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THE DEVONIAN-CARBONIFEROUS BOUNDARY : COMPARISON BETWEEN THE DINANT SYNCLINORIUM AND THE NORTHERN BORDER OF THE RHENISH SLATE MOUNTAINS

A sequence-stratigraphic view

by

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(9 figures)

ABSTRACT.- A comparison of the Devonian-Carboniferous transitional interval at the northern border of the Rhenish Slate Mountains with that in the Belgian Dinant Synclinorium shows how the different litho- and biostratigraphic patterns in both areas can be related to the same relative sea-level fall.

A biostratigraphic hiatus near the Devonian-Carboniferous (*praesulcata-sulcata* conodont) boundary has been associated with a basinward shift of the lithofacies in the mixed carbonate-siliciclastic ramp setting of the Belgian Dinant Synclinorium. The facies shift resulted from a relative sea-level fall at the end of the Devonian. In the neighbouring northern border of the Rhenish Slate Mountains, where the slopes of Devonian reef complexes are exposed, the Devonian-Carboniferous boundary is obliterated in a different way. In such settings either condensed sections occur, or the upper part of the deep-water *praesulcata* range is truncated by shallow-water strata carrying a different conodont biofacies. This paper suggests that the relative sea-level fall recorded in the Dinant Synclinorium is also responsible for the incision of shoal and slope areas (Seiler Channel) and for the subsequent lowstand fill (Seiler Conglomerate, Hangenberg Shale and Sandstone, Stockum Sandstone), in the Rhenish Slate Mountains. These lowstand deposits are devoid of the deep-water conodonts that currently define the D/C boundary. A deeper-water fauna, consisting of Carboniferous assemblages, was re-established only after a further relative sea-level rise (Hangenberg Limestone and Liegende Alaunshiefer), and now provides good biostratigraphic control.

Understanding the litho- and biostratigraphic response to different rates of relative sea-level change may help to refine lateral correlations within D/C boundary intervals of non-conclusive biostratigraphic control, both within and between different basins.

1.- INTRODUCTION

Sequence stratigraphy (Vail *et al.*, 1977; Posamentier & Vail, 1989; Posamentier *et al.*, 1989; Van Wagoner *et al.*, 1987, 1989, Vail *et al.*, 1991) is based on an interdisciplinary approach and provides a framework that allows a subdivision of transgressive-regressive cycles in the rock record into sequences, and into systems tracts that are genetically related to a particular rate of relative (combined eustacy and subsidence) sea-level rise or fall. Such a framework can explain why non-sequences and marked changes in facies sometimes resulted in incomplete or non-conclusive biostratigraphic control, as is the case around the time of the boundary between the Devonian and Carboniferous systems (*praesulcata-sulcata*

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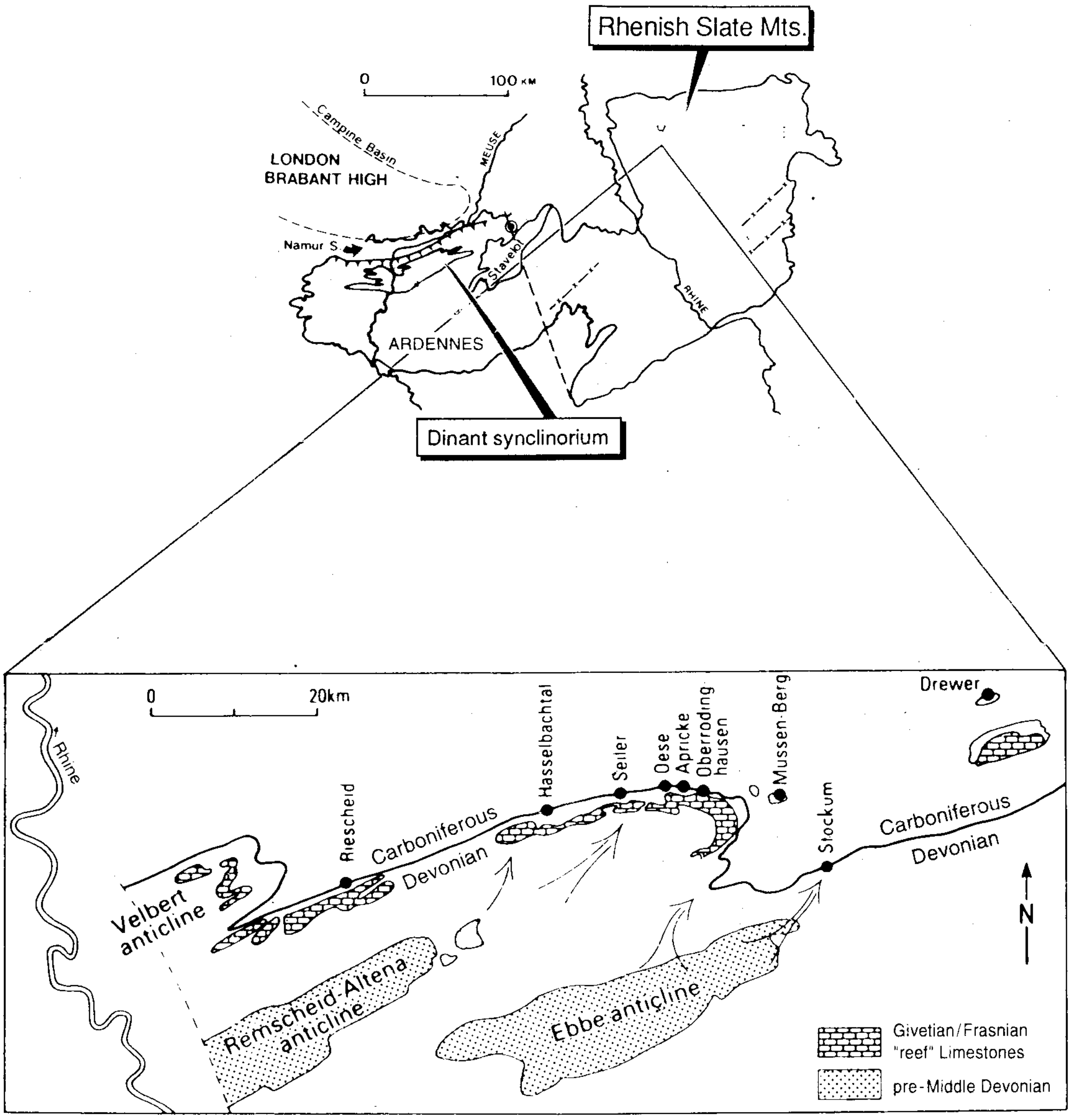


Fig. 1.- Location of Rhenish Slate Mountains (Germany) relative to the Dinant Synclinorium (Belgium). The northern part of the Rhenish Slate Mountains contains a discontinuous belt of submarine 'shoals' formed by Givetian-Frasnian reef masses. The Devonian-Carboniferous boundary outcrops on the northern flank of these shoals. Arrows indicate suggested transport directions of siliciclastic influx during the latest Devonian. (After Becker *et al.*, 1984, slightly modified.)

boundary, Lane *et al.*, 1980). In such intervals a sequence-stratigraphic approach may enable significant refinement of lateral correlations within and between basins.

In this paper, a brief comparison is made of the Devonian-Carboniferous (D/C) transition in the Dinant Synclinorium (Van Steenwinkel, 1988, 1990, in press) with that of the neighbouring northern border of the Rhenish Slate Mountains (Fig. 1). A sequence-stratigraphic framework for that part of the Rhenish Slate Mountains, based on biostratigraphic and sedimentological data from previous literature, is suggested to stimulate new views on the D/C boundary problem.

Both the Dinant Synclinorium and the Rhenish Slate Mountains were palaeogeographically part of the Cornwall-Rhenish Basin, which was characterised by back-arc extension and rapid subsidence during the Late Devonian and earliest Carboniferous (Leeder, 1987). The Dinant Synclinorium was situated at the northern margin of the Cornwall-Rhenish Basin. Missing conodont zones in this area and the sudden faunal change from a Devonian to a Carboniferous 'style' of fossils have led to a sequence-stratigraphic analysis of the D/C transition (Van Steenwinkel, 1988, 1990, in press). This approach was based on sedimentary facies analyses and combined with the biostratigraphic data known from previous studies.

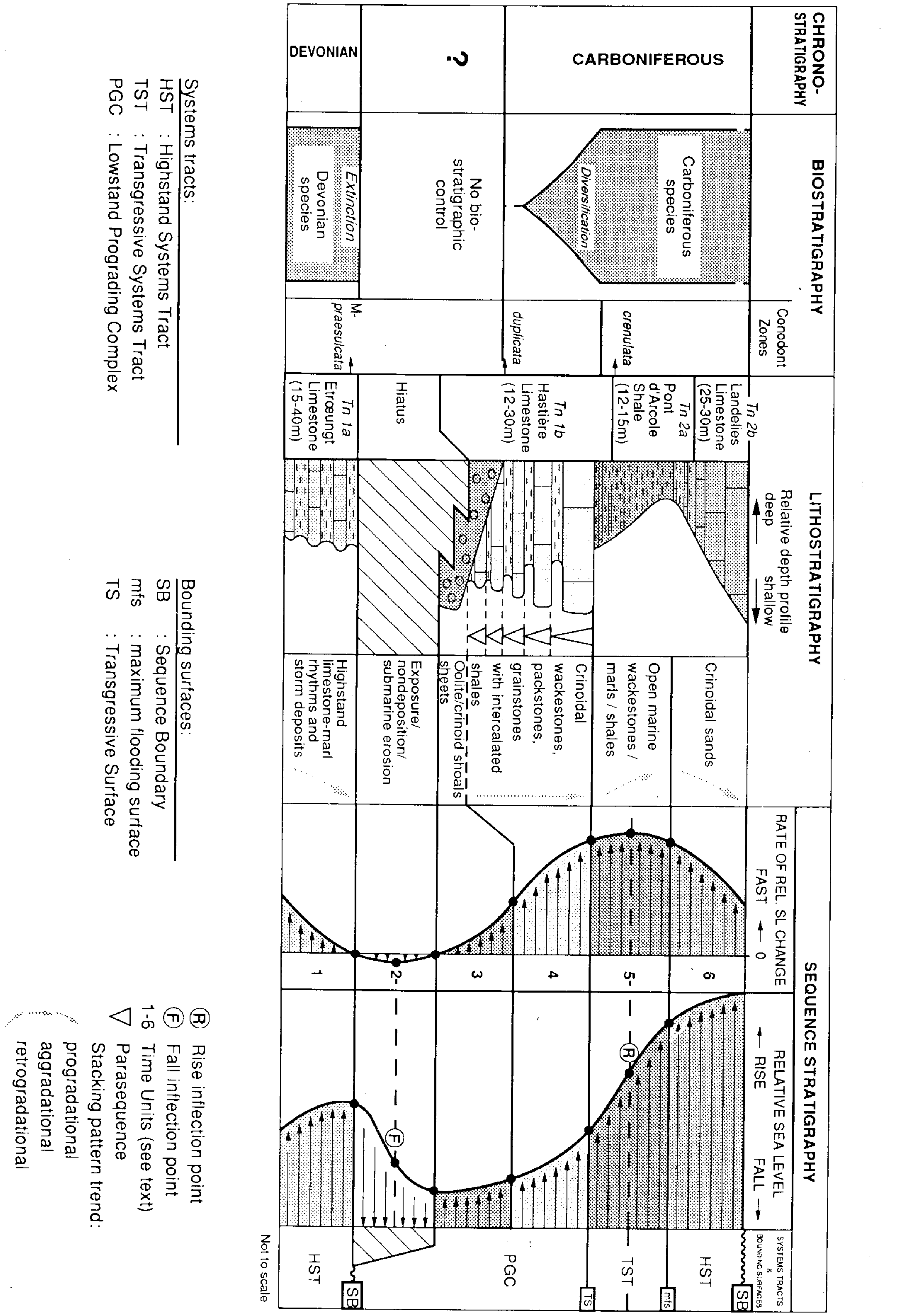


Fig. 2.- Summary of chrono-, bio- and lithostratigraphy in a sequence-stratigraphic framework for the Devonian-Carboniferous boundary in the Dinant Synclinorium. The biostratigraphic hiatus between the Devonian and the Carboniferous and the corresponding downward facies shift are interpreted as consequences of a relative sea-level fall at the end of the Devonian. (After Van Steenwinkel, in press).

The Rhenish Slate Mountains form the eastern basinward extent of the Dinant area (e.g. Franke *et al.*, 1975; Paproth, 1986). The first definition of the D/C boundary was established here (Jongmans & Gothan, 1937) at the first appearance of the goniatite *Gattendorfia subinvoluta*. This area contains a discontinuous belt of submarine 'shoals' formed by Givetian-Frasnian reef masses, such as in the Remscheid-Altena anticline (Paproth, 1986; Fig. 1). A succession of Famennian stages occurs on the northern flank of these shoals, with the Wocklumerian stage uppermost. On top of the Wocklum Limestone (Middle-*praesulcata* Zone) incision has occurred, represented by the 'Seiler Channel'. This incision event and the associated facies and biostratigraphy are compared with the facies succession and biostratigraphic succession in the Dinant Synclinorium.

THE DINANT SYNCLINORIUM

1.- BIOSTRATIGRAPHY

As shown by numerous authors (e.g. Bouckaert & Groessens, 1976; Conil, 1968; Conil *et al.*, 1964; Poty, 1984, 1986; Sandberg *et al.*, 1978; Sandberg & Ziegler, 1979; Streel, 1971, 1983; Van Steenwinkel, 1984a, in press), the D/C biostratigraphic evolution in the Dinant Synclinorium is incomplete. Many Devonian fossils become extinct at the top of the Etroeungt Limestone (Middle-*praesulcata* Zone; e.g. Schindewolf, 1928; Brauckmann & Hahn, 1984; Price & House, 1984). Typical Devonian conodont species (e.g. *Pelekysgnathus* sp., *Bispathodus costatus* and *Protognathodus kockeli*), occur no higher than the basal bed of the overlying Hastière Limestone. Carboniferous species (*Siphonodella duplicata*, *S. quadruplicata*, S, *cooperi* and *Patrognathus variabilis*) are recorded higher in the Hastière Limestone and show an upwardly increasing diversification (Van Steenwinkel, in press). The Devonian Middle-*praesulcata* Zone, the Carboniferous *sulcata* and possibly part of the *duplicata* Zones are missing. Consequently, the Devonian-Carboniferous (*praesulcata-sulcata*) boundary cannot be precisely established. It corresponds to an unidentified level in the lower ('problematic') part of the Hastière Limestone, between 'known Devonian' and 'known Carboniferous' (Fig, 2).

2.- LITHOSTRATIGRAPHY

From the succession of sedimentary facies, relative depth trends have been deduced for different palaeogeographical positions (Van Steenwinkel, 1988, in press). The facies analysis was based on sedimentary structures from the outcrops, rock slabs and acetate peels, combined with petrographic and faunal analyses from more than 700 thin sections. It has led to the distinction of larger and smaller deepening events and of stacking pattern trends (progradational, aggradational, retrogradational) of genetically related rock packages, summarised (Fig. 2) as follows. The Etroeungt Limestone - and the laterally equivalent Comblain-au-Pont Formation (Tn 1a) are characterised by open-marine, lower-ramp limestone-marl rhythms and storm deposits over most of the Dinant Synclinorium. They show a slightly progradational pattern towards the top. The boundary between the Etroeungt/ Comblain-au-Pont Formations and the overlying Hastière Limestone (Tn 1b) is an abrupt, lithoclastic contact with much shallower, upper-ramp facies above. The top of the Hastière Limestone shows evidence of subaerial exposure in the inner ramp areas (e.g. pending cements and leached cement zones, as seen under cathodoluminescence). The Hastière Limestone (Tn 1bα) contains oolite and grapestones at the base. The main part of this formation consists of small-scale shallowing-upward cycles (parasequences) of crinoidal wackestones to grainstones, stacked in an aggradational to progradational way. The marine flooding events, corresponding to the parasequence bounding surfaces, are used for lateral correlation beyond the scale of biostratigraphic resolution. This formation is laterally differentiated at its base, where locally oolitic and crinoidal shoals occur, but becomes progressively more uniform upwards. The upper part of the Hastière Limestone (Tn 1bγ) is characterised by a sudden deepening, followed by increasingly deeper-water facies into the open-marine Pont d'Arcole Shale, indicating retrogradation. Overlying the deepest interval in the Pont d'Arcole Shale, there is a shallowing-upward facies sequence, culminating in the Landelies Limestone.

3.- SEQUENCE STRATIGRAPHY

The fact that marine flooding surfaces and stacking pattern trends can be recognised regardless of the palaeogeographic setting (i.e. with facies variations down the depositional slope) points to relative sea-level changes as the common factor controlling these surfaces and trends. This is independent of local differences in the sedimentation or subsidence rates. A sequence-stratigraphic interpretation of the D/C boundary in the Dinant Synclinorium, based on the integration of sedimentological and biostratigraphic data (Van Steenwinkel, 1988, 1990), is summarised as follows (Figs 2 and 3). The D/C interval - from the Etroeungt to the Landelies Limestone - is believed to be the sedimentary response to six time intervals,

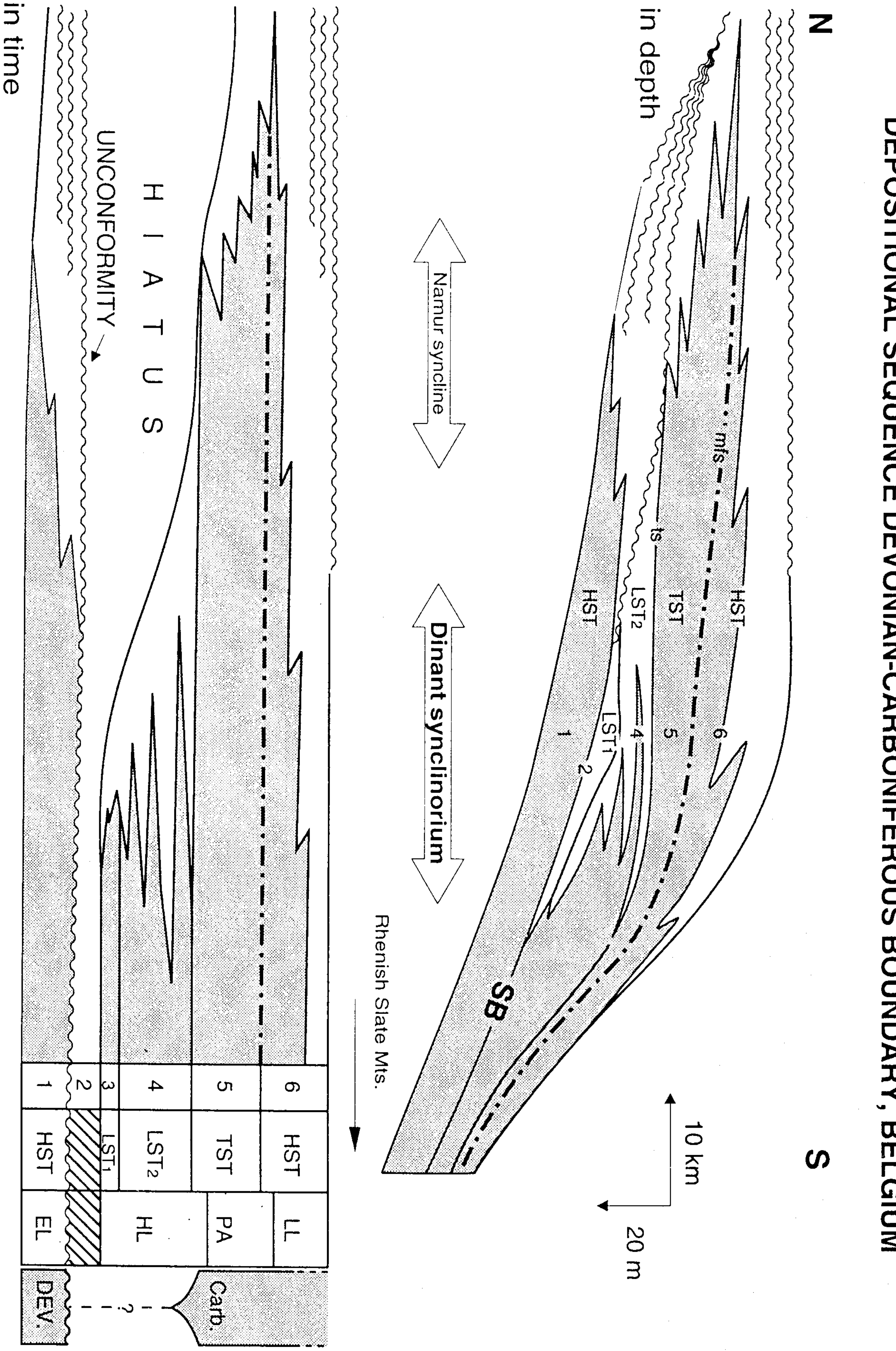
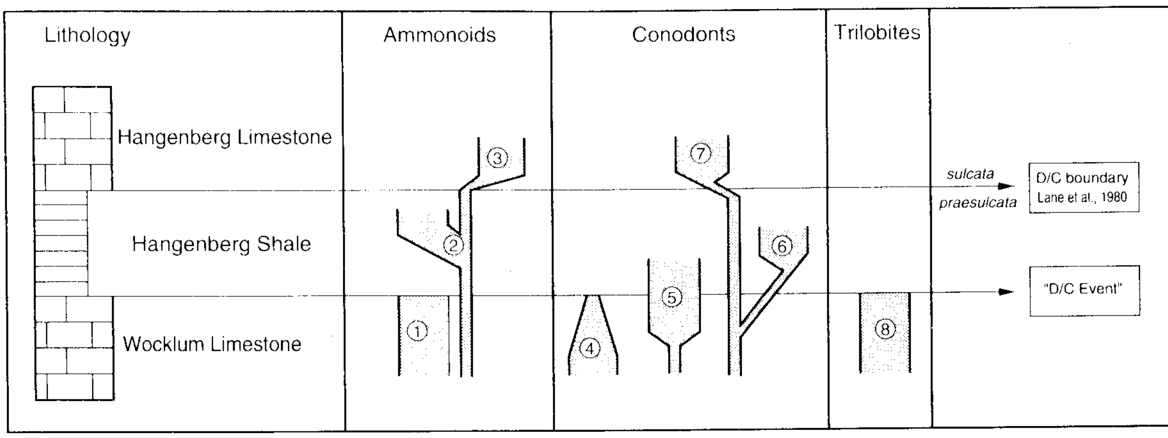


Fig. 3.- Depositional sequence of the Belgian Devonian-Carboniferous boundary. Light stipples = upper-ramp, above-wave-base facies; dense stipples = lower-ramp, below-wave base facies. Symbols: see fig. 2: LST1-2 = Lowstand Prograding Complex. (After Van Steenwinkel, in press).



① *Wocklumeria sphaeroides* : Sudden extinction at top of Wockium Limestone
② *Imitoceras* : Survival and subsequent radiation in Hangenberg Shale
③ *Gattendorfia subinvoluta* : First appearance at base of Hangenberg Limestone
④ *Palmatolepis* : Extinction after gradual reduction
⑤ *Bispathodus* : Survival without disturbance
⑥ *Protognathodus* : Radiation soon after the crisis, within Hangenberg Shale
⑦ *Siphonodella* : Radiation within Hangenberg Limestone
⑧ *Phacopida* : Extinction

Fig. 4.- Outline of faunal changes near the Devonian-Carboniferous (D/C) boundary in the Rhenish Slate Mountains, showing 'the D/C event', associated with the extinction of many fossil groups and with the rapid diversification of the groups that survuved the crisis (based on Walliser, 1984). Note that the position of the *praesulcata-sulcata* boundary, chosen as the D/C boundary (Lane *et al.,* 1980), is at a higher level than this event, but still prior to the zone of faunal re-establishment.

which are associated with different rates of relative sea-level change. The late-Devonian highstand sedimentation (Etroeungt Limestone; Time Unit 1), with its large, open-marine faunal diversity, was brought to a halt as a consequence of a relative sea-level fall (Time Unit 2). This resulted in a period of nondeposition in this area, as evidenced by the combination of the biostratigraphic hiatus, local subaerial exposure, and the abrupt shift to shallow -water facies with an erosional, lithoclastic base. After this hiatal period, sedimentation resumed but in a much shallower, lowstand prograding-complex setting (Hastière Limestone, Time Units 3 to 4), almost devoid of the deep-water conodonts that currently define the D/C boundary. Only after increased deepening during the subsequent transgressive systems tract (top Hastière Limestone, Pont d'Arcole Shale; Time Unit 5) was a deeper-water fauna with more evolved Carboniferous species re-established and able to provide good biostratigraphic control. This unit of maximum flooding is finally overlain by a progradational one that culminated in the shallow-water, crinoidal limestones of the Landelies Limestone (Time Unit 6).

THE RHENISH SLATE MOUNTAINS

1.- BIOSTRATIGRAPHY

Biostratigraphic correlations of the D/C transition have been extensively studied over the years (e.g. Becker *et al.*, 1984; Bless & Groos-Uffenorde, 1984; Brauckmann & Hahn, 1984; Higgs & Streel., 1984; Keupp & Kompa, 1984; Paproth & Streel, 1971, 1984; Paproth & Sevastopulo, 1989; Price & House, 1984; Ziegler & Sandberg, 1984). In the Rhenish Slate Mountains the uppermost Devonian is characterised by the interruption of the pelagic siphonodellid conodont biofacies, which is replaced by a more nearshore *Protognathodus* biofacies (Ziegler & Leuteritz, 1970; Alberti *et al.*, 1974). These faunal changes, associated with profound lithological changes elsewhere in Europe, are thought to be the result of some kind of 'D/C event' (Fig. 4), characterised by the extinction of many fossil groups and with a subsequent rapid diversification of others that survived the event (Walliser, 1984). Besides on conodonts, this event also had a strong influence on ammonoids, trilobites, ostracods, echinoderms, foraminifera and

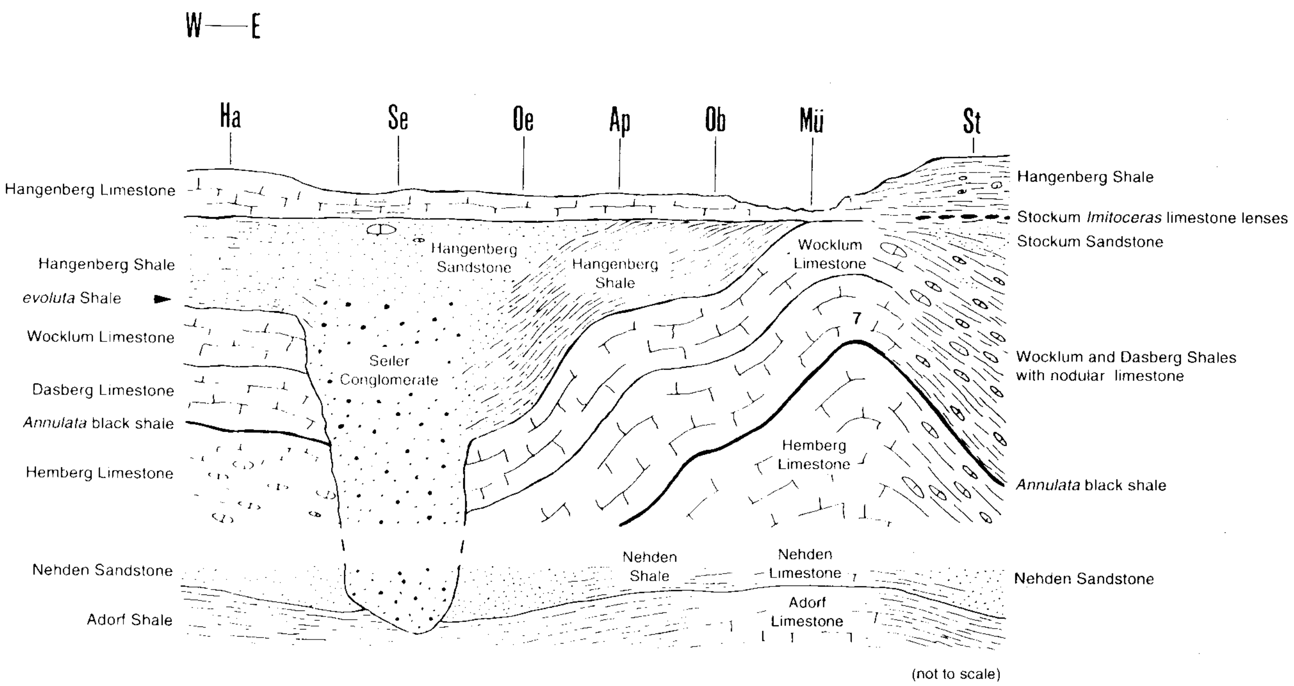


Fig. 5.- Outline (not to scale) of upper Famennian and lower Tournaisian lithologies between Hasselbachtal and Stockum (after Paproth, 1986, Fig. 6; Higgs & Streel, 1984 and Schmidt, 1936). Localities see Fig. 1. Ha: Hasselbachtal; Se: Seiler; Oe: Oese; Ap: Apricke; Ob: Oberrödinghausen; Mü: Müssenberg; St: Stockum.

corals. It coincides with the occurrence of the goniatite *Cymaclymenia evoluta* (Higgs & Streel, 1984). The position of the *praesulcata-sulcata* boundary, immediately preceding the entry of *Gattendorfia* at the base of the Hangenberg Limestone, is at a higher level than this D/C event but not yet in the zone of faunal re-establishment. This implies that the event of faunal crisis may lie within the latest Devonian.

2.- LITHOSTRATIGRAPHY

The Wocklum Limestone

The Wocklum Limestone (Fig. 5) is a widespread, irregularly bedded to semi-nodular and nodular limestone, composed of calcareous ooze with intercalated calcareous shales. This formation, up to a few metres thick, contains a diverse open-marine fauna, consisting of three (sub-) zones of clymeniids (Schindewolf, 1937), and of goniatites, trilobites (Richter & Richter, 1926, 1951; Brauckmann & Hahn, 1984), foraminifera and conodonts. Upper *expansa*, Lower- and Middle-*praesulcata* Zones are recorded in this formation (Ziegler & Sandberg, 1984). Spores indicate the occurrence of the LE Zone at Hasselbachtal, 50 cm below the top of the Wocklum Limestone (Higgs & Streel, 1984, p. 161), which is covered by the *evoluta* black shales. It is not clear yet in how far the top of the Wocklum Limestone is isochronous (LE-Zone).

The '*evoluta* Shale'

Immediately on top of the Wocklum Limestone lie 25-30 cm of black alum shales with abundant flattened specimens of *Cymaclymenia evoluta*. This '*evoluta* Shale' is a condensed unit, created by sediment starvation. This interval has often been described as the basal part of the Hangenberg Shales. It is not entirely clear whether this *evoluta* Shale is local, or whether it corresponds to a worldwide event. Walliser (1984) associates it with the 'global event' (Fig. 4) neat the Devonian-Carboniferous boundary, because this time interval is characterised by the extinction of many fossil groups (including ammonoids, Price & House, 1984).

The Seiler Channel incision

The Wocklum Limestone - and possibly also the *evoluta* Shale - has been incised by the 'Seiler channel' (Fig. 5). This channel is thought to run roughly from south to north (Fig. 6) and has been observed over a distance of approximately 4 km in west-eastern direction (Schmidt, 1936; Heinke, 1978). The incision is thought to have occurred after the deposition either of the Wocklum Limestone, or of the *evoluta* Shale, and correponds to the LE or/and LN Zones (LE-LN Zones, Streel, pers. com.). It cuts into the LE and LL Zones and locally even into much older sediments, like the lower Famennian Nehdener Plattensandstein. The channel is filled, in a later stage, with the Seiler conglomerate.

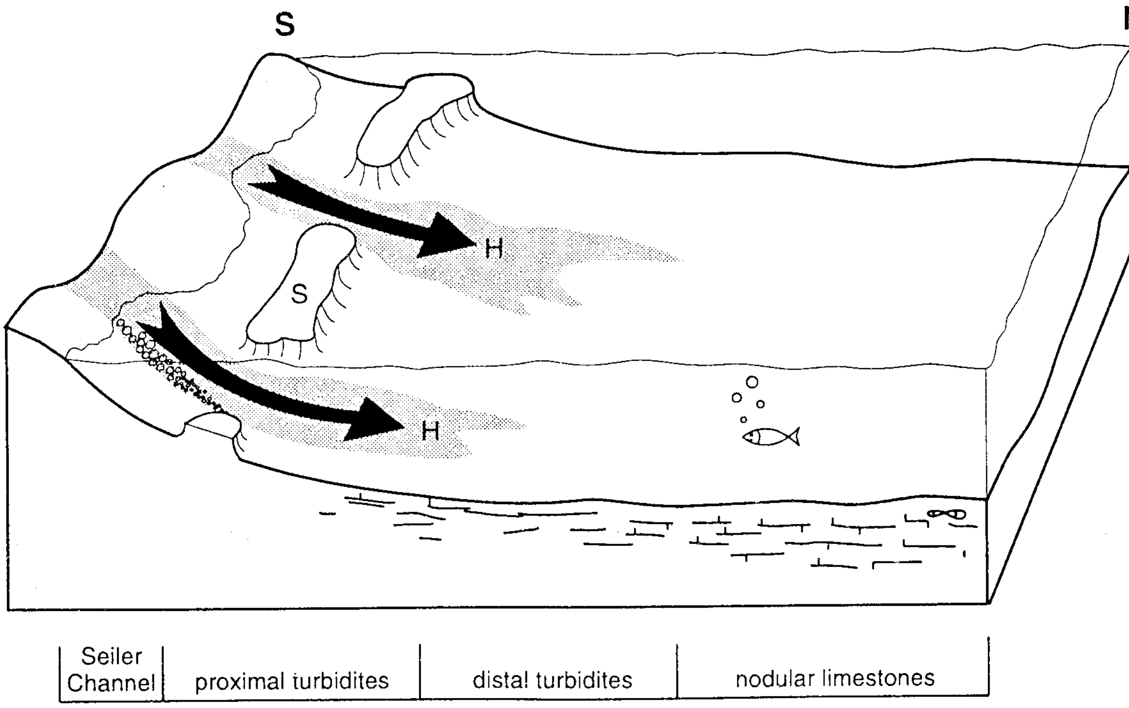


Fig. 6.- Interpretation (after Paproth, 1986) of the youngest Devonian facies distribution in the Rhenish Slate Mountains. H: Hangenberg Sandstone; S: Shoal formed by Givetian-Frasnian reef complexes.

The 'Seiler Conglomerate'

This conglomerate, known over a thickness of 95 m (Koch *et al.*, , 1970. Keupp & Kompa, 1984), consists of quartz- and limestone pebbles, carbonate ooids, and mica-bearing, carbonaceous sandstones, siltstones and mudstones. It contains spores of the LE-LN Zones. In 1984, Higgs & Streel had suggested that the abundance of spores in the Seiler Conglomerate was related to downslope mass movement. The Remscheid-Altena shoal (Fig. 1) is believed to be the source area. Some ostracod and conodont faunas described from the Seiler Conglomerate might well be reworked, which was also documented by Streel (1971).

The Hangenberg Shales and Sandstone

The Hangenberg Shales were deposited in the basin and onto the slopes. They are documented all around the Rhenish Massif, being absent at the top of highs (Müssenberg; Fig. 5). They are between 6 and 15 m thick, or even more when containing more sand. The Hangenberg Shales are generally regarded as widespread background sedimentation. However, the variety of facies in this formation and the locally high silt and sand contents suggest that maybe not all of it is background sedimentation. Black, relatively condensed shale units, absent of spores (Higgs & Streel, 1984. Paproth & Streel, 1971), such as occur in Drewer and Stockum, or at the top of the Hangenberg Shale formation (uppermost meter), probably do represent background sedimentation (LE-LN age, Streel, pers. com.). However, very often the Hangenberg Shales are very silty or sandy and show flat lamination and current ripples (Van Steenwinkel, 1984b) characteristic of distal turbidites. They are mostly very rich in miospores (Higgs & Streel, 1984). A shallow-water *Protognathodus* conodont fauna (Ziegler, 1971) has been recorded in this formation.

In some areas (e.g. Oese) sandstones predominate. They have been described (Keupp & Kompa, 1984) as being particularly rich in light-coloured mica. Some quartzite and chert pebbles are present as well. Sedimentary structures include channelling, cross bedding, ripple-cross bedding, flaser bedding and flat lamination. Mud clasts may occur at the base of beds. Plant fragments are common and miospores are rare (LN Zone, Higgs & Streel, 1984). This unit has been interpreted by Keupp & Kompa (1984) and Higgs & Streel (1984) to represent 'the finer-grained, lateral equivalent of the Seiler Conglomerate, and is presumably in immediate contact with it' (Fig. 6).

The Hangenberg Shales and Sandstone are here interpreted as follows. The sudden predominance of clastic material (clay, silt and fine-grained sand) in the Hangenberg Shales, the flat lamination with current ripples, the influx of abundant miospores, the absence of the diverse, basinal Devonian fauna that characterised the underlying Wocklum Limestone, and the replacement of deep-water conodonts by a more shallow-water *Protognathodus* fauna suggest that the Hangenberg Shale may be composed of distal turbidites and hemipelagic shales. The Hangenberg Sandstone, with its cross bedding, ripple-cross bedding, flaser bedding, flat lamination and mud clasts, may represent proximal turbidites or turbidite overbank deposits that built up as channel- bounding levees or channel-attached lobes. The presence of turbiditic channels - and their associated levees - would certainly be expected on the slope after canyon incision (see below). The Hangenberg Sandstone may also represent channel-fill sediments in some locations, as indicated by its channelling structures. The existing outcrops are too small and too scarce to enable the exact sedimentary significance of these sands to be determined. However, in general, the Hangenberg Shale and Sandstone can be interpreted as made up of levee channel complexes with attached lobes and associated turbidites and suspension deposits. Only the locally preserved black layers would represent the background sedimentation during times of channel abandonment in those particular areas. In more distal areas (e.g. towards the north), the Hangenberg Shales are expected to be more condensed, indeed representing background sedimentation.

The Stockum Sandstone

This is a sandstone unit about 25 m thick, which occurs in the Stockum area, at the northern flank of the Ebbe Anticline (Fig. 1) and the southern flank of the Nuttlar Syncline. Petrologic and sedimentologic characteristics are similar to those of the Hangenberg Sandstone. However, the Stockum Sandstone, although deposited in a short time interval (Keupp & Kompa, 1984), is at least slightly younger in parts (Paproth, 1986). It was supplied from the Ebbe shoal.

The Stockum *Imitoceras* Limestone lenses

At Stockum, limestone nodules occur in the upper part of the Stockum Sandstone (Fig. 5). They probably reflect a time of sediment starvation.

The Hangenberg Limestone

The Hangenberg Limestone (Fig. 5) is a semi-nodular to nodular limestone (1-3 m thick), composed of bioturbated bioclastic wackestones with intercalated calcareous shales. The nodular fabric is thought (Van Steenwinkel, 1984b) to be the result of sedimentary boudinage and interstratal sliding, associated with differential compaction. Carbonate redistribution has played an additional role; later pressure solution has emphasized the nodular appearance. Four goniatite (Vöhringer, 1960) and conodont (sub-) zones (Voges, 1960; Sandberg *et al.*, 1978) have been described. Conodont (sub-) zones are the *sulcata,* Lower- and Upper *duplicata* and *sandbergi* Zones (see Oberrödinghausen, Oese and Apricke sections, Higgs & Streel, 1984). Additionally, there are foraminifera, trilobites (Richter & Richter, 1926, 1951; Brauckmann & Hahn, 1984), ostracods and some echinoid fragments. A quiet-water, open-marine environment, at least below storm-wave base, is envisaged for this sediment, which seems to be draping over part of the Hangenberg Shales. The long duration (four conodont and goniatite subzones) of deposition for this thin unit indicates low sedimentation rates.

The 'Liegende Alaunschiefer'

Middle-Tournaisian (*crenulata* Zone at the base, HD spore biozone : Higgs & Streel, 1984) black alum shales are 5 to 30 m thick and occur everywhere in the Rhenish Slate Mountains and the Harz. They contain many, excellently preserved plant remains (Paproth, pers. com.) and phosphatic geodes, and overly the Hangenberg beds (Hangenberg Limestone/ Hangenberg Shales).

3.- A SEQUENCE STRATIGRAPHIC FRAMEWORK : A HYPOTHESIS

The overall section from Wocklumeria Limestone to Liegende Alaunschiefer is here put in a sequence stratigraphic framework, integrating the biostratigraphic, sedimentologic, petrographic and palaeogeographic data described above. The time units discussed for the Dinant Synclinorium (Fig. 2) are believed to correspond to the same phases of relative rates of sea-level change as seen in the northern Rhenish Slate Mountains. The sedimentary response during these various phases is discussed below (Figs 7 and 8).

TIME UNIT 1

The Wocklum Limestone : The Wocklum Limestone (LL-LE Zones) characterised the late-Devonian of the northern edge of the Rhenish Slate Mountains. Since it is incised by the Seiler Channel and contains a diverse open-marine Devonian fauna that is abruptly terminated at the top to be replaced by platform-derived fauna ('faunal crisis' in the Middle-*praesulcata* Zone, Higgs & Streel, 1984. Price & House, 1984; Walliser, 1984), it is interpreted as part of a previous depositional sequence. In order to determine the position of the Wocklum Limestone within that sequence, the significance of the overlying *evoluta* Shale plays a major role (see below).

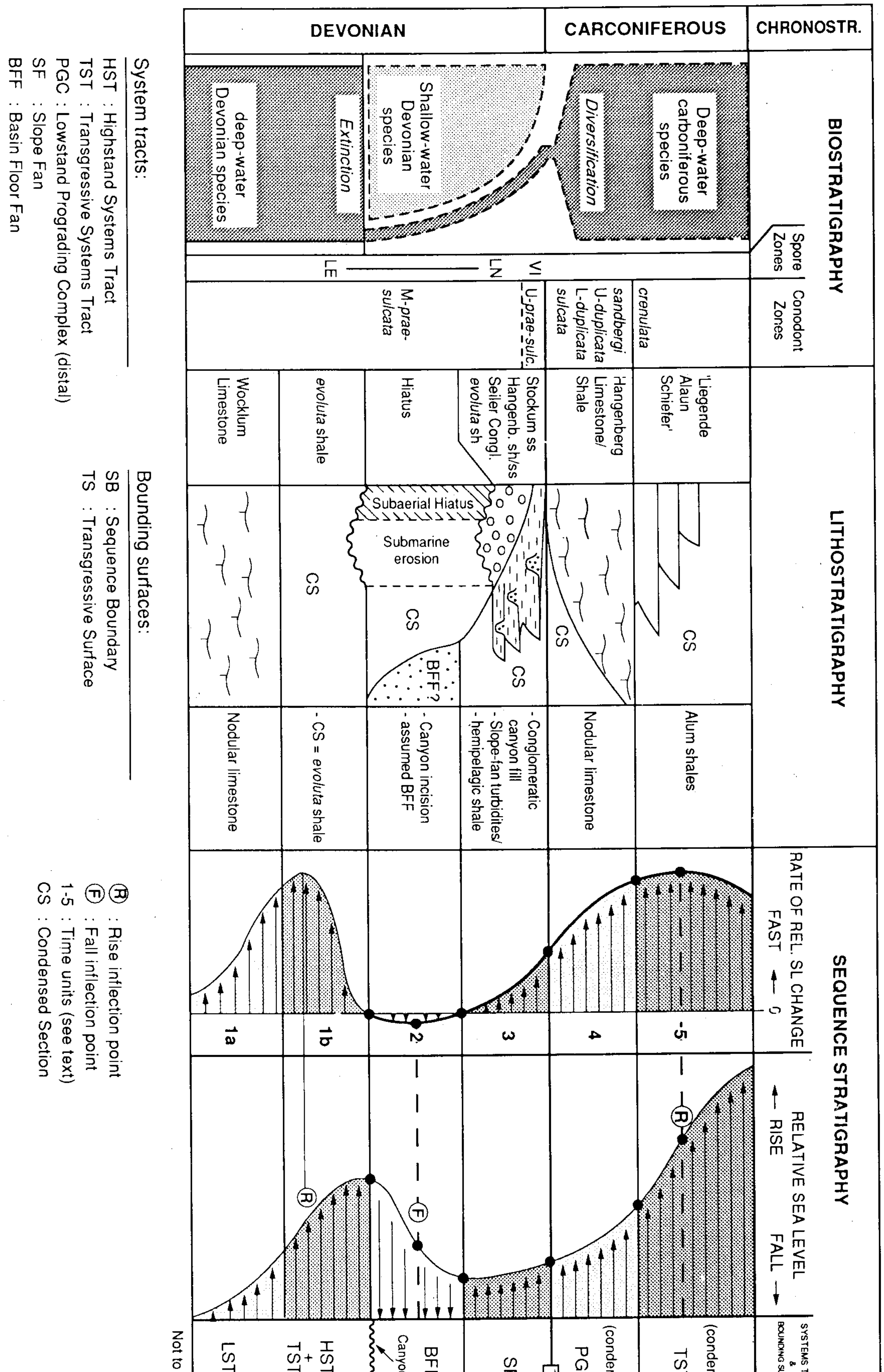


Fig. 7A

Fig. 7.- Summary of chrono-, bio- and lithostratigraphic data in a sequence-stratigraphic framework, for the Devonian-Carboniferous boundary at the northern border of the Rhenish Slate Mountains. The truncation of the deep-water *praesulcata* range by the shallow-water *protognathodus* fauna and the incision of the Seiler Channel with the subsequent Hangenberg Shale-Sandstone lowstand fill are interpreted as consequences of the end-Devonian relative sea-level fall. These lowstand deposits are time-equivalent to the hiatus (Time-Unit 2) in the Dinant Synclinorium (see: Fig. 2). A and B represent 2 different scenarios: If the *evoluta* Shale has a worldwide significance and is older than the incision event,

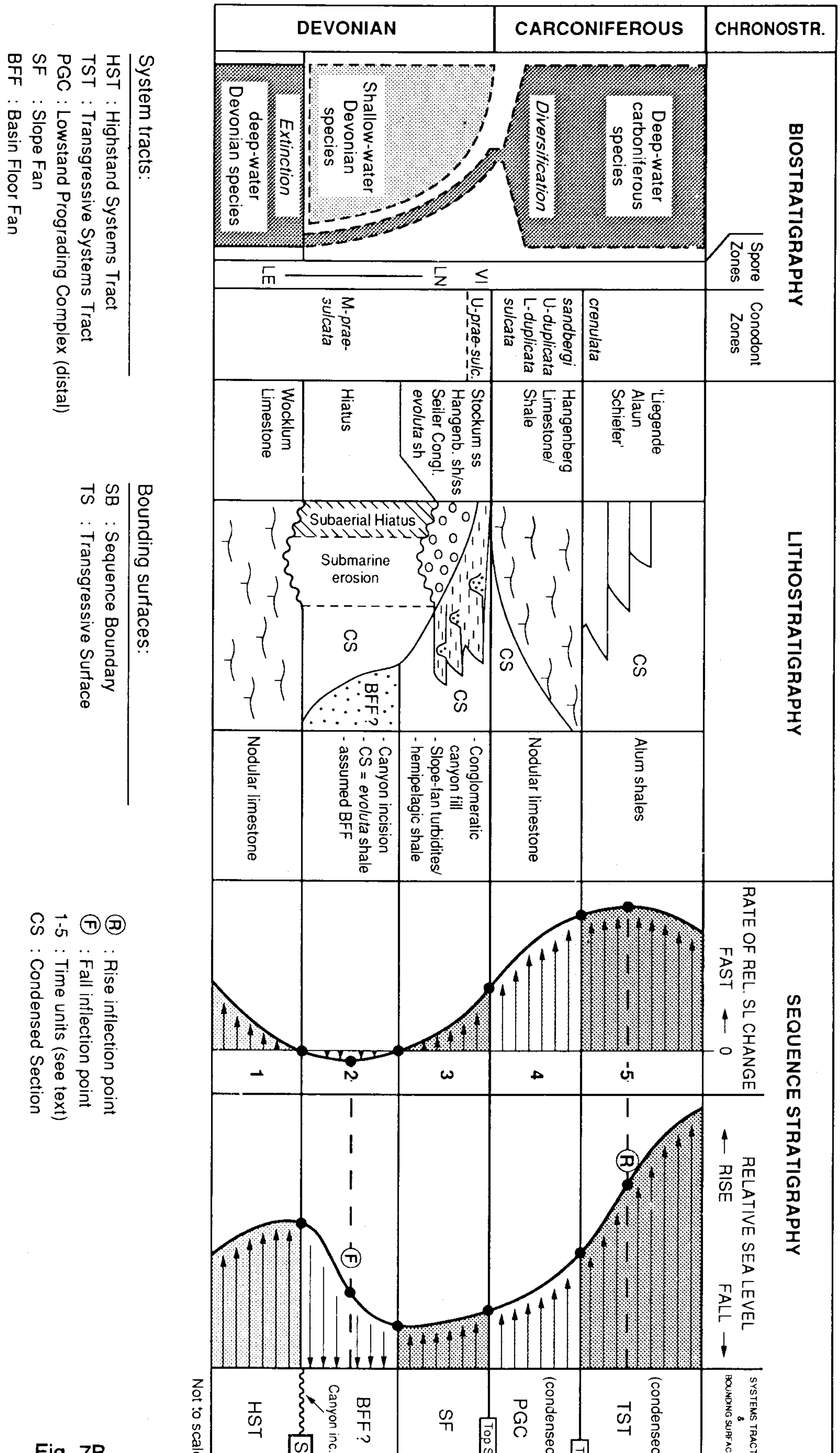


Fig. 7B

it would represent the condensed latest-Devonian Transgressive and Highstand Systems Tracts (TST+HST) of the previous sequence. In this case, the Wocklum Limestone would represent the underlying Lowstand (LST). B: If the *evoluta* Shale is locally restricted (e.g. Rhenish Slate Mountains), and its age is the same or younger than that of the incision event, then it would rather represent a condensed section between the basin-floor fan (BFF) and the Hangenberg Shales/Sandstone slope fan (SF). The Wocklum Limestone would then represent the highstand of the previous sequence.

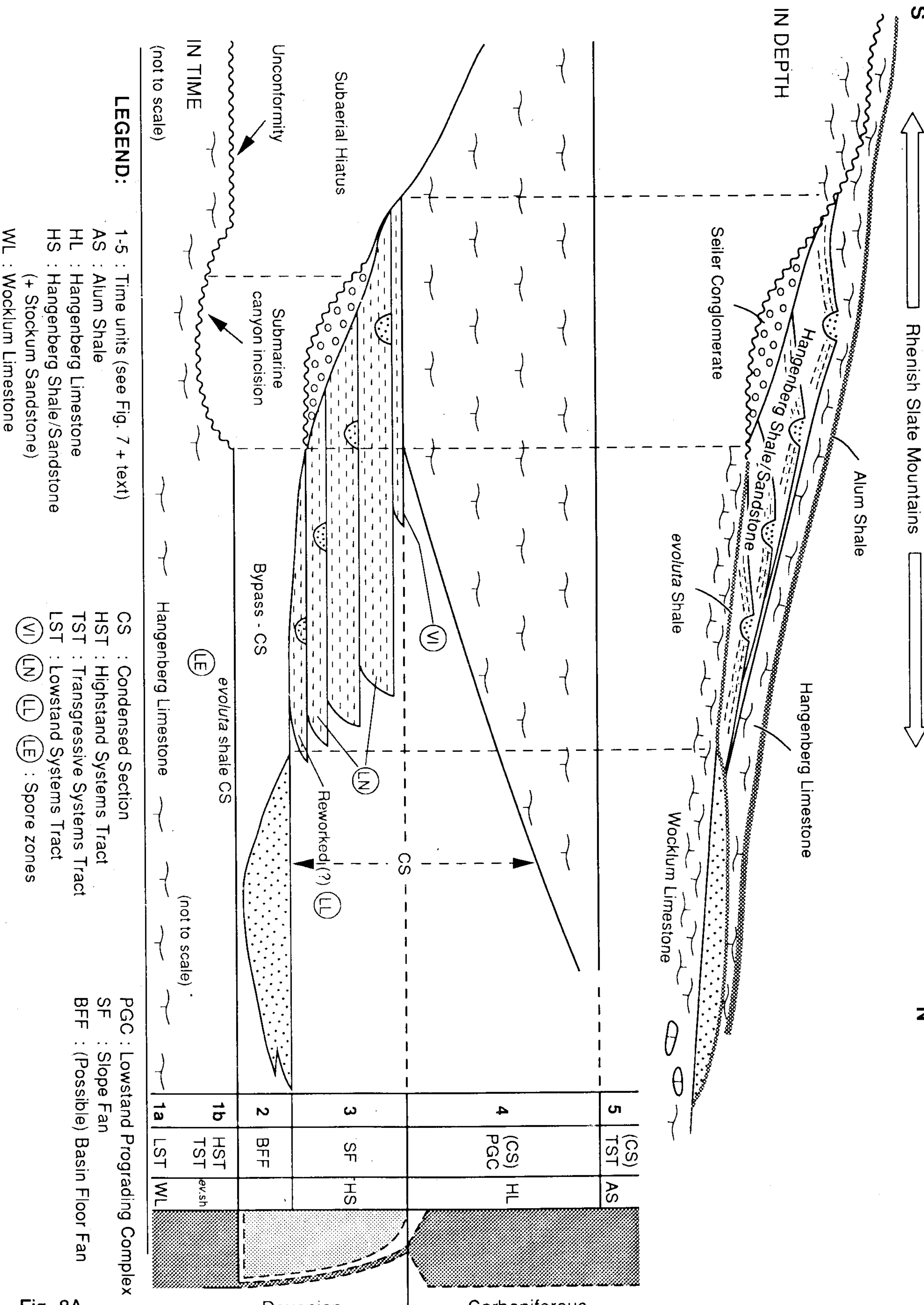


Fig. 8A

Fig. 8.- Depositional sequence of the Devonian-Carboniferous transitional interval for the northern border of the Rhenish Slate Mountains. Scenarios A and B correspond to A and B of Fig. 7.

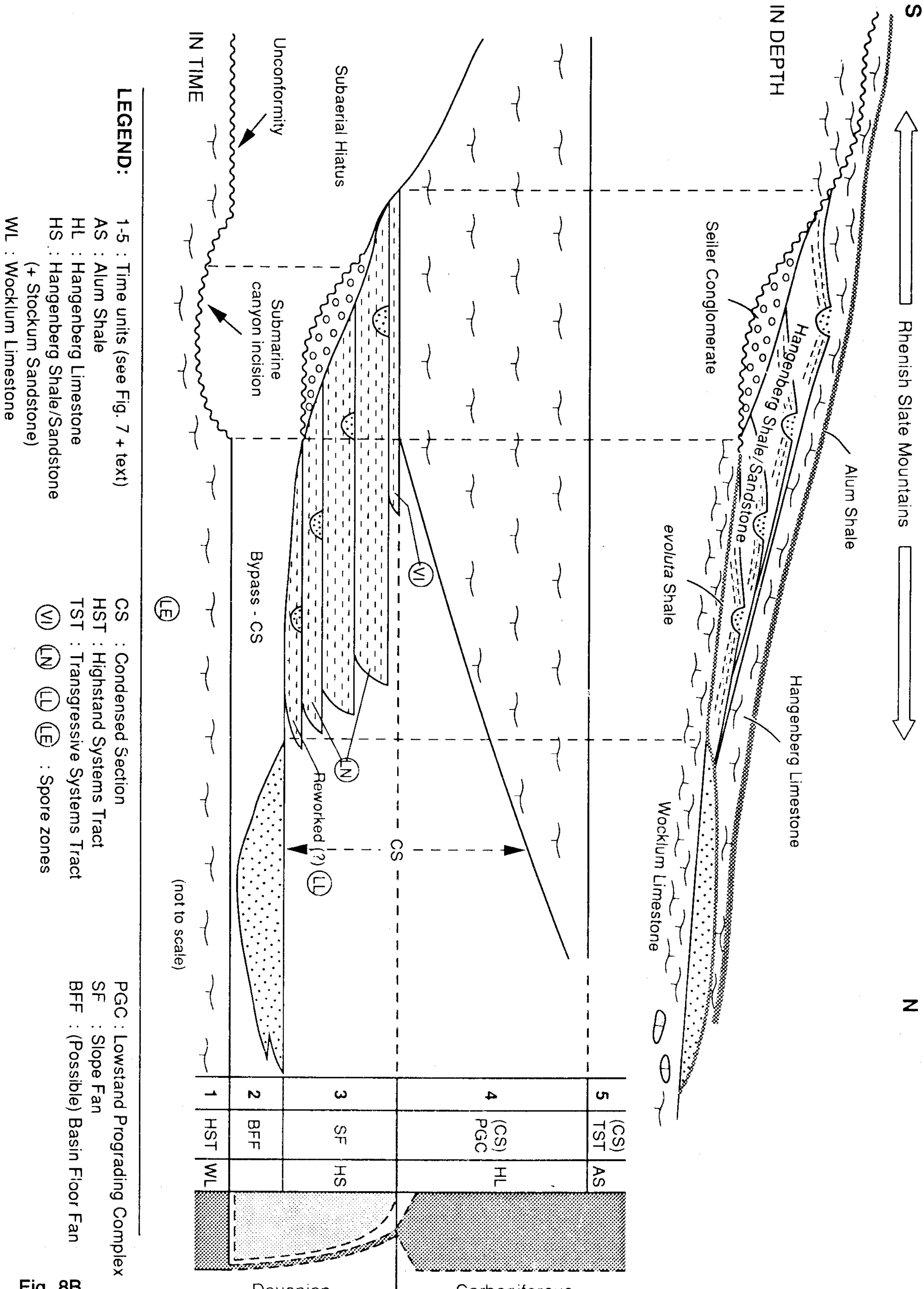

S
N
Rhenish Slate Mountains
IN DEPTH
Alum Shale
Seiler Conglomerate
Hangenberg Shale/Sandstone
evoluta Shale
Hangenberg Limestone
Wocklum Limestone
Subaerial Hiatus
Unconformity
IN TIME
Submarine canyon incision
Bypass - CS
VI
LN
Reworked (?) LL
CS
LE
(not to scale)
5 (CS) TST AS
4 (CS) PGC HL
3 SF HS
2 BFF
1 HST WL
Devonian
Carboniferous
LEGEND:
1-5 : Time units (see Fig. 7 + text)
AS : Alum Shale
HL : Hangenberg Limestone
HS : Hangenberg Shale/Sandstone (+ Stockum Sandstone)
WL : Wocklum Limestone
CS : Condensed Section
HST : Highstand Systems Tract
TST : Transgressive Systems Tract
VI LN LL LE : Spore zones
PGC : Lowstand Prograding Complex
SF : Slope Fan
BFF : (Possible) Basin Floor Fan

Fig. 8B

The *evoluta* Shale : These black alum shales with abundant *Cymaclymenia evoluta* obviously represent a condensed unit, created by sediment starvation. For its stratigraphic significance, two scenarios are envisaged, depending on (1) the exact age of the *evoluta* Shale relative to the timing of the incision event, and (2) its lateral extension and its either local or global significance. If the *evoluta* Shale has a worldwide significance and is older than the incision event, it most likely represents the condensed latest-Devonian Transgressive and Highstand Systems Tracts (TST+HST) of the previous sequence. In this case, it would represent a first, worldwide event, characterised in this area by basinal condensation during a maximum rate of eustatic sea-level rise; the Wocklum Limestone would represent the underlying Lowstand (LST; Figs 7a and 8a). This transgressive event is then followed by a second event : the sea-level fall that has caused the Seiler incision (see below). Alternatively, if the *evoluta* Shale is locally restricted (e.g. Rhenish Slate Mountains), and its age can be proven to be the same or younger than that of the incision event, then it would rather represent just a condensed section between the basin-floor fan (BFF) and the Hangenberg Shale/Sandstone slope fan (SF, see below; Figs 7b and 8b). Vail *et al.* (1991, p. 646, 648) mention a condensed section with a faunal abundance peak commonly present at the base of the slope fan complex. In this case, the *evoluta* Shale would be related to the sea-level fall that was responsible for the incision of the Seiler Channel (see below). Figure 8 shows where condensed sections are to be expected.

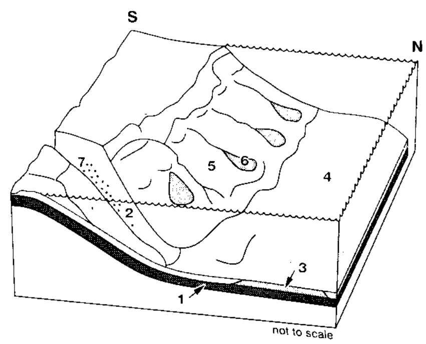
TIME UNIT 2

The Seiler incision : The Late-Devonian shoals and slopes were incised by submarine canyons in the Middle-*praesulcata* Zone (Johnson *et al.*, 1986). Canyons cutting into the shelf and slope are likely to be initiated during major sea-level falls (Haq, 1991. Carlson & Karl, 1988). The Seiler Channel is believed to be a submarine canyon that formed as a consequence of a relative sea-level fall, which interrupted the normal, open-marine Devonian sedimentation. The depth of incision during this fall is not clear. Though the canyon-fill conglomerate is known over a thickness of 95 m, it is not certain whether the incision was entirely formed during the sea-level fall, or whether and how much the erosion was emphasised during the subsequent rise. The sequence boundary that resulted from this fall is believed to be the same as the one reflected in the unconformity on top of the Etroeungt Limestone in the Dinant Synclinorium. According to Streel (pers. com.), this canyon incision, corresponding to the LE-LN Zones, seems to be also time equivalent to the tillites supporting a late-Famennian glaciation phase in South America, which contain the same miospore Zones.

The heavy sediment load during falling sea level induced turbidity currents with great erosive power to cut and deepen canyons. During the lowstand phase the canyons could channel turbidity currents and debris flows and their dense sediment load to the basin floor. However, the type and timing of turbiditic events may vary in different turbidite systems (Kolla & Macurda, 1988). The Seiler channel acted as a submarine feeder channel for the siliciclastic supply, which bypassed the shoals and was fed directly into the basin to produce lowstand submarine fans. Such fans (Basin Floor Fan; Fig. 8 : BFF) - if present - are probably to be found to the north of the exposed area.

TIME UNIT 3

The Hangenberg Shales and Sandstone and the Seiler Channel Conglomerate are characteristic of slope fan (Fig. 8 : SF) complexes, which typically form during lowstands at the early stages of relative sea-level rise.



LEGEND:

7	Canyon-fill conglomerate		proximal Slope Fan
6	Hangenberg/Stockum sandstone	: Channel-fill sands and channel-attached turbiditic overbank deposits	Slope Fan
5	Hangenberg shale	: Fine-grained distal turbidites/ hemipelagic shale	Slope Fan
4	Condensed Section of thin, black shales with *Cymaclymenia evoluta*		Condensed Section
3	Possible bypassed, massive turbiditic sands		Basin Floor Fan
2	Submarine canyon incision (Seiler)		Sequence Boundary
1	Wocklum Limestone: biopelagic argillaceous lime mud		Highstand Systems Tract of previous sequence

Fig. 9.- Block diagram showing an interpretation of the Hangenberg Shale/Sandstone and Stockum Sandstone as a lowstand slope-fan complex, consisting of a turbidite system. Deposition took place on the flanks of shoals probably during the initial phase of relative sea-level rise that followed the end-Devonian (M-*praesulcata*) sea-level fall. Modified after Van Wagoner *et al.,* 1989.

The Hangenberg Shales and Sandstone and the Stockum Sandstone : The complex turbiditic system, including thin-bedded turbidites, hemipelagic shales, massive channel fills in the upper part, laminated levee overbank turbidites, attached channel lobes with turbiditic sands, and fine-grained turbidites of which this unit is composed, are characteristic of slope fans (Vail *et al.* , 1991). Slope fans typically form during lowstands, at the early stages of relative sea-level rise, e.g. when eustatic fall becomes slower than subsidence so that new accommodation space is created (by subsidence) higher up the slope. However, depending on factors like tectonic setting, available grain size, basin size, gradients, and so on, in addition to sea level, the type and timing of turbidite events may vary in different turbidite systems (Kolla & Macurda, 1988). In this case, the sediment that bypassed the shelf is channelled by density currrents onto the slope - in the area of Oese, Apricke and Oberrödinghausen -, which has become sufficiently gentle to allow point-sourced submarine slope fans to form (Fig. 9). The more condensed, black-shale facies of the Hangenberg Shales are interpreted as the background sedimentation during relative starvation in a basinward position, or during channel-abandonment phases on the slope.

The Seiler Channel Conglomerate : The Seiler-Channel conglomeratic fill can be associated with the proximal portion of a slope fan complex. As sea level continued to rise, the sediment load settled in the canyon heads in the upper parts of the slope, terminating canyon formation (Vail *et al.*, 1991).

Because of sedimentary bypass of the platform and shoals in lowstand times, lowstand deposits like the Seiler Conglomerate, the Hangenberg Shales and Sandstone and Stockum Sandstone have no contemporaneous platform or shoal equivalent. They have been deposited during the time represented by the unconformity between the Etroeungt and Hastière Limestone formations in the Dinant Synclinorium.

The Stockum *Imitoceras* Limestone lenses 1

These nodules are interpreted to represent local sediment starvation after the time of the Hangenberg slope fan complex (Fig. 8).

TIME UNIT 4

The Hangenberg Limestone : The Hangenberg Limestone, characterised by a low sedimentation rate, is a relatively condensed unit that draped over the previous slope-fan complex, before the sea-level rise came to a maximum rate (Liegende Alaunschiefer : see below). This limestone unit, containing the first typical Carboniferous fauna, is the time equivalent of the Hastière Limestone in the Dinant syclinorium. It is considered as the distal equivalent of the Hastière Limestone lowstand prograding complex.

TIME UNIT 5

The 'Liegende Alaunschiefer' (Alum Shale) : The Alum Shale is a condensed, black-shale unit, the base of which is time equivalent (*crenulata* Zone) to the base of the Pont d'Arcole Shale in the Dinant Synclinorium. It is interpreted as the result of transgressive drowning, which also explains the abundance of plant remains in the sediment. This drowning occurred when the rate at which accommodation space was created reached a relative maximum.

As shown in Fig. 7, the overall drowning (maximum flooding : Alum Shale, Pont d'Arcole Shale) and the most abrupt shallowing and/or incision (sequence boundary : Etroeungt/Hastière contact, base Seiler Channel and Hangenberg Shale/Sandstone), correspond respectively to the intervals near the rise and fall inflection points of relative sea-level change. This is where the rising and falling limbs of the amplitude curve are steepest and where the rate curve reaches a maximum in rise and fall, respectively. The units in between are related to the relative sea-level phases between these major events, as described above.

SUMMARY AND CONCLUSIONS

Based on the combination of (1) detailed previous biostratigraphic studies, (2) sedimentological and petrographical characteristics, and (3) the stratigraphic relations of lithological units, a sequence-stratigraphic framework for the Devonian-Carboniferous boundary interval for the northern border of the Rhenish Slate Mountains is suggested and compared with that of the Belgian Dinant Synclinorium.

The biostratigraphic complexity near the Devonian-Carboniferous (*praesulcata-sulcata*) boundary is thought to be related to depositional dynamics that resulted from a relative sea-level fall at the end of the Devonian (Middle-*praesulcata* Zone). As a result of sea-level fall, the latest Devonian highstand sedimentation, represented by the Wocklum Limestone or the *evoluta* Shale (discussion : see above) in the Rhenish Slate Mountains and by the Etroeungt Limestone in the Dinant Synclinorium, ceased. In the Rhenish Slate Mountains this fall resulted first in submarine-canyon incision of the Devonian shoals and slope (Seiler Channel). A slope-fan complex (Hangenberg Shale/Sandstone, Stockum Sandstone and Seiler Conglomerate) was subsequently deposited as turbiditic lobes onlapping onto the slope during the initial phases of relative sea-level rise. Hence, as opposed to the general viewpoint that the Hangenberg Shales represent basinal background sediments, it is here suggested that they form part of a lowstand turbiditic slope-fan complex. Only the more condensed, black-shale facies within the formation are thought to represent the background sedimentation during relative starvation in a basinward position, or during channel-abandonment phases on the slope.

These lowstand sediments carry a different, shallow-water biofacies, which ended the latest Devonian, deep-water evolutionary range. There are no lateral equivalents of these lowstand units in platform areas, such as the Dinant Synclinorium. In the latter, the result of the sea-level fall is a depositional break and a biostratigraphic hiatus, associated with an unconformity surface between the Etroeungt and Hastière Limestone formations. The first deposition after the fall was the Hastière Limestone lowstand prograding wedge, which is almost devoid of the deep-water conodonts that currently define the D/C boundary. Scarce Carboniferous fauna within the Hastière Limestone indicate its time equivalence with the more distal and relatively condensed Hangenberg Limestone in the Rhenish Slate Mountains. In the latter, deep-water fauna is more abundant due to its relative basinward position, and the *praesulcata-sulcata* transition could be recorded at the base of the formation. Well-established Carboniferous assemblages providing good biostratigraphic control occur later also in the Dinant Synclinorium, after maximum deepening (Pont d'Arcole Shale, *crenulata* Zone).

Palaeoslope areas, such as that north of the Remscheid-Altena Anticline, contain slope-fan sediments deposited during a time of depositional hiatus upslope and of condensed sedimentation basinward. Hence, such palaeoslope areas represent relatively complete lowstand sequences. Although the deep-water index fauna of the previous highstand was suddenly replaced by shallow-water biofacies, such a slope area is the first one in which the later, re-established deep-water fauna was not obliterated either by basinal, extreme condensation, or by updip, nondeposition or shallow-water environments. This later, re-established open-marine fauna contains the Devonian-Carboniferous (*praesulcata-sulcata*) boundary.

In the scenario (discussed above) that the *evoluta* shale has a worldwide significance and is older than the Seiler incision, this condensed shale would then represents a eustatic transgressive event. Although this *evoluta* Shale is immediately overlain by the Hangenberg Shales, the significance of these two shale units is entirely different : the *evoluta* Shale would represent the transgressive unit of a previous sequence, whereas the Hangenberg Shales would represent the lowstand deposits of the next sequence. Taking one event for the other might explain the controversies in the literature of either a transgressive or a regressive significance of the 'D/C event'.

Since the D/C boundary is associated with similar biostratigraphic complexity in all the Devonian-Carboniferous basins worldwide, the end-Devonian relative sea-level fall may be assumed to be due to a eustatic fall. Consequently, the sequence boundary associated with this fall should be found worldwide and could be used as a reference marker where the biostratigraphic *praesulcata-sulcata* marker is not recorded.

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