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LATE PALEOZOIC STRATIGRAPHY AND PETROGRAPHY OF THE THINI CHU GROUP (MANANG, CENTRAL NEPAL): SEDIMENTARY RECORD OF GONDWANA GLACIATION AND RIFTING OF NEOTETHYS

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Key-words: Tethys Himalaya, Stratigraphy, Carboniferous, Permian, Sandstone petrography, Gondwana glaciation, Conodonts, Brachiopods, Corals, Pelecypods.

Riassunto. La successione Permo-Carbonifera del Manang (Nepal Centrale) è potente da 1000 a 1500 metri. Essa è costituita da biocalcareniti a Crinoidi di età Tournaisiana (Formazione del Lago Tilicho), seguite da alternanze di livelli di argilliti nere e di corpi arenacei quarzosi a base netta (Gruppo di Thini Chu). Lo studio stratigrafico di dettaglio di questa unità ha consentito di riconoscere e istituire 5 nuove formazioni e 8 nuovi membri. La Formazione della Marsyandi, di età Viseana, registra un forte apporto di terrigeni quarzo-so-feldspatici. Due sequenze deposizionali sono caratterizzate da areniti trasgressive ricche in Brachiopodi nel Serpukhoviano ("strati a *Syringothyris*"). Segue un potente intervallo di argilliti nere con orizzonti quarzarenitici intercalati (Argillite di Col Noir). Quindi, nella sezione prossimale di Bangba, tilloidi contenenti frammenti di dolomie documentano l'avanzata dei ghiacciai sulle spalle del rift in attivo sollevamento già durante la prima parte del Carbonifero superiore. Queste diamictiti sono sostituite lateralmente verso ovest da quarzareniti seguite da argilliti nere (Formazione di Bangba) caratterizzate da concrezioni carbonatiche localmente contenenti Chetetidi al loro nucleo, e quindi presumibilmente attribuibili al Bashkiriano-Moscoviano.

In seguito, conglomerati glaciomarini passanti lateralmente ad arenarie e argilliti di piattaforma sono arricchiti in detrito di derivazione prima magmatica e poi arenacea (Formazione di Braga). La natura del detrito vulcanico suggerisce una fase di magmatismo bimodale durante l'acme del rifting, seguita dall'erosione di successioni sedimentarie attorno al limite tra Carbonifero e Permiano.

Una fase trasgressiva, forse coincidente con la fine della glaciazione gondwaniana, è poi seguita da arenarie conglomeratiche ricche di selce e deposte prevalentemente in ambienti di estuario, seguite da areniti e argilliti di piattaforma ricche di Brachiopodi, Bivalvi e Briozoi (Formazione di Puchenpra). Il Gruppo di Thini Chu è sigillato ovunque da calcari condensati di piattaforma esterna/scarpata superiore ("biocalcareniti sommitali"). Questa grande trasgressione finale, che col passaggio da arenarie quarzose ad areniti bioclastiche di piattaforma e infine a carbonati pelagici condensati sutura la fase di rifting, è caratterizzata da facies marcatamente eterocrone. Sedimenti fossiliferi di piattaforma aperta risalgono al Boloriano a Bangba, al Murgabiano-Midiano a Col Noir e probabilmente solo allo Djulfiano a Tilicho, mentre condizioni pelagiche sono raggiunte nel Boloriano-Kubergandiano a Bangba e nello Djulfiano-Dorashamiano più a ovest. Questo indica che la subsidenza termica legata all' apertura della Neotetide è cominciata già nel Permiano inferiore, e precocemente nella parte orientale dell' area studiata.

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Il miglioramento delle condizioni climatiche seguito alla glaciazione gondwaniana è iniziato già nella parte alta del Permiano inferiore, con faune temperato-calde dominate da Productidi, ma Conodonti di acque temperato-fredde sono registrati nel Permiano medio e possibili "dropstones" fino allo Djulfiano, suggerendo che solo alla fine del Permiano climi temperato-caldi hanno caratterizzato le coste meridionali della Tetide in via di espansione.

Abstract. In the Manang area (north Annapurna Range; Nepal Himalaya), the Permo-Carboniferous succession is 1000 to 1500 m thick. Crinoidal biocalcarenites (Tilicho Lake Fm.) pass upward to alternating black shales and sharp-based white quartzose sandstones (Thini Chu Group). Detailed stratigraphic analysis of this unit allowed us to recognize and establish 5 new formations and 8 new members. The Marsyandi Fm., of Visean age, records an increase of subarkosic terrigenous detritus during the initial stage of Neotethyan rifting, and is capped by two sequences ("*Syringothyris* beds") characterized by transgressive sandstones rich in Serpukhovian brachiopods.

The overlying black shales with subordinate quartzarenites (Col Noir Shale) are followed in the more proximal Bangba section by diamictites yielding dolostone rock fragments, documenting the first advance of glacial ice on rift shoulders, actively uplifted since the Bashkirian-Moscovian (Bangba Fm.). Next, glacio-marine to transgressive shelfal deposits are enriched first in igneous detritus and then in arenaceous rock fragments (Braga Fm.). Mafic to felsic magmatism during the climax of rifting was thus followed by active erosion of sedimentary successions, probably around the Carboniferous/Permian boundary.

A major Early Permian transgression, coinciding with ameliorating climates at the end of the Gondwana glaciation, was followed by mainly estuarine chert-bearing quartzose pebbly sandstones capped by richly bioclastic shelfal deposits (Puchenpra Fm.). This second major transgression, associated with quartzose sandstones documenting subdued rift reliefs, is dated as Bolorian at Bangba, as Murgabian-Midian at Col Noir and as Djulfian at Tilicho. The base of the condensed outer shelf/upper slope carbonates capping the Thini Chu Group ("topmost biocalcarenites") is also strongly heterochronous, being dated as Bolorian to Kubergandian-Murgabian at Bangba and as Djulfian-Dorashamian at Col Noir and Tilicho. Thermal subsidence associated with the opening of Neotethys thus began as early as the Early Permian.

Introduction.

Highly metamorphosed Paleozoic and less deformed Triassic and Jurassic units belonging to the Tethys Himalayan Zone are exposed to the north of the High Himalaya crystalline belt ("Dalle du Tibet" of French Authors), and south of the Indus-Tsangpo suture. Cretaceous formations are preserved only in the Thakkhola Graben, which is a late orogenic 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; Bordet et al., 1971).

During our October 1991 Ev-K2-CNR expedition, we focused on the Permo-Carboniferous succession cropping out along the Marsyandi and Kali Gandaki Valleys (Fig. 2). Three detailed stratigraphic sections and one log were measured between east of Manang (Bangba/Braga) and Thinigaon (Thakkhola); about 150 samples were collected for paleontological and petrographical analysis.

The aim of the present paper is threefold:

a) to provide accurate and integrated stratigraphic, biostratigraphic, sedimentologic and petrographic data for the Gondwanian Upper Paleozoic succession exposed in the extremely rugged north Annapurna mountain range, adding new information to previous works (Bodenhausen et al., 1964; Bordet et al., 1971, 1975; Colchen et al., 1986; Fuchs et al., 1988);

b) to propose for the first time a detailed lithostratigraphic framework for the Carboniferous to Permian succession of the central Nepal Tethys Himalaya, with introduction of five new formations. Most of these can be broadly correlated with sedimentary sequences exposed in the adjacent regions of central-eastern Nepal (Fuchs, 1977; Garzanti & Pagni Frette, 1991; Garzanti et al., 1992) and as far as the Spiti-Zanskar Synclinorium and Kashmir (NW Himalaya) (Hayden, 1904; Gaetani & Garzanti, 1991; Garzanti et al., 1993);

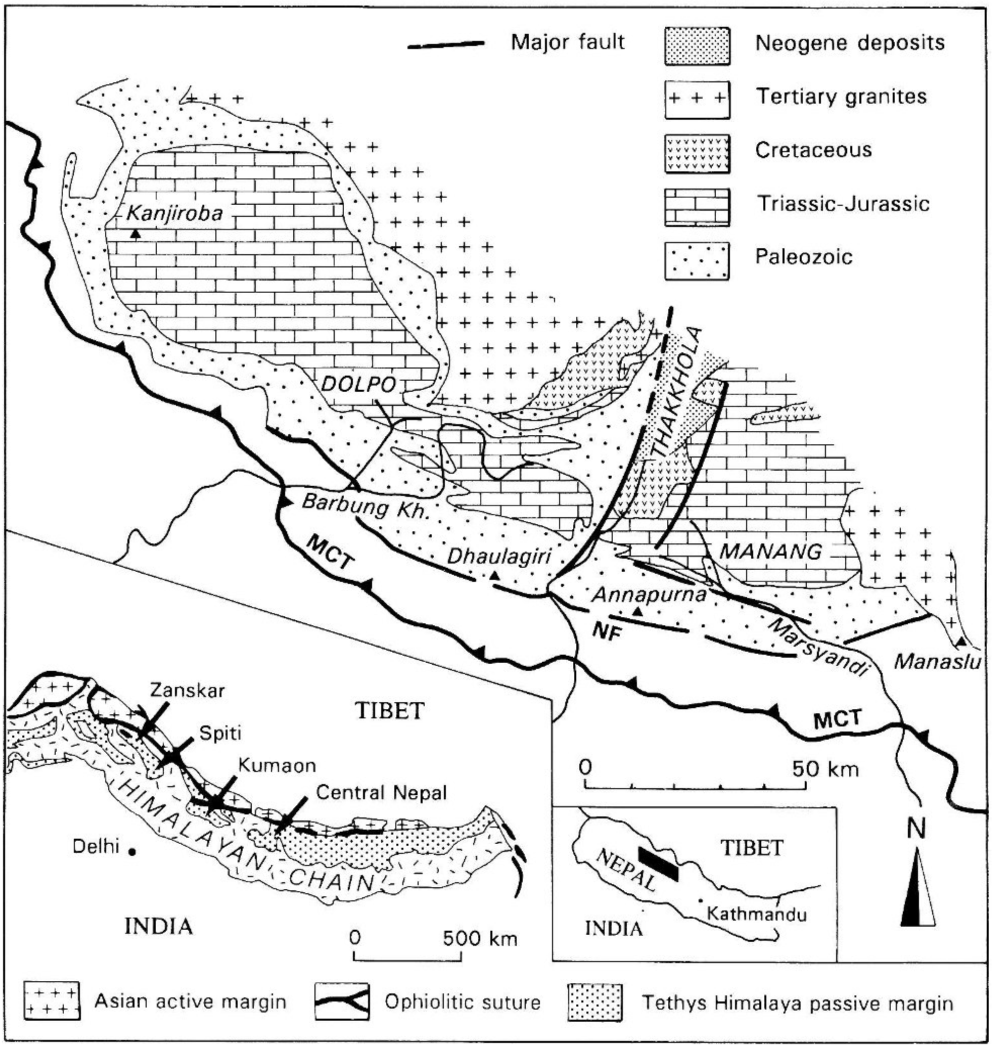


Fig. 1 - Geological sketch map of Dolpo-Manang Synclinorium (compiled after Gansser, 1964; Fuchs, 1977; Bordet et al., 1971, 1975; Colchen et al., 1986; Fuchs et al., 1988). Areal distribution of Tethyan passive margin sediments in the Himalayan Chain shown in inset. MCT) Main Central Thrust; NF) High Himalayan normal fault.

c) to reconstruct from the sedimentary record the evolving paleogeographic and paleogeodynamic scenarios during initial opening of Neo-Tethys, and to unravel the complex interactions between a wide range of geologic factors, including tectonic extension during rifting, asthenosphere upwelling and magmatic activity, and climate changes leading to the advance of continental ice.

For information on the overlying Triassic succession the reader is referred to the companion paper by Garzanti et al. (1994b).

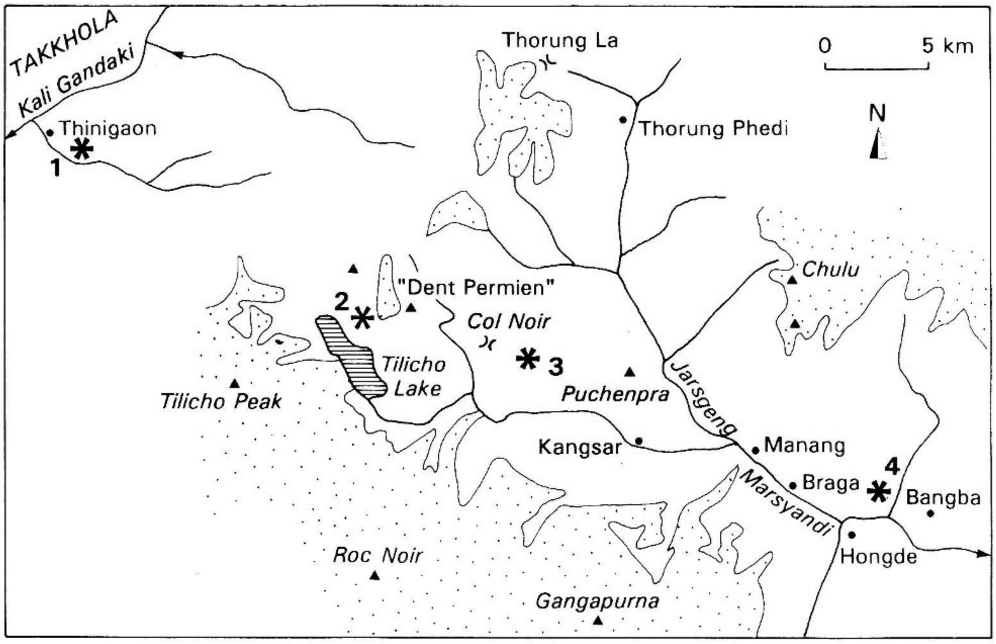


Fig. 2 - Geographic map of studied Manang area. Asterisks indicate location of stratigraphic sections and logs measured through the Thini Chu Group: 1) Thinigaon; 2) Tilicho; 3) Col Noir; 4) Bangba/Braga. Glaciated areas are stippled.

Methods.

Sandstones were point-counted (at least 300 points on each of the 81 analyzed sections) according to the Gazzi-Dickinson method (Zuffa, 1985). Petrographic parameters (Q= quartz; F= feldspars; L= aphanitic lithic fragments) and sandstone classification are after Dickinson (1970, 1985) and Folk (1980) respectively; the L pole includes carbonate extrabasinal grains (Zuffa, 1985). Analysis of intrabasinal grains (CI= carbonate; NCI= non-carbonate) followed criteria outlined by Zuffa (1980, 1985) and Garzanti (1991). Grain size was determined according to the semiquantitative method described in Garzanti (1986a).

Clay mineralogy was analyzed at AGIP SpA (15 samples; data kindly provided by L. Martellini, AGIP, 1992), according to the methodology described in Garzanti & Brignoli (1989) and Garzanti et al. (1994a).

The lower part of the Tethys Himalayan succession.

The Lower to mid-Paleozoic succession of central Nepal comprises very thick shallow-water metacarbonates (Nilgiri Limestone, largely Ordovician in age), quartzites (North Face Quartzite), deeper-water graptolite-bearing slates and shallow-water dolostones (Dark Band Formation, largely Silurian in age), and finally thick grey schists and calcschists (Tilicho Pass Formation, largely Devonian in age; Bodenhausen et al., 1964; Bordet et al., 1975). Our sedimentologic observations, although cursory, do not support a turbiditic origin for the Tilicho Pass sediments (Fig. 3), as inferred

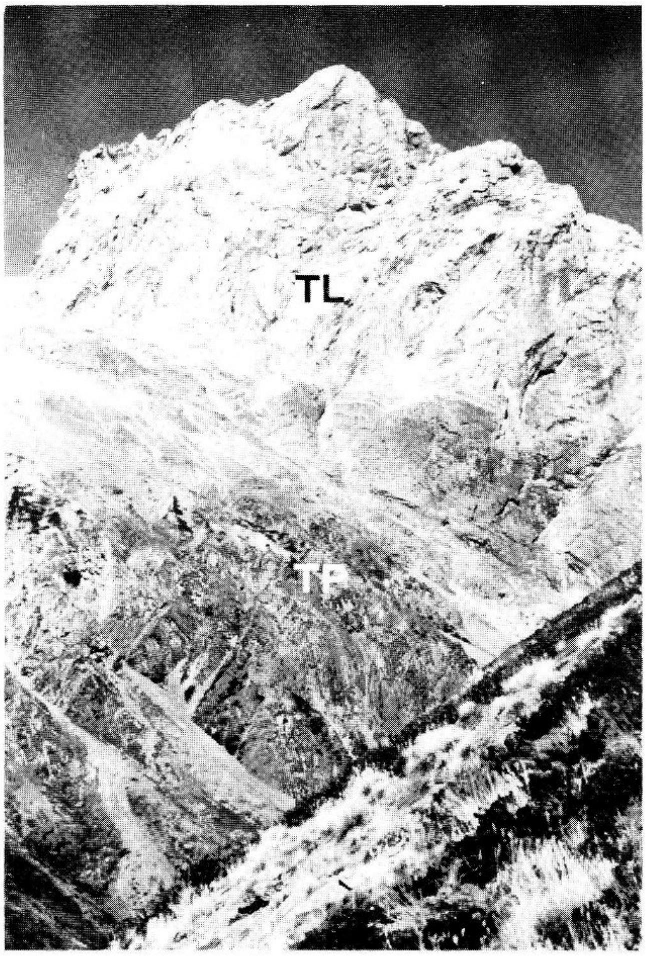


Fig. 3 - In the upper Marsyandi Valley W of Kangsar, grey pelites of Tilicho Pass Fm. (TP) pass upward to massive biocalcarenites of Tilicho Lake Fm. (TL) ("Dent carbonifère" of Bordet et al., 1975). This thick succession, spanning the Late Devonian (Frasnian) to earliest Carboniferous (Tournaisian), was deposited at accumulation rates of 30 m/Ma or more (time scale after Harland et al., 1989). Photo faces NW.

by previous authors. Occurrence of Frasnian conodont faunas in both the middle and upper parts of the unit (Fuchs et al., 1988) hints at strong accumulation rates and subsidence at this stage, as documented also in central Dolpo (Garzanti et al., 1992).

This lower part of the Paleozoic succession has undergone lower greenschist to higher-grade metamorphism at temperatures between 370°C and over 530°C during the Tertiary Himalayan Orogeny (Schneider & Masch, 1993). Metamorphism decreases north of a major fault system extending along the Marsyandi Valley. Epizonal conditions reach as high as the Lower Carboniferous (Garzanti et al., 1994a), represented by 200 to 250 m thick massive biocalcarenites rich in large crinoid stems (Fig. 3), followed by about 150 m thick more thinly-bedded carbonates reported to contain fenestellid bryozoans (Tilicho Lake Fm.; Bodenhausen et al., 1964).

Lithostratigraphy of the Thini Chu Group

The Thini Chu Formation of Bodenhausen et al. (1964), 800 to 900 m thick and consisting of alternating intervals of white quartzose sandstones and black shales (Fig. 4), is here elevated at group rank. Detailed stratigraphical, sedimentological and petrographical observations allowed in fact recognition of five new formations (and 8 new members overall), which can be broadly correlated all along the Marsyandi Valley (Fig. 5). Four sections were measured: in Thakkhola above Thinigaon (poorly exposed and faulted in the middle-upper part); north of Tilicho Lake, just west of the glacier in front of the "Dent permienne" (Thini Chu in the map of Bordet et al., 1975); east of Col Noir; west of Bangba (number 6 in Bordet et al., 1975, fig. 51), between the East Chulu Khola and above Braga.

Marsyandi Formation.

The unit, 300 to 500 m thick, is best exposed on the south flank of the "Dent permienne" in the upper Marsyandi Valley. It overlies the Tilicho Lake Fm. and can be subdivided into two members (*lower member* and *Syringothyris beds*).

Lower Member. Commonly burrowed black shales, with up to lower fine-grained rippled subarkoses intercalated in the upper part, are sharply overlain by medium-grained subarkoses to coarse-grained quartzarenites with wave ripples at Thinigaon and Tilicho (18 to 21 m); two sandstone intervals with tidal cross-lamination and black mudclasts are separated by interbedded sandstones and shales at Bangba (26 m).

Estimated overall thickness of these black shales and subarkosic sandstones ranges from over 250 m at Thinigaon to possibly over 400 m at Bangba, where successive sandstone intervals are seen in the landscape (Bordet et al., 1975, fig. 50, 51).

Syringothyris beds. Two distinct sequences with fossiliferous horizons in their middle part from Thinigaon (where the upper one is poorly exposed) to Col Noir are recognized (Fig. 6). Thickness increases from 50 - 53 m between Thinigaon and Col

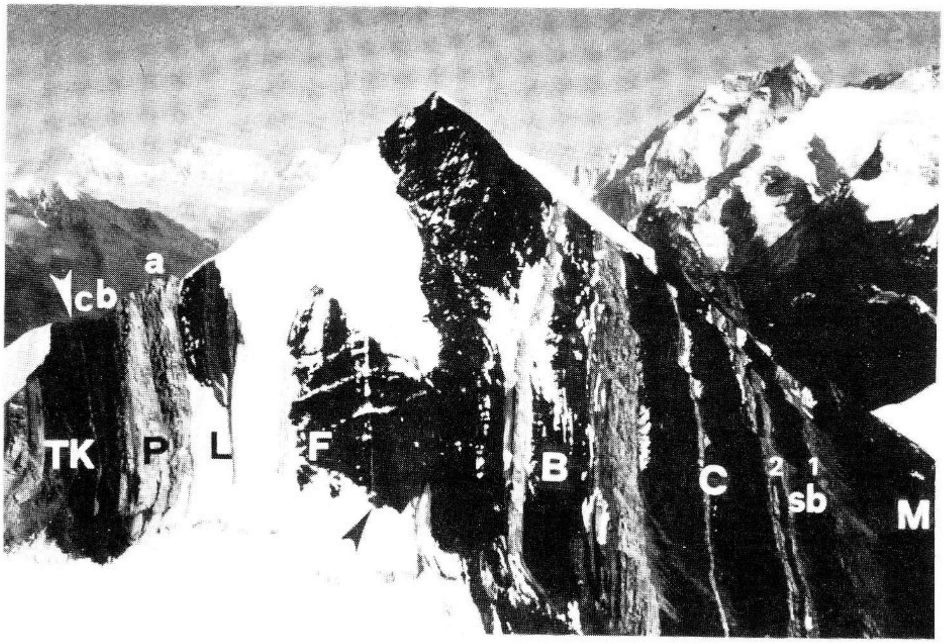


Fig. 4 - Thini Chu Group at Tilicho ("Dent permienne" of Bordet et al., 1975). Black pelites of lower member of Marsyandi Fm. (M) pass upward to sharp-based quartzarenites abruptly transgressed by brachiopod-rich calcirudites (*Syringothyris* beds; sb); two such sequences (1 and 2) are overlain by Col Noir Shale (C) and Bangba Fm. (B). Transgressive base of Braga Fm. (black arrow) is marked by abrupt decrease of mineralogical stability (F= feldspathic lower member; L= lithic upper member). Puchenpra Fm. (P) consists of regressive quartzarenites (a= member A), overlain by a thin paralic coarsening-upward cycle (b= member B), followed in turn by transgressive pelites and ironstones (c= member C), and finally capped by condensed pelagic carbonates ("topmost biocalcarenites"). Transition to Tamba Kurkur Fm. (TK) coincides with Permo-Triassic boundary (white arrow). Photo faces E.

Noir to 65 m at Bangba, where the member is only sporadically fossiliferous and characterized by prevailing quartzarenites displaying herringbone cross-lamination, lenticular to flaser bedding, interference ripples, mud drapes and black mudclasts.

In the lower sequence, cross-laminated microconglomeratic quartzarenites (6 to 8 m) are overlain abruptly by up to coarse-grained microcline-bearing biocalciruditic quartzarenites with brachiopods, locally very abundant fenestellid bryozoans, crinoids and phosphate nodules (8 to 11 m); black shales follow (22 to 25 m), with laminated to rippled sandstones becoming predominant upward (5 m at Col Noir).

In the upper sequence, sharp based, fine-grained subarkoses to medium and coarse-grained quartzarenites showing bipolar cross-lamination (8 to 9 m at Tilicho and Col Noir, 15 m at Bangba) are abruptly overlain by lower medium-grained subarkoses to coarse-grained quartzarenites yielding brachiopods, crinoids and bryozoans (0.5 to 1 m at Tilicho and Col Noir), followed by locally bioclastic black shales (3.5 m at Tilicho).

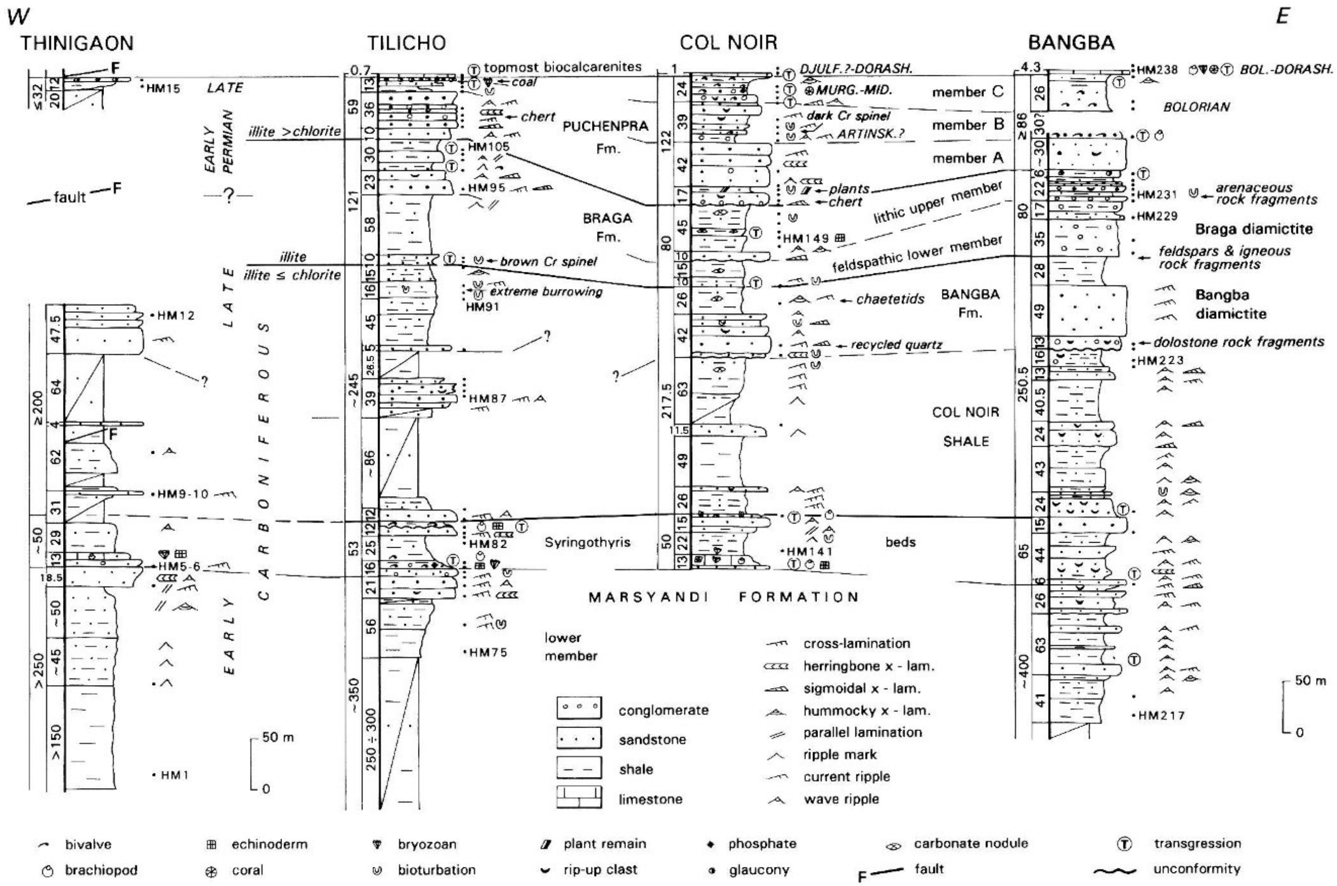


Fig. 5 - Stratigraphic columns and sedimentary features for Thini Chu Group. Thicknesses, fossils and first appearance of key detrital grains are indicated. Faunal assemblages show marked heterochroneities at top of Thini Chu Group. In its middle part (Col Noir Shale to Braga Fm.), correlations are based on lithology and petrographic composition alone; lack of fossils prevents to solve a few ambiguities, such as occurrence of an extra 81 m-thick quartzarenite/shale cycle in the upper part of Bangba Fm. at Tilicho.

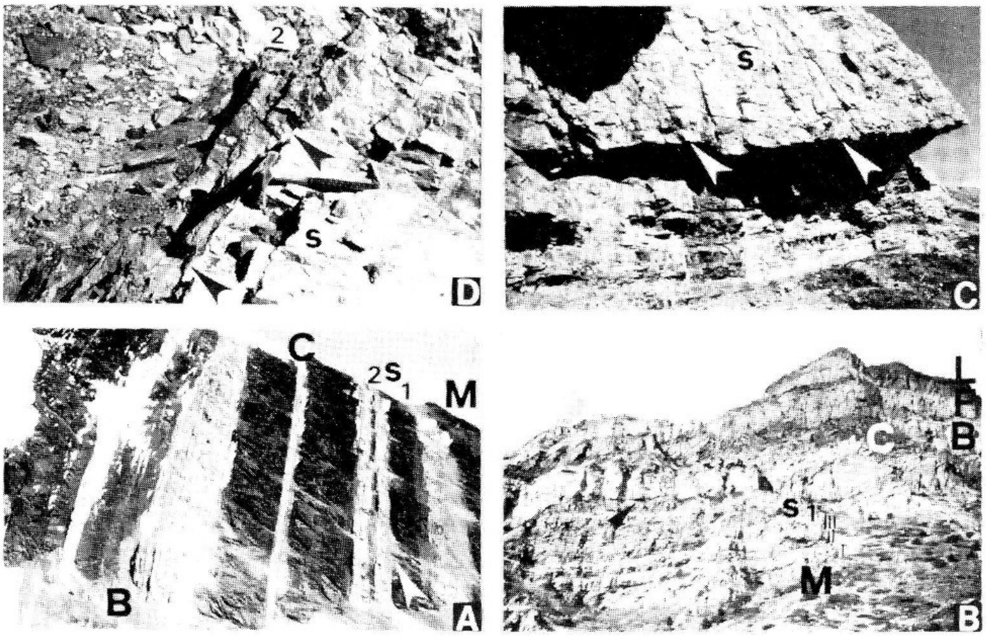


Fig. 6 - Stratigraphy in the lower-middle part of Thini Chu Group (M= lower member of Marsyandi Fm.; s= *Syringothyris* beds; C= Col Noir Shale; B= Bangba Fm.). A) Tilicho section (arrow shows same sharp regression as in C). B) Bangba section (I, II and III= three estuarine quartzarenite intervals below *Syringothyris*-bearing horizon 1; F and L= feldspathic lower and lithic upper members of Braga Fm.). Arrow shows same sharp regression as in C. C) Sharp-base (arrows) of shoreface quartzarenites document a "forced regression" (sequence 2 of *Syringothyris* beds at Col Noir). D) Abrupt contact (arrows; hammer for scale) between shoreface quartzarenites and brachiopod-bearing calcirudites document rapid transgression (sequence 2 of *Syringothyris* beds at Tilicho).

Col Noir Shale and Bangba Formation.

The 220 to 250 m thick central part of the Thini Chu Group, mostly unfossiliferous and showing significant lateral variability of lithologic intervals, is a stratigraphic puzzle: sandstones are mostly quartzarenites, and no single petrographic marker horizon could thus be identified and traced throughout the studied area. Nevertheless, it can be subdivided into a pelitic lower unit, characterized by prevailing black shales and subordinate quartzarenite intercalations (*Col Noir Shale*), and a coarser-grained upper unit (*Bangba Formation*), characterized by lithic-bearing diamictites at Bangba.

Col Noir Shale. The basal part at Tilicho consists of felsite-bearing quartzarenites (12 m) sharply transgressed by poorly exposed black shales.

From Col Noir to Bangba, shales and thin sandstones with lenticular, wavy and flaser bedding overlain by black shales pass laterally to prevailing quartzarenites with herringbone and sigmoidal cross-lamination overlain by shales and thin rippled sandstones (21 to 22 m); this sequence is capped by a sharp-based and medium- to coarse-grained rippled quartzarenite (3 to 4 m).

The following black shales, interbedded with thin-bedded limonitic mudstones, seemingly decrease westward in thickness (from about 60 m at Thinigaon to 49 m at Col Noir and 43 m at Bangba). They are sharply overlain by medium-grained white quartzarenites, showing tidal cross-lamination at Bangba (4 m at Thinigaon, 11.5 m at Col Noir and 24 m at Bangba).

The upper part at Col Noir entirely consists of black shales with ochre-weathering lenses interbedded with thin rippled sandstones (63 m). At Bangba, black shales and subordinate rippled sandstones (40.5 m) are followed abruptly by quartzose sandstones (13 m); these are sharply transgressed by shales with intercalated burrowed quartzarenites containing sparse pebbles (16 m).

This formation, characterized by two quartzarenite intervals occurring in the lower and middle part, is best exposed at Bangba; most typical pelitic facies characterize however the Col Noir section. Overall thickness is 150 to 160 m at Thinigaon, Col Noir and Bangba. The Tilicho section, only about 100 m thick, is largely covered.

Bangba Formation. At Thinigaon, an about 47 m thick interval of cross-laminated white quartzarenites is folded and truncated in the upper part.

At Tilicho, 39 m thick, medium-grained, cross-laminated white quartzarenites (burrowed and finer-grained at the top) are sharply followed by black to pinkish shales (26.5 m). These two intervals, which correlate well lithologically with other sections to the west and east, are overlain by a mostly pelitic sequence which was not found elsewhere. It consists of sharp-based quartzarenites (5 m), followed abruptly by black shales with intercalated ochre-weathering mudstones and thin rippled sandstones increasing upward in abundance (45 m). These are overlain in turn by interbedded dark shales and up to medium-grained quartzarenites characterized by extreme burrowing and interference ripples ("tadpole nests") (16 m), capped by interbedded black shales and laminated sandstones (15 m).

At Col Noir, up to coarse-grained white quartzarenites are characterized by tidal cross-lamination (sigmoids, herringbones, rippled caps, flasers) (42 m). This interval, showing sharp contacts at the base, within and at the top, is followed by black to pinkish shales with carbonate concretions locally yielding chaetetids (26 m).

At Bangba, brownish and clay-rich pebbly sublitharenites to poorly-sorted pebble to cobble conglomerates (maximum diameter 10 cm) with sharp base and abundant mudclasts (13 m) (Fig. 7A) are overlain by amalgamated massive sandstones showing cross-lamination in the upper part (49 m). Black to pinkish shales with intercalated thin-bedded sandstones sharply follow (28 m).

Within the formation, well exposed in all studied sections along the Marsyandi Valley, an arenaceous lower part (62 to 39 m) is invariably followed by a shaly upper part (28 to 26 m). Overall thickness thus varies from 90 m at Bangba to 68 m at Col Noir; however, the extra 81 m measured at Tilicho, locally characterized by extreme burrowing, hint at significant heterochroneities. Characteristic tilloid facies occur only at Bangba (*Bangba diamictite*).

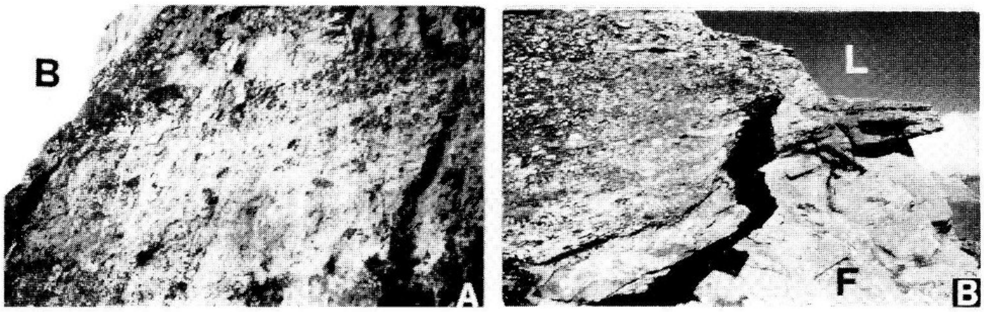


Fig. 7 - Glacio-marine sediments at Bangba/Braga. A) Poorly-sorted, matrix-supported and crudely-stratified diamictites at base of Bangba Fm. (B); these beds, containing dolostone rock fragments (see Fig. 11D) and abundant mudclasts, may represent glacio-marine drift (Easterbrook, 1982). B) Framework-supported lithic conglomerates with scoured base (3.6 m thick), probably diamictites reworked by meltwater, mark transition from feldspathic lower (F) to lithic upper (L) member of Braga Formation.

Braga Formation.

This heterogeneous unit (121 m at Tilicho, 80 m at Col Noir and Bangba), well exposed throughout the study area but containing tilloids only in the Bangba/Braga section (*Braga diamictite*), can be subdivided into two members characterized by different petrographic composition.

Feldspathic lower member. At Tilicho and Col Noir, locally microconglomeratic transgressive beds of ferruginous subarkoses to feldspathic quartzarenites with bimodal sorting and yielding sparse bivalves are followed by black shales with rare parallel-laminated to rippled sandstones (68 m at Tilicho, only 25 m at Col Noir).

At Bangba/Braga, very poorly-sorted pebbly conglomerates with greenish matrix are interbedded with subordinate sandstones, mudstones and pelites in the upper part (52 m).

Lithic upper member. At Tilicho, sharp-based quartzarenites with sigmoidal cross-lamination, mud drapes, reactivation surfaces and interference ripples (23 m) are sharply overlain by a bioclastic sublitharenite with burrowed base, followed by black shales with upward-increasing rippled sandstones (17 m). Next, another burrowed surface is overlain by a cross-laminated quartzarenite passing rapidly to black shales and rare rippled sandstones (13 m).

At Col Noir, white quartzose sandstones with sharp base (10 m) (Fig. 8A) are abruptly overlain by pink-weathering dark shales, interbedded with thin mudstones showing illitic drapes and with thin sandstones displaying interference ripples in the upper part (15.5 m). The following shales, strongly burrowed and yielding long crinoid stems and septaria-like nodules (6.5 m) (Fig. 8B), are intercalated with thin-bedded sandstones and sparse limonitic carbonate concretions in the upper part (23 m).

At Bangba/Braga, a channellized framework-supported conglomerate with cobbles of sandstone up to 25 cm in diameter (3.6 m) (Fig. 7B) is followed by para-

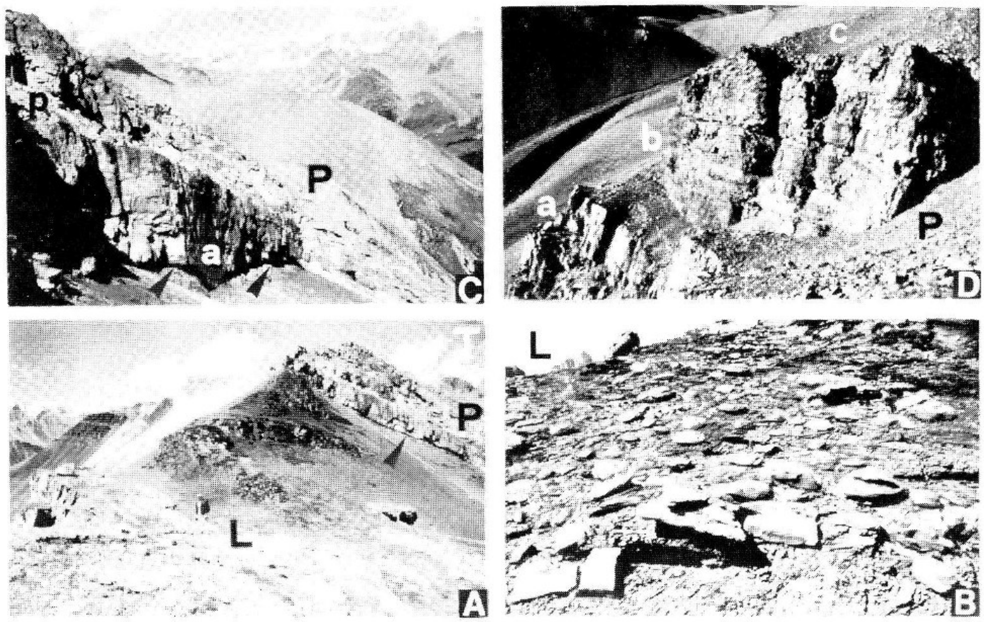


Fig. 8 - Stratigraphy in the upper part of Thini Chu Group at Col Noir. A) Lithic upper member of Braga Fm. (L) consists of quartzose tidal sandstones abruptly transgressed by dark shales (sherpa Tenzi for scale). Puchenpra Fm. (P) unconformably follows (arrow), and Lower Triassic Tamba Kurkur Fm. is visible in the background against the Nupra pyramid (T). B) Abundant carbonatic concretions in dark shales (lithic upper member of Braga Fm.; rucksack for scale). C) Unconformable base of Puchenpra Fm. (arrows) is overlain by estuarine sublitharenites (a= member A) with locally interbedded coal lenses rich in plant remains (p). D) Puchenpra Fm. displays an overall transgressive trend, with transition from estuary channel (a= member A) to estuary mouth (b= member B) and finally shelfal deposits (c= member C).

conglomerates with ochre to black matrix and mudclasts (maximum diameter 20 cm), interbedded with moderately well-sorted fine-grained subarkoses to medium-grained sublitharenites, mudstones and pelites showing illitic drapes (14.5 m). In the upper part, dark burrowed pelites (4 m) are capped by coarse-grained dark green quartzarenites, interbedded with shales and rich in silicate to phyllosilicate peloids and ooids, phosphatic matrix and embayed quartz grains (6 m).

Puchenpra Formation.

This unit, best represented in the Col Noir section to the W of Puchenpra (Fig. 2), can be subdivided into four members. *Member A*, dominated by unfossiliferous pebbly quartzose sandstones (46 m at Tilicho; 59 m at Col Noir), is overlain by the sparsely bioclastic *member B* (11 m at Tilicho; 39 m at Col Noir); next, the richly bioclastic *member C* (varying in thickness from only 2 m at Tilicho to 24 m at Col Noir and at least 26 m in the Bangba/Braga section) is capped in turn by bioclastic dolomitic limestones ("*topmost biocalcarenites*", increasing in thickness from 0.7 m at Tilicho to 1 m at Col Noir and 4.3 m above Braga).

Member A. At Tilicho, white quartzarenites with sharp base, cross-lamination and flaser bedding (10 m) are sharply followed by thick-bedded white quartzarenites with tidal cross-lamination, alternating with moderately well-sorted channellized pebbly conglomerates (36 m). Coal lenses were observed at Thinigaon by Bordet et al. (1971, p.111).

At Col Noir, a strongly erosive base mantled by pebbly lags is followed by locally microconglomeratic sublitharenites lacking feldspars and displaying sigmoidal cross-lamination (11.5 m) (Fig. 8C), overlain by burrowed chloritic shales and limonitic and dolomitic mudstones rich in plant remains with an intercalated sandstone bed (5.5 m). The following thick-bedded sublitharenites are locally pebbly or display herringbone cross-lamination (about 42 m).

At Bangba/Braga, tectonized white quartzose sandstones locally with gravelly beds are at least 30 m thick.

Member B. At Tilicho, poorly exposed pelites with intercalated coarse-grained grey burrowed quartzarenites (6 m) are overlain by thickening-upward medium-grained yellow-weathering grey burrowed quartzarenites, with graphitic pelites at the top (5 m) (Fig. 9A).

At Col Noir, brownish-grey burrowed siltstones interbedded with poorly-sorted pebbly sublitharenites (8 m) are overlain by fine-grained, brownish, strongly burrowed and occasionally bioclastic sandstones, passing upward to medium-grained cross-laminated pinkish sandstones containing bivalves and black mudclasts (31 m) (Fig. 8D).

At Bangba/Braga, coarse-grained sublitharenites with large brachiopods are followed by some 30 m of faulted and poorly exposed pelites.

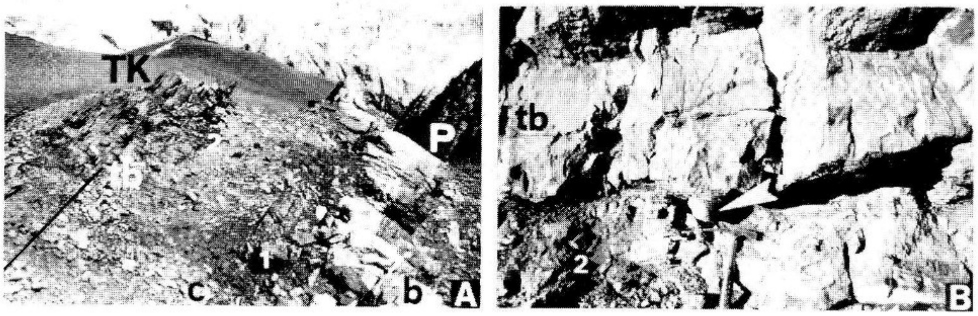


Fig. 9 - Stratigraphy at top of Thini Chu Group at Tilicho. A) At top of Puchenpra Fm. (P), coarsening-upward quartzarenites capped by graphitic pelites (b= member B) are sharply transgressed by shelfal pelites (c= member C) containing at base (1) and top (2) NCI-rich hybrid arenites. A paraconformity separates "topmost biocalcarenites" (tb; Dorashamian) from Tamba Kurkur Fm. (TK; lowermost Triassic). B) Rounded quartzite cobbles up to 15 cm in diameter (dropped by icebergs or floating wood?) (arrow; hammer for scale) are found at the paraconformable boundary between member C of Puchenpra Fm. (2= NCI-rich ironstone) and "topmost biocalcarenites" (tb).

Member C. At Tilicho, pebbly sublitharenites rich in non-carbonate intrabasinal grains (illitic, glauconitic or silicate peloids; NCI of Garzanti, 1991), yielding mud-clasts, brachiopods and bryozoans, are followed by black shales, capped in turn by coarse-grained NCI-rich quartzarenites containing quartzite cobbles (2 m) (Fig. 9B). Authigenic dolomitization of micrite is locally extensive.

Similar medium-grained NCI-rich quartzarenites occur at the top of the Thinigaon section (4 m), where Bordet et al. (1975, p.95) report a rubefied erosion surface and a condensed brachiopod-rich layer.

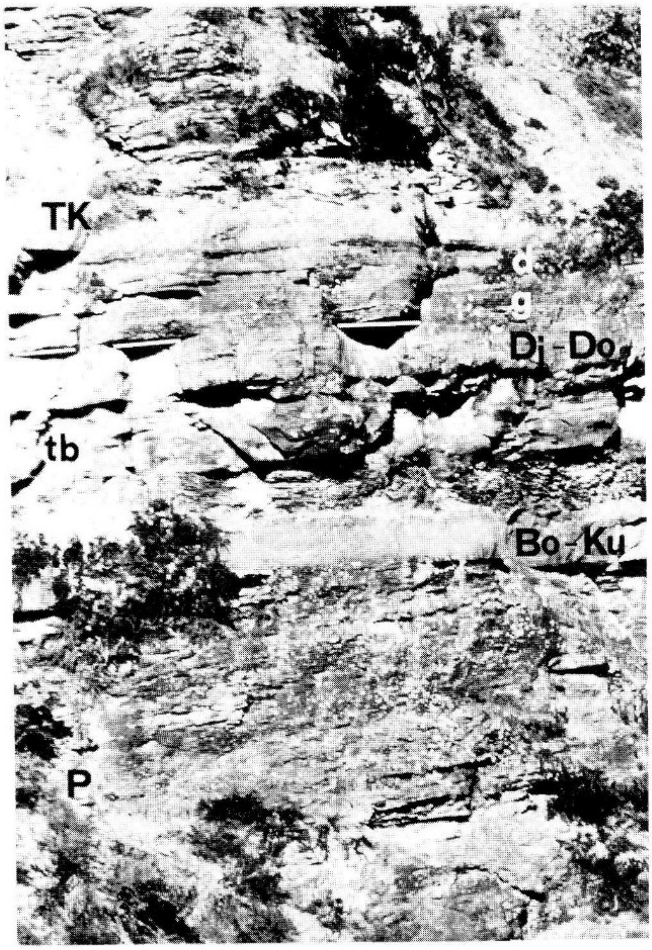


Fig. 10 - Permo-Triassic boundary above Braga. Shales in the upper part of Puchenpra Fm. (P) are capped by "topmost biocalcarenites" (tb). This member (4.3 m thick) consists of three condensed pelagic carbonate horizons: the first one contains Bolorian to Kubergandian-Murgabian conodonts (Bo-Ku) and the third one Djulfian-Dorashamian conodonts (Dj-Do). The basal carbonate band of Tamba Kurkur Fm. (TK) is dated as Griesbachian (g) to Early Dienerian (d).

At Col Noir, pebbly quartzarenites containing frequently silicified brachiopods, bivalves, and mudclasts (7 m) are overlain by poorly exposed bioclastic sandstones, followed in turn by biocalcirudites, by yellowish-grey micaceous sandstones, by reddish ferruginous and phosphatic richly bioclastic sandstones, and finally by micaceous siltstones and very fine-grained sandstones with hummocky cross-lamination (17 m).

Above Braga, bioclastic sublitharenites intercalated with pelites and calcirudites rich in brachiopods (at least 20 m), are capped by ferruginous siltstones with rippled sandstones at the top (6 m).

Topmost biocalcarenites. The Thini Chu Group is invariably capped by condensed reddish biocalcarenites yielding brachiopods, fenestellid bryozoans, corals, crinoids, bivalves and reworked phosphatic nodules (0.7 m at Tilicho; 1 m at Col Noir). Above Braga, three metric biocalcarenitic horizons containing abundant bryozoans and brachiopods are separated by two pelitic intervals with intercalated brachiopod-bearing arenites (4.3 m) (Fig. 10). Late diagenetic dolomitization of the micritic groundmass was extensive, but bioclasts are still mostly calcareous.

Fossils, age and regional correlations

Age-diagnostic fossils occur at several stratigraphic intervals within the Thini Chu Group. Fossils were not found in the lower member of the Marsyandi Formation, which is assigned a Visean age according to stratigraphic position.

Marsyandi Formation.

Two richly fossiliferous horizons characterize the *Syringothyris* beds at Tilicho (about 426 to 430 m and 462 to 470 m below the top of the Paleozoic succession) and Col Noir (420 to 422 m and 460 to 470 m below the top of the Paleozoic). The lower biocalciruditic horizon is also recognized in the tectonized Thinigaon section. At Bangba, where biocalcarenitic lenses with *Syringothyris* are reported in this stratigraphic position by Bordet et al., 1975, p.88), quartzarenites with a few punctate spiriferids were recorded at the top of three prominent quartzose sandstone intervals (Fig. 6B) and 45 m above (about 435 and 480 m below the top of the Paleozoic).

Brachiopod assemblages in the lower horizon at Tilicho (HM 81; Pl. 1) are dominated by spiriferids [*Syringothyris* cf. *lydekkeri* Diener, 1899, *Ectochoristites* sp., *Alispirifer* aff. *middlemissi* (Diener, 1915), *Spiriferellina* sp.] and rhynchonellids [*Stenoscisma dowhatensis* (Diener, 1915)]. *Syringothyris* is particularly common in shaly layers, whereas *Stenoscisma* and *Alispirifer* prevail in crinoidal limestone beds; since most specimens appear to have suffered little transport, type of substratum and environment are inferred to be important factors, beside age and climate, in controlling brachiopod distribution.

The fossil association indicates a late Early Carboniferous age (Serpukhovian); lack of productids suggests cool-water conditions at middle-high southern latitudes.

The Marsyandi Formation thus correlates with the Po Formation of Spiti. The lower member broadly corresponds with the Thabo Stage of Hayden (1904), whereas the *Syringothyris* beds may be correlative with the lower part of the "Fenestella Shale".

Col Noir Shale and Bangba Formation.

Brachiopods and fenestellid bryozoans are abundant only at the base of the Col Noir Shale, which can be assigned a mid-Carboniferous age according to stratigraphic position. This unit thus corresponds in part with the "Fenestella Shale" of Spiti and Kashmir.

In the shaly upper part of the Bangba Formation at Col Noir, chaetetids (B. Senowbari-Daryan, pers. comm. 1993) were found at the core of lens-shaped carbonatic concretions (small bioherms?). A Bashkirian-Moscovian age is thus suggested (West & Kershaw, 1991).

Braga Formation.

Bivalves occur at the base of the feldspathic lower member at Tilicho; bivalves or large crinoid stems were also found in the lithic upper member at Tilicho and Col Noir respectively. According to stratigraphic position, age may be late Late Carboniferous (Kasimovian-Gzelian) to earliest Permian (Asselian-Sakmarian).

The Braga diamictite corresponds with the middle-upper Sisne Fm. of the Nepal Lesser Himalaya (Sakai, 1991) and with the Ganmachidam diamictite of Spiti (Garzanti et al., 1993). The topmost NCI-bearing layers might be correlated with the transgressive Member A of the Chumik Formation in the Zanskar Range, dated as Late Sakmarian (Gaetani et al., 1990; Archbold & Gaetani, 1993).

Puchenpra Formation.

Abundant plant debris, formed by bits of woody tissue remained after prolonged maceration in still water, is found in member A at Col Noir (HM 157); two small fragments of presumed foliage show a net venation reminding one of *Glossopteris* (R.H. Wagner, written comm. 1994), part of the typical cool Permian flora of Gondwanaland. This otherwise unfossiliferous member may be correlated with Member B of the Chumik Formation in the Zanskar Range, dated as Late Sakmarian/Artinskian? (Gaetani et al., 1990).

In member B at Col Noir, the calcareous benthic foraminifer *Nodosaria* aff. *grandis* Lipina, 1949, recorded 9 m above the base, points to the Early Permian (possibly Sakmarian-Artinskian: D. Vachard, writ. comm. 1994; Colchen & Vachard, 1975). Member B of the Puchenpra Fm. thus roughly correlates with the Ritung Bioturbated Mudstone of the Nepal Lesser Himalaya (Sakai, 1991), which contains mid-Early Permian bryozoans (Sakagami & Sakai, 1991).

In member C above Braga, a rich brachiopod fauna was found 29 m below the top of the Paleozoic (Pl. 1). Abundance of productids (*Marginifera* ex gr. *typica* Waagen, 1884, *Waagenoconcha* sp., *Linoproductus* sp.), associated with subordinate spiriferids (*Spiriferellina* sp., Spiriferacea indet.) and common crinoids and bivalves (Pectinacea), suggests temperate-warm conditions at middle southern latitudes in the late Early Permian (Bolorian to possibly Early Kubergandian).

At Col Noir, a brachiopod [*Fusispirifer* cf. *nitiensis* (Diener, 1897), *Costiferina alata* Waterhouse, 1966] and bivalve (*Atomodesma* sp.) fauna, found from 8 to 12 m below the top of the Paleozoic, points to the early Late Permian (Murgabian-Midian?; Pl. 1). Because of predominance of left valves of *Atomodesma* sp. - characterized by strong radial folds and sulci which aided in stabilizing the shell (Kauffman & Runnegar, 1975) - and of pedicle valves of *Costiferina* sp., the assemblage is considered as autochthonous. A similar faunal assemblage characterizes the "*Costiferina* arenites" of central Dolpo (Garzanti et al., 1992, p. 279).

At Tilicho, the brachiopod *Neospirifer moosakailensis* (Davidson, 1862) was observed in the scree; these condensed NCI-rich layers might thus be correlated with the late Late Permian upper part of the Thini Chu Group of central Dolpo ("ochre pelites" to "Kuling Formation" of Garzanti et al., 1992).

Member C is thus confined to the late Early Permian (Bolorian) at Bangba, whereas it is largely or entirely Late Permian at Tilicho and Col Noir.

The topmost biocalcarenites from Tilicho to Col Noir and Manang Gompa yielded conodonts of Djulfian-Dorashamian [*Hindeodus typicalis* (Sweet, 1970) transitional form to *H. julfensis* (Sweet, 1973)] to Late Dorashamian age [*Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. (previously considered as *H. typicalis*: Kozur, writ. comm. 1993); *Gondolella orientalis transcaucasica* Gullo & Kozur] (Pl. 2). The rich faunal assemblage at Tilicho includes the brachiopod *Spiriferella rajah* (Salter, 1865) (Pl. 1) and the coral *Plerophyllum schindewolfi* Flügel, 1966, documenting the latest Permian (Dorashamian; determination by H.W. Flügel, 1992).

Above Braga, the first of the three biocalcarenitic horizons yielded at its base the conodont *Vjalovognathus shindyensis* (Kozur, 1976), a cool-water form restricted to the Tethyan margins of Gondwana and indicating the latest Early Permian (Bolorian), associated with *Gondolella phosphoriensis* Youngquist, Hawley & Miller, 1951, a cool to cold-water form documenting the mid-Permian (Kubergandian-Murgabian; determinations by H. Kozur, 1993) (Pl. 3). The overlying thin pelitic interval and second biocalcarenitic horizon may correlate with the much thicker mid-Permian pelites and biocalcarenites found almost at the top of the Col Noir section and with the NCI-rich hybrid arenites recorded almost at the top of the Tilicho and Thinigaon sections. The third biocalcarenitic horizon yielded the same Djulfian-Dorashamian conodont, brachiopod and coral assemblage as the condensed carbonate bed found in other sections to the west. Paleontologic data thus document strongly condensed deposition above Braga, where 4.3 m of sediment (Fig. 10) represent the latest Early Permian and all of the Late Permian (12 to 14 Ma according to the time scale of Harland et al., 1989).

Mineralogy of detritus and dispersal patterns

Sandstone petrography.

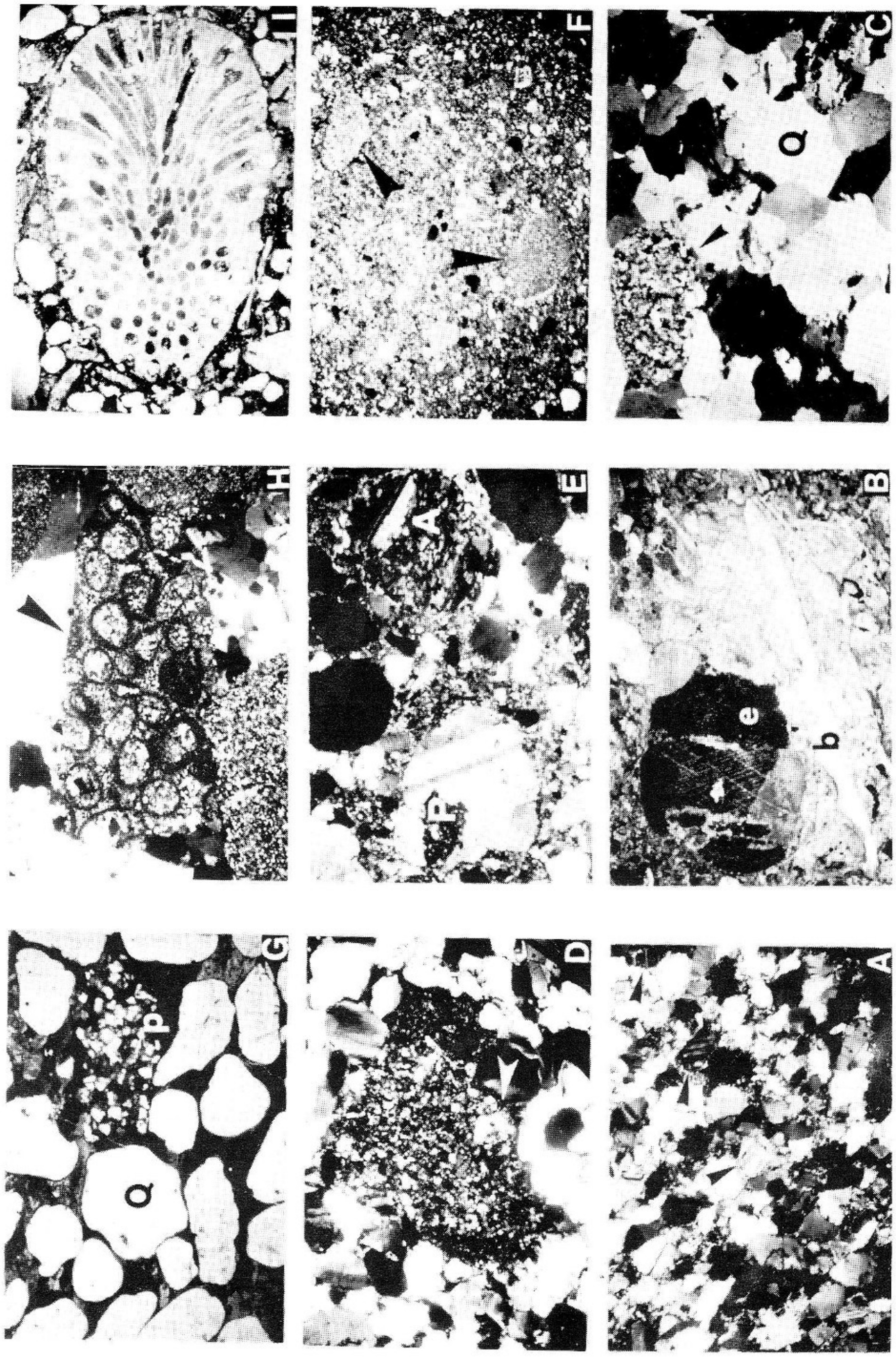
Marsyandi Formation. In the *lower member*, average modal composition of sandstones changes abruptly from Q 82±2 F 16±2 L 1±1 (HM 2-76-218) to Q 92±4 F 6±3 L 2±2 in the uppermost part (HM 3-4-77-97-219). This upward increase in mineralogical stability is partly controlled by grain size (Odom et al., 1976), since the quartz/feldspar ratio rapidly increases from about 5 in very fine to lower fine-grained sandstones (Fig. 11A) to 10 ÷ 50 in medium to coarse-grained sandstones.

Mineralogical stability increases further in the overlying *Syringothyris* beds (Fig. 11B), where detrital modes reach Q 96±4 F1±2 L2±2 (HM 5-6-7-78-79-80-83-84-85-142-220). Even though the quartz/feldspar ratio is still strongly controlled by grain size (being 15 ÷ 25 in fine to lower medium-grained sandstones and ≥ 100 in upper medium and coarser-grained sandstones), an increase in Q/F by two to four times is documented within each grain size fraction with respect to the lower member.

Col Noir Shale and Bangba Formation. Sandstones interbedded in the *Col Noir Shale* are invariably quartzarenites, with detrital modes varying from Q 97±2 F 1±1 L2±2 in the basal part (HM 9-10-98-99-221), to Q 100 F 0 L 0 in the middle part at Col Noir (HM 143), and finally to Q 97 F 2 L 1 in the topmost part at Bangba (HM 224) where igneous to metamorphic detritus was recorded.

Sandstones rich in pseudomatrix occur in all sections (HM 100-144-224) at the transition with the *Bangba Formation*. The latter unit invariably contains pure quartzarenites from Thinigaon (Q 100 F 0 L 0; HM 12) to Tilicho (Q 99±1 F 1±1 L 1±1; HM 87-88-100-89-90-91) (Fig. 11C). Felsite and chert lithics, as well as reworked overgrowths on quartz grains and bimodal roundness of heavy minerals, were observed at Col Noir (Q 97±3 F 1±0 L 2±3; HM 144-145). Lithic grains increase further towards the east, and dolostone rock fragments containing echinoderm remains (Fig. 11D) occur in the basal diamictite at Bangba (Q 91±7 F 2±3 L 7±4; HM 222-225).

Fig. 11 - Arenite petrography in the Thini Chu Group. A) Fine-grained subarkoses of lower member of Marsyandi Fm. (arrows show twinned microcline and plagioclase grains; Bangba, HM 218; 22x, 2N). B) Echinoderm (e) and brachiopod (b) remains from *Syringothyris* beds biocalcirudites (Tilicho, HM 81; 11x, 2N). C) Very coarse-grained quartzarenites of Bangba Fm. with exclusive monocrystalline (Q) to polycrystalline (arrow) detrital quartz (Tilicho, HM 90; 7x, 2N). D) Dolostone rock fragment containing echinoderm remains (arrow) (base of Bangba diamictite; Bangba, HM 225; 11x, 2N). E) Abundance of feldspars and granitoid detritus (P= plagioclase in granitoid rock fragment; A= alkali-feldspar with chessboard twinning) in coarse-grained subarkoses (base of Braga diamictite; Bangba/Braga, HM 226; 18x, 2N). F) Rounded dolostone rock fragments (arrows) in tilloid wacke (feldspathic lower member of Braga diamictite; Bangba/Braga, HM 227; 11x, 2N). G) Coarse-grained transgressive quartzarenites yielding quartz grains with rounded to concave outlines (Q), silicate peloids (p) and abundant phosphatic matrix cap Braga diamictite (Bangba/Braga, HM 235; 18x, 1N). H) Ooidal chert (arrow) in microconglomeratic sublitharenites (member A of Puchenpra Fm.; Tilicho, HM 109; 23x, 2N). I) Reworked bryozoan in NCI-rich hybrid arenites (member C of Puchenpra Fm.; Tilicho, HM 115; 7x, 1N).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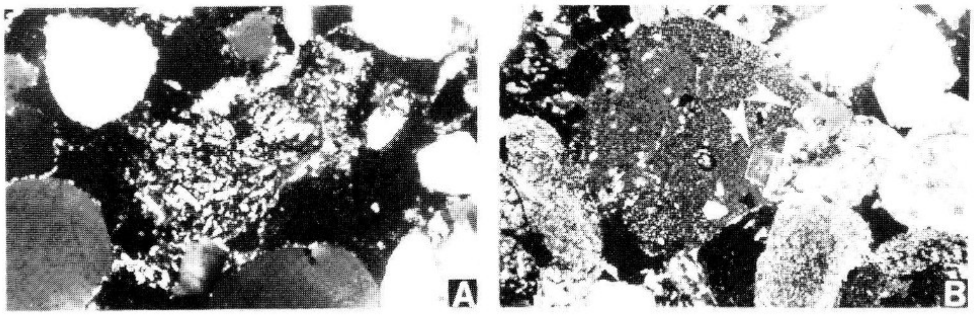

Fig. 12 - Volcanic rock fragments in Braga diamictite document bimodal magmatism typical of rift settings. A) Mafic microlitic grain at base of feldspathic lower member (HM 226; 44x, 2N). B) Felsitic grain with phenocrysts of quartz and plagioclase showing chessboard-like twinning (arrows) at base of lithic upper member (HM 230; 21x, 2N).

Braga Formation. In the *feldspathic lower member*, detritus from igneous rocks (plagioclase, orthoclase, microcline, chessboard-albite, volcanic to hypabyssal and plutonic grains, yellow-brown chromian spinel) is associated with mainly dolostone sedimentary rock fragments and minor metamorphic lithics. Average detrital modes are Q 94±4 F 5±5 L 1±1 at Tilicho (HM 93-94-102) and Col Noir (HM 147), where lithics are rare and feldspars are common (F= 11) only in the finest sample (1.75 Φ). In the diamictite at Bangba/Braga, feldspars are common even in upper coarse-grained sandstones (Fig. 11E), which contain significant sedimentary detritus (sandstone, dolostone; Fig. 11F) (Q 80 F 10 L 10; HM 226). Plagioclase and subordinate alkali feldspars are most abundant in fine to medium-grained sandstones (Q 69±5 F 23±3 L 8±8; HM 229, AD 196). Mafic microlitic to felsitic volcanic rock fragments are minor (Fig. 12A), as well as metamorphic lithics.

The *lithic upper member* is characterized instead by an abundance of detritus derived from sedimentary rocks (mainly quartzose siltstone to sandstone and sericitic shale). Chert grains are most significant at Tilicho (Q 95±4 F 2±1 L 3±3; HM 95-96-105). In the diamictite at Bangba/Braga, sandstone composition does not appear to be significantly controlled by grain size. At the base (HM 230), dolostone rock fragments are still common and volcanic lithics (felsitic and pumiceous vitric to microlitic and lathwork types; Fig. 12B) occur (Q 75 F 3 L 22). Higher up (HM 231-232-233, AD 195), feldspars and metamorphic grains decrease in abundance, whereas dolostone rock fragments rapidly vanish (Q 83±7 F 7±4 L 10±4). At the top (HM 234-235, AD 193), transgressive arenites are characterized again by ultrastable detrital modes (Q 98±2 F 1±1 L 1±1; Fig. 11G).

Puchenpra Formation. *Member A* is characterized by abundance of arenaceous rock fragments and locally ooidal chert (Fig. 11H). Detrital modes vary little from Tilicho (Q 92±5 F 2±1 L 6±5; HM 106-107-108-109) to Col Noir (Q 93±3 F 1±1 L 7±4; HM 154-158).

Member B at Tilicho is characterized by chert-bearing quartzarenites (Q 96 F 0 L 4; HM 110), passing upward to pure quartzarenites (Q 100±0 F 0±0 L 0±0; HM

111-112). At Col Noir, sublitharenites containing chert and felsites (Q 93 F 0 L 7; HM 159) are overlain by quartzose sandstones yielding also dark to reddish-brown chromian spinel (Q 94±3 F 3±2 L 3±2; HM 160-161-162). Similar compositions are recorded at Bangba/Braga (Q 92 F 4 L 4; HM 236).

Member C is characterized by NCI-rich arenites (Fig. 11I) with arenaceous to quartzite rock fragments, chert and rounded quartz grains at Thinigaon (Q 98±1 F 1±1 L 1±1; HM 13-14-15-16) and Tilicho (Q 92±6 F 1±1 L 7±5; HM 113-114-115-116-117). Felsitic, metamorphic, terrigenous and chert grains occur at Col Noir (Q 97±1 F 1±1 L 2±1; HM 163-164-166).

Clay mineralogy.

Clay minerals change from illite-chlorite in the lower part of the Thini Chu Group to mainly illite in the upper part. In the Marsyandi Fm., illite (51 to 64 %) is slightly more abundant than chlorite (36 to 49 %), whereas in the Col Noir Shale and Bangba Fm. chlorite (53 %) slightly prevails over illite (47 %). In the overlying Braga Fm. composition changes abruptly to 100% illite, and is still mostly illitic (88 to 100%) in the Puchenpra Fm., where samples with 100 % chlorite (HM 157) and 27% mixed layers (HM 112) however occur.

Clay mineral assemblages are clearly diagenetic, and do not reflect original mineralogy. Chlorite in fact disappears just in the Braga Fm., which was deposited at polar latitudes where chlorite is today most abundant (Griffin et al., 1968). At any rate, Quaternary illite-dominated assemblages may be found at latitudes well above the Polar Circle (Kuhlemann et al., 1993).

Paleocurrents.

Analysis of 211 paleocurrent indicators in the Thini Chu Group suggests that the source of detritus was located in the south. Similar conclusions were reached for the Sisne Fm. of the Nepal Lesser Himalaya, pointing to provenance at least partly from the Indian continental block (Sakai, 1991). In all of the studied sections, directions of straight-crested wave ripples indicate that the coastline ran about ESE-WNW, approximately parallel to present-day distribution of outcrops along the Marsyandi Valley; sigmoidal cross-lamination consistently testifies to deposition in estuaries dominated by strong NE-ward ebb tidal currents. Dip of cross-laminae at both small (current ripple marks) and large scale (tidal bars, herringbones) is more varied but invariably bipolar, documenting deposition by mainly NE-ward ebb tidal currents and subordinate SW-ward flood tidal currents at Bangba, by both ENE to ESE-ward and WSW to WNW-ward reversing longshore tidal currents at Col Noir, and finally by mainly NW-ward (but also ENE to ESE-ward and SW-ward) longshore currents at Tilicho.

Paleogeographic changes during rifting of Neotethys

Sedimentary evolution.

The Thini Chu Group was deposited in coastal to shelfal settings influenced by both tidal currents and waves, as shown by sedimentary features (Fig. 13, 14) and occurrence of open marine fauna at several stratigraphic intervals (*Syringothyris* beds, upper part of the Bangba Fm., Braga Fm., upper part of the Puchenpra Fm.).

Marsyandi Formation. *Lower member.* These thick mid-shelf shales are interbedded with inner shelf (Fig. 13I) to lower shoreface deposits in the upper part at Tilicho, documenting a regressive trend capped abruptly by coastal sands (Fig. 13G; "sharp-based shoreface sequences" of Plint, 1988). More proximal environments are documented in the Bangba section, where at least five such "forced regressions" (Posamentier et al., 1992) are recorded in the upper 100 metres. The first three are onlapped by either upper or lower shoreface sands (Fig. 13H), in turn transgressed abruptly by shelfal shales locally with a thin ferruginous basal sand layer; the last two are instead overlain by coarser estuarine sands followed by subtidal sands and muds (Fig. 13F).

Great thickness and abundance of feldspars in finer-grained fractions (Fig. 15) point to rapid tectonic subsidence and erosion of uplifted basement blocks during initial rifting of Neotethys in the Early Carboniferous.

Syringothyris beds. These two Serpukhovian sequences consist of sharp-based lowstand coastal sands influenced by both waves and tidal processes, followed by ravinement and deposition of coarse bioclastic transgressive sands (Fig. 14A), overlain in turn by highstand shelfal shales with thin interbedded storm sands increasing upward in abundance. The two laterally extensive marker horizons with rich open marine fauna document major (glacioeustatically-controlled?) events of rapid sea-level rise (Fig. 16).

Greater mineralogical stability of these coarse-grained sandstones, consisting almost exclusively of detrital quartz and microcline (Blatt, 1967), may be at least partly

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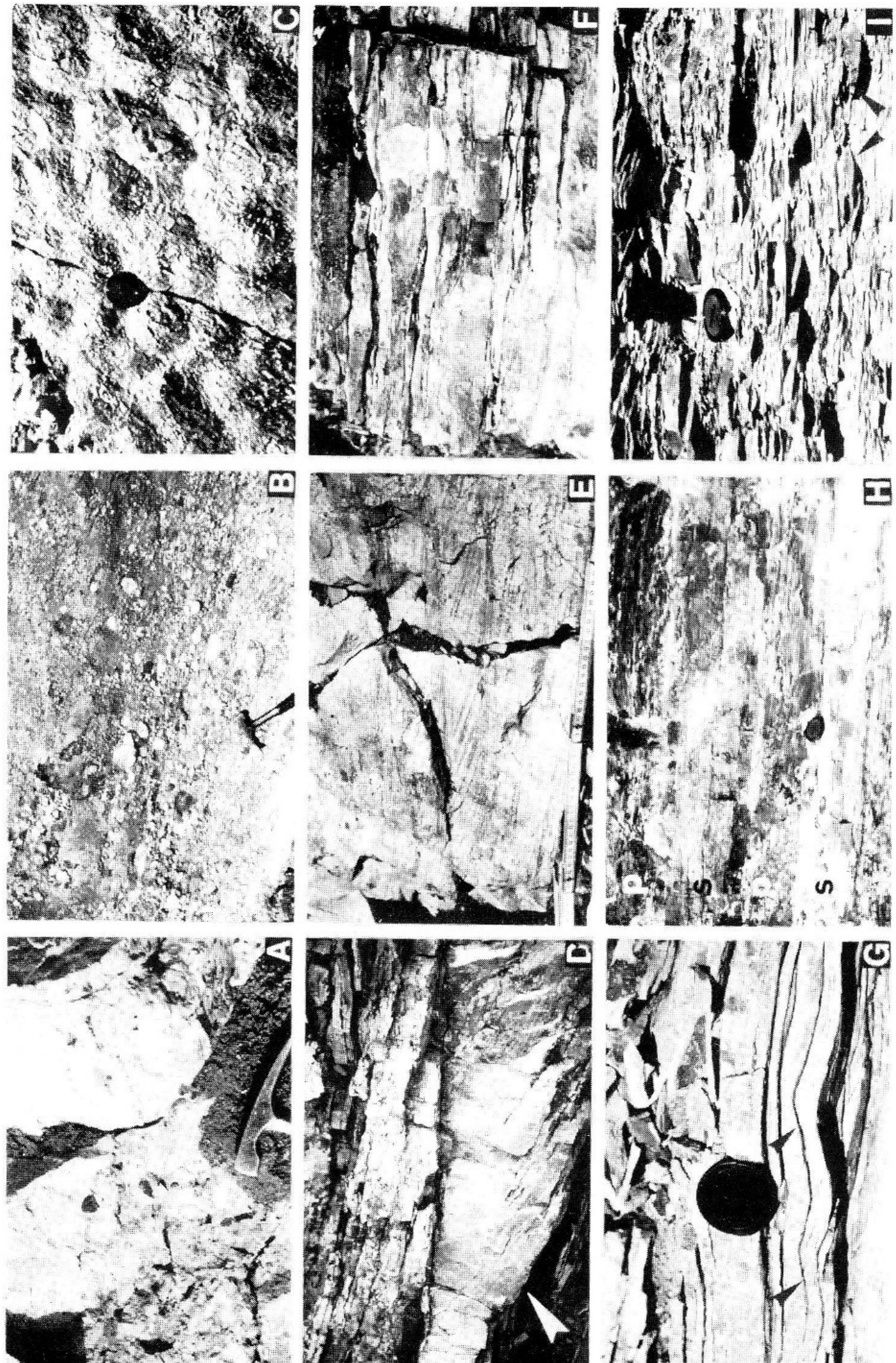
Fig. 13 - Paralic to coastal terrigenous deposits in the Thini Chu Group (lens cap, hammer or rule for scale). A) Estuarine channel-lag pebble conglomerate (member A of Puchenpra Fm.; Tilicho). B) Matrix-rich and poorly-sorted glacio-marine cobble conglomerates (feldspathic lower member of Braga diamictite; Bangba/Braga). C) Interference ripples ("tadpole nests") draped by extremely burrowed, paralic to lagoonal shales (Bangba Fm.; Tilicho). D) Tidal-channel quartzarenites showing scoured base (arrow), sigmoidal cross-lamination to lateral accretion bedding (lithic upper member of Braga Fm.; Tilicho). E) Herringbone cross-lamination in intertidal sandstones (member A of Puchenpra Fm.; Tilicho). F) Flaser-bedding in heterolithic subtidal sands and muds (topmost lower member of Marsyandi Fm.; Bangba). G) Wave-ripple lamination (arrows) in upper shoreface sandstones (topmost lower member of Marsyandi Fm.; Tilicho). H) Lower shoreface wave-rippled sandstones (s) interbedded with dark siltstones (p) (lower member of Marsyandi Fm.; Bangba). I) Current-rippled sandstones in isolated lenses (arrows) and thin flat beds (subtidal environments below fair-weather wave base; upper part of lower member of Marsyandi Fm. at Tilicho).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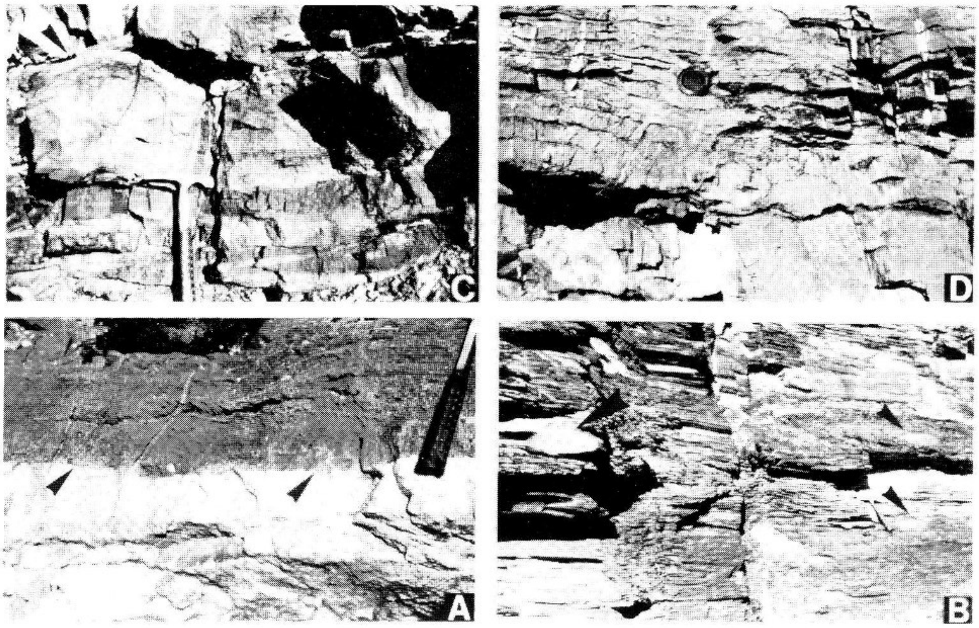

Fig. 14 - Shelfal deposits in the Thini Chu Group (hammer or lens cap for scale). A) Dark coloured, open-marine, brachiopod-rich quartzose biocalcirudites sharply transgress (arrows) white upper shoreface quartzarenites (first sequence of *Syringothyris* beds at Thinigaon). B) Mid-shelf black shales with sparse ochre-weathering mudstone lenses (arrows) (upper part of Col Noir Shale at Col Noir). C) Outer shelf, NCI-rich arenites; paraconformity at top (arrow) is marked by sparse cobbles (see Fig. 9B; top of member C of Puchenpra Fm. at Tilicho). D) Outermost shelf, orange-weathering condensed carbonates ("topmost biocalcarenites" at Tilicho).

ascribed to reworking of shoreline sediments and deposition in high-energy shallow-marine environments during transgression.

Col Noir Shale. This unfossiliferous formation largely consists of black shelfal shales intercalated with lenticular limonitic mudstones (Fig. 14B) or thin storm sand beds; two sharp-based cross-laminated coastal sandbodies with mainly tidal structures and laterally variable thickness might be interpreted as valley-fills incised at low sea-level. Water depth never exceeded some tens of metres.

Pure quartzarenitic composition at this stage (Fig. 15) may suggest either more subdued reliefs and reduced uplift rates during a stage of relative tectonic quiescence or, conversely, recycling of older quartzofeldspathic deposits during incipient inversion of rift basins. At the top of the unit in the Bangba section, in fact, appearance of possible dropstones and slight increase of basement-derived detritus hint at the onset of the Gondwana glaciation, triggered in nearby areas by cooling climates probably coupled with initial uplift of rift shoulders in the early Late Carboniferous.

Bangba Formation. The unit begins with another sharp-based coastal clastic interval decreasing W-ward in thickness and grain size. A lens of diamictite rich in matrix and mudclasts, occurring only in the lower part at Bangba, was seemingly deposited under the influence of glacial ice. The diamictite is markedly enriched in dolostone rock fragments locally containing echinoderm remains, and thus derived from erosion of Paleozoic carbonates (possibly Lower Carboniferous equivalents of the Tilicho Lake Fm.). Petrographic composition thus points to active uplift of rift shoulders and erosion of pre-rift strata (Evans, 1990). Preservation of carbonate rock fragments is consistent with minimal weathering in cold climates. Erosion of pre-rift Paleozoic to Precambrian sedimentary successions is suggested also by a few polycyclic grains (abraded overgrowths, bimodally rounded heavy minerals) contained in tidal sandstones at Col Noir, followed sharply by shelfal pinkish shales yielding chaetetids. Subsident proximal lagoonal environments are instead documented by thick and very extensively burrowed muds and rippled sands at Tilicho (Fig. 13C).

Braga Formation. In the *feldspathic lower member*, the first appearance of plutonic detritus from unroofed basement rocks, occurring both in glacio-marine diamictites at Bangba/Braga (Fig. 13B) and in marine transgressive sandstones followed by shelfal shales in the W, suggests that the climax of rifting was reached at the close of the Carboniferous. Uplift of continental blocks was coupled with differential subsidence of rift basins. Water depths however never exceeded a few tens of metres.

The *lithic upper member* begins with a regressive event, documented by channellized glacio-fluvial? conglomerates at Bangba/Braga; sharp-based estuarine to tidal point bar sediments (Fig. 13D; De Mowbray, 1983; Smith, 1988) were instead deposited on a mesotidal coast in the W, which was at least seasonally ice-free. The upper part of the member displays everywhere an overall transgressive trend: at Tilicho it ends with two distinct sequences characterized by markedly transgressive basal sands, locally yielding fossils and sharply followed by shelfal shales with upward-increasing thin storm beds; at Col Noir it mostly consists of shelfal shales locally yielding open marine fauna; and finally at Bangba/Braga glacio-marine diamictites are followed by pelites capped by transgressive NCI-bearing sands.

Rapidly changing petrographic composition suggests a complex morphological and tectonic evolution of source areas (Fig. 15). The increasing abundance of arenaceous to shale rock fragments coupled with vanishing dolostones suggests that different sedimentary successions were now eroded (probably the Upper Precambrian to Lower Paleozoic of the Lesser Himalaya; Jain, 1981), with decreasing contribution from plutonic and mafic to felsic volcanic rocks. Detritus was presumably transported northward both directly by glaciers and by streams originated by melting ice.

Markedly transgressive deposits at the top of the member, capping diamictites at Bangba/Braga, testify to a stage of sea-level rise possibly caused by the end of the Gondwana glaciation in the Sakmarian (Dickins, 1993). The following sharp regression (Fig. 16) may thus be ascribed to either isostatic rebound after melting of continental ice (Veevers & Powell, 1987) or doming and shoulder uplift led by asthenosphere upwelling (Stampfli et al., 1991).

Puchenpra Formation. *Member A* begins with a sharp-based sequence of tidal quartzarenites locally interbedded with coal lenses. At Col Noir, estuarine channel

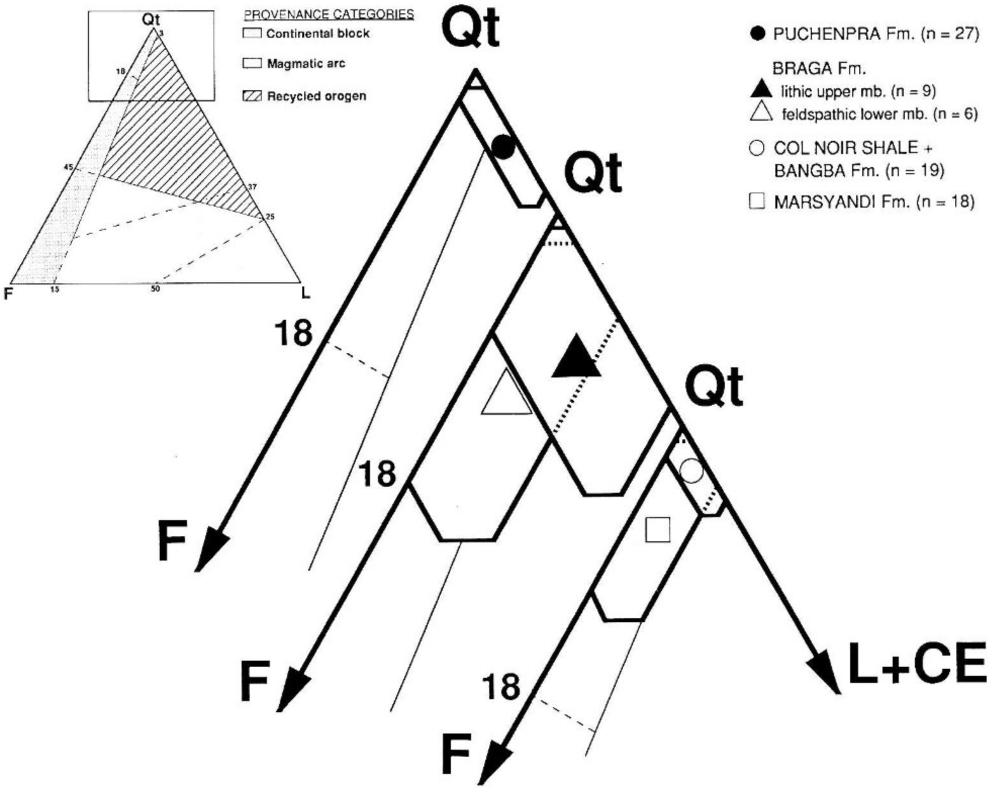

Fig. 15 - Detrital modes for successive stratigraphic intervals of Thini Chu Group. Subarkosic compositions, suggesting unroofing of uplifted basement blocks, alternate with more quartzose sublitharenitic compositions, pointing to stages of active uplift and recycling of pre-rift to syn-rift strata (Evans, 1990; Soreghan & Cohen, 1993). Bimodal magmatic rocks emplaced during rifting provided only minor coeval igneous detritus to rift basins (see Fig. 12; Ingersoll, 1990). Plagioclase prevails over K-spar throughout Thini Chu Group. Provenance categories and petrographic parameters after Dickinson (1985) and Zuffa (1985); polygons are one standard deviation each side of the mean (n= number of samples).

deposits (Allen & Posamentier, 1993; "meander zone" of Nichols et al., 1991) are overlain by swamp muds with macerated plant remains. Next, another major downward shift of coastal onlap is followed by locally pebbly estuarine channel deposits at both Col Noir and Tilicho (Fig. 13A, E). The abundance of locally ooidal chert and arenaceous grains, coupled with sparse metamorphic to felsite clasts and vanishing granitoid detritus, seemingly suggests continuing erosion of largely Proterozoic Lesser Himalayan sedimentary successions to the south.

Member B at Tilicho is a regressive sequence of burrowed muds passing upward to paralic sands and carbonaceous marsh muds. At Col Noir it consists of estuary-funnel gravelly sand and bioturbated silt, overlain by sparsely bioclastic tidal bars interbedded with shallow-marine burrowed sandy siltstones.

In the overall transgressive *member C*, occurrence of age-diagnostic fossils at several horizons allows detection of very significant lateral and vertical changes of both environments and accumulation rates, ascribed to high tectonic mobility at the close of the Paleozoic.

Above Braga, estuary mouth bioclastic sands were followed by interbedded muds and biocalciruditic sands rich in open marine fauna and deposited on a deepening shelf already during the late Early Permian. At Col Noir, estuary mouth pebbly and bioclastic quartzose sandstones pass upward in the Murgabian-Midian to transgressive storm-deposited NCI-bearing bioclastic sands and shelfal muds. The *Atomodesma* bivalves found in these layers (belonging to the 5th form-category of Kauffman & Runnegar, 1975) are indicative of muddy shelf bottoms at water depths between 15 and 45 m. At Tilicho and Thinigaon, two transgressive horizons of condensed sands rich in NCI-grains and open marine fossils (Fig. 14C) document rapid deepening to offshore shelf environments, which probably occurred in the Djulfian.

Mostly quartzarenitic composition at the top of the Thini Chu Group (Fig. 15), with a few volcanic, metamorphic or chert grains, attests to subdued relief at the end of rifting and transgression of rift shoulders taking place as early as the late Early Permian.

A major paleogeographic change occurred during deposition of the Puchenpra Fm.: the Bangba/Braga section was characterized by more proximal environments during the Carboniferous (Marsyandi Fm. to Braga Fm.), whereas in the Permian offshore shelf conditions were established much earlier here than in other sections to the W. A major change in paleocurrents from NW-ward to ESE-ward, documented at the top of member A of the Puchenpra Fm. at Col Noir, may have been the consequence of incipient opening of Neotethys in the east at this stage.

Topmost biocalcarenites. Condensed sedimentation of this marker horizon (Fig. 14D), the base of which is strongly heterochronous, started already in the late Early Permian and still in cool waters in the relatively distal Bangba area. Continuing subsidence during this starvation phase led to deep outer shelf conditions throughout the Manang area at the end of the Permian (water depth up to over a hundred metres). Such an early start of thermal subsidence of the Tethys Himalayan passive margin would imply that sea-floor spreading in the Tethys has been active since at least the Bolorian.

Magmatic evolution.

The sudden appearance of euhedral yellow-brown Al-rich chromian spinel and microlitic volcanic grains at the base of the *Braga Fm.* hints at erosion of mafic rocks emplaced during rifting (Bonatti, 1987). This early stage of mafic to bimodal magmatism (Fig. 12) can be dated as latest Carboniferous. Similar early rifting alkalic activity is recorded by basaltic (Carboniferous; Vannay & Spring, 1993) to granitic dykes (284 ± 1 Ma; Spring et al., 1993) in Northern India, and by nepheline syenites (315 to 297 Ma; Le Bas et al., 1987) in Northern Pakistan.

The first appearance of dark reddish to coffee-brown Cr-rich chromian spinel in transgressive strata containing probable Artinskian foraminifers (*member B* of the *Puchenpra Fm.*; in central Dolpo it occurs at the base of the Upper Permian "*Costiferina*" arenites: our unpublished data) suggests more extensive melt production in the terminal rifting stages (Dick & Bullen, 1984; Bonatti, 1987). It is important to note that, in the nearby Nar region W of the Manaslu and as far as the Tsum region further to the E, up to 300 m thick spilitic basalts are reported to lie in direct contact with tilloid deposits or to be separated from them by plant-bearing shales (Bordet et al., 1975, p.97; Le Fort, 1975; Colchen et al., 1986, p. 85). These spilites are characterized by relatively low total iron and titanium and high chromium (Le Fort, 1975; Colchen et al., 1986, p. 129). They thus compare better chemically with the mid-Permian (Artinskian-Bolorian according to Srikantia & Bhargava, 1983) tholeiitic Panjal Trap basalts of the northwestern Himalaya (Nakazawa & Dickins, 1985; Gaetani et al., 1990; Baud et al., 1993), than with the associated but probably older alkalic dykes (Honegger et al., 1982; Gaetani et al., 1986, p. 455; Papritz & Rey, 1989; Vannay & Spring, 1993). Stratigraphic position of the central Nepal spilites still needs to be precisely assessed.

From the early Late Carboniferous to the early Late Permian, during 50 Ma at least, rift magmatism along the Tethys Himalaya thus changed in character from alkalic in the first stages of crustal stretching to tholeiitic in the final break-up stage. It is noteworthy that this period of time corresponds well with the Kiaman reversed polarity interval. Paleogeographic evolution from rifting to drifting may thus have been associated with the Pennsylvanian-Permian "superplume" event (Hill, 1991; Larson, 1991; Garzanti, 1993).

Climatic evolution.

During the Early Carboniferous, climatic conditions turned from warm tropical, as documented by richly bioclastic carbonates all along the Tethys Himalaya (e.g., *Tilicho Lake Fm.*), to temperate, as suggested by the Serpukhovian cool brachiopod assemblages of Manang (*Syringothyris* beds). By this time India had thus started, due to rotation of Gondwanaland, to be rapidly displaced southward towards the Antarctic Polar Circle (Scotese & Barrett, 1990). Sharp regressions and transgressions recorded in the upper part of the *Marsyandi Fm.* are consistent with waxing and waning of ice caps onto other parts of Gondwana in the Serpukhovian (around 330 Ma; Veevers & Powell, 1987).

Temperate-high latitudes were reached by the Nepal Tethys Himalaya in the early Late Carboniferous (Scotese & McKerrow, 1990), when the first diamictites were deposited in eastern Manang (*Bangba Fm.*). The western Tilicho and Col Noir sections at this stage are characterized respectively by extreme burrowing of rippled sandstones and associated shales, and by occurrence of chaetetids. Vigorous burrowing activity, although seemingly not typical of modern high-latitude tidal flats (Dionne, 1988), may characterize glacio-marine sediments deposited even above the Polar Circle (Aitken & Gilbert, 1994). The same may be true for the small chaetetid bioherms: even though sclerosponges generally occur in warm-water latitudes, biogenic carbonates may develop even in shallow-water polar seas during relatively warm interglacial stages (Freiwald et al., 1994; Phillips et al., 1994).

Deposition of diamictites persisted in eastern Manang through the uppermost Carboniferous and Asselian, when northern India lay close to the Antarctic Polar Circle. At this time the Gondwanian ice caps reached their maximum expansion (Frakes et al., 1975; Martin, 1981; Caputo & Crowell, 1985; Veevers & Powell, 1987).

Climatic conditions started to ameliorate after the retreat of glacial ice in the Sakmarian, when peat swamps and bogs developed at middle-high latitudes (Scotese & McKerrow, 1990). Temperate-warm waters are suggested by brachiopod assemblages in the Bolorian middle part of the *Puchenpra Fm.*, but cool-water conodonts still occur in the overlying Bolorian to Kubergandian-Murgabian pelagic carbonates ("topmost bio-calcarenites"). Possible dropstones are contained in NCI-rich Djulfian sediments (Fig. 9B) at the base of this richly fossiliferous condensed pelagic carbonate interval, which documents that widespread warm conditions resumed only at the end of the Permian (Dickins, 1993).

Conclusions

Detailed stratigraphic studies in the Manang area, coupled with quantitative petrographic analysis of sandstones and new paleontologic information, allowed to reconstruct the complete Carboniferous to Permian record of sedimentary events which punctuated the geodynamic evolution of the central Nepal Tethys Himalaya during rifting of Neotethys.

The notable thickness of the Upper Paleozoic succession (900 to 1000 m ascribed to the Lower Carboniferous, 100 to 200 m to the Upper Carboniferous and 110 to 180 m to the Permian) (Fig. 16), documents strong differential tectonic subsidence particularly active in the Early Carboniferous and probably starting as early as the Late Devonian (Frasnian). Such an early initiation of rifting is documented also in Northern India (Garzanti, 1986b, pp.68-69; Steck et al., 1993) to Pakistan (Pogue et al., 1992).

The Thini Chu Group, overlying the Tilicho Lake platform carbonates, records an increase of subarkosic terrigenous detritus, derived from uplift and erosion of continental blocks in the south during the initial stage of Neotethyan rifting. Within the Thini Chu Group, over 20 depositional sequences can be recognized.

In the lower member of the *Marsyandi Fm.* (Visean), sequences typically begin with sharp-based medium to very coarse-grained coastal quartzarenites inferred to have been deposited at lowstand stages as estuary mouth bars, tidal bars and shoreface sands from proximal (Bangba) to distal (Col Noir, Tilicho and Thinigaon) areas. Sharp transition to black shelfal shales (or to heterolithic subtidal sands and muds in proximal

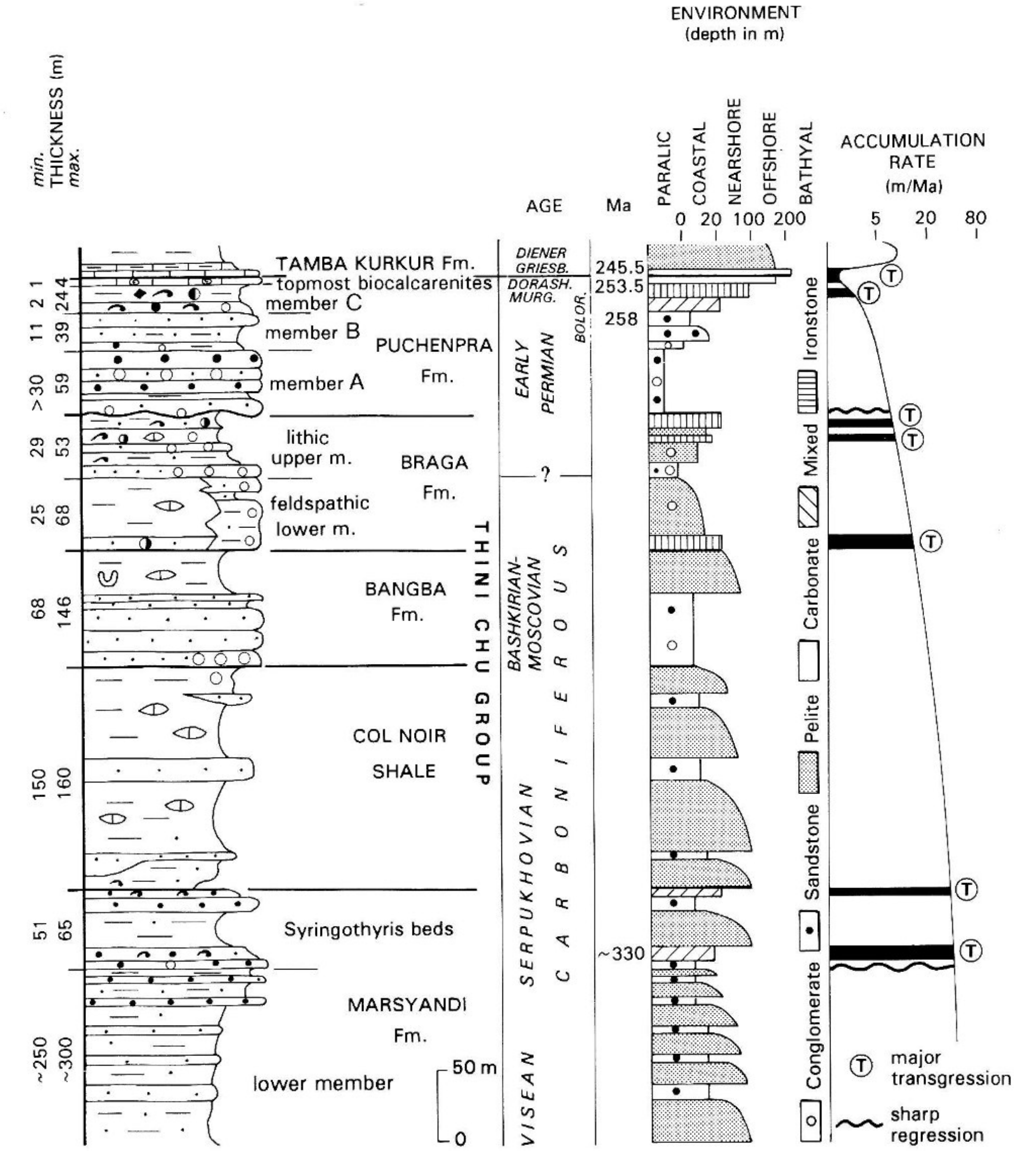

Fig. 16 - Permo-Carboniferous succession of Manang (Visean to lowermost Triassic), with inferred depositional environments and accumulation rates. Stratigraphic column is an idealized composite section (minimum and maximum thicknesses given for each unit). In spite of rapid facies changes, with major heterochroneities documented particularly in the upper part of Puchenpra Fm., about 20 downward shifts of coastal onlap and at least 8 major transgressive surfaces (mostly interpreted as either tectonically-enhanced or glacio-eustatic in origin) may be recognized and tentatively traced along the Marsyandi Valley. Absolute ages according to time scales of Harland et al. (1989; Early Carboniferous to Early Permian) and Haq et al. (1988; Late Permian to Early Triassic).

areas) marks the transgressive part of the sequence, characterized by ravinement and open marine biocalcirudites in the still Lower Carboniferous *Syringothyris* beds (Serpukhovian). Highstand deposits are characterized by thin interbedded storm sand layers increasing upward in abundance.

The mid-Carboniferous (Serpukhovian-Moscovian) is characterized by black shales with interbedded pure quartzarenites. If the *Col Noir Shale* was possibly deposited during a stage of relative tectonic quiescence, increasing lithic detritus at the transition with the *Bangba Fm.*, characterized in the type section by diamictites yielding dolostone rock fragments, documents active uplift of rift shoulders and erosion of pre-rift strata. Tectonic uplift thus apparently triggered the first advance of glacial ice in the central Nepal Tethys Himalaya (Veevers & Powell, 1987; Sakai, 1991). Next, intensely burrowed lagoonal deposits (Tilicho) and shelfal shales with locally chaetetid-bearing concretionary mudstones (Col Noir) are sharply transgressed by illitic shales and subarkoses containing brown Al-rich chromian spinel. This event possibly occurred in the central part of the Late Carboniferous (i.e. about 300 Ma).

The overlying glacio-marine clastics at Bangba/Braga are enriched in plutonic and volcanic detritus (feldspathic lower member of the *Braga Fm.*), documenting penecontemporaneous mafic to felsic magmatism during the climax of rifting at the close of the Carboniferous. Next, the lithic upper member of the *Braga Fm.* testifies to erosion mainly of older (Proterozoic to mid-Paleozoic?) arenaceous successions; NCI-rich or bioclastic transgressive shelfal sands at its top were deposited at the close of the Gondwana glaciation in the Early Permian.

The *Puchenpra Fm.* (Sakmarian-Dorashamian), showing great lateral variability, was characterized by estuarine channel to estuary mouth and tidal bar pebbly to sandy deposits, locally capped by carbonaceous marsh muds (members B to C). Abundance of chert and arenaceous grains suggests continuing erosion of Proterozoic successions to the south, whereas first appearance of dark Cr-rich chromian spinel might suggest a terminal stage of tholeiitic magmatism, documented by spilitic basalts in adjacent regions to the E. This event occurred around 270 Ma.

Next, heterochronous richly bioclastic coarse quartzarenites, NCI-rich arenites, storm sands and shelfal pelites (member C) are capped by condensed outer shelf deposits ("topmost biocalcarenites"). This major stepwise transgression, which began in the Bolorian above Braga, around the Murgabian at Col Noir and in the Djulfian at Tilicho, is ascribed to thermal subsidence. Increasingly quartzose detritus in the Puchenpra Fm. points in fact to subdued relief, submergence and progressive onlap of rift shoulders at the end of rifting. Opening of Neotethys is thus inferred to have occurred as early as the Early Permian.

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AN, AT and EG worked in the field and are responsible respectively for microfossil, megafossil and general stratigraphic analysis and interpretation. LA studied brachiopod associations; DS quantitatively analysed sandstone mineralogy. Am Puri sherpa, Tenzi sherpa and porters skilfully helped to solve our logistic problems. Curzio Malinverno made excellent thin sections and Giovanni Chiodi printed numerous photographs; Magda Minoli made the drawings. The expedition was supported by Ev-K2-CNR and by MURST 40% to M.Gaetani; printing expenses were covered by MURST 40% to M.Gaetani, Milano.

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PLATE 1

Carboniferous to Permian brachiopods from central Nepal

Fig. 1 - *Costiferina* sp. Ventral valve interior. Col Noir section, Puchenpra Fm.; sample AD114; x 1.
Fig. 2 - *Marginifera* ex gr. *typica* Waagen. Ventral valve. From above Braga, Puchenpra Fm.; sample AD184; x 1.
Fig. 3 - *Marginifera* ex gr. *typica* Waagen. Ventral valve. From above Braga, Puchenpra Fm.; sample AD184; x 1.
Fig. 4 - *Waagenoconcha* sp. Ventral valve. From above Braga, Puchenpra Fm.; sample AD184; x 1.
Fig. 5 - *Spiriferella rajah* Salter. Ventral valve. Tilicho section, Puchenpra Fm.; sample AD142; x 1.
Fig. 6 - *Stenoscisma dowhatensis* (Diener). Complete specimen in posterior view. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 7 - *Stenoscisma dowhatensis* (Diener). Ventral valve. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 8 - *Syringothyris* cf. *lyddekeri* Diener. Complete specimen in postero-dorsal view. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 9 - *Syringothyris* cf. *lyddekeri* Diener. Ventral valve in dorsal view showing the syrinx. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 10 - *Syringothyris* cf. *lyddekeri* Diener. Ventral valve in dorsal view. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 11 - *Ectochoristites* sp. Ventral valve. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 12 - *Alispirifer* aff. *middlemissi* (Diener). Dorsal valve. Tilicho section, Marsyandi Fm.; sample HM81; x 1.
Fig. 13 - *Spiriferellina* sp. Ventral valve. Tilicho section, Marsyandi Fm.; sample HM81; x 1.

PLATE 2

Late Permian conodonts from central Nepal.

Fig. 1 a, b, d - *Hindeodus typicalis* (Sweet) transitional form to *Hindeodus julfensis* (Sweet). Sample AD 118; a, b) x 70; d) enlargement of fig. 1a) x 250.
Fig. 2 a, b - *Gondolella orientalis transcaucasica* (Gullo & Kozur). Sample AD 118; a) x 70; b) x 70.
Fig. 3 b, c - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. Sample AD 118; b) x 100; c) x 95.
Fig. 4 - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. Sample AD 118; x 75.
Fig. 5 - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. Sample AD 142; x 75.
Fig. 6 - *Hindeodus typicalis* (Sweet). Sample AD 178; x 90.
Fig. 7 a, b, c - *Gondolella carinata* Clark. Sample AD 142; a, b) x 75; c) x 80.
Fig. 8 b, c - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. Sample AD 142; b, c) x 75.
Fig. 9 b, c - *Hindeodus latidentatus* (Kozur, Mostler & Rahimi-Yazd) emend. Juvenile ontogenetic stage. Sample AD 142; b, c) x 100.

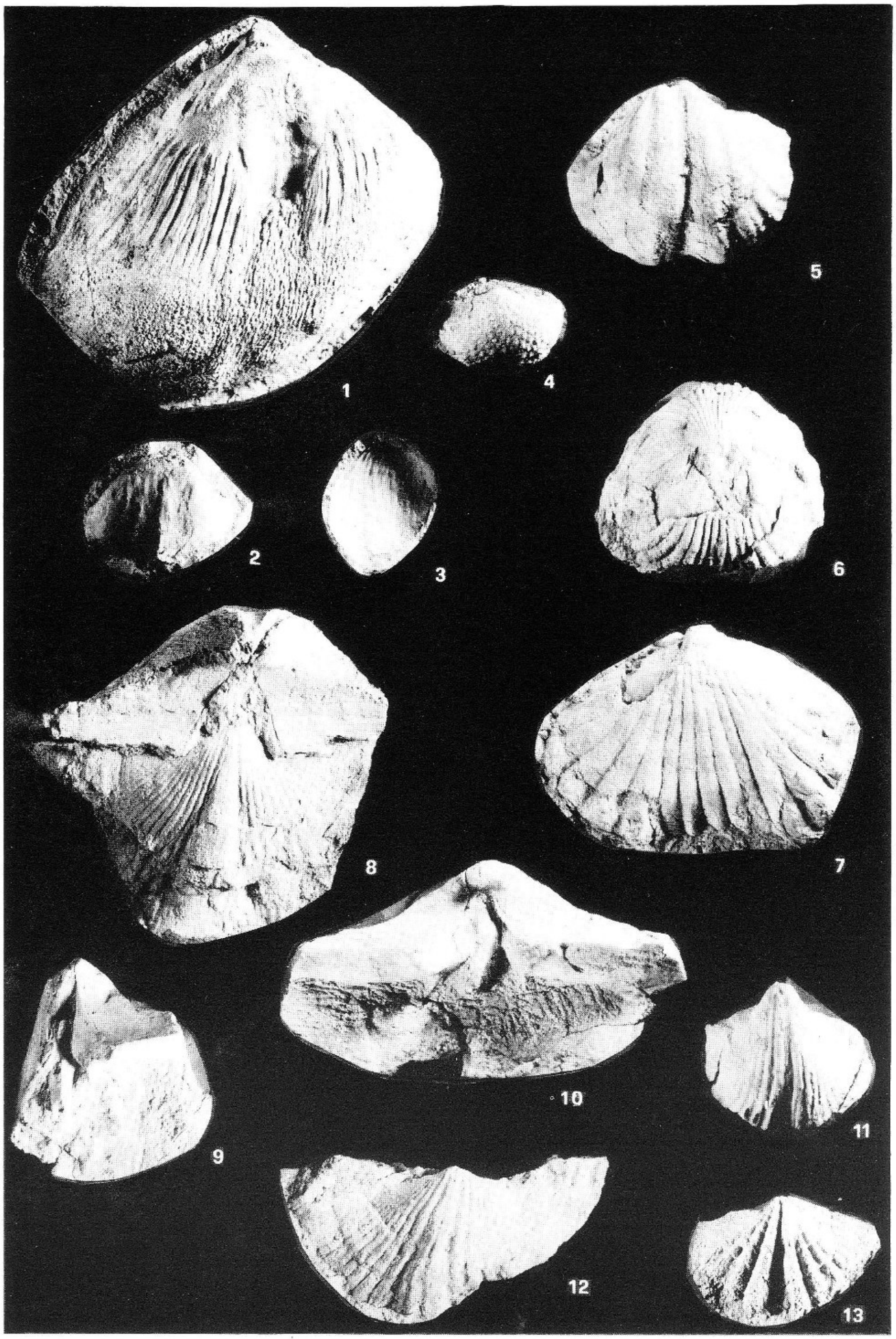
Samples AD 118 from Col Noir section; AD 142 from Tilicho section; AD 178 from Manang section (for frequency distribution and precise stratigraphic location see Garzanti et al. 1994b, fig. 4 and tab. 2,3,4).
a) Upper view; b) lateral view; c) lower view; d) enlargement.

PLATE 3

Mid-Permian conodonts from central Nepal.

Fig. 1 a, c, d, e - *Vjalovognathus shindyensis* (Kozur). Sample AD 185; x 100.
Fig. 2 a, c, d, e, f - *Vjalovognathus shindyensis* (Kozur). Sample AD 185; a, c, d, e) x 100; f) enlargement of fig. 2a) x 250.
Fig. 3 a, c, d, f - *Vjalovognathus shindyensis* (Kozur). Sample AD 185; a, c, d) x 100; f) enlargement of fig. 3a) x 150.
Fig. 4 a, b, c - *Gondolella phosphoriensis* Youngquist, Hawley & Miller. Sample AD 185; a, b) x 50; c) x 60.
Fig. 5 a, c - *Gondolella phosphoriensis* Youngquist, Hawley & Miller. Sample AD 185; x 75.

All samples from Braga section (for distribution and stratigraphic location see Garzanti et al. 1994b, fig. 4 and tab. 5).
a) Upper view; b) lateral view; c) lower view; d, e) oblique/lateral view; f) enlargement.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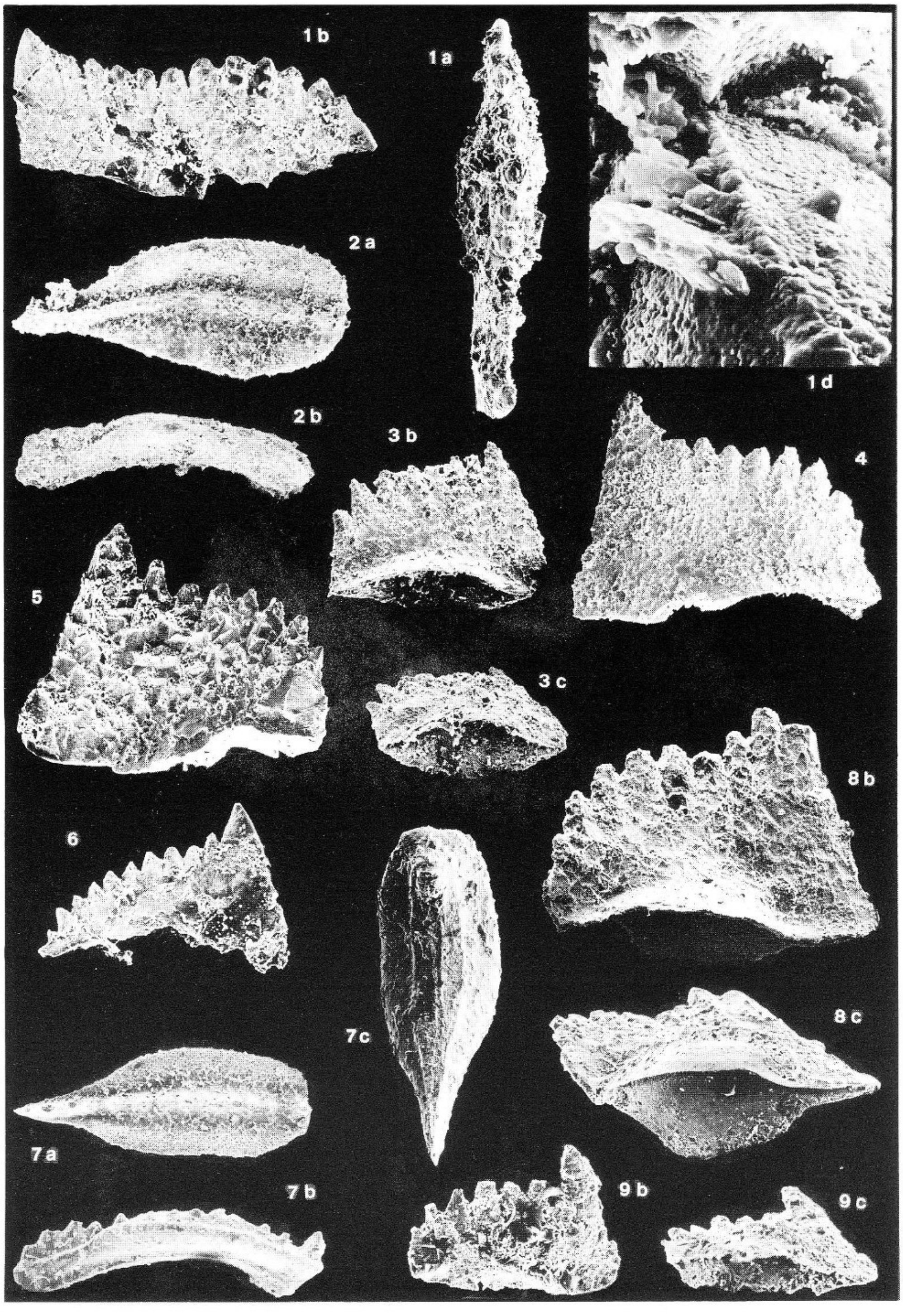
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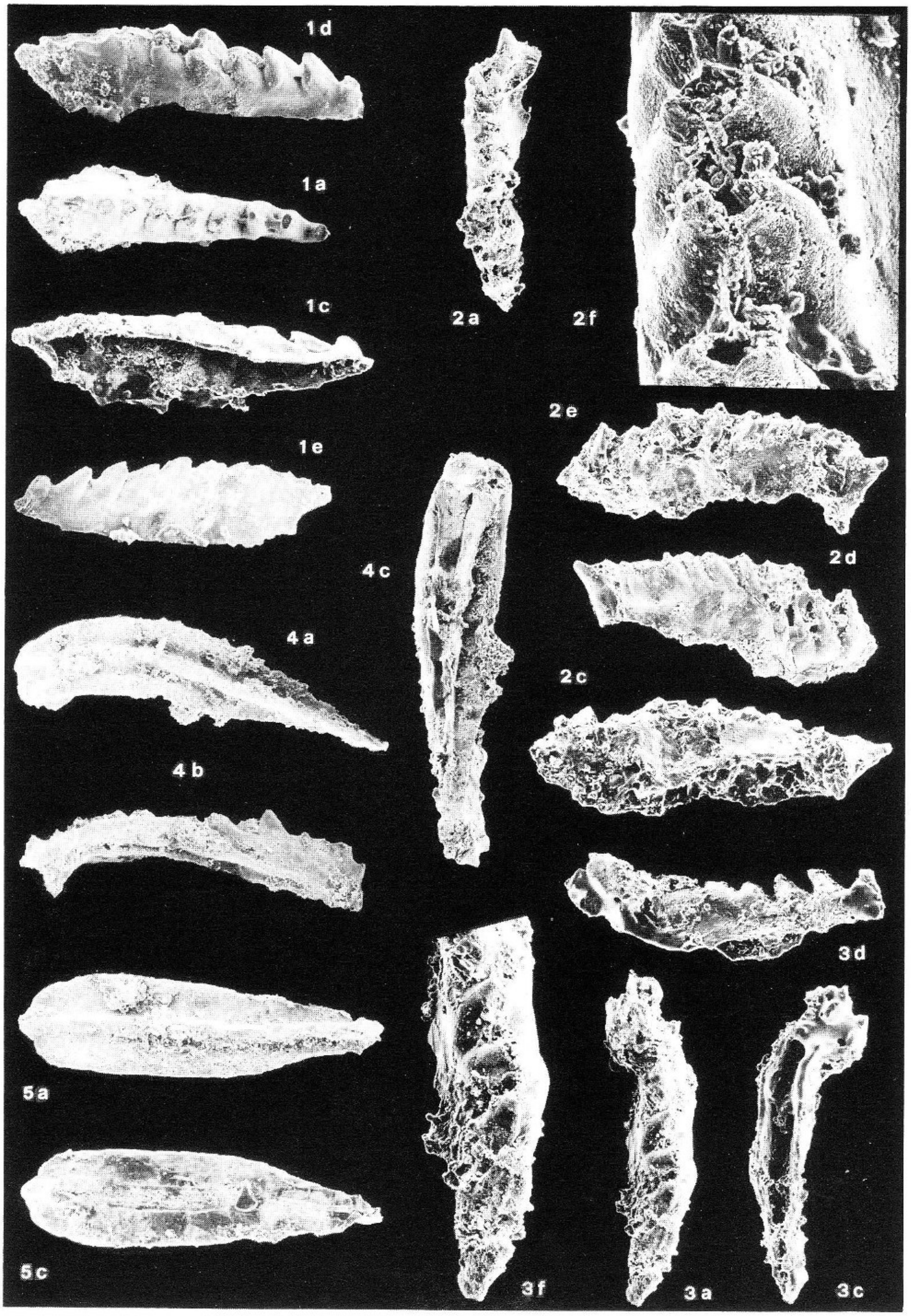
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