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Autor: Garzanti, Eduardo / Brignoli, Gianfranco

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Low temperature metamorphism in the Zanskar sedimentary nappes (NW Himalaya, India)

By Eduardo Garzanti[1]) and Gianfranco Brignoli[2])

ABSTRACT

After the Eocene collision between India and Asia, the Tethys Himalaya sedimentary succession has undergone polyphase fold-thrust deformation at very low to low metamorphic grade, as indicated by X-ray and petrographical data. Analysis of illite "crystallinity" in particular allowed us to trace four zones of transition from diagenesis to metamorphism north of the High Himalayan mountain chain and across the Zanskar Range.

The Paleozoic succession and the mostly Mesozoic sequence south of the Oma Chu thrust are characterized by widespread illite and chlorite, respectively with epizonal (Phugtal Unit) and upper anchizonal "crystallinity" (Lower Zangla Unit). Lower anchizonal conditions were reached in the Zumlung Unit, as indicated by higher illite and chlorite "crystallinity" indexes and by vitrinite reflectance data.

Metamorphism thus progressively decreases north of the High Himalayan Crystalline, from lower to structurally higher thrust sheets, until at the core of the Zanskar synclinorium (Upper Zangla and Yelchung Units) transition from diagenesis to anchimetamorphism is testified by poor "crystallinity" and preservation of illite/smectite mixed layers and glauconite. Underneath the Spongtang Klippe, however, metamorphism increases upward through the stack of thrust sheets, and the poorly recrystallized muds of the Yelchung Slices are tectonically overlain by the upper anchizonal sediments of the Lingshed Nappe. Discontinuous inverse metamorphic zonation, also indicated at the base of the Khurna Unit, suggests that post-metamorphic thrusting was an important phenomenon in the Tethys Himalayan Zone.

RÉSUMÉ

Après la collision d'âge Eocène entre l'Inde et l'Eurasie, la succession sédimentaire de l'Himalaya téthysien à été engagée dans une déformation polyphasée en plis et chevauchements et dans un métamorphisme à degré faible à très faible, comme l'indique l'analyse aux rayons X et en lame mince. La «cristallinité» de l'illite, en particulier, nous a permis de reconnaître quatre zones de transition entre la diagenèse et le métamorphisme au nord du cristallin de la Haute-Chaîne et au travers de la Chaîne du Zanskar.

La succession Paléozoïque et les sédiments d'âge surtout Mésozoïque au sud de la faille de l'Oma Chu sont marqués par la présence constante de l'illite et de la chlorite, avec une «cristallinité» typique, aussi bien de l'épizone (Unité de Phugtal) que de l'anchizone supérieure (Unité de Zangla inférieure). L'anchizone inférieure est documentée dans l'Unité de Zumlung par la «cristallinité» moins élevée de l'illite et de la chlorite et par la réflectivité de la vitrinite.

Le métamorphisme donc décroît progressivement au nord de la Haute-Chaîne et des unités inférieures aux supérieures, jusqu'au centre du synclinorium du Zanskar (Unité de Zangla supérieure et Écailles de Yelchung), où le passage entre diagenèse et métamorphisme est documenté par la «cristallinité» peu élevée de l'illite et de la chlorite et par la préservation des interstratifiés gonflants illite/smectite et de la glauconite.

Cependant, au-dessous de la Klippe de Spongtang, le métamorphisme augmente vers le haut de la séquence de nappes, et les pélites à faible cristallinité des Ecailles de Yelchung sont chevauchées par les sédiments d'anchizone supérieure de la Nappe de Lingshed. Ce métamorphisme transporté, documenté aussi à la base de l'Unité de la Khurna, montre que les chevauchements post-métamorphiques ont eu un rôle majeur dans l'Himalaya téthysien.

[1]) Dipartimento di Scienze della Terra, Via Mangiagalli 34, Milano (Italy).

[2]) AGIP SpA, S. Donato Milanese, Milano (Italy). Present address: SILENA SpA, Cernusco sul Naviglio, Milano (Italy).

Introduction

The Zanskar mountains (Fig. 1) are made up of sedimentary rocks deposited on the northern margin of the Indian Plate since the late Precambrian. In the earliest Eocene, marine sedimentation suddenly ceased, due to closure of the Neotethys Ocean and thrusting of the Indian passive margin underneath the Asian active margin (GARZANTI et al. 1987). After collision, the sedimentary sequence of the Indian continental terrace was dismembered into several thrust sheets, which were stacked and deformed during the Tertiary Himalayan Orogeny. The tectonic overburden of the Asian overthrust

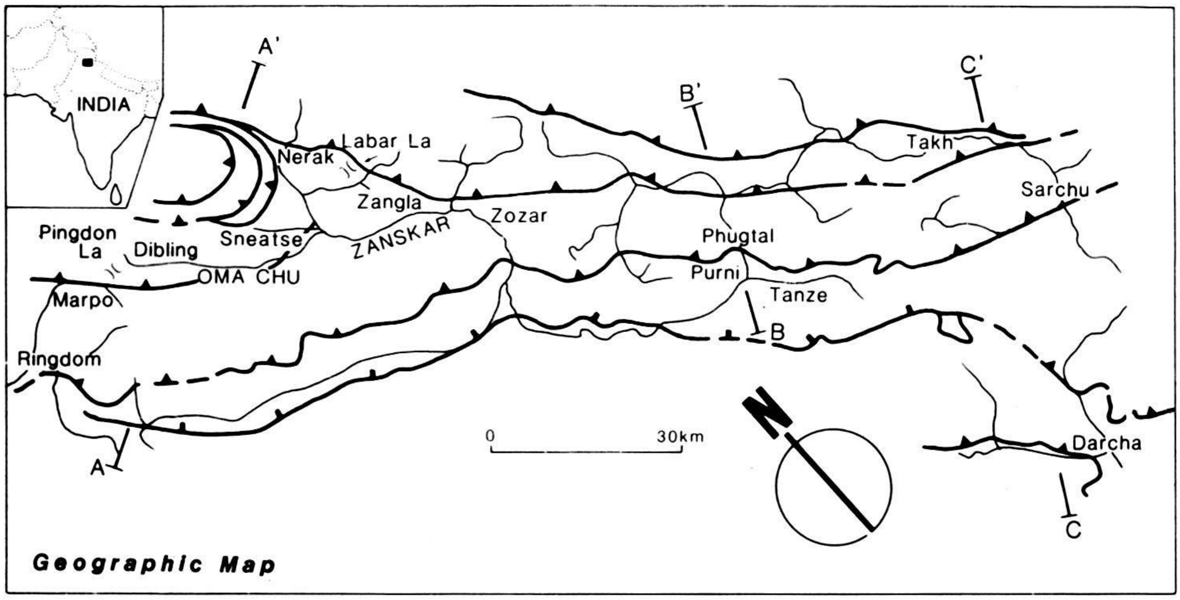

Fig. 1. Geographic map of the Zanskar Range with location of cross-sections (see Fig. 8).

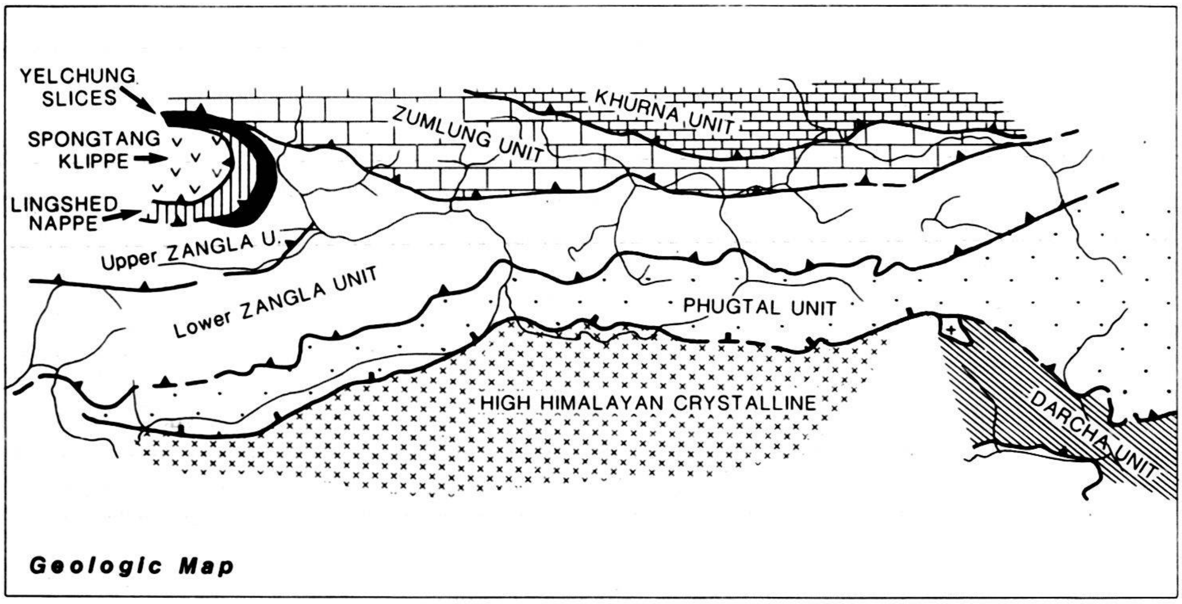

Fig. 2. Simplified geologic map of the Zanskar Tethys Himalaya (mod. after GAETANI et al. 1985b).

wedge, now partly preserved in the Spongtang oceanic Klippe (Fig. 2), was so thick that very low grade metamorphic conditions were attained during deformation even in Tertiary rocks at the top of the Tethys Himalayan succession (NICORA et al. 1986).

In order to investigate in greater detail the multiphase deformation history of the Zanskar Range and to obtain additional information for structural interpretation, X-ray diffraction analysis on clay minerals and determination of illite "crystallinity" were carried out. An attempt to assess coal rank through reflectivity measurements was also made by Marta Gorza (AGIP SpA).

The aim of the present paper is to illustrate the relationships between illite and chlorite "crystallinity", coal rank and growth of metamorphic minerals in the Tethys Himalayan sedimentary rocks, and to discuss the structural implications of illite "crystallinity" data. For further information on the geologic evolution of the Zanskar region, the reader is referred to SRIKANTIA et al. (1980), BAUD et al. (1982), FUCHS (1982), KELEMEN & SONNENFELD (1983), GAETANI et al. (1985a), GARZANTI et al. (1986), REUBER et al. (1987).

Sampling

Sixty very fine grained sandstones, siltstones and shales contained in clastic formations of all ages within each tectonic unit were sampled during four expeditions across the Zanskar Range. Samples were all collected, while measuring stratigraphic sections, in areas where deformation is least. They come from the Khurna (1), Zumlung (16), Lingshed (3), Yelchung (4), Upper Zangla (14), Lower Zangla (15), Phugtal (6) and Darcha (1) tectonic units, and cover an area approximately 175 km in length and 35 km in width.

Methods

X-ray powder diffraction analyses were performed on whole rock samples in order to estimate semiquantitatively the overall mineralogical composition. The relative abundance of clay minerals was subsequently assessed through analysis of the less than 2 μm fraction.

Whole-rock analysis

Samples were pulverized at less than 230 Mesh size in a vibrating cup mill. The powders were scanned from 2°2ϑ to 60°2ϑ with a PHILIPS APD15 computerized diffractometer (CuKα radiation Ni filtered, 40 kV, 20 mA, scanning speed 0.5°2ϑ/min). Reference mixtures with fixed concentration of quartz, K-feldspar, plagioclase, calcite, dolomite and phyllosilicates were used in order to calculate empirical correction factors and convert areas of characteristic reflection peaks into percentages for each mineral in natural samples.

Less than 2 μm fraction analysis

Samples were crushed manually in an agate mortar and then disaggregated in distilled water in an ultrasonic bath. Carbonate-rich samples were treated with 1N HCl at 60°C in order to dissolve both calcite and dolomite. H+ excess was eliminated by washing in distilled water and centrifuging. The less than 2 μm fraction was separated by sedimentation in a cylinder and filtered with a 0.2 μm millipore filter. A concentrated suspension of this fraction was dried on glass slides, obtaining a thin film of oriented clay particles. Density of analyzed material it 3 to 4 mg/cm^2. In order to identify swelling clay minerals, air-dried slides were treated with ethylene glycol vapour at 70°C for four hours. Samples were heated at 550°C for 1 hour and treated with 3N HCl for another hour, in order to distinguish chlorite from kaolinite. Treatment with 1N $MgCl_2$ and 1N KCl allowed recognition of vermiculite.

Oriented samples were scanned from 2°2ϑ to 30°2ϑ with a PHILIPS PW1710 computerized diffractometer (CuKα radiation Ni filtered, 40 kV, 20 mA, scanning speed 2°2ϑ/min.; chart speed 1°2ϑ = 10 mm on paper; ratemeter $2 \cdot 10^3$ cps – rarely $1 \cdot 10^3$ – at time constant 2; slits 1°–0.2mm–1°). Reference mixtures were prepared by using standards provided by the "Clay Mineral Society", and correction factors allowed us to convert into percentages the areas of basal reflections for each clay mineral (illite 10Å, chlorite 7Å, smectite 17Å, mixed layers 11Å to 13Å). The areas were computed on XRD patterns of glycolated samples (Biscaye 1965).

Illite and chlorite "crystallinity"

The illite "crystallinity" index (I.C.) was determined by measuring in mm the width at half-height of the illite 10Å reflection on both air-dried and glycolated slides (Kübler 1967; 1968). Values obtained on three standard samples prepared by B. Kübler (kindly provided by G. Liborio, Univ. Milano) are in good agreement with expected values. "Crystallinity" values given in the text are all on air-dried slides; chart speed is such that $I.C.\Delta°2\vartheta = 0.1 \cdot I.C.mm$.

The absence of kaolinite in the studied samples allowed calculation of the chlorite "crystallinity" index (C.C.) by measuring the width at half-height of the chlorite 7Å peak.

In order to test data for consistency, samples from the same outcrop and of identical lithology were analyzed by different operators at various stages of the work. The effect of lithology on I.C. was also tested. Care was taken to discard samples with detrital micas.

Vitrinite reflectance

Samples were crushed in a porcelain mortar and treated with HCl and HF in order to dissolve the mineral fraction. The residue was centrifuged with ethyl alcohol and then with a high-density bromoform-alcohol solution. The superficial fraction thus separated was centrifuged with ethyl alcohol and finally the residual organic matter was mounted on a plexiglass plug and polished. Vitrinite reflectance analyses were performed with a Leitz Orthoplan Microscope system (reflected light, oil immersion) at a total magnification of 350×.

Results

Whole-rock mineralogy

Quartz is generally around 50%, but ranges from 20% to 96%. K-feldspar and plagioclase are virtually always present in subequal amounts; K-feldspar generally predominates, reaching up to 36%, but plagioclase may prevail in Albian volcanic arenites (up to 33%). Calcite is abundant (up to 79%) in marly samples (Laptal and Kangi La Fms.) or in fine grained sandstones with extensive late diagenetic replacements (Quartzite Series, Giumal and Chulung La Fms.). Dolomite is abundant only in the Eocene Kong Fm. (around 35%) and in the Ordovician Thaple Fm. (up to 66%). Petrographic analysis indicates an authigenic origin for dolomite in the former unit and a clastic origin in the latter.

Clay minerals

Phyllosilicates are abundant only in the shale samples, where they range from 33% to 58%. In siltstones and very fine grained sandstones, phyllosilicates are often barely enough (respectively 10% to 22% and 3% to 14%) to allow determination of illite "crystallinity". Illite is widespread and in most samples is over 50%. Chlorite is also very common, and prevails over illite in the Yelchung and Lingshed Units (where it ranges from 35% to 78%). Chlorite predominates also in many samples from the Giumal Sandstone of the Upper Zangla Unit, where illite abundance was not sufficient to obtain a reliable "crystallinity" measure. Iron-rich chlorite is recurrent in ironstone layers and in the Yelchung and Upper Zangla Units.

Mixed-layers were never found in the Phugtal, Lingshed and Lower Zangla Units, whereas vermiculite or smectite/vermiculite mixed layers occur in nearly half of the samples from the Zumlung Unit, where they reach up to 28%. Illite/smectite mixed layers with very high illite percentage or paragonite/phengite mixed layers (up to 30%) were recorded in the Yelchung and Upper Zangla Units. Kaolinite was never detected, whereas smectite occurs in traces in a few Late Triassic (Lower Zangla Unit) and Middle Jurassic (Khurna Unit) samples.

Both glauconite (G) and stilpnomelane (S) occur in Albian ironstone beds of the Upper Zangla Unit cropping out at Pingdon La (G/S = 3.5), Sneatse (G/S = 2.5) and Nerak (G/S = 2). Glauconite thus gradually decreases eastward, until at Labar La it occurs only in traces. Glauconite is common also in Cretaceous greensands of the Zumlung Unit, but stilpnomelane occurs in the Triassic ironstones of the Zumlung gorges and it becomes exclusive in most Permo-Triassic sections of the southern Lower Zangla Unit.

Illite "crystallinity"

Illite "crystallinity" is maximum in the Paleozoic sediments of the Phugtal and Darcha Units (I.C. values under 3.0 and as low as 1.5 in garnet-bearing Ordovician conglomerates south of Sarchu; Fig. 3). In the Zangla Unit, "crystallinity" is distinctly higher in the south (mostly between 2.0 and 4.6) than in the north (5.8 to 11.5). This marked discontinuity in illite "crystallinity" is observed across the Oma Chu thrust fault, which separates the Lower from the Upper Zangla thrust sheets (Fig. 2). The Zumlung Unit has I.C. values mostly between 4.2 and 6.8, whereas the Lingshed Nappe is characterized by lower values (3.4 to 4.1). The poorest "crystallinity" is recorded in the Yelchung Slices (7.9 to 16.5). "Crystallinity" is controlled by structural position within the Zanskar pile of thrust sheets and it is only indirectly correlated with age or elevation above sea-level.

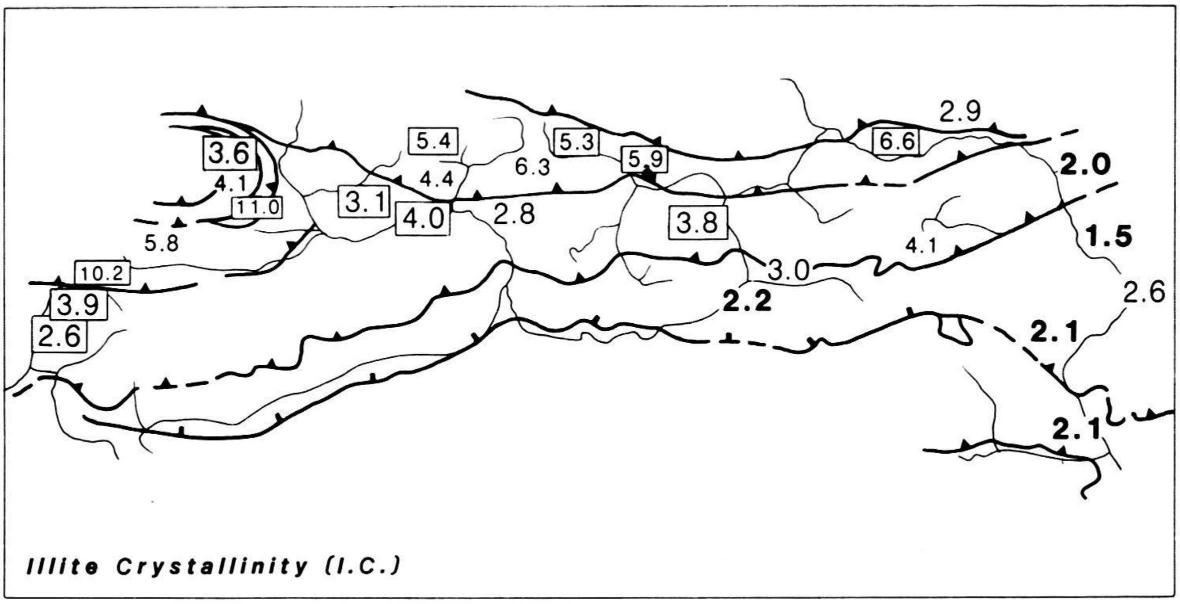

Fig. 3. Distribution of illite "crystallinity" data (air-dried slides; I.C. in mm, KÜBLER 1967). Size of numbers are inversely proportional to crystallinity index (epizonal values are bold-face). Enclosed in rectangles are averages of two to five samples from the same locality.

Influence of lithology is generally negligible, but in a few analyzed sandstones of the Zumlung Unit illite is slightly less "crystallized" than in the interbedded pelites, in contrast to what was observed by most authors (DUNOYER 1970, NYK 1985, FREY 1987). This effect might be ascribed to retrogradation.

As to the role of chemical composition, correlation between illite "crystallinity" and intensity ratio of the 5Å (I002) and 10Å (I001) reflections, which partly depends on the aluminum versus iron and magnesium content in the octahedral layer (ESQUEVIN 1969, HUNZIKER et al. 1986), displays different trends in the Upper Zangla and Yelchung, Zumlung, Lower Zangla and Lingshed, Phugtal and Darcha tectonic units, which compare in this order with type II to V clusters recognized by DUNOYER (1970).

The decrease in "crystallinity" index after glycol solvation indicates the presence of a few expansible layers in the less crystallized illites (I.C. >4; KISCH & FREY 1987).

Chlorite "crystallinity"

The lowest values are recorded in the Phugtal and Darcha Units (C.C. mostly between 1.8 and 2.6; Fig. 4) and at the eastern and western edges of the Lower Zangla Unit (1.9 at Sarchu, 2.0 to 2.6 at Marpo), whereas the highest values are found in the Yelchung Slices (up to 6.2). Intermediate values characterize the Linghsed (2.5 to 2.8), Lower Zangla (2.6 to 3.9), Zumlung and Khurna Units (2.7 to 3.3). In the Upper Zangla Unit, C.C. values decrease eastward from the upper Oma Chu (3.0 to 3.9) to the Sneatse (2.7 and 2.9) and Labar La (2.5 and 2.6) regions.

Areal distribution of chlorite "crystallinity" is thus consistent with that of illite, although less significant. Correlation between I.C. and C.C. values is good for highly recrystallized samples (corr. coeff. = 0.7, significant at the 0.1% sign. lev.; Fig. 5). Correlation becomes poor and not significant for higher I.C. values, due to enlargement of the

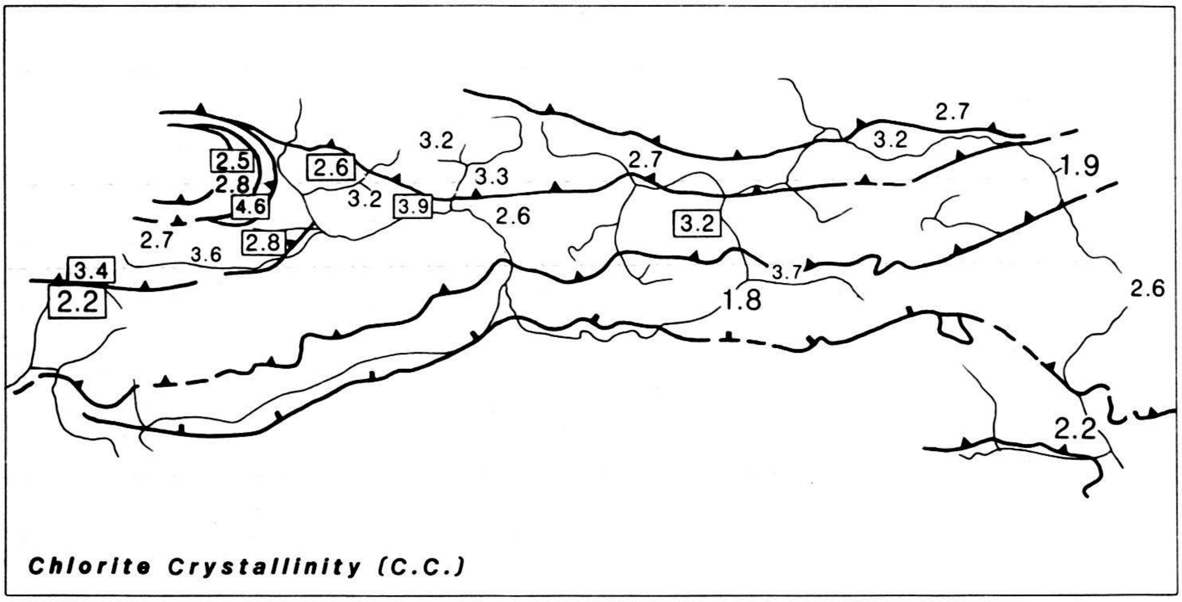

Fig. 4. Distribution of chlorite "crystallinity" data (air-dried slides). Size of numbers is proportional to anchimetamorphic recrystallization. Averaged values are enclosed in rectangles.

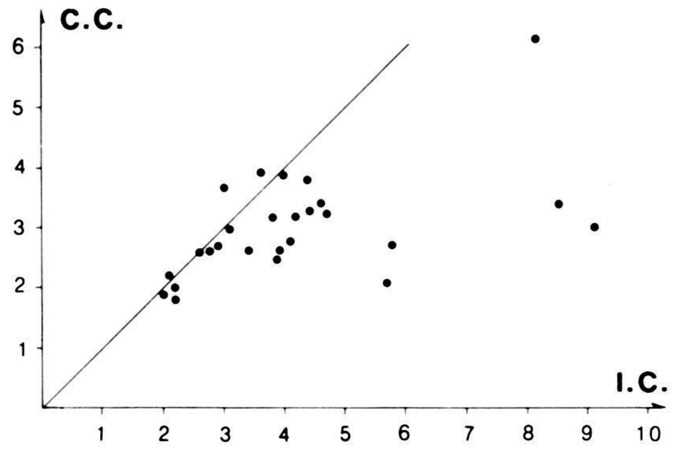

Fig. 5. Illite versus chlorite "crystallinity" (cf. FREY 1987, fig. 2.6). The line I.C. = C.C. is shown for orientation purposes. Note that chlorites are generally better "crystallized" than illites in anchizonal samples (I.C. 2.5 to 6 and C.C. 2.5 to 4), while "crystallinity" indexes are very close in the epizone (I.C. and C.C.< 2.5).

10Å illite reflection caused by the presence of illite/smectite mixed layers and probably also to easier alteration of less recrystallized phyllosilicates during retrogradation.

Vitrinite reflectance

The analysed samples, all from Early Cretaceous black shales of the Zumlung Unit (Spiti and Giumal Fms.), contain small amounts of black metamorphic organic matter. Vitrinite fragments with high anisotropy show indicative R_o values between 3.2 and 4.5% (I.C. ranges from 4.6 to 9.1 in the same samples). Only in one sample reliable vitrinite reflectance data could be obtained (R_o min = 3.2%; R_o m = 3.7%; R_o max = 4.1%; I.C. in the same sample is 5.7).

Himalayan deformation and metamorphism

X-ray analysis, along with observation of mineralogical and textural features in thin section (quartz recrystallization, growth of metamorphic minerals such as muscovite, biotite, epidote, pumpellyite, stilpnomelane, garnet; Fig. 6) and data on alteration of organic matter (conodont colour, vitrinite reflectance) allowed us to recognize four zones of transition between "diagenesis" and greenschist facies metamorphism in the Zanskar sedimentary nappes (Fig. 7).

ZONE 1, comprising the base of the Upper Zangla Unit and the Yelchung Slices, is characterized by authigenic clay mineral assemblages including illite, often Fe-rich chlorite, illite/smectite or phengite/paragonite mixed-layers. Illite and chlorite "crystallinity" are poor (I.C. over 7; C.C. around or over 3.5). Glauconite is preserved in ironstone layers, and stilpnomelane growth is confined to the rims of glaucony peloids. Only slight migration of quartz crystal boundaries is observed.

ZONE 2, corresponding to the Zumlung Unit and part of the Upper Zangla Unit, is characterized by clay mineral assemblages including illite, glauconite and either chlorite, vermiculite or vermiculite/smectite mixed-layers. The I.C. index is comprised between 4.2 and 7, the C.C. index is around 3 and vitrinite reflectance is over $R_o = 3\%$. Quartz recrystallization is incipient; epidote and stilpnomelane may be found. In the Eocene Chulung La Fm., at the top of the Upper Zangla Unit, the presence of authigenic pumpellyite, epidote and carbonates may imply a higher XCO_2 than the occurrence of prehnite (K. Honegger pers. comm 1987, Liou et al. 1987).

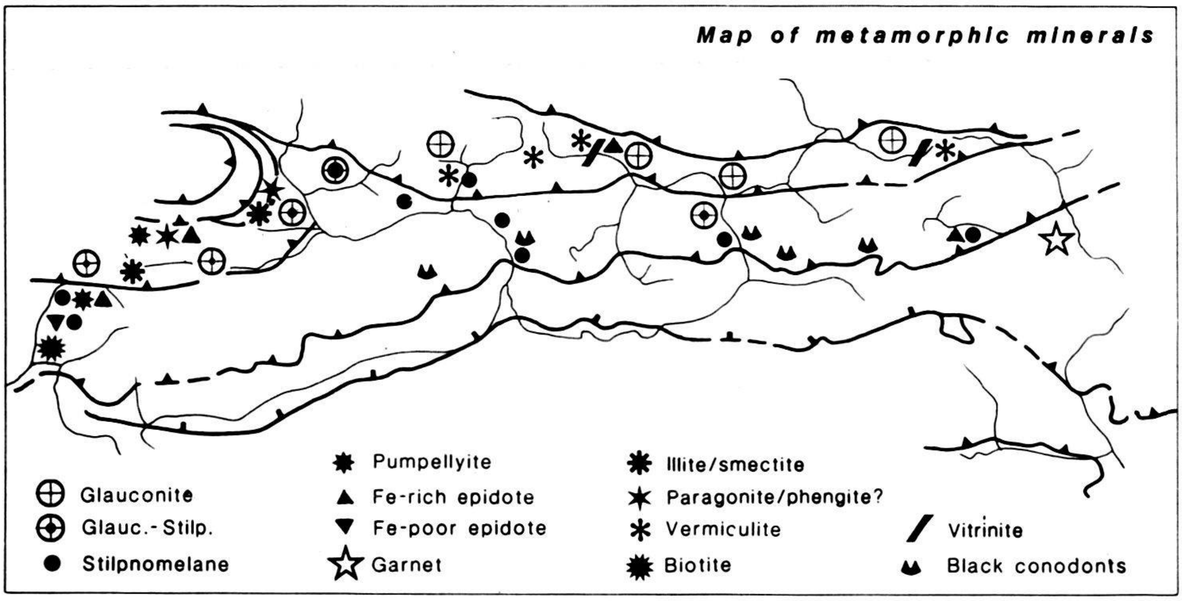

Fig. 6. Map of metamorphic minerals and alteration of organic matter in the Zanskar sedimentary succession.

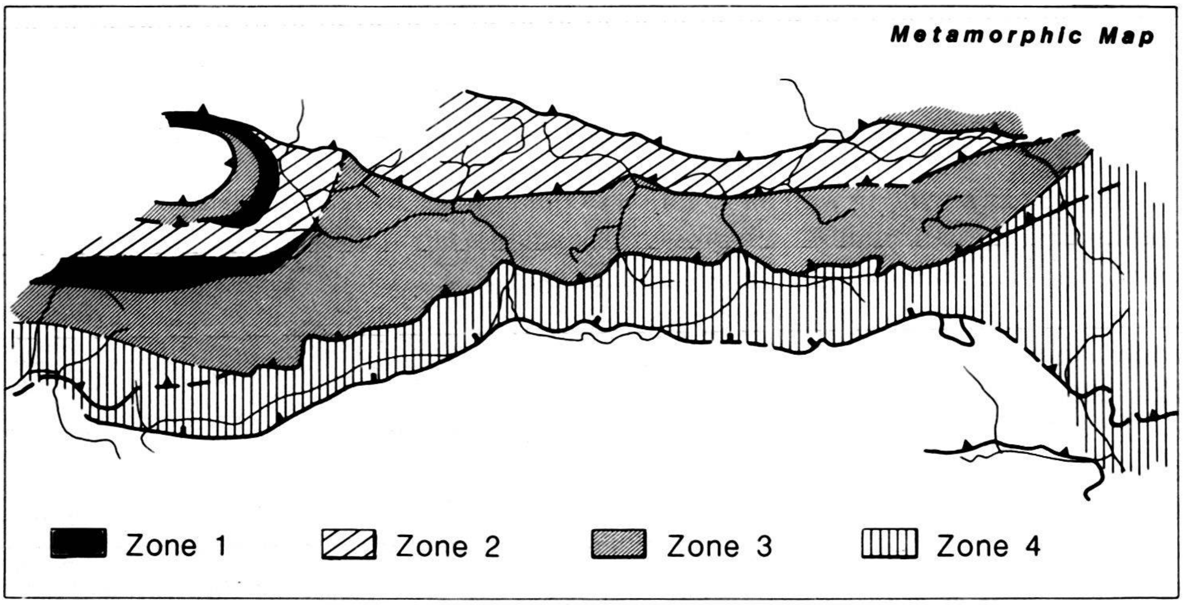

Fig. 7. Tentative metamorphic map for the Zanskar Range. Inverse metamorphic zonation all around the Spongtang Klippe and at the base of the Khurna Unit, truncation of "isocrysts" at the Shillakong-Zumlung Nappe front and closeness of isograds at the northern and southern boundaries of the Phugtal Unit point to the importance of post-metamorphic tectonics in the Tethys Himalayan Zone.

ZONE 3, comprising the Lower Zangla thrust sheet and the Lingshed Nappe, is characterized by predominant illite (I.C. between 2.5 and 4.2) and chlorite (C.C. between 2.5 and 3). Mixed-layers and glauconite have disappeared, while tiny white micas, stilpnomelane needles and epidote occur. Newly-grown quartz crystals and sericite developed in areas of intense tectonic stretching ("zone of quartzitic structures"; KOSSOVSKAYA & SHUTOV 1970), but only sporadically in the mildly deformed Lingshed Nappe. Conodonts are dark grey to black (C.A.I. = 4.5 to 5; scale of EPSTEIN et al. 1977, HARRIS 1979).

ZONE 4, comprising the Paleozoic rocks of the Phugtal and Darcha Units and the Triassic rocks of the Lower Zangla Unit in the Sarchu and Ringdom areas, is characterized by widespread illite and chlorite (I.C. and C.C, under 2.5) and by extensive phyllosilicate and quartz recrystallization ("zone of phyllite-like schists"; KOSSOVSKAYA & SHUTOV 1970).

Transition from burial diagenesis to orogenic metamorphism

The Zanskar sedimentary rocks were all strongly deformed during the Himalayan orogeny and affected by temperatures much higher than those reached during burial diagenesis prior to the India-Asia collision. Preservation of glauconite, illite/smectite mixed-layers and unaltered detrital biotite, associated with incipient growth of quartz, paragonite and stilpnomelane in Zone 1 suggests proximity to the onset of anchimetamorphism (beginning of "zone II" of FREY et al. 1973; "laumontite zone" of KISCH 1983; "subpumpellyite zone" of MERRIMAN & ROBERTS 1985). Zones 2 and 3 represent respectively the "lower" and the "upper anchizone" (anchizone s.s.), whereas Zone 4 corresponds to the epizone. The term epizone is used here as synonimous with lower greenschist facies, whereas the term anchizone is used in a broad sense and corresponds to the prehnite-pumpellyite facies (Table 1; very low metamorphic grade of WINKLER 1976; FREY 1986).

Closeness of metamorphic isograds and late normal faulting

In the Purni-Tanze area, rapid transition from anchizonal to epizonal conditions is observed, with relatively poor "crystallinity" (I.C. = 3.0, C.C. = 3.7) recorded in a packet of Ordovician conglomerates delimited by imbricate faults truncated by the sole of the Lower Zangla Unit. This feature, ascribed to thrust tectonics by GAETANI et al. (1985b), has been subsequently reactivated as a late stage normal fault associated with culmination collapse and underplating according to MCELROY (1987) and SEARLE et al. (1988). A similar problem exists for the boundary between the Tethys Himalayan sedimentary zone and the mesograde metamorphic nappes of the High Himalayan Crystalline, where all Barrovian zones up to sillimanite are represented (HONEGGER et al. 1982). This tectonic contact, interpreted as a thrust by BAUD et al. (1984), according to HERREN (1987) corresponds to a late shear zone with normal sense of displacement, where transition from upper amphibolite to lower greenschist facies occurs within 200 m. In the Darcha area, however, the boundary between the Phugtal and Darcha Units does not correspond to a discontinuity in illite "crystallinity", and the major metamorphic break occurs further to the southwest (POGNANTE et al. 1987).

Metamorphic grade :				VERY LOW			LOW	
Facies :	Zeolite			Prehnite-Pumpellyite			lower Greenschist	
				ANCHIZONE			EPIZONE	
			Lower		Upper			
Indicative temperature:		250			300		350	400
ZONES	1		2		3		4	
TECTONIC UNIT	Upper ZANGLA YELCHUNG		ZUMLUNG		LINGSHED Lower ZANGLA		DARCHA PHUGTAL	
Illite (I.C.) :		7		4.2		2.5		1.5
Chlorite (C.C.) :		3.5		3		2.5		
Conodont (C.A.I.) :					4.5 - 5			
Vitrinite (Ro%) :			3.7					
Textures :					QUARTZITE		PHYLLITE	
		Boundary migration				Recrystallization		
Newly-grown quartz :	- - - -	- - - -	- - - -	- - - -	--------	--------	--------	--------
Glauconite :	--------	--------	--------	--------				
Stilpnomelane :	- - - -	- - - -	- - - -	- - - -	--------	--------	?	
Pumpellyite :		--------	--------	--------	--------	--------		
Fe-rich epidote :		--------	--------	--------	--------	--------	--------	--------
Fe-poor epidote :						--------	--------	--------
Garnet :								---
Illite/smectite :	--------	--------						
Paragonite/pheng.? :	--------	--------						
Fe-rich chlorite :	--------	--------	- - - -	- - - -	- - - -	- - - -		
Chlorite :	--------	--------	--------	--------	--------	--------	--------	--------
Illite :	--------	--------	--------	--------	--------	--------	--------	--------
Biotite :	Unaltered detrital							Incipient authigenic
Vermiculite :		--------	--------					

Table 1. Tentative recognition of four zones of transition between diagenesis and low grade metamorphism in the Zanskar Range. Assessment of anchimetamorphic grade and maximum temperatures are based on occurrence of metamorphic minerals in layers of suitable chemical composition and alteration of organic matter. Also quartz recrystallization, although dependent on tectonic strain, grain size and quartz abundance, is a valuable anchimetamorphic indicator if a considerable number of thin sections is available for each outcrop.

Discontinuities in illite "crystallinity"

Across the Oma Chu thrust fault, illite "crystallinity" jumps from an average value of 3.9 in the Lower Zangla Unit to an average value of 10.2 in the Upper Zangla Unit (Fig. 8). This metamorphic break was independently recognized from marked differences in quartz and calcite recrystallization (confront Figs. 6b and 6e vs. 6f in NICORA et al. 1986, and paleontologic plates in GAETANI et al. 1983 vs. 1980). Illite "crystallinity" data thus confirm that the Oma Chu thrust is a major structural element of the Zanskar Range.

Inversions in "crystallinity" and post-metamorphic faulting

Another phenomenon, observed in other mountain belts and referred to as "transported metamorphism" or "inverse metamorphic zonation" (BREITSCHMID 1982, FREY 1988), is the inversion of illite "crystallinity" across nappe boundaries, with the higher nappe showing higher metamorphic grade. In the Zanskar Range, the best example is testified by the tectonic units underneath the Spongtang Klippe, where illite and chlorite "crystallinity" increases progressively toward the top of the Zanskar pile of nappes (Fig. 8). On the south-western side of the Klippe, the Upper Zangla Unit in the Dibling area passes from average I.C. values of 10.2 in the Early Cretaceous to 5.8 in the Eocene, whereas on the south-eastern side the high "crystallinity" indexes recorded in the Maastrichtian muds of the Yelchung Slices (I.C. = 7.9 to 16.5; C.C, = 3.4 to 6.2) pass rapidly to much lower values in the overlying Lingshed Nappe (I.C. = 4.1, C.C. = 2.8 in the Paleocene and I.C. = 3.4 to 3.9, C.C. = 2.5 to 2.6 in the Eocene). These data suggest that metamorphism of the Tertiary Zanskar sediments underneath the thick Asian overthrust wedge preceded final thrusting and emplacement of the oceanic allochton with its sedimentary sole on top of the Yelchung Slices. Subsequent uplift may have hindered complete thermal re-equilibration.

Another example occurs at Takh, with transition from average I.C. values of 6.6 (C.C. = 3.2) in the Zumlung Unit to lower indexes (I.C. = 2.9; C.C. = 2.7) in tectonic slices at the base of the overlying Khurna Unit. Since we analysed only one sample from the Khurna Unit, its improved "crystallinity" may be also ascribed to local increase in temperature due to frictional heat (APRAHAMIAN & PAIRIS 1981).

Tentative temperature estimates

Zone 1 corresponds to the transition to prehnite-pumpellyite facies conditions, at temperatures close to 250° C (NICORA et al. 1986, GARZANTI et al. 1989). The persistence of illite/smectite up to the lower boundary of the anchizone and the occurrence of paragonite/phengite suggest high Na/K environments (KISCH 1987). In the Zumlung Unit (Zone 2), the available textural, mineralogical, "crystallinity" and vitrinite reflectance data point to maximum temperatures exceeding 250° C (VOLL 1976, FREY et al. 1980, SCHIFFMAN et al. 1984, FREY 1987). The presence of vermiculite or vermiculite/smectite mixed-layers in several samples is ascribed to late degradation of chlorite, which occurs only in vermiculite-free samples (THOREZ & VAN LECKWIJCK 1967).

In the Lower Zangla Unit (Zone 3), temperatures around 300°C were inferred from extensive stilpnomelane growth, quartz recrystallization and colour of Triassic conodonts (Baud et al. 1984, Garzanti et al. 1989). Illite "crystallinity" data now allow us to extend such estimate to the Lingshed Nappe.

In the Pingdon La-Ringdom profile (Fig. 8), the transition to low grade metamorphism gradually occurs within the 10 km width of the Lower Zangla Nappe, across pumpellyite (Eocene), clinozoisite (Jurassic to Early Tertiary), and biotite (Triassic) zones. Incipient crystallization of biotite at Ringdom points to maximum temperatures

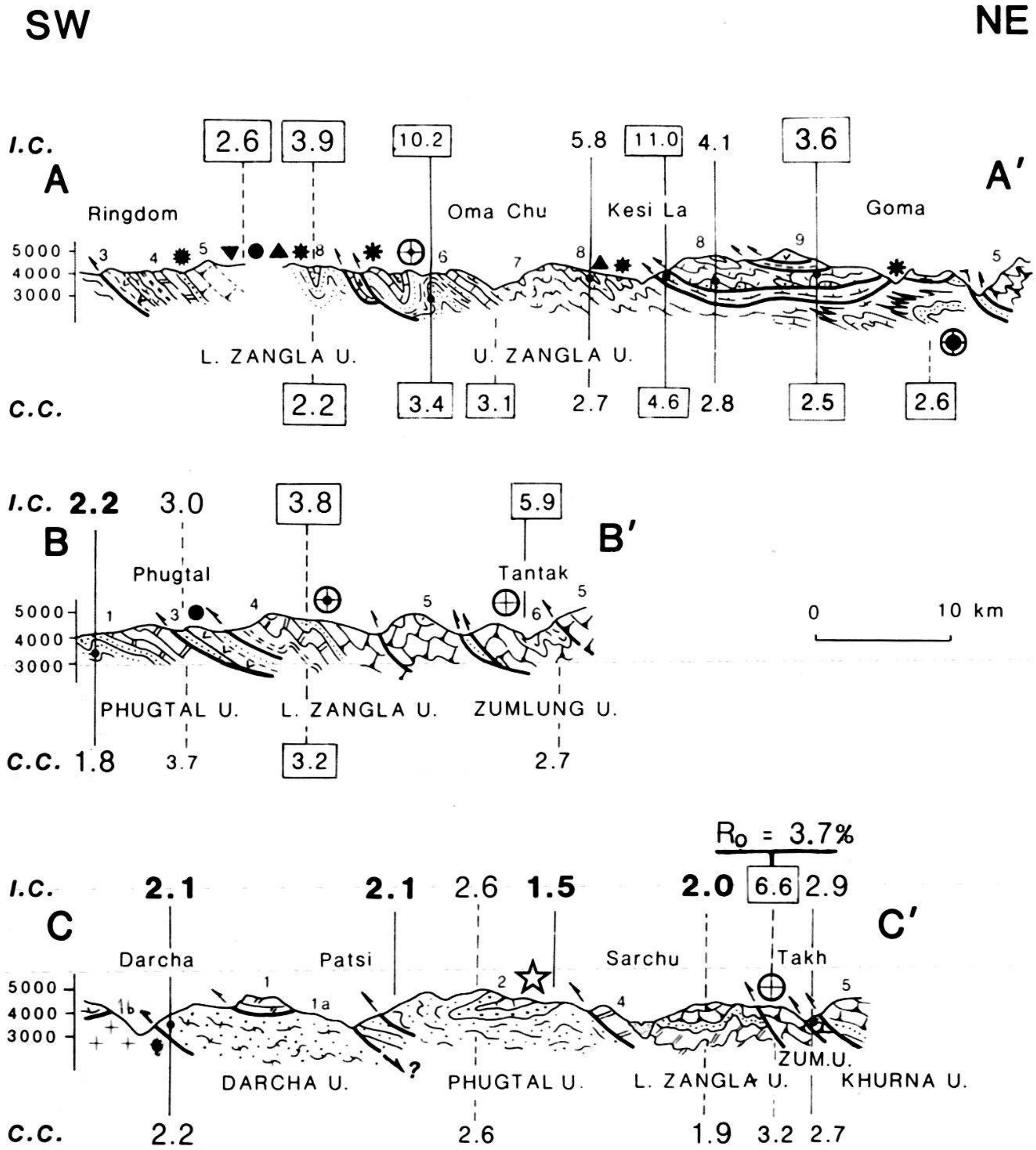

Fig. 8. Simplified cross-sections across the western, central and eastern Zanskar Range (see Fig. 1 for location), with distribution of illite and chlorite "crystallinity". Major metamorphic minerals (symbols as in Fig. 6) and vitrinite reflectance are also indicated. I.C. values are represented above and C.C. values below each cross-section, with size of numbers proportional to "crystallinity" and averaged values enclosed in rectangles. Dashes indicate projection from adjacent areas. 1 = Cambrian (1a = Darcha phyllites; 1b = Kade granodiorite); 2 = Ordovician to Carboniferous; 3 = Permian; 4 = Triassic; 5 = Jurassic; 6 = Early Cretaceous; 7 = Late Cretaceous; 8 = Early Tertiary; 9 = Spongtang Ophiolite.

around 350° C, and similar values may be suggested for large parts of the Phugtal Unit and for the Triassic in the Sarchu area (Zone 4). Even higher temperatures were reached in the Phugtal Unit south of Sarchu, as indicated by the appearance of garnet (BAUD et al. 1984).

Age and evolution of metamorphism

The Zanskar passive continental margin began to be subducted underneath the Asian arc-trench system at the Paleocene/Eocene boundary. Fold-thrust deformation with SW-directed thrust stacking and consequent crustal thickening were shortly followed by prograde regional metamorphism, and temperatures close to 300° C were reached even at the top of the Indian continental terrace. The thickness of the overthrust wedge, a remnant of which is represented by the Spongtang Allochton, was thus originally close to 10 km, if a geothermal gradient of 30° C/km is assumed.

Barrovian metamorphism reached its climax around the end of the Eocene on both sides of the Zanskar Range, in the High Himalayan Crystalline (M1 phase of STÄUBLI 1989) and in the Indus Basin (K/Ar dates on phyllites at 35 ÷ 40 My; VAN HAVER et al. 1986).

A successive metamorphic phase in the HHC (M2), characterized by synmetamorphic uplift, doming and incipient anatexis and contemporaneous with thrusting along the MCT (KÜNDIG 1989), culminated with migmatisation and leucogranitic intrusions around 20 My (SEARLE & FRYER 1986, FERRARA et al. 1987). Finally, an M3 retrograde metamorphic phase was probably associated with continuing uplift, extension and normal faulting in southern Zanskar, with out-of-sequence thrusting in northern Zanskar and with north-directed back-thrusting in the Indus suture Zone (SEARLE et al. 1988). If the evolution of deformation and metamorphism in the Tethys Himalayan sediments can be compared with that of the High Himalayan Crystalline and of the Indus suture, post-metamorphic tectonics and retrogradation in Zones 1 and 2 may be ascribed to this M3 phase (phases Z3 and Z4 of BASSOULLET et al. 1983).

Conclusions

The study of illite "crystallinity" in the Tethys Himalayan Zone has shown that the late Precambrian to early Eocene sedimentary succession of the Zanskar mountains has been affected by incipient regional metamorphism during the Himalayan Orogeny even in Tertiary sediments at the top of the Zangla and Shillakong Units, on either side of the Lingshed-Spongtang Klippe. The Spongtang Ophiolite itself shows at its base intense deformation with growth of minerals such as prehnite, pumpellyite and both Fe-rich and Fe-poor epidote (HONEGGER et al. 1982, BASSOULLET et al. 1983).

Metamorphism progressively increases away from the core of the Zanskar synclinorium, from higher to structurally lower thrust sheets, until lower greenschist facies is reached in the Paleozoic sediments of the Phugtal Unit. Inverted metamorphism, however, is observed at the base of the Khurna Unit and particularly underneath the Spongtang Klippe, where the upper anchimetamorphic Lingshed Nappe tectonically lies on top of the less recrystallized muds of the Yelchung Slices. Breaks and inversions of metamorphic grade give independent and conclusive evidence of the occurrence of major thrust contacts and of both pre- to syn-metamorphic and post-metamorphic nappe tectonics in the Tibetan Zone (for an opposite view see FUCHS 1987).

Illite "crystallinity" principally depends on structural position, and remains remarkably constant within each unit all along the Zanskar region up to its western and eastern ends, where the Tethys Himalayan sediments reach biotite facies in Triassic sandstones at Ringdom and up to garnet facies in Ordovician conglomerates near Sarchu.

Metamorphism increases also toward the Indus Suture, and greenschist facies is reached in the Nimaling Dome, at the northern edge of the Indian Plate (STUTZ & STECK 1986). The oceanic rocks of the suture, after a Cretaceous blueschist facies metamorphic event (VIRDI et al. 1979, HONEGGER et al. 1989), have undergone prehnite-pumpellyite to lower greenschist facies metamorphism during the Himalayan deformation (HONEGGER et al. 1982, BASSOULLET et al. 1983). North of the suture, metamorphism decreases towards the Ladakh batholith, but lower anchizonal conditions are still recorded both in the southern and northern flanks of the Indus forearc basin, as shown by illite "crystallinity" data and by epidote and paragonite growth (VAN HAVER et al. 1984, GARZANTI & VAN HAVER 1988).

All of the rocks involved in the India-Asia collision and now preserved in the core of the Himalayan chain have thus undergone intense polyphase fold-thrust deformation and low temperature metamorphism during the Himalayan Orogeny. Attempts to draw metamorphic maps for the sedimentary cover may considerably help in understanding the tectonic structure of the Zanskar Range and must be taken into account when reconstructing the relative timing of deformation and metamorphism in the Tethys Himalayan Zone.

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