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STRATIGRAPHIC SUCCESSION OF THE THAKKHOLA REGION (CENTRAL NEPAL) - COMPARISON WITH THE NORTHWESTERN TETHYS HIMALAYA

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Riassunto. La successione stratigrafica della alta valle Kali Gandaki (Thakkhola, Nepal centrale) inizia con potenti carbonati di piattaforma di età cambro?-ordoviciana, seguiti nel Siluriano e nel Devoniano da unità pelitiche deposte in ambienti più profondi e a tassi di accumulo molto più elevati rispetto alle coeve formazioni dell'Himalaya nord-occidentale. Durante il Carbonifero inferiore si depositarono calcari fossiliferi, seguiti nel Carbonifero superiore e nel Permiano da una potente alternanza di peliti, quarzareniti e calcari bioclastici. La presenza di lacune e discordanze stratigrafiche in questa unità documenta la fase tettonica distensiva che portò all'apertura della Neotetide. La successione triassica e giurassica del Nepal centrale mostra caratteristiche analoghe a quelle riscontrate lungo tutta la zona sedimentaria dell'Alto Himalaya. Per la forte subsidenza termo-tettonica, il margine meridionale della Neotetide in via di formazione venne ricoperto nel Triassico inferiore da un mare sempre più profondo, in cui andavano depositandosi calcari nodulari ad Ammoniti, seguiti da marne e calcari marnosi di età da anisica a carnica. Nel Norico la velocità di accumulo aumentò con la deposizione di una potente alternanza di peliti e arenarie quarzo-feldspatiche, alimentate dal ringiovanimento del continente indiano situato a meridione. Il passaggio a detrito esclusivamente quarzoso nel Retico sembra suggerire rilievi via via meno pronunciati o condizioni climatiche più umide, con maggiore alterazione chimica in suoli e depositi temporanei. Nel Giurassico inferiore, calcari di piattaforma, spesso oolitici, furono seguiti da areniti ibride bioclastiche di età bajociana-bathoniana. Un orizzonte a ooidi ferruginosi, che nel Calloviano inferiore segnò un momento di sedimentazione condensata in tutta la zona sedimentaria dell'Alto Himalaya, venne seguito dalla deposizione di argille nere ad Ammoniti in condizioni di piattaforma relativamente profonda.

L'evoluzione sedimentaria cretacea fu influenzata dalla frammentazione finale del supercontinente di Gondwana e dalla apertura dell'Oceano Indiano. Nel Neocomiano, il rapido aumento del detrito quarzo-feldspatico, proveniente dalla erosione del continente indiano in sollevamento, fu seguito dalla deposizione di potenti arenarie deltaiche ricche di frammenti di roccia vulcanici. Al termine della fase distensiva, la progradazione verso nord dei prismi deltizi si arrestò, ed essi furono ricoperti da un intervallo condensato glauconitico, seguito nell'Albiano superiore da marne pelagiche a Foraminiferi in facies di Scaglia.

Nel Terziario, in seguito alla collisione tra India e Asia, la successione sedimentaria si è scollata ed è stata coinvolta nella deformazione. Il metamorfismo, che nelle unità mesozoiche non ha superato condizioni pre-an-

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chizonali, ha raggiunto il grado medio alla base della successione Paleozoica, ed è stato seguito dal sollevamento, dalla formazione del graben della Thakkhola, e dalla deposizione di potenti sedimenti fluvio-lacustri nel Plio-Pleistocene.

Abstract. The stratigraphic succession of the Thakkhola region (central Nepal) begins in the Cambro-Ordovician with thick shallow-water carbonates, followed in the Siluro-Devonian by pelitic units deposited in deeper-water environments and at much higher accumulation rates with respect to the northwestern Himalaya sequence. During Carboniferous and Permian times, shallow-water limestones and coarse quartzose arenites were deposited, with major unconformities related to the initial opening of Neotethys. The following Triassic to Jurassic sedimentary units display comparable features all along the Tethys Himalaya. Owing to strong thermo-tectonic subsidence, the newly-formed Indian margin was rapidly drowned in the Early Triassic, and covered by thick marly limestones in Anisian to Carnian times. The Norian was characterized by very fine-grained quartzo-feldspathic detritus derived from the rejuvenated Indian foreland, while exclusive quartzose detritus suggests latitudinal drift towards more humid climates or more subdued relief in the Rhaetian. Shallow subtidal Early Jurassic limestones were covered in the Bajocian-Bathonian by bioclastic hybrid arenites, capped by a widespread condensed ironstone in the Early Callovian. In the Late Jurassic, black shales were deposited in outer shelf-slope conditions.

The Cretaceous sedimentary evolution was related to the final fragmentation of Gondwanaland and initial opening of the Indian Ocean. Renewed quartzose detritus in the early? Neocomian was followed by deposition of thick deltaic to shallow-marine sandstones invariably characterized by abundant volcanic rock fragments. The northward-prograding deltaic complexes were overlain by a glauconitic condensed section, followed by late Albian pelagic marls. After the onset of collision between India and Asia, the sedimentary units were involved in fold-thrust deformation at pre-anchimetamorphic to medium metamorphic grade, followed by uplift, formation of the Thakkhola graben and deposition of thick fluvio-lacustrine sediments in the Plio-Pleistocene.

Introduction.

The upper Kali Gandaki Valley (Thakkhola) is a northeast-southwest oriented graben situated north of the High Himalaya Chain between the Annapurna and Dhaulagiri massifs, and capped by thick fluvio-lacustrine sediments of Plio-Pleistocene age (Fort et al., 1980). In this area (Fig. 1), a stratigraphic succession belonging to the Tethys Himalaya Zone and ranging in age from the Early Paleozoic up to the late Early Cretaceous crops out. These sedimentary rocks were deposited on the northern continental margin of the Indian Plate, and were crumpled, stacked and deformed as a consequence of collision between India and Eurasia in the early Eocene (Garzanti et al., 1987; Searle et al., 1987). The Thakkhola region is of considerable geological interest, for in this narrow downthrown block post-Jurassic rocks escaped erosion, while they underwent strong uplift in the latest million years and were completely removed in the adjacent Dolpo and Manang regions (Fuchs, 1977; Fuchs et al., 1988). Since India detached from the southern Gondwana landmass in the Early Cretaceous, the Thakkhola region is one of the few sites in the central Himalaya where such evolution can be reconstructed from the rock record.

During the october 1989 Ev-K2-CNR expedition, after a short reconnaissance work in the Paleozoic units (Tukuche - Thini - Dangardzong area), we focused on the Mesozoic succession (Jomosom - Kagbeni - Muktinath area), dedicating particular attention to the terrigenous clastic units. 161 samples have been collected in the field while measuring stratigraphic sections or sedimentologic logs.

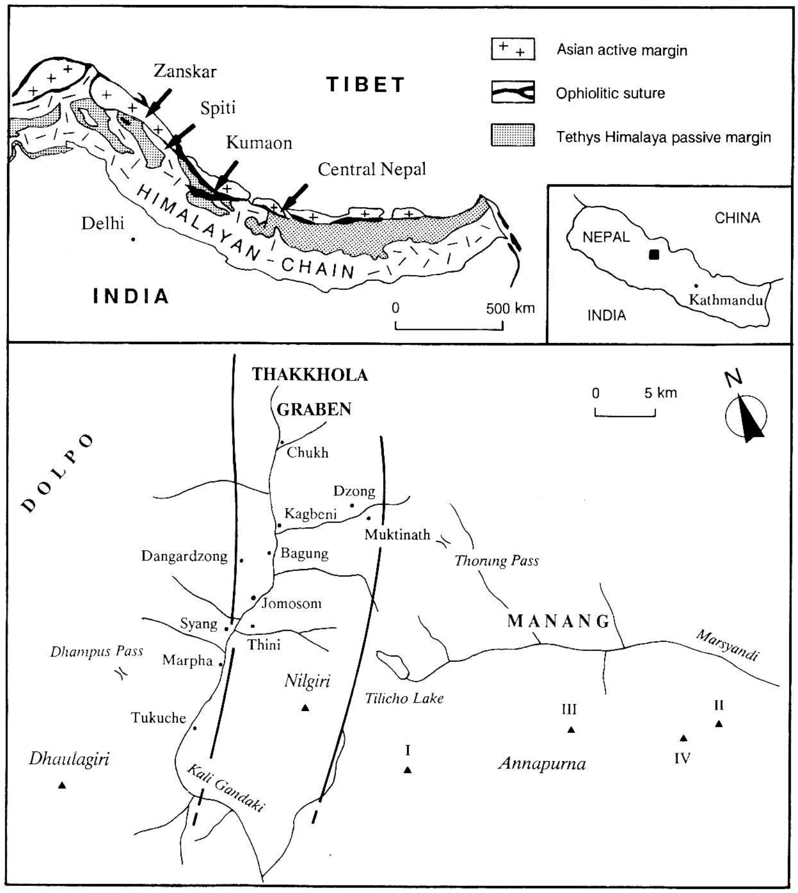

Fig. 1 - Location map of the studied area, with the geology of the Himalayan Chain shown in inset.

The purpose of the present work, which is a preliminary report of the expedition, is to describe briefly a complete stratigraphic section through the Tethys Himalaya margin. Provenance of terrigenous detritus and sedimentary evolution of Mesozoic units will be dealt with in detail in subsequent articles. In this paper the Mesozoic stratigraphic nomenclature used by various scientific parties who worked in the Thakkhola region in the past thirty years is briefly reviewed (Fig. 2). Also, the Thakkhola succession is compared with the sedimentary units exposed to the west in Kumaon, Spiti, and particularly in the northwestern Himalaya (Zanskar Range). The latter area has been studied in great detail during the past ten years by our Italian research team (Gaetani et al., 1986; Gaetani & Garzanti, 1991).

In the following description of the central Nepal succession we adopted formational names that are both long-established and widely used in the Himalayan litera-

ZANSKAR	SPITI	KUMAON	CENTRAL NEPAL		CENTRAL NEPAL NOMENCLATURE ACCORDING TO PREVIOUS AUTHORS					
Gaetani & Garzanti, 1991	Fuchs, 1982	Heim & Gansser, 1939; Sinha, 1989	This work		Gradstein et al., 1989	Fuchs, 1977; Fuchs et al., 1988	Bassoullet & Mouterde, 1977		Bordet et al., 1967, 1971	Bodenhausen et al., 1964
Chikkim-Fatu La		"Upper flysch"		MUDING	Dzong			Muding	"calcaires de teinte claire"	
Giumal	Giumal	Giumal	CHUKH GROUP	DZONG (b) DZONG (a) KAGBENI DANGARDZONG	Muding Kagbeni Kagbeni Chukh		CHUKH	Dzong Dzong Kagbeni ?	"grès verts" "grès verts" "g. à plantes" "g. brunâtres"	Tangbe (Chukh) (Checkpost)
Spiti Fe Oolite Laptal Kioto Quartzite (c)	Spiti "Dogger" (Fe Ool. & lumachelles) Kioto Quartzite	Spiti Fe Oolite Laptal Kioto		SPITI Fe OOLITE LAPTAL KIOTO QUARTZITE	Nupra Bagung Bagung Jomosom Thini	Spiti --- Lumachelle Kioto Quartzite		Spiti Fe Oolite Lumachelle Jomosom Quartzite	"Malm" "Callovien" "Bajoc.-Bath." "Lias" "Rhétien"	(Saligram) Ferruginous Beds upper Lumachelle Jomosom lower Lumachelle
Quartzite (a, b) Zozar - Hanse Tamba Kurkur	Juvavites-Monotis Daonella-Tropites Scytho-Anisian	Kuti Kalapani Chocolate	THINI-GAON GROUP	TARAP MUKUT TAMBA KURKUR		Tarap Mukut Tamba Kurkur		Thinigaon c Thinigaon b Thinigaon a	"Trias sup." "Trias moy." "Trias inf."	Thinigaon

Fig. 2 - Mesozoic lithostratigraphy of the northwestern (Zanskar, Spiti) and central (Kumaon, Nepal) Himalaya. Nomenclature adopted in the present paper is compared with that proposed for the central Nepal succession by previous research teams.

ture (Fig. 2). In fact we feel that, given the still imprecise knowledge of internal stratigraphy and age of many units and the paucity of available toponyms, the confusion generated by the proliferation of new local terms will rapidly dim what Himalayan sequences have in common. For the Paleozoic succession the adopted nomenclature is after dutch authors (Bodenhausen et al., 1964), who established the basic stratigraphy of Thakkhola in their pioneering 1962 expedition. Nomenclature for the Triassic and Jurassic is after Fuchs (1977; Fuchs et al., 1988), while for the Cretaceous it is after Bassoullet & Mouterde (1977). Only at the base of the Cretaceous have detailed stratigraphic and petrographic observations allowed us to distinguish formally a new quartzose unit (Dangardzong Fm.) from the overlying volcaniclastic sequences.

The Paleozoic sedimentary succession.

"Basement".

Intensity of multiphase Tertiary metamorphic deformation rapidly increases southward along the Kali Gandaki Valley. A major metamorphic gap occurs across the Dangardzong Fault, separating pre-anchizonal Mesozoic deposits at Jomosom from mid-Paleozoic greenschists (biotite zone) at Syang and Marpha (Fig. 3). This temperature jump (in excess of 100°C, as indicated by vitrinite reflectance data) points to a vertical throw possibly even greater than the 3 km indicated by previous authors (Bodenhausen et al., 1964; Bordet et al., 1971).

Metamorphism continues to increase southward, reaching amphibolite facies in Early Paleozoic metacarbonates south of Tukuche. Many uncertainties therefore exist about this metamorphic lowermost part of the Tibetan sedimentary succession ("Ante-Llanvirnian formations" of Colchen et al., 1986), which is detached above the High Himalaya Crystalline and forms the backbone of the Annapurna and Dhaulagiri massifs. Metasedimentary units are also found involved within the highly metamorphic "Tibetan Slab", and the continental basement of the Tibetan Series is unknown (Le Fort, 1975).

To the east, the disharmonic contact between the isoclinally folded "infrastructure" and the more openly folded "superstructure" corresponds to a regional metamorphic gap, with transition from sillimanite to greenschist facies within a few hundred metres, and also represents the floor of leucogranitic intrusions, such as the Manaslu pluton (Le Fort, 1988). In other parts of the Himalaya such contact is a major normal fault, formed due to culmination collapse at a late stage of Tertiary deformation (Burg et al., 1984; Burchfiel & Royden, 1985; Herren, 1987).

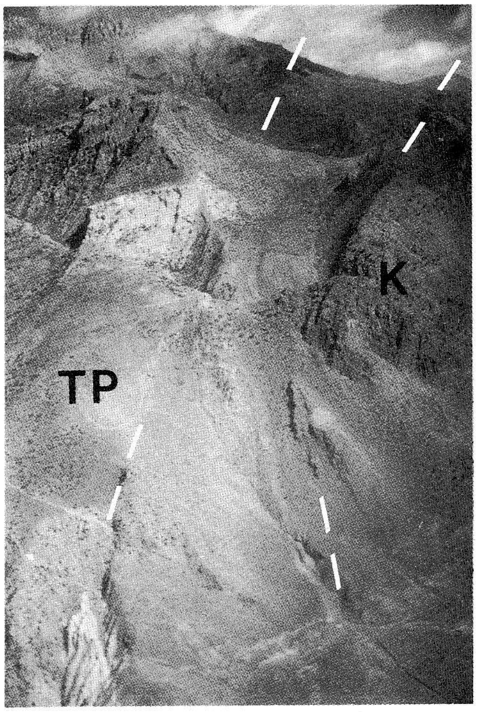

Fig. 3 - The Dangardzong Fault (Hagen, 1959; aerial view from south to north), which along the Jomosom-Dangardzong ridge separates low-grade Devonian metapelites (TP = Tilicho Pass Fm.) from pre-anchimetamorphic Jurassic sediments (K = Kioto Limestone).
This late trans-tensional fault, with both vertical and sinistral components of some km, is the major tectonic feature of the Thakkhola graben. The formation of the latter has been probably controlled by the Precambrian grain of the Indian foreland (Gansser, 1964; Bordet et al., 1971, p. 264).

Cambrian? and Ordovician.

The oldest dated sedimentary unit of the central Nepal succession consists of very thick ochre-weathering shallow-water limestones, showing ripple marks, low to high-angle cross-lamination and bioclastic layers with orthid brachiopods, gastropods, bivalves, nautiloids and crinoids (Dhaulagiri - Nilgiri - Drongkhang Limestones; Colchen et al., 1986). An early Middle Ordovician (Llanvirnian) brachiopod fauna was found in the lower part of the Nilgiri Limestone (Bordet et al., 1967), while highly metamorphosed units seemingly belonging to the same carbonate complex possibly extend down into the Cambrian (Annapurna - Larjung - Mutsog metacarbonates; Bodenhausen et al., 1964; Fuchs et al., 1988).

The Nilgiri Limestone is overlain by the North Face Quartzite, which consists of sandstones, siltstones and carbonates containing a brachiopod-echinoderm fauna of Late Ordovician (Caradoc?) age (Bordet et al., 1971).

No trace of Ordovician molassic conglomerates, typical of the Zanskar-Spiti Synclinorium (Fuchs, 1982; Garzanti et al., 1986), are found in the Thakkhola region. Clastic influences however are observed in the upper part of the Dhaulagiri Limestone in western Dolpo (Fuchs, 1977), while conglomerates occur further to the west in Kumaon (Ralam Series, tentatively ascribed to the basal Cambrian by Heim & Gansser, 1939; Sinha, 1989).

Evidence is too scanty to conclude that the central and northwestern Himalaya were part of the same continental margin at the onset of the Phanerozoic. Certainly the vast area of Central Asia affected around the Cambrian-Ordovician boundary by Late Pan-African granitoid intrusions (Garzanti et al., 1986; Le Fort et al., 1986; Stutz & Thöni, 1987) extended up to the Nepal Himalayas (Le Fort, 1988), suggesting that the latter region was part of Gondwanaland at least from the Ordovician onward.

Silurian and Devonian.

Higher up in the sequence, which is invariably quite disturbed tectonically, a dark pelitic unit (Dark Band Formation) is commonly observed at the core of refolded or north-verging recumbent antiforms (Fig. 4). The Dark Band Fm. is ascribed to the Early Silurian (Llandovery) after the first graptolite finding in the Himalayas (Strachan et al., 1964). Dark limestones and marls in the upper part of the unit yielded late Early Devonian (late Siegenian-early Emsian) monograptids and tentaculitids (Bordet et al., 1967, 1971).

The sequence continues with the hundred m-thick grey pelites of the Tilicho Pass Formation. In the upper part, micaceous siltstones and grey-green up to fine grained sandstones in beds up to 1 m thick, commonly displaying sharp base and lenticular or convolute lamination, intercalate with yellow-weathering metric carbonate beds associated with ferruginous layers.

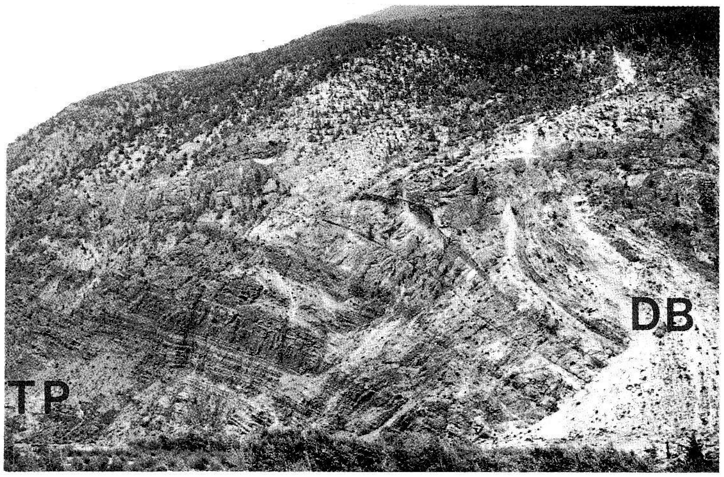

Fig. 4 - Recumbent north-verging antiform in mid-Paleozoic units in front of Marpha, on the eastern bank of the Kali Gandaki (DB = Dark Band Fm.; TP = Tilicho Pass Fm.).

Corals or brachiopods of Middle Devonian (late Eifelian-Givetian) age were found in the lower-middle part of the unit both in the Thakkhola (Bordet et al., 1967, 1971) and Dolpo regions (Fuchs, 1977), while in the Manang area the middle-upper part yielded Late Devonian (Frasnian) conodonts (Fuchs et al., 1988).

The Silurian and Devonian sediments of central Nepal show a marked difference and were deposited in a deeper environment with respect to the northwestern Himalaya, where this period was characterized by the supermature beach quartzarenites of the Muth Fm. (Srikantia, 1981; Fuchs, 1982; Gaetani et al., 1986). Lateral transition from chiefly basinal pelites to exclusively shallow-water carbonates and coastal quartzarenites progressively took place across the Dolpo and Kumaon regions (Fuchs, 1977; Sinha, 1989).

Carboniferous and Permian.

The fossiliferous Tilicho Lake Formation (Ice Lake Fm. of Bodenhausen et al., 1964) unconformably overlies the Tilicho Pass Formation and contains fenestellid bryozoans, productid and spiriferid brachiopods, corals, bivalves, crinoids, conodonts and ammonoids of Early Carboniferous age (Tournaisian-early Visean; Bordet et al., 1971; Fuchs et al., 1988).

The overlying Thini Chu Formation is much thicker and consists of several metric to decametric quartzarenite intervals alternating with dark pelites, hybrid arenites and fossiliferous grey limestones yielding fenestellid bryozoans, spiriferid and productid brachiopods, crinoids, corals, trilobites and forams. Fine to coarse-grained snow-white quartzarenites display low-angle to trough cross-lamination and herring-bone structures. The unit spans from the late Visean to the latest Permian and consists of different intervals separated by major hiatuses (Colchen et al., 1986). Unfortunately the internal litho- and bio-stratigraphic subdivisions are still imprecisely defined since the lower pelitic part is poorly fossiliferous and the brachiopods collected in the central part gave inconsistent ages (Bordet et al., 1971, p. 110). While productids suggest a late Visean to Namurian age, spiriferids point to correlation with the younger (Early Permian) "*Eurydesma*"- bearing units of the northwestern Himalaya ("Agglomeratic Slates" of Kashmir; Bion & Middlemiss, 1928; Reed, 1932; Chumik Fm. of Zanskar; Gaetani et al., 1990). Spiriferid brachiopods contained in the uppermost part, where ferruginous or coal layers occur, indicate a Late Permian age (Bordet et al., 1971). Mid to Late Permian units yielding similar faunal assemblages were found in central Dolpo (Waterhouse, 1966; Garzanti et al., 1991), and in western Dolpo (Waterhouse, 1978), where they rest disconformably upon Devonian strata (Fuchs, 1977).

The major hiatuses contained within the Thini Chu Fm. are observed in many Tethys Himalayan sections up to the Spiti region (Jain et al., 1980; Fuchs, 1982), and may document erosion or non-deposition during uplift related to the initial opening of Neotethys (Baud et al., 1989b; Gaetani & Garzanti, 1989, 1991). If this interpretation is correct, the Permo-Carboniferous rift sequence, with locally preserved mid-Permian basaltic lavas and continental clastics and tilloids (Colchen et al., 1986), progressively filled downthrown hemigrabens and gradually onlapped the shoulders of the rift. The thickness of the Permo-Carboniferous succession in fact significantly decreases from several hundred m in the Manang and Thakkhola regions to a few tens of m of Upper Permian strata in western Dolpo (Fuchs et al., 1988).

The lithology, age and depositional environment of the Tilicho Lake and lower-middle Thini Chu units broadly compare to those of the Lipak, Po and Chumik Formations of the northwestern Himalaya (Gaetani et al., 1990) and with the Syringothyris Limestone, Fenestella Series and Agglomeratic Slates of Kashmir (Middlemiss, 1910). Also the Early Permian foreland sequences are characterized by onset of rift volcanism and widespread clastic deposition at the close of the Gondwanian glaciation, from the Lesser Himalaya (Agglomeratic Slates in Kashmir, Blaini Boulder Beds in Kumaon, Sisne Fm. in central Nepal; Sakai, 1983; Sinha, 1989) to the Indian Peninsula and Salt Range (Talchir Boulder Beds; Gansser, 1964). In the northwestern Himalaya, transgressive marine arenites are followed by the Panjal Trap intraplate basaltic lavas (Gaetani et al., 1990).

The final marine transgression on the newly-formed actively subsiding passive continental margin facing Neotethys occurred everywhere in the Late Permian, from the Chhidru Fm. of the Salt Range (Pakistani-Japanese Research Group, 1985) to the Zewan and Kuling Fms. of the northwestern Himalaya, up to the Canning and Bonaparte Basins of northwestern Australia (Archbold, 1987; Boote & Kirk, 1989; Gaetani & Garzanti, 1991).

The Mesozoic sedimentary succession.

Thinigaon Group (Bodenhausen et al., 1964 - Thakkhola).

The Permo-Triassic boundary (Bassoullet & Colchen, 1977; Baud et al., 1989a), often covered in the studied area, is followed by a calcareous to terrigenous sequence exposed between Thini and Jomosom and originally designated as Thinigaon Formation (Bodenhausen et al., 1964). Subsequently, the latter was subdivided into three members (Bassoullet & Mouterde, 1977), which were given formation rank and traced throughout the Manang-Dolpo Synclinorium (Fuchs, 1977; Fuchs et al., 1988). In the present paper we adopt Fuchs' terminology and the name Thinigaon is consequently elevated to the rank of group, the corresponding unit in the Spiti-Zanskar Synclinorium being the Lilang Group.

Tamba Kurkur Formation (Srikantia, 1981 - Spiti).

Grey to reddish nodular limestones, a few tens of m thick and containing conodonts and ammonoids of Scythian to early Anisian age (Fuchs et al., 1988), occur up to the Zanskar-Spiti Synclinorium (Srikantia et al., 1980; Nicora et al., 1984). These condensed deposits testify to fairly deep depositional environments, rapid thermotectonic subsidence and reduced sedimentation rates immediately after break-up (Gaetani & Garzanti, 1991).

Mukut Limestone (Fuchs, 1967 - Dolpo).

The Mukut Lst. consists of alternating thin-bedded marls and marly limestones a few hundred m thick and containing crinoids, brachiopods, bivalves, conodonts and ammonoids of late Anisian to latest Carnian-earliest Norian age (Fuchs et al., 1988). The unit, deposited in mixed terrigenous-carbonate offshore environments, correlates with the condensed Kalapani Limestone of Kumaon (Heim & Gansser, 1939; Sinha, 1989), with the Daonella Shale, Daonella Limestone, Halobia Limestone, Grey Beds and Tropites Limestone of Spiti (Hayden, 1904; Fuchs, 1982) and with the Hanse and Zozar Formations of Zanskar (Gaetani et al., 1986).

Tarap Shale (Fuchs, 1967 - Dolpo).

Poorly fossiliferous grey pelites interbedded with very fine-grained orange-weathering decimetric arkoses and subarkoses showing sharp base and hummocky cross-lamination are exposed north of Jomosom along the eastern bank of the Kali Gandaki. Up to metric sandstone bars display low-angle cross-lamination. The unit, some hundred m thick, is ascribed to the Norian (Fuchs, 1977; Fuchs et al., 1988) and was deposited on a terrigenous storm-dominated shelf mostly above average storm wave base. The Tarap Shale correlates with the Kuti Shale of Kumaon (Heim & Gansser, 1939; Sinha, 1989), with the Juvavites Beds, Coral Limestone and Monotis Shale of Spiti

(Hayden, 1904; Fuchs, 1982) and with members a) and b) of the "Quartzite Series" of Zanskar (Jadoul et al., 1990).

The significant increase of quartzo-feldspathic terrigenous detritus recorded in the early Norian all along the Himalaya may be ascribed to rejuvenation of the southern Indian foreland during a major episode of extensional tectonic activity (Gaetani & Garzanti, 1991).

"Quartzite Series" (Hayden, 1904 - Spiti).

The formational name "Quartzite Series" has been used in central Nepal by most authors (Bassoullet & Mouterde, 1977; Bassoullet et al., 1986; "Quartzite Beds" of Fuchs, 1977; Fuchs et al., 1988). Other names have been introduced ("lower Lumachelle" of Bodenhausen et al., 1964; Thini Fm. of Gradstein et al., 1989), but they are rather unfortunate. In fact, the term "lumachelle" is widely used to designate a Dogger stratigraphic unit ("upper Lumachelle" of Bodenhausen et al., 1964) and the name Thini has already been given to the underlying Permo-Carboniferous (Thini Chu Fm.) and Triassic (Thinigaon Gr.) strata. Moreover, the "Rhaetian" quartzarenites are not exposed at Thini village. We feel that paucity of toponyms does not justify having two "Tilicho" followed by three "Thini" units, and rather prefer to maintain the long-established name "Quartzite Series" for this late? Norian-Rhaetian unit which can be traced all along the Himalaya (G. Fuchs, pers. comm. 1990).

Our reference section crops out along the western bank of the Kali Gandaki about 3 km north of Jomosom (JO3 section of Gradstein et al., 1989). Observations on another (JO4) section, some intervals of which unfortunately are severely affected by tectonics, were made at Jomosom along the eastern bank of the Gandaki.

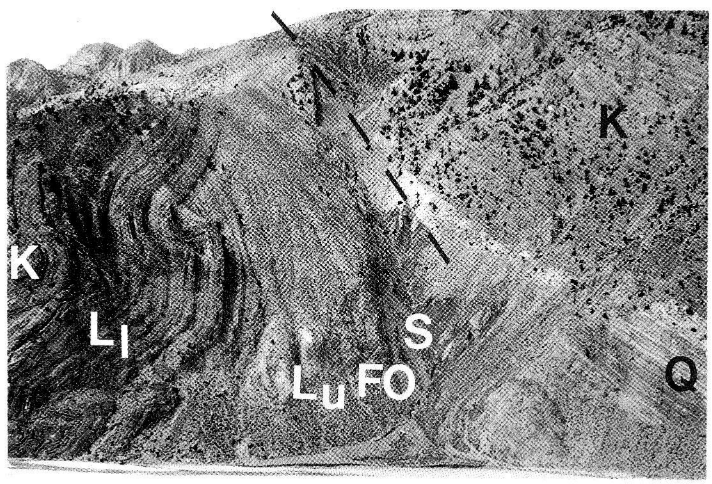

Fig. 5 - Fold-thrust deformation on the western bank of the Kali Gandaki between Jomosom and Bagung (JO3 locality). The subvertical to slightly overturned Jurassic succession to the left (K = Kioto Lst.; Ll & Lu = lower and upper Laptal Fm.; FO = Ferruginous Oolite Fm.; S = Spiti Shale) is overthrust by another slab of Jurassic rocks with the Late Triassic "Quartzite Series" (Q) at the base.

The "Quartzite Series" consist of white quartzarenites interbedded with burrowed micritic limestones, biocalcarenites, dolostones and hybrid arenites. The base of the JO3 section is covered and in fault contact with the Spiti Shale (Fig. 5). The boundary with the underlying Tarap Shale was never observed in the studied area. The top of the unit consists of a "white quartzarenitic marker bed" 22 m thick. Total measured thickness of the JO3 section is 114.8 m. Correlations with the JO4 section (thickness 106 m) are not obvious, due to lateral lithological variations and tectonic deformation in the latter.

According to stratigraphic position, the unit is considered as "Rhaetian" or late Norian-Rhaetian by most authors (Bassoullet et al., 1986; Fuchs et al., 1988). Biostratigraphic evidence, however, is poor and inconclusive.

The "Quartzite Series" were deposited in a shallow-marine to coastal environment in proximity to an active river mouth but chiefly influenced by the action of tidal and subordinately storm currents. Detritus was transported by a northward-flowing river system draining the Indian foreland. The latter was probably fringed by subdued reliefs formed during the Late Pan-African event at the beginning of the Paleozoic.

Kioto Limestone (Hayden, 1908 - Spiti).

The local name Jomosom Limestone, introduced by Bodenhausen et al. (1964), has been adopted by French authors (Bassoullet & Mouterde, 1977; Bassoullet et al., 1986). Other authors (Fuchs, 1977; Fuchs et al., 1988) retained the name Kioto Limestone for this calcareous unit which recurs with similar facies all along the Tethys Himalaya.

We measured the lower 235 m of the unit south of Bagung (JO3 locality), where its base is best exposed in continuity with the underlying "Quartzite Series" (Fig. 5), and studied sedimentologic logs in the Jomosom area.

The Kioto Limestone consists of biocalcarenites (bivalves, gastropods, echinoderms), pelletal mudstones/wackestones and oolitic grainstones. Dolomitic limestones and sandstones still occur in the basal part. The upper boundary, which is more difficult to define than in the northwestern Himalaya where it is invariably disconformable, is placed at the top of an oolitic interval some to tens of m thick and yielding a foraminiferal association of Middle Jurassic affinity (top of unit 8 of Bordet et al., 1971, p. 142; unit I of Gradstein et al., 1989). The total thickness of the formation is comprised between 250 and 350 m. We never had the chance to observe in place the spectacular megalodontid and *Lithiotis* layers which are so common in the northwestern Himalayas. A few blocks with *Lithiotis* however do occur.

According to poorly diagnostic fauna and stratigraphic position, the Kioto Limestone in central Nepal seems largely confined to the Early Jurassic (global supercycles UAB-2 to UAB-4; Haq et al., 1988) (Fig. 8), as suggested by the recent finding of middle Liassic forams even in the lower part of the unit (Fuchs et al., 1988). Its top may range up in the Middle Jurassic.

The Kioto Limestone was deposited on a shallow-water carbonate platform. In its lower part, arenite bars with bipolar paleoflows (W-ward and ENE-ward, similar to the underlying "Quartzite Series") testify to tidally-influenced sedimentation.

Laptal Formation (Heim & Gansser, 1939 - Kumaon).

Several authors (Fuchs, 1977; Bassoullet et al., 1986) adopted the term "Lumachelle" Formation (originally introduced as "upper Lumachelle" by Bodenhausen et al., 1964) to designate the stratigraphic interval comprised between the Kioto Limestone and the Ferruginous Oolite. Gradstein et al. (1989) recently described a few reference sections on the banks of the Kali Gandaki, some of which rather folded, and renamed the unit as "Bagung Formation", including also the Ferruginous Oolite at the top. We do not feel that the introduction of a new name is justified. Moreover, the Callovian Ferruginous Oolite has to be considered as a separate unit, since its base corresponds to a major unconformity probably associated with a significant hiatus. If the informal term "Lumachelle" is not considered as suitable, we rather suggest to adopt the long-established term "Laptal Series", updated to Formation, since this stratigraphic interval recurs with similar facies all along the Tethys Himalaya (Bassoullet et al., 1986), from central and western Nepal (Bordet et al., 1967; 1971, p. 262; Fuchs, 1977), to Kumaon (Heim & Gansser, 1939; Sinha, 1989) and the Zanskar-Spiti Synclinorium (Fuchs, 1982; Jadoul et al., 1990).

The unit consists of coquina layers with bivalves (mostly ostreids), gastropods, brachiopods, crinoids, belemnites and rare fish fragments, interbedded with hybrid arenites and grey marls. The thickness of our reference section, which crops out complete and undisturbed above Jomosom at an altitude of 3100 m asl, is 122.2 m (units M to P of Gradstein et al., 1989). The total thickness of the formation (units L to P) is estimated at 170÷180 m.

The formation is considered Middle Jurassic in age (largely Bajocian-Bathonian; Bordet et al., 1967; Bassoullet et al., 1986; Fuchs et al., 1988; supercycles LZA 1? - 2 of Haq et al., 1988) (Fig. 8). It was deposited on a mixed carbonate-siliciclastic storm-influenced shelf at water depths of a few m to several tens of m, from well above (lower arenitic part) to around and below average storm wave-base (central and upper pelitic parts; Fig. 5).

Ferruginous Oolite Formation (Heim & Gansser, 1939 - Kumaon).

The Ferruginous Oolite Fm. is a some m to some tens of m thick marker interval found in Middle Jurassic Tethys Himalayan sections from Zanskar to Nepal (Bassoullet et al., 1983, 1986; Krishna, 1983; Jadoul et al., 1985). In the Thakkhola region, along the Jomosom-Dangardzong ridge, the unit is only 6÷7 m thick, and consists of hybrid arenites with megaripple cross-lamination, containing ferruginous ooids, siliciclasts and bioclasts (belemnites, ammonoids, brachiopods, bivalves, echinoderms, foraminifers and anellids).

The Ferruginous Oolite Fm. contains brachiopod and ammonoid faunas of late Bathonian? to early Callovian age (Gradstein et al., 1989). Faunal and sedimentological characteristics indicate deposition on a high-energy storm-influenced starved shelf during a major transgression.

The lower boundary with the Laptal Formation is sharp and corresponds to a major type I unconformity, which may correlate with the global sea-level fall at 158.5 My (Haq et al., 1988). The unit is correlative with global supercycle LZA-3.1 (Fig. 8), and its top represents another major unconformity, with an associated hiatus spanning from the late early Callovian to the early Oxfordian (about 6 My). Locally, however, shales and bioclastic limestones containing late Callovian ammonoids are found, and the gap is confined to the middle Callovian (Cariou et al., 1990).

The generally reduced thickness of the Ferruginous Oolite Fm. in the central Himalaya with respect to the Spiti-Zanskar Synclinorium (Bassoullet et al., 1983, 1986; Jadoul et al., 1985) is thus ascribed to the frequent absence of global supercycle LZA-3.2 (Haq et al., 1988), which was deposited and preserved only in downthrown sectors during an extensional stage which preluded to the detachment of India from Australia-Antarctica (Audley-Charles et al., 1988; Gaetani & Garzanti, 1991).

Spiti Shale (Stoliczka, 1866 - Spiti).

The Spiti shales were deposited all along the Tethys Himalayan margin, and comparable Late Jurassic black shales extend from the Chichali Fm. of the Trans-Indus Salt Range to Indonesia (Hallam & Maynard, 1987). The local name Nupra Formation, recently proposed by Gradstein et al. (1989) to designate this classic unit studied for more than a century, is considered as a junior synonym.

In the Thakkhola region, the unit is more than a hundred m thick and consists of black shales rich in terrestrial to marine organic matter, containing abundant limonitic concretions up to 1 m in diameter and locally extremely rich in ammonoids of middle to late Oxfordian, Kimmeridgian and early to late Tithonian age (Bordet et al., 1967, 1971). Gradstein et al. (1989) describe also a rich agglutinated foraminiferal assemblage of Late Jurassic age. The early Oxfordian is most probably missing, and the base of the Spiti Shale may correlate with the global unconformity at 150.5 My (Haq et al., 1988). The unit spans supercycles LZA-4 and LZB-1 (Fig. 8), and in the Thakkhola region seemingly does not reach into the Cretaceous (Bordet et al., 1971).

The Spiti Shale was deposited in undisturbed outer shelf/slope environments with scarce oxygenation. Water depth was of several tens of metres (up to 250÷300 m according to Gradstein et al., 1989).

Chukh Group (Bodenhausen et al., 1964 - Thakkhola).

The name Chukh Formation was introduced by Bodenhausen et al. (1964), adopted by French authors (Bassoullet & Mouterde, 1977; Colchen et al., 1986), who subdivided it into two members, and formally elevated to group rank by Gradstein et al. (1989).

This clastic succession, which is not preserved elsewhere in Nepal, shows a number of differences in age and lithology with respect to the Giumal Sandstone of the Zanskar-Spiti Synclinorium (Garzanti, in preparation). Available informations on the "Giumal Sandstone" of the Kumaon region (Heim & Gansser, 1939; Sinha, 1989) are insufficient to establish whether these rocks compare more closely with the clastics of the

Nepal or Zanskar Himalaya. In the present paper, we adopt most of the internal stratigraphic subdivisions introduced by Bassoullet & Mouterde (1977) and reject the nomenclature of Gradstein et al. (1989), who use the very same names to designate different stratigraphic intervals (see Fig. 2). Also, the latter authors include within the Chukh Group the overlying Scaglia-like calcareous muds, which are separated from the deltaic

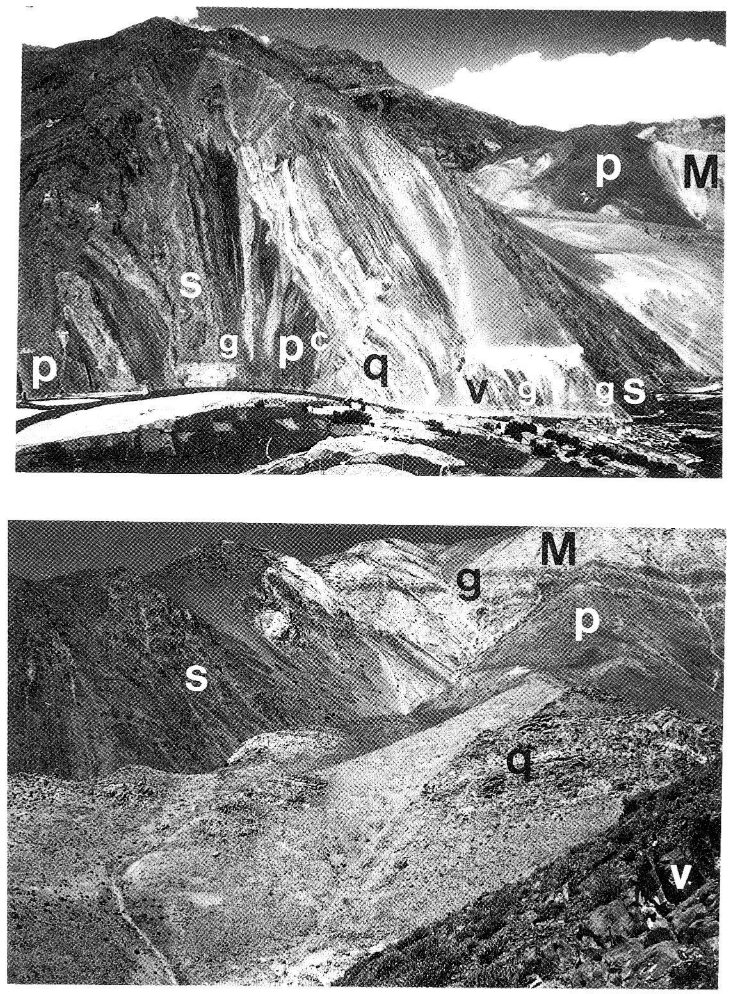

Fig. 6 - Fold-thrust tectonics in the Early Cretaceous succession at Kagbeni (top) and on the Dzong ridge (bottom), respectively to the west and east of the Kali Gandaki. The terrigenous units of the Chukh Group (q = Dangardzong quartzarenites; v = Kagbeni volcaniclastics; s = lower Dzong sandstones; p = upper Dzong pelites) are often in anomalous contact, and the occurrence of coal (c) and glauconitic (g) marker layers is of great help to unravel in detail the original stratigraphy in this complex structure.
A major greensand interval (g) marks the upper boundary with the Muding pelagic limestones (M).

to shelfal clastics by a major condensed section and have a totally different lithology and environmental, paleogeographic and geodynamic significance. The sedimentological features and paleontological content of the Early Cretaceous clastic formations have long been known (Bordet et al., 1967, 1971). However, owing to intense polyphase fold-thrust deformation, ambiguities as to internal stratigraphy abound in the geological literature, beginning with the initial mistake of Bodenhausen et al. (1964), who placed their "Checkpost" and "Chukh" units (corresponding to the Dangardzong and Kagbeni Formations) below, and their "Tangbe" (Dzong) Formation directly above the "Saligram" (Spiti) shales. Even the detailed sections of Gradstein et al. (1989) were unfortunately measured along the well exposed but also highly deformed Kagbeni outcrops (locality KA1; Fig. 6).

Dangardzong Formation (This work - Thakkhola).

This formational name is here introduced to designate the quartzose sandstones at the base of the Cretaceous, which can be easily distinguished lithologically and mineralogically from the overlying volcanic-derived clastics. The unit has already been described by Bordet et al. (1967, 1971) as "grès gris-brunâtres" at the base of their "grès continentaux de Wealdien", and by Gradstein et al. (1989) as "Chukh Unit" at the base of the Chukh Group. The formation is best exposed in isolated outcrops along the Jomosom-Dangardzong ridge, where two reference stratigraphic sections were measured, and was also observed in front of Kagbeni (where their greater thickness is largely ascribed to tectonic repetitions), along the Dzong ridge (Fig. 6), and in the Muktinath area.

The formation, at least 45 m thick, consists of quartzose sandstones showing parallel to cross-lamination, truncated wave ripples and microconglomeratic lags. Locally, bivalves, phosphatic nodules, clay chips, plant fragments and carbonaceous lenses are found. The basal contact with the Spiti Shale is well exposed west of Muktinath (locality JK1 of Gradstein et al., 1989), while in most other sections the finer-grained sandstones of the lower part of the unit are unfortunately largely covered. The middle part consists of amalgamated sandstone beds 10 to 80 cm thick, arranged in thickening-upward cycles and lacking pelitic interbeds. The top is best observed north of Bagung, on both sides of the Kali Gandaki. Fossil content is poor and not age-diagnostic. The unit, which was deposited in high-energy, shallow-marine environments, is ascribed to the early? Neocomian according to stratigraphic position.

Kagbeni Formation (Bassoullet & Mouterde, 1977 - Thakkhola).

The unit, corresponding to the "grès continentaux", "grès à plantes" or "Wealdien" (Bordet et al., 1967, 1971; Colchen et al., 1986), is exposed at several localities in the Kagbeni area, where stratigraphic thickness is reduced due to tectonic deformation. Our reference section, measured just above Bagung, is undisturbed for the lower 116 m, and reaches up to 130 m or more if the uppermost faulted part is added. Sedimentologic logs were made also on the opposite eastern side of the Kali Gandaki.

The Kagbeni Formation consists of volcanic-derived microconglomerates commonly rich in large intraclasts and wood fragments, sandstones, and carbonaceous siltstones locally with coal lenses, arranged in fining-upward sequences and deposited in a deltaic environment influenced by fluviatile processes. Its base is sharp and corresponds to the sudden increase of mafic volcanic detritus. Paleocurrent directions were mostly to the NNE. According to stratigraphic position, a Neocomian to Barremian? age is inferred for this unit.

Dzong Formation (Bassoullet & Mouterde, 1977 - Thakkhola).

The unit, corresponding to the "grès verts" of Bordet et al. (1967, 1971), is never exposed continuously from bottom to top in the Kagbeni area. A nearly complete composite section could be reconstructed from two partial sections of 216 m (lower part) and 147 m (upper part) measured on the Dzong ridge.

The formation can be subdivided into two members, both capped by glauconitic horizons. The lower green volcanic arenites (a) are about 300 m thick and comprise a basal interval of dark pelites and orange-weathering very fine-grained sandstones some tens of m thick. They were deposited in medium-energy nearshore environments close to a river mouth, as testified by abundant shallow-marine bivalve faunas and largely volcanic-derived terrigenous detritus. The upper black shales (b), interbedded with hummocky cross-laminated orange-weathering arenites in the lower part and channelized deposits yielding ammonoids in the middle part, are 80 to 100 m thick and were accumulated in deeper, less disturbed offshore settings.

The unit correlates with the Giumal Formation of the Zanskar-Spiti Synclinorium (Garzanti, in preparation), even if volcanic detritus predominates throughout the unit, while in Zanskar it is recorded only in the upper part.

Early Aptian ammonoid faunas were found at several localities (Bordet et al., 1971), even though a douvilleiceratid ammonoid collected in place in the middle part of the upper black shales is more comparable with early Albian *Douvilleiceras* sp. rather than with Aptian *Cheiloniceras* (A. Tintori, pers. comm., 1990). Planktonic foraminifers contained in the uppermost greensand interval indicate a late Albian age (*Biticinella breggiensis* to *Rotalipora ticinensis* Zones; I. Premoli Silva, pers. comm., 1991).

Muding Formation (Bassoullet & Mouterde, 1977 - Thakkhola).

The unit, corresponding to the "Calcaires de teinte claire" of Bordet et al. (1971), is exposed on the Dzong ridge north of Kagbeni, where a 40 m thick section was measured in stratigraphic continuity with the underlying Dzong Formation. The upper part of the unit is covered and we never observed Upper Cretaceous deposits in the surveyed area. Shallow-water oyster-bearing layers of unspecified age are reported at the top of the Thakkhola sequence (Bordet et al., 1971).

The Muding Formation consists of thin-bedded marls and marly limestones yielding a pelagic fauna (planktonic foraminifers, calcareous nannofossils, ostracods, calcispheres). Diagnostic foraminiferal and nannofossil assemblages of latest Albian age (*Rotalipora appenninica* - *Eiffellithus turriseiffelii* Zones) were found up to 35 m above the base of the unit (determinations by I. Premoli Silva, A. De Poli and F. Lottaroli). The early/late Aptian foraminiferal assemblage reported by Bordet et al. (1967, 1971) was not found anywhere in the section. It either comes from a different locality or the determination needs reconsideration.

After the final drowning of the Chukh deltaic complex, which occurred in late Albian times, the Muding foraminiferal mudstones were deposited in a deep-water environment. New biostratigraphic evidence from Nepal thus suggests that drowning episodes where synchronous in the central and northwestern Himalaya, with deposition of Scaglia-like facies beginning everywhere in the late Albian, contrary to what previously suspected. The Muding Formation is the youngest unit preserved in the Thakkhola region, where the Early Cretaceous succession is unconformably followed by thick fluvio-lacustrine deposits of Plio-Pleistocene age (Fig. 7).

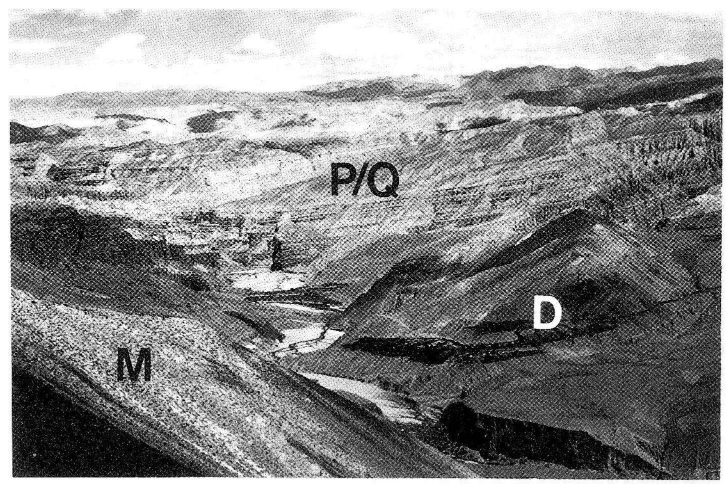

Fig. 7 - At the top of the Tethys Himalaya succession, Aptian-Albian sediments of the Dzong (D) and Muding (M) Formations are unconformably overlain by the Plio-Quaternary (P/Q) fluvio-lacustrine fill of the Thakkhola graben. View is from above Dangardzong towards Tibet.

Conclusions.

The sedimentary succession of the Kali Gandaki Valley (central Nepal) was deposited on the northern margin of the Indian sub-continent. After a prolonged period of shallow-water carbonate and then siliciclastic sedimentation in the Cambro-Ordovician (Nilgiri Limestone and North Face Quartzite), the Siluro-Devonian was characterized by deep-water conditions and higher accumulation rates with respect to the northwestern Himalaya (Dark Band and Tilicho Pass Formations). Thick shallow-water carbonate to terrigenous deposits accumulated at Carboniferous and Permian times (Tilicho Lake and Thini Chu Formations), when major unconformities and local volcanic activity reflected the initial opening of Neotethys.

Owing to strong thermo-tectonic subsidence, the newly-formed Indian margin was rapidly drowned in the Early Triassic (Tamba Kurkur Formation), and covered by thick marly limestones in the Anisian, Ladinian and Carnian (Mukut Limestone). In the Norian Tarap Shale, the sharp increase in quartzo-feldspathic detritus testifies to rejuvenation of the Indian continental block located to the south, while virtually exclusive monocrystalline quartz at the top of the Rhaetian? "Quartzite Series" suggests latitudinal drift towards more humid climates and/or more subdued reliefs.

The Early Jurassic was characterized by monotonous deposition of the shallow subtidal Kioto Limestone, which was covered by lumachellic hybrid arenites deposited on a storm-controlled continental shelf in the Bajocian and Bathonian (Laptal Formation). A widespread ironstone interval testifying to condensed sedimentation in the early Callovian (Ferruginous Oolite Fm.) was followed by the black Spiti Shale, rich in ammonoids and deposited in outer shelf/slope conditions. All of the stratigraphic units recognized in the Triassic to Jurassic central Nepal succession can be traced through Kumaon up to the Zanskar-Spiti Synclinorium, and all events of renewed clastic influx and tectonic subsidence triggered by break-up episodes, or major climatic and eustatic changes related to latitudinal shifts or global fluctuations, can be correlated along the Tethys Himalayan Zone (Fig. 8; Gaetani & Garzanti, 1991).

In the Early Cretaceous, sedimentation was affected by a major geodynamic event which led to the opening of the Indian Ocean (Garzanti & Jansa, 1990). At first (Dangardzong Formation), renewed quartzose detritus is ascribed to domal uplift of continental blocks during incipient separation between India and western Australia (Boote & Kirk, 1989; Von Rad et al., 1989). Next, as testified by invariably predominant volcanic detritus derived from the south in the overlying deltaic sandstones (Kagbeni and Dzong Formations), huge eruptions of intraplate basaltic lavas took place, reaching a climax around 115 My ago, when hot-spot magmatic activity during rifting affected a large area from the Kerguelen plateau to the Rajmahal Traps of northeastern India (Mahoney et al., 1983; Baksi et al., 1987; Schaming & Rotstein, 1990).

The end of magmatism and progradation of deltaic complexes in central Nepal was marked by a glauconitic condensed section, covered by late Albian pelagic marls (Muding Formation). This major drowning episode, followed by deposition of widespread Scaglia-like deep-water sediments, was recorded at the same time also in the central and western Tethys Himalaya ("upper flysch" of Kumaon; Heim & Gansser, 1939; Sinha, 1989; Chikkim and Fatu La Fms. of Zanskar; Gaetani et al., 1986; Garzanti et al., 1989). This event, marked by condensed glauco-phosphorites or organic-rich black shale tongues in the whole Tethyan domain (Arthur et al., 1990; Delamette, 1990), was related not only to regional tectonic episodes, but also to global eustatic fluctuations, modifications of plate motion, increased volcanic activity and changes in athmospheric

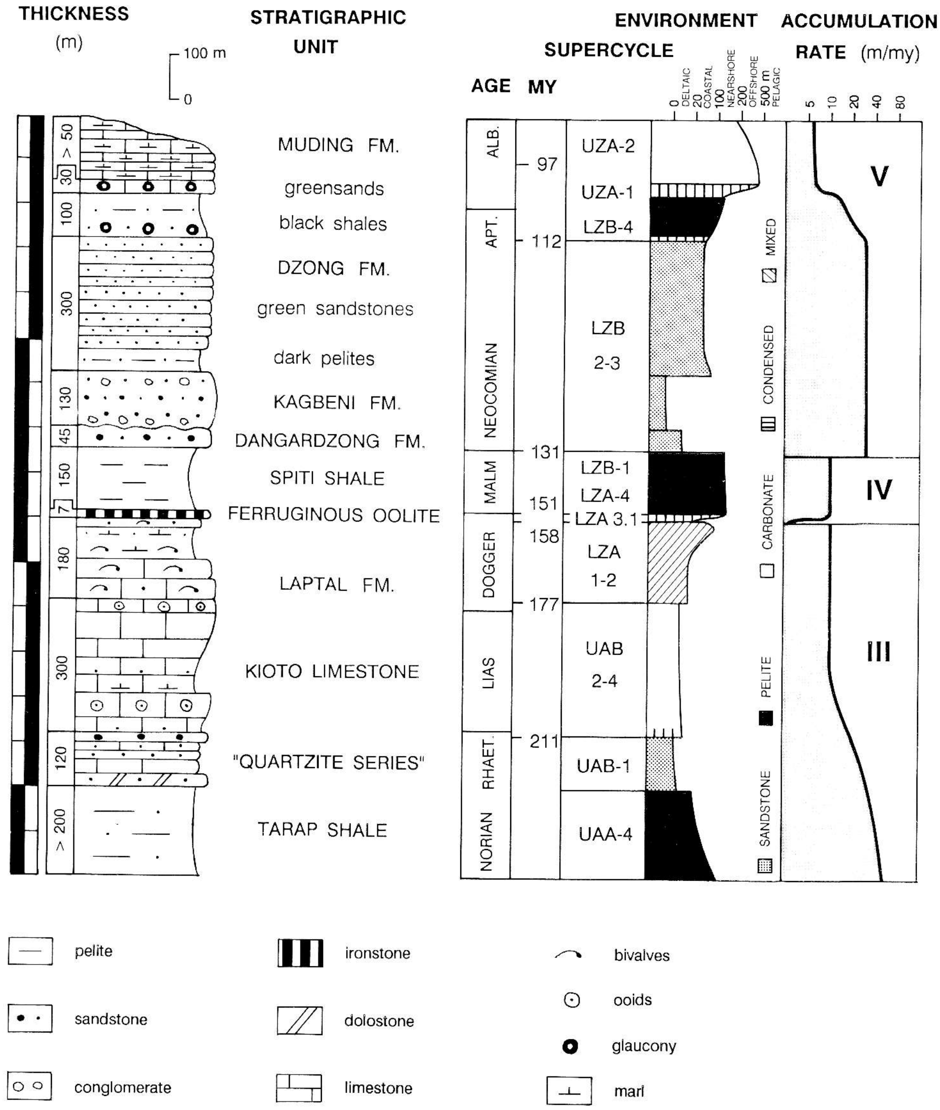

Fig. 8 - The stratigraphic succession of the Thakkhola region, with inferred depositional environments and accumulation rates. Correlation with the global sea-level curve of Haq et al. (1988) is tentative. Roman numerals correspond to the tectonic supersequences of Gaetani & Garzanti (1991).

and oceanographic conditions induced by the final disintegration of the Gondwana superplate and initial opening of the Indian and Atlantic Oceans.

In the Tertiary, during the early stages of collision between India and Asia, the Tethys Himalayan sedimentary succession has undergone fold-thrust deformation at pre-anchizonal (Mesozoic strata of the Thakkhola graben) to low and medium metamorphic grade (Paleozoic strata west of the Dangardzong Fault), followed by uplift, formation of the Thakkhola graben and unconformable deposition of fluvio-lacustrine sediments in the Plio-Pleistocene.

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