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LITHOSTRATIGRAPHY, CONODONT BIOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF THE MIDDLE DEVONIAN (GIVETIAN) TO EARLY CARBONIFEROUS (TOURNAISIAN) LIPAK FORMATION IN THE PIN VALLEY OF SPITI (NW INDIA)

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Riassunto. Lo studio strato per strato di sezioni litostratigrafiche, combinato con la stratigrafia sequenziale e la biostratigrafia a conodonti, fornisce nuove informazioni sull'ambiente deposizionale e le età della Fm. Lipak nella valle di Spiti (India). La formazione comprende nella parte inferiore sedimenti carbonatici e silicoclastici misti, mentre nella parte superiore si osservano due intervalli distinti di arenarie, e mudstone scuri seguiti da un sottile intervallo di siltiti.

Il limite superiore della Fm. Lipak è definito da una discordanza angolare sotto le arenarie della Fm. Gechang di età Permiana. Correlazioni litologiche con sezioni coeve nel Lahaul indicano che nella Valle di Pin la formazione è troncata appena sotto il caratteristico orizzonte con gesso. Il limite inferiore del Fm. Lipak è transizionale dalla arenarie costiere della Fm. Muth. Il limite cartografabile è posto con la comparsa di argilliti e di siltiti scure, carbonacee ed argillitiche.

Le strutture sedimentarie, le microfacies e le faune a conodonti indicano un ambiente deposizionale di bassa profondità per la Fm. Lipak nella Valle di Pin. Sono state distinte cinque sequenze stratigrafiche. I dati dei conodonti dimostrano che i 35 m inferiori della Fm. Lipak nella valle di Pin sono riferibili alla parte alta della Sottozona a *varcus* inferiore con specie caratteristiche dei generi *Icriodus* e *Bipennatus*. Una lacuna mai riconosciuta in precedenza a circa 33 m sopra la base, al limite tra le sequenze stratigrafiche S1 e S2, corrisponde all'intervallo tra la Sottozona media a *varcus* sino almeno alla fine della Zona a *expansa* inferiore del Famenniano superiore. Poiché questa lacuna non corrisponde ad un limite cartografabile, non vengono proposte suddivisioni della Fm. Lipak in unità stratigrafiche denominate formalmente, bensì noi indichiamo informalmente i sedimenti rappresentati dal ciclo S1 come Lipak A, e i sedimenti rappresentati dai cicli S2-S5 come Lipak B. L'attribuzione della Lipak A alla Sottozona a *varcus* inferiore fornisce l'età più giovane possibile per il limite transizionale della sottostante Fm. Muth.

A 75 m dalla base della sezione composita della Fm. Lipak vi è un orizzonte di 58 cm di argilliti da nere a grigio scuro entro i calcari fossiliferi del Famenniano superiore. Ragionevolmente questo coincide con l'"Evento Hangenberg" (fine della Zona media a praesulcata). Le faune a conodonti più giovani della Fm. Lipak - dominate da specie di *Clydagnathus*, ma in cui sono anche rappresentate specie di *Bispathodus* e *Pseudopolygnathus* - si estendono sino alla Zona a *crenulata* inferiore del Tournesiano medio.

Abstract. Bed-by-bed lithostratigraphic sections combined with sequence stratigraphy and conodont biostratigraphy provide new information on the depositional environment and age of the Lipak Formation in the Pin Valley (Spiti). The formation comprises mixed siliciclastic and calcareous sediments at lower levels, richly fossiliferous limestones with two distinct sandstone incursions at higher levels, and dark mudstones followed by a thin siltstone interval.

The upper limit of the Lipak Formation is defined by the angular unconformity below the sandstones of the Permian Gechang Formation. Lithologic correlation with sections in upper Lahaul indicates that, in the Pin Valley, the formation has been truncated just below its characteristic gypsum horizon. The lower boundary of the Lipak Formation is gradational from coastal arenites of the Muth Formation; the mappable boundary is drawn at the first appearance of dark carbonaceous, argillaceous siltstone and shale.

Sedimentary structures, microfacies and conodont faunas indicate a general shallow marine depositional environment of the Lipak Formation in the Pin Valley; five sequence stratigraphic units have been distinguished. Conodont data demonstrate that the lowest 33 m of the Lipak Formation of the Pin Valley is mid to late Early *varcus* Subzone with characteristic species of *Icriodus* and *Bipennatus*. A previously unrecognised hiatus at c. 33 m above the base, at the boundary of sequence stratigraphic units S1 and S2, represents the interval Middle *varcus* Subzone to at least the end of the late Famennian Early *expansa* Zone. Because this hiatus does not correspond to a mappable boundary, no division of the Lipak Formation into named stratigraphic units is suggested, but we refer informally to the sediments represented by cycle S1 as Lipak A, and the sediments represented by cycles S2-S5 as Lipak B. Determination of S1 as Early *varcus* Subzone provides a maximum age for the gradationally underlying Muth Formation.

At 75 m above the base of the composite Lipak Formation section, a 58 cm black to dark grey shale interval within late Famennian fossiliferous limestones conceivably correlates with the Hangenberg Event (end-Middle *praesulcata* Zone). Younger conodont faunas of the Lipak Formation - dominated by species of *Clydagnathus* with species of *Bispathodus* and *Pseudopolygnathus* also represented - is shown to extend to the mid-Tournaisian Early *crenulata* Zone.

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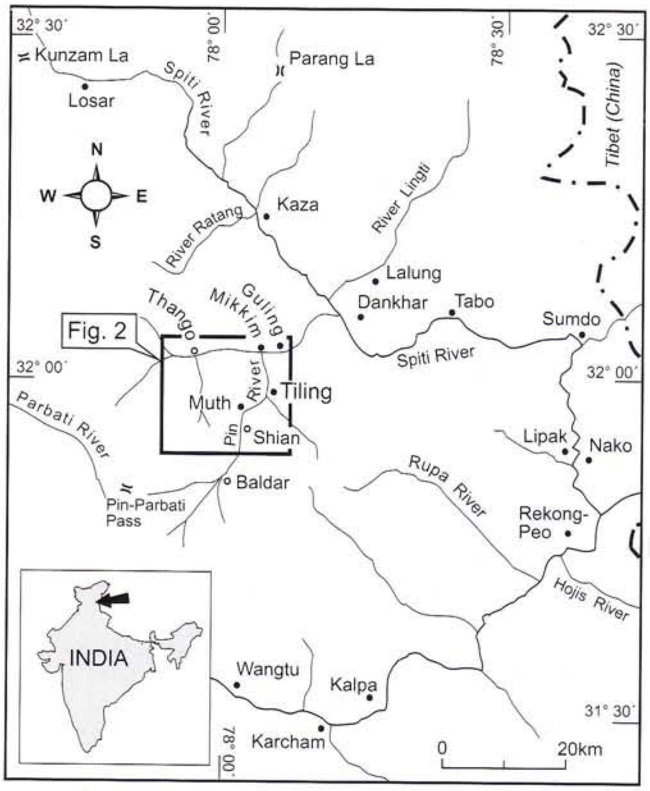

Fig. 1 - The Pin Valley in relation to the Spiti Valley and adjoining regions of Himachal Pradesh, NW India. The square indicates the area of investigation in the Pin Valley shown in Fig. 2.

Introduction

The Pin Valley of Spiti, NW India (Fig. 1, 2), has long been an "El Dorado" for geologists and palaeontologists - renowned for superb outcrops, richness of fossil content, its spectrum of lithologies, and almost continuous stratigraphic sequence from Neoproterozoic to Cretaceous, a situation with few analogues globally. Lying midway between the Kashmir and Kumaon synclinoria, it has special importance in correlation of the north Indian Tethyan sedimentary successions (Hayden 1904), but bed-by-bed stratigraphic or biostratigraphic data are rare, and there are persistent problems of stratigraphic nomenclature. The problem was compounded by spurious palaeontological reports by V. J. Gupta in numerous publications in the 1970s and 1980s, some of these having considerable chronologic implications, particularly for the Silurian-Triassic sequences of the region. Even if this pollution (Talent et al. 1988; Talent 1989; Shanker et al. 1993) is ignored, clarification of the stratigraphy and biostratigraphy on the basis of a more extensive database is desirable (Talent et al. 1988).

The present report provides bed-by-bed lithostratigraphic data (Fig. 3-6) and conodont biostratigraphy for sections of the Lipak Formation - a shallow marine mixed siliciclastic to calcareous succession - near Mikkim and near Muth in the Pin Valley of Spiti (Fig. 1, 2). The goals of this investigation were: (1) precise lithostratigraphy of the Lipak Formation; (2) accurate age constraints from conodonts; (3) interpretation of the depositional environments; (4) sequence stratigraphic interpretation and (5) comparison of the Pin Valley section with approximately coeval sediments from elsewhere along the northern margin of the Indian sub-continent.

Previous work

The first stratigraphy of Spiti, based on reconnaissance, was presented by Stoliczka (1866). Griesbach (1891) continued Stoliczka's investigations, comparing the successions in Spiti with those in Kumaon. Hayden (1904, 1908) mapped a major part of Spiti and wrote penetratingly on the geology of the region; his analysis of the stratigraphy has retained broad validity until today. Reed (1910, 1911, 1912) described Palaeozoic fossils from the Pin and Parahio Valleys. Srikantia (1981) and Bagati (1990) contributed usefully on aspects of the lithostratigraphy of Spiti. The 1:50.000 geological map by Fuchs (1982) has facilitated fieldwork in the Pin Valley.

Much valuable sedimentologic and stratigraphic research was carried out in Spiti and Zanskar in the 1980s and the first half of the 1990s by workers from Milano (Gaetani et al. 1986, Gaetani & Garzanti 1991, Garzanti et al. 1993, 1996a, 1996b and ref. therein). Vannay (1993) investigated the stratigraphy, sedimentology, depositional environment and conodonts of the Lipak Formation in upper Lahaul. Recently, Bhargava & Bassi (1998) presented an important monograph on the geology of Spiti including a summary of the history of geological investigation, and an exhaustive bibliography.

Geological setting

Spiti shows sedimentary successions ranging in age from Neoproterozoic to Cretaceous and an exposed thickness of more than 7 km (Hayden 1904, Fuchs 1982, Bagati 1990, Bhargava & Bassi 1998). Neoproterozoic to Cambrian deposits are dominated by continental slope to shelf siliciclastics of the Haimanta Group. The angular unconformity at the top of the Haimanta Group below the basal conglomerate of the Shian Formation (Griesbach 1891, Fuchs 1982, Garzanti et al. 1986) represents a depositional gap of latest Cambrian to earliest Ordovician time and broadly coincides with widespread granitic intrusions around 470-480 Ma (Le Fort et al. 1986, Miller et al. 2001) and weak deformation (Grasemann et al. 1997, Wiesmayr 2000) in the Higher Himalaya tectonic unit. The Haimanta Group is succeeded above the angular unconformity by relatively thin, siliciclastic-dominated epicontinental to shelf sedi-

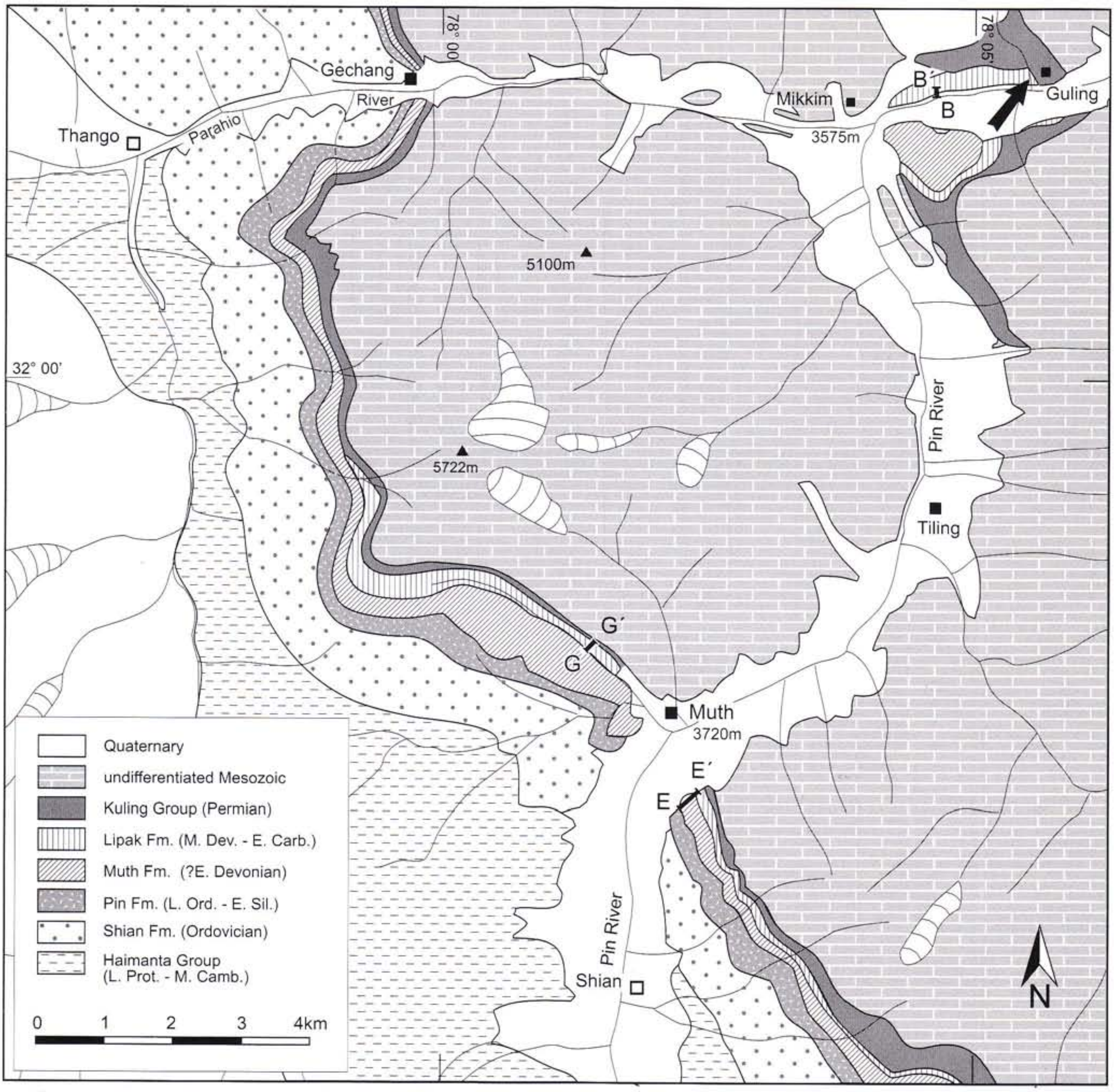

Fig. 2 - Geological map of the Pin Valley, modified from Fuchs (1982), with location of sections (arrow indicates the section W of Guling). Squares indicate villages and seasonal shelters. Note gradual northwestward deepening in level of erosion at the base of the Kuling Group.

ments until the Permian: the Shian, Pin, Muth and Lipak Formations (Fig. 3) (Gaetani & Garzanti 1991, Brookfield 1993).

After a major unconformity, thick slope to pelagic carbonate-dominated sediments were deposited during Mesozoic times. The angular unconformity at the base of the Permian Kuling Group has been connected with opening of the Neo-Tethys Ocean during the Early Permian and development of a pronounced rift shoulder in parts of the Tethyan Himalaya (Stampfli et al. 1991, Gaetani & Garzanti 1991, Garzanti et al. 1996a). Dependent on position relative to the rift shoulder and possibly controlled by a horst-graben pattern, the depth of erosion (incision into the underlying sequence) shows considerable regional variation, e.g. there is hardly any gap in the Spiti Valley and upper Lahaul, but nearly the entire Carboniferous and the earliest Permian are missing in the Pin Valley (Hayden 1904, Vannay 1993, Garzanti et al. 1996a, Bhargava & Bassi 1998).

The Pin Valley (Fig. 2) is dominated structurally by prominent large-scale inclined horizontal folds with maximum wavelengths of approximately 5 km and axes trending NW-SE (Fuchs 1982, Wiesmayr 2000). These fault-propagation folds are related to crustal thickening

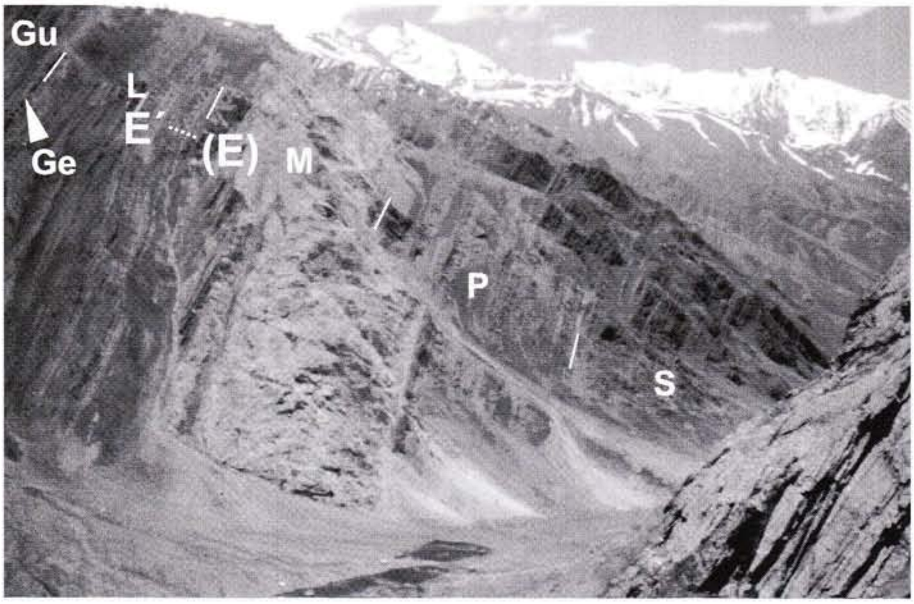

Fig. 3 - Overview of the Palaeozoic stratigraphy in the upper Pin Valley; view from the ravine NW of Muth village towards the SE. Location of the upper part of section E-E´ covering lower parts of the Lipak Formation is indicated; S = Shian Formation; P = Pin Formation; M = Muth Formation; L = Lipak Formation, Ge = Gechang Formation, Gu = Gungri Formation

during Eo-Himalayan deformation, dated between 42-45 Ma by Ar-Ar dating on newly formed illite within axial plane cleavages (Wiesmayr 2000). Illite crystallinity values connected with the Himalayan Orogeny increase in metamorphic grade to the SW. The sampled sections at Muth show slightly increased overprint compared with samples from Mikkim, but still within diagenetic conditions (Wiesmayr 2000). Conodonts from Mikkim and Muth show conodont alteration index (CAI) values of 4-5 (H.-J. Gawlik, pers. comm. 1999), supporting the illite data.

Stratigraphic context

Stoliczka (1866) embraced all sediments above his Muth Series (= Shian and Pin Formations of Goel & Nair 1977, and Muth Formation as defined in Fuchs 1982, Bhargava & Bassi 1998, and Draganits 2000) and below the basal Triassic strata (= Tamba Kurkur Formation of Srikantia 1981) within his Kuling Series, an assemblage of five formations: Lipak of Hayden (1908), Po of Hayden (1904), and Ganmachidam, Gechang and Gungri of Srikantia (1981), and assigned it a Carboniferous age.

Griesbach (1891) mentioned "flaggy, dark grey, to blue limestone beds" yielding *Athyris royssii* and *Productus* sp. below Permian "crumbling shales" (Gungri Formation) and above the "white quartzite" (Muth Formation) with a sharp contact to the former and a gradual contact to the latter. Hayden (1904) described the sandstone/carbonate succession directly above the white quartzarenites of the Muth Formation as "Dark limestone with *Productus* sp.". Later he (Hayden 1908) introduced the name "Lipak series" after outcrops in the valley of the Lipak River, a right-bank tributary of the lower Spiti River. Srikantia (1981) modified the name to Lipak Formation.

In the Pin Valley, the upper limit of the Lipak Formation is easily identified by the angular unconformity below the sandstones of the wedge-shaped Gechang Formation [Kuling Group of Garzanti et al. (1996a)] (Fig. 5) - in some areas with a basal conglomerate (Fuchs 1982, Garzanti et al. 1996a). Fuchs (1982), Garzanti et al. (1996a) and Draganits (2000) report intraformational breccias at this boundary to the Gechang Formation. In this work we include these breccias - comprising dark, angular mudstone clasts in a dark mudstone matrix, characters typical of the upper part (upper levels of sequence S4 and lower levels of sequence S5) of the Lipak Formation - in the Lipak Formation (Fig. 5).

Missing in the Pin Valley is a distinctive gypsum horizon, well displayed in the Lipak Valley, (Hayden 1904), Lingti Valley, Spiti Valley (Srikantia 1981, Bagati 1990, Garzanti et al. 1993, Bhargava & Bassi 1998), upper Lahaul (Vannay 1993) and Zanskar (Gaetani et al. 1986). Mallet (1866) interpreted the gypsum beds as formed by sulphurous thermal springs, but they are now interpreted as Carboniferous evaporites (Gaetani et al. 1986, Vannay 1993). In the sections referred to above, the upper boundary of the Lipak Formation is gradational with the white sandstones and black pelites of the Po Group (Garzanti et al. 1996b). Bhargava & Bassi (1998), incidentally, drew the upper boundary of the Lipak Formation at the disappearance of carbonate beds in the uppermost part of the sequence.

The gradational contact between the Muth and Lipak Formations hampers boundary definition. Garzanti et al. (1996a) included "biocalcarenites and coral patch reefs" of the basal Lipak Formation (as defined herein) within the Muth Formation. Recently, Bhargava (1997) and Bhargava & Bassi (1998) advocated drawing the base of the Lipak Formation at the first

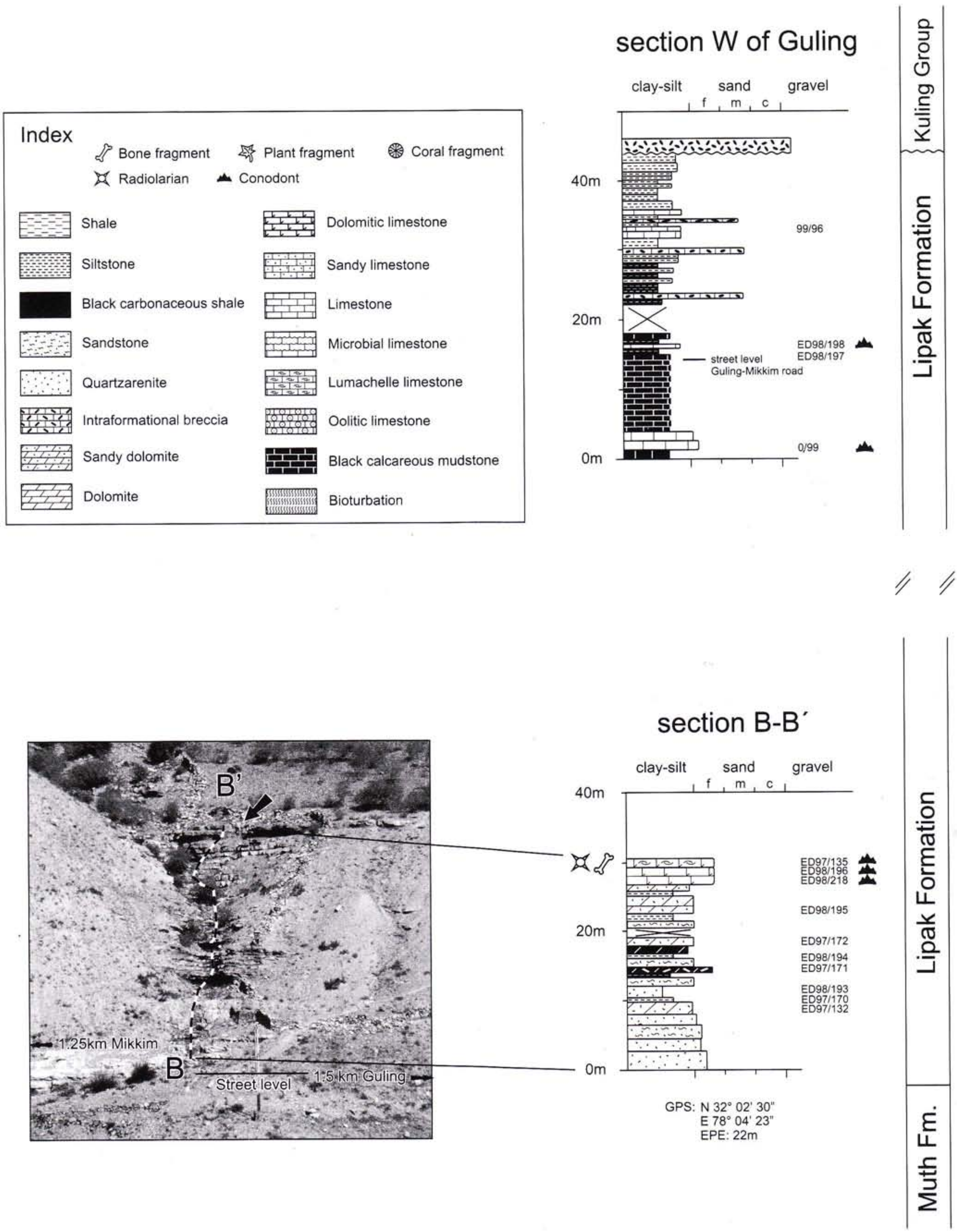

Fig. 4 - Stratigraphic sections of the base and top of the Lipak Formation in the Pin Valley near Guling village (for locations see Figure 2) and lithologic index; stratigraphic position of samples is indicated. The distance of both sections is in proportion to their estimated lithostratigraphic relationship in the field. General view of section B-B´ in a gully above the road between Mikkim and Guling; view towards N. Arrow points to Leo Krystyn for scale.

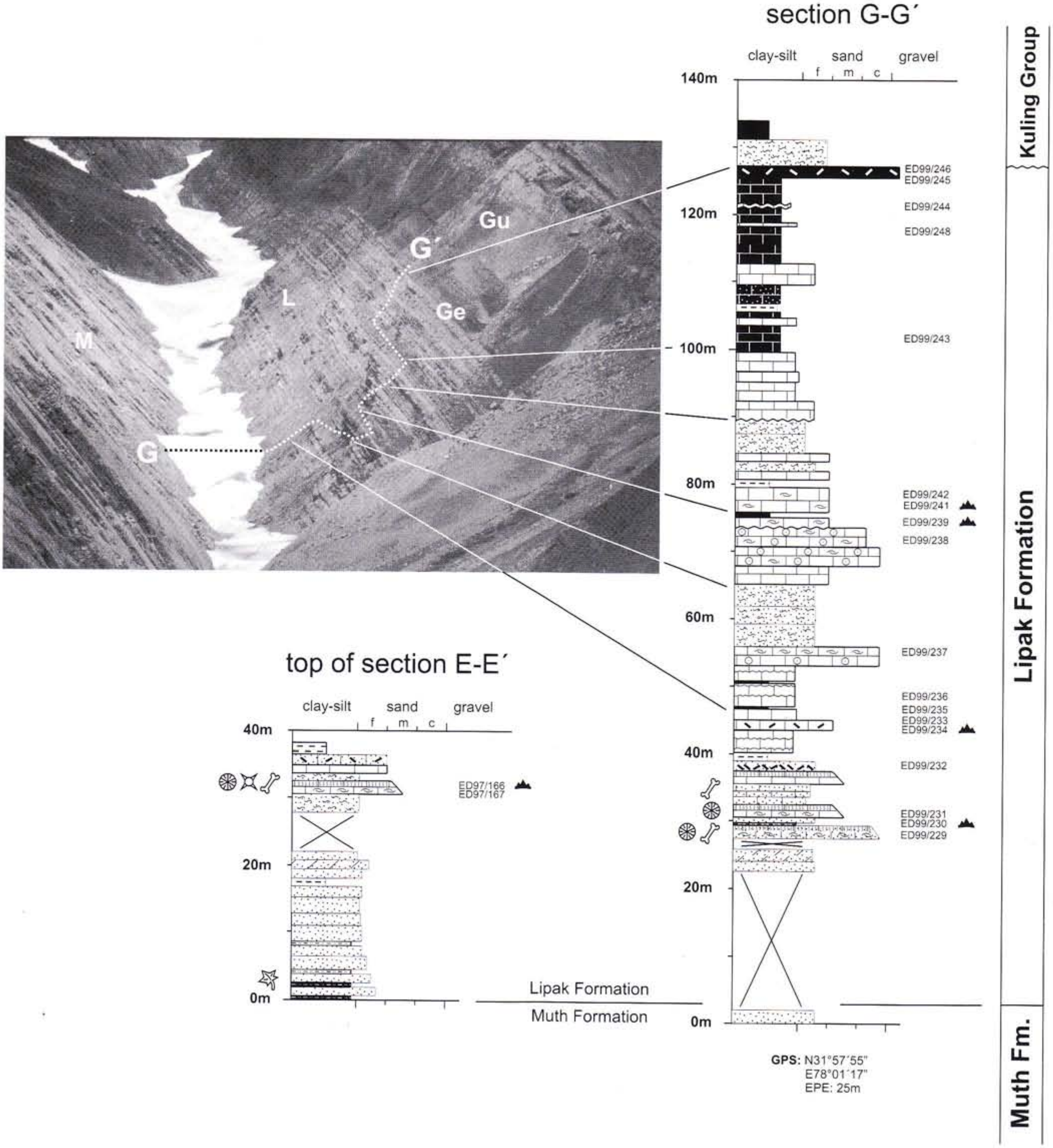

Fig. 5 - Stratigraphic sections of the Lipak Formation in the Pin Valley near Muth village (for locations see Figure 2). Beds containing brachiopods are often also rich in crinoid fragments. Note occurrence of macro-sized coral and vertebrate fragments in similar levels of the sections (compare also with Fig. 4). Stratigraphic position of samples is indicated. General view towards W of section G-G´ in the ravine SW of Muth; M = Muth Formation; L = Lipak Formation, Ge = Gechang Formation, Gu = Gungri Formation

appearance of carbonates. In the present work, the incursion represented by unfossiliferous, arenaceous dolomite and the pure, white quartzarenite above it (Draganits 2000) are interpreted as still part of the Muth Formation because of intimate facies relation with the rest of the Muth. The boundary between the Muth and Lipak Formations is drawn at the first appearance of obviously lithologically different sediments, namely dark carbonaceous, argillaceous siltstone and shale (with plant fragments) interbedded with impure arenites typical of the Lipak Formation, indicating a fundamental change in sedimentation from the mature, unfossiliferous quartzarenites of the Muth Formation - interpreted as barrier-island depositional environments (Draganits

2000). A similar view was adopted by Fuchs (1982), Talent et al. (1988) and Bagati (1990). The angular unconformity between the Muth and Lipak Formations in the Pin Valley SE of Muth reported by Jain et al. (1980, fig. 5), incidentally, is an artefact of an oblique view of the outcrop; it is therefore rejected (Fig. 3).

Description of sections

Sections and/or descriptions of the Lipak Formation have been published from Zanskar (Gaetani et al. 1986), upper Lahaul (Vannay 1993), the Takche Valley (Garzanti et al. 1993, Bhargava & Bassi 1998) and the Lipak Valley (Hayden 1904, Bhargava & Bassi 1998).

A generalized complete lithologic section of the Lipak Formation, pieced together from different sections in Spiti, would consist of sandstones and sandy dolomites at the base grading into fossil-rich tempestites. Higher in the section, beds of stromatolitic laminated limestone are succeeded by a thick sequence of fossiliferous grainstones with two distinct sandstone horizons. A dark mudstone-marl sequence is then followed by a thin siltstone interval and a conspicuous gypsum horizon; the top of the Lipak Formation consists of sandstones, limestones and marls. In general, the sections from the Pin Valley described below consist only of the lower part of the Lipak Formation (below the gypsum interval); upper levels were eroded away prior to inception of Gechang Formation sedimentation in this region.

Section B-B

The section in the lower Pin Valley on the left bank of the Pin River, c. 1.25 km E of Mikkim in a small gully below Gungri, starts above the Mikkim-Guling road and runs approximately S-N upslope in the gully (Fig. 2, 4). GPS data of the first bed above the road are: N32°02'30"; E78°04'23"; EPE 22 m; alt.: 3600 m.

Section B-B´ near Guling displays part of the lowest levels of the Lipak Formation (sequence S1, i.e. Lipak A), correlating broadly with the interval of Lipak Formation in section E-E´, both being dated as Early *varcus* Subzone (see section on Conodont data and age implications). The boundary between the Muth and Lipak Formations is not exposed, but is probably very close to the base of the section. Wiesmayr (2000) drew a detachment fault between the Muth and Lipak Formations in this area, related to Eo-Himalayan fault-propagation folding. The contact might therefore be marred.

The lowest part of the section comprises cross-bedded, white to light grey quartzarenite, differing from Muth Formation quartzite by small ferruginous spots and greenish mud chips in basal parts of the beds. The quartzite becomes gradually impure up-section and is followed by intercalations of sandstone, siltstone and sandy dolomite. In the middle part of the section, dark, fine-grained beds are common; they often show lamination of mud- and silt-sized laminae disturbed by bioturbation. Sand-sized, sub-angular quartz clasts floating in the matrix are frequent in these fine-grained beds. Rare casts of brachiopods were found in coarser-grained beds. Sandy dolomite beds increase in number higher in the section (Fig. 4)

The section ends with grey, relatively thick, massive, strongly dolomitized beds with completely re-crystallized crinoid fragments floating in the matrix; carbonate- and quartz-filled hollows up to several centimetres are common. Because of resistance to weathering they form a conspicuous horizon in the field (Fig. 4). Bed boundaries are even and parallel. Residues from acid-leaching of samples from these beds yielded conodonts (ED97/134, ED97/135 and ED98/218) as well as radiolarians and vertebrate bone fragments (ED97/135). In general, conodonts from this section are not as well preserved as conodonts from sections E-E´ and G-G´. The fragments of vertebrates support correlation with the bone-fragment-containing beds of sections E-E´ and G-G´ near Muth (Fig. 5).

Section W of Guling

The section is located in the lower Pin Valley on the left bank of the Pin River at the western end of Guling village (Fig. 2). In contrast to the other sections, this one has not been recorded bed-by-bed, but lithologic variations have been documented in detail. The section commences in the floor of the gully, Chut Nalla, and continues in a narrow curve to the W end of Guling from where it runs upslope to the N (Fig. 2). GPS data are not available. This section comprises the uppermost parts of the Lipak Formation (sequence S5 in Lipak B of this report); the lower parts of the formation (S1-S4) are not exposed in the gully.

The first beds of the section above Quaternary debris (Fig. 4) consist of peloidal, bioclastic pack- to wackestone with small fragments of brachiopods, gastropods and rare crinoids, followed by several metres of well-bedded, partly laminated dark grey limestone (Fig. 4). Sample 0/99 taken from this limestone (Fig. 4) produced the most diverse and abundant conodont fauna from the area (Tab. 1). Below an unexposed area, dark shales with lenses of peloidal wackestone occur. Higher in the section, dark shales dominate with thinner siltstone beds and rarer intraformational limestone breccia. The uppermost part shows calcareous, finely laminated siltstones truncated by the basal conglomerate of the overlying Gechang Formation. The contact is exposed next to a *chorten* (Tibetan stupa). Three conodont samples from this section represent faunas from the highest parts of the Lipak Formation in the Pin Valley (Fig. 4, 8, Tab. 1).

Section E-E´

The section is located in the Pin Valley on the right bank of the Pin River, c. 1.25 km SSE of Muth (Fig. 2, 5). GPS data are not available. The section is located at an altitude of 4245 m near an almost vertical, E-W trending sinistral strike-fault with a displacement of some tens of meters (Fig. 3). This section is situated in the limb area of the Eo-Himalayan fold train and therefore was scarcely affected by deformation compared with section B-B´ (Wiesmayr, 2000).

This section - the basal part of the Lipak Formation (sequence S1, i.e. Lipak A) - correlates broadly with section B-B' and the base of G-G'. The boundary with the underlying Muth Formation - defined by the first occurrence of carbonaceous, argillaceous beds - occurs above a prominent irregular, wavy bed at the top of the Muth. The first 22 m of section is impure, massive quartzarenite, becoming increasingly impure and grading into sandstone intercalated with dark grey siltstone. Some upper bed surfaces are bioturbated. Mud chips occur occasionally and dolomitic influence increases slightly but visibly. Above c. 6 m without exposure, the terrigenous clastic influence decreases and grey calcareous sandstone appears. The beds are commonly graded and contain crinoid fragments and brachiopods in basal parts. Bioturbation on upper bed surfaces is frequent.

The succeeding brownish weathering grey bioclastic grainstone beds contain brachiopods, echinoid fragments, vertebrate bones, fish scales, corals, bryozoans, conodonts and radiolarians (sample ED97/166); they probably represent tempestites and still show a considerable amount of quartz grains. This characteristic limestone horizon correlates well with very similar levels in sections B-B´ and G-G´ (Fig. 4, 5). Biocalcarenite beds then follow, some containing large clasts of limestone reworked from below, and with bioturbation on upper surfaces. The final part of the section consists of dark grey siltstone and marl.

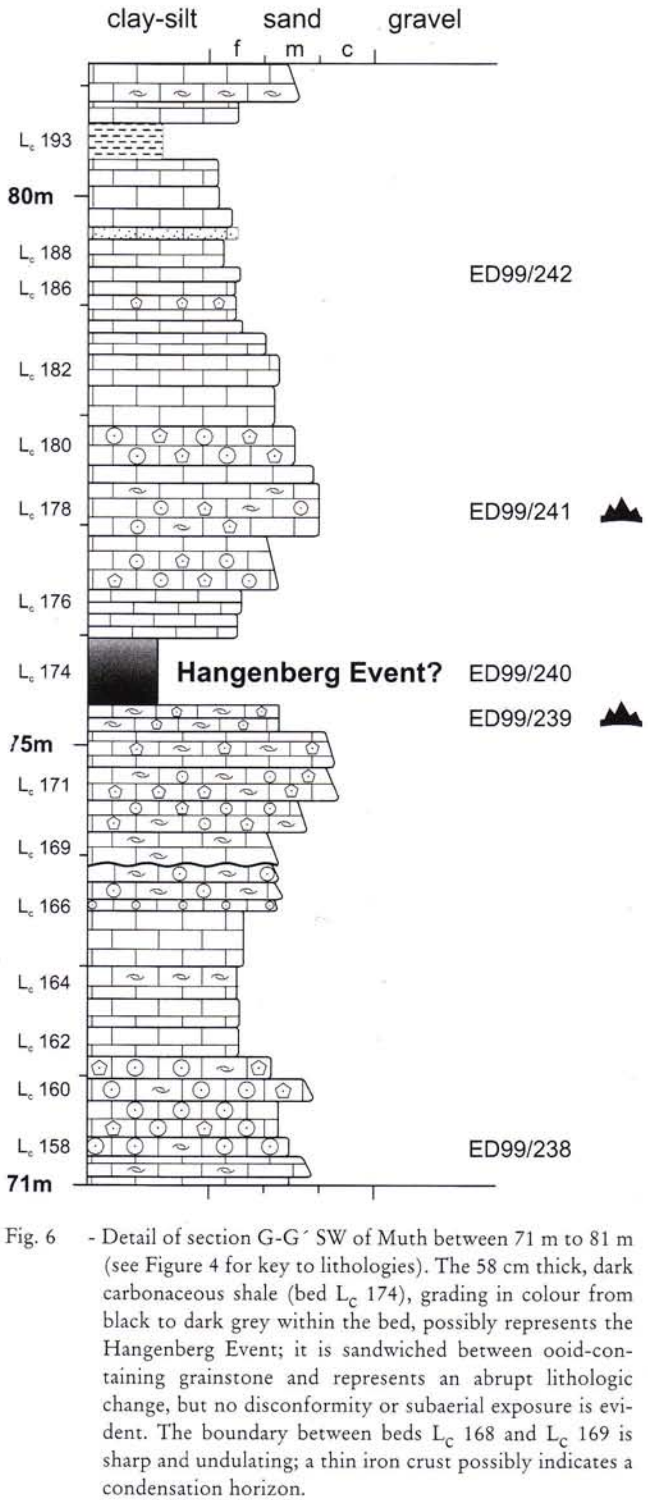

Fig. 6 - Detail of section G-G´ SW of Muth between 71 m to 81 m (see Figure 4 for key to lithologies). The 58 cm thick, dark carbonaceous shale (bed L_c 174), grading in colour from black to dark grey within the bed, possibly represents the Hangenberg Event; it is sandwiched between ooid-containing grainstone and represents an abrupt lithologic change, but no disconformity or subaerial exposure is evident. The boundary between beds L_C 168 and L_C 169 is sharp and undulating; a thin iron crust possibly indicates a condensation horizon.

Section G-G´

This section is on the left bank of the Pin River in the ravine separating the Muth Formation from the Lipak Formation, 1.5 km NW of Muth (Fig. 2, 5). GPS data at the base of the section are: N31°57'55"; E78°01'17"; EPE 25 m; alt.: 3980 m. The section, trending SW-NE uphill on a steep slope (Fig. 5), is the most complete section of the Lipak Formation near Muth (121 m).

The basal c. 21 m of Lipak Formation in the ravine was covered by snow. Fortunately this level is easily to correlate with the nearby section E-E´. The first exposed beds consist of dolomitic sandstone with minor quartzite, followed by brown-weathering, grey, graded, heavily dolomitized bioclastic grainstone with minor siliciclastic influence; the limestones are interleaved with thin siltstones and show bioturbation on upper bedding surfaces. The grainstone beds are extremely rich in juvenile brachiopod or mollusc shell debris and rarer larger brachiopod shells (< 10 mm); additionally, echinoid fragments with rarer vertebrate bone and recrystallized coral fragments occur. Correlation with the bone-bearing horizons in sections B-B´ and E-E´ appears unequivocal (Fig. 4, 5). Fossils and grainsize decrease up-section; grainstones to packstones predominate; the intensity of dolomitization decreases. Some cm-sized well-preserved bryozoan fragments are present (B. Hubmann, pers. comm., 2001) (Fig. 7a); the appearance of the cements seems to indicate lack of meteoric influence. Thin marly and sandstone beds with basal intraformational breccia occur; bioturbation is generally pronounced.

This interval is followed by fine-grained, horizontally laminated, well-developed microbial limestone (Fig. 7b), sometimes showing intraformational breccia and tepee structures. Within these microbial limestones, beds of lithoclastic to bioclastic grainstone, sometimes graded from grainstone to wackestone, occur. They contain variable amounts of brachiopod shell fragments, peloids, oncoids, gastropods, echinoderm fragments, algae and ostracods (Fig. 7c). This calcareous interval continues with wackestone showing lamination of oolitic- and ostracod-bearing bearing laminae (Fig. 7d) disturbed by bioturbation; it is terminated by bioclastic grainstone with densely packed fragments of brachiopods, echinoids and crinoids. Above follows an 8 m interval of thickly bedded, grey sandstone, weathering reddish-brown, followed by occasionally graded beds of biocalcarenite and several horizons of dolomitized oolitic grainstone with rare, partly micritized brachiopod fragments. The sandstone horizon seems to have its lower boundary gradational and upper boundary well defined.

A prominent 58 cm interval of black to dark grey, carbonaceous shale (1.40 % TOC [total organic carbon]) occurs sandwiched between crinoidal grainstones (Fig. 7e). The grainstones contain disarticulated, often fragmented, recrystallized crinoid ossicles, abundant ooids and brachiopod shells and rarer coral fragments. The well-rounded lithoclasts are partly dolomitized and show oncoidal encrustation (Fig. 7e). There is no disconformity or evidence of subaerial exposure associated with the abrupt lithologic change. The biocalcarenite above the black shale resembles those from below, but becomes gradually finer grained and the contents of macro-fossils in the outcrop decreases; this calcareous interval is interrupted by a second sandstone interval, very similar to the lower sandstone interval (Fig. 5).

The uppermost 25 m of Lipak Formation in this section is dominated by black mudstone containing rare ostracods and marls showing angular quartz clasts floating in the matrix (Fig. 7f). Beds of calcarenite interrupt these fine-grained sediments (Fig. 5). Very few macrofossils occur in this interval. A conspicuous bed of pink, crystalline calcite with irregular upper and lower boundaries - interpreted as a horizon of emergence - occurs 6 m below the top of the formation.

At the top the Lipak Formation are beds of dark breccia consisting of up to dm-sized mudstone clasts in strongly dolomitized, very fine-grained lithoclastic matrix, with intercalated dark mudstone beds (Fig. 5). The contact with the overlying Gechang Formation sandstones is an angular unconformity, equating with absence of a sedimentary record for virtually the entire Carboniferous regionally (Garzanti et al. 1996a).

Conodont data and age implications

Hayden (1904) and Fuchs (1982) suggested a Late Devonian to Early Carboniferous age for the Lipak Formation in Spiti, mainly on the basis of its diverse brachiopod fauna, whereas Reed (1911) advocated a late Middle to Late Devonian age, based on fossils collected by Hayden and von Krafft in the Lipak Valley in 1901. Chatterji et al. (1967) suggested a late Middle or early Late Devonian to Early Carboniferous age for the formation in the Lipak Valley, whereas Garzanti et al. (1996b) reported late Famennian (Middle *expansa* Zone) conodonts from the basal part of the formation in the Pin Valley. Farther afield, Baud et al. (1984) found brachiopods and bryozoans in the Lipak Formation in Zanskar and suggested an Early Carboniferous age; limestones immediately below the gypsum horizon were regarded as middle Tournaisian to early Visean by Gaetani et al. (1986). Conodonts from the Lipak Formation in upper Lahaul were assigned an early Tournaisian age (Vannay 1993).

The conodont data presented here are derived from acid-leaching of 19 samples from four stratigraphic sections and one spot sample; 12 of the samples produced useful conodonts (Tab. 1; Pl. 1-4); they constrain the age of the Lipak Formation in the Pin Valley to early Givetian and late Famennian - early Tournaisian; conodont date further confine a previously unrecognised hiatus at c. 33 m above the base, at the boundary between sequence stratigraphic units S1 and S2, representing a large part of the Givetian, all the Frasnian and most of the Famennian.

1. Middle Devonian faunas

Samples from Section B-B´ (ED98/218, ED97/135, ED98/196), Section E-E' (ED97/166) and low in Section G-G´ (ED99/230) have yielded conodont faunas (Table 1) that are dated as mid to late Early *varcus* Subzone because of overlap of either *Bipennatus bipennatus* alpha morph or *Icriodus regularicrescens* with either *I. brevis* or *I. difficilis*. Although the upper limit of *I. arkonensis* is normally considered to be just beneath the base of the Early *varcus* Subzone, it has been reported from the Middle *varcus* Subzone in the Prout Dolomite (Sparling 1988) and from the Pine Point Formation south of Great Slave Lake in the Northwest Territories of Canada (Uyeno 1998). *I.* aff. *I. arkonensis* occurs in horizons referred to the Early *varcus* Subzone in the Bou Bîb Formation in pre-Sahara Morocco (Bul-

		LIPAK A					LIPAK B								
		ED98/218	ED98/196	ED99/230	ED97/135	ED97/166	ED99/233	ED99/234	99/95	ED99/239	ED99/241	0/99	ED98/198	Lahaul	Syringo. Ls
Bipennatus bipennatus alpha morph	Pa			2		1									
Icriodus arkonensis	Pa	5			1	11									
I. sp. cf. *I. arkonensis*	Pa	1													
I . brevis	Pa	11	7		1	2									
I. difficilis	Pa	3	9		1										
I. expansus	Pa			1	1	1									
I. obliquimarginatus	Pa					4									
I. regularicrescens	Pa	3	1			6									
Icriodus spp.	Pa	8	4		6					3					
Bispathodus aculeatus aculeatus	Pa								3	2	3	1		X	
Bi. aculeatus anteposicornis	Pa								2			1	2		
Bi. aculeatus plumulus	Pa						5		2	1					X
Bi. bispathodus	Pa						1								
Bi. spinulicostatus	Pa									2					
Bi. stabilis (juvenile)	Pa											8			X
Clydagnathus cavusiformis	Pa									4	5	72	7	X	
	Pb											3			
	Sa											1			
	Sb											2			
	Sc											4			
Cly. gilwernensis	Pa								1			11		X	X
Hindeodus cristulus	Pa											10		X	
Mitrellataxis sp. cf. *M. coronella*	C_1											26			
	C_P											29			
Polygnathus communis communis	Pa														X
Pseudopolygnathus primus	Pa									4	22	1	1	X	
Unassigned elements	Pa		1												
	Pb					1				1	2	4			
	M						1				2	1			
	Sa						1				1	1	1		
	Sb	3	1	1			2		2	1	4	2	1		
	Sc	1	1				2	1	4		8	7	5		
		Givetian					Late Famennian-early Tournaisian								

Table 1 - Distribution of Lipak Formation conodonts. Pin Valley localities are arranged in approximate stratigraphic order, left to right, followed by reports of conodonts from Lahaul (Vannay 1993) and the *Syringothyris* Limestone of Kashmir (Savage 1977), abbreviated to Syringo. Ls. Abbreviations for conodont elements may be conveniently found in Clark et al. (1881) and Sweet (1988). The ?Hangenberg Event occurs between ED99/239 and ED99/241.

tynck 1987).

2. Late Devonian/Early Carboniferous faunas

Precise dating of Late Devonian - Early Carboniferous conodont faunas from dolomites and very shallow water limestones is difficult, and is exacerbated by the dearth of documentation of faunas representing such biofacies. Conodont faunas from the Lipak Formation of the Pin Valley lack species of the genera usually employed in attempting high precision stratigraphic alignments, namely *Palmatolepis, Siphonodella* and species of *Bispathodus* other than those encountered in this investigation. Species of *Clydagnathus* dominate the Lipak Formation faunas with species of *Pseudopolygnathus* and shallow-water species of *Bispathodus*.

Problems arose in making stratigraphic alignments with such faunas because, when first described, *Cly. cavusformis* and *Cly. gilwernensis* were thought to be restricted to the Early Carboniferous (e.g. Rhodes et al. 1969). However Beinert et al. (1971) recognized a specimen identified by Glenister & Klapper (1966) as '*Spathognathodus*' *aculeatus* to be a specimen of *Cly. cavusformis.* Because it occurred in a Western Australian sample (WAPET DF 10-3) including a palmatolepid, extension of its range downwards into the Late Devonian age was established. Sandberg & Ziegler (1979, p. 193) noted the occurrence of *Cly. cavusformis* in faunas from the Late *expansa* Zone in Belgium. Wang & Ziegler (1982), after reassessing conodonts from the Shaodong Member, the topmost member of the Hsikuangshan Formation of South China, assigned the member a Late Devonian age. Until then the fauna of the Shaodong Member (including *Cly. cavusformis*) was considered to be Early Carboniferous in age.

A second taxonomic problem concerns *Pseudopolygnathus*. The similar forms *Ps. dentilineatus* and *Ps. primus* were originally discriminated on the basis of width of the basal cavity, the former being considered to be a Devonian form and the latter with a narrow basal cavity being thought to be restricted to the Carboniferous. Klapper (1977), after examining the types in the Branson & Mehl and E.R. Mehl collections, synonymised the two because he found the collections contained material transitional from one species to the other.

The incoming of *Bispathodus aculeatus* has been used for definition of the base of the Middle *expansa* Zone (Ziegler & Sandberg 1984, p. 184). Such occurrences are exemplified in many works, for example by Çapkinoglu (2000) who documented *B. aculeatus aculeatus* from the Middle *expansa* Zone in the Istanbul Terrane of NW Turkey. As *Bi. a. plumulus* first appears in sample ED99/233, this horizon must be no older than Middle *expansa* Zone. There are no reports of icriodid conodonts having survived the Hangenberg Event (cf. *inter alia*, Streel et al. 2000) at the end of the latest Famennian Middle *praesulcata Zone*. It is therefore assumed that the faunas from spot sample 99/95 and from ED99/233 to at least ED99/239, where the last fragments of icriodids occur (Tab. 1), are no younger than the latest Late Devonian Middle *praesulcata* Zone. *Bi. bispathodus*, though known only from a single specimen from ED99/233, also became extinct in the Middle *praesulcata* Zone.

Sample ED99/241 collected c. 1.2 m above the approximately 0.58 cm recessive, black carbonaceous shale interval between ED99/239 and ED99/241, lacks icriodids, even fragmentary ones. We suggest that the recessive black carbonaceous shale interval could therefore reflect the Hangenberg Event and be end-Middle *praesulcata* Zone but stress that the evidence is tenuous; other conodont data from stratigraphically above ED99/241 are consistent with this interpretation. Conodont faunas from stratigraphically higher horizons include species that arose in the Late Devonian and cross the Devonian-Carboniferous boundary, specifically *Bispathodus aculeatus aculeatus*, *B. a. plumulus*, *Bi. a. anteposicornis*, *Pseudopolygnathus primus* and *Clydognathus cavusformis* but the entry of *Hindeodus cristulus* is indicative of Early Carboniferous (Tournaisian).

Of the six major biotic crises during the Late Devonian to Tournaisian (Walliser 1996), five, including the major Upper Kellwasser Event (Schindler 1990), must be excluded from consideration because our conodont data indicate no preserved record in the Pin Valley for the Frasnian and most of the Famennian. The latest Famennian Hangenberg event, one of the largest Phanerozoic mass extinction events, is the most probable candidate in terms of age and lithologic succession. Discussion of possible causes and boundary conditions connected with this event and its profound impact on marine and terrestrial biota is beyond the scope of this paper (cf. Walliser 1984, Streel et al. 2000, Caplan & Bustin 1999, Fig. 3).

The youngest horizons in the Lipak Formation were sampled in the section W of Guling (Fig. 2). Sample 0/99 (Fig. 4, 8) produced the largest and most diverse fauna of conodonts including *Hindeodus cristulus*, *Bispathodus stabilis*, *Clydognathus gilwernensis*, *Cly. cavusformis* and *Pseudopolygnathus primus*. This, incidentally, is the lowest unequivocally Carboniferous horizon in the Lipak Formation; there is no chronologic control on the sequence between the black carbonaceous shale interval (between ED99/239 and ED99/241) and this horizon. According to Klapper (in Ziegler 1981), the upper range in Europe of *Ps. primus* is the "*Siphonodella triangulus triangulus*" Zone of Voges (1959) (= *sandbergi* Zone of current usage), although Voges (1959, Tab. 1, p. 269) questions this upper limit. Klapper (in Ziegler 1981) indicates the upper limit of *Ps. primus* in North America as Kinderhookian, i.e. including the Early *crenulata* Zone. Sandberg et al. (1978) and also Sweet (1988) show it extending to late in the Early *crenulata* Zone, as has been shown for the Ruxton Formation of NE Australia (Mawson & Talent 1998). This, considered in conjunction with *Clydognathus cavusformis* being not known from horizons younger than late in the Early *crenulata* Zone (Sweet 1988), leads to the conclusion that horizon 0/99 is best regarded as Early *crenulata* Zone, with little possibility that it is any younger. Also present in 0/99 are specimens of *Mitrellataxis* sp. cf. *M. coronella*. Chauff & Price (1980) described such cone-like elements from the Sulphur Springs Formation of Missouri (Late Devonian, *postera* to *expansa* zones). The Tournaisian specimens from the Lipak Formation therefore extend the range of this rare genus.

The fauna from sample ED98/198, the highest horizon in the Lipak Formation to produce useful conodonts (Fig. 8), is less diverse than 0/99. It has produced *Bi. a. anteposicornis*, *Cly. cavusformis* and *Ps. primus*, forms also present in 0/99. The first of these, though earlier quoted as ranging from Late *praesulcata* Zone through the *duplicata* Zone (Ziegler 1975) is now known from the late Tournaisian (Osagean: *typicus* and *anchoralis-latus* zones and seemingly extending into the texanus Zone; Sweet 1988) of Alaska (Dumoulin & Harris 1993), and in Eire from horizons as high as the *multistriatus* interval of the *typicus* Zone (Johnston & Higgins 1981; Varker & Sevastopoulo 1995, p. 184). No conodonts from sample ED98/198 indicate an age younger than that indicated by the fauna from 0/99, i.e. no younger than somewhere late in the Early *crenulata* Zone (Table 1).

3. Review of identifications from adjoining regions

In his study of conodonts from the low in the *Syringothyris* Limestone in the Liddar Valley, Kashmir, Savage (1977) identified *Cly. gilwernensis*, *P. communis*

communis, *Bi. stabilis* and *Bi. aculeatus plumulus*, forms now known to have appeared late in the Late Devonian. At the time of Savage's publication, it was thought that *Cly. gilwernensis* was restricted to the Early Carboniferous (e.g. Rhodes et al. 1969), hence the *Syringothyris* Limestone conodont fauna was assigned an early Tournaisian age and, on the basis of the assumed age of *Bi. aculeatus plumulus*, to be no younger than *sulcata* Zone. It is now recognised that *Cly. gilwernensis* occurs also in the Late Devonian (e.g. Sweet 1988). It is thus possible that the base of the *Syringothyris* Limestone may be somewhat older than previously thought (Tab. 1).

Vannay (1993) illustrated conodonts from the Lipak Formation in upper Lahaul including *Bispathodus aculeatus* (= Vannay's "*Spathognathodus*" *tridentatus*), *Clydagnathus cavusformis* (= his *Cly. gilwernensis*), *Pseudopolygnathus primus* (= his *Ps. lacinatus asymmetricus*) as well as *Clydagnathus unicornis*, a form synonymised by Nicoll & Druce (1979, p. 23) with *Cly. cavusformis* (see discussion in section on Systematics). Because of the presence of *Ps. primus*, Vannay's fauna cannot be older than Late *expansa* Zone (late Famennian) or younger than late in the Early *crenulata* Zone (mid Tournaisian).

4. Implications for the age of the underlying Muth Formation

Conodont faunas from the lower Lipak Formation, c. 30 m above the Muth Formation in the Pin Valley (Tab. 1) are dated as mid to late Early varcus Subzone (Middle Devonian) because of overlap of either *Bipennatus bipennatus* alpha morph or *Icriodus regularicrescens* with either *I. brevis or I. difficilis*; this age represents a well-constrained minimum age for the underlying Muth Formation.

Our conodont data from low in the Lipak Formation, transitional from the Muth Formation, demonstrate that V. J. Gupta, despite numerous publications (see Talent et al. 1988, for discussion) failed to present an acceptable age for the Muth Formation or even an approximation to the environments represented. He repeatedly asserted a Middle Devonian age for the Muth Formation on the basis of a jumble of poorly preserved Late Ordovician/Llandovery pre-Muth shelly fossils, plus pictures of Eifelian brachiopods and other fossils from Padaukpin (Myanmar) cut out of F. R. C. Reed's (1908) monograph, plus a scatter of Late Devonian ammonoids from sub-Saharan Morocco, plus a mixture of latest Givetian - early Frasnian conodonts (three, ?four zones) from the North Evans Limestone of New York State. No Eifelian or Frasnian horizons nor post-Early *varcus* Subzone Givetian have been encountered in the Muth Lipak sequence.

Depositional environment

The general depositional environment of the Lipak Formation in the Pin Valley, interpreted by sedimentary structures and microfacies, is shallow marine, an interpretation supported by the clydagnathid-bispathodid conodont faunas believed to be very shallow marine. In discussing shallowest-water Tournaisian conodont faunas, Sweet (1988, p. 121) opined that "cavusgnathid conodonts [including *Cavusgnathus* and *Clydagnathus*] are common ... in marginal marine ... environments ... characterized by shallow water of variable salinity".

Species of *Bispathodus*, exemplified by *Bi. aculeatus plumulus* and *Bi. a. anteposicornis* encountered in the Lipak Formation, occur in extremely shallow situations. They are among the first conodont forms encountered up-sequence in sedimentary packages grading from indubitably non-marine to near-shore, as in the gradual transition from Lollypop Formation to Hardwick Formation in the Burdekin Basin of NE Australia (Mawson & Talent 1997, and unpub. data), and in limestones in arguably very shallow dolomitic sequences, e.g. in the Yellow Drum Sandstone of the Canning Basin of NW Australia (Nicoll & Druce 1979). It should be noted that various species of *Bispathodus*, such as *Bi. ultimus* and *Bi. costatus*, occur in deeper water (or more pelagic) biofacies where - associated with palmatolepids - they have zonal importance in the late Famennian (see, *inter alia*, Ziegler et al. 1974 Sandberg & Dreesen 1984 Ziegler & Lane 1987).

The regional homogeneity of the Lipak sediments may be explained by deposition on a low relief sea floor on a very gently inclined ramp-type shelf. No synsedimentary deformation structures have been found in the Lipak Formation in the Pin Valley; in contrast, Vannay (1993) described growth faults in the Lipak Formation of upper Lahaul. The existence of syn-sedimentary tectonics possibly influenced the relative sea-level curve; comparison with the eustatic sea level is therefore not attempted here.

The basal arenites, sandstones and dolomitic sandstones show a slow, gradual deepening from the coastal arenites of the barrier-island environments of the Muth Formation (Draganits 2000). The packstones to grainstones with remains of brachiopods, echinoderms, corals, fish scales and vertebrate bone indicate moderate to high-energy conditions above fair weather wave base in a maximum-flooding-surface setting. Petrographically, the sandstones represent arkoses; whether the compositional differences between these arkoses and the arenites of the Muth Formation below were controlled by tectonic activity, e.g. growth faults described by Vannay (1993) and deformation bands in the Muth Formation (Draganits 2000), or by climatic variations (e.g. Streel et al. 2000) remains unsolved.

After a time-gap corresponding to absence of a biostratigraphic record for the later Givetian, the entire Frasnian and most of the Famennian, there is a thin

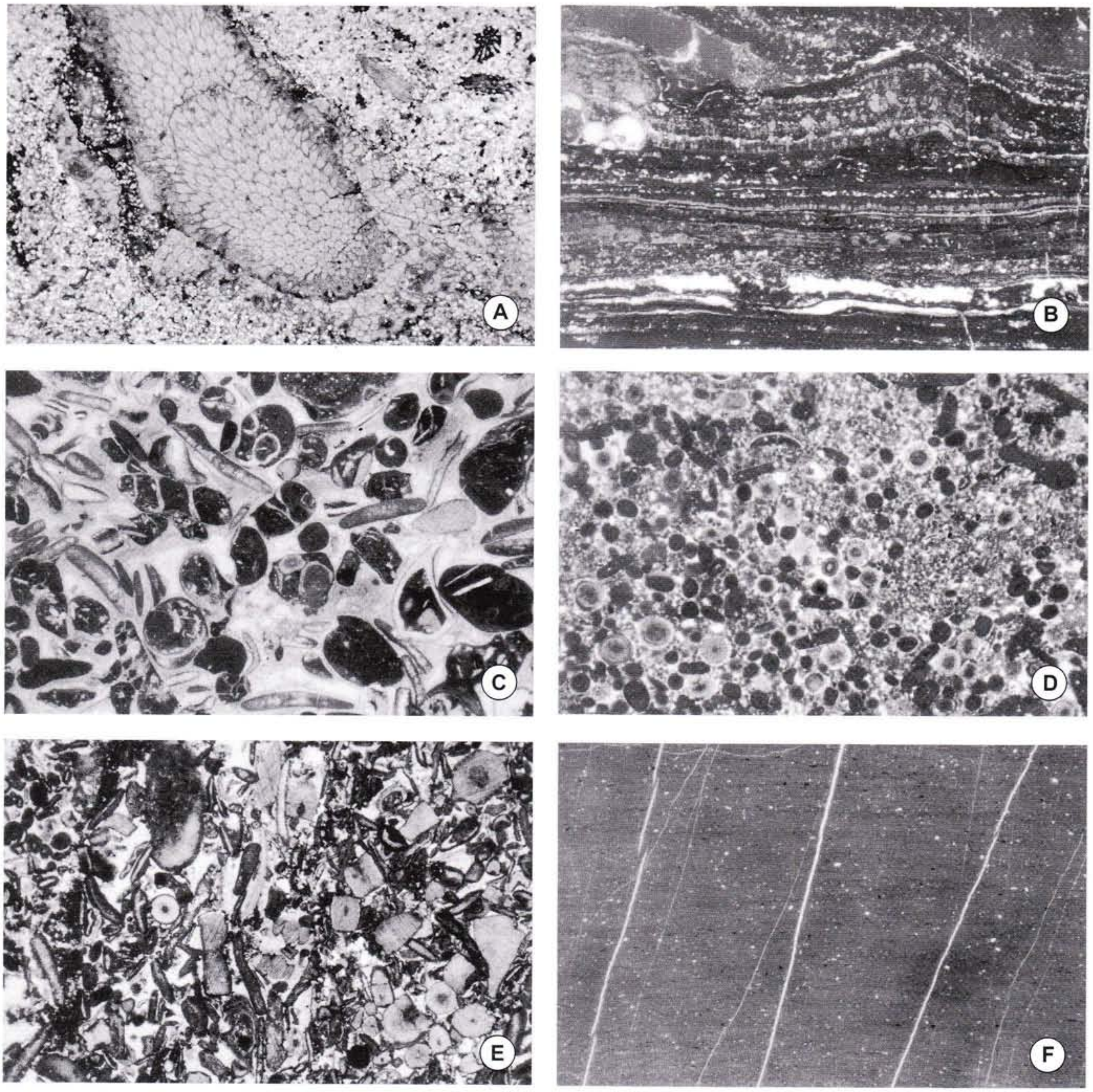

Fig. 7 - Microfacies of the Lipak Formation in section G-G´ near Muth village; distances in parentheses indicate position of the samples above the base of the formation in metres. A) Bryozoan fragment (B. Hubmann, pers. comm. 2001) floating in sandy matrix (26 m); field of view (FV) = 11 mm. B) Microbial mats (33 m); FV = 9 mm. C) Bioclastic grainstone with well-rounded lithoclasts (41 m); FV = 10 mm. D) Oolitic packstone to grainstone with small ostracod shells (50 m); FV = 7 mm. E) Poorly sorted grainstone with crinoid ossicles and micritized brachiopods (70 m); FV = 9 mm. F) Laminated mudstone with silt-sized quartz grains (114 m); FV = 6 mm.

quartzarenite interval, and a thick interval of microbial mats (Fig. 7b) interpreted as protected intertidal, highstand sediments. Several intraformational breccias, rare brachiopod-containing grainstones (Fig. 7c) and oolites (Fig. 7d) occur higher up-section within this interval; these are also consistent with a peritidal setting.

Brachiopod-containing wackestone to grainstone, well developed oolites and echinoderm grainstones (Fig. 7e) above the second sandstone interval and below the prominent black carbonaceous shale signify high-energy peritidal settings. Limestones above the black shale and below the third sandstone interval closely resemble the oolitic, echinoderm-bearing wacke- to grainstone down sequence. The black shale bed at c. 73 m above the base, probably representing the Hangenberg Event, is interpreted in sequence stratigraphic terms as a maximum flooding surface.

Wackestones to rarer grainstones above the third

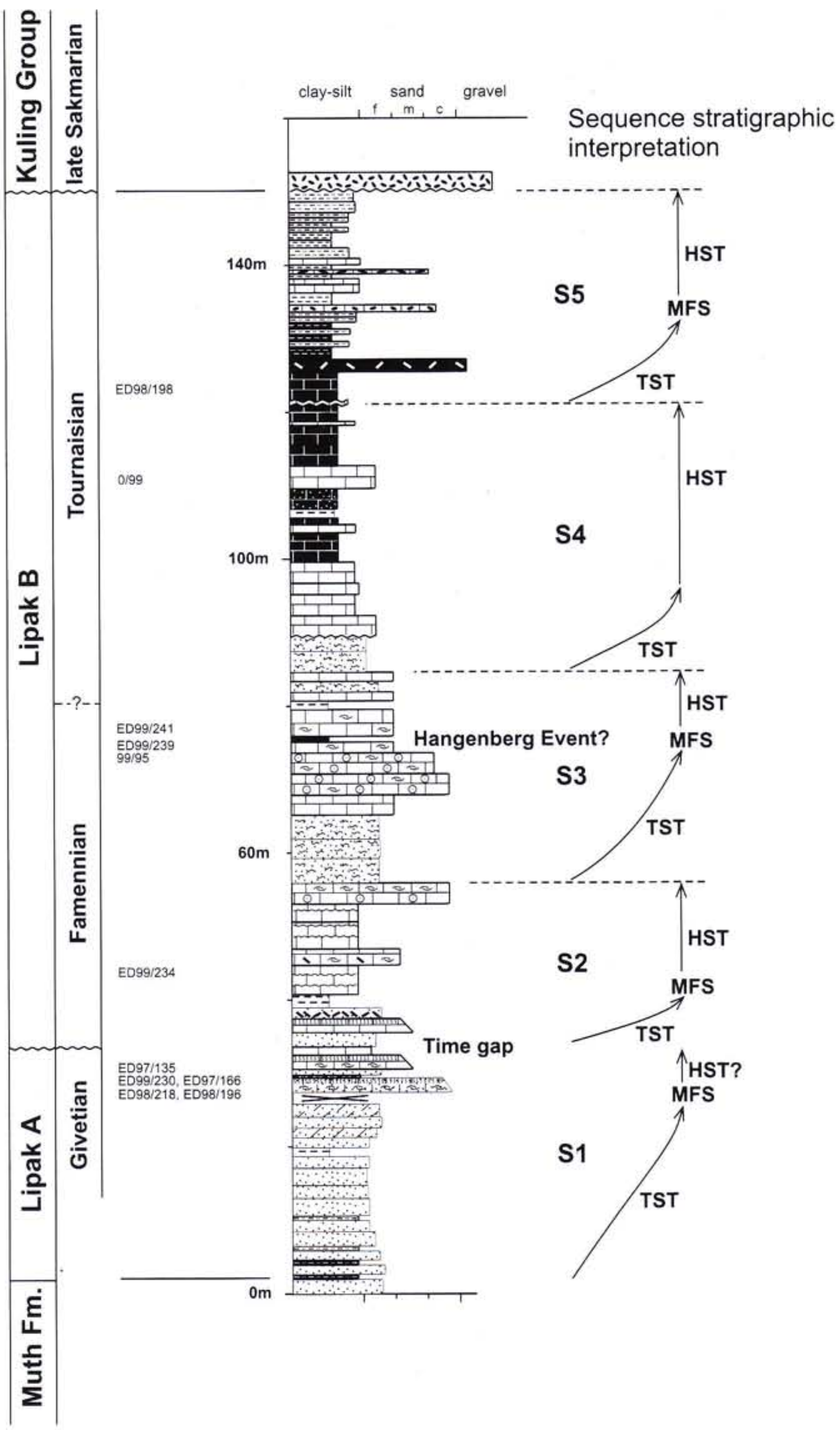

Fig. 8 - Sequence stratigraphic interpretation of the Lipak Formation in the Pin Valley with salient samples collected in pursuit of conodont data. S1-S5 are the discriminated sequences (S1 is Lipak A; S2-S5 is Lipak B). HST (highstand systems tract); MFS (maximum flooding surface); TST (transgressive systems tract). Lowstand systems tracts are typically not recorded in this shallow marine environment. The general lithological section of the Lipak Formation has been pieced together from sections E-E´, G-G´ and the section W of Guling (Fig. 4, 5; see Fig. 4 for lithologic index).

sandstone horizon are poorer in their macro-fossil contents but are still interpreted as peritidal, moderate- to high-energy sediments. The thick interval of black mudstone (Fig. 7f) higher up-section is interpreted as a protected, shallow marine deposit, an interpretation also supported by the presence of a completely recrystallized limestone bed with evidence for emergence.

Sequence-stratigraphic interpretation

Based on the sections studied, a sequence-stratigraphic interpretation is presented (Fig. 8), even though the area is not extensive. The Lipak Formation of Spiti, however, displays distinct lithologic and facial characters that allow long-distance lithostratigraphic alignments with other areas in the NW Himalayas (see section on Correlation). Uniformity of the Lipak sediments in Spiti and other regions may be explained as due to a particular basin-margin architecture - a low relief sea floor on a very gently inclined (less than 0.5%) ramp-type shelf. Due to the persistently shallow water environments represented, even during maximum transgressive phases, palaeobathymetry of a few tens of meters was never exceeded. Such shelf topography may produce erosionally well-marked sequence boundaries with little probability for accumulation of lowstand deposits. Moreover, as a consequence of low relief and shallow seas, even minor sea level changes may cause wide lateral facies shifts.

Abrupt vertical changes from relatively coast-remote carbonate environments below to comparably nearshore clastic deposits above are used to identify sequence boundaries in the lower and middle part of the Lipak Formation - depositional sequences S1 to S4, respectively (Fig. 8). The lower boundary of sequence S5, lying within a carbonate package (and contrasting with the preceding abrupt carbonate-siliciclastic transitions) is a striking, reddish, strongly recrystallized, karstified, calcareous emersion horizon; it is therefore interpreted as a distinct type 1 sequence boundary. Lowstand system tracts have not been identified anywhere in the Lipak sequences of the Pin Valley.

The lower four sequences all start with environmentally very shallow sandstones interpreted as early transgressive systems tracts (TST). They change to bioclastic calcarenites with varying amounts of shelly fauna (predominantly brachiopods) and subordinate crinoids during the late TST. Oolites are common only in S3. Intervals representing the maximum flooding surface (MFS) are well displayed in sequences S1 to S3 by crinoidal-brachiopod pack- to grainstones rich in marine microvertebrates and conodonts. No MFS has been identified in S4 whereas S5 shows a single bioclastic grainstone bed bracketed by shales and mudstones in the section W of Guling; it has been used for determining the MFS.

Lithologically, the sequence boundary between S1 and S2, c. 33 m above the base of the Lipak Formation, is very similar to those between S2-S3 and S3-S4, but represents an unexpected depositional gap spanning a large part of the Givetian, all the Frasnian and most of the Famennian . The gap is constrained solely by conodont biostratigraphy; no sedimentological indications such as hardgrounds or erosion surfaces have been found, though the very thin highstand interval of S1 might indicate some erosion.

The prominent, sharply defined 58 cm black to dark grey carbonaceous shale interval, bed Lc174, sandwiched between crinoidal grainstones (Fig. 7e), is an abrupt lithologic break reflecting a short-lived, drastic event. In section G-G´ this bed coincides with breakdown in carbonate production in the underlying beds, followed by abrupt renewal of carbonate production again. This shale bed within the MFS interval of sequence S3, with late Famennian conodont ages below and immediately above, may represent the Hangenberg Event.

All highstand systems tracts (HSS) of sequences S1 to S4 consist of different types of shallow water carbonates. The rather thin HST of S1 consists of pure bioclast-rich grainstones indicating the presence of only early highstand deposits. Finer grained sediments typical of a late highstand are missing. Their absence is inferred to be connected with the pronounced stratigraphic gap indicated by the conodont faunas (Tab. 1). Highstand sediments of S2 are dominated by fine-grained laminated to stromatolithic limestones; biocalcarenites dominate in S3 and mudstones in S4. Mudstones of S4 may be interpreted as quiet water deposits built on a rather restricted and considerably enlarged shelf during the maximum Lipak transgression.

A drastic environmental change is reflected in the siliciclastic HST of the uppermost S5 in the section W of Guling. It corresponds to the beginning of a regressive cycle, culminating in evaporites in the upper part of the Lipak Formation - a cycle fully developed in the Zanskar, Lahaul (Vannay 1993, Fig. 8), Takche and Lipak valleys, but missing in the Pin Valley due to erosion during Permian times.

Two transgression-regression cycles have been identified as having occurred in the late Famennian: beginning at the base of the Early *expansa* Zone, and beginning at the base of the Late *expansa* Zone, with major regression late in the *praesulcata* zones (Johnson et al. 1985; Johnson & Sandberg 1989). This could correspond to our cycles S2 (including ED99/234 with a Middle *expansa* fauna) and S3. Others (e.g., Perri & Spalletta 2000) indicate a single T-R event with its inception at the base of the Middle *expansa* Zone, terminating late in the *praesulcata* zones.

Ross & Ross (1988) suggested four transgressive events during Tournaisian times, but conodont data for the onset of these was not presented. The onset of the first of these, at or about the beginning of the Tournaisian (*sulcata* Zone), seems to align with the onset of our sequence S4. Four other Tournaisian transgressive events have been discriminated on the Russian Platform (Rukina 1996; cf. Makhlina 1996). Inception of each of these coincided with salient changes in foraminiferal communities, but alignment of these events with the conodont zonal scheme is problematic. One transgressive event nevertheless had its inception at the base of the Late *duplicata* Zone (Girard 1994), and another occurred within or at the base of the *sandbergi* Zone (Mawson & Talent 1997, 1999; Perri & Spalletta 2000). Our conodont data are too sparse for discrimination of these events in the Pin valley. The timing of initiation of our Lipak cycle S5 is problematic; limestones in this interval (Fig. 8, sample 99/96) failed to produce conodonts.

Correlation

Northern Pakistan

The mid-Givetian transgression expressed by the

Muth-Lipak transition is paralleled in Chitral, NW Pakistan, where the Charun Quartzite passes upwards gradationally into the lithologically diverse Shogrām Formation. The age of the Charun Quartzite, like that of the Muth Formation, is not well constrained chronologically, apart from the age of its uppermost or immediately overlying beds, namely mid-Givetian, Middle *varcus* Subzone (Talent et al. 1999). The Shogrām Formation, as presently construed, spans at least the interval from mid-Givetian to early Famennian.

In the northern Karakoram, Palaeozoic sediments are found in at least six different tectonic thrust sheets to the N of the Reshun Fault (Zanchi et al. 2001). There, in the upper Yarkhun Valley, the Muth Formation finds its equivalents in the Charun Formation and its lateral equivalents, the peritidal dolostones of the Chilmarabad Formation (Gaetani et al. 1996). They are followed by the late Givetian - early Famennian Shogrām Formation, which is overlain by crinoidal limestones assigned to a new Early Carboniferous unit, the Ribat Formation (M. Gaetani pers. comm. 2001; Angiolini et al. 2001), and these in turn by the Late Palaeozoic Gircha Formation (Gaetani et al. 1996), a suite of quartzarenites and arenaceous slates with minor carbonates. In the Karambar thrust sheet, where the Devonian-Carboniferous successions are most complete, a late Tournaisian age is indicated by conodonts from about 30 m above the base of the Ribat Formation (M. Gaetani pers. comm. 2001), indicating a slightly younger age for the Ribat Formation than the Lipak Formation in Spiti.

In the Khyber region of northern Pakistan, W of Peshawar, a similar quartzite sequence passes upwards into a lithologically diverse siliciclastic-carbonate sequence. At the base, it is ?late Givetian (with the compound rugose coral *Phillipsastraea*), passing upwards through Frasnian and Famennian horizons into the early Tournaisian (Molloy et al. 1997). Similar relationships seem to occur in the Devonian sequences outcropping around the E and NE margins of the Peshawar Basin (Mawson et al. 2002, and unpub. data). According to age and lithologies, there is obvious similarity to the Muth-Lipak and Charun-Shogrām sequences in Spiti and Chitral respectively. Similar sequences occur farther W in southern Afghanistan and Iran; these typically have an interval with *Phillipsastraea* near the base but usually lack age-diagnostic conodonts at that level.

The Muth-Lipak transition and the Lipak Formation are thus examples reflecting a global transgression during early mid-Givetian times along the northern Gondwana margin, and indeed globally (Johnson et al. 1985, Mawson & Talent 2002 and unpub. data).

Kashmir

Middlemiss (1910) formulated a Palaeozoic stratigraphy for SE Kashmir, based on the first investigation of the region by Lydekker (1883). This was modified by Srikantia & Bhargava (1983) and Kumar et al. (1987). Due to a depositional gap during Late Devonian to mid-Carboniferous times, the Palaeozoic stratigraphy of NW Kashmir (Wadia 1934) lacks Lipak Formation correlatives. Because of political inaccessibility, the area has not been the subject of reinvestigation; its stratigraphy is thus less well established than for Zanskar and Spiti.

In the Liddar Valley of SE Kashmir, the Muth Formation grades upwards into dark limestone with subordinate shale and sandstone, the *Syringothyris* Limestone (Middlemiss 1910), by decrease in proportion of quartzite beds and increase in carbonate and carbonaceous matter. Some authors separate this transitional interval as an independent formation (Wazura Formation of Srikantia & Bhargava [1983], Aishmuqam Formation of Kumar et al. [1987]). No evaporites, characteristic of the complete Lipak sections in Zanskar (Nanda & Singh 1977, Gaetani et al. 1986) and Spiti (Garzanti et al. 1993), have been reported from Kashmir. Contact with the overlying *Fenestella* Shales, generally correlated with the *Fenestella* Shale (Po Group, Garzanti et al. 1996b) in Spiti, is conformable (Middlemiss 1910, Kumar et al. 1987).

Correlation between the Lipak Formation and the *Syringothyris* Limestone is generally assumed, but Savage (1977), on the basis of conodonts, reported an earliest Tournaisian age for lower parts of the *Syringothyris* Limestone in the Liddar Valley but the fauna recorded by him is also typical of the latest Devonian (see section on Conodont data and age implications). Conodonts from the Liddar Valley indicate the age of the *Syringothyris* Limestone to lie somewhere between the Late *expansa* Zone and the *sulcata* Zone (see Fig. 9 for alignment of conodont zonal schemes). This implies that an appreciable part of the Lipak Formation is not represented in Kashmir, a situation similar to that in Zanskar. Equivalents of the lower Lipak Formation may however equate with some or all of the Wazura/Aishmuqam Formation (Srikantia & Bhargava 1983, Kumar et al. 1987), in an interval without age-diagnostic fossils.

Southern Zanskar and upper Lahaul

The Lipak Formation (= Tanze Formation, Members A and B [Nanda & Singh 1977]) is up to 250 m in S Zanskar (Fuchs 1987) and upper Lahaul (Vannay 1993). The lower boundary of the formation is reported to be sharp (Srikantia et al. 1978, Baud et al. 1984), but may be gradual, represented by transition from quartzarenites of the Muth Formation to sandstone, shale and carbonate (Gaetani et al. 1986, Vannay 1993).

In Lahaul, Vannay (1993) discriminated four members (L1-L4). The lowest member, L1, consists of orange sandstones and gritty limestones, grading into about 120 m of dark mudstones; its lower boundary is

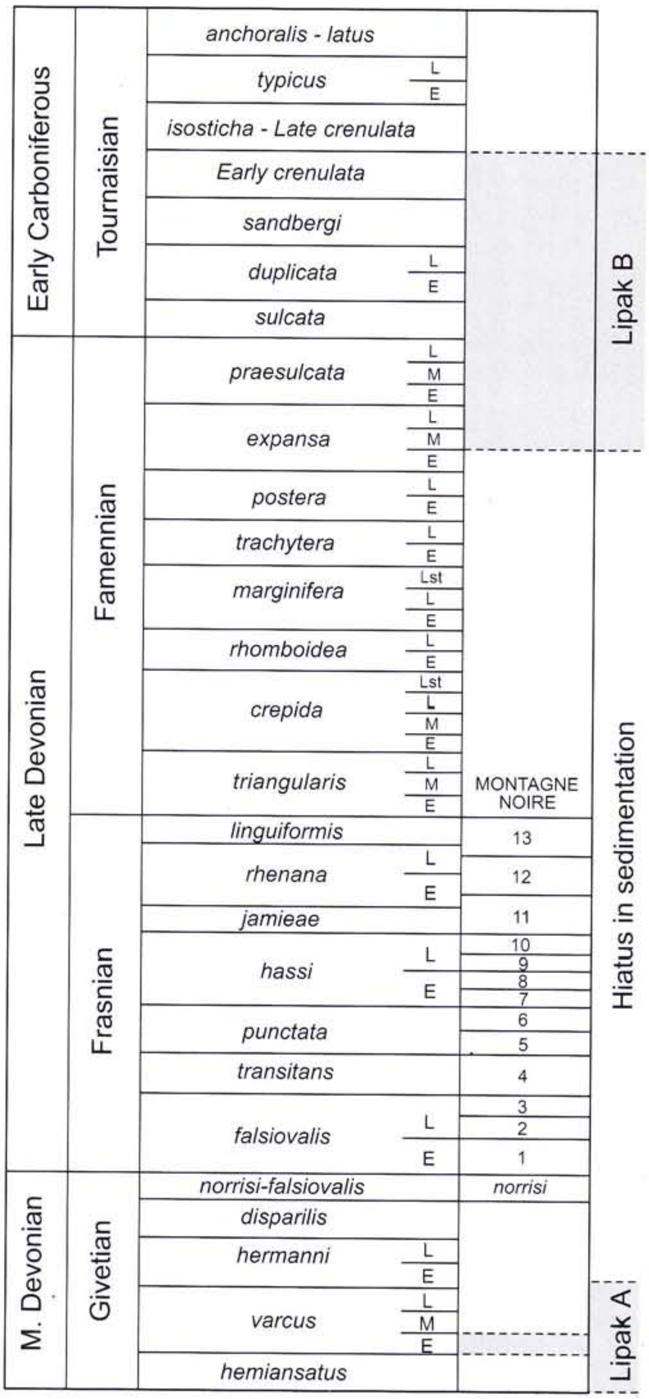

Fig. 9 - Alignment of Middle Devonian (Givetian), Late Devonian and Early Carboniferous (Tournaisian) conodont zonal schemes.
The Late Devonian zonation is based on Ziegler & Sandberg (1990), the portion for the Middle Devonian follows Weddige (1996); the Montagne Noire intervals (1-13) are based on Klapper (1989) and Klapper & Becker (1999).
The Tournaisian conodont zonation follows Sandberg et al. (1978) and Ziegler & Lane (1987). E = early; M = middle; L = late; Lst = latest. The biostratigraphic range of the Lipak Formation is indicated.

gradational with the underlying Muth Formation. Member L2, not exceeding 20 m thickness, consists of siltstones, dark shales, calcareous sandstones, dolomites and carbonate breccia; it is overlain by Member L 3 consisting of less than 50 m of white gypsum. The youngest member, L4, consists of dolomites, dolomitic limestones and sandstones; it resembles member L1 and has a gradational contact with the overlying Po Formation. This lithologic succession, with its salient gypsum interval (Gaetani et al. 1986), is very similar to relatively complete sections in the Takche Valley and the lower Spiti Valley (Garzanti et al. 1993, Bhargava & Bassi 1998).

The Lipak section near Muth village in the Pin Valley lacks the siltstone interval, the gypsum horizon, and the succeeding dolomites and sandstones (members L2-L4 of Vannay 1993), inferred to have been eroded away below the base of the Gechang Formation (Fig. 5). In the section near Guling, the presence of siltstones at the top of the Lipak Formation comparable to those of member L2 of Vannay (1993) indicates less erosion of the formation than near Muth (Fig. 4). Correlation of the siltstones at the top of the section near Guling (Fig. 4) indicates that this section of the Lipak Formation has been truncated to below the gypsum interval.

Vannay (1993) regarded conodonts he obtained from the Lipak Formation in Lahaul as Tournaisian. One might therefore assume the Givetian - Late Devonian part of the Lipak Formation reported here from the Pin Valley, to be missing from the sequence in upper Lahaul or to be represented only by the unfossiliferous, basal, sandy dolomite (Vannay 1993). Reassessment of Vannay's conodont fauna (see section: Conodont data and age implications and Tab. 1) indicates the conodont faunas from upper Lahaul to possibly span some or all of the interval from Late *expansa* Zone (late Famennian) to late in the Early *crenulata* Zone (mid-Tournaisian).

Spiti Valley *sensu lato* and NW Kinnaur

Stoliczka (1866) mentioned differences in the Late Palaeozoic sequences of the lower Spiti Valley and the Pin Valley, introducing "southern facies" for the former and "eastern facies" for the latter, but erred in correlating the Po Group (Garzanti et al. 1996b) of the lower Spiti Valley with his Babeh and Muth Series in the Pin Valley. Hayden (1904) improved the stratigraphic alignments for the two areas, stating that the Po Formation was much younger than Stoliczka (1866) had thought, and stressed that the marked difference between the two areas was due to differences in what was preserved below the Permian Kuling Group. This is displayed very clearly in the maps by Bhargava & Bassi (1998).

In the Pin Valley, the upper boundary of the Lipak Formation is represented by an erosive angular unconformity below the Permian Kuling Group (Griesbach

1891); nearly the entire Carboniferous is missing (Garzanti et al. 1996a). Towards the NW, erosion below the Kuling Group reached deeper and deeper levels, even reaching the Pin Formation in the Parahio Valley (Fig. 2) (Fuchs 1982). Gradual increase in the stratigraphic extent of the Lipak Formation towards the Spiti Valley leads to the observation of well-developed sections in the Takche Valley near Losar, in the Lingti Valley, and in the lower Spiti Valley near Tabo and Po (Stoliczka 1866, Hayden 1904, Garzanti et al. 1993). In these areas the upper part of the Lipak Formation (with evaporites) and the entire Po Group and Ganmachidam Formation are preserved; the contact with the overlying Gechang Formation of the Kuling Group is more or less gradual. A thin tuff horizon in the Lingti Valley, incidentally, may indicate the presence of Panjal Trap correlatives in Spiti (Draganits 2000). Despite the much greater thickness of the Lipak Formation in the Lipak Valley (c. 500 m, Hayden 1904) than in the Pin Valley (121 m), the successions are very similar lithologically. Noteworthy are the two sandstone intervals in the section near Muth at 60 m and 85 m (Fig. 5); these are well displayed in the type section in the Lipak Valley (Hayden 1904), but comparable intervals are not present in Lahaul (Vannay 1993).

Southeast Kinnaur, Kumaon and Nepal

East of Spiti, in SE Kinnaur and Kumaon, the upper boundary of the Muth Formation is represented by an erosional surface below the Permian Kuling Group (Heim & Gansser 1939, Kumar et al. 1977, Bassi 1989, Sinha 1989) implying non-deposition and/or erosion of the entire Late Devonian to Early Permian sequence.

Due to pronounced E-W facies differences in the Devonian sediments in Nepal (Fuchs 1967), correlation is challenging. In W Dolpo a shallow marine, thick-bedded arenaceous dolomitic sequence with interbedded quartzites has been correlated with the Muth Formation of Spiti (Fuchs 1977). It reaches about 1000 m thickness and is devoid of determinable fossils, but an interval with dark limestones, marls and dolomites in the upper third of this formation produced a diverse Middle Devonian (Givetian) fauna (Flügel 1966, Fuchs 1977). The contact with the overlying Permian Thini Chu Group (Garzanti 1999, i.e. Thini Chu Formation, Bodenhausen et al. 1964) is erosional; the entire Late Devonian to Early Permian is missing.

In central Dolpo, the informal term "fossiliferous Late Devonian limestone" has been used (Garzanti et al. 1992) for dolomites, calcarenites, marls and an ironstone horizon unconformably overlying dolomites - possible correlatives of the Muth Formation (Fuchs 1977) of western Dolpo; precise correlation with western Dolpo and Manang areas remains problematic, though a probable Frasnian age has been suggested (Flügel & Tintori 1993).

In the Pin Valley, a distinctive horizon with large bryozoan fragments (B. Hubmann, pers. comm. 2001) (Fig. 7a), associated with corals, vertebrate bone fragments, brachiopods, crinoids and radiolarians, occur in the lower part of the formation (c. 31 m above the base, in sequence S1). The Givetian conodont age of this horizon accords with the prolific reef development globally during Givetian-Frasnian times, with reefs growing even in abnormally high latitudes (Kiessling et al. 1999). This warm period was followed by climatically unstable periods with several short-term glaciations during the Famennian (Streel et al. 2000). Flügel & Tintori (1993) mention a rich coral fauna from "fossiliferous Late Devonian limestone" in central Dolpo, dated as probably Frasnian - an interval missing from the Lipak Formation in the Pin Valley according to our conodont data. Devonian corals are also reported from the mid-Givetian to early Famennian Shogram Formation of Chitral, Pakistan (Talent et al. 1999, which see for earlier literature).

The "fossiliferous Late Devonian limestone" is paraconformably followed by "dark pelites" believed also to be Late Devonian in age. A possible correlation with the Tilicho Pass Formation of the Thakkhola area has been suggested (Garzanti et al. 1992). The "fossiliferous Late Devonian limestone" and "dark pelites" succession of central Dolpo resemble the Lipak Formation of the Pin Valley - sandstone, dolomitic sandstone and calcarenite in lower levels followed by a thick dark mudstone interval (Fig. 5); broad correlation is indicated.

Farther E in the Thakkhola and Manang regions of central Nepal, the Tilicho Pass Formation (Bodenhausen et al. 1964) - dark grey pelites and siltstones in the lower part and siltstones, sandstones and crinoidal limestones in the upper part - is unconformably followed by dark crinoidal calcarenites and shales of the Tilicho Lake Formation (Bordet et al. 1971). The former has produced corals and brachiopods of late Eifelian - Givetian age from its lower middle part in the Thakkhola region (Bordet et al. 1971), and Frasnian conodonts from its upper part in the Manang area (Fuchs et al. 1988); the existence of Frasnian intervals in Nepal contrasts with the Pin Valley sections. The Tilicho Lake Formation has been assigned a Tournaisian to Visean age (Bordet et al. 1971, Fuchs et al. 1988). Thus, ages from the Manang area indicate that the lower part of the Tilicho Pass Formation is broadly age-equivalent to the Muth Formation, whereas the upper part of the Tilicho Pass Formation and the lower part of the Tilicho Lake Formation may correlate with the Lipak Formation of Spiti. Some or all of the hiatus found in the Lipak Formation of the Pin Valley is represented by pelites, sandstones and crinoidal limestones of the Tilicho Pass Formation (Fuchs et al. 1988). These sequences and possibly others in Spiti and S Zanskar have the potential to provide insights into events during the later Givetian, Frasnian

PLATE 1

Fig. 1, 2, 7, 9, 14 x90; Fig. 3, 4, 8, 18 x100; Fig. 5, 16, 17, x120; Fig. 6, 15 x105; Fig. 10, 11, 12 x75; Fig. 13 x110.

Fig. 1, 2, 6-8, 13 *Icriodus difficilis* Ziegler & Klapper 1976: 1, 2) lower and upper views respectively of AMF 119237; ED98/196; 6) upper view of AMF 1192240; ED98/196; 7) upper view of AMF 119242; ED98/218; 8) upper view of AMF 119242; 13) upper view of AMF 119246; ED98/218.

Fig. 3-5 *Bipennatus bipennatus* Bischoff & Ziegler 1957 alpha morph: 3, 4) upper and lower views respectively of AMF 119238; ED97/166; 5) upper view of AMF 119239; ED99/230.

Fig. 9-12, 14 *Icriodus arkonensis* Stauffer 1938: 9) upper view of AMF 119243; ED98/218; 10, 11) lower and upper views respectively of AMF 119244; ED98/218; 12) upper view of AMF 119245; ED97/166; 14) upper view of AMF 119247; ED97/166.

Fig. 15-18 *Icriodus brevis* Stauffer 1940: 15) upper view of AMF 119248; ED97/166; 16, 17) upper and lower views respectively of AMF 119249; ED97/166; 18) upper view of AMF 119250; ED98/218.

PLATE 2

Fig. 1, 2, 6, 13, 16, 18, 19 x90; Fig. 3, 12, 14, 17 x105; Fig. 4, 5, 9, 11, 15 x75; Fig. 7, 10 x110; Fig. 8 x100.

Fig. 1, 2, 7 *Icriodus regularicrescens* Bultynck 1970: upper and lower views respectively of AMF 119251; ED98/196; 7) upper view of AMF 119256; ED97/166.

Fig. 3-6 *Icriodus arkonensis* Stauffer 1938: 3) upper view of AMF 119252; ED97/166; 4) upper view of AMF 119253; ED97/166; 5) upper view of AMF 119254; ED97/166; 6) upper view of AMF 119255; ED97/166.

Fig. 8 *Icriodus* sp. cf. *I. arkonensis* Stauffer 1938: upper view of AMF 119257; ED98/218.

Fig. 9` *Icriodus ?obliquimarginatus* Bischoff & Ziegler 1957: upper view of AMF 119258; ED97/166.

Fig. 10 *Icriodus expansus* Branson & Mehl 1938: upper view of AMF 119259; ED99/230.

Fig. 11 *Icriodus* sp.: upper view of fragment of AMF 119260; ED99/239.

Fig. 12 *Bispathodus spinulicostatus* (E.R. Branson 1934): upper view of AMF 119261; ED99/239.

Fig. 13-15 *Clydagnathus cavusformis* Rhodes, Austin & Druce 1969: upper views of AMF 119262, AMF119263, AMF 119264 respectively; all from ED99/239.

Fig. 16 *Bispathodus* sp. cf. *aculeatus plumulus* (Rhodes, Austin & Druce 1969): lateral view of AMF 119265; ED99/233.

Fig. 17, 18, 19 *Pseudopolygnathus primus* Branson & Mehl 1934: upper views of AMF 119266, AMF 119267 and AMF 119268, respectively; all from ED99/239.

PLATE 3

Fig.1, 3, 4 x140; Fig. 2, 8-10, 15 x90; Fig. 5, 11, 12 x75; Fig. 6 x100; Fig. 7 x165; Fig. 13 x 105; Fig. 14 x110.

Fig. 1, 2 *Clydagnathus gilwernensis* Rhodes, Austin & Druce 1969: upper views of AMF119269, AMF119270 respectively; 0/99.

Fig. 3-12 *Clydagnathus cavusformis* Rhodes, Austin & Druce 1969: 3) lateral view of AMF119271; ED98/198; 4) lower view of AMF 119272; ED98/198; 5) lateral view of AMF 119273; 0/99; 6) lower view of AMF 119274; 0/99; 7) upper view of AMF119275; 0/99; 8, 9) lower and upper views respectively of AMF119276; 0/99; 10) lower view of AMF 119277; 0/99; 11) lateral view of AMF 19278; 0/99; 12) upper view of AMF 119279; ED99/241.

Fig. 13, 15 *Pseudopolygnathus primus* Branson & Mehl 1934: 13) upper view of AMF119280; ED99/241; 15) upper view of AMF 119282; ED99/241.

Fig. 14 *Bispathodus aculeatus aculeatus* (Branson & Mehl 1934): upper view of AMF 119281; 99/95.

PLATE 4

Fig. 1 x105; Fig. 2, 13 x90; Fig. 3, 5 x200; Fig. 4 x230; Fig. 6 x150; Fig. 7, 8, 11, 14, 15 x75; Fig. 9, 10 x110; Fig. 12 x120.

Fig. 1 *Bispathodus aculeatus anteposicornis* (Scott 1961): lateral view of AMF 119283; 99/95.

Fig. 2 *Bispathodus* sp. cf. *aculeatus plumulus* (Rhodes, Austin & Druce): 1969): lateral view of AMF 119284; 99/95.

Fig. 3, 6 *Hindeodus cristulus* (Youngquist & Miller 1949) lateral views of AMF 119285 and AMF 119288 respectively; both from 0/99

Fig. 4, 5 *Bispathodus stabilis* (Branson & Mehl 1934): upper views of juvenile specimens AMF 119286 and AMF119287 respectively; 0/99.

Fig. 7, 8, 10-12, 14, 15 *Clydagnathus cavusformis* Rhodes, Austin & Druce 1969: 7, 8) lateral view of Pb elements AMF119289 and AMF 119290 respectively; both from 0/99; 10, 12) lateral views of Sb elements AMF 119292 and AMF 119294 respectively; 0/99; 11) lateral view of Sc element AMF 119293; 0/99; 14, 15) lateral views of AMG119296 and AMF 119297 respectively; 0/99.

Fig. 9, 13 *Mitrellataxis* sp. cf. *M. coronella* Chauff & Price 1980. 9) lateral view of C_1 element AMF119291, 0/99; 13) lateral view of C_p element and AMF 119295, 0/99.

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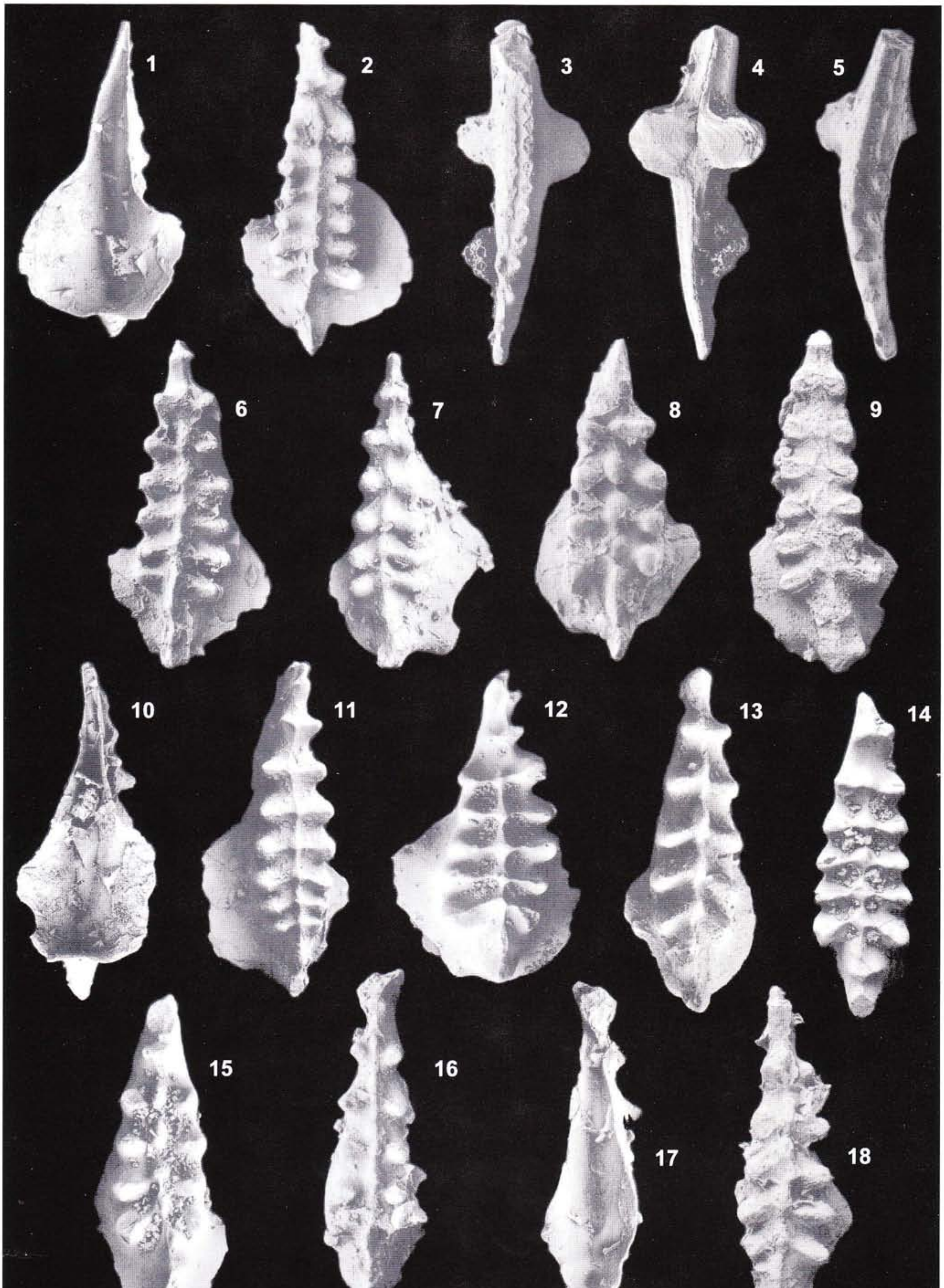
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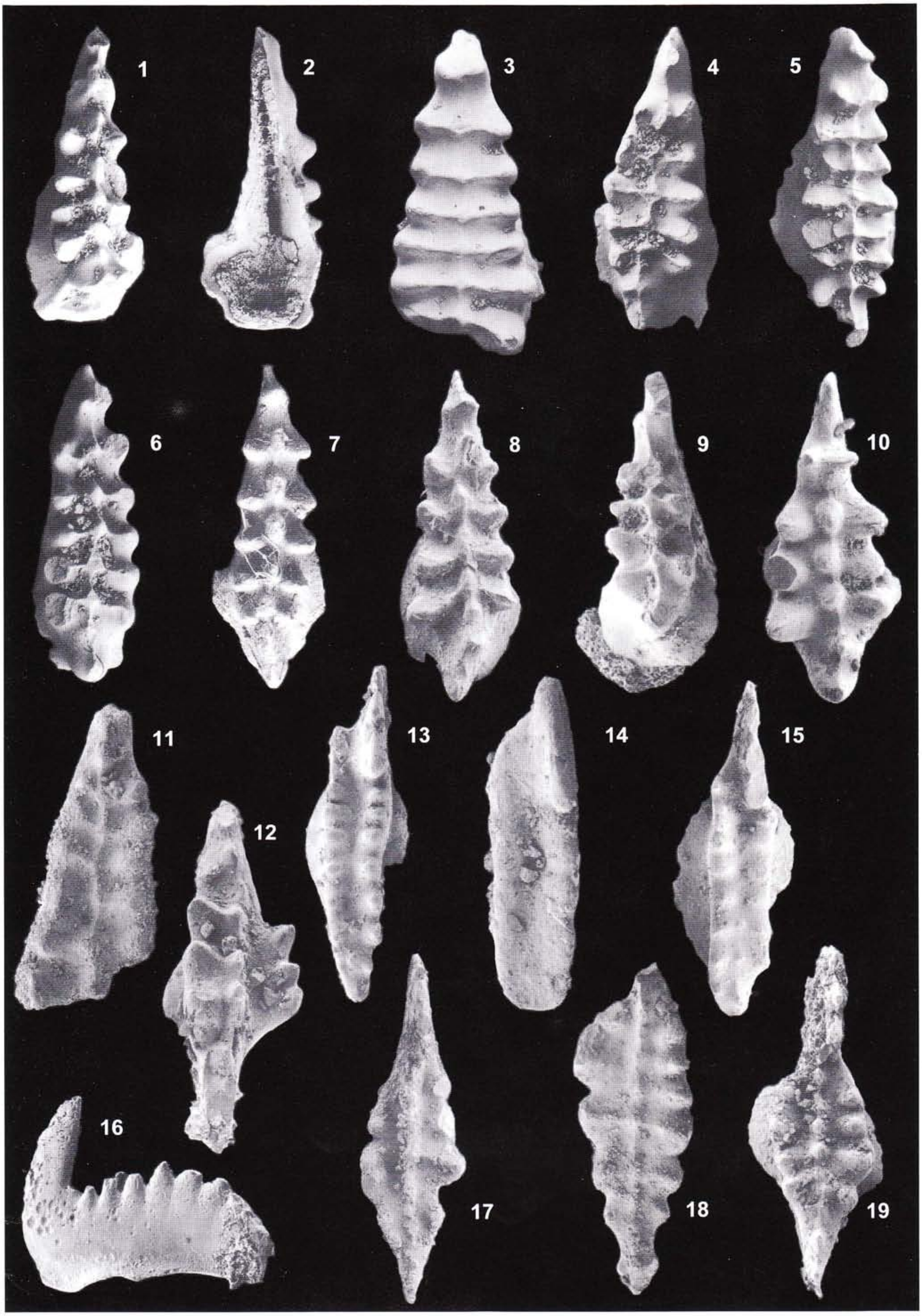
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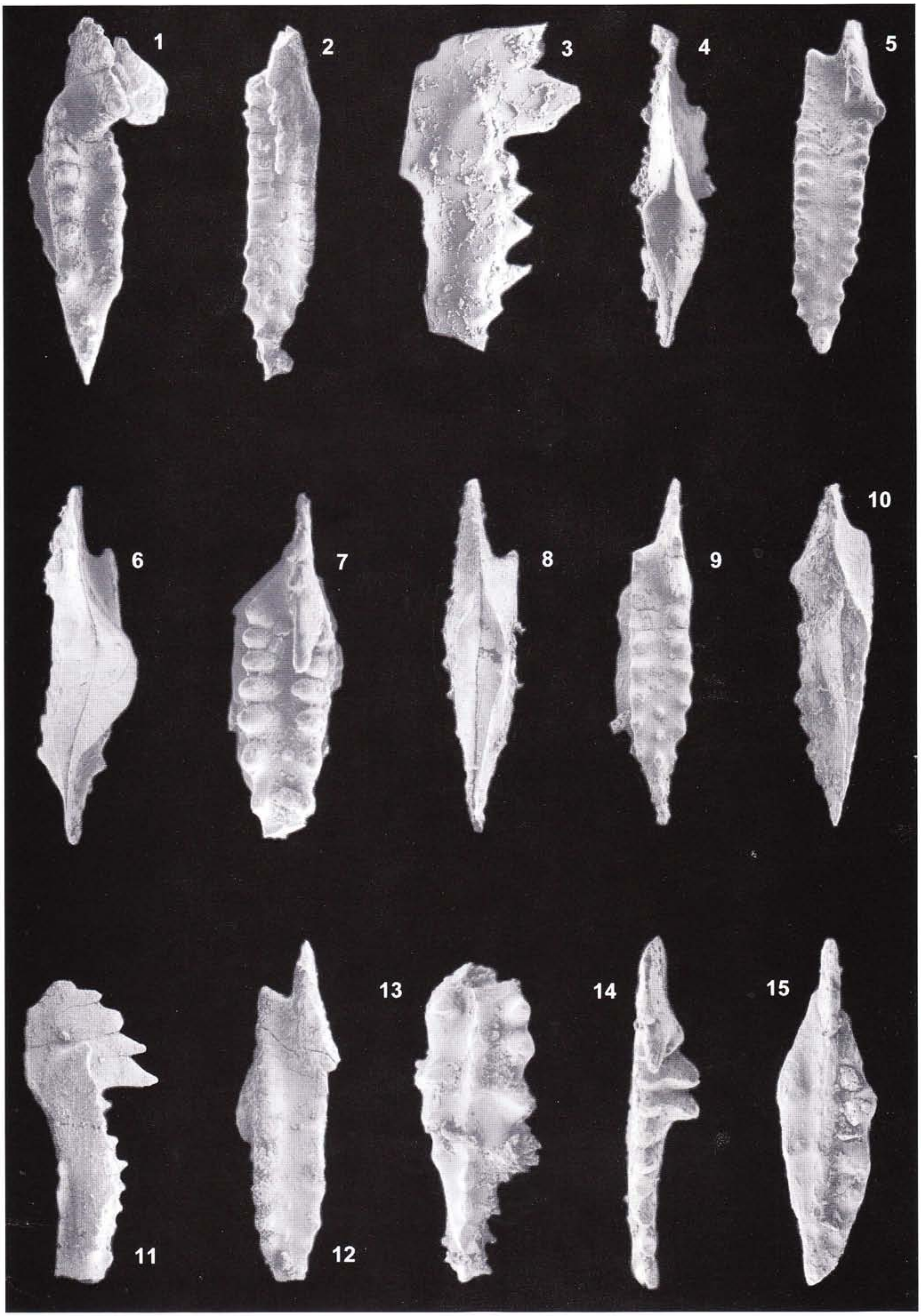
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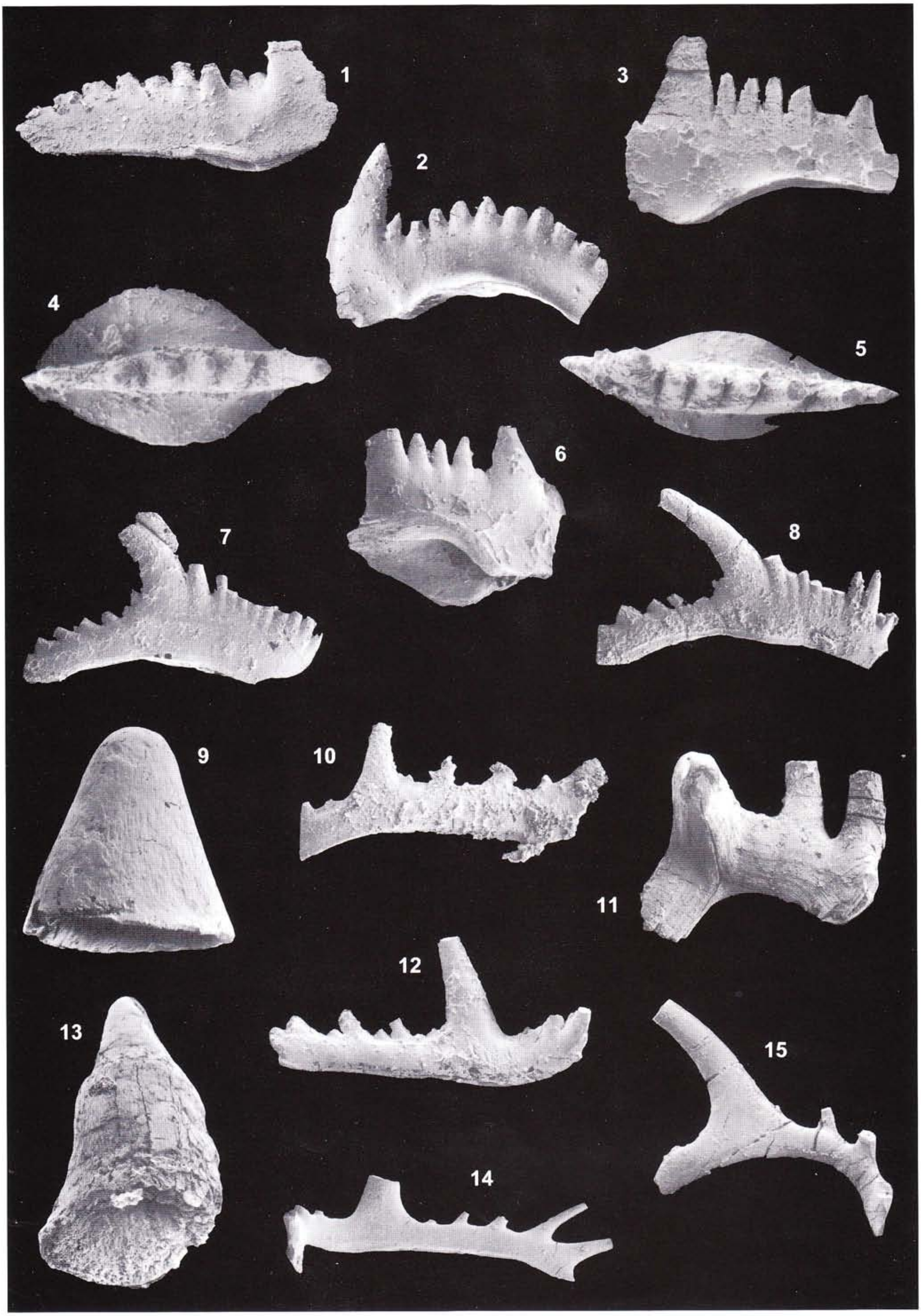
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and the *pre-expansa* Zone Famennian. Documentation of conodont data from these regions, preferably based on bed-by-bed sampling, is essential for improving understanding of, and more precise timing of, sedimentary events in the Himalayan region during the S1-S2 hiatus in the Pin valley.

Taxonomic notes

The conodont faunas from the Lipak Formation of the Pin Valley are sparse (392 specimens), of low diversity, and with a high percentage of abrasion/breakage - consistent with faunas from very shallow marine environments. Because most of the forms encountered in the study have been documented elsewhere, especially in the Catalogue of Conodonts (Ziegler ed. 1973-1991), they are not formally described but are recorded on the distribution table (Table 1), the best materials are illustrated - some, because of imperfections, without views that could be given had material been elegant - (Plates 1-4), and their chronologic importance discussed in the text. Because of the above limitations, taxonomic comment is confined only to species for which new data are available. Figured specimens are housed in the collections of the Australian Museum, Sydney (AMF). Locality data for each sample can be obtained by reference to the illustrations (Pl. 1-4) and distribution table (Tab. 1).

Family ?Protopanderodontidae Lindström, 1970

Genus *Mitrellataxis* Chauff & Price, 1980

Mitrellataxis sp. cf. **M. coronella** Chauff & Price, 1980

Pl. 4, fig. 9, 13

For synonymy of *Mitrellataxis coronella* see Chauff & Price (1980, p. 184).

Remarks. Elements of a species of *Mitrellataxis* are compared with *M. coronella* because of the similarity of the C_1 element to specimens illustrated by Chauff & Price (1980, pl. 3, fig., 6, 10, 24, 26). The C_p elements of the material from Lipak Formation (Lipak B) differ from those of the type species in being short, straight-sided cones without an apparent waist-like constriction rather than being crown-like cones with such a constriction between the basal cavity and the upper surface - compare Chauff & Price (1980, pl. 3, fig. 1-5) with Pl. 4, fig. 9 herein).

The Late Devonian (*postera-expansa zone*) specimens of *M. coronella* from the Maple Mill Shale, SE Iowa, and the Sulphur Springs Formation in east-central Missouri and those from the Carboniferous (no younger than *sandbergi* or late Early *crenulata* Zone) in the Lipak Formation (Lipak B), bear faint striations radiating from the cusp of the cone; the striations are especially evident in C_1 elements of the Spiti material.

Possibly because elements of *Mitrellataxis* closely resemble fish remains, very little has been published about their age and distribution. Most reports are from the USA - Iowa, Missouri and Illinois (Chauff & Dombrowski 1977, Chauff & Price 1980), Utah and Colorado (Sandberg 1976) - and all are from Late Devonian horizons. The Carboniferous specimens from the Lipak Formation, Spiti, therefore appreciably extend the range of the genus.

Family Anchignathodontidae Clark, 1972

Genus *Hindeodus* Rexroad & Furnish, 1964

Hindeodus cristulus (Youngquist & Miller, 1949)

Pl. 4, fig. 3, 6

Hindeodus cristulus (Youngquist & Miller, 1949) - Ziegler (1977, pp. 209-214, Hindeodus pl. 1, fig. 1-6).
Anchignathodus cristulus (Youngquist & Miller 1949) - Nicoll & Druce (1979, p. 20-21, pl. 5, fig. 7-12).
Hindeodus cristulus Youngquist & Miller, 1949 - Ni (1984, p. 282, pl. 45, fig. 4).

Remarks. Pa elements herein identified as *Hindeodus cristulus* have a large, prominent anterior denticle, an arched lower margin with the posterior margin downturned, and a large, cup-like basal cavity extending to, or almost to, the posterior margin.

Although Sweet (in Ziegler 1977, 1988) suggests that the first illustrated appearance of *H. cristulus* is from the St Louis Limestone of Kansas (Mississippian, Meramecian = early Visean), Nicoll & Druce (1979, fig. 12) report H. cristulus from close to the base of the Laurel Formation, late in their "*Clydagnathus gilwernensis* Assemblage Zone", an interval suggested by them to be probably late in the early Tournaisian 1b. This horizon could be as old as *sulcata* Zone, but there is better chronologic control for a specific section (their WCB 012) where *H. cristulus* occurs *inter alia* with *Siphonodella* cf. *S. cooperi hassi* (= *S. isosticha*) and the long-ranging *Clydognathus gilwernensis* and *Cly. cavusformis.* Constrained by the overlap of *S. isosticha* and *Cly. gilwernensis*, this latter horizon is *Early crenulata* Zone. H. sp. cf. *H. cristulus* has been reported from the Bonaparte Gulf Basin of NW Australia (Druce 1969) where it first appears in horizons said to be low in the *sulcata* Zone (based on two specimens referred to *Siphonodella sulcata*), and extends through to horizons thought to be just above the base of the *typicus Zone*. We reject, however, the identification of *S. sulcata* and, with it the inference that forms of *Hindeodus* resembling *H. cristulus* occur early in the Tournaisian in that region.

Rhodes et al. (1969) recorded specimens of *H. cristulus* with, inter alią, *Ps. primus*, in their "Z Zone" in the Avon Gorge Limestone in the Bristol area of the United Kingdom. Although they figured specimens from higher in their sections, Rhodes et al. (1969, p.

228) commented that the first occurrence of *H. cristulus* in the Avonian of the Bristol area is "considerably older than that known in other parts of the world".

In Europe, unequivocal *H. cristulus* appears close to the base of the Visean (*texanus* Zone), but *H.*? cf. *cristulus* is reported from England as appearing low in the *typicus Zone* (Varker & Sevastopoulo, 1985, p. 180); *H. cristulus* or forms close to it appear not to have been encountered in earlier horizons. In the Yangtze Gorge area of China, *H. cristulus* has been reported from late in the Tournaisian (*typicus or anchoralis-latus* zones) and a more denticulate form, *H. paracristulus* Ni, from the texanus Zone early in the Visean (Ni 1984, pp. 55, 282-283)

In summary, forms referable to *H. cristulus* (or close to it) occur in horizons as old as the Early *crenulata* Zone, becoming more widespread in the late Tournaisian.

Family Cavusgnathidae Austin & Rhodes, 1981

Genus *Clydagnathus* Rhodes, Austin & Druce, 1969

Clydagnathus cavusformis Rhodes, Austin & Druce, 1969

Pl. 4, fig. 7, 8, 10-12, 14, 15

For basic synonymy see Nicoll & Druce (1979, p. 22-23).

Remarks. Attention is drawn to the synonymy and the discussion given by Nicoll & Druce (1979, p. 22-23) especially in relation to the suppression of *Cly. unicornis*. It should also be noted that although *Cly. unicornis* was erected on the basis of having a "restricted anterior lateral blade, consisting essentially of one large denticle" (Rhodes et al. 1969, p. 88), the illustration of a specimen designated as a paratype of *Cly. unicornis* (Rhodes et al. 1969, pl. 2, fig. 3b, 3c) bears a very strong resemblance to that of the inner lateral view of the holotype of *Cly. cavusformis* (Rhodes et al. 1969, pl. 1, fig. 11b). The face of the lateral blade of both appears to have at least 3 small denticles in front of the main denticle. It appears, therefore, that the suppression of *Cly. unicornis* is justified. The range of *Cly. cavusformis* is therefore extended to incorporate the *Late crenulata* Zone.

Conclusions

Sedimentary structures, lithofacies, sequence stratigraphy and conodont faunas indicate a generally shallow marine depositional environment for the Lipak Formation in the Pin Valley. Lithologic correlation with sections in upper Lahaul indicates that the formation in the Pin Valley has been truncated just below its characteristic gypsum horizon.

Five sequence-stratigraphic units have been distinguished, most of them showing transgressive systems tracts starting with sharply-based sandstone beds grading into variable shallow marine carbonates of the highstand systems tracts. Because of the shallow marine environment, lowstand sediments are not preserved.

Conodont faunas date the first sequence (S1, lowest 33 m of the Lipak Formation, i.e. Lipak A) as mid to late Early *varcus* Subzone characterised by species of *Icriodus* and *Bipennatus*. A previously unrecognised hiatus between sequences S1 and S2 represents the interval Middle *varcus* Subzone (Givetian) to at least the end of the Early *expansa* Zone (Famennian); sequences S2 to S5 of the Lipak Formation above this hiatus refer informally to Lipak B. At 75 m above the base of the composite section, a 58 cm black to dark grey shale interval within late Famennian fossiliferous limestones conceivably correlates with the Hangenberg Event (end-Middle *praesulcata* Zone).

Younger conodont faunas of the Lipak Formation - dominated by species of *Clydagnathus* with species of *Bispathodus* and *Pseudopolygnathus* also represented - is shown to extend to as young as the mid-Tournaisian Early *crenulata* Zone.

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