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Geology of the Neelum valley, district Muzaffarabad, Azad Kashmir, Pakistan

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ABSTRACT: *The central and north-western parts of Neelum valley have been mapped, proposing a new lithostratigraphic division for the region. The area comprises two main tectonic units: the Lesser Himalayan Crystalline Unit (LHC) and the Higher Himalayan Crystalline (HHC), separated from each other by the Main Central Thrust (MCT). The two units are characterized by a similar stratigraphy and share a common low grade metamorphic assemblage. They, however, differ in the intensity of the imprints of the Himalayan metamorphism. The lithostratigraphic units comprise, from base to the top, Naril Group (Precambrian basement), the Kundalshahi Group (pre-Himalayan cover) and Surgun Group (an Upper Paleozoic to Mesozoic Himalayan metasedimentary cover comprising paragneisses, mica schists, marbles, amphibolites, calc-schists and impure quartzite). This lithostratigraphic sequence is intruded by a megacrystic granite, similar to that of Mansehra (Early Cambrian) and meta-doleritic dykes, correlated with the Permo-Carboniferous Panjal Trap volcanics. Geochemistry reveals an igneous granitic calc-alkaline origin for the Naril granulitic gneiss, whereas, the sediments of Kundalshahi Group are characterized by a high SiO_2 and highly variable trace element contents except REE. In the Surgun Group two types of marbles have been distinguished on the basis of high CaO and low MgO. The amphibolites in the Surgun Group as well as of Himalayan cover share the same igneous protolith and are basaltic in composition. Geothermo-barometric studies indicate polyphase metamorphic evolution for the lithological units of the Neelum valley in the Tertiary Himalayan event. The P-T-t path suggests a prograde metamorphic evolution up to Upper Cretaceous-Eocene times, followed by a retrograde path, essentially of decompressive type. The final part of the path being accompanied by a decrease in temperature. The LHC tectonic unit and a southern portion of the HHC unit followed a different P-T trajectory, under greenschist-facies conditions. The $^{40}Ar/^{39}Ar$ determinations on muscovite and biotite from these low grade rocks yield middle Oligocene cooling ages. Four phases of deformation have been distinguished. Isoclinal overturned to recumbent folds represent the D1 and D2 phases; contemporaneous with the regional Himalayan metamorphism, during upper Cretaceous to Miocene. The MCT developed after D2 phase of deformation generating the LHC and HHC nappes and the reversed metamorphic zonation of Neelum valley. The D3 structures comprise of open large megascopic flexural slip buckle folds trending NE-SW. The D4 deformation affects the Hazara Kashmir syntaxis.*

INTRODUCTION

The mapped area is located about 30 km NE of Muzaffarabad (Fig. 1). This area is oriented NE-SW and constitutes the northern flank of Neelum valley, between the localities of Tithwal and Kel. The upper limit is delineated by the northern crest line separating Neelum valley from Kaghan valley and Northern areas. River Neelum is the lower boundary separating the study area from the Indian held Kashmir. The study area is characterized by rugged topography and high relief where elevation ranges from 1000 m at Tithwal to over 5000 m at Chatthewala.

The lithological units of the Neelum valley were collectively termed as the Salkhala Series, Dogra Slates and Tanawal (Wadia, 1931; 1934). Ghazanfar et al. (1983) classified the rocks outcropping between Titwal and Lawat comprising of psammitic - pelitic sequence as Tanol, whereas, the pelitic- calcareous sequence found north of Lawat was included in Sharda Group instead of the Salkhala Formation. Three different granitic batholiths were identified; two southern ones were described to be Tertiary, while the northern, Kel granite was assigned a Paleozoic age.

The present investigations (Schouppe et al., 1991; 1992; 1993) encompass geological studies in a 1500 km^2 area in the Neelum valley. Owing to inaccessibility of area, vertical Spot B&W Panchromatic images were used to assist the field mapping on a scale of 1: 50,000. Photogeological interpretations of some inaccessible or snow covered areas were integrated with the field data to produce the final geological map (Fig. 1). Over 2000 structural measurements were plotted combined with petrofabric analysis. The laboratory studies include petrography of about 700 samples (Table 1) and major and trace element analyses using ICP and XRF for over 100 samples. Twenty-two $^{40}Ar/^{39}Ar$ analyses were performed on phengite white mica and biotite.

GEOLOGICAL SETTING

Tectonic sub-division

The major Himalayan tectonic units are well exposed along the relatively accessible Indus, Kaghan, Jehlum and Neelum valleys. They are the result of the collision between the Asian (N) and Indian (S) plates (Bossart et al., 1984; 1988; 1992). Along the rivers Hunza and Indus, five principal fault zones can be recognized (Fig. 2), the Northern Suture (NS), the Main Mantle Thrust (MMT) or Indus Suture (IS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) (Tahirkheli, 1979; Treloar et al., 1989b). These fault zones trend E-W, dividing the Himalayan orogenic belt in five main tectonic zones: the Asian plate (AP), the Kohistan arc (KA), the Higher Himalayan Crystalline Unit (HHC), the Lesser Himalayan Crystalline Unit (LHC) and the sub-Himalayan Unit (SH).

The E-W trend of the fault zones is disturbed locally by two tectonic semi-windows (Wadia, 1931; Calkins et al., 1975), the Nanga Parbat Syntaxis (NPS) and the Hazara-Kashmir Syntaxis (HKS) (Fig. 2). The area connecting these two syntaxes (including the project area) is still being affected by an exceptional rate of uplift, presently reaching 7 mm /year (Zeitler et al., 1989). Several of these tectonic units are encountered in an SW-NE traverse along the Neelum valley. The MBT which separates the SH from the LHC, lies near the bridge of Nauseri, 40 km NE of Muzaffarabad. Near the village Lawat, 100 km from Muzaffarabad on Neelum valley road, the MCT separates the LHC to the south from the HHC, which extends north and east to the village of Kel. These tectonic units share the same stratigraphic features, but differ in their tectono-metamorphic evolution. Metamorphic grade and ductile deformation increase from the youngest and lower most unit (i.e.,

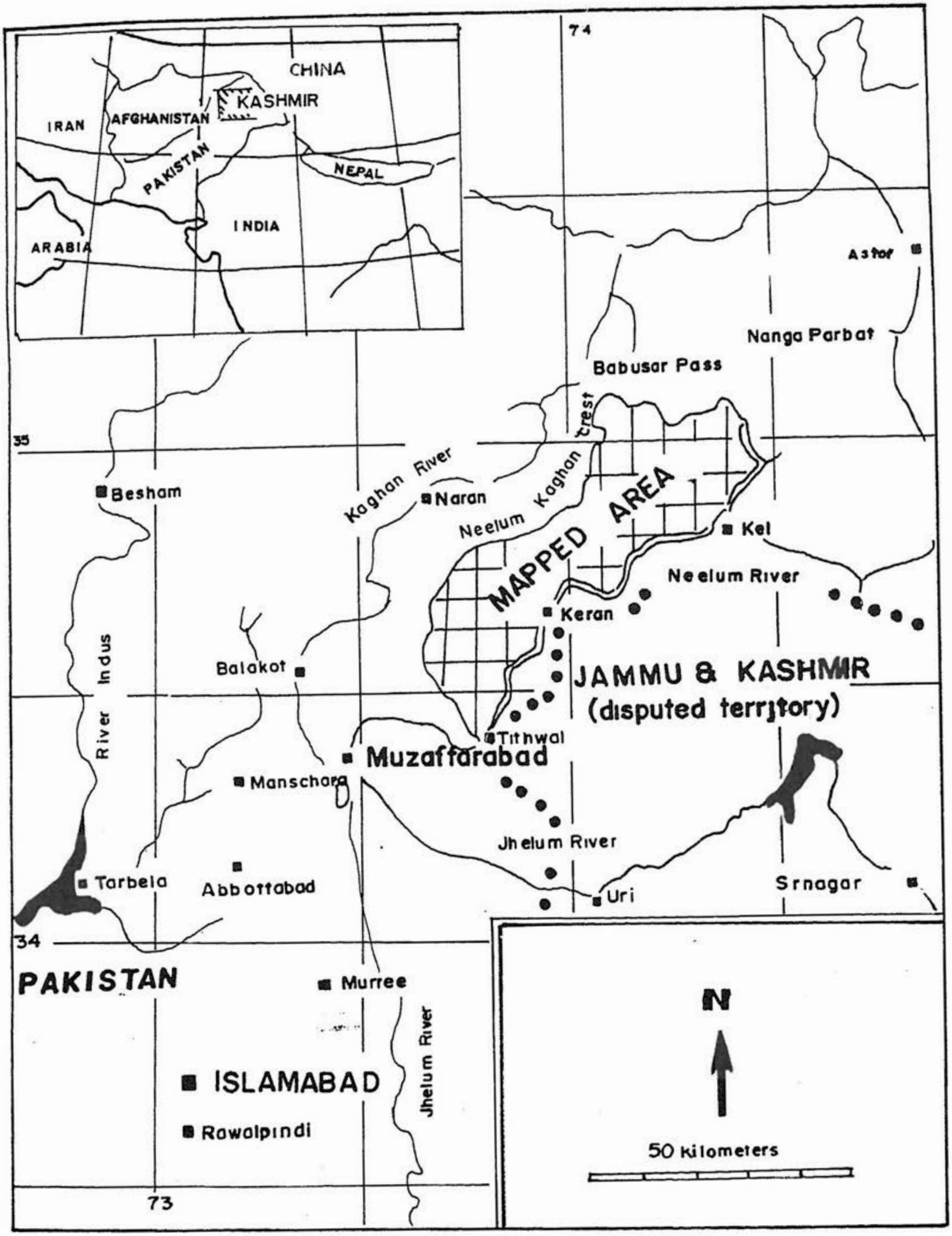

Fig. 1. Location of the mapped area. The dotted line represents the border between the Indian held Kashmir and the Azad Kashmir.

TABLE 1. PETROGRAPHY AND TEXTURAL CHARACTERISTICS OF THE VARIOUS LITHOSTRATIGRAPHIC UNITS CONSTITUTING THE UPPER NEELUM VALLEY

Metamorphic Zone	Mineral Assemblage	Textural Remarks
	KUNDALSHAHI GROUP	
Garnet Zones	garnet + biotite + white mica with accessory plagioclase + quartz ± ilmenite ± rutile ± titanite ± epidote ± carbonate ± chlorite. Amphibole is rare and forms random porphyroblasts partially replaced by biotite.	Some garnet porphyroblasts contain "S" inclusion trails of quartz and rare white mica. Two generations of garnet porphyroblasts and three phases of foliation development are noticeable.
Staurolite-Kyanite Zone	Quartz, biotite, white mica, garnet, kyanite, staurolite, plagioclase, chlorite, epidote illmenite, rutile and ore.	
Silliminite Zone	White mica (replaced by biotite), almandine, silliminite and biotite nodules.	Almandine forms elongated aggregates, parallel to the foliation and anhedral porpyroblasts in equilibrium with sillimanite and biotite. Old kyanite porphyroblasts are totally replaced by random overgrowths of fine grained prismatic sillimanite.
	MANSEHRA-TYPE GRANITE	
Garnet Zone	Relics of magmatic texture and assemblages composed of primary potash feldspar, plagioclase, quartz, biotite and muscovite. Garnet, black tourmaline, apatite, zircon and opaque are accessory minerals.	Magmatic biotite and muscovite are partially replaced by metamorphic biotite and muscovite.
Staurolite-Kyanite Zone	Relics of the magmatic minerals (potash feldspar, plagioclase, quartz, biotite and muscovite). Green muscovite, kyanite, garnet and biotite aggregates totally replace the cordierite grains.	Foliation, defined by the metamorphic white mica and biotite crystals, surrounds the magmatic minerals in a mortar texture.

Metamorphic Zone	Mineral Assemblage	Textural Remarks
Silliminite Zone	Plagioclase and muscovite are completely replaced by fine-grained prismatic sillimanite.	Mortar texture with potash feldspar as augens.
	METABASITES	
Garnet Zone	Relict magmatic mineral assemblage comprising discontinuously zoned plagioclase, clinopyroxene with corona of green amphibole and rare olivine. Primary magmatic assemblage imprinted upon by metamorphic amphibole, chlorite, biotite, plagioclase, epidote and carbonate.	The transition into amphibolites is accompanied by development of foliation.
Staurolite-Kyanit Zone	Omphacite, garnet, rutile, phengite and ilmenite in a granoblastic assemblage. The eclogitic assemblage partially replaced by clinopyroxene-plagioclase symplectite, amphibole, biotite and epidote.	
Silliminite Zone	Intergranular texture comprising ortho-, clinopyroxene and plagioclase, with relict magmatic and eclogitic assemblages locally preserved.	
	THE COVER SEQUENCE (SURGUN GROUP)	
Garnet Zone	Marbles contain carbonates (calcite dominating over dolomite) with minor quartz, white mica, tremolite and talc.	Elongated quartz grains and white mica and tremolite delineate a discontinuous foliation.
Staurolite-Kyanite Zone	**Marble:** Calcite, rare ankerite and dolomite, white mica, phlogopite and biotite, Ca- rich plagioclase, diopsid (partially replaced by tremolite), epidote, Na and Ca rich scapolite, quartz, ruby (partially replaced by green muscovite), tremolite, green-brown amphibole, chlorite,	

Metamorphic Zone	Mineral Assemblage	Textural Remarks
	garnet (grossularite), rutile and opaque minerals.	
	Pelitic rocks:	
	Garnet+ biotite+ white mica+ plagioclase + graphite + kyanite+ quartz ± staurolite ± silliminite ± amphibole ± illminite ± rutile ± titanite ± epidote ± carbonate ± chlorite. Chloritoid has been found as relic within garnet porphyroblasts (garnet 1).	
Silliminite Zone	**Marbles:** Calcite, quartz, garnet, scapolite, olivine, spinel, zoisite/clinozoisite and white mica. Spinel, garnet and olivine occur as porphyroblasts embedded in the carbonate matrix.	Olivine porphyroblasts zoned. Clinopyroxene partially transformed into aggregate of plagioclase, zoisite and tremolite. Garnet porphyroblasts including clinopyroxene and biotite.

Note: The basement gneisses of the Naril Group show a homogeneous mineral composition and are described in text.

sub-Himalayas) to the oldest and upper most unit (i.e., Higher Himalayas) (Bossart et al., 1988; 1992; Greco et al., 1989; 1993, Spencer, 1993).

Lithostratigraphy

The crystalline rocks outcropping in the mapped area are subdivided into three main lithostratigraphic units, the Precambrian Naril Group, the Precambrian Kundalshahi Group and the Upper Paleozoic to Mesozoic Surgun Group (Fig. 3). The Naril Group is considered to be the pre-Himalayan basement. The Kundalshahi Group forms the pre-Himalayan cover while the Surgun Group represents the Himalayan cover. All the above mentioned groups are intruded by meta-dolerites and amphibolites, collectively called metabasites. All the lithostratigraphic units described below occur both in the LHC and HHC and have undergone variable grade of metamorphism. Petrographic details of each of these lithostratigraphic units are give in Table 1.

The Naril Group: The granulitic gneisses of the Naril Group mainly outcrop in two separated areas north of the Richmori Fault (RF) and in the Chatthewala, Gumot and Naril areas. The gneisses are acid granulitic whitish banded rocks containing quartz, feldspar, garnet and biotite. Two kinds of garnets are encountered. The large garnets are zoned, showing a darker core and a pinkish rim, whereas, smaller (<1mm) are homogeneously pinkish. The contact between the Naril and Kundalshahi groups is sharp and is interpreted as an old unconformity folded during the strong Himalayan deformation. In the Chatthewala,

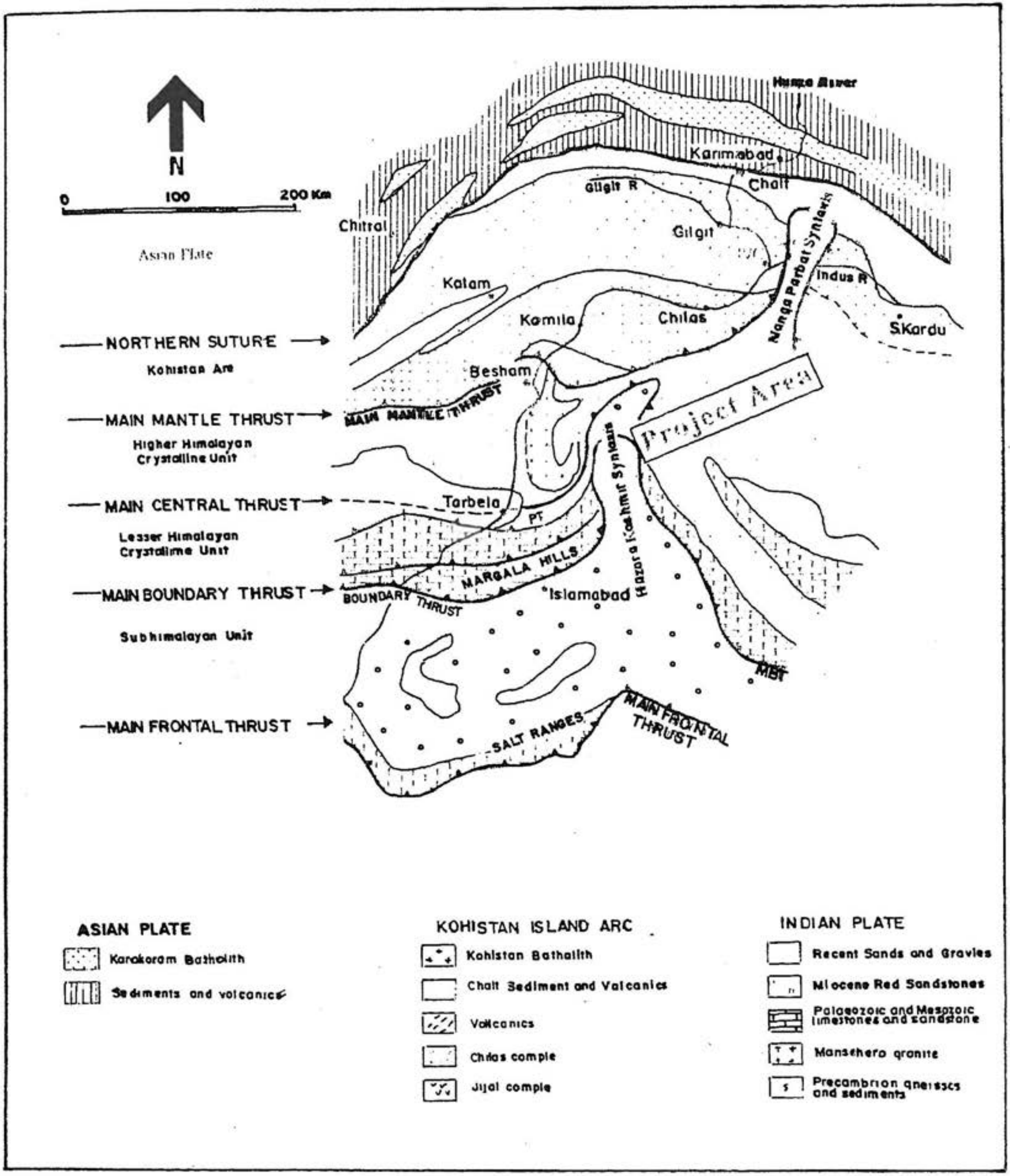

Fig. 2. Geological map of NE Pakistan showing the principal thrusts, the tectonic units and the Hazara and Nanga Parbat syntaxes.

Gumot and Naril areas, the acid granulitic gneisses are highly sheared, metamorphosed and show migmatization. Melanocratic gneisses are scarcely found.

Compositionally, the rocks consist of quartz (35%, plagioclase 10 to 25%, biotite 10 to 25%, K-feldspar 10% and garnet 0 to 10% by volume. Accessories include apatite, sillimanite, chlorite and zircon. The Naril Group has been intruded by dolerites now metamorphosed to amphibolits In certain cases the amphibolites grade into eclogites. Eighteen samples were analyzed for major and trace elements. General chemical composition of the rocks is: SiO_2, 60 to 78.55%; TiO_2, 0.12 to 0.81%; Al_2O_3, 13 to 19.92%; Fe_2O_3, 1.39 to 6.53%; MnO, 0.05 to 0.24%; MgO, 0.32 to 1.85%; CaO, 0.4 to 1.74%; Na_2O, 1.32 to 6.08%; K_2O, 3.19 to 6.35; P_2O_5, 0.05 to 0.16%. The $Fe_2O_3 + TiO_2 + CaO$- SiO_2 - Al_2O_3 diagram suggests an igneous origin of the gneisses. Similarly, higher values of Ni (9 to 23 ppm) and Cr (29 to 71 ppm) and REE suggest an igneous granitic calc-alkaline origin for the Naril granulitic gneisses. There is no age data available for these gneisses and are tentatively correlated with the 1850 My old Iskere gneiss outcropping in the Nanga Parbat area (Zeitler et al., 1989). The granulitic gneisses of the Naril Group are intruded by the Mansehra type leucogranites of Cambrian age (LeFort et al., 1980).

The Kundalshahi Group (pre-Himalayan cover): The metasediments of the Kundalshahi Group outcrop: (a) south of the MCT, (b) north of the MCT and (c) in the Chatthewala, Naril and Tarli Domel areas.

a. South of the MCT, the Kundalshahi Group is subdivided into Kuttar, Babun and Kattha units (Fig. 4). The Kuttar Unit consists of interlayering of semi-pelitic schists and meta-psammites with minor quartzite, marbles and meta-conglomerates. The weathered outcrops are typically grayish to brownish. The schists are fine-grained, sometimes phyllitic. The mineral assemblage includes biotite, white mica, quartz, garnet, chlorite and epidote. The psammites show the same grain size and mineral assemblage. Sometimes, relics of sedimentary graded bedding are observed. The planes which separate the schists from the meta-psammites have been recognized as stratification planes S0. Calcsilicate boundins are widespread in the schists as well as in the meta-psammites.

   Outcrops belonging to the Kattha and Babun units are easily distinguished in the field through their bluish (Babun Unit) and blackish (Kattha Unit) colours. The rocks consist of meta-psammites (Babun and Kattha units) and fine grained quartzites (Kattha Unit). The quartzites have preserved numerous sedimentary structures such as ripple marks, graded bedding, crossbedding. Centimetric marble layers and scattered calcsilicate boudins are rarely found. Basic dykes crosscut the stratification throughout the three units. Sometimes, the primary doleritic texture and the initial-magmatic minerals are preserved. The mineral assemblage comprises pyroxene, plagioclase and, rarely, the olivine. Most of the time, the basic dykes are converted to foliated amphibolite. In such rocks, amphibole, plagioclase, epidote and chlorite have totally replaced the magmatic minerals.

b. The Kundalshahi metasedimentary sequence outcropping north of the MCT shows the same lithostratigraphic features as described south of MCT. Only the grade of metamorphism is higher. The common metamorphic assemblage includes garnet, biotite, muscovite, kyanite, and locally, staurolite. North of the Richmori fault, both the Kuttar Unit and the Babun Unit have been recognized. The contact between these units have been found to be sharp and parallel to S0 fabric.

c. In the Chatthewala, Naril and Tarli Domel areas the Kundalshahi group shows higher grades of metamorphism and ductile deformation than in the area mentioned above. The Babun and Kattha units are not outcropping. Only the alternating schists and

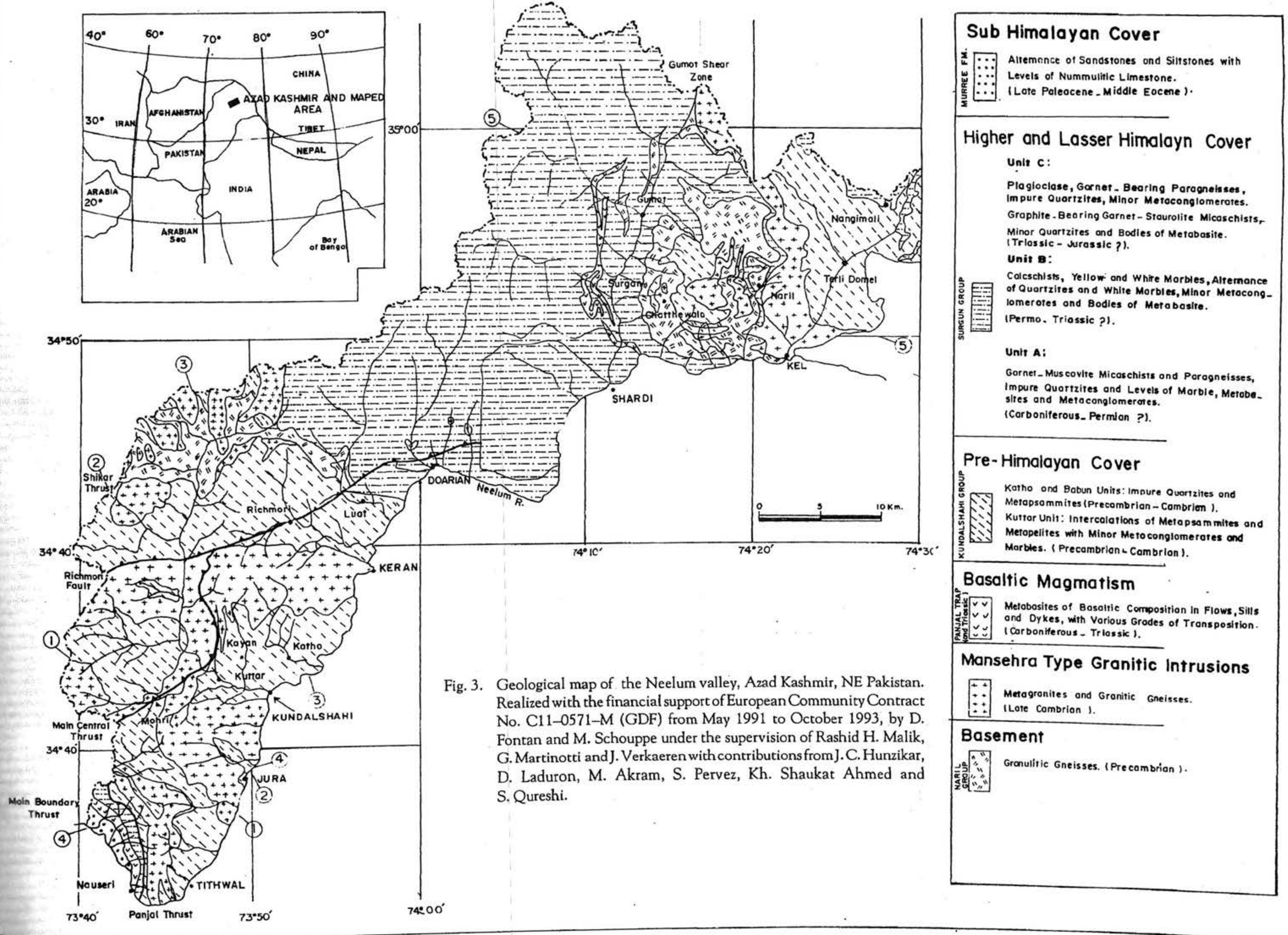

Fig. 3. Geological map of the Neelum valley, Azad Kashmir, NE Pakistan. Realized with the financial support of European Community Contract No. C11–0571–M (GDF) from May 1991 to October 1993, by D. Fontan and M. Schouppe under the supervision of Rashid H. Malik, G. Martinotti and J. Verkaeren with contributions from J. C. Hunzikar, D. Laduron, M. Akram, S. Pervez, Kh. Shaukat Ahmed and S. Qureshi.

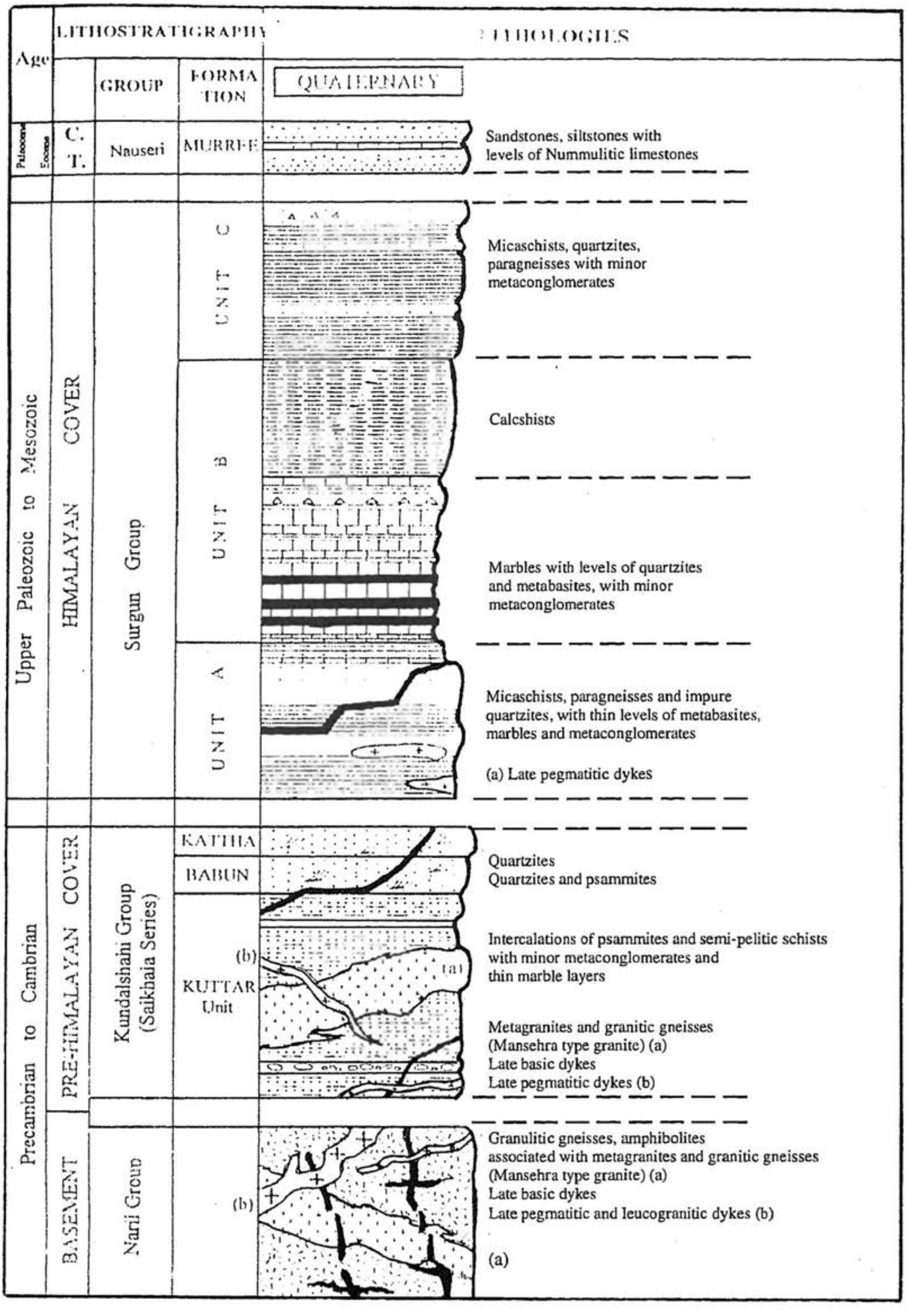

Fig. 4. Lithostratigraphic column of the Neelum valley.

meta-psammites of the Kuttar Unit have been recognized. In comparison with the areas (a) and (b), the Kuttar metasediments show paragenesis typical for the upper amphibolitic facies of metamorphism, i.e. garnet, biotite, muscovite, kyanite and (Chatthewala area) sillimanite. Panjal Trap related dykes (Khan & Ashraf, 1974; Nakazawa et al., 1975; Papritz & Rey, 1989) crosscut the Kuttar metasediments. They generally show amphibolitic assemblages (green amphibole, garnet, epidote, plagioclase, biotite) and are foliated. In a few cases only relics of garnet-omphacite eclogitic assemblages, partially replaced by non oriented millimetric hornblende and biotite have been discovered. These eclogitic assemblages are generally preserved in the core of foliated garnet-bearing amphibolites. Moreover, basaltic textures similar to those observed in some metabasites south of MCT are sometimes preserved inside the core of the eclogitic/ amphibolitic dykes.

Twenty-two samples were analyzed for major and trace elements. Chemically, the sediments of the Kundalshahi Group are characterized by a high SiO_2 content (61-78%). The results for the other major elements are as follows:-

> Fe_2O_3 (3.1-4.3 wt.%), Al_2O_3 (10.3-17.6 wt.%), Na_2O (0.0-4.1 wt.%), K_2O (1-4.3 wt.%), MgO (0.29-2.11 wt.%), MnO (0.01-0.26 wt.%), TiO_2 (0.34-1.36 wt.%) and P_2O_5 (0.04-0.20 wt.%). The trace elements contents are highly variable, except for the rare-earth elements (REE). The REE spectra are very similar to that of the NASC (North American Shale Composite) and especially to that of the Post Archean Shales, except for the negative Eu anomaly. The use of different discriminating diagrams confirms that the metamorphosed Kundalshahi sedimentary sequence is made up of a mixture (alternation) of sandy shales and more or less shaly arenites, probably deposited in a sedimentary environment of distal turbidities and/or contourites. These sediments originated from the erosion of a basement composed of acid and intermediate igneous rocks, probably the Naril Group, and from a quartz-rich sedimentary cover.

The Kundalshahi Group may be correlated with the Precambrian Salkhala Series and with the Hazara Formation defined on the eastern side of the Hazara Kashmir Syntaxis.

The Mansehra type leucogranite: The Mansehra type leucogranite outcrops in the studied area form sheet-like kilometric-scale bodies isoclinally folded together with the Naril and Kundalshahi groups. Generally, the core of the sheet is massive or less deformed than the peripheral zone where it rather appears as a luecocratic orthogneiss. Its chemical and mineral compositions range from granite to granodiorite. The typical mineral assemblage includes quartz, plagioclase, potash feldspar, muscovite, biotite and accessory garnet and tourmaline. Metasedimentary xenoliths of variable size (upto several tens of meters) are frequent. The leucogranite of the Neelum valley can be correlated with the 516 My old Mansehra granite of the western side of the HKS and with the 400-500 My old Shengus Gneiss of the Nanga Parbat area (LeFort et al., 1980; Zeitler et al., 1989).

The Surgun Group: The Surgun Group represents the Himalayan cover which unconformably overlies the pre-Himalayan Naril and Kundalshahi groups. In the Neelum valley, the Surgun Group outcrops in three separated areas including (a) the western part of the mapped area near Nauseri, (b) between the villages of Luat and Shardi and north of the Dorian village and

(c) the eastern part of the mapped area along the Naril valley and near the village of Nangimali.

The geology of the Nauseri area is complicated by the imbrication of several tectonic slices along the Panjal Thrust and minor related thrusts. The rocks exposed between the MBT and the Panjal Thrust can be correlated with the Surgun Group observed in the two other areas (b) and (c). It is a succession of clastic rocks [pyrite-bearing graphitic phyllites, sericite-chlorite-bearing schists and rare metaconglomerates, volcanic rocks (lava flows and tuffaceous layers identified as Panjal Trap volcanic) and carbonatic rocks (white-grey lower Triassic to Middle Jurassic fossiliferous dolomitic marbles, quartzites and schists)].

The area north of Doarian, the Naril valley and the Nangimali area represent a very large zone covering about 40% of the mapped area (800 km^2). The Surgun Group in these areas is subdivided into three units, A, B and C.

Unit A (siliceous) consists of paragneisses, garnet-muscovite-mica schists and impure quartzites associated with minor marbles, meta-conglomerates and amphibolitic dykes. The mica schists are particularly rich in muscovite flakes which define the principal schistosity. Graded bedding is still preserved in some quartzitic layers. The thickness of Unit A is highly variable. Sometimes this unit is completely absent.

Unit B comprises, from the bottom to the top, an alternation of marbles, brownish calcschists and quartzites grading to whitish marbles occasionally ruby-bearing, and calcschists. Permo-Carboniferous doleritic/basaltic dykes, sills and flows are highly concentrated at the base of Unit B and associated with the marbles and the calcschists. The coarse-grained calcitic matrix includes platy silicates such as muscovite, phlogopite and biotite, opaque minerals such as graphite, magnetite, pyrite and pyrrhotite, and scattered silicates or oxides such as tremolite, amphibole, plagioclase, garnet, diopside, olivine, spinel or ruby (Pluger, 1995).

The calcschists are lepidoblastic. Muscovite and biotite layers occur alternating with quartzo-feldspathic layers. The metabasites appear as foliated garnet-epidote amphibolites, showing sometimes relics of eclogitic assemblages in the core of the basic bodies.

Unit C (pelitic) is a thick sequence of garnet-mica schists grading into quartzites, paragneisses and minor metaconglomerates towards the top. Porphyroblasts of kyanite, staurolite, biotite and garnet cross the principal foliation formed by an older generation of muscovite and biotite.

The lithological characteristics of the Unit A are similar to those of the Tanol or Tanawal Formation. The presence of (Panjal Trap related) basaltic/doleritic dykes, sills and flows at the base of Unit B points out its Permo-Carboniferous age. Rocks belonging to the upper parts of units B and C are considered to be Triassic on the basis of regional correlation with similar lithologies from the Kaghan valley (Spencer, 1993).

Twenty three samples were analyzed for major and trace elements from the Surgun Group. The geochemistry of the detritic rocks from the units A and C indicate a passive continental margin environment of deposition.

Geochemically, two kinds of marbles have been distinguished in Unit B. The first one comprises marbles characterized by high percentages of CaO (46-53 wt.%) and very low percentage of MgO (1-1.5 wt.%). They are typically white and ruby-bearing. The second group of marbles includes dolomitic yellow marbles showing much higher percentages of MgO (upto 19 wt.%) and a lower percentage of CaO. These marbles are devoid of ruby mineralization.

METAMORPHIC EVOLUTION

Rocks forming the Naril Group, the Kundalshahi Group and Surgun Group were deformed and metamorphosed during the Tertiary Himalayan events. The various metamorphic assemblages found in the HHC and LHC tectonic units express the different P-T-t paths followed during this metamorphic history. The mineral equilibria observed in the mapped area provide many criteria indicating the physical conditions at the time of their formation. Reactions involving several mineral phases (petrogenetic grids), exchange equilibria between two phases (e.g, garnet and biotite), or variations within the same mineral group, such as the amphiboles, have been used for this purpose (Essene, 1989; Raase, 1974).

To link P-T evolution with time, a geochronological study has been based on twenty-two $^{40}Ar/^{39}Ar$ analyses. Petrological and geochronological data have been integrated and compared with those proposed by other authors in adjacent areas (Baig & Lawrence, 1987; Maluski & Matte , 1984; Treloar et al., 1989a, b), in an attempt to determine the metamorphic evolution of the Neelum valley rocks (Fig. 5).

The first metamorphic event (Stage I) is marked by the occurrence of chloritoid, quartz and white mica-bearing assemblages preserved as trails in the core of zoned garnets in the mica-schists of the Surgun Group (Unit C). Available data obtained in similar units in the Kaghan valley (Spencer, 1993; Greco & Spencer, 1993) suggest low-grade conditions with a maximum temperature of green schist/ blue schist conditions.

The second metamorphic event (Stage II) is characterized by P-T conditions of eclogite facies in the medium-grade HHC. The most extreme eclogitic conditions have been estimated on the basis of the garnet-clinopyroxene Mg-Fe exchange (as "thermometer") and on the jadeite content of omphacite (as "barometer"). These data indicate a temperature of 600±50°C and pressures range of 13-14 kb. Such P-T estimates are in accordance with those proposed by other authors for the eclogites in the adjacent Kaghan valley (Pognante & Spencer, 1991; Villa et al., 1992) (Fig. 1).

The third metamorphic event (Stage III), developed under conditions of decompression associated with a decrease of temperature, separable into two steps (IIIa and IIIb; Fig. 5). The first P-type retrograde path (IIIa) has been evaluated using the symplectite intergrowth development after omphacite. Diopside-plagioclase "thermometer" indicate temperatures around 600°C. The albite-jadeite-quartz "barometer" furnishes pressures ranging from 8 to 10 kb. The second step P-T conditions (IIIb) may be evaluated using Fe-Mg distribution in biotite-garnet assemblage in the pelitic rocks for temperature determination and the associated garnet-kyanite-plagioclase-quartz for pressure determination in the same rocks. The data compiled indicate temperatures ranging from 450 to 550°C and pressures ranging from 3.5 to 4.5 kb. The $^{40}Ar/^{39}Ar$ determinations on muscovite and biotite from medium grade rocks yield upper Oligocene to Lower Miocene cooling ages.

All these data (cf. Fig. 5) suggest a prograde metamorphic evolution up to Upper Cretaceous-Eocene times, when the most severe metamorphic conditions were prevalent. This was followed by a retrograde path which is essentially of decompressive type; the final part of the path being accompanied by a decrease in temperature.

The calculated rate of uplift for the period between the upper Cretaceous and the lower Miocene is of the order of 1 millimeter per year, a value which is in agreement with the general evolution of the Himalayan chain (Zeitler et al.,

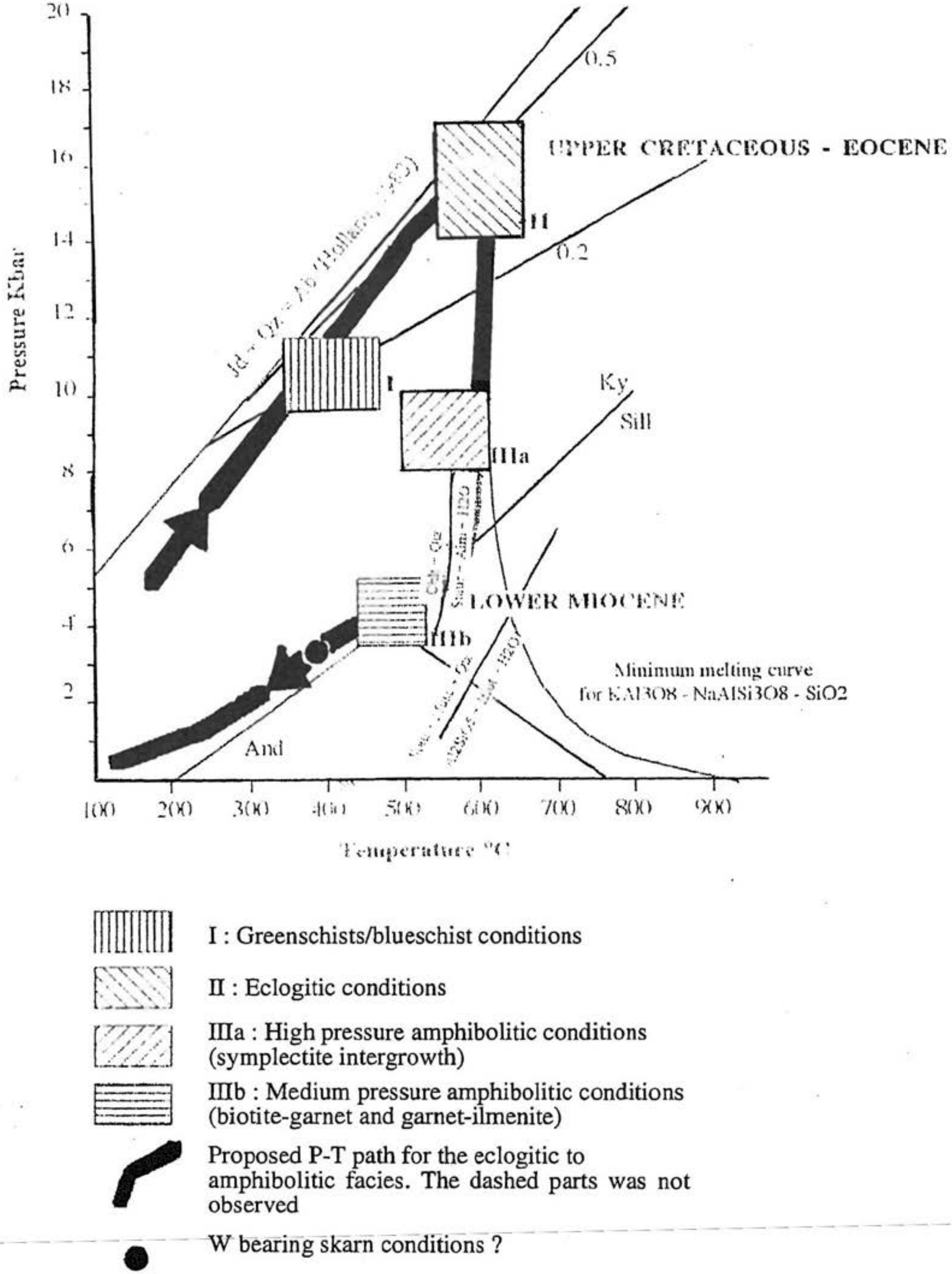

Fig. 5. Pressure-Temperature-Time path of the medium-grade metamorphic rocks.

1989). The LHC tectonic unit and a southern portion of the HHC unit followed a different P-T trajectory, under green schist conditions (low-grade). The $^{40}Ar/^{39}Ar$ determinations on muscovite and biotite from these low grade rocks yield middle Oligocene cooling ages.

STRUCTURAL GEOLOGY

Four principal phases D1, D2, D3, and D4 have been distinguished in the study area. All are Himalayan in age since they have affected both the Himalayan cover and the Precambrian basement.

In the HHC, the D1 and D2a structures (Fig. 6) mainly consist of isoclinal overturned to recumbent folds and show 3 fold- type interference pattern. They are characterized by a wavelength of about 2 km and by a composite foliation S1-2a. The foliation S1 is locally preserved in D2a isoclinal hinge zones or as an internal foliation inside helicitic garnets I. The folds are approximately coaxial everywhere except in the northern part of the HHC. North of the Shardi (Fig. 6), the Chatthewala dome is interpreted as a megascopic noncylindrical fold. The outcrop pattern of such non-cylindrical megascopic fold is analogous to a multi-kilometric dome or basin pattern that has been flattened in the S1 axial-plane and stretched parallel to a N-S direction (Fig. 7a). The result on the map (Fig. 6) is a 180° rotation of the F1 axis along the N-S trend which corresponds to the transport direction of the main tectonic nappes. In some amphibolites and orthogneisses, a mineral extension lineation L1-2 is locally observed parallel to the N-S tectonic transport direction. In the HHC, rocks did not deform during the D1-D2a phases in as ductile manner as the HHC rocks. This explains the absence of non-cylindrical folds; the D1-D2a folds are isoclinal and coaxial (Fig. 7a).

The D2b phase of deformation mainly consists of the syn-metamorphic development of the MCT, generating the LHC and HHC nappes. The shear regime also produced later D2b folds simply undulating the previous structures. In some places, the D2b folds simply undulate the previous structures. In other places, tight D2b folds have developed an axial plane crenulation cleavage S2b (Fig. 7c). D2a and D2b folds show most frequently interference fold pattern of type 3 (coaxial).

The D3 structures show a very different trend and seriously complicate the megascopic geometry of the rocks of Neelum valley. They comprise open large megascopic flexural-slip buckle folds (Fig. 6), trending NE-SW with a wavelength of about 6.5 km. The F3 and F1-F2a axes are approximately perpendicular. The fold interference pattern is an intermediate dome-basin/ arrowhead structure of type 1-2 (Fig. 7d). A set of (D3 ?) multi-kilometric reverse to oblique slip faults dislocates the outcrops of the Neelum valley. Fault breccia has been encountered close to these steeply dipping fault planes.

A D4 doming affects the HKS whose eastern flank crosses the Neelum valley along the MBT through Nauseri (Fig. 3). Eastward, the uplift of the previous D2-D3 domes of Ganji and Shikar and the large NNW-SSE oriented synform ("basin") of Doarian (Fig. 6) are interpreted as other D4 structures. In Neelum valley, these structures, with wavelengths of > 15 km, govern the geographical distribution of the meta-sedimentary and meta-igneous units of the Himalayan (Tethyan) cover and the Precambrian basement.

Other late, mesoscopic structures such as kinks, chevron folds, slightly inclined shear planes and conjugate, steeply inclined reverse fault sets have affected the less ductile LHC. All these

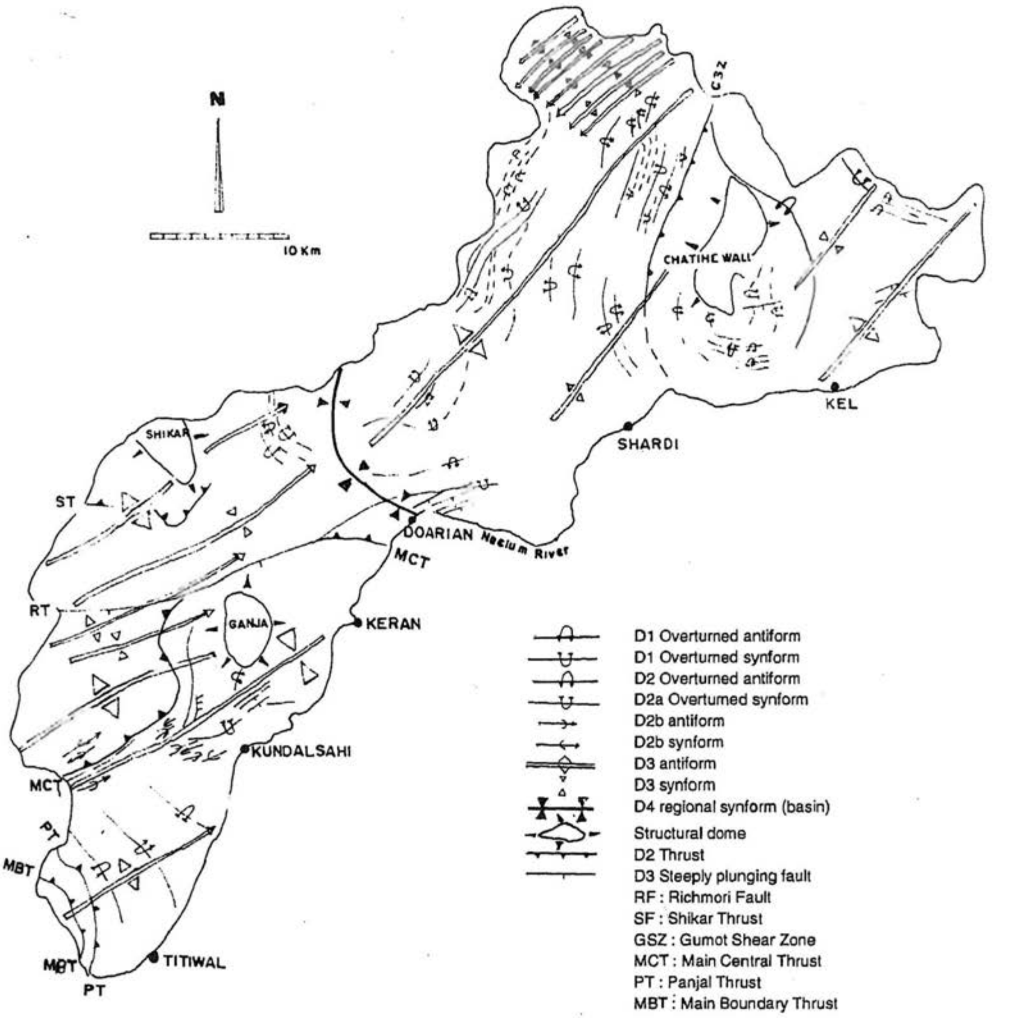

Fig. 6. Map showing the faults and the main mesoscopic and megascopic folds in Neelum valley.

structures are compatible with a late relaxation of the LHC.

TECTONIC EVOLUTION

The deformation history of the Neelum valley rocks is strongly related to the plate tectonic model describing the progressive convergence of the Indian and Asian plates, and with the described metamorphic evolution (Patriatt & Achache, 1984; Powell, 1979; Searle, 1986; Windley, 1983) .

In Pakistan, the first manifestation of the N-S convergence between the two plates was the southward to south-eastward overthrusting (more than 150 km) of the Kohistan island arc over the northern margin of the Indian continent along

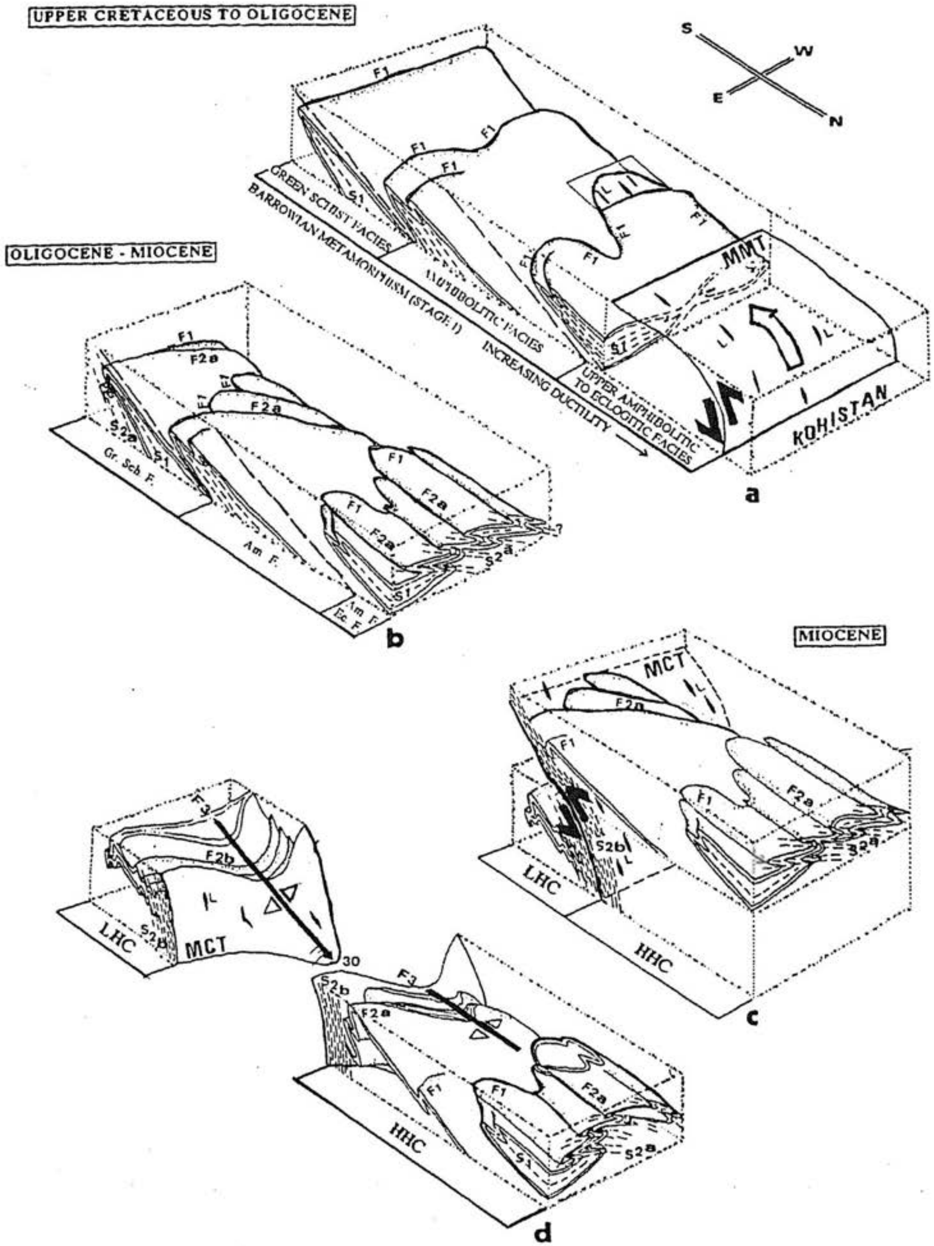

Fig. 7. Kinematic evolution of the Himalayan deformation in Neelum valley.

a. D1 phase of deformation: development of D1 cylindrical isoclinal folds in the low-grade area and D1 non cylindrical sheet like folds in the high-grade area close to the MMT.

   L = extension lineation; F1 = D1 fold axis; S1 = D1 axial plane.

b. D2a phase of deformation: development of D2a isoclinal folds with F2a fold axes trending E-W in the low-grade area and N-S in the high-grade area.

the MMT (Fig. 7a). The early thrusting probably occurred between the Cretaceous and the Eocene at the latest. During the same period, rocks of the Neelum valley suffered compressive and shearing stress associated with the progressive development of the Barrovian-type Himalayan metamorphism (first and second prograde stages of metamorphism).

The D1 phase of deformation mainly predated the stage II of the Himalayan metamorphism. The repetition of the rocks was initiated through isoclinal folding. In the HHC, the shearing component and the ductile behaviour of the rocks increased towards the MMT. This could explains the formation of non-cylindrical folds, mainly in the northern part of the HHC (Fig. 7a).

The D2a phase of deformation was syn-metamorphic, in respect to the second metamorphic event (Stage II), during Paleocene to Eocene. Overturned isoclinal folds with southward (?) vergence further transpose the pre-Himalayan rocks of the Indian plate and the Tethyan metasediments (Fig. 7b).

The D1-D2a crustal thickening of the sheared Himalayan deformation front was such that new ductile syn-metamorphic shear zones appeared south of the MMT. In the Neelum valley, these are represented by the Gumot Shear Zone (GSZ) and, later by the MCT (Fig. 6). The development of the MCT occurred during the D2b phase of deformation which marks the emplacement of the HHC unit over the LHC unit (Fig. 7c). Petrofabric analyses and $^{40}Ar/^{39}Ar$ age determinations show that the late shear movement along the MCT postdated the second stage of Himalayan metamorphism and occurred during the third metamorphic event (Stage III) from Oligocene to Lower Miocene. The D2b shear strain was concentrated close to the MCT. The same process of crustal thickening under shear stress continued the southward migration of the Himalayan deformation front, generating after the GSZ and the MCT, the more brittle Panjal Thrust, Main Boundary Thrust and Frontal Thrust. The new NE-SW tending megascopic open folds of the D3 phase can be interpreted in terms of a drastic change in the orientation of the principal compressive components (previously N-S oriented). The apparent 70° anticlockwise rotation of the stress components is compatible with the plate tectonic model which envisages an anticlockwise rotation of India relative to Africa beginning around 37 My ago. This rotation hypothesis is consistent with other field data from Ladakh and Hazara. The D3 phase of deformation was post-metamorphic (past Stage III). The D2b and D3 structures folded the previous D1-D2a structures of the valley, thus explaining the sinuous trace of the MCT on the maps, and the local re-activation of the MBT.

The doming of the HKS and the continuing abnormal uplift of the area enclosed be-

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Figure 7 continues

F2a = D2a fold axes; S2a = D2a axial plane; ? = when seen, S2a dips westwards, but the original attitude is unknown.

c. D2b phase of deformation: southward thrusting of the HHC nappe over the LHC nappe, and development of tight D2b folds and the S2b crenulation cleavage.

d. D3 phase of deformation: development of large open folds with fold axes trending NE-SW. The F3 fold axes have a medium (30°) plunge in the LHC, but are subhorizontal in the HHC. Fold interference produced domal structures.

tween the Hazara and the Nanga Parbat syntaxes characterized the D4 phase of deformation. A late episode of relaxation is observed in the LHC.

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REFERENCES

Baig, M. S. & Lawrence, R. D., 1987. Precambrian to Early Paleozoic orogenesis in the Himalaya. Kashmir Jour. Geol., 5, 1–22.

Bossart, P., Dietrich, D., Greco, A., Ottiger, R. & Ramsay, J. G., 1984. A new structural interpretation of the Hazara-Kashmir Syntaxis (Southern Himalaya) Pakistan. Kashmir Jour. Geol., 2, 19–36.

Bossart, P., Dietrich, D., Greco, A., Ottiger, R. & Ramsay, J. G., 1988. The tectonic structure of the Hazara-Kashmir Syntaxis, southern Himalayas, Pakistan. Tectonics, 7(2), 273–297.

Bossart, P., Chaudhry, M. N., Dietrich, D., Ghazanfar, M., Greco, A., Meier, A., Ottiger, R., Papritz, K., Ramsay, J. C., Rey, R., Spencer, D. & Wahrenberger, C., 1992. A review of the geology of the northern Indian plate, Kaghan valley, NE Pakistan. In: 7th Himalayan-Karakoram-Tibet Workshop (M.P. Searle & P.J. Treloar, eds.). Oxford University, pp. 6.

Calkins, J. A., Offield, T. W., Abdullah, S. K. M. & Tayyab Ali, S., 1975. Geology of the southern Himalaya in Hazara, Pakistan and adjacent areas, USGS Prof. Paper, 716C, 29 pp.

Essene, E. J., 1989. The current status of thermobarometry in metamorphic rocks. In: Evolution of Metamorphic Belts (J. S. Daly, R. A. Cliff & W. W. D. Yardley, eds.). Geol. Soc. Spec. Publ., pp. 1–44.

Ghazanfar, M., Baig, M. S. & Chaudhry, M. N., 1983. Geology of Tithwal Kel area Neelum valley, Azad Jammu & Kashmir. Kashmir Jour. Geol., 1, 1–10.

Greco, A., Martinotti, G., Papritz, K., Ramsay, J. G. & Rey, R., 1989. The Himalayan crystalline nappes of the Kaghan valley (NE-Pakistan). Eclogae Geol. Helv.

Greco, A. & Spencer, D. A., 1993. A section through the Indian plate, Kaghan valley, NW Himalaya, Pakistan. In: Himalayan Tectonics (P.J. Treloar & M.P. Searle, eds.). Spec. Publ. Geol. Soc. London, 74, 221–236.

Khan, M. S. & Ashraf, M., 1989. Panjal volcanics: geochemistry and tectonic setting in Azad Jammu-Kashmir & Kaghan valley, NW Himalaya. Kashmir Jour. Geol., 6, 61–80.

LeFort, P., Debon, F. & Sonet, J., 1980. The "Lesser Himalayan" cordierite granite belt. Typology and age of the Mansehra pluton of (Pakistan). Geol. Bull. Univ. Peshawar, 13, 51–62.

Maluski, H. & Matte, Ph., 1984. Ages of Alpine tectonometamorphic events in the north-western Himalaya, north Pakistan by the $^{40}Ar/^{39}Ar$ method. Tectonics, 3, 1618.

Nakazawa, K., Kapoor, H. M., Ishii, K., Bando, Y., Okimura, Y. & Tukuoka, T., 1975. The Upper Permian and the Lower Triassic in Kashmir, India. Mem. Fac. Sci. Kyoto Univ., Ser. of Geol. & Mineral., 27(1), 1–106.

Papritz, K. & Rey, R., 1989. Evidence for the occurrence of Permian Panjal trap basalts in the Lesser and Higher Himalayas of the western syntaxis area, NE Pakistan. Eclogae Geol. Helv., 82(2), 603–627.

Patriatt, Ph. & Achache, J., 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature, 311, 615–621.

Pluger, Ph., 1995. Etude du marbre a rubis de Nangimali (Azad Kashmir, NE Pakistan). Memoire UCL, 58p.

Pognante, U. & Spencer, D. A., 1991. First report of eclogites from the Himalayan belt, Kaghan valley (northern Pakistan). Eur. J. Mineral., 3, 613–618.

Powell, C. McA., 1979. A speculative tectonic history of Pakistan and surroundings: some constraints from the Indian Ocean. In: Geodynamics of Pakistan (A. Farah & K.A. deJong, eds.). Geol. Surv. Pak. Quetta, 5–24.

Raase, P., 1974. Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism. Contrib. Mineral. Petrol., 45, 231–236.

Schouppe, M., Fontan, D., Verkaeren, J. & Martinotti, G., 1991. Regional geological mapping and ore potential assessment in Neelum valley, Azad Kashmir (Pakistan): Periodical Report, 1991, EEC CII–0571–M(GDF), 12p.

Schouppe, M., Fontan, D., Verkaeren, J., Laduron, D. & Martinotti, G., 1992. Regional geological mapping and ore potential assessment in Neelum valley, Azad Kashmir (Pakistan): Periodical Report, 1992, EEC CII–0571–M(GDF), 27p.

Schouppe, M., Fontan, D., Verkaeren, J., Laduron, D. & Martinotti, G., 1993. Regional geological mapping and ore potential assessment in Neelum valley, Azad Kashmir (Pakistan): Periodical Report, 1993, EEC CII–0571–M(GDF), 27p.

Searle, M. P., 1986. Structural evolution and sequence of thrusting in the Higher Himalayan Tibetan-Tethys and Indus Suture Zones of Zanskar and Ladakh, Western Himalaya. J. Struc. Geol. 8, 923–936.

Spencer, D. A., 1993. Tectonics of the Higher and Tethyan Himalaya, Upper Kaghan valley, NW Himalaya, Pakistan: Implications of an early collisional, high pressure (eclogite facies) metamorphism to the Himalayan belt. Ph.D. thesis, Mitt. Geological Inst., ETH, Zurich.

Tahirkheli, R. A. K., 1979. The India-Eurasia Suture Zone in Northern Pakistan: Synthesis and interpretation of recent data at plate scale In: Geodynamics of Pakistan (A. Farah & K. A. deJong, eds.). Geol. Surv. Pak., Quetta, 125–130.

Treloar, P.J., Broughton, R.D., Williams, M.P., Coward, M.P. & Windley, B.F., 1989a. Deformation, metamorphism and imbrication of the Indian plate, south of the Main Mantle Thrust, north Pakistan. Jour. Met. Geol. (special issue on Himalayan Geology), 7, 111–125.

Treloar, P. J., Coward, M. P. & Williams, M. P., 1989b. Metamorphism and crustal stacking in the north Indian plate, north Pakistan. Tectonophysics, 165, 167–184.

Villa, I. M., Tonarini, S., Oberli, F., Meier, M., Spencer, D. A., Pognante, U. & Ramsay, J. G., 1992. Eocene age of eclogite metamorphism in Pakistan Himalaya. In: 7th Himalayan-Karakoram-Tibet Workshop (M. P. Searle & P. J. Treloar, eds.). Oxford University.

Wadia, D. N., 1931. The syntaxis of the northwest Himalayas: Its rocks, tectonics and orogeny. Rec. Geol. Surv. India, 65, 189–220.

Wadia, D. N., 1934. The Cambrian-Trias sequences of north-western Kashmir, parts of Muzaffarabad and Baramula district. Rec. Geol. Surv. India, 66, 212–234.

Zeitler, P. K., Sutter, J. F., Williams, I. S., Zartman, R. & Tahirkheli, R. A. K., 1989. Geochronology and temperature of the Nanga Parbat-Haramosh Massif, Pakistan. Geol. Soc. Am. Spec. Pap., 232, 1–22.