quartz usually shows intensive alteration along the rims; the texture is conformable with the advanced stage of the „zone of spiny-like structures and chlorite micaceous cement" (KOSSOVSKAIA & SHUTOV 1958; FREY 1969). In the Khaira oolites chlorite and idiomorphic tourmaline were rarely newly formed along with quartz. No reactions between quartz and dolomite were observed.

The crystallinity of the white micas from the Garsāh-Berinag unit is somewhat higher than that in the Khaira-Shali slates and at the same time there is definite rise in the $I_{(002)}/I_{(001)}$-ratio of the illite-(muscovite-)peaks (Fig. 17). According to KUBLER's classification of the diagenesis/metamorphism transitional zone (KUBLER 1968), most of the illite samples studies (2μ fraction), with an illite crystallinity of 3,5 to 5,5 are in the field of uppermost epimetamorphism or very weak to weak metamorphism (according to the subdivision by KUBLER 1966, the anchi- to epimetamorphic zone). The colour-change in the reddish sediments of the Khaira-Group from red to violet or grey, which is due to a more intensive incorporation of special elements (TiO_2) in the haematite lattice or to a transformation of the haematite to magnetite or ilmenite (FREY 1970), a reaction which is generally observed in the transition-zone from anchi- to epimetamorphism, has not completely taken place (red-spotted quartzites).

In summary, it is correct to say that the Khaira-Shali series of the southern window area are characterized by the transitional stage of anchi- to epizonal metamorphism. The metamorphic grade increases slightly towards the northeast.

Estimates of the p-T conditions permit the assumption of temperatures of 350°C and (mostly considerably) above as being most probable. Unambiguous minerals which would corroborate high-pressure metamorphism do not occur in the LKR-Window (? stilpnomelane), but for regional geologic-tectonic reasons, somewhat higher pressures are a more likely possibility than low ones. The metamorphism in the LKR-Window may be considered as a prograde-monophasic event (there are no relic-textures within the parageneses observed); it is bound to alpidic tectonics (see ch. 5). Precambrian sediments (see p.181) would thus have been preserved unchanged until into tertiary times.

Field observation permits the assumption that the isograds are more or less parallel to the steeply NE-dipping s(s)-surfaces and thus that there exist within the LKR-Window steeply dipping to inverted metamorphic zones (cf. p. 175). On the other hand, metamorphism does not visibly increase from top to bottom (crests – valleys). This is probably a case of partly synmetamorphic verticalizing



illite crystallinity
Illitkristallinität
I(002)/I(001) white mica
Hellglimmer
non metamorphic
nicht metamorph
(Diagenese)
anchimetamorphic
anchimetamorph
epimetamorphic
epimetamorph
diagenesis, non metamorphic
Diagenese, nicht metamorph
beginning
beginnende
metamorphism
Metamorphose
beginning-very low
metamorphism
beginnende bis sehr schwache
Metamorphose
very low to
sehr schwache bis
low metamorphism
schwache Metamorphose
epizone
Epimetamorphose
T 334
T 328
T 322
T 319
T 187
T 325
T 145
T 323
T 318
T 261
T 223
T 179
T 257
T 310
T 300
T 262
T 327
T 305
T 306
T 263
T 206
T 185
T 172
T 260
T 324
T 196
T 259
T 313
T 224
T 216
T 144
T 142
T 180
T 217
T 177
T 190
T 208
T 215
T 301
T 191
T 192
T 178
T 207

Fig. 17

and thickening of the metamorphic zones; this situation would have become „fixed", as the result of a rapid rise of the rock series.

However, the limits within which the p-T conditions range are too confined to permit a definite conclusion.

6.2 Bajaura Nappe

Judging by the coarsely-recrystallized fabrics, the conditions of metamorphism in the Bajaura Nappe were somewhat higher than in the LKR-Window. The presence of biotite and sometimes of almandine-rich garnet is an indication of at least deeper low-stage-conditions. As further index minerals are not present, it is not possible to decide whether there is a (possibly slight) hiatus in the metamorphic grade in respect of the overlying metamorphics of the Crystalline Nappe (see p.172).

6.3 The Metamorphism in the Crystalline Nappe

6.31 General informations; Textures

Almost everywhere in the Crystalline Nappe the conditions of metamorphism were more rigorous than in the LKR-Window. In fact, next to lithology and structure features, it is mainly criteria of metamorphism which enable us to separate out a higher tectonic unit and which are evidence of the thrusting of this unit, which was influenced partly by much higher p-T conditions, over a totally different underground.

The slaty cleavage which is typical for the slates of the window area is only visible in the weakest metamorphic parts of the metapsammites and metapelites of the Crystalline Nappe, for instance in the meta-sandstones and -siltstones near the Bubu Jot, west of Kulu. Metamorphic crystal blastasy has greatly altered the sedimentary grain-fabrics. Within the Crystalline Nappe there is a ± continuous change in the metamorphic fabrics; first of all, a considerable coarsening in grain size can be observed from south to north. There is an increase in the degree of recrystallization; deformed and undulatory minerals, which occur still frequently in the Aut – Bajaura area, become rarer to the north. In the upper Kulu Valley, metamorphic processes have visibly altered the primary sedimentary bedding in the metapelites, probably because of an increasing material mobilization.

Fig. 17: The illite crystallinity of 42 slate samples from the LKR-Window and the intensity ratio $I_{(002)}/I_{(001)}$ of these illites. ● slates from the Khaira-Shali-group; △ Garsāh slates; □ schists from the Berinag-group. To the right (and cut lines) the classification of the field diagenesis/metamorphism based on the illite crystallinity after KUBLER (1968).

Die Illitkristallinität von 42 Schieferproben aus dem LKR-Fenster gegenüber dem Intensitätsverhältnis $I_{(002)}/I_{(001)}$ der Hellglimmer. ● slates der Khaira-Shali-Gruppe; △ Garsāh slates; □ Schiefer der Berinag-Gruppe. – Diagramm nach ESQUEVIN (1969) aus FREY (1970). - - Rechts (unterbrochene Linien) die Einteilung des Übergangsbereiches Diagenese/Metamorphose aufgrund der Illitkristallinität nach KUBLER (1968).

The weakly metamorphic schists to meta-siltstones southwest and west of Kulu are good examples of texture development in a more or less isochemical series, in conjunction with rising p-T conditions. Beginning with fine-grained quartz-muscovite-chlorite-schists with single porphyroblasts of biotite, clearly recognizable detrital grain-shapes as well as preserved sedimentary structures (ripple marks) and generally well-defined slaty cleavage near the Bubu Jot, we observe in the direction to the floor of the valleys gradually better recrystallized biotite-schists, and finally, at Kulu, coarsely-grained garnet-mica-schists with an enhanced crystalloblastic texture.

6.32 Index minerals and Isograds; p-T conditions

B i o t i t e . The p-T conditions necessary for the formation of biotite were attained in all parts of the Crystalline Nappe which were studied. In the weakly metamorphic crystalline areas, among the many and complex reactions which lead to the formation of biotite, the following:

pheng . mus I + chl → bio + ms II + qz + H_2O (MIYASHIRO 1973, p.208)

is the one that obviously occured most frequently (although „such a reaction has not yet been recognized" until now; WINKLER 1976). In the higher parts of the meta-siltstone series on the crest between the Beas and Uhl Valley, the conditions of formation for biotite from chl + ms + qz – apart from albite/oligoclase no other minerals occur in the studied parageneses – were probably only just attained. In this case, therefore, we are in the boundary field of an isograd, which is to be designated „qz-chl out/biotite in isograd" (WINKLER 1970). On the basis of statistical thin section analysis we can state that biotite becomes more frequent than chlorite in areas with higher metamorphism.

G a r n e t . The absence of garnet in the Bubu Jot – Berlanga Pass – Kali Hain Pass area is probably due to the fact that p-T conditions during metamorphism were to low for the formation of this mineral. As for the rest, in the remaining, lithologically as well as chemically largely uniform crystalline mass, almandine-rich garnet is widespread. Possibly the relatively late appearence of almandine-rich garnet as compared with biotite (the contrary process was observed in the middle Chandra Valley) is due, in particular, to somewhat lower pressure conditions (P_S), as almandine-rich garnet has so far been known to occur in such metapelites which were subjected to metamorphic conditions with rather higher pressures (WINKLER 1970; 1976, p.215).

P l a g i o c l a s e . In view, for one thing, of the low content of feldspar in the metamorphics, plagioclase was of little value as an index or facies mineral in the area under study; moreover, so-called critical parageneses (WENK 1962) are rare because of the low content of other Ca-minerals (calcite, calc-silicate minerals), especially parageneses where plagioclase is frequently in contact with hornblende and/or epidote-zoisite minerals. On the whole, however, even in the Ca-poor metapelites we find increase in the An-content of plagioclase as we proceed towards areas of higher metamorphism : albite/oligoclase is widespread in the southern crystalline mass, in the north, on the other hand, one finds mainly oligoclase (to andesine), with albite only rarely (see Fig. 6). The relatively frequent occurrence of oligoclase besides to albite in the weakly metamorphic, often still garnet-free

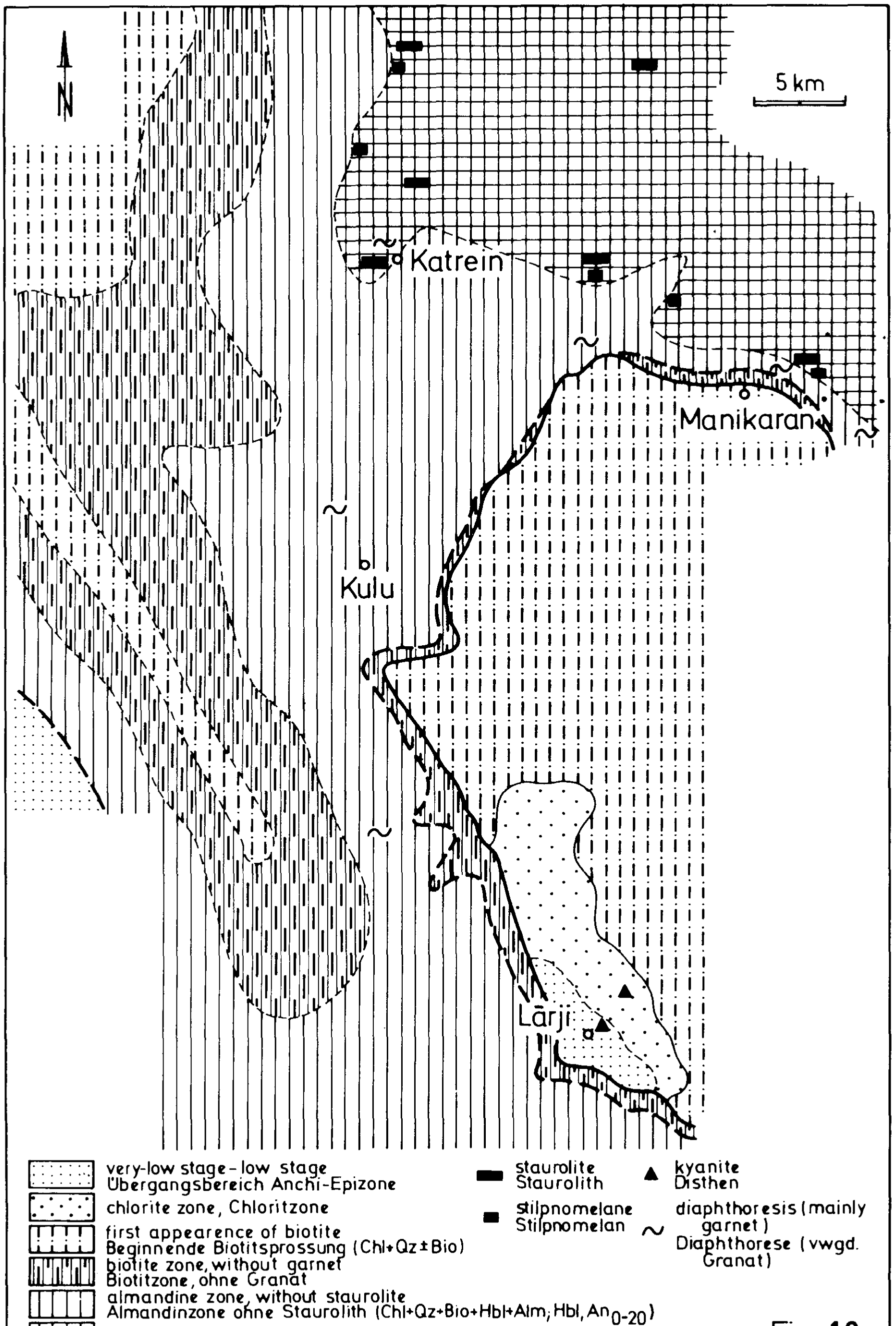


Fig. 18

The metam. zones of the Kulu area Mineralzonen des Kulu-Tales series in the southwest is surprising and probably due to the fact that plagioclase, being mostly the only Ca-bearing mineral in these rocks, absorbed all the available calcium. It is interesting, in this connection, to point out the change of Ca-content in some garnets (Fig. 8): in zoned metacrysts the Ca-content sometimes decreases from the core towards the rim of the mineral.

S t a u r o l i t e and the boundary low-stage – medium-stage. The following reaction seems the most likely for the formation of staurolite:

$$chl + ms = staur + bio + qz + H_2O.$$

The data for this reaction, as assertained by HOSCHEK (1969) with reversed runs in a system where the MgO/MgO + FeO ratio was 0,4, are 540 ± 15°C at 4000 bars H_2O pressure or 565 ± 15°C at 7000 bars H_2O pressure. Nowhere was primary chloritoid observed as a possible mineral of origin for staurolite formation. As a result of the above mentioned reaction, primary chlorite (chlorite I) is used up if the necessary p-T conditions are attained (WINKLER 1970, p. 214).

Recent petrographic work, however, has shown (in WINKLER 1976, p. 221) that in Mg-rich metapelites a Mg-rich chlorite can be stable together with staurolite + muscovite + quartz ± biotite well within the medium grade, up to approximately 50–60°C above the boundary low grade – medium grade.

Thirteen out of the 20 investigated staurolite-bearing samples from the northern part of the crystalline mass contain primary chlorite (and quartz and often muscovite), sometimes also as major constituent (over 20 vol-%). Parageneses which stand out in this respect are biotite-kyanite-rich chlorite-staurolite-schists (T 471–T 473) from the upper Kulu Valley between Patlikuhl and Bran, with poikiloblastic-idioblastic staurolite and coarse-flaky chlorite (see p. 149) as major constituents. Microscopically we could not find arguments which would point to conditions of disequilibrium in the parageneses. Two chemical bulk analyses from these chlorite-staurolite-schists have shown that they are very rich in Mg (T 473 : 15,3 % MgO). The chlorites, analysed with the EMP (6 mineral analyses in polished thin sections), gave a Mg/MgO + FeO ratio of 0,52–0,57.

With the first appearence of staurolite we therefore have a well-defined temperature-mark: temperatures of 545 ± 15°C were reached during the metamorphism of the northern crystalline mass (north of Katrein) and sometimes even greatly surpassed. Thanks the presence of Mg-rich chlorite in paragenesis with staurolite (see Fig. 21 f) near the northern border of the mapped area it is possible to calculate the temperatures of the metamorphism during which these parageneses have been formed in the range of approximately 550–600°C. These metamorphic conditions correspond to the staurolite-chlorite-biotite zone of the [almandine-] medium grade (WINKLER 1976, p. 221). In the upper Parbati Valley temperatures of 600°C probably were exceeded (formation of sillimanite). Because of the frequent presence of kyanite within the same parageneses (T 473) – which is the only Al_2SiO_5 modification present here – the pressure attained can be roughly estimated at not less than 5 to 6 kb (RICHARDSON et al. 1964; ALTHAUS 1966; HOLDAWAY 1971).

The estimation of the p-T conditions for the formation of biotite is more complicated. If one accepts the reaction given on p. 170 for the first formation of this mineral as the most probable one for prograde metamorphism, one may assume p-T conditions of at least 350°C at 3 to 5 kb (WINKLER 1970). At present the „biotite in" isograd in the field rises somewhat above the peak plateau, in a distance of at most 4000 m from the staurolite isograd. This gives a geothermal gradient of 3,7°C for the time of metamorphism, with an additional 10 km as minimum thickness for the rock pile overlying today's peak level.

Generally speaking, metamorphism in the Crystalline Nappe is of the Barrowian type, with an apparently elevated temperature gradient.

The border lines shown in Fig. 18 are not to be strictly considered as isograds. They merely indicate the first appearence of the particular mineral (or paragenesis) in the field. However, it may be assumed that these lines give a general indication of where a first appearence is possible, in the sense of the mineral's stability in relation to the p-T conditions, provided that the chemical conditions in the rock were suitable.

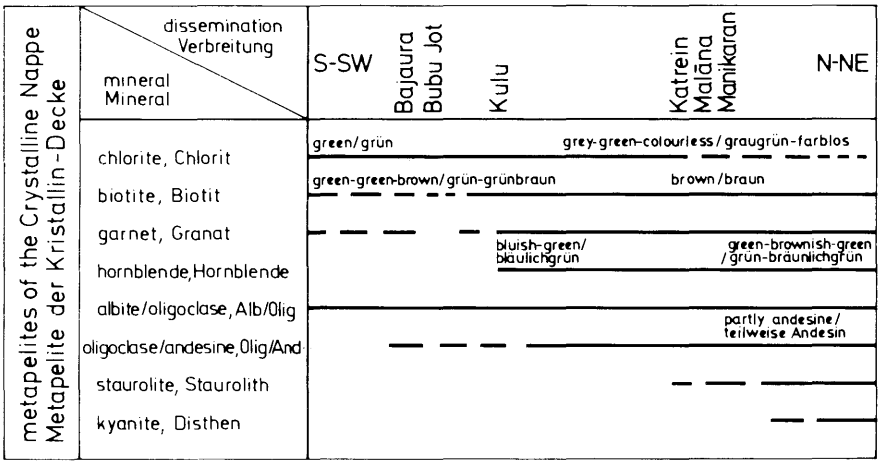


Fig. 19: Distribution of rock-forming minerals within the Crystalline Nappe.
Verbreitung wichtiger gesteinsbildender Minerale in der Kristallindecke.

6.33 Evolution of the Metamorphism in the Crystalline Nappe

The morphology, degree of orientation and internal fabrics (inclusion trails) of the metamorphic minerals observed support the conclusion that metamorphism in the Crystalline Nappe was mainly a synkinematic event. Mention should be made here of the definite s-orientation of the phyllosilicates – sometimes with the exception of chlorite, the linear orientation of disthene, more rarely of hornblende and zoisite, and the elongation of biotite in the direction of B_1 (see p. 157). The most conclusive proof of synkinematic crystallization is furnished by displaced internal fabrics in various porphyroblasts, mainly garnet, but also staurolite and hornblende (Kulu, Katrein). The main crystallization Cr_1 is considered to be essentially a simultaneous event of the deformation phase D_1 and partly of D_2 (see Fig. 16).

Changes in grain-shape, such as idiomorphic rims of rotated garnet porphyroblasts which are rich in insets are not considered to be due to separate crystallization phases but to inhomogeneities in the material and to discontinuity in the paracrystalline deformation.

The well-defined, continuous, regionally traceable zonation in garnets (Fig. 8) suggests a progressive-monophase metamorphism in the Crystalline Nappe (cf. STURT 1962; ATHERTON, 1968). We can find no proof of a polyphase metamorphic evolution, as postulated by some authors for the upper Kulu Valley (PANDE & KUMAR 1974; KUMAR 1975).

The alteration of feldspars in the pre-metamorphic granitic gneisses with strong recrystallization of the alteration products (sericite- and zoisite-microlites) is considered to be a pre- to synmetamorphic process. In the granitoids of the higher metamorphic areas it is possible, because the temperature rise during metamorphism was considerably higher here than in the south, that a secondary homogenizing of the unmixed feldspars took place: the minerals are optically „fresh" in appearence.

D i a p h t h o r e s i s . In a late phase of tectonic activity, partial retrograde alteration of the young mineral parageneses occured due to selective tectonization of incompetent, easily deformable rock horizons, intensified gas transfer and presumably through the onset of rigorous erosion. This „phase" of diaphthoresis Cr_2 is considered to have occured at the same time as the deformation phase D_3 and is probably due mainly to the late alpidic thrusting of the already metamorphic crystalline mass against the Lesser Himalayas. Diaphthoresis is especially wide-

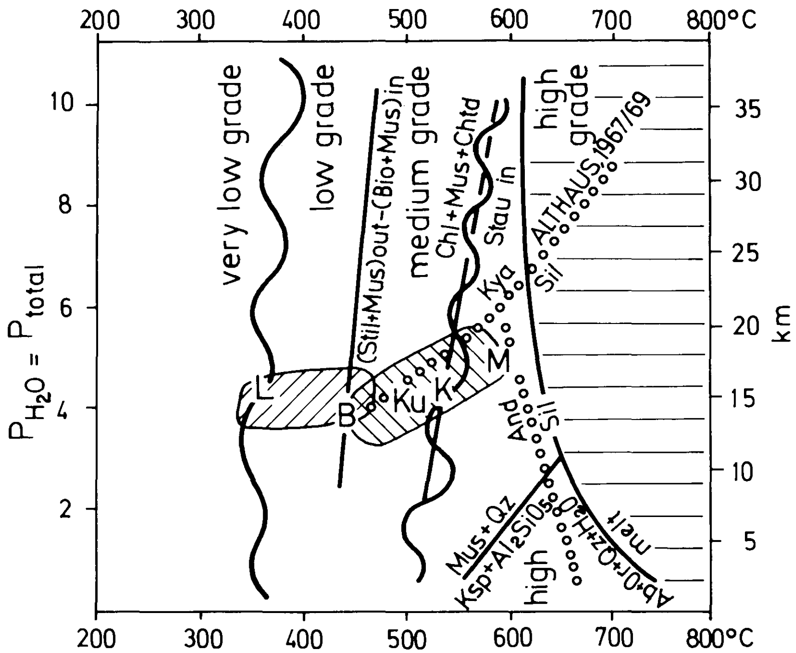


Fig. 20: The area investigated within the pT-diagram (after WINKLER 1974, simplified).
Die ungefähre Lage der untersuchten Metamorphite im pT-Feld (nach WINKLER 1974, vereinfacht).
L = Lārji; B = Bubu Jot; Ku = Kulu; K = Katrein; M = Manali, Manikaran NE.

spread in the mica-rich horizons of the basal Crystalline Nappe; it ranges from slight alteration of the rims or at fissures of cataclastically deformed grains to the formation of pseudomorphs and affects primarily garnet (chloritization), less frequently hornblende and staurolite. This selective and only locally effective diaphthoritic event does not, however, permit us to speak of genuine polymetamorphism within the crystalline mass.

Isograd behaviour. In the areas of medium-grade metamorphism, isograds run more or less s-parallel. In the weakly metamorphic southwestern part, on the other hand, the metamorphic zones bisect the s(s)-planes, in part, discordantly. The metamorphic grade within these series increases considerably from the crests (Bubu Jot) to the floors of the valleys (Lag Nāl, Uhl Valley), with the s-surfaces dipping steeply. Similar observations were made in the Berlanga Pass – Sarbari Nāla – Shiȓir Gād area, as well as Phojal Nal. It may be assumed that the crystallization of garnet and biotite outlasted the later macro-tectonic movements (partly folding and verticalizing of the s-surfaces).

In short, metamorphism in the Crystalline Nappe can be characterized as a progressive-monophase, synkinematic event of Alpidic (Himalayan) age.

6.34 Reversed Metamorphism

a) Geological situation. In the Malāna–Parbati Valley, the crystalline rocks are found above the steeply dipping Berinag quartzites in the form of a more or less isochemical metapelite series, several kilometers thick, with a extensive granite plate on the top (Fig. 22). Within the metapelite sections the following changes in the mineral parageneses can be observed from bottom to top:

– The content of primarily-formed chlorite (chlorite I) decreases rapidly; this mineral does not occur in the topmost part of the unit.

– Staurolite and kyanite occur only in the higher parts; the presence of sillimanite is known from the contact area to the granites in the upper Parbati Valley (T 535).

– The An-content in plagioclases shows a slight increase.

Parallel to the changes in mineral content a more or less continuing change in textures can be observed. The degree of recrystallization and the mineral grainsize show a considerable increase from bottom to top (see Fig. 21). Diaphthoritic textures (mainly chloritization of garnet) are restricted to certain horizons in the lower part of the section; no pseudomorphs after medium- and high-grade metamorphic minerals (such as staurolite) were observed.

Analyses of staurolite-free mica-schists of the middle parts of the profiles show that, given a bulk composition necessary for the formation of staurolite, the p-T conditions for the formation of this mineral were not realized in these parts of the sections.

No dislocation-planes or any large-scale folding could be observed. The metapelites are thus considered to be a more or less undisturbed, coherent metamorphic rock pile. Isograds are oriented ± s-parallel over more than 20 km of horizontal distance.

The western flank of the Kulu Valley is dominated by the giant-fold of Phojal-Kallath. The isograd-course for the medium-grade metamorphic core-region of this

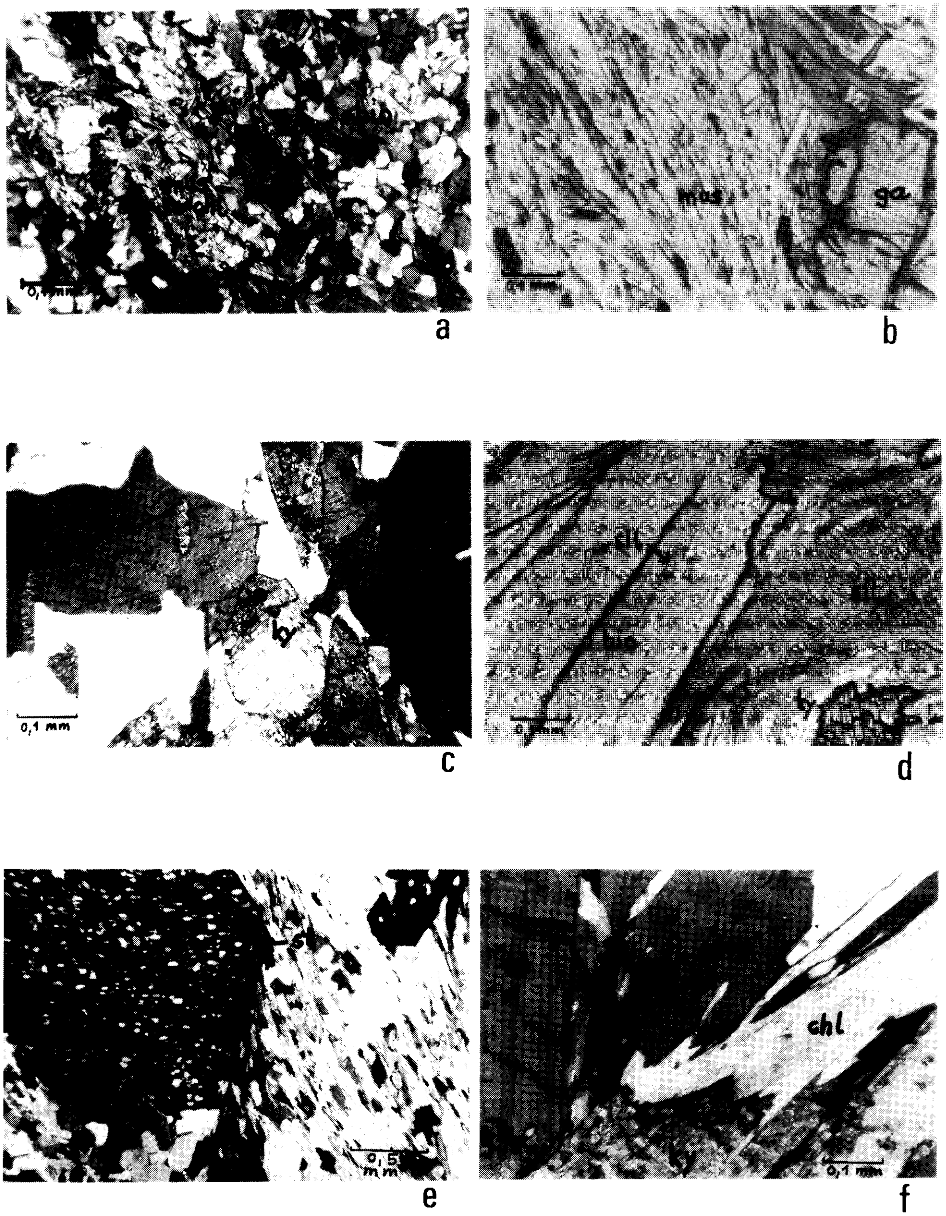


Fig. 21

giant structure in the Kallath area can be given as being ± s-parallel, thanks to staurolite- and kyanite-bearing layers. The degree of metamorphism decreases towards the fore limb as well as towards the back limb of the fold: in the peak area west of the Phojal Nāl and of the Khānpari Dhār, fine-grained, almost biotite-free rocks are widespread. The metapelites of the upper Kulu Valley strike without interruption towards east to southeast into the upper Parbati Valley; nevertheless, the continuation of the axial plane of the fold towards the east could not be found, despite exact field observation. Due to the strong bulging of the underground (LKR-Window) the metamorphics of the Crystalline Nappe have been largely eroded.

The mineral formation in the central area of the giant fold is, in view of the deformation phase D_1, to be considered generally synkinematic; but mineral growth and recrystallization lasted even longer than the D_2-phase, during which the giant structure must have been mainly formed.

b) Interpretation of the Reversed Metamorphism. As prekinematic metamorphism, and, in this sense, the transportation of an already metamorphic and cooled Crystalline Nappe, can be excluded on the grounds named above, one must consider the folded isograds as a product of a (synmetamorphic) process, through which temperature-zones were inverted during internal mechanical deformation (folding; continuous s-parallel movement) and transport. Two possibilities exist:

a) synmetamorphic folding of temperature-zones, more or less parallel to the s(s)-surfaces during the folding of a bedded rock pile; thus a section of inverted metamorphism and lithostratigraphy would be produced in the bottom limb of the fold. The isograd pattern is more or less s-parallel if metamorphism does not last much longer than the movements.

Temperature inversion (actual formation of a „metamorphism-fold“) can be produced by continuous rolling up of the hinge of the fold (Fig. 23, case a_1) or – more probably – through continuous twisting in the area of the lower hinge of the fold (Fig. 23, case a_2). The first case is hardly likely because of the strong tectonization which usually occurs at the crest of a giant fold, rapid cooling and erosion.

Fig. 21: Evolution of metamorphic textures of the inverse metamorphic metapelite series of Parbati Valley from bottom (a) to top (c, d), a = slightly biotite-bearing quartzitic muscovite-chlorite-schist; b = garnetiferous schist; c = kyanite-bearing paragneiss; d = new formed fibrolithic sillimanite in a coarse-grained micaschist of upper Parbati Valley; e = idioblastic staurolite with rotated internal quartz-fabric (Kulu Valley); f = Mg-rich chlorite-kyanite-staurolite-schist from the high-grade metamorphic core of Phojal-Kallath-macrofold. – No difference in exaggeration.

Gefügeentwicklung in den invers metamorphen Metapelitserien des Parbatitales (NE Manikaran) von Liegend (a) nach Hangend (c, d). a = schwach biotitführender quarzitischer Muskowit-Chlorit-Schiefer; b = granatführender Schiefer; c = disthenführender Paragneis; d = Bildung von fibrolithischem Sillimanit in Biotit; T 535, disthenführender Glimmerschiefer, inneres Parbatital; e = Staurolithidioblast mit verlegtem Quarzinterngefüge bei Patlikuhl (Kulutal, T 346); f = Mg-reicher Chlorit in Berührungsparagenese mit Staurolith und Disthen (T 471), hochmetamorpher Kernbereich der Phojal-Kallath-Großfalte, 13 km S Manali. – Alle Abbildungen haben gleiche Vergrößerung.

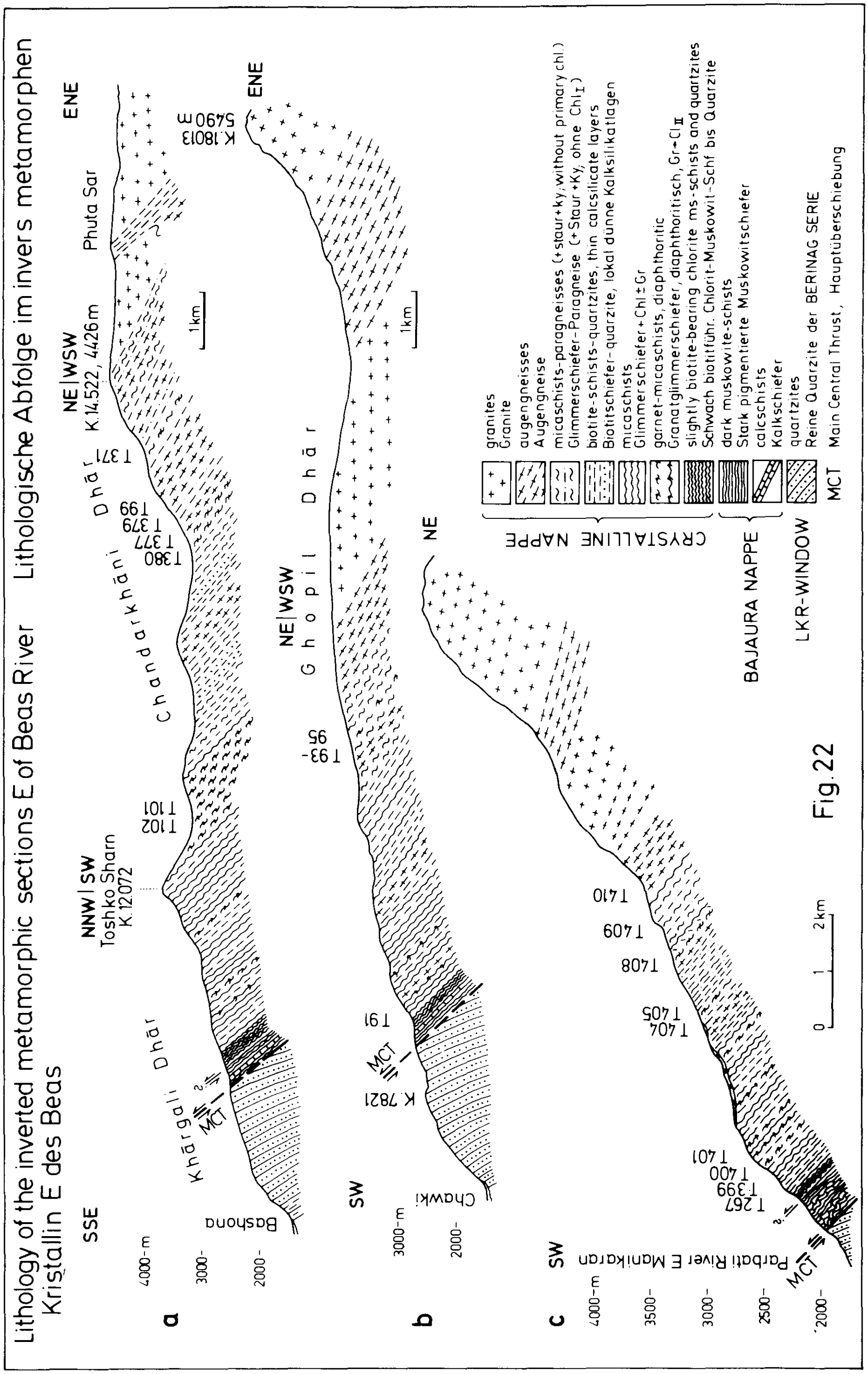
bio = biotite, Biotit; chl = chlorite, Chlorit; mus = muscovite, Muskowit; ga = garnet, Granat; st = staurolite, Staurolith; ky = kyanite, Disthen; plag = plagioclase, Plagioklas; sil = sillimanite, Sillimanit.

β) synmetamorphic „shear folding" of temperature zones without folding of the layered rock series. The isograds run incomformably to the s(s) surfaces in the crest area of this „metamorphism-fold".

Possibility α), has, in all probability, been realized in the central area of the Phojal-Kallath-giant-fold. Both cases α) and β), are possible as far as the Parbati Valley is concerned. As has been discussed above, the continuation of the giant fold eastwards to southeastwards as a structure cannot be directly observed and is thus doubtful. In the east, the metapelites, as part of a giant fold, would represent (at least partially) the fore limb of this structure with an inverted lithostratigraphic sequence as well as inverted metamorphic zoning at the bottom of the granite plate. From the point of view of material kinetics, however, it is probable that the deformation conduct within the incompetent metapelite series in the Parbati Valley between the stiff Berinag quartzites at the bottom and the massive granite plate at the top is different than that of the uniform, more or less homogeneous and more easily foldable schist series in the Kulu Valley. All in all, there are more arguments for not considering the inverse metamorphic sections in the east – since the beginning of alpidic metamorphism – as inverted lithostratigraphic units (case β), see above), from which, with a rising homogeneity of material towards the top and the bottom and thus also a rising tendency to folding, laterally (towards the west), within a short horizontal distance, a giant fold-structure is developed. A smaller fold-structure (100 m-size) was observed on the west flank of the Malāna Valley, in a position adequate to that of the axial surface of the giant structure. This small fold may be considered the easternmost visible part of the giant fold.

This mechanism for the formation of inverted metamorphic zones by means of synmetamorphic shear-folding of temperature zones with upright bedding (stratigraphy) is only effective if the temperature zones cut the s(s)-surfaces obliquely during deformation and transport of the warmed crystalline, and, in this case, rise from south to north. It should be mentioned here that the forming of inverted metamorphic zoning is not possible without internal deformation of the transported rock pile (cf. LE FORT 1975).

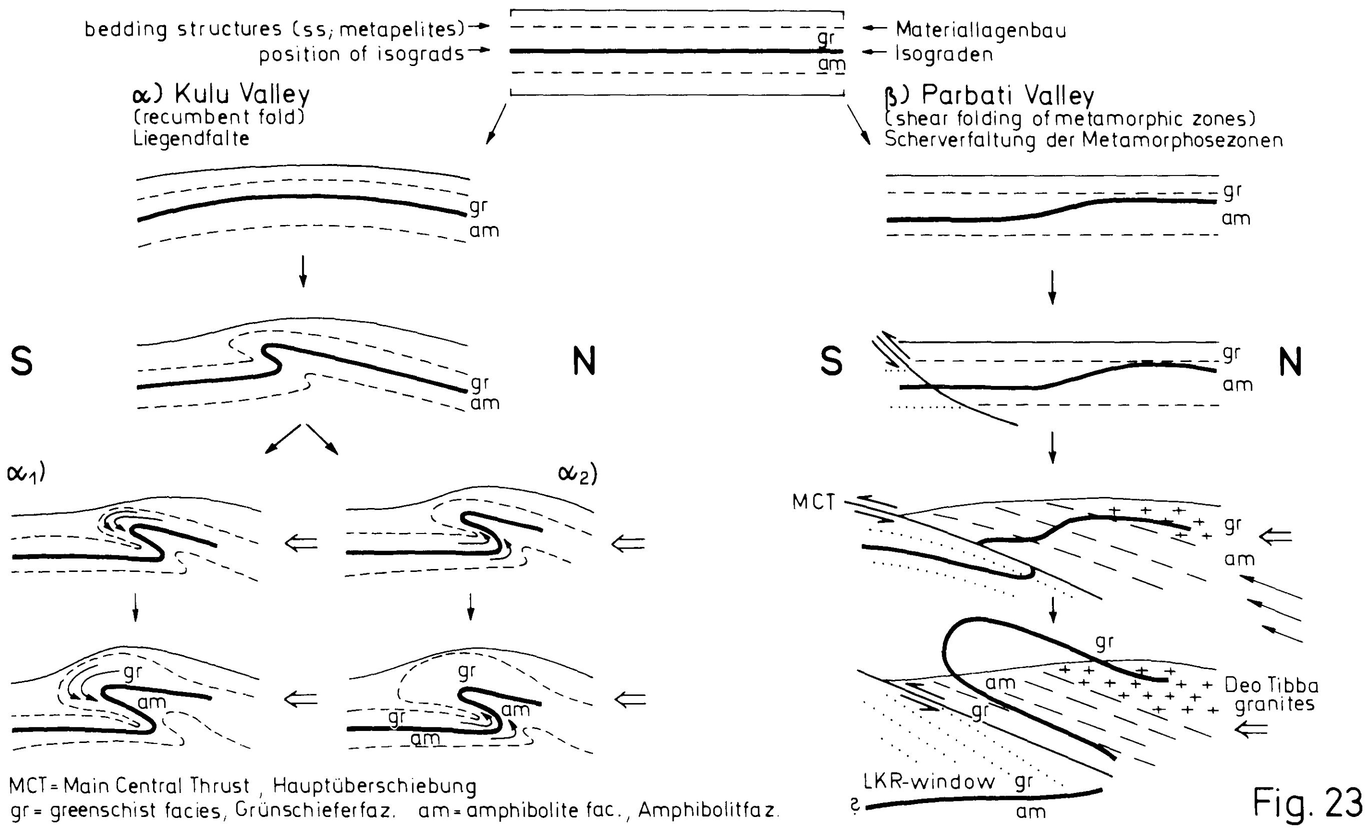
The formation of reversed metamorphic zoning (a phenomenon widespread in the Himalayas; RAY 1947; GANSSER 1964; NAHA & RAY 1970; FRANK 1972; LE FORT 1975) necessitates a very high speed of transportation of the higher-temperated part over the cooler underground, as a temperature compensation towards the top occurs comparatively rapidly. It is to be expected, with a rapidly-occuring cooling during this process, that syngenetic minerals from such metamorphics show only slight differences in their cooling-age values. This has been partially confirmed for the upper Kulu Valley (FRANK 1973/74). The rapid southward transport of the Crystalline Nappe is explained by plate tectonic movements. The extraordinarily rapid northward drift of the Indian subcontinent is well documented by paleomagnetic measurements and radiometric dating of the paleogene Deccan traps (RAMA 1964; WELLMANN & McELHINNEY 1970); the rate of drift has been calculated to be in the range of 10 cm per y. (WENSINK 1973, p.41; MOLNAR et al. 1977; see also KLOOTWIJK 1976). The reason for the strong reduction of the rate of drift which occured about 40 m.y. ago is considered to be the collision of India and Asia (MOLNAR et al. 1977). The gigantic décollements of the Crystalline Nappe occured only after presumably longer-lasting compression



Lithology of the inverted metamorphic sections E of Beas River   Lithologische Abfolge im invers metamorphen Kristallin E des Beas

Fig. 22

Evolution of the inverted metamorphic sections, Zur Entstehung inverser Metamorph.



MCT = Main Central Thrust, Hauptüberschiebung
gr = greenschist facies, Grünschieferfaz. am = amphibolite fac., Amphibolitfaz.

Fig. 23

of both plates or after the beginning subduction of the southern one and may be placed temporally in the lower Miocene (see mica ages, FRANK 1973/74).

The formation of real temperature inversions (JAEGER 1957) could be explained by the rapid movement of the Crystalline Nappe towards the south (at least 5 cm/y.). Thus the inverse metamorphic section of the Kulu Valley and east of it would be the product of a southward-trending temperature front, undercooled from the south.

7. PALEOGEOGRAPHY AND DEVELOPMENT HISTORY

The arguments presented in Chapter 3 show that the rocks of the Crystalline Nappe as well as those of the LKR-Window must be of Precambrian, in the Crystalline Nappe at best of early Paleozoic, sedimentation age.

Based upon lithological, structural and metamorphic conditions, the following history of development may be set up for the studied region (Fig. 24):

The metamorphics of the Crystalline Nappe were formed in an area further north than their present-day position. During the Proterozoic, thick, clayey-sandy sediments were poured into a wide ocean trough (basin). Roughly at the same time, the non-fossiliferous quartzite-schist-carbonate series of today's northern Lesser Himalayas (Chail-Shali) were formed further south, in a shallow-water area close to the Indian plate (see SRIKANTIA & BHARGAVA 1974 b). The paleogeographic relationship between the two large units, the Crystalline Nappe and the Lesser Himalayas, especially their extension towards the north and the south, remains unknown up to the time of alpine orogenesis.

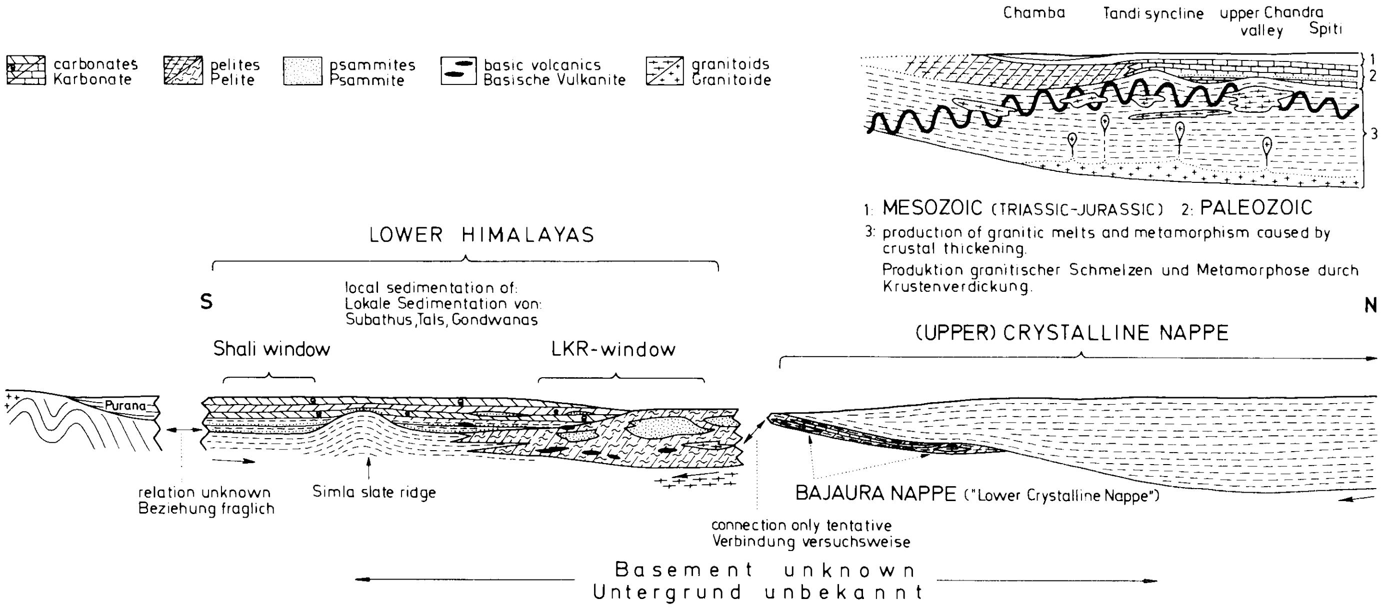
Sedimentation in the north (present-day Crystalline Nappe) lasted, at least in the southern margin of this zone, from the Proterozoic through to the upper Mesozoic : the southern shelf sediments of the Tethys (Tibetan) zone follow uncomformably over the metamorphics of the northern Crystalline Nappe. The Tandi Syncline in the Chandra Valley may be considered as a southern offset of the these shelf sediments (with stratigraphical interruptions).

The intrusion of the granites (Deo Tibba) of the Crystalline Nappe occured in early paleozoic times (see radiometric age determinations; FRANK 1973/74). These intrusion caused local bulging in the sedimentation area and partial interruption of sedimentation (Spiti). In the lower parts of the pile of the precambrian sediments one may assume (a more static) metamorphism.

The paleogeographic relationship of the thin but regionally widespread Bajaura Nappe to the two large tectonic units is not clear. Lithological similarities between the microcline-augen-gneiss in the Bajaura Nappe and the metavolcanic rocks in the Berinags of the LKR-Window permit the assumption for the Bajaura Nappe of a formation area close to that one of the sediments of the Lesser Himalayas – perhaps as a northern marginal zone of the Berinag (Shali) sedimentation area.

In mesozoic to early tertiary times, the Indian subcontinent moved northwards with an unusually high rate of drift. Following its collision with the Asiatic continent and the presumably connected or subsequent thickening of the crust, metamorphism was initiated in the rock mass which forms today's Crystalline Nappe. The sediments of the southern depositional area (= today's Lesser Himalayas) were folded, and the partly strongly heated zone (crystalline) was thrust over the cool

Fig. 24: Schematic paleogeographic section of Kulu-Lahul area
Paläogeographischer Schnitt durch das Gebiet Kulu-Lahul



southern foreland in the form of a nappe, during which process the Bajaura Nappe presumably served as a basal „glide slice".

Due to rapid southward transport with simultaneous internal deformation of the crystalline mass, the temperature zones within this unit were partially overturned towards the south, thus forming inverse metamorphic series with a freshly-preserved, synkinematically crystallized mineral content. Pre-alpidic structures and mineral parageneses which were then possibly present were completely eliminated or overprinted by alpidic events.

Thanks. For the successful completion of this study, I would first like to thank my teacher and helper, Doz. Dr. W. FRANK. Furthermore, my thanks go to all members of the 1972 expedition group, especially to Prof. Dr. F. PURTSCHELLER and to Dr. G. HOINKES, for their friendly aid during work at the EMP, as well as to Prof. Dr. W. RICHTER for the preparation of 19 chemical analyses. For the financing of the field work, I wish to thank, first of all, the „Fonds zur Förderung der wissenschaftlichen Forschung in Österreich" (project Nr. 1509 and 2158), further, the „Österreichischer Alpenverein", the province of Tyrol, the city of Innsbruck and the „Zentralsparkasse der Gemeinde Wien". Thanks are also due to Prof. A.G.JHINGRAN (New Delhi) for his valuable organizatorial aid in taking samples out of India. My special thanks go to my two carriers KASHMIRI SINGH of Ladakh and NAWANG CHHRING SHERPA of Khumbu, who both became simple, good friends to me during often difficult field conditions and who, during this period, catered to my personal needs and to the transport of the samples.

The drawings were made by L.LEITNER; to H.M.LIEBERMAN I am very grateful for translating the manuscript in English.

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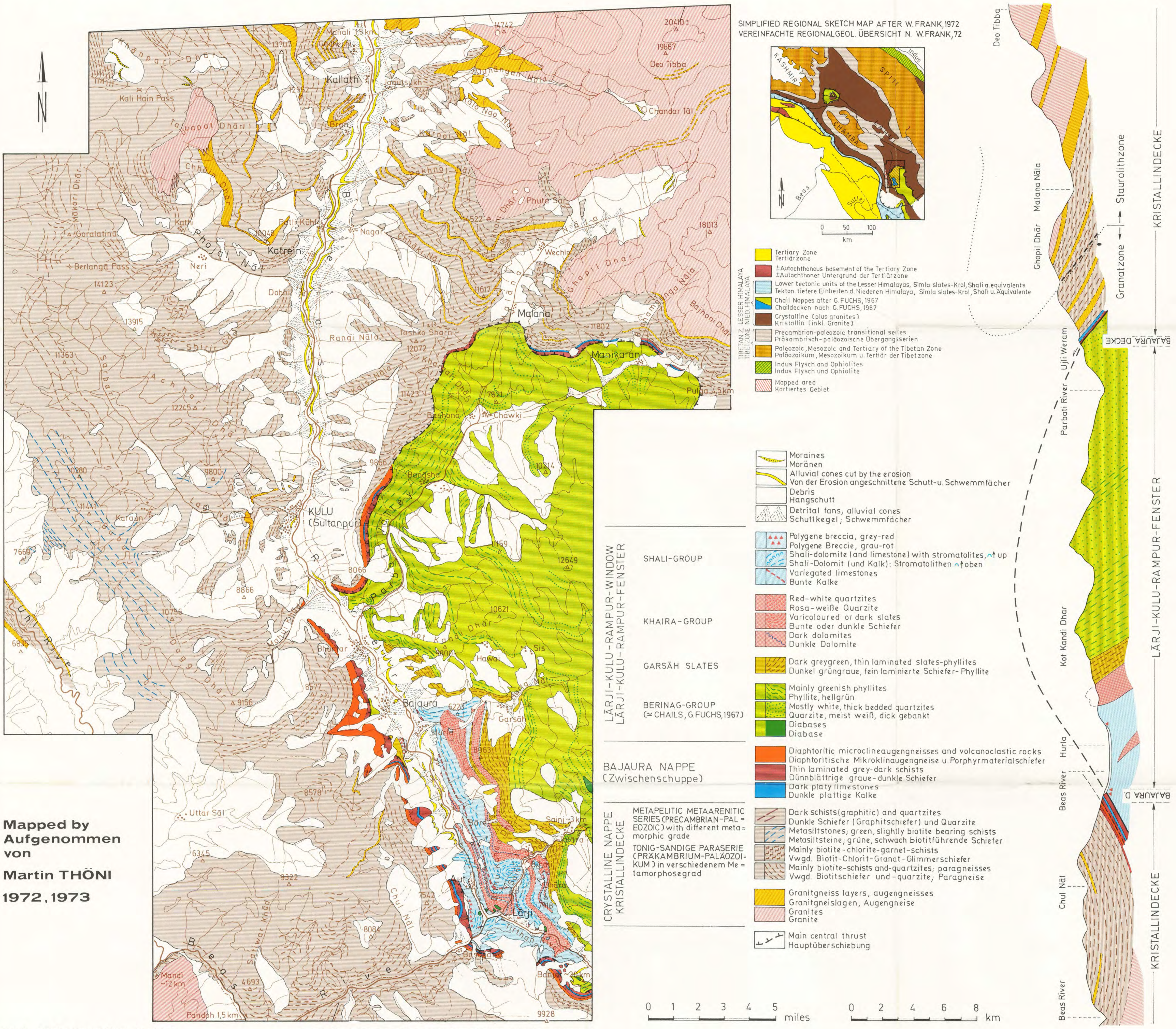
Corrections of the map (plate 13):

Dark schists (graphitic) and quartzites occur NW of Kali Hain Pass, W of Mākori Dhār, in the Lag Nāl near Karaun and W of Bubu Jot at the height of K. 7669. In these places the brown interrupted lines (and the blue ones respectively: W Bubu Jot) have to be replaced by black ones (see signatures).

GEOLOGICAL MAP OF KULU VALLEY BETWEEN MANALI AND PANDOH, HIMACHAL PRADESH, NW HIMALAYA, INDIA
GEOLOGISCHE KARTE DES KULU - TALES ZWISCHEN MANALI UND PANDOH, HIMACHAL PRADESH, NW HIMALAYA, INDIEN

PLATE 13
TAFEL



Mitt. Ges. Geol-Bergbaustud. Österr. Bd. 24, 1977

Druck: Institut für Kartographie der Technischen Universität Wien 1040 Wien, Karlsgasse 11