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Transition from diagenesis to metamorphism in the Paleozoic to Mesozoic succession of the Dolpo-Manang Synclinorium and Thakkhola Graben (Nepal Tethys Himalaya)

EDUARDO GARZANTI,[1] MARTA GORZA,[2] LORENZO MARTELLINI[2] & ALDA NICORA[1]

Key words: Metamorphism, Nepal, Tethys, Himalaya, Paleozoic, Mesozoic

ABSTRACT

Determination of illite and chlorite "crystallinity", vitrinite reflectance and conodont color alteration index, along with observation of other metamorphic indicators such as index minerals and textural-mineralogical changes, allowed us to evaluate the intensity of metamorphism which affected the Paleozoic to Mesozoic Tethys Himalayan sedimentary rocks cropping out in the Dolpo, Thakkhola and Manang regions of central Nepal.

Very low to medium-grade metamorphism took place during the Tertiary Himalayan Orogeny, when the Tethys Himalayan passive margin was thrusted underneath the Asian active margin as a consequence of the India/Asia collision. All along the southern part of the Dolpo-Manang Synclinorium, metamorphism increases progressively from north to south, reaching greenschist to amphibolite facies in Devonian to Lower Paleozoic units cropping out along the Tarap Khola, Kali Gandaki and Marsyandi valleys. Minor changes in metamorphic conditions, increasing eastward both in the studied central Dolpo area and in the Manang region along the Marsyandi Valley, occur along strike.

The epizone/anchizone boundary, which might correspond to temperatures as high as 380°C, is typically recorded within the thick Upper Devonian pelites. The anchizone/"diagenesis" boundary, occurring at temperatures close to 300°C, is instead mainly testified within the Triassic section.

The Mesozoic succession of the Thakkhola Graben is characterized by much poorer illite "crystallinity" and lower vitrinite reflectance. Within this unique area of the Himalayan Range, maturation of organic matter reached only the "dry gas" or even the "wet gas" stage, at estimated temperatures of only 200°-250°C. Major metamophic gaps are recorded across both faults delimiting the graben. An abrupt temperature jump of at least 150°C characterizes the western Dangardzong master fault. The Muktinath Fault instead corresponds to only a minor jump, and metamorphism progressively increases eastward in a broad area comprised between the Kali Gandaki and the Jarsgend Khola.

RIASSUNTO

L' analisi della "cristallinità" dell' illite e della clorite, della riflettanza della vitrinite e dell' alterazione del colore dei conodonti, oltre all' osservazione di altri indicatori metamorfici come i minerali indice o le modificazioni tessiturali e composizionali, ha consentito di valutare l' intensità del metamorfismo che ha interessato le rocce sedimentarie appartenenti alla Zona del Tethys Himalaya nel Nepal centrale.

Nelle regioni del Dolpo, della Thakkhola e del Manang, la successione paleozoica e mesozoica ha subito durante l'orogenesi himalayana di et à Terziaria un metamorfismo di grado da molto basso a medio. Sul fianco meridionale del Sinclinorio Dolpo-Manang, il grado metamorfico aumenta progressivamente da nord a sud, raggiungendo la facies a scisti verdi o la facies anfibolitica nelle unità di età da devoniana a paleozoica inferiore che affiorano lungo i corsi della Tarap Khola, della Kali Gandaki e della Marsyandi.

[1] Dipartimento di Scienze della Terra, Via Mangiagalli 34, Milano – Ev-K[2]-CNR, Via Ampère 56, Milano
[2] AGIP SpA, S. Donato Milanese, Milano

Il limite tra l' epizona e l' anchizona, che sembra corrispondere a temperature fino a 380°C, tipicamente cade all' interno delle potenti peliti del Devoniano superiore. Il passaggio tra anchizona e "diagenesi", che avviene a temperature vicine ai 300°C, è in genere contenuto nella successione Triassica. Le condizioni metamorfiche tendono peró a variare lateralmente: esse aumentano verso oriente sia nella piccola area studiata nel Dolpo centrale, sia nella regione di Manang lungo la valle della Marsyandi.

La successione mesozoica del Graben della Thakkhola è caratterizzata da una assai minore "cristallinità" dell' illite e da più bassi valori di riflettanza della vitrinite. In tutta la catena himalayana, solo in quest' area ristretta la maturazione della materia organica ha raggiunto solo lo stadio del "gas secco" o addirittura del "gas umido", a temperature di soli 200°C ÷ 250°C. Salti importanti nelle condizioni metamorfiche sono associati a entrambe le faglie che delimitano il graben. A Dangardzong, la faglia principale corrisponde a un salto brusco di almeno 150°C, mentre il salto registrato attraversando la faglia di Muktinath è meno importante, e verso est il metamorfismo cresce progressivamente in un' ampia regione compresa tra il corso della Kali Gandaki e quello della Jarsgend Khola.

Introduction

Sedimentary rocks belonging to the Tethys Himalayan succession are exposed in the Dolpo-Manang Synclinorium (central Nepal; Fig. 1), a nearly 200 km long structure formed as a consequence of the collision between India and Asia in the Early Tertiary. Strongly deformed Lower Paleozoic units invariably lie tectonically above the High Himalaya Crystalline belt and form the backbone of the Annapurna and Dhaulagiri massifs. The disharmonic contact between the highly metamorphic "Tibetan Slab" ("infrastructure") and the more openly folded Tethys Himalayan metasediments ("superstructure") represents the floor of leucogranitic intrusions of latest Oligocene/earliest Miocene age, such as the Manaslu pluton (Le Fort 1988). All along the Himalayan Range, this contact corresponds to a regional metamorphic jump – transition from the sillimanite zone to the epizone occurs in many cases within a few hundred metres – and is interpreted as a major detachment normal fault, formed in the earliest Miocene synchronously with southward thrusting of the High Himalayan Crystalline along the MCT (Burg et al. 1984; Herren 1987; Hodges et al. 1992; Guillot et al. 1993). Within the Paleozoic to Mesozoic Tethys Himalayan sedimentary units, intensity of tectonic deformation and metamorphic grade progressively decrease northward, towards the Indus-Tsangpo ophiolitic suture. Cretaceous formations are preserved only in the Thakkhola Graben, which is a late orogenic (Late Neogene) feature running northeast-southwest between the Annapurna and Dhaulagiri massifs, and separating the Manang (Nyi Shang) region to the east from the Dolpo region to the west (Fig. 1).

During three expeditions from 1989 to 1991, research groups of the University of Milano studied the Paleozoic and Mesozoic succession in the Thakkhola Graben (Garzanti & Pagni Frette 1991), central Dolpo (Garzanti et al. 1992) and Manang areas (Garzanti et al. 1994). Several tens of pelitic samples were collected for determination of both illite "crystallinity" and coal rank, through X-ray diffraction analysis and measurement of vitrinite reflectance respectively. Moreover, conodont color alteration was evaluated on over a hundred Triassic limestone samples, and textural-mineralogical modifications of both framework and interstitial components were analyzed on several hundred thin sections of arenite beds.

The aim of the present paper is to provide information on the transition from low to very low-grade metamorphism along south-to-north geological transects studied in three tectonically distinct domains of central Nepal, also in order to better constrain structural

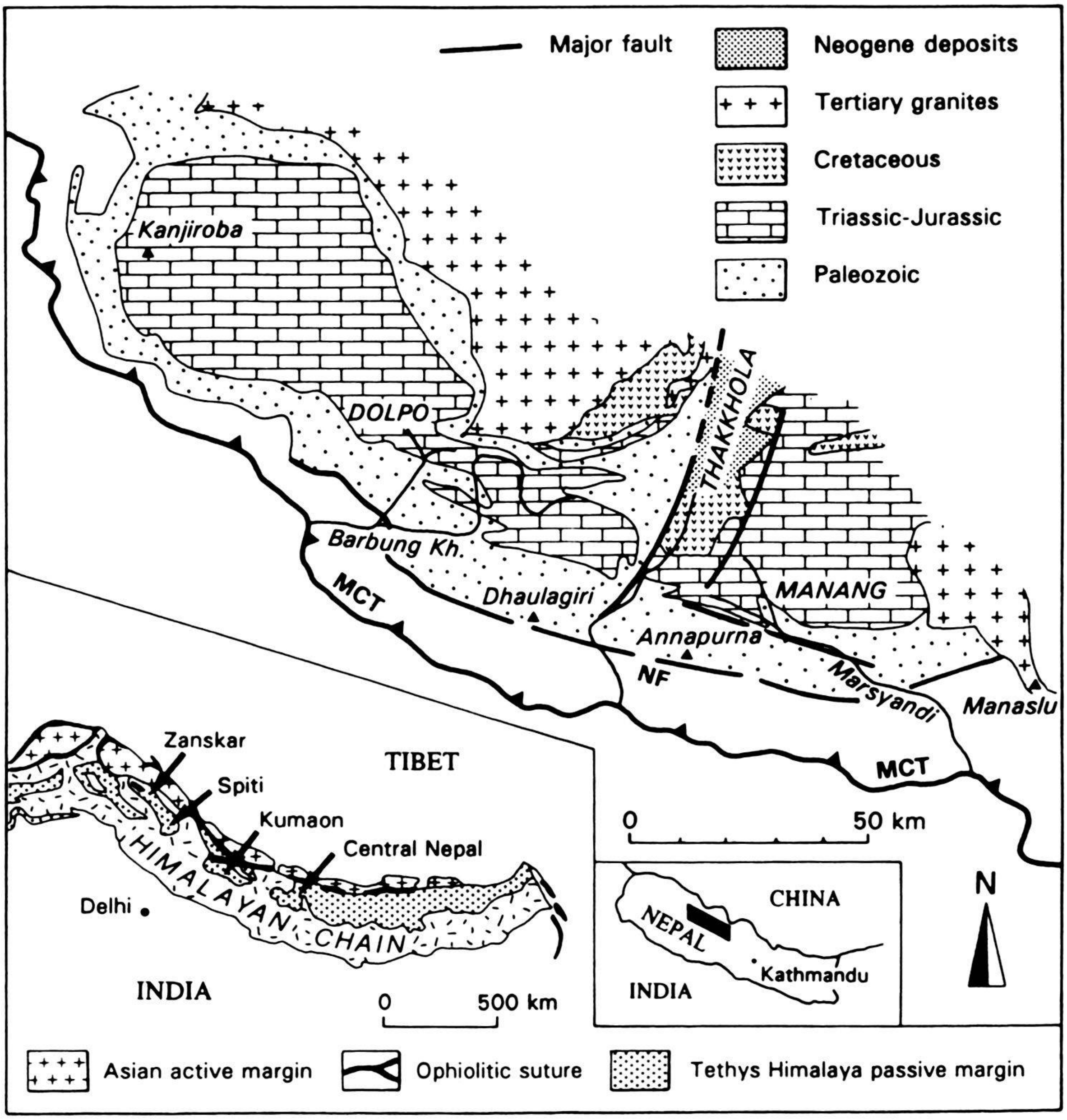


Fig. 1. Geological map of the Dolpo-Manang Synclinorium (after Gansser 1964; Colchen et al. 1986). MCT = Main Central Thrust; NF = Normal Fault. Location and geology of the Himalayan Chain is shown in inset.

interpretations of tectonic evolution during the Tertiary Himalayan Orogeny. These new results are compared with similar data previously obtained in the Zanskar sedimentary nappes (NW Himalaya; Garzanti & Brignoli 1989; Spring 1993), and show how different indicators of very low-grade metamorphism correlate within the Tethyan sedimentary belt of the Himalayan Range.

Sampling and methods

Eighty-four siltstones and shales, mostly collected while measuring stratigraphic sections in areas where tectonic deformation is least, were processed for analysis of illite "crystallinity", chlorite "chrystallinity" and vitrinite reflectance. Samples are from clastic formations of Paleozoic to Mesozoic age cropping out in Dolpo (29), Manang (30) and in the Thakkhola Graben (25). Care was taken to avoid samples containing detrital micas or showing superficial alteration.

Clay mineralogy

X-ray powder diffraction analyses were performed on whole rock samples in order to estimate semiquantitatively the overall mineralogical composition.

The relative abundace of clay minerals was subsequently assessed through analysis of the less than 2 µm fraction. 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. 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° – 0.1° mm – 1°).

Illite and chlorite "crystallinity"

The illite "crystallinity" index (I. C., measured as δ°2θ CuKα) was determined by measuring the width at half-height of the illite 10Å reflection on both air-dried and glycolated slides (Kübler 1968). "Crystallinity" values given in the text are all on air-dried slides. Boundaries between "diagenesis" and the anchizone (I. C. 0.42 δ°2θ) and between the anchizone and the epizone (I. C. 0.25 δ°2θ) are according to Kübler (1968) and Kisch (1987).

The chlorite "crystallinity" index (C. C.) was determined by measuring the width at half-height of the chlorite 7Å peak.

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 zinc chloride 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 350x.

Conodont color alteration index

Color alteration index (CAI) was determined on conodonts extracted from over a hundred carbonate samples collected all in Upper Permian to Middle Triassic offshore shelf carbonates, representing an only about 50 m thick marker stratigraphic interval continuous from Dolpo to Manang (Harris 1979; Rejebian et al. 1987).

Textural-mineralogical changes

During orogeny, sedimentary rocks undergo textural modifications and recrystallization, along with growth of new minerals at the expense of both framework and interstitial components, as a response to increasing temperatures in an oriented stress field. Changing textures and mineralogy with increasing metamorphic grade are used here according to methods and concepts described by Kossovskaya & Shutov (1970), Voll (1976), Powell (1979) and Frey (1987).

Results

Central Dolpo

Metamorphism progressively decreases from amphibolite facies in Lower Paleozoic calc-silicate marbles to the thick and folded Silurian-Devonian succession exposed along the upper Tarap Khola, where epizonal to upper anchizonal conditions are testified (I. C. 0.19 to 0.32 δ°2θ; Fig. 2A; Tab. 1). Metamorphic growth of muscovite, biotite and Fe-poor epidote, along with advanced quartz recrystallization and development of anastomosing cleavage with locally complete fabric realignement (Powell, 1979), indicates greenschist facies conditions.

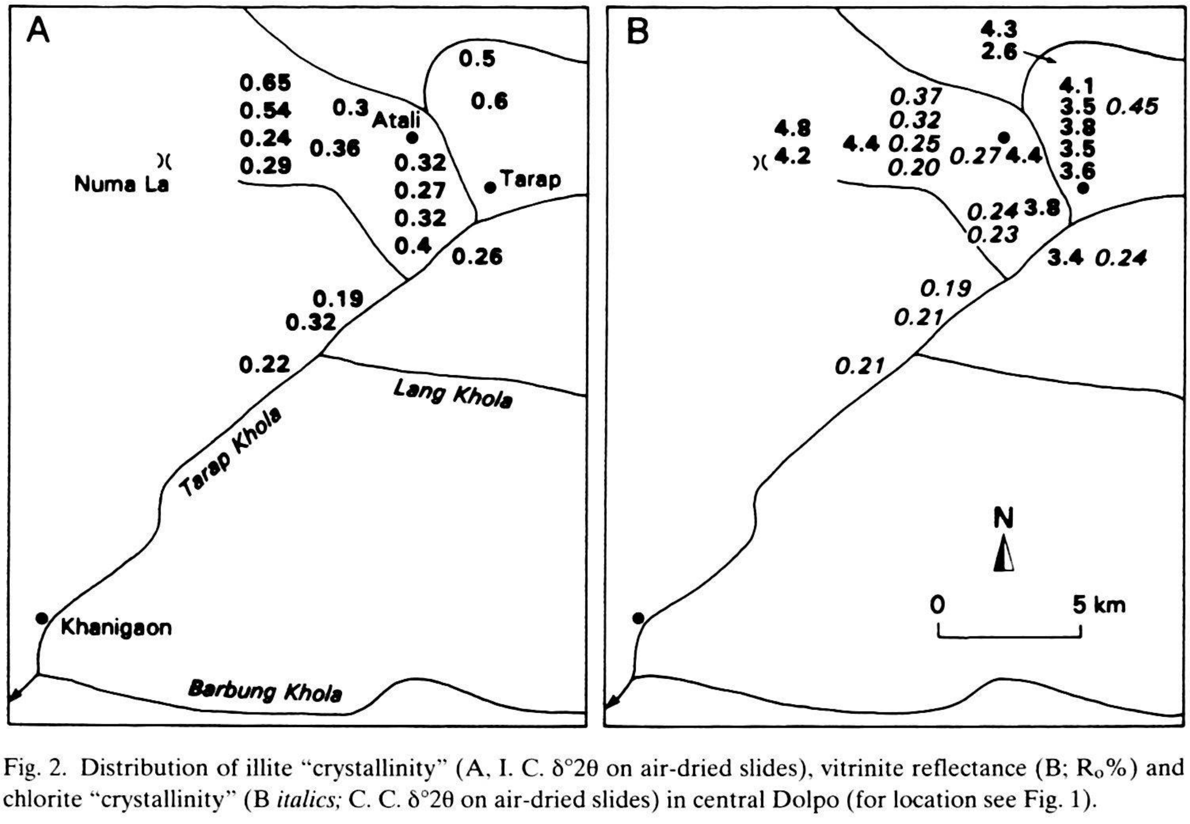


Fig. 2. Distribution of illite "crystallinity" (A, I. C. δ°2θ on air-dried slides), vitrinite reflectance (B; R_o%) and chlorite "crystallinity" (B *italics;* C. C. δ°2θ on air-dried slides) in central Dolpo (for location see Fig. 1).

Transition to the anchizone is documented in the less deformed Upper Devonian succession ("Dark pelites" of Garzanti et al. 1992, Fig. 4; I. C. 0.24 to 0.29 $\delta^{\circ}2\theta$, but for one sample where I. C. is 0.54 $\delta^{\circ}2\theta$; R_o 3.4 to 4.8%), as confirmed by oriented growth of calcite or sericite beards in pressure shadows and development of stylolitic to anastomosing cleavage.

The overlying succession, from the Permian Thini Chu Formation to the base of the Norian Tarap Shale, also indicates the anchizone (I. C. 0.27 to 0.36 $\delta^{\circ}2\theta$, but for one sample containing ordered mixed-layers, where I. C. is 0.65 $\delta^{\circ}2\theta$; R_o 3.8 to 4.4%). Pronounced migration of quartz crystal boundaries, extensive deformation and recrystallization of calcite, growth of calcite and sericite beards in pressure shadows, and develop-

AGE	LOCALITY	SAMPLES	I.C. ($\delta^{\circ}2\theta$)	Std. Dev.	C.C. ($\delta^{\circ}2\theta$)	Std. Dev.	R_o %	Std. Dev.	min %	max %	CAI	Zone
	Dolpo	**29**										
Norian	Atali North	2	0.50	----	----	----	3.5	1.2	2.1	5.1	---	2
Norian	Tarap	12	0.46	0.20	0.36	0.13	3.8	0.4	2.6	4.7	---	2
Per./m.Trias	Atali South	3	0.44	0.19	0.37	----	---	---	---	---	5	TR3
Permian	Tarap	3	0.33	0.07	0.24	0.01	3.8	---	2.8	4.5	5	3
Devonian	Numa La	5	0.36	0.16	0.26	0.06	4.5	0.3	3.5	5.5		3
Dev./Sil.	Tarap Khola	4	0.25	0.06	0.21	0.02	3.4	---	2.7	4.1		TR4
	Thakkhola	**25**										
Cretaceous	Dangardzong	2	1.30	0.07	----	----	(0.9	---	0.6	1.2)		0
Cretaceous	Kagbeni	8	1.67	0.25	0.42	0.03	1.5	0.1	0.9	2.0		0
u.Jur./Cret.	Muktinath	5	0.97	0.32	0.36	0.04	2.3	0.2	1.7	2.8		1
m.Tr./m.Jur.	Jomosom	5	0.84	0.09	0.31	0.08	2.4	0.4	1.8	3.5		1
Car./l.Trias	Thini	4	0.47	0.03	0.31	0.01	3.8	---	3.0	4.2	4½	2
Carbonif.	Dangardzong	1	0.25	----	----	----	---	---	---	---		TR4
Sil./Dev.	Marpha/Syang	2	0.45	---	0.33	----	---	---	---	---		TR4
	Manang	**30**										
Jurassic	Thorung	3	0.64	0.42	0.29	0.04	4.1	0.1	3.2	5.1		2
u.Trias	Jarsgend	6	0.37	0.16	0.27	0.07	4.5	0.2	3.4	5.8		3
u.Trias	Tilicho	2	0.57	0.03	0.27	0.02	4.0	0.1	3.2	5.2		2
Car./Per.	Tilicho	4	0.46	0.06	0.30	0.03	4.3	0.4	3.5	5.5	5	TR3
Car./Per.	Col Noir	6	0.44	0.12	0.32	0.10	4.6	0.1	3.8	5.8	5	3
Car./Per.	Manang	3	0.25	0.00	0.26	0.02	---	---	---	---	5	TR4
Car./Per.	Bangba	3	0.27	0.02	0.23	0.05	---	---	---	---	5½	TR4
Dev./Sil.	Marsyandi	3	0.22	0.02	0.20	----	3.4	---	2.1	5.0		4

Tab. 1. Illite "crystallinity", chlorite "crystallinity", vitrinite reflectance (minimum and maximum values recorded for single fragments are also given) and conodont color alteration data from the Dolpo-Manang Synclinorium and Thakkhola Graben.

ment of stylolitic cleavage with weak fabric realignement, are recorded particularly in the Tarap section, indicating eastward increasing metamorphic temperatures. Stilpnomelane growth took place at the expense of glaucony grains in topmost Permian strata. In the thick Upper Triassic succession, characterized by mostly "diagenetic" values of illite "crystallinity", very low-grade metamorphism – as indicated by widespread calcite recrystallization, growth of illite and chlorite, and incipient development of stylolitic cleavage –, was stronger north of Tarap (I. C. 0.32 to 0.6 $\delta°2\theta$; R_o 3.5 to 4.4%) and weaker north of Atali (I. C. 0.5 $\delta°2\theta$; R_o 2.6 to 4.3%; Fig. 2B), where migration of quartz crystal boundaries was less extensive and growth of calcite and sericite beards in pressure shadows uncommon.

Thakkhola

In the Tukuche area, Lower Paleozoic metacarbonates were deformed at amphibolite facies during the Tertiary Himalayan Orogeny (Bordet et al. 1971, p. 265). In the Marpha-Syang area, the mid-Paleozoic succession west of the Dangardzong Fault testifies to greenschist facies metamorphism, with development of schistosity, widespread quartz recrystallization and extensive growth of biotite, muscovite and chloritoid (Zone III of Frey et al. 1973).

Within the Thakkhola Graben east of the Dangardzong Fault, the Upper Paleozoic Thini Chu Formation at Thini documents transition to "diagenetic" conditions (I. C. 0.45 to 0.50 $\delta°2\theta$; R_o 3.8%; Fig. 3A and B; Tab. 1), with migration of quartz crystal boundaries and growth of stilpnomelane recorded up to the top of the Permian (Zone II of Frey et al. 1973).

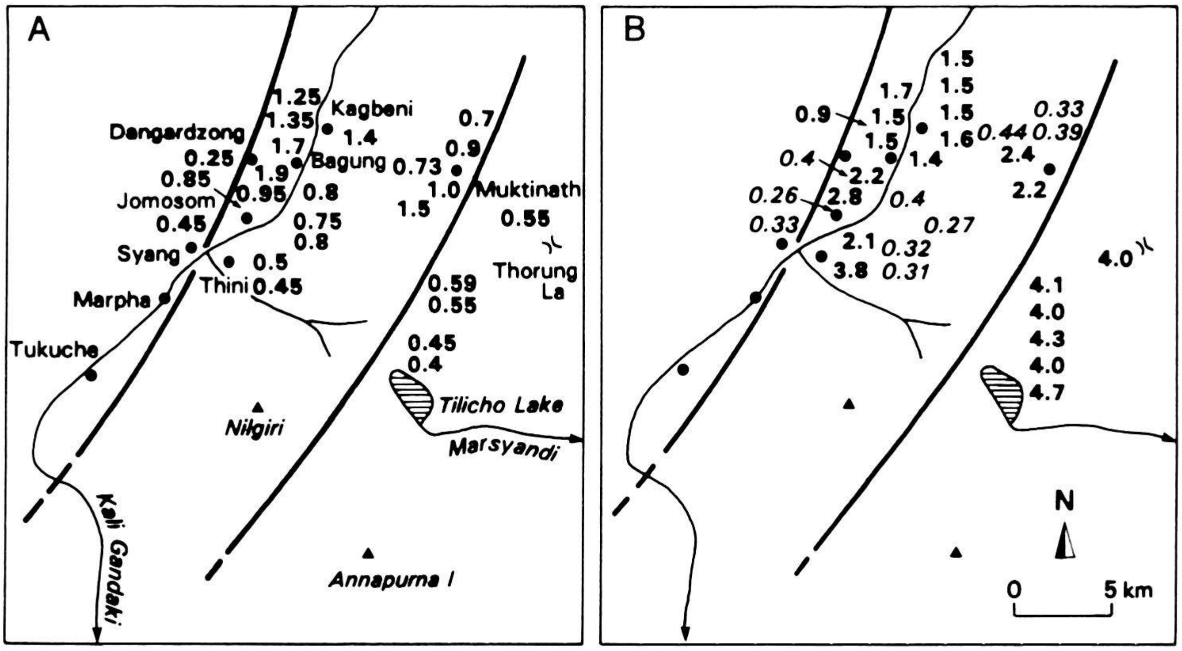


Fig. 3. Distribution of illite "crystallinity" (A; I. C. $\delta°2\theta$ on air-dried slides), vitrinite reflectance (B; R_o%) and chlorite "crystallinity" (B *italics;* C. C. $\delta°2\theta$ on air-dried slides) in the Thakkhola Graben (for location see Fig. 1). Note sharp metamorphic jump across the Dangardzong Fault; increase in metamorphic grade is more gradual across the eastern side of the graben.

Metamorphism is much weaker than in the adjacent Dolpo and Manang areas in Mesozoic strata, which show nothing more than strong diagenetic overprint. In the Upper Triassic (I. C. increasing along the Kali Gandaki valley from 0.75 $\delta°2\theta$ at Jomosom, to 0.80 $\delta°2\theta$ northward, to 0.95 south of Bagung; R_o 2.1 to 2.2%), incipient migration of quartz crystal boundaries and recrystallization of the illite-chlorite epimatrix are observed, along with post-depositional development of undulose extinction in quartz grains and rare stylolites. Micrite is locally preserved in topmost Triassic to Lower Jurassic samples. In the Middle Jurassic (I. C. 0.85 $\delta°2\theta$ and R_o 2.8% above Jomosom), micrite recrystallization and stylolite development are only incipient, detrital biotite may be unaltered and stilpnomelane is absent (Zone I of Frey et al. 1983).

Metamorphic deformation further decreases upsection. In the Lower Cretaceous of the Kagbeni area green glaucony is preserved, kaolinite and mixed-layers may be abundant, zeolite-like minerals sporadically occur and motion of quartz crystal boundaries is negligible to incipient. On the other hand, authigenic Fe-rich epidote is locally recorded, illite and chlorite predominate, strong undulatory extinction developed within quartz grains, stylolites occur and microsparite is common. A sharp metamorphic jump from "diagenesis" (I. C. around 1.3 $\delta°2\theta$ and R_o as low as 0.9% in the lowermost Cretaceous) to epizonal/anchizonal conditions (I. C. 0.25 $\delta°2\theta$ and extensive quartz recrystallization in the Upper Paleozoic Thini Chu Formation) is observed across the Dangardzong Fault on the western side of the Thakkhola Graben. Change in metamorphism is much more gradual on its eastern side. Illite "crystallinity" and vitrinite reflectance increase already within the graben from the Lower Cretaceous at Kagbeni (I. C. 1.4 to 1.9 and R_o 1.3 to 1.7%) to the Upper Jurassic-lowermost Cretaceous units cropping out around Muktinath (I. C. 0.7 to 1.5 $\delta°2\theta$; R_o 2.1 to 2.4%). To the east of the Muktinath Fault, across the Thorung La, Middle to Upper Jurassic units document eastward transition to the anchizone.

Manang

The Lower Paleozoic metacarbonates of the Nilgiri-Annapurna massif were deformed at amphibolite facies (Schneider & Masch 1993). In the Bangba area, metamorphic conditions decrease from epizonal in the Silurian-Devonian units (I. C. 0.20 to 0.23 $\delta°2\theta$, to upper anchizonal in the Carboniferous-Permian Thini Chu Formation (I. C. 0.26 to 0.30 $\delta°2\theta$; Fig. 4A; Tab. 1). In the latter unit, development of stylolitic to anastomosing cleavage and widespread "quartzitic structures", locally with oriented growth of coarse-grained sericite lamellae, document transition from the "Zone of hydromica-chlorite matrix" to the "Zone of muscovite-chlorite matrix" (Frey 1987).

Metamorphism continues to decrease regularly from anchizonal to "diagenetic" conditions both through the Carboniferous to Triassic succession, and westward along the Marsyandi Valley, from the Marsyandi/Jarsgend confluence (I. C. constantly 0.25 $\delta°2\theta$), to the Col Noir section (I. C. 0.29 in the Carboniferous to 0.57 at the top of the Permian, where stilpnomelane is recorded; R_o constantly around 4.6%), to the Tilicho section (I. C. 0.40 $\delta°2\theta$ in the Carboniferous, to 0.55 $\delta°2\theta$ at the top of the Permian, to 0.59 $\delta°2\theta$ in the Upper Triassic; R_o 4.7% in the Carboniferous to 4.0% in the Upper Triassic; Fig. 4B). Strong migration of quartz crystal boundaries, oriented growth of sericite, and incipient development of cleavage and "quartzitic structures" are observed only in Carboniferous samples from the lower part of the latter section, whereas fragile behaviour of quartz

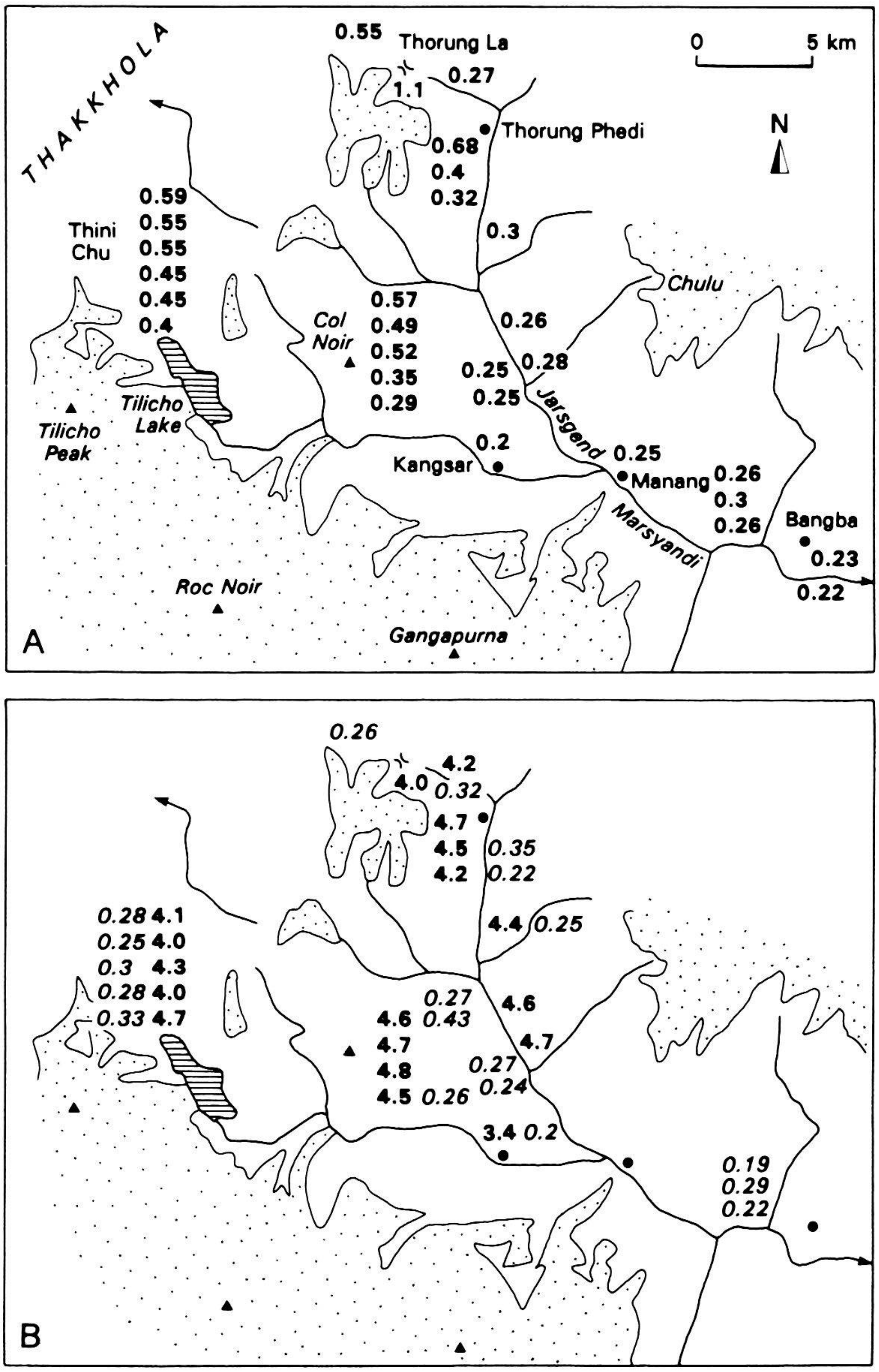


Fig. 4. Distribution of illite "crystallinity" (A; I. C. δ°2θ on air-dried slides), vitrinite reflectance (B; R_o%) and chlorite "crystallinity" (B *italics;* C. C. δ°2θ on air-dried slides) in the Manang region (for location see Fig. 1).

crystals characterizes the Permian sandstones. Also the intensity of carbonate recrystallization decreases in Triassic limestones, documenting transition to the "Zone of altered clay matrix" (Frey 1987).

Along the Jarsgend Valley, the Upper Triassic to Middle Jurassic succession still indicates the anchizone (I. C. 0.26 to 0.40 $\delta°2\theta$; R_o 4.2 to 4.7%), with widespread development of mica beards ("quartzitic structures" of Frey 1987) and calcite in pressure shadows, thorough calcite recrystallization, migration of quartz crystal boundaries with local quartz recrystallization and stilpnomelane growth.

Lower anchizonal to "diagenetic" conditions are indicated in the Upper Triassic succession above Thorung Phedi (I. C. 0.32 to 0.68 $\delta°2\theta$), where oriented growth of calcite in pressure shadows is still observed, as well as migration of quartz crystal boundaries, stilpnomelane growth and development of stylolitic cleavage (Powell 1979), and west of Thorung La towards the Thakkhola Graben (I. C. 0.55 $\delta°2\theta$). An anomalously high illite "crystallinity" value (I. C. 1.1 $\delta°2\theta$; R_o 4.0) was found in a black shale sample collected at the core of the Thorung La Syncline and containing both mixed layers and paragonite.

Conodont color

Conodonts found in mostly Lower Triassic carbonates from Dolpo to Manang are invariably black (CAI around 5). Color variations both within each sample and from sample to sample are minor, and specimens never approach CAI 6. Deformation and incipient alteration of surface textures, turning to pitted and grainy, is commonly recorded, as well as changing color of the white matter confined to the denticles (being still grey in the Thakkhola Graben and totally black in eastern Manang).

Chlorite "crystallinity"

Areal distribution of chlorite "crystallinity" is broadly consistent with that of illite (Fig. 2B, 3B and 4B). Chlorite "crystallinity" is very close to illite "crystallinity" in highly recrystallized samples (I. C. $\leq$ 0.25 $\delta°2\theta$), whereas in less and less recrystallized samples the width of the 7Å chlorite peak increases slower than the width of the 10Å illite peak (the relationships between I. C. and C. C. shown in Figure 5 of Garzanti & Brignoli 1989 are proved valid also for Nepal).

In the Dolpo-Manang Synclinorium, C. C. values range between 0.19 and 0.25 $\delta°2\theta$ in the Silurian-Devonian and between 0.19 and 0.29 $\delta°2\theta$ in the Caroniferous-Permian, with poorer "crystallinity" recorded in Thakkhola and locally also at Tilicho (C. C. 0.30 $\div$ 0.33 $\delta°2\theta$). In the Triassic-Jurassic, C. C. values are mostly comprised between 0.25 and 0.35 $\delta°2\theta$; poorer "crystallinity" characterizes the Thakkhola Graben (C. C. 0.39 $\div$ 0.40 $\delta°2\theta$), whereas C. C. values down to 0.22 $\delta°2\theta$ are recorded in the Upper Triassic of the Jarsgend Valley. The highest C. C. values were found in the Cretaceous of Thakkhola (0.40$\div$ 0.44 $\delta°2\theta$).

Kerogen composition

Due to the high thermal alteration attained by most samples ("organic metamorphism"), optical analysis on kerogen composition gave significant results only in the Upper Jurassic to Lower Cretaceous succession preserved in the Thakkhola Graben. Here a prevalence of woody fragments and herbaceous remains suggests a mostly continental origin of the kerogen for the Cretaceous Chukh Group, with possibly greater abundance of amorphous marine organic matter in the Jurassic Spiti Shale.

Discussion

Textural-mineralogical changes

Modifications of textural features and mineralogy of the Nepal Tethys Himalayan sediments progressively decrease in intensity from Paleozoic to Mesozoic units within the Dolpo-Manang Synclinorium (Tab. 2). These changes are strictly related to northward-decreasing metamorphic grade, as documented independently by illite "crystallinity", chlorite "crystallinity" and vitrinite reflectance.

Detailed observations on several hundred thin sections (mostly quartzose arenites, with subordinate carbonates, pelites and volcanic arenites) allowed recognition of seven zones of gradual transition between "diagenesis" and greenschist facies metamorphism. They correspond to Zones 1 to 4 recognized in the Zanskar sedimentary nappes (Garzanti & Brignoli 1989), with addition of a "Zone TR4" (upper anchizone and transition to the epizone), and of a "Zone TR3" (lower anchizone and transition to "diagenesis"). Finally, a "Zone 0", found only within the Thakkhola Graben and not present in the Zanskar Range, represents the lowest grade sediments recognized within the whole Himalayan Range so far.

Within *Zones 0 to 1,* micrite is largely recrystallized into microsparite, and calcite is strongly deformed and twinned. Quartz crystals show widespread post-depositional development of undulose extinction, but motion of crystal boundaries is only incipient. Stylolites are rare and appear concentrated in more pelitic portions of the rock.

Phyllosilicates are only locally recrystallized, kaolinite and mixed-layers still occur and green glaucony is preserved. Detrital biotite is altered. Authigenic Fe-rich epidote is locally abundant in volcanic arenites; prehnite and pumpellyite instead were never detected.

Within *Zones 2 to TR3,* calcite recrystallization and stylolites become widespread. Migration of quartz crystal boundaries is significant. The clay fraction is transformed into illite and chlorite, with incipient oriented growth of tiny sericite lamellae wrapping detrital grains ("pre-sericite beards") or filling fractured quartz overgrowths ("pre-quartzitic

Zones	Migration Qtz. bound.	Calcite	Phyllosilicates	Glaucony	Fabric realign.	Cleavage	Matrix structures	Authigenic Minerals
Zone 0	Incipient	Micrite/microsp.	Kaolinite and	Glaucony	None	(Stylolites)	(Un)altered	Fe-rich epidote
Zone 1	Very weak	Micrite/microsp.	mixed-layers.	Glaucony	None	(Stylolites)	Altered	
Zone 2	Weak	Microsparite	Illite-chlorite	Gl./Sti.	Very weak	Stylolites	Illite-chlor.	
Zone TR3	Medium	Pseudosparite	Pre-sericite	Gl./Sti.	Weak	Incipient	Pre-quartzite	
Zone 3	Strong	Calcite beards	Sericite beards	Stilpno.	Medium	Stylolitic	Quartzite	
Zone TR4	Recryst.	Calcite beards	Pre-muscovite	Stilpno.	Strong	Anastomosing	Pre-phyllite	
Zone 4	New cryst.	New crystals	Muscovite/Biot.	Biotite	Complete	Rough/Smooth	Phyllite	Fe-poor epidote Chloritoid

Tab. 2. Progressive textural-mineralogical changes observed in thin sections of sedimentary rocks through the seven zones of transition between "diagenesis" and metamorphism (after Kossovskaya & Shutov 1970; Frey et al. 1973; Völl 1976; Powell 1979; Frey 1987).

structures"). Stilpnomelane begins to grow in glaucony-bearing arenites (Garzanti et al. 1989). Fabric realignement and development of stylolitic cleavage are incipient.

Within *Zones 3 to TR4,* fabric realignement is medium to strong, with common oriented growth of calcite and sericite beards (or even large lamellae; "pre-muscovite") in pressure shadows, and local development of anastomosing cleavage (Powell 1979, "quartzitic" to "pre-phyllite" structures; Kossovskaya & Shutov 1970, Frey 1987). Pronounced motion of quartz crystal boundaries is observed, with incipient growth of small annealed new crystals (Young 1976). Stilpnomelane largely replaces green grains within glaucony-bearing arenite beds.

Zone 4 documents greenschist facies conditions, with growth of muscovite, biotite, Fe-poor epidote or even chloritoid in layers of suitable chemical composition. Recrystallization of quartz, calcite and phyllosilicates ("phyllite" structures) is widespread, and fabric realignement is strong to complete, with development of smooth cleavage in mudrocks and rough cleavage in sandstones.

Timing of Himalayan metamorphism

Soon after the onset of the India/Asia collision, close to the Paleocene/Eocene boundary (Garzanti et al. 1987), tectonic burial and consequent heating of the Northern India sedimentary and basement rocks took place during thrusting underneath the Transhimalayan accretionary prism (Maluski & Matte 1984, Pêcher 1989, Smith et al. 1992, Villa et al. 1992).

It is difficult to find direct evidence on the age of peak Barrovian metamorphism. Available radiometric evidence from the Nepal (Bordet et al. 1971, p. 191) to the Zanskar Tethys Himalaya sedimentary succession (Bonhomme & Garzanti 1991) indicates that the Himalayan metamorphism was not strong enough to reset the K/Ar clock of illites in the "diagenetic" field (up to Zone 2 of Garzanti & Brignoli 1989), where the obtained Cretaceous to older ages attest detrital inheritance with only weak post-depositional heating. In the anchizone, Cretaceous to Paleocene pre-collision mixed ages are still recorded (119 to 57 Ma), even though a possibly significant cluster of Middle Eocene synpost collisional ages is obtained at the transition to the epizone (47 to 44 Ma; Bonhomme & Garzanti 1991). The latter ages suggest that south of the Indus suture metamorphic recrystallization occurred about 10 m.y. after collision onset. In the katazone, both in the Tethys Himalaya and in the High Himalaya Crystalline, only Late Oligocene to Early Miocene cooling ages are obtained (27 to around 20 Ma), marking a phase of rapid tectonic unroofing (Hodges et al. 1992; Guillot et al. 1993).

According to the availble radiometric information, a duration of heating of around 20 m.y. may be assumed (from 44±5 Ma to 27±3 Ma; Spring, 1993, p. 123). Average heating rates might be tentatively estimated as 20°C/m.y. (from around 100°C at the base of the $3 \div 4$ km thick Mesozoic and Cenozoic sedimentary pile at the time of collision, to 300°C 10 m.y. later).

Tentative temperature estimates

Conversion of data obtained from analysis of various metamorphic indicators into temperatures is by no means straightforward; however, such exercise may turn useful to shed new light on the tectonic evolution of a complex mountain belt such as the Himalaya. A multi-method approach is considered essential to constrain the inferred temperature ranges and minimize errors. Vitrinite reflectance proved for instance to be most useful in the "diagenetic" field (where the sporadic occurrence of mixed-layers locally caused rapid broadening of the 10Å illite peak) up to the transition to the anchizone.

Conversely, illite "crystallinity" proved to be most reliable through the anchizone and the epizone, where very poor information is provided by vitrinite reflectance (Tab. 3).

Epizonal conditions were reached in mid-Paleozoic units both in Dolpo and Manang (Zone 4 of Garzanti & Brignoli 1989; lower greenschist facies). In the Manang area, calcite/dolomite thermometry data point to temperatures between 390°C and 460°C for these rocks and around 370°C for the overlying anchizonal Carboniferous succession (Schneider & Masch 1993), suggesting a temperature as high as 380°C for the epizone/anchizone boundary. Calcite/dolomite thermometry data recently obtained from eastern Zanskar (both with XRD and electron microprobe on iron-poor samples; Spring et al. 1993), point to similar temperatures for the epizone (380° ÷ 470°C), but somewhat lower for the anchizone (270°÷ 330°C).

In the Dolpo-Manang Synclinorium, transition to the anchizone generally occurs within the thick Upper Devonian succession. Due to the occurrence of little "overcooked" organic matter, vitrinite reflectance could be determined only in a few of these epizonal to upper anchizonal samples, where R_o may be as low as 3.4% (with minimum values down to 2.1%; Fig. 5). Such broad scatter of reflectance values is commonly observed at the transition from anthracite to meta-anthracite ASTM coal rank and ascribed to the beginning of pre-graphitization (Teichmüller 1987). The Carboniferous-Permian Thini Chu Formation mainly shows anchizonal illite "crystallinity" (R_o between 3.8 and 4.8%; anthracite ASTM coal rank; Zone 3 of Garzanti & Brignoli 1989; upper prehnite-pumpellyite facies).

In Nepal, the anchizone/"diagenesis" boundary, as defined by illite "crystallinity", corresponds with R_o invariably over 3.8% in Dolpo and Thakkhola and as high as 4.7%

Zones	I.C. (δ°2θ)	C.C. (δ°2θ)	R_o %	min %	max %	CAI	Temperature	Facies	Coalification	ASTM coal rank
Zone 0 (Catagenesis)	1.00-1.90	0.40-0.44	1.3-1.7	0.9	2.0		200°-225°C	zeolite	wet gas	low/med.-vol. bitum.
Zone 1	0.70-1.00	0.35-0.40	2.1-2.8	1.7	3.5		225°-250°C		dry gas	semi-anthracite
Zone 2 (Metagenesis)	0.42-0.70	0.25-0.35	3.5-4.3	2.6	5.2	4½	250°-275°C	lower P&P	organic met.	anthracite
Zone TR3	0.40-0.50	0.27-0.33	3.9-4.7	3.7	5.8	5	275°-300°C	middle P&P	anthracitiz.	anthracite
Zone 3 (Anchizone)	0.25-0.42	0.22-0.26	4.2-4.8	3.4	5.8	5	300°-350°C	upper P&P		anthracite
Zone TR4	0.24-0.27	0.20-0.29	(3.4)	2.7	5.5	5½	350°-380°C	Pump./Act.		meta-anthracite
Zone 4 (Epizone)	0.19-0.25	0.19-0.24	(3.4)	2.1	5.0		380°-470°C	Greenschist	graphitiz.	meta-anthr./semigr.

Tab. 3. The seven zones of transition between "diagenesis" and low-grade metamorphism in the Nepal Tethys Himalaya, with inferred temperature ranges and correspondence with metamorphic facies (Winkler 1976), illite "crystallinity" (Kisch 1987), chlorite "crystallinity" and coal rank (Teichmüller 1987). Minimum (min) and maximum (max) reflectivity values obtained on single vitrinite fragments are also given. Correlation between temperatures and conodont color (Rejebian et al. 1987) assumes a duration of heating around 20 m.y. (Bonhomme & Garzanti 1991; Spring 1993).
Out of the 84 analyzed samples, 3 high I. C. values (samples containing mixed-layers as indicated by much higher values obtained on glycolated slides and/or lower C. C.) and 2 low R_o values were discarded. Anomalous C. C. values in 4 samples bearing kaolinite (C. C. as high as 0.32 δ°2θ in Zone 3 and 0.45 δ°2θ in Zone 2) and in 3 samples from Thakkhola (C. C. as low as 0.26 δ°2θ in Zone 1 and as high as 0.33 in Zone 4) were also discarded.

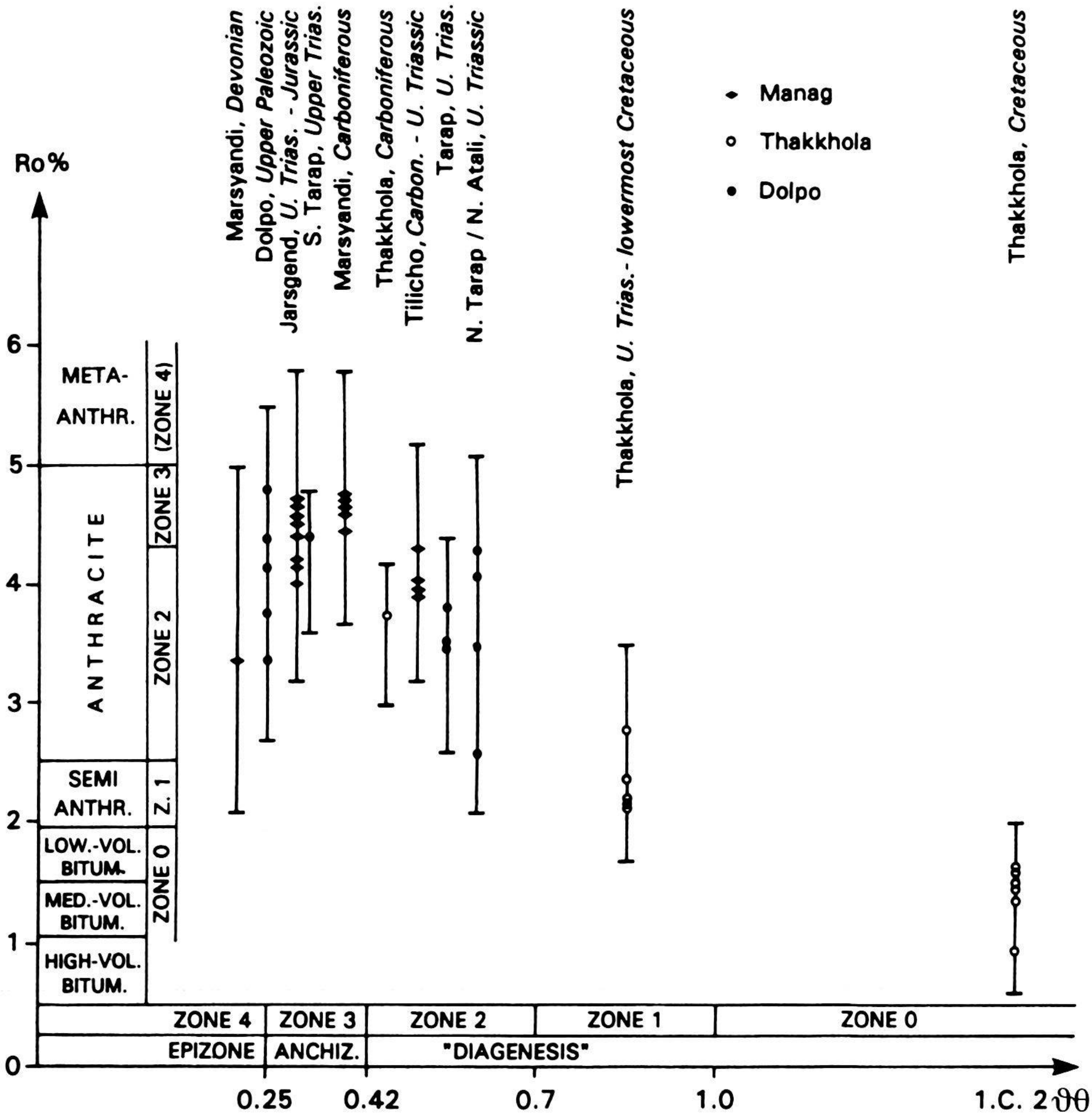


Fig. 5. Correlation between illite "crystallinity" (I. C. δ°2θ) and vitrinite reflectance (R_o%) in the Nepal Tethys Himalaya. Note how scatter of vitrinite reflectance becomes broader within the anchizone (with minimum values decreasing down to 2.1% with increasing metamorphic grade), marking the beginning of the meta-anthracite stage and the onset of pre-graphitization (Teichmüller 1987, Fig. 4.30). Boundaries between metamorphic zones (Garzanti & Brignoli 1989) are correlated with coal rank (Teichmüller 1987, Fig. 4.18) and illite "crystallinity" (Kübler 1968).

in Manang (where data are consistent and more abundant). This correlation, unusual in other sedimentary successions (Kisch 1987; M. Frey, written comm. 1993), seemingly holds true also for the Tethys Himalaya sedimentary nappes of Zanskar (Garzanti & Brignoli 1989, Tab. 1). Existing vitrinite reflectance geothermometers thus suggest temperatures close to or even above 300°C (Barker & Goldstein 1990, Fig. 3; Sweeney & Burnham 1990, Fig. 2a; Suzuki et al. 1993, Fig. 2). Temperatures in the 300°÷ 350°C range for the anchizone are independently indicated by the invariably black color of thousands of conodonts (Harris 1979, Fig. 5; Rejebian et al. 1987, Fig. 2B and 4).

Transition between the anchizone and the "diagenetic" field (I. C. between 0.45 and 0.65, R_o between 3.5 and 4.3%; Zone 2 of Garzanti & Brignoli 1989; lower prehnite-pumpellyite facies) occurs within the very thick Upper Triassic succession of central Dolpo, within the Lower Carboniferous succession of the Thakkhola Graben, and in different stratigraphic intervals (Upper Triassic to Permian and Lower Carboniferous) west of the Jarsgend Valley in Manang, towards the Thakkhola Graben. Here metamorphism decreases upsection both within the Upper Paleozoic to Triassic succession of the upper Marsyandi Valley and within the Upper Triassic to Jurassic succession of the Thorung La area. Significant upward increase of illite "crystallinity" values observed within each measured stratigraphic section independently of lithology suggests rather high geothermal gradients (Fig. 6).

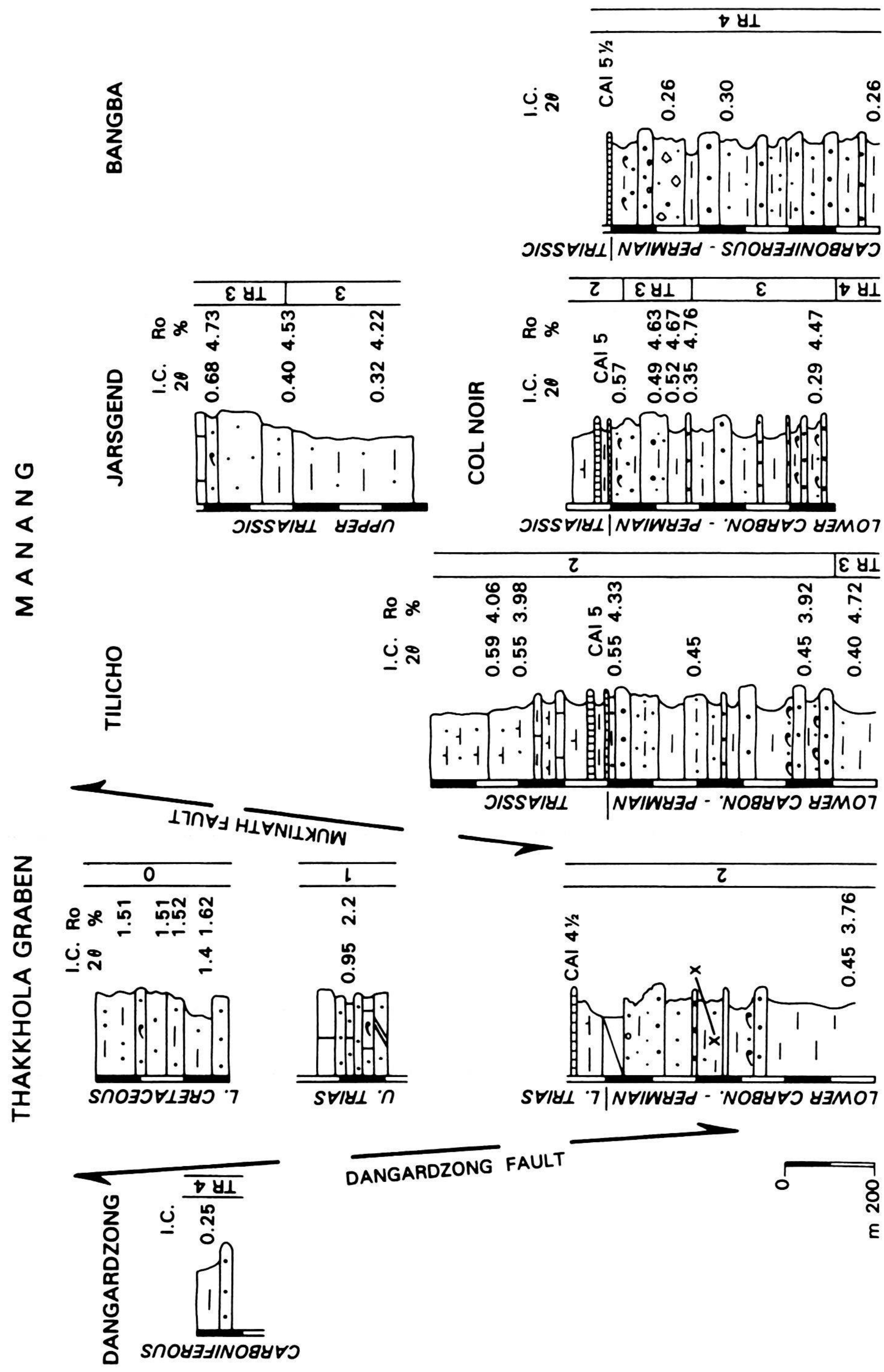
The Mesozoic succession of the Thakkhola Graben is characterized by diagenetic values of illite "crystallinity" (I. C. ≥ 0.70; $R_o < 3.0\%$). Maximum temperatures were seemingly still in the 250°÷ 300°C range at the base of the Triassic, as indicated by black color of conodonts. In the Uppermost Triassic to Middle Jurassic, vitrinite reflectance indicates the semi-anthracite ASTM coal rank, above the "wet gas floor" (R_o between 2.1 and 2.8%; Teichmüller 1987, Fig. 4.18; Zone 1 of Garzanti & Brignoli 1989). Temperatures were possibly up to around 260°C (Bostick 1979, Tab. 4; Barker & Goldstein 1990), even though values as much as 50°C lower would be calculated if a strong dependence of reflectance on duration of heating is assumed (Bostick et al. 1978 in Teichmüller 1987, Fig. 4.23; Sweeney & Burnham 1990 Fig. 2a and 5; see Barker 1991, and lively discussion by Sweeny & Burnham 1993 and by Bostick 1993, on this highly controversial point).

In the Upper Jurassic, organic matter reached a "dry gas stage" of maturation, as shown by the gas seeps burning as a holy flame in the Muktinath temple (R_o 2.2%). Lower Cretaceous samples from the Kagbeni area display instead medium to low-volatile bituminous ASTM coal rank (R_o around 1.5%; "wet gas/condensate" field; zeolite facies). These data compare well with those of Gradstein et al. (1989, Fig. 41) from the underlying Spiti Shale (average R_o 1.8%; low-volatile bituminous ASTM coal rank).

The occurrence of Fe-rich epidote in Lower Cretaceous sandstones testifies rather high diagenetic temperatures reached during the Himalayan very low grade metamorphism even at the top of the sedimentary succession preserved within the Thakkhola Graben (epidote in fact first appears over 200°C in most geothermal fields; Aumento et al. 1982; Cavarretta et al. 1982; Schiffman et al. 1984).

Temperatures probably did not exceed about 225°C, as indicated by common preservation of mixed-layers, kaolinite and glaucony (Elders et al. 1984 in Barker 1991). Similar temperatures (Bostick 1979, Tab. 4) are given by vitrinite geothermometers implying rapid response to temperature increase and stabilization after a geologically short period of heating (Barker & Goldstein 1990; see also Price 1983 in Kisch 1987, Fig. 7.2). Temperatures notably lower than 200°C, given by vitrinite geothermometers generally held to be more appropriate to derive temperature in orogenic belts (see Sweeney & Burnham 1990, Fig. 5 and cited references), are thought to be incompatible not only with occurrence of epidote but also with geological setting and deformation history of the central Nepal Tethys Himalaya.

From these considerations we estimate that well over 10 kilometers have been eroded away from both Dolpo and Manang after peak metamorphism. Only about 8 km were



THAKKHOLA GRABEN
M A N A N G
DANGARDZONG
TILICHO
JARSGEND
COL NOIR
BANGBA
DANGARDZONG FAULT
MUKTINATH FAULT
CARBONIFEROUS
L. CRETACEOUS
U. TRIAS
LOWER CARBON. - PERMIAN | L. TRIAS
LOWER CARBON. - PERMIAN | TRIASSIC
UPPER TRIASSIC
CARBONIFEROUS - PERMIAN | TRIASSIC
I.C. 2θ
Ro %
CAI 4 ½
CAI 5
CAI 5 ½
TR 3
TR 4
m 200

instead stripped from above Thakkhola prior to the formation of the graben in the Late Neogene, when very low grade metasediments as those exposed today on its shoulders were downthrown and now lie buried at a depth of several kilometers. The metamorphic jump documented across the Dangardzong Fault at Dangardzong points in fact to a difference in metamorphic temperatures of at least 150°C (and thus to a vertical throw of 5 km or more; Garzanti & Pagni Frette 1991, Fig. 3).

The missing Upper Cretaceous to Lower Tertiary original stratigraphic cover of the Tethys Himalaya passive margin can only account for less than 1 km. It is thus necessary to admit that either a stack of sedimentary nappes (belonging to the continental margin of the Indian block), or a huge oceanic allochton (similar to the Jungbwa Ophiolite of Kumaon and Spongtang Ophiolite of Zanskar), was emplaced also on top of the central Nepal passive margin succession during the earlier phases of collision in the Early Eocene (Garzanti et al. 1987). These rocks have been later eroded in the course of the Late Tertiary and Quaternary evolution of the chain.

Conclusions

In the late Early Tertiary, as a consequence of the India-Asia collision, the Central Nepal Tethys Himalayan sedimentary succession underwent very low to medium-grade metamorphism during thrusting underneath the Asian active margin.

In the sedimentary rocks of the Dolpo-Manang Synclinorium, metamorphism increases progressively southward, reaching greenschist to amphibolite facies in Devonian to Lower Paleozoic units. Evidence of inverse metamorphic zonation was never recorded, contrary to what commonly observed in the Zanskar sedimentary nappes (Garzanti & Brignoli 1989, p. 679; Spring et al. 1993).

The epizone/anchizone boundary, estimated through calcite/dolomite thermometry data to correspond to temperatures as high as 380°C, typically occurs within thick Upper Devonian pelites (Tilicho Pass Fm.). The anchizone/"diagenesis" boundary is generally testified within thick Upper Triassic pelites (Tarap Shale), even if in the upper Jarsgend Khola the anchizone reaches into the Middle Jurassic, whereas it hardly extends up to the Lower Carboniferous within and just east of the Thakkhola Graben. In the Tethys Himalaya from Zanskar to Nepal, the anchizone/"diagenesis" boundary, as defined through illite "crystallinity", corresponds to unusually high vitrinite reflectance ($R_o \geq 4\%$). Temperatures around 300°C, significantly higher than those inferred in most sedimentary basins, are thus indicated.

Within the graben, the whole Mesozoic succession is characterized by poor "crystallinity" of illite and chlorite and by low vitrinite reflectance, suggesting that only the "wet to dry gas stage" of maturation was reached (as shown by the holy gas seeps of the Muktinath temple), at low maximum temperatures (indicatively between 200° and 250°C).

Fig. 6. Distribution of illite "crystallinity", vitrinite reflectance and conodont color alteration in selected measured stratigraphic sections (Manang region and Thakkhola Graben). Note how illite "crystallinity" regularly decreases upward throughout most of the sections and westward from Bangba to Thakkhola. Vitrinite reflectance is more erratic in the upper anchizone due to onset of pre-graphitization (see Fig. 5). Note metamorphic jumps on both sides of the Thakkhola Graben, across the Muktinath Fault and particularly sharp across the Dangardzong Fault.

Different geometries of isograds characterize the two sides of the graben. A sharp metamorphic jump from epizonal/anchizonal (Zone TR4) to catagenetic conditions (Zone 0) – corresponding to a temperature jump of at least 150°C – is recorded across the Dangardzong Fault at Dangardzong. Illite "crystallinity" and vitrinite reflectance tend instead to increase gradually in the eastern part of the graben, until a minor metamorphic jump from semi-anthracite (Zone 1) to anthracite coal rank (Zone 2) is observed across the Muktinath Fault at Muktinath (Fig. 3). Metamorphism continues to increase eastward, until the anchizone is reached along the Jarsgend Valley.

In Manang, progressive vertical decrease of metamorphism from the anchizone to "diagenesis", observed in Carboniferous to Triassic continuous stratigraphic successions measured and sampled in the upper Marsyandi and Jarsgend valleys (Fig. 6), points to significant geothermal gradients during Himalayan metamorphism.

The latter most probably started at Middle Eocene times and lasted until the Early Miocene, when detachment normal faulting led to exhumation and cooling of the High Himalayan nappe pile. Gradients of 25 to 30°C/km would imply post-metamorphic erosion of a rock overburden over 10 km thick above Dolpo and Manang and only 7 to 8 km thick above the Thakkhola Graben. The nature of the tectonic cover under which the Tethys Himalayan sediments have been deformed and metamorphosed during the Tertiary Himalayan Orogeny – possibly an overthrust wedge belonging, to the Asian subduction complex – remains hypothetical.

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