EUSTATIC CYCLES AROUND THE DEVONIAN-CARBONIFEROUS BOUNDARY AND THE SEDIMENTARY AND FOSSIL RECORD IN SAUERLAND (FEDERAL REPUBLIC OF GERMANY)

by

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(5 figures and 1 table)

ABSTRACT.- A review of the sedimentary and fossil record around the Devonian/Carboniferous (D/C) boundary in Sauerland at the northern border of the Rhenish Slate Mountains (Rheinisches Schiefergebirge; Germany) forms the basis for the recognition of a succession of relative sea level changes in that area. This transgression/regression (T-R) curve shows a remarkable similarity with the one constructed for the La Serre D/C boundary stratotype (Montagne Noire, France). It is therefore suggested that these T-R curves are closely related to global (eustatic) sea level changes.

1.- INTRODUCTION

The timing of presumably eustatic transgression-regression (T-R) cycles around the Devonian-Carboniferous (D/C) boundary can be distilled from papers by (among others) Johnson *et al.* (1985, 1986), Sandberg *et al.* (1986) and Van Steenwinkel (1990). They coincide in their acceptance of "a major regression" starting in the middle *praesulcata* conodont zone slightly below the D/C boundary and a "major rise in sea level" in the early *crenulata* conodont zone above this boundary. They also agree about the existence of one or more "minor transgressions" in the earliest Carboniferous *sulcata* through *sandbergi* conodont zones.

This model matches the sedimentary and fossil record in Sauerland, at the northern border of the Rhenish Slate Mountains (Rheinisches Schiefergebirge) in Germany, as illustrated by the Hönnetal section at Oberrödinghausen (fig. 1). This section was proposed as the reference section for the D/C boundary at the Heerlen Congress in 1935 (Jongmans & Gothan, 1937 : 7). The major regression starting in the middle *praesulcata* zone is easily recognized at the boundary between the Hangenberg Black Shale (HBS) overlying the nodular cephalopod limestone (Wocklum Limestone) with conodonts of the "middle and upper *costatus*"* (= early and middle *praesulcata*) zone and the overlying silty Hangenberg Shale (cf. Walliser, 1984). The cephalopod-bearing Hangenberg Limestone (with the cephalopod *Gattendorfia* and conodonts of the *sulcata* through *sandbergi* zones) represents the earliest Carboniferous "minor transgression" of the above mentioned authors, whereas the Lower Alum Shale (Liegende Alaunschiefer) with conodonts of the early *crenulata* zone must have been deposited during the early Middle Tournaisian "major rise in sea level" (the Event 15 of Sandberg *et al.*, 1983; cf. also Sandberg *et al.*, 1986), which has been recognized as well in South China (*crenulata* transgression of Bai & Ning, 1989).

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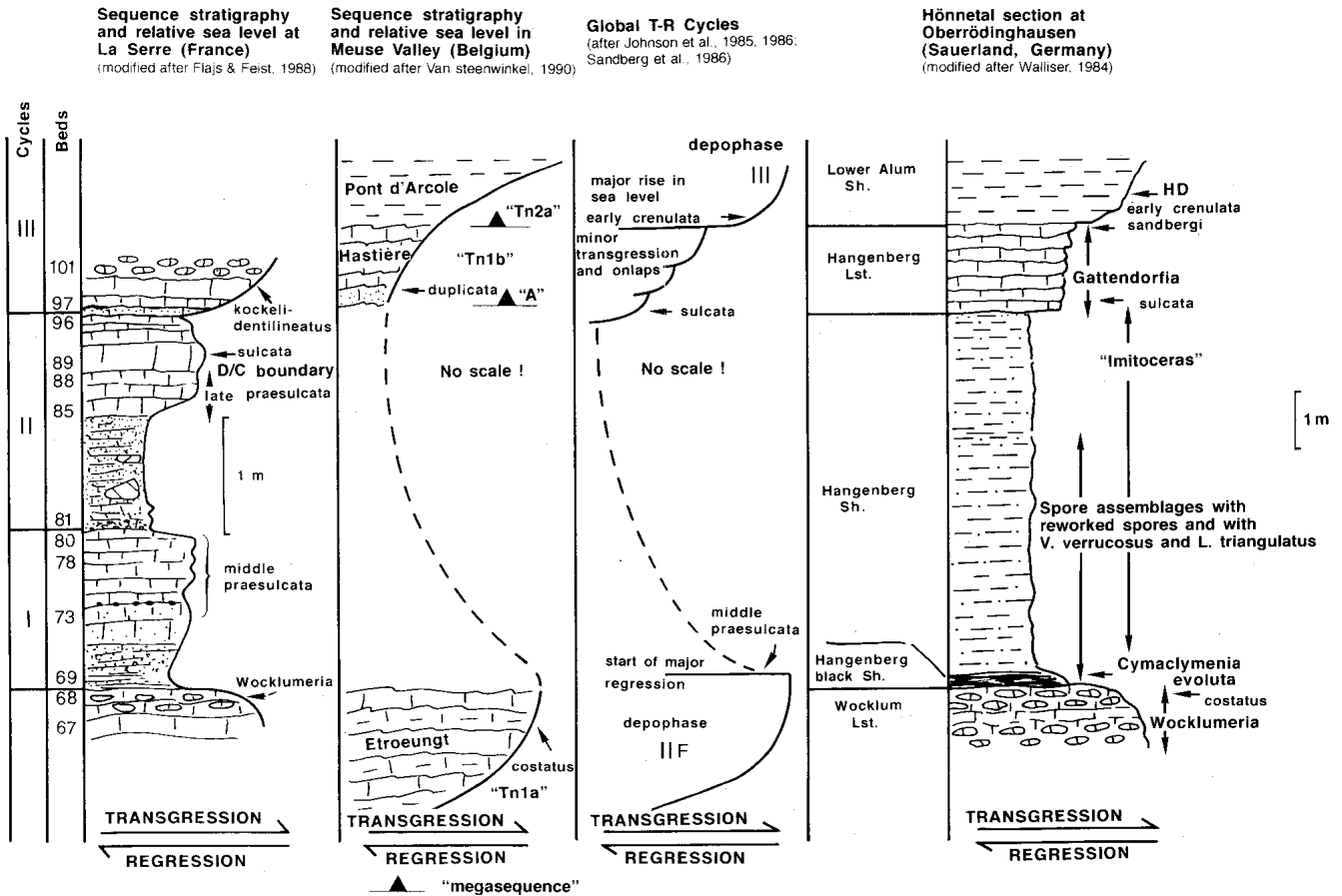
Fig. 1.- Comparison between global T-R cycles (after Johnson *ert al.,* 1985, 1986 and Sandberg *et al.,* 1986) and local or regional relative sea level changes around the D/C boundary at La Serre (Montagne Noire, France) and Oberrödinghausen (Sauerland, Germany) and in the Meuse Valley (Belgium).

Unfortunately, the sedimentary and fossil record in between the Wocklum Limestone and the Hangenberg Limestone is incomplete at Oberrödinghausen. Limestone lenses in the upper part of the Hangenberg Shale containing conodonts of the "lower and upper *Protognathodus* faunas" are absent, although these have been recognized in several other (nearby) sections in Sauerland, such as Seiler, Oese, Müssenberg, Drewer and Stockum (cf. Higgs & Streel, 1984; Luppold *et al.,* 1984; Clausen *et al.,* 1989; Korn, 1991). The *"Imitoceras"* cephalopod assemblage from the Hangenberg Shale at Oberrödinghausen is poorly documented (cf. Paproth & Streel, 1970; House, 1993) in comparison with those from the sections at Müssenberg, Drewer and Stockum (cf. Luppold *et al.,* 1984; Clausen *et al.,* 1989; Korn, 1984, 1991, 1993).

The spore assemblages from the lower part of the Hangenberg Shale at Oberrödinghausen include a certain amount of reworked material derived from older deposits (Paproth & Streel, 1970). These assemblages have been assigned to the LL spore zone (Higgs & Streel, 1984) and consequently this stratigraphic interpretation triggered the discussion about a diachronous (Higgs & Streel, 1984; Bless *et*

al., 1988) or isochronous (Korn, 1991; Becker, 1988, 1993a) boundary between the Wocklum Limestone and the overlying HBS. The same question was raised by Korn (1988) after his discovery of the cephalopod *Cymaclymenia evoluta* just below the topmost bed of the Wocklum Limestone at Drewer, because until then this species was regarded as a marker for the basal Hangenberg Shale. This, of course, led to other questions.

How will a diachronous or isochronous top of the Wocklum Limestone fit in the scheme of a global (eustatic) regression ? Is it possible to recognize one or more minor T-R cycles in the interval limited by the Wocklum Limestone and the Hangenberg Limestone? and if so, will these match the minor T-R cycles observed in the La Serre E' section (Montagne Noire, Southern France), the "Global Stratotype Section and Point for the Devonian-Carboniferous Boundary" (Flajs & Feist, 1988; Paproth *et al.,* 1991) ?

The biostratigraphic and lithostratigraphic data from nine sections in Sauerland are reviewed here in an attempt to answer at least some of these questions. The studied sections are : Riescheid,

Table 1.- Correlation table of conodont, cephalopod and spore zonations inasfar as used in Sauerland.

1):   The base of the *acutum* zone possibly matches the base of the "upper *Protognathodus* fauna" if we accept the find of *Acutimitoceras acutum* 2 cm above the LN/VI spore zones boundary in Hasselbachtal. This specimen occurs, however, some 15 cm below the first *Siphonodella sulcata* in that section. Therefore, it cannot be excluded that the base of the *acutum* zone s.l. is just below the *sulcata* and "upper *Protognathodus*" conodont zones. However, there is no evidence for *Gattendorfia* or other strictly Carboniferous goniatite genera at such an early level. The *Gattendorfia* genozone (Becker, 1993a = *acutum* base of former authors) postdates the "upper *Protognathodus*" level.

2):   The HD Zone has been found with the conodont *duplicata* zone in the Namur Syncline in Belgium (Higgs *et al.*, 1992) and might even be older.

	CONODONT ZONES cf. Dreesen et al., 1986		CEPHALOPOD ZONES Korn, 1993	Schmidt, 1925 Vöhringer, 1960	Becker, 1993	SPORE ZONES Higgs & Streel, 1984
	"BASIN"	"SHELF"				
CARBONIFEROUS	crenulata				Goniocyclus	HD
	sandbergi		patens	Ga. crassa	[Paralytoceras]	
	duplicata		westfalicus		Pseudarietites	═ ═ ═2)
			dorsoplanus	Ga. subinvoluta	Paprothites	VI
	sulcata	kockeli- dentilineatus	acutum		Gattendorfia	
		upper Protognathodus	═ ═ ═1)═			
DEVONIAN	late praesulcata	lower Protognathodus	prorsum	Wocklumeria	Acutimitoceras	LN
	middle praesulcata	‖‖‖‖‖‖			Cymaclymenia	
		upper costatus	upper paradoxa			LE
	early praesulcata	middle costatus			Wocklumeria	LL

Hasselbachtal, Seiler, Oese, Apricke, Oberröding-hausen, Müssenberg, Drewer and Stockum. They are all located on the northern border of the Rhenish Slate Mountains (figs. 2-3).

2.- BIOSTRATIGRAPHIC AND LITHOSTRATIGRAPHIC FRAMEWORK

The biostratigraphic framework in Sauerland is provided principally by conodonts, ammonoids and spores (table 1). Zonations based on trilobites (for instance, Brauckmann & Hahn, 1984; Luppold *et al.*, 1984) or on entomozoacean ostracodes (for instance, Groos-Uffenorde & Uffenorde, 1974; Bless & Groos-Uffenorde, 1984) have not been taken into account, because of the limited amount of data so far obtained from these sections.

The lithostratigraphic framework consists of an alternation of frequently cephalopod-bearing limestones, (sandy/silty) shales and sandstones. The isochroneity of the boundaries between these lithologies is accepted if this is supported or at least not contradicted by biostratigraphic evidence. The same concept is followed in the treatment of special lithologies, such as the Seiler Conglomerate and black shale layers.

2.1.- CONODONTS

Conodont assemblages have been described from all the nine sections. First of all, the study of conodonts has been practically limited to limestones. Therefore, the conodont zonation around the D/C boundary in Sauerland is characterized by some more or less important observation gaps, corresponding
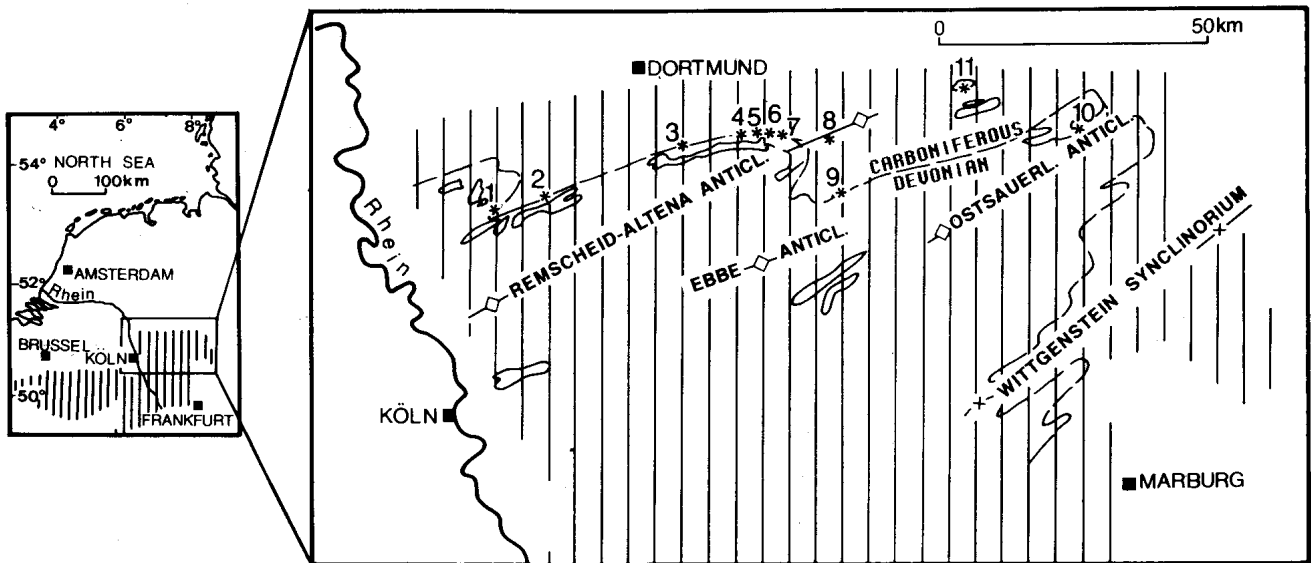
Fig. 2.- Location of principal D/C boundary outcrops at the northern border of the Rhenish Slate Mountains (Rheinisches Schiefergebirge) in Germany. Vertical hatching : outcropping Paleozoic deposits. 1: Aprath, 2: Riescheid, 3: Hasselbachtal, 4: Seiler (Iserlohn), 5: Oese, 6: Apricke, 7: Oberrödinghausen (Hönnetal), 8: Müssenberg, 9: Stockum, 10: Hoppecke (Brilon), 11: Drewer

to the siliciclastic intervals. Secondly, many of the studied assemblages consist of only a small number of individuals and may therefore lack the marker species which are vital for biozonal interpretation. This becomes a problem when a conodont zone is defined by the disappearance of species, as in the case of the middle *praesulcata* zone (cf. Dreesen *et al.*, 1986).

The stratigraphic interpretation of these data can be somewhat ambiguous due to sometimes vague biozonal interpretations, especially in the distinction of the late *expansa* through middle *praesulcata* zones (cf. Clausen *et al.*, in press; Kürschner *et al.*, 1993). For instance, a limestone nodule in the greenish silty shales at Riescheid yielded an example of a rather vague biostratigraphic interpretation : "*costatus* zone" according to Lane & Ziegler *in* Paproth & Streel (1982). This matches the top of the early *expansa* to lower part of the middle *praesulcata* zones (cf. Dreesen *et al.*, 1986 : fig. 2).

An example of an at best contradictory biostratigraphic interpretation can be deduced from the comparison of data and interpretations provided by Luppold *et al.* (1984) and Clausen *et al.* (1989) for the Müssenberg section. According to Luppold *in* Clausen *et al.* (1989), the conodont assemblages from the 1.5 m thick succession of limestones with cephalopods of the lower and upper *paradoxa* zone belong to the middle *praesulcata* zone. He defined the base of this zone by the extinction of *Palmatolepis gracilis gonioclymeniae* (cf. Clausen *et al.*, 1989 : 359 and fig. 3). However, this taxon has been recognized

in the topmost layer of this succession (bed 4; cf. Luppold *et al.*, 1984 : table 3; Clausen *et al.*, 1989 : figs. 2-3) by Luppold *et al.* (1984 : table 3).

Comparable problems exist at La Serre, where Flajs & Feist (1988) assigned the cephalopod-bearing nodular limestone of bed 68 to the late *expansa* zone "since Protognathodids and *Siphonodella* are failing" (Flajs & Feist, 19788 : 55). Paproth *et al.* (1991), however, placed this bed in the upper part of the early *praesulcata* zone because of the presence of the cephalopod *Wocklumeria* (indicating the upper *paradoxa* zone), and because of the fact that the conodont "*Pseudopolygnathus marburgensis trigonicus* occurs without protognathodids" (Paproth *et al.*, 1991 : 332). Flajs & Feist assigned the beds 71 through 80 in the same section to the "early and (?) middle *praesulcata* subzones" (Flajs & Feist, 1988 : 56). But the absence of *P. gracilis gonioclymeniae* above bed 68 suggests that this interval belongs to the middle *praesulcata* zone (see discussion here above for the Müssenberg section).

The distinction between the "lower and upper *Protognathodus* faunas" forms another point of discussion. In theory, the "upper *Protognathodus* fauna" is distinguished by the appearance of *Protognathodus kuehni* (cf. Ziegler & Sandberg, 1984), as illustrated in the Seiler trenches and presumably also in the Stockum trenches (Ziegler & Sandberg, 1984; Clausen *et al.*, in press). At Müssenberg, however, the basal portion of bed "3" has been assigned to the late *praesulcata* ("= lower *Protognathodus*"; cf. Ziegler & Sandberg, 1984; Dreesen *et al.*, 1986) zone despite
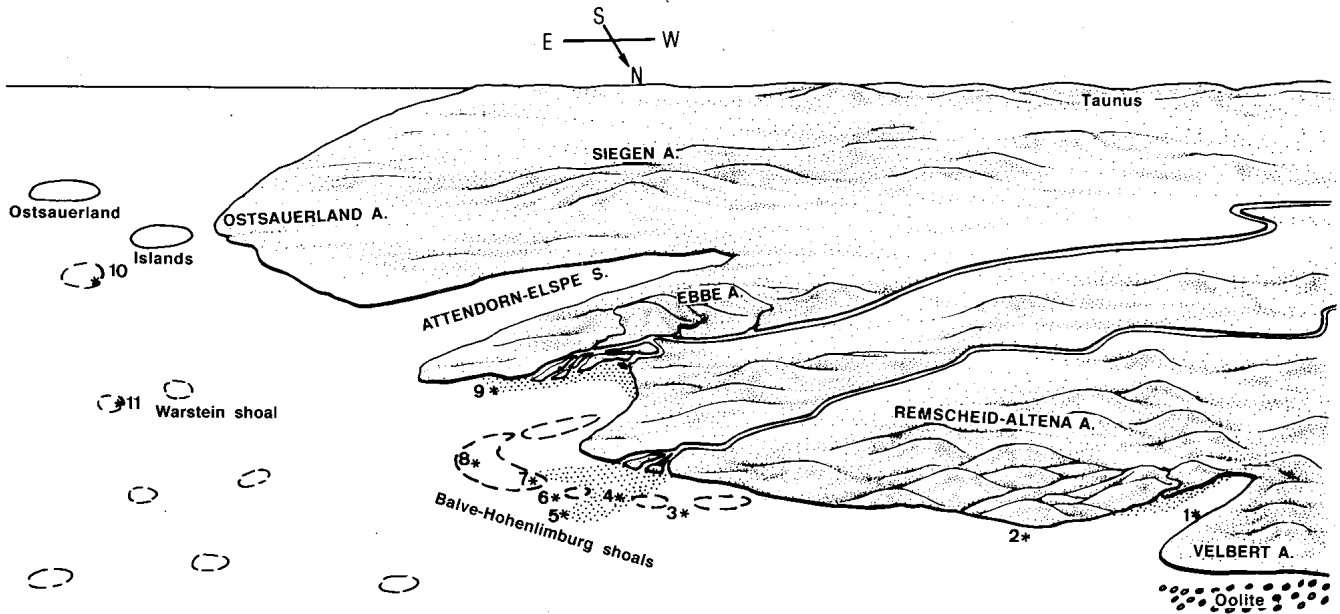
Fig. 3.- Strunian paleogeography at the northern border of the Rhenish Slate Mountains. Localities as in figure 2. Fine stipples : coarse-grained siliciclastic deposits (Seiler Conglomerate and Hangenberg Sandstone). Coarse stipples : oolite (in Velbert area)

the presence of *P. kuehni* (Luppold *et al.,* 1984; Clausen *et al.,* 1989). The obvious advantage of this anomalous interpretation is, that beds with a "Stockum-type" *Acutimitoceras* cephalopod fauna would yield a "lower *Protognathodus* conodont fauna" in Sauerland, at least at Stockum (Clausen *et al.,* in press), Drewer (Korn, 1991) and Müssenberg (Clausen *et al.,* 1989). And this, in turn, would favour the concept of a more or less synchronous appearance of *Acutimitoceras* "Stockum-type" faunas in that area. The disadvantage of this interpretation is, of course, that it would no longer be possible to distinguish between the "lower and upper *Protognathodus* faunas".

The alternative solution is the assignment of the basal portion of bed "3" at Müssenberg (with *P. kuehni*) to the "upper *Protognathodus* fauna". This implies the acceptance of an observed diachronous appearance of *Acutimitoceras* Stockum-type faunas in Sauerland. We have adopted this as the correct solution and follow the concept of Ziegler & Sandberg (1984) that the appearance of *P. kuehni* marks the base of the "upper *Protognathodus* fauna". Our main argument for doing this is the fact that *P. kuehni* is the presumable descendant of *P. kockeli* (cf. Luppold *et al.,* 1984), a taxon that "by definition" appears at the base of the "lower *Protognathodus*" (= late *praesulcata*) fauna (cf. Dreesen *et al.,* 1986). A succession of two horizons both bearing *Acutimitoceras* has been documented at a section at Drewer by Korn (1991).

Despite or rather because of these problems, the following synthesis can be made (fig. 4, based on papers by Koch *et al.,* 1970; Alberti *et al.,* 1974; Higgs & Streel, 1984; Luppold *et al.,* 1984; Ziegler & Sandberg, 1984; Clausen *et al.,* 1989; Korn, 1991; Clausen *et al.,* in press) :

- The conodont assemblages from the upper portion of the Wocklum Limestone and the limestone nodules in the presumably coeval Wocklum Shale at Stockum and greenish silty shales at Riescheid point to the "middle or upper *costatus* zone", or, in terms of the new Zonal Scheme the (upper portion of the) early or (lower portion of the) middle *praesulcata* zone.

- The overlying siliciclastics of the Hangenberg Shale/Hangenberg Sandstone/Seiler Conglomerate have not yielded conodont assemblages.

- Frequently sandy or silty, sometimes cephalopod-bearing *(Acutimitoceras)* limestone lenses occur in the upper half of the Hangenberg Shale. In the ideal case (at Seiler, and presumably also at Drewer and Stockum) two clusters can be distinguished which are separated by a thin shale layer. The lower cluster of limestone lenses has yielded conodonts of the "lower *Protognathodus* fauna" and the upper one conodonts of the "upper *Protognathodus* fauna". The distribution of these limestone lenses is extremely irregular, even at a single locality (cf. Ziegler & Sandberg, 1984 : fig. 4; Korn, 1991 : fig. 2; Clausen *et al.,* in press : fig. 7; Higgs *et al.,* 1993). The base
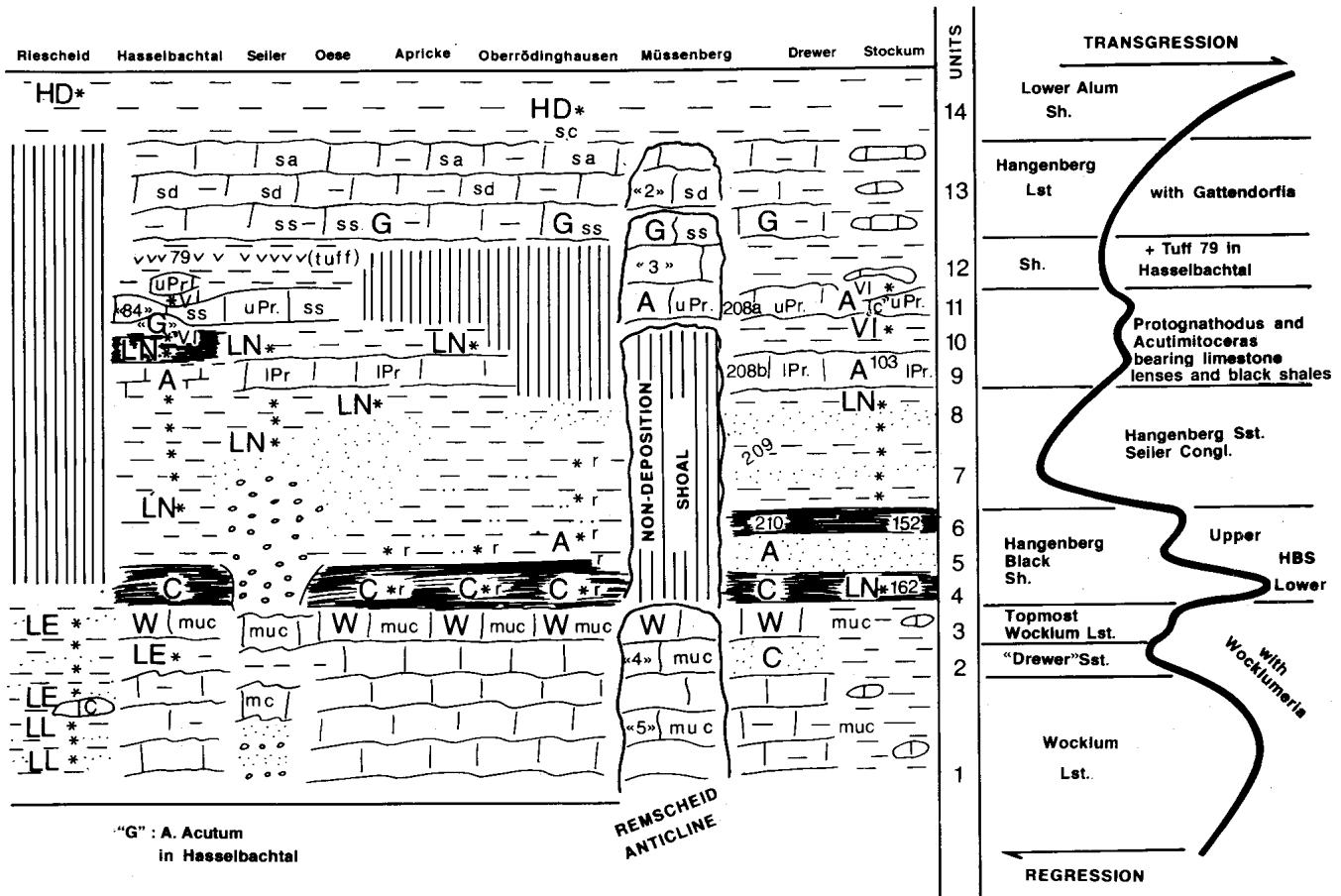
Fig. 4.- Outline of main latest Devonian and early Dinantian lithologies and biostratigraphic markers in sections at the northern border of the Rhenish Slate Mountains (not to scale). Vertical hatching indicates presumed non-deposition. Bed numbers in Hasselbachtal section from Becker et al. (1984), in Müssenberg section from Luppold et al. (1984), in Drewer section from Korn (1991; section WJ on his figure 2), and in Stockum section from Clausen et al. (in press). Only first and/or last occurrences of biostratigraphic markers are indicated. LL, LE, LN, VI and HD: miospore assemblages (asterisks show position of productive spore samples; r: reworked spores). W (Wocklumeria sphaeroides), C (Cymaclymenia evoluta), A (Acutimitoceras), G (Gattendorfia) and "G" (Acutimitoceras acutum at Hasselbachtal): cephalopods. c (costatus), mc (middle costatus), muc (middle-upper costatus), IPr (lower Protognathodus), uPr (upper Protognathodus), ss (Siphonodella sulcata), sd (duplicata), sa (sandbergi) and sc (crenulata): conodont assemblages.

of the "upper Protognathodus fauna" coincides with the base of the sulcata zone, although Siphonodella sulcata usually appears somewhat later in Sauerland, namely at the base of the cephalopod-bearing (Gattendorfia) Hangenberg Limestone. An exception to this is Bed 84 of the Hasselbachtal section. This bed (with S. sulcata and P. kuehni) is tentatively correlated with the basal "upper Protognathodus faunas" of Seiler, Müssenberg and Stockum (cf. fig. 4) due to the presence of S. sulcata in the "upper Protognathodus fauna" at Seiler (Ziegler & Sandberg, 1984) and because of the succeeding interval (Beds 83 to 81) which has typical "upper Protognathodus faunas" (Stoppel in Becker et al., 1984; Kürschner et al., 1993).

- A thin silty shale layer separates the Protognathodus-bearing limestone lenses from the overlying Gattendorfia-bearing Hangenberg Limestone. At Müssenberg, however, this shale is either absent or replaced by a limestone layer (situated in between the Acutimitoceras-bearing basal portion and the Gattendorfia-bearing upper portion of bed "3"; cf. Clausen et al., 1989).

- The Gattendorfia-bearing Hangenberg Limestone has yielded conodonts of the sulcata, duplicata and sandbergi zones.

- Conodonts of the early crenulata zone have been recognized at the base of the Lower Alum Shale (= Liegende Alaunschiefer) at Seiler and Oberrödinghausen.

2.2.- CEPHALOPODS

Ammonoids have been described from seven of the nine Sauerland sections. Detailed studies during the past decade have led to the distinction of

three or four cephalopod zones at the D/C boundary (table 1). Although the upper *paradoxa* zone was not formally subdivided by Korn (1991), he distinguished an upper portion within this zone characterized by the Hangenberg Black Shale (HBS), its base being marked by a major extinction of cephalopods, notably *Linguaclymenia similis, Lissoclymenia wocklumeri, Finiclymenia wocklumensis, Parawocklumeria paradoxa, Mimimitoceras liratum, Wocklumeria sphaeroides* and a variety of other goniatite groups *(Tornoceratidae, Sporadoceratidae, Posttornoceratidae).*

Price & House (1984) and Becker (1988, 1993a) assigned the interval in between this extinction level and the first appearance of *Acutimitoceras* or *A. prorsum* to the *Cymaclymenia* or *C. evoluta* zone or subzone. This roughly matches the HBS at the base of the Hangenberg Shale at Oberrödinghausen. The base of the *C. evoluta* zone is also marked by the major extinction of ammonoids at the top of the Wocklum Limestone (Becker, 1988), because the index taxon occurs already below the top of the Wocklum Limestone (Korn, 1988). Did this top constitute, however, a true extinction level ? In fact, the cephalopod material from the HBS at Oberrödinghausen, Oese, etc. "is typically crushed to such an extent that it cannot be identified with certainty" (Korn, 1991 : 559). This statement merely confirms an earlier one that the label of *C. evoluta* "has been applied rather uncritically to any clymeniids, or even planispiral gastropods encountered in the Hangenberg Shales or their equivalents" (Price & House, 1984 : 19). The most recent information reveals that at least two of these presumably extinct taxa *(Lissoclymenia wocklumeri* and *Wocklumeria sphaeroides*)* occur in beds of the *prorsum* or *Acutimitoceras* zone (Korn, 1993). This diminishes the significance of a *C. evoluta* partial range or ecostratigraphical zone.

However, it is strange that all surviving taxa are only known from single specimens and fragments in the *prorsum* Zone which perhaps may be the result of reworking of material from the Wocklum Limestone.

In Korn's (1991) subdivision, the lower boundaries of the *prorsum* and *acutum* zones are defined by the first appearance of their respective marker taxa, *Acutimitoceras prorsum* and *A. acutum.* The base of the *Acutimitoceras* or *A. prorsum* zone is immediately on top of the lower HBS at Drewer, where *Acutimitoceras* sp. occurs in sandstone bed 014 of section WB (Korn, 1988, 1993) and *Mimimitoceras (?) substriatum* (perhaps belonging to *Acutimitoceras* according to Korn, 1993) in sandstone bed 116 of Drewer section WG (Korn, 1991). Most likely, these sandstone beds belong to one single lenticular sandstone body that was deposited between the lower and upper HBS in section WG (compare figs. 1-2 in Korn, 1991 with fig.

5 in Korn, 1993). The presence of *Acutimitoceras* immediately above the lower HBS at Drewer matches the first occurrence of ammonoids of the *"Imitoceras"* group at Oberrödinghausen, 5 cm above the top of the HBS. Although the preservation of *"Imitoceras"* in the silty to sandy shales at Oberrödinghausen is very poor, there is little doubt that they belong to the same *"Imitoceras"* group observed elsewhere in the Hangenberg Shale. Some of the better preserved specimens at Oberrödinghausen have been tentatively identified as *"Prionoceras"* (Paproth & Streel, 1970) or *Acutimitoceras subbilobatum* (Korn, 1993).

A special problem forms the first occurrence of *Acutimitoceras acutum* in the Hasselbachtal section (cf. Korn, 1993 : fig. 4). This specimen is questioned by Becker (1993b) but if we accept it, then it represents the index species of the *acutum* zone, the lowermost of the four *Gattendorfia* zones (cf. Paproth, 1986 : table 3; Korn, 1993 : fig. 11). Up to now, it was believed that the base of *A. acutum* matches the base of *Gattendorfia* as well as the base of the *"kockelidentilineatus* conodont assemblages", this is slightly above the first occurrence of *S. sulcata* (cf. Paproth, 1986 : table 3). At Hasselbachtal, however, *A. acutum* presumably appears 12 cm below the top of bed 85, that is 2 cm above the boundary between the LN and VI spore zones (Korn, 1993 : fig. 4; Higgs & Streel, 1984; Becker *et al.,* 1984 : 187). This boundary occurs below the base of the "upper *Protognathodus"* assemblages at Seiler and Stockum (see discussion below on spores) which is also well developed in Beds 83 and 81 at Hasselbachtal. Nowhere else do "upper *Protognathodus* faunas" range into the level with *Gattendorfia.* Presumably, the base of the *acutum* zone at Hasselbachtal coincides with the base of the "upper *Protognathodus* fauna" at Seiler and Stockum. But this model implies that the base of the *acutum* zone occurs some 12-15 cm below the first appearance of *S. sulcata* at Hasselbachtal. Thus, bed 84 (with *S. sulcata*) in the Hasselbachtal section would be a fraction younger than the base of the beds with "upper *Protognathodus"* at Seiler and Stockum.

Taking into account these observations, the following synthesis can be made (fig. 4) :

- The top of the Wocklum Limestone (characterized by a transition from the "middle into the upper *costatus*" or from the early into the middle *praesulcata* conodont zone) contains a diverse *Wocklumeria* or upper *paradoxa* cephalopod fauna. A slight decrease in diversity and number of specimens has been

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*   *W. sphaeroides,* found at Drewer section WB might be reworked, according to a note in Korn (1993), added after the first proof.

reported for the topmost layers at, for instance, Müssenberg (Luppold et al., 1984; Clausen et al., 1989; Korn, 1993). The only new taxon appearing in this uppermost portion of the Wocklum Limestone is C. evoluta (Korn, 1988).

- The base of the HBS is marked by the mass extinction of cephalopod taxa, especially clymeniids (Price & House, 1984; Becker, 1993a; Korn , 1993). Recent discoveries of C. evoluta, C. striata, W. sphaeroides and L. wocklumeri in Acutimitoceras-bearing strata (Korn, 1989, 1991, 1993) suggests, however, that an as yet unknown number of "Wocklum taxa" survived this extinction event. An unexplained feature is their extreme rarity in the prorsum-zone before their final extinction.

- The observed base of the Acutimitoceras faunas is diachronous in Sauerland. A best-fit correlation (see discussion above and fig. 4) suggests that "Imitoceras"/Acutimitoceras faunas appear in the basal portion of the Hangenberg Shale, immediately overlying the (lower) HBS, at Drewer and Oberrödinghausen. Acutimitoceras appears above the base of the "lower Protognathodus fauna" (= late praesulcata zone) at Stockum (Higgs et al., 1993; Clausen et al., in press), and at the base of the "upper Protognathodus fauna" at Müssenberg (Clausen et al., 1989). In North America (e.g. Louisiana Limestone, Bedford Shale), Moravia and South Ireland, it is known from the "lower Protognathodus fauna" or from the LN miospore zone correlative with the same level.

- The entry of Gattendorfia postdates the entry of S. sulcata and appears to be contemporaneous at Oberrödinghausen, Oese, Drewer, Müssenberg, Gattendorf in the Saalfeld area, and in the Carnic Alps. At Hasselbachtal A. acutum may perhaps appear earlier at a level matching the late praesulcata zone at Seiler and Stockum. In its present definition the base of the acutum zone thus is possibly diachronous (and Gattendorfia subinvoluta obviously is a better zonal fossil).

2.3.- MIOSPORES

Miospores assemblages have been described from seven of the nine Sauerland sections. They are preferably extracted from shale layers, in contrast to the conodonts which are usually extracted from the limestones. However not all shales yield miospore assemblages, perhaps because of post-sedimentary oxidation processes or because of the fact that the offshore deposition area was beyond the limits of miospore dispersal (cf. Paproth & Streel, 1970). This explains the observation gaps in the spore zonation in Sauerland.

It should be emphasized that miospores are just as important for the biostratigraphic framework in Sauerland as conodonts and ammonoids. The spore zonation for the latest Devonian (Strunian) and earliest Carboniferous (Tournaisian) of Britain and Ireland (Clayton et al., 1978; Higgs et al., 1988) has been successfully applied to areas as distant as the European part of the former Soviet Union (Byvsheva et al., 1984; Avchimovitch et al., 1988) and the Parnaíba Basin in Brazil (Loboziak et al., 1992). It is therefore no surprise that the succession of miospore assemblages at the D/C boundary in Sauerland (LL, LE, LN, VI and HD zones) is exactly the same as in Ireland and Britain (cf. Higgs & Streel, 1984; Higgs et al., 1993). Moreover, miospores occur where conodonts have not been found, especially in the Hangenberg Shale in between the Wocklum Limestone and the Hangenberg Limestone. Therefore, the biostratigraphic information provided by them is fully complementary to that provided by conodonts.

The biostratigraphic interpretation of the miospore assemblage is, however, not always and everywhere unequivocal. There may be miospores from "hinterland" floras which remain isolated for topographical reasons and are recorded in coastal areas only when their acme zone starts, somewhat higher in the stratigraphic column (see continental Westphalian/ Stephanian examples in Bless et al., 1977; Clayton et al., 1977). The assemblages may also contain miospores which have been reworked from older deposits (cf. Streel & Bless, 1980). In both cases, one has to invoke restriction in the lateral distribution of the miospores which, due to the longshore currents, is normally widespread in nearshore marine basins where the fluvial discharge deposits most of the microfloral material.

These problems seem to play a role in the miospore assemblages from the Hangenberg Shale at Oese, Apricke and Oberrödinghausen. The presence of reworked miospores derived from the "PLm-i zone" (= "middle" LV zone according to Streel, 1986 fig. 3) was already noticed by Paproth & Streel (1970). Higgs & Streel (1984) assigned these assemblages to the LL zone, but mentioned the anomalous presence of Lophozonotriletes triangulatus and Vallatisporites verrucosus, two taxa which normally appear in the younger LE zone in Ireland (Higgs & Streel, 1984). The same is true at Riescheid, where these taxa are absent in the samples attributed to the LL zone and appear slightly above the base of the LE zone (Higgs & Streel, 1984). A further difference between the samples from Oese, Apricke and Oberrödinghausen and those form the LL zone at Riescheid consists in the almost absence of miospores of the Diducites complex, which are

"particularly abundant" in the LL biozonal assemblages of the Riescheid section (Higgs & Streel, 1984).

One might question why these assemblage had not been assigned to a higher zone. The discovery of *Hymenozonotriletes explanatus* or perhaps even *Verrucosisporites nitidus* would have solved the problem, because the base of these miospore zones is defined by the first appearance of its zonal index taxon. The presence of *H. explanatus* would have allowed an assignment to the LE zone, and the presence of *V. nitidus* to the LN zone. Otherwise, the assemblages of the LL, LE and LN zones are rather similar. But these for the recognition of the LE or LN zone "vital" taxa have not been found (specimens identified as V. nitidus by Paproth & Streel, 1970, belong to *V. mesogrumosus*). The fact, however, that these assemblages occur together with ammonoids of the *"Imitoceras"* group in the Hangenberg Shale of the Oberrödinghausen section is considered as an important argument for the correlation of the same with the lowermost occurrence of *Acutimitoceras/ Mimimitoceras (?) substriatum* at Drewer within or immediately on top of the HBS. This in turn is correlated with the lithological succession in between the HBS beds 162 and 152 at Stockum that has been dated by miospores as belonging to the LN zone (Higgs & Streel, 1993). Thus, the (incomplete) ammonoid evidence from the Hangenberg Shale at Oberrödinghausen indicates that the miospores assemblages from the Hangenberg Shale at Oese, Apricke and Oberrödinghausen should not be older than the LN zone.

Hangenberg Shale sequences in the Oese, Apricke and Oberrödinghausen sections were deposited during the maximum of the regression (see 3.), in a somewhat isolated small basin in the immediate eastern area near the Seiler deltaic deposits (see fig. 3). The small basin was enclosed by the emergence of some shoals (like in Müssenberg) and therefore might have been separated from the longshore currents. In front of this small basin, onshore erosional processes might have reworked exceptionnally abundant LL- aged sediments seawards with reworked miospores largely outnumbering those produced by the contemporaneous flora. In light of these questions, several of these sections are being once more reinvestigated (see note at the end of the text).

The following synthesis of the miospore zonation is based on papers by Higgs & Streel (1984) and Higgs *et al.* (1993).

- Miospore assemblages typical of the LL zone have only been recognized at Riescheid, where they occur between 12,5 and 15 m below the top of

a succession of greenish silty shales. The lower boundary of this zone has not been established in Sauerland. The presence of a limestone nodule with conodonts of the *"costatus* zone" above the highest miospore sample of the LL zone suggests that the top of this zone is situated below the top of the *"costatus* zone".

- Miospore assemblages of the LE zone have been found at Riescheid and Hasselbachtal. At Riescheid, they occur between 1 and 10 m below the top of the greenish silty shales (Higgs & Streel, 1984). At Hasselbachtal, a shale layer some 50 cm below the top of the Wocklum Limestone has yielded an LE biozonal assemblage, this is below the highest sample yielding a "middle *costatus* conodont assemblage", and well below the topmost occurrence of the cephalopods *W. sphaeroides* and *P. paradoxa* (cf. Becker *et al.*, 1984; Higgs & Streel, 1984).

- Miospore assemblages of the LN zone occur in six sections. It is emphasized once more that the index taxon *V. nitidus* has not been found in the samples from the (lower portion of the) Hangenberg Shale at Oese, Apricke and Oberrödinghausen (see discussion above). The observed base of typical LN assemblages is therefore strongly diachronous in Sauerland. The lowermost occurrence is in the lower HBS (bed 162) of the Stockum II-1988 trench (Higgs *et al.*, 1993). Miospore assemblages of the LN zone are known from some 4 m below the top of the Hangenberg Shale in the Hasselbachtal borehole (Higgs *et al.*, 1993), this is some 1-2 m above the top of the Wocklum Limestone. At Oese, typical LN assemblages only occur in the upper 2 m of the Hangenberg Sandstone, this is some 10-11 m above the top of the Wocklum Limestone. The only typical LN assemblage in the Apricke section occurs above a limestone bed that is tentatively equivalent to the "lower *Protognathodus* fauna".

- The top of the LN zone and the boundary with the overlying VI zone has been established 14 cm below limestone bed 84 (with the conodont *S. sulcata*) at Hasselbachtal (Becker *et al.*, 1984; Higgs & Streel, 1984). This is 2 cm below the first but questionable appearance of the cephalopod *A. acutum* (cf. Korn, 1993). The evidence at Seiler (miospores of the LN zone in between limestones of the "lower and upper *Protognathodus* faunas") and at Stockum (miospores of the VI zone below Bed c in the Stockum I trench, belonging to the "upper *Protognathodus* fauna"; cf. discussion in Higgs *et al.*, 1993 and in Clausen *et al.*, in press) proves that the LN zone ranges within the "lower *Protognathodus* fauna" and that the VI zone starts just below the base of the "upper *Protognathodus* fauna",

probably in the topmost "lower *Protognathodus* fauna" range.

- Miospore assemblages of the VI zone have been described from two sections : Hasselbachtal and Stockum. Only the basal portion of this zone has been recognized : 18.5 cm at Hasselbachtal and 1.3 m at Stockum. In both cases this corresponds to shale layers just below and in between limestone lenses of the basal "upper *Protognathodus* fauna" or basal *sulcata* zone.

- The basal portion of the black Lower Alum Shale at Riescheid and Oberrödinghausen has yielded miospore assemblages of the HD zone.

3.- T-R CYCLES

The litho- and biostratigraphic succession in Sauerland consists of fourteen units, which are tentatively compared with the T-R cycles of Johnson *et al.* (1985, 1986), Sandberg *et al.* (1986), Van Steenwinkel (1990, 1993) and Flajs & Feist (1988). In upward order the following units are recognized (fig. 5) :

Unit 1 - Wocklum Limestone. The top of this unit is correlated with the *Wocklumeria* Limestone (bed 68) at La Serre, and presumably represents the end of the IIf transgression in Johnson *et al.* (1986) and the Etroeungt transgression in Van Steenwinkel (1990).

Unit 2 - The thin sandstone with the first *C. evoluta* at Drewer (here referred to as Drewer Sandstone) presumably represents a minor regression, correlatable with the layer carrying the LE spore assemblage in Hasselbachtal and the sandy slate bed 69 at La Serre. Other sections of the Sauerland show increasing condensation and fossil-richness towards the top of the Wocklum Limestone (Becker, 1993a e.g. Oese section).

Unit 3 - The topmost Wocklum Limestone in Sauerland is characterized by an "upper *costatus* conodont assemblage" and the beginning of the *hemisphaerica-latior* (ostracode) interregnum (cf. Bless & Groos-Uffenorde, 1984; Becker *et al.*, 1984). This is considered as an inceptive transgressive pulse that will reach its acme in the next lithological unit.
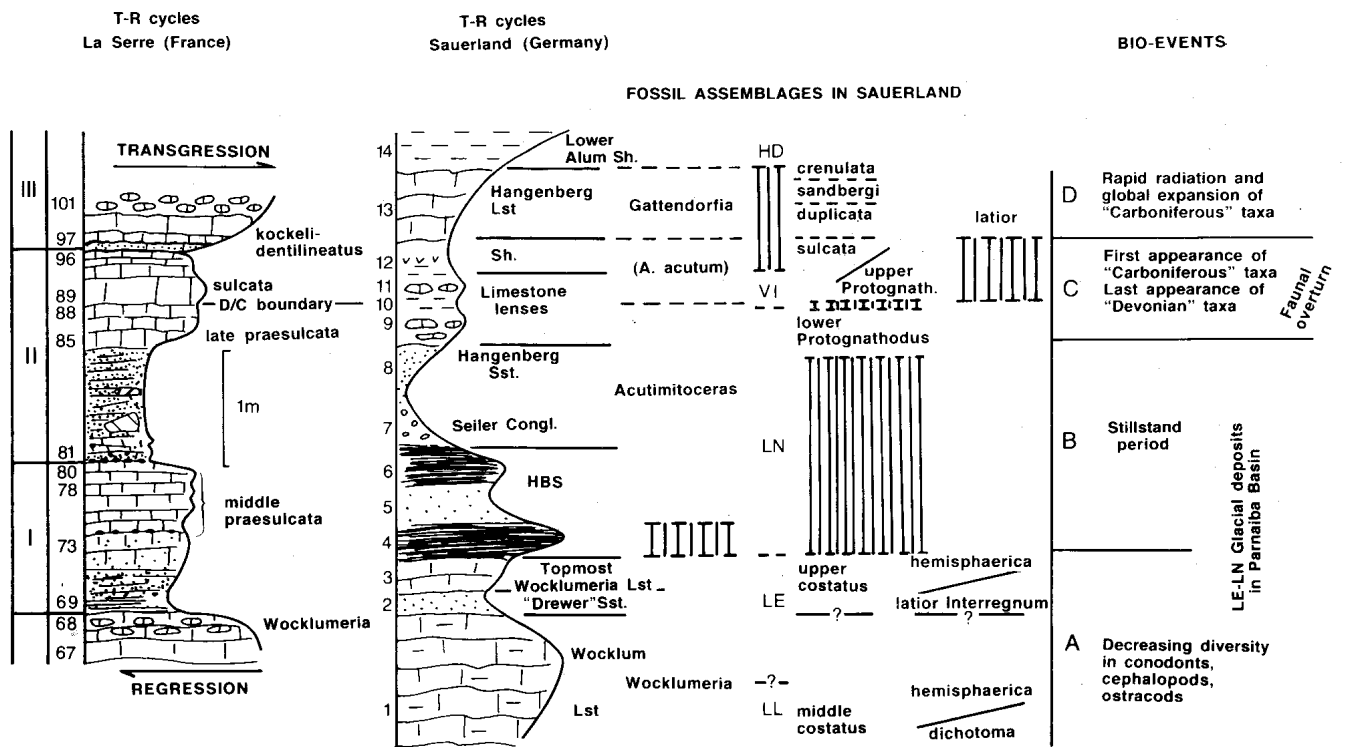

Fig. 5.- Comparison between principal bio-events around D/C boundary and the lithostratigraphic/biostratigraphic framework and relative sea level changes at La Serre (Montagne Noire, France; after Flajs & Feist, 1988, and Paproth *et al.*, 1991) and in the Sauerland area (northern border of Rhenish Slate Mountains, Germany; this paper).

Units 4-6 (bed 210 in section WJ) - The anoxic episode of the basal HBS forms the acme of a short-lived transgression that started in unit 3. Regression (unit 5) followed by a minor, equally short-lived transgression (unit 6) is illustrated by the succession of shale/sandstone and the upper HBS at Drewer and Stockum (there developed as a black, argillaceous and bituminous limestone : bed 152). Unit 4 is marked by the first LN spore assemblage and unit 5 by the first "*Imitoceras*"/*Acutimitoceras/Mimimitoceras (?)* faunas.

Unit 2 to 6 are correlated with cycle I (beds 69-80) at La Serre because of the presence of middle *praesulcata* (= "upper *costatus*") conodont faunas in both.

Units 7-8 - These units represent the acme of regression in Sauerland as illustrated by the widespread occurrence of coarser-grained siliciclastics (Seiler Conglomerate and Hangenberg Sandstone). This interval is either absent or very condensed at Drewer (possibly limited to bed 209 in section WJ; cf. Korn, 1991 : fig. 2). At Stockum, it corresponds to beds 109-151 (cf. Clausen *et al.,* in press : fig. 3). This interval is correlated with the lower portion (beds 81-84) of Cycle II at La Serre.

Units 9-11 - This interval is characterized by lenticular, frequently cephalopod-bearing limestone beds, which point to a minor transgression. These limestones with conodonts of the "lower (unit 9)and upper (unit 11) *Protognathodus* faunas" and first *S. sulcata* (at Hasselbachtal and Seiler) are correlated with the upper portion of Cycle II (beds 85-96) at La Serre, wherein conodonts of the late *praesulcata* and basal *sulcata* zones occur. The minor shale intercalation (unit 10) in between these limestones coincides with the boundary between spore zones LN and VI, and points to a small regressive pulse producing the oolithic Bed 84 at Hasselbachtal. This regressive tendency is also noticed at La Serre in beds 87-88 at the top of the late *praesulcata* zone.

Unit 12 - A cm to dm thick shale/mudstone interval (with a tuff layer at Hasselbachtal and Seiler) possibly represents a faint regressive tendency. This interval is correlated with the regression following Cycle II (bed 97) at La Serre and it must have caused the removal or non-deposition of the Stockum Limestone at Oberrödinghausen.

Units 13-14 - The inception of the *Gattendorfia*-bearing Hangenberg Limestone marks the beginning

of a major transgression *sensu* Van Steenwinkel (1990, 1993). This transgression continues and accelerates during the deposition of the Lower Alum Shale (coeval with the Middle Tournaisian Pont d'Arcole Shale in Belgium). The base of this transgression is correlated with the base of Cycle III (beds 98-100) at La Serre.

4.- BIO-EVENTS

Four main episodes (A-D) can be distinguished in the faunal succession around the D/C boundary in Sauerland (fig. 5) :

Episode A - The top of the Wocklum Limestone is marked by an overall decrease in faunal diversity, and sometimes even decrease in the relative number of individuals. This is noticed, for instance, among conodonts, ostracodes, cephalopods and trilobites (cf. Dreesen *et al.,* 1986; Bless & Groos-Uffenorde, 1984; Blumenstengel, 1993; Luppold *et al.,* 1984; Korn, 1986; Becker, 1993a). This interval corresponds to the LE spore zone (Higgs & Streel, 1984). In the South American Parnaíba Basin (Brasil), sediments with LE-LN spore assemblages have been interpreted as glacial deposits (Loboziak *et al.,* 1992). Perhaps there is a causal correlation between the start of this glaciation, the minor regression at the end of the Wocklum time (Drewer Sandstone) and the decrease in faunal diversity ?

Did the end of the Wocklum time really constitute a moment of mass extinction ? The available evidence is at least incomplete. There exists an observation gap between the top of the Wocklum Limestone and the base of the limestone lenses with "lower *Protognathodus* conodont assemblages" as far as conodonts, entomozoacean and Thuringian-type ostracodes, trilobites and perhaps even cephalopods (see discussion under 2.2. on cephalopods from HBS) are concerned. Perhaps the major regression during the deposition of the HBS, Seiler Conglomerate and Hangenberg Sandstone produced a more gradual process of mass extinction ?

Episode B - Rather poor and monotonous fossil assemblages illustrate the unfavourable ecological conditions during the short-lived transgressions (marked by the anoxic deposits of the HBS) and major regressions of episode B. Most likely, this was a stillstand period for evolution. Only very few survivors could adapt themselves to these rapidly changing environments and evolve into new taxa.

Acutimitoceras seems to be an outstanding representative of this group.

It is at least a tempting thought to look for a causal connection between the major sea level fall during episode B and the presence of glacial/interglacial deposits of the LE-LN spore zones in the Parnaíba Basin (Loboziak *et al.,* 1992). Could the short-lived HBS transgressions correspond to interglacial phases (see also Streel 1986) ?

Episode C - The minor transgression around the D/C boundary coincided with the appearance of new faunal elements among cephalopods (diversification of *Acutimitoceras*), trilobites *(Perliproetus),* conodonts *(P. kockeli-kuehni* lineage, *S. praesulcata-sulcata* lineage) and entomozoacean ostracodes (new species of *Maternella* and *Richterina;* cf. Bless & Groos-Uffenorde, 1984). Devonian-type cephalopod taxa *(Cymaclymenia, Wocklumeria, Lissoclymenia)* and some Devonian conodont groups including the latest icriodids occur for the last time immediately below the D/C boundary in beds with *Acutimitoceras* and "lower *Protognathodus* conodont assemblages" (although one species of *Cymaclymenia* occurs within or immediately above the late *praesulcata* zone at Müssenberg in bed 3B; cf. Korn, 1989). This means that the final faunal overturn coincided with the apparently small regressive pulse (unit 10) just before the D/C boundary. Evidently, this event must have been much more important than can be deduced at present from the lithological successions in Sauerland and at La Serre. It coincides with the major microfloral change (LN/VI) which corresponds to the extinction event for plants/miospores.

Episode D - A major radiation and dispersal of "Carboniferous" taxa took place from the very beginning of this episode (base of Hangenberg Limestone and time equivalents) onwards. This has been documented for ammonoids by Becker (1993a) and Korn (1993), for trilobites by Brauckmann *et al.* (1993), for conodonts by e.g. Dreesen *et al.* (1986) and for ostracodes by Tschigova (1975), Bless & Groos-Uffenorde (1984) and Blumenstengel (1993).

CONCLUSION

The transgression/regression (T-R) curve showing a remarkable similarity with the one constructed for the La Serre D/C boundary stratotype (Montagne Noire, France), it is suggested that these T-R curves are closely related to global (eustatic) sea level changes.

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Note added after the first proof :

Specimens of *V. nitidus* have recently been found by one of us (K.H.) 0-10 cm and 10-30 cm above the base of the HBS at Oberrödinghausen railway cut.