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LATE CRETACEOUS SEA LEVEL RISE AND INVERSION : THEIR INFLUENCE ON THE DEPOSITIONAL ENVIRONMENT BETWEEN AACHEN AND ANTWERP[1]

by

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(13 figures, 1 table and 3 plates)

RESUME.- Des recherches pluridisciplinaires dans les dépôts du Crétacé supérieur (Santonien à Maastrichtien) entre Aachen et Antwerpen (NE Belgique, SE Pays-Bas et région d'Aachen en République fédérale allemande) ont démontré leur histoire sédimentaire relativement complexe. Des corrélations entre différentes lithologies sont basées sur des bioclastes, des Foraminifères, des Ostracodes, des Belemnites et des logs pétrophysiques des sondages. Le dépôt a été contrôlé par une montée continue du niveau de la mer du Santonien à la fin du Maastrichtien supérieur et par des mouvements tectoniques (inversion de subsidence à partir du Campanien inférieur, relâchement de l'inversion à partir de la partie moyenne du Maastrichtien supérieur, gauchissement différentiel des blocs au sud de la région de la vallée de la Rur, en particulier du Campanien supérieur au début du Maastrichtien supérieur).

Un changement majeur dans les assemblages fossiles, à l'entrée de la partie moyenne du Maastrichtien supérieur, est marquée par l'apparition d'éléments méditerranéens, par une modification brusque de la composition quantitative des assemblages de bioclastes, et par une diversification plutôt brutale et accentuée de la plupart de groupes fossiles. Ce changement correspond au début du relâchement de l'inversion dans la région de la vallée de la Rur et il est interprété comme un des événements écostratigraphiques régionaux induits par la tectonique.

ABSTRACT.- Pluridisciplinary investigations on Upper Cretaceous (Santonian to Maastrichtian) in the Aachen-Antwerp area (NE Belgium, SE Netherlands and Aachen area of Federal Republic of Germany) have revealed the rather complex sedimentary history of the same. Correlations between different lithologies are based on bioclasts, foraminifera, ostracodes, belemnites and petrophysical borehole logs. Deposition was controlled by continuous sea level rise during the Santonian to late Upper Maastrichtian and by tectonic movements (inversion of subsidence since the Lower Campanian, relaxation of the inversion since the middle Upper Maastrichtian, differential warping of blocks to the south of the Rur Valley area notaby during the Upper Campanian to early Upper Maastrichtian).

A major change in the fossil assemblages at the onset of the middle Upper Maastrichtian is noticed in the appearance of mediterranean elements, in a dramatic change in the quantitative composition of bioclast assemblages, and in a rather abrupt and pronounced diversification of most fossil groups. This change matches the beginning relaxation of the inversion in the Rur Valley area and it is interpreted as one of several regional, tectonically induced ecostratigraphical events.

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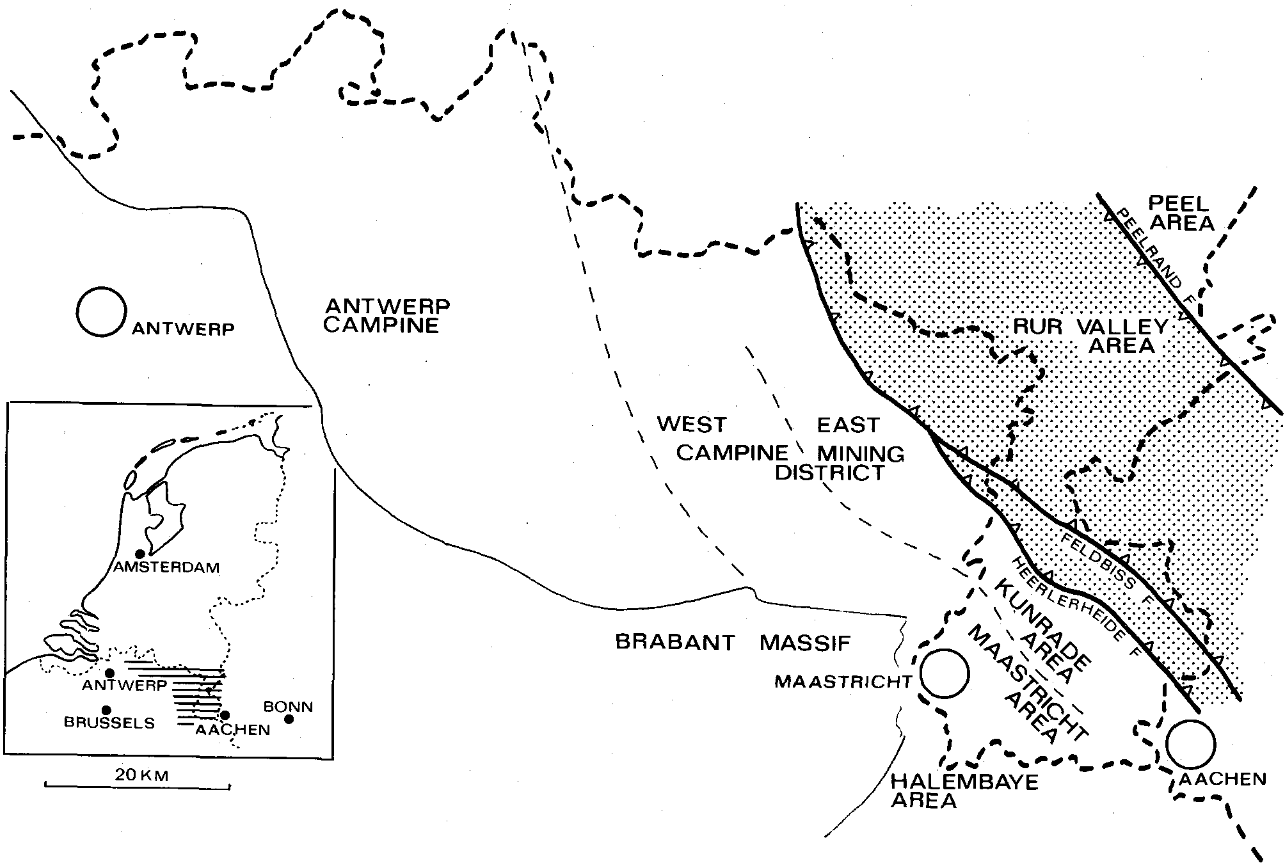

Fig. 1.- Localisation of paleogeographic areas distinguished in the present report. The edge of the Brabant Massif is defined here by the Dinantian subcrop.

I.- INTRODUCTION

Upper Cretaceous to basal Tertiary (Lower Paleocene) sediments have been observed in many boreholes and outcrops between Aachen (Federal Republic of Germany) and Antwerp (Northern Belgium). Among these are the classical outcrops of the Upper Maastrichtian chalk around Maastricht (South Limburg, Southeastern Netherlands). Deposits of this age are presumably absent or extremely reduced and incomplete in the Rur Valley Graben which is marked to the southwest by the Heerlerheide Fault and Feldbiss Fault and to the northeast by the Peelrand Fault. A poorly known Upper Cretaceous sequence occurs immediately north of the Peelrand Fault in the Peel area (fig. 1).

The chrono-, bio- and lithostratigraphic subdivisions of the Upper Cretaceous and basal Tertiary deposits have been subject of numerous studies (fig. 2). Recent reviews have been published by Robaszynski *et al.* (1985) and P.J. Felder *et al.* (1985a, 1985b).

Three Upper Cretaceous (Santonian, Campanian, Maastrichtian) and one Lower Paleocene (Danian) stages have been distinguished. However, the Santonian age of the Aachen Formation has not yet been confirmed by biostratigraphic methods. The subdivision of the Campanian and Maastrichtian stages is based on belemnites (Schmid, 1959, 1967), whereas that of the Lower Paleocene has been made by using benthic foraminifera (Hofker, 1966).

CHRONO-STRATIGRAPHY (Schmid 1959)	BIO/ECO-STRATIGRAPHY (Hofker 1966)	LITHO-STRATIGRAPHY (W.M.Felder 1975)	MARKER HORIZONS
			Lutterade
Paleocene	R Q P	Houthem	
			Vroenhoven
Maastrichtian	M L K I H G (O J)	Maastricht	
			Lichtenberg
	F E D C B	Gulpen	
	A		Slenaken Zeven Wegen
Campanian	A'-upper A'-middle A'-lower	Vaals	
			Raren
Santonian	---	Aken	
			Hergenrath

Fig. 2.- Classical subdivision of the Upper Cretaceous in the southeastern Netherlands (South-Limburg) according to Schmid (1959 ; chronostratigraphy), Hofker (1966 : bio-/ecostratigraphy) and W.M. Felder (1975 : lithostratigraphy).

Benthic foraminifer assemblages allow a detailed subdivision of the Campanian to Lower Paleocene deposits (Hofker 1957, 1966). However, lateral changes in the sedimentary environment have controlled these assemblages to such extend that different zonations had to be established for the Maastricht and Kunrade areas. A revised correlation between these foram zones has been proposed by P.J. Felder *et al.* (1985a, 1985b). The lithostratigraphic subdivision of these strata was formally introduced by W.M. Felder (1975). This author distinguished five formations (in ascending order : Aachen, Vaals, Gulpen, Maastricht and Houthem), which may be subdivided into members separated by supposedly widespread marker horizons.

Pluridisciplinary analysis of bioclast, ostracode and foraminifer assemblages and of petrophysical borehole logs has yielded strong arguments for a renewed discussion on the value of the field characteristics on which these formations, members and marker horizons are based (P.J. Felder *et al.,* 1985a, 1985b). Apparently, the lateral and vertical relationships between these formations and members are more complex than had been accepted thus far (fig. 3). Moreover, the correlation of individual marker beds between different outcrops and boreholes may need a thorough revision (fig. 4).

The final proof of the correctness of the here proposed correlations between marker horizons, members and formations will be yielded by a detailed investigation of belemnites and ammonites. Most surprisingly, these have only been studied from a rather limited number of beds and localities (Schmid, 1959, 1967; Van der Tuuk & Bor, 1980; Jagt, 1984; Robaszynski *et al.,* 1985). However, a first broad-brush survey of the material stored in different collections has shown that such a detailed revision will largely corroborate the correlations on which this paper is based (a.o. J. Jagt, pers. comm.).

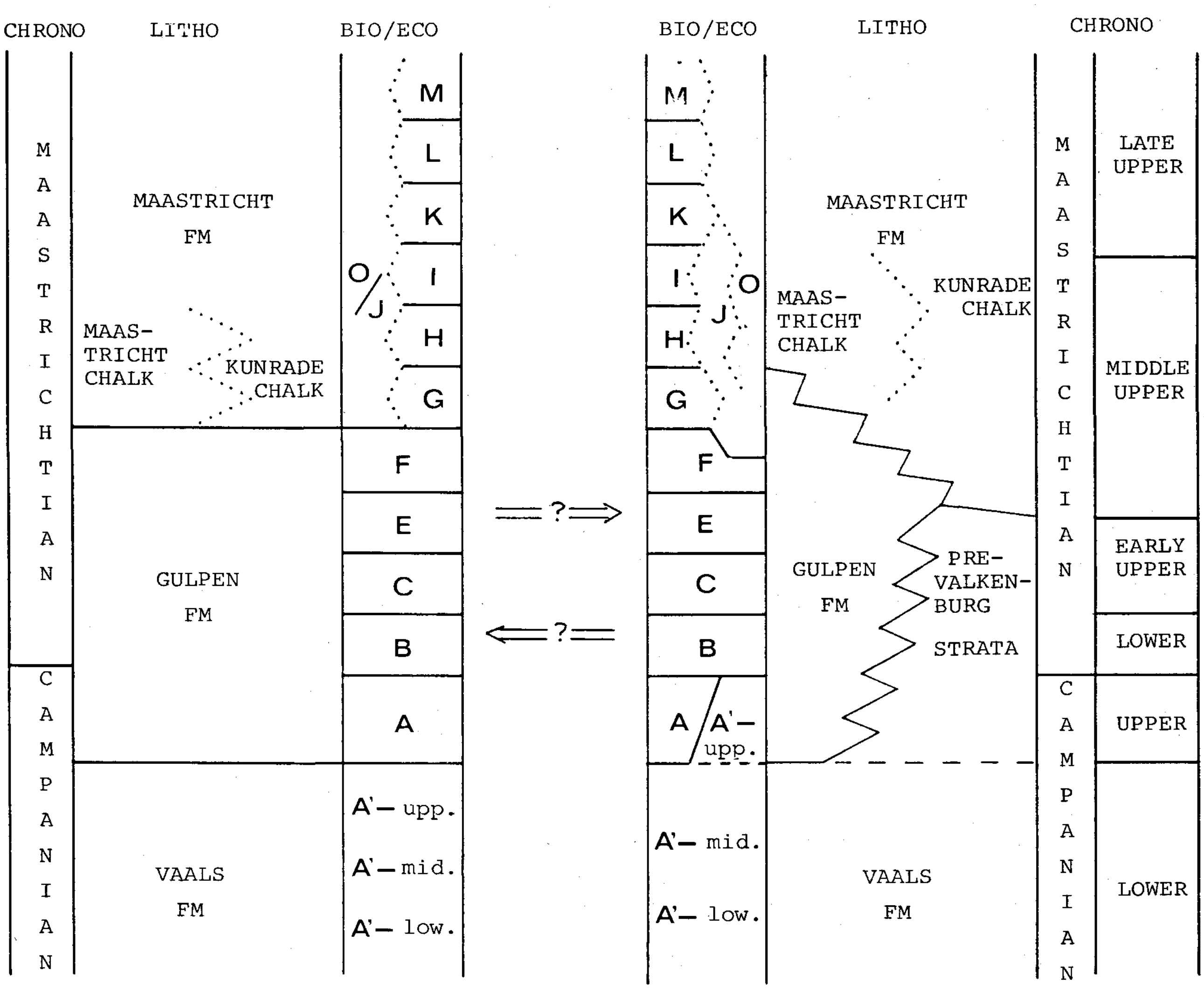

Fig. 3.- Comparison between the classical subdivision of the Campanian and Maastrichtian (left part of figure; compare with figure 2) and the here adopted concept (right side; after P.J. Felder *et al.,* 1985a, 1985b).

VOGELRESERVAAT	LANAYE	ENCI	DOLEKAMER	NEKAMI
		Laumont	Laumont	Laumont
		Lava	Romontbos	Romontbos
		Romontbos	Schiepersberg	---
		---	---	Schiepersberg
Romontbos	(Romontbos)	Schiepersberg	---	St.Pieter
St.Pieter	(St.Pieter)	---	---	---
Lichtenberg	---	?ENCI	St.Pieter	---
	Lichtenberg	St.Pieter	---	---
	Flint layer 20	Lichtenberg	Lichtenberg	---
	Flint layer 9	Flint layer 9		Lichtenberg
	Nivelle	Nivelle		

MARKER HORIZONS

VOGELRESERVAAT	LANAYE	ENCI	DOLEKAMER	NEKAMI
Eroded	Eroded	Emael	Emael	Emael
Emael	Emael	Schiepersberg	Schiepersberg	Schiepersberg
Schiepersberg Gronsveld	Schiepersberg Gronsveld	Gronsveld	Gronsveld	Gronsveld
Valkenburg	Valkenburg	Valkenburg	Valkenburg	Valkenburg
Lanaye	Lanaye	Lanaye	Lanaye	Lanaye

MEMBERS

Fig. 4.- Revised correlation of marker horizons (upper part) and members (lower part) in the middle Upper Maastrichtian. Naming of horizons and members for different locations according to existing literature (cf. P.J. Felder *et al.*, 1985b for references). Location of sections is shown on map in figure 6. Correlations based on assemblages of bioclasts, foraminifera and ostracoda (after P.J. Felder *et al.* 1985b).

The following chapter briefly discusses the different lithologies and their fossil contents in the main chronostratigraphic intervals. Subsequently, an analysis is made of the vertical and lateral variations of lithofacies and fossil assemblages and their relationship to the regional Late Cretaceous inversion tectonics and paleogeography.

2.- CHARACTERISTICS OF MAIN CHRONOSTRATIGRAPHIC INTERVALS

2.1.- SANTONIAN

Strata assigned to this interval have not been formally dated by paleontological methods. All the deposits belong to the Aachen or Aken Formation consisting of sandy to silty clays, silty to clayey sands and fine to coarse-grained sands. Locally thin seatearths and lignite lenses are intercalated. Coalified (lignite), pyritized or silicified wood-fragments, plant seeds, megaspores and pollen may be abundant. The same holds for pyrite and marcasite concretions. Mud-sands with poorly sorted, angular lithoclasts suggest local torrential fan-deposits of local origin. Cross-bedded sands with subrounded to well-rounded quartz grains and exhibiting intercalated beds with a clear bioturbation are interpreted as beach and dune deposits. Clayey to silty deposits with seatearths and lignite lenses may point to alluvial or lagoonal swamp environments. The Aachen Formation has not been recognized on the Brabant Massif nor in the Antwerp Campine. This formation is practically absent north of the Heerlerheide Fault.

2.2.- LOWER CAMPANIAN

The age of the strata assigned to this interval has been established by the study of belemnites (notably *Gonioteuthis quadrata;* Schmid 1959, 1967; Van der Tuuk & Bor, 1980; Jagt, 1984; Robaszynski *et al.,* 1985). In practice this interval is recognized by the benthic foraminifer assemblage characterizing Hofker's foram zone A'-lower to A'-middle (P.J. Felder *et al.,* 1985a, Robaszynski *et al.,* 1985). All the deposits belong to the Vaals Formation (formerly frequently called «Herve») consisting of slightly calcareous to marly sands and silts with varying amounts of authigenic glauconite. More sandy sediments predominate in the Campine Mining area and Kunrade area, whereas those of the Antwerp Campine, Brabant Massif, Maastricht and Halembaye areas are usually more clayey. These marine deposits are characterized by high amounts of mollusc clasts (among which frequently fragments of belemnites) and frequently high percentages of ornamented ostracodes (Bless *et al.,* 1983; P.J. Felder *et al.,* 1985a, 1985b). The abundance of authigenic glauconite and the common occurrence of burrows points to a shallow marine environment. The Vaals Formation is practically absent in the area north of the Heerlerheide Fault.

Remarkable is the relatively high number of planktonic foraminifera (with a double keel) in the rather clayey strata (with low glauconite contents) of the Antwerp Campine. This suggests a relatively deeper, and maybe more open marine environment.

2.3.- UPPER CAMPANIAN

The age of the sediments included in this interval has been established by the occurrence of a.o. the belemnite *Belemnitella mucronata* (Schmid, 1959, 1967; Van der Tuuk & Bor, 1980; Jagt, 1984; Robaszynski *et al.,* 1985). In practice this interval is recognized by benthic foraminifer assemblages characterizing Hofker's zone A which equates Hofker's zone A'-upper (P.J. Felder *et al.,* 1985a, 1985b). Two completely different lithofacies are distinguished :

- Coarse-grained (mean 37 μ) calcisiltites of the Zeven Wegen Chalk (basal member of Gulpen Formation sensu W.M. Felder 1975), and
- sandy to silty, glauconitic marls, locally with chalk intercalations, which have been assigned either to the (upper) Vaals Formation or upper Hervian (notably in the Kunrade area) or to the lower Pre-Valkenburg deposits (P.J. Felder *et al.,* 1985a for eastern Campine Mining District, there formerly also identified as either «Craie de Nouvelles» or «Herve»).

The Zeven Wegen Chalk occurs in the Antwerp Campine, on the northeastern part of the Brabant Massif, and in the Halembaye and Maastricht areas. The glauconitic marls have been recognized in the Campine Mining District and in the Kunrade area.

The correlation between these two lithologies is based on petrophysical borehole logs (between Antwerp Campine and Eastern Campine Mining District), benthic foraminifera (presence of *Globorotalites micheliniana* and absence of *Gavelinella clementiana* with dorsal ornamentation; *Bolivinoides decorata* with 3-4 pustules on last chamber is practically restricted to the chalk facies - foram zone A -, whereas *Lenticulina triangularis* seems characteristic for the glauconitic marls of foram zone A'-upper), and ostracodes (low numbers of ornamented specimens, this in contrast to Lower Campanian; *Cuneoceratina* characterizes the chalk facies and *«Xestoleberis» bidentata* the glauconitic marls - figure 5). Moreover, in the Kunrade area two specimens of the ammonite *Pachydiscus* cf. *stobaei* (a guide for the lower half of the Upper Campanian in NW Germany) have been detected (J. Jagt, pers. comm.) as well as several specimens of the belemnite *Belemnitella mucronata* (equally a guide for the Upper Campanian; J. Jagt, pers. comm.). A note on these finds in the Kunrade area will be published by J. Jagt, M.J.M. Bless, P.J. Felder and J.P.M.Th. Meessen in the Natuurhistorisch Maandblad van Limburg (1). Moreover, it should be noticed that no sections are known where foram zone A occurs on top of foram zone A'-upper, and that sequences with foram zone A are of about the same thickness as those with foram zone A'-upper. Both the chalk and the glauconitic marls of Upper Campanian age contain high amount of mollusc clasts (P.J. Felder *et al.,* 1985a, 1985b). Upper Campanian sediments have not been recognized in the recent borehole Thermae 2000 in Valkenburg (Bless *et al.,* 1986), but occur a few kilometers to the east in the borehole Walem (P.J. Felder *et al.,* 1985b), where *Bolivinoides decoratus* occurs in glauconitic marls.

(1) Since this paper had been submitted for printing, the presence of *Belemnitella mucronata* in the glauconitic marls of the Pre-Valkenburg deposits of the «De Dael» section in the Kunrade area has been confirmed by Dr. Walter Kegel Christensen (Copenhagen, pers. comm. 15-9-1986). This may be considered as a final proof that part of the Pre-Valkenburg strata (formerly described as «Hervian» or Vaals sediments, or as «Benzenrade Chalk») is of the same chronostratigraphic age as the Zeven Wegen Chalk in the Maastricht area. By inference this supports the earlier mentioned correlation between Hofker's foram zone A and A'-upper.

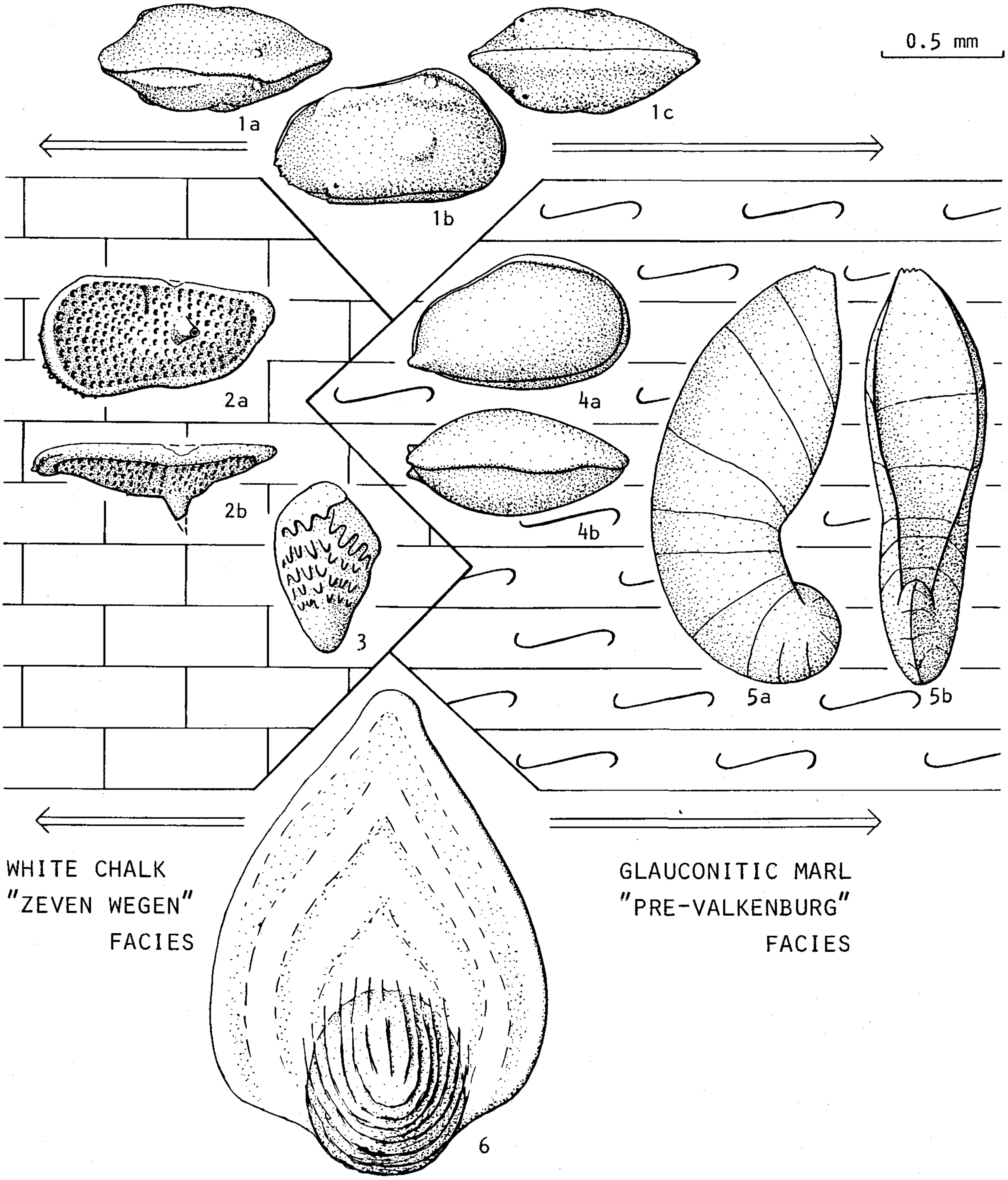

Fig. 5.- Occurrence of some rare foraminifera and ostracodes in the Upper Campanian of the Aachen-Antwerp area. Species like *Cuneoceratina pedata* (2) and *Bolivinoides decorata* (3) preferably occur in the white chalk of the «Zeven Wegen» facies (Antwerp Campine, Brabant Massif, Maastricht-Halembaye areas). Others such as «*Xestoleberis*» *bidentata* (4) and *Lenticulina triangularis* (5) apparently preferred the glauconitic marls of the «Pre-Valkenburg» facies (Campine Mining District, Kunrade area). Many species however seem to have been independent of the lithofacies. This appears to be the case for a.o. *Mosaeleberis rutoti* (1) and *Flabellina radiata* (6).

1: *Mosaeleberis rutoti*, Borehole Kunderberg, 36-37 m; 2: *Cuneoceratina pedata*, Borehole Poederlee, 678 m; 3: *Bolivinoides decorata*, Borehole Zeven Wegen, 1.0-1.5 m; 4: «*Xestoleberis*» *bidentata*, Borehole Kunderberg, 15-16 m; 5: *Lenticulina triangularis*, Borehole Kunderberg, 36-37 m; 6: *Flabellina radiata*, De Dael section, 4.5-5.0 m.

2.4.- LOWER MAASTRICHTIAN

The belemnite *Belemnella lanceolata* characterizes this time interval (Schmid, 1959, 1967; Van der Tuuk & Bor, 1980; Robaszynski *et al.,* 1985). In practice this interval is recognized by the benthic foraminifer assemblage characterizing Hofker's zone B (P.J. Felder *et al.,* 1985a, 1985b). Also the Lower Maastrichtian sediments exhibit two different lithologies, which are roughly comparable to those of the Upper Campanian :

- Coarse-grained (mean 51 μ) calcisiltites of the Beutenaken Chalk (second member of Gulpen Formation sensu W.M. Felder, 1975) which may be marly in the lower portion of the sequence («Beutenaken Marl» sensu Demyttenaere & Dusar *in :* P.J. Felder *et al.,* 1985a), and
- sandy to silty, glauconitic marls, locally with chalk intercalations, which have been assigned either to the (upper) Vaals Formation or upper Hervian (notably in the Kunrade area) or to the upper Pre-Valkenburg deposits (P.J. Felder *et al.,* 1985a for eastern Campine Mining District; there formerly also identified as either «Craie de Nouvelles» or «Herve»).

The Beutenaken Chalk is present in the Antwerp Campine, on the northeastern part of the Brabant Massif and in the Maastricht area. In the Halembaye area this chalk is limited to some local pockets and burrow fillings in the underlying hardground on top of the Zeven Wegen Chalk. This suggests either incomplete deposition or non-deposition, or erosion of the chalk before the Upper Maastrichtian sedimentation started. The glauconitic marls have been described from the Campine Mining District and from the Kunrade area.

Lower Maastrichtian sediments have not been observed thus far around Valkenburg (Bless *et al.,* 1986). Possibly this was an area of non-deposition separating the chalk sedimentation to the southwest and the glauconitic marl deposition to the northeast.

The correlation between these two lithologies is based on petrophysical borehole logs (between Antwerp Campine and Eastern Campine Mining District), benthic foraminifera (foram zone B, largely restricted to chalk facies; but presence of *Eponides beisseli* and *Stensiöina pommerana* along with absence of *Globorotalites micheliniana* is accepted as strong evidence for foram zone B, particularly since this association occurs in borehole KS18 in Eastern Campine Mining District together with *Bolivinoides australis* with 4-5 pustules on last chambers, see P.J. Felder *et al.,* 1985a), belemnites (*Belemnella lanceolata* seems largely restricted to chalk facies, but one occurrence in glauconitic marl has been cited by Jeletzky, 1951, p. 16, from the uppermost part of Hervian greensand in Shaft Emma II near Heerlen) and maybe ammonites (cf. Jeletzky, 1951, p. 16 : «*Diplomoceras* cf. *cylindraceus*» and «*Pachydiscus colligatus*»).

Low numbers of ornamented ostracodes are characteristic for the chalk facies, but these are rare in the glauconitic marls (impoverished assemblages).

The Lower Maastrichtian chalk and glauconitic marl are both characterized by high amounts of mollusc clasts among which a high percentage of fragments of the prismatic layer of pelecypods (Inoceramids?, P.J. Felder *et al.,* 1985a, 1985b).

2.5.- UPPER MAASTRICHTIAN

The base of this substage is characterized by the appearance of the belemnite *Belemnitella junior* (Schulz *et al.,* 1984). Several belemnite zones have been recognized in the Upper Maastrichtian between Aachen and Antwerp (Schmid, 1959, 1967; Van der Tuuk & Bor, 1980; Robaszynski *et al.,* 1985). However, belemnite finds are relatively rare and therefore these fossils have only a limited value for regional correlations.

A subdivision of the Upper Maastrichtian by means of benthic foraminifer assemblages has been proposed by Hofker (1966). However, this author recognized already the problem that different zonations had to be established for different lithologies, since benthic foraminifer assemblages seem facies-controlled to a considerable extent. The lithology is rather variable. An **unformal** subdivision of the Upper Maastrichtian into «early», «middle» and «late» is used here for the description of the lithologies.

2.6.- EARLY UPPER MAASTRICHTIAN

The early Upper Maastrichtian sediments exhibit two different lithologies, which are roughly comparable to those of the Upper Campanian and Lower Maastrichtian :

- Coarse-grained (mean grain-size between 30 and 45 μ), frequently flint-bearing calcisiltites of the Vylen Chalk and Lixhe Chalk (third and fourth member of Gulpen Formation sensu W.M. Felder, 1975), and
- sandy to silty, glauconitic marls, locally with chalk intercalations, which have been assigned either to the uppermost Vaals Formation or uppermost Hervian (notably in the Kunrade area) or to the topmost Pre-Valkenburg deposits (P.J. Felder *et al.,* 1985a for eastern Campine Mining District; there formerly also identified as either «Craie de Nouvelles» or «Hervian»).

The chalk sediments occur in the Antwerp Campine, on the northeastern part of the Brabant Massif and in the Maastricht and Halembaye areas. They are characterized by benthic foraminifer assemblages indicating foram zones C to E of Hofker (1966). However, at many places an impoverished, non-diagnostic assemblage occurs that cannot be used for the distinction between the Vylen and Lixhe Chalk. Usually, these calcisiltites yield low numbers of bioclasts (among which molluscs and echinoderms alternate as predominant clasts). Ornamented ostracodes are extremely rare. Presumably the upper portion of this sequence is marked by either important condensation or by sedimentary gaps in the Antwerp Campine.

The glauconitic marls are locally present in the Campine Mining District and in the Kunrade area. The deposits generally lack any diagnostic fossils, but are marked by low numbers of bioclasts (with frequent predominance of molluscs and sometimes echinoderms) and by the practical absence of ornamented ostracodes.

2.7.- MIDDLE UPPER MAASTRICHTIAN

The middle Upper Maastrichtian sediments are completely different from those of the Upper Campanian to early Upper Maastrichtian. Glauconitic sediments are restricted to thin lenses, calcarenites are common to predominant. The following lithologies are distinguised :

- Flint-bearing coarse-grained calcisiltites to fine-grained calcarenites (mean grain-sinze 71 μ) of the Lanaye Chalk (upper member of Gulpen Formation sensu W.M. Felder, 1975),
- flint-bearing fine-grained to medium-grained (mean grain-size upward increasing from some 90 to 120 μ) calcarenites of Valkenburg Chalk, Gronsveld Chalk, Schiepersberg Chalk and Emael Chalk (lower half of Maastricht Formation sensu W.M. Felder, 1975), and
- fine-grained to coarse-grained (mean grain-size 105 μ) calcarenites with subordinate terrigeneous clastics (quartz grains, quartzite pebbles, shale flakes and coal pebbles), usually showing alternation of soft, friable chalk and hard, well-cemented beds (presumably representing hardgrounds), which belong to the Kunrade Chalk (Kunrade facies of Maastricht Formation sensu W.M. Felder, 1985).

The lateral and vertical boundaries between these lithologies are poorly defined. Marker horizons between and within these different chalk facies cannot be recognized by field characteristics because of rapid lateral changes of the lithofacies (cf. a.o. Bless *et al.*, 1986; fig. 6). However, correlation of individual beds is possible by using quantitative and qualitative variations of selected bioclast groups, ostracodes and benthic foraminifera (P.J. Felder *et al.*, 1985a, 1985b; Bless *et al.*, 1986). The flint-bearing chalks of Lanaye, Valkenburg, Gronsveld, Schiepersberg and Emael are usually grouped in the so-called «Maastricht facies» in order to distinguish them from the «Kunrade facies» s.s. The chalk of the Maastricht facies is characterized by benthic foraminifera of Hofker's zones F-I and sometimes zones F-J, whereas the chalk of the Kunrade facies is marked by benthic foraminifera of Hofker's zones J and O. The Maastricht facies predominates in the Maastricht and Halembaye areas and on the northeastern part of the Brabant Massif, whereas the Kunrade facies is largely restricted to the areas bordering the Rur Valley Graben (Antwerp Campine, Campine Mining District and Kunrade area).

Presumably, the Kunrade facies characterizes an extremely shallow nearshore marine environment, whereas the other («Maastricht facies») lithologies represent slightly deeper, more open-marine shelf deposits.

The deposits contain varying amounts of bioclasts (among which echinoderms predominate; crinoid ossicles are common in the lower half of the sequence). Ornamented ostracode specimens are common (frequently more than 20 %).

2.8.- LATE UPPER MAASTRICHTIAN

The late Upper Maastrichtian calcarenites exhibit a rather uniform lithofacies throughout the area considered. The chalk is usually soft and friable, but may be hard and well-cemented in hardgrounds. The calcarenites are medium-grained to occasionally coarse-grained (mean grain-sizes between 120 and 150 μ). Flints are rare or absent. The sediments belong to the Nekum Chalk and Meerssen Chalk (upper half of Maastricht Formation sensu W.M. Felder, 1975). The exact boundary between these members is often difficult to trace. The sequence is marked by benthic foraminifera belonging to Hofker's zones K-N. The number of bioclasts between 1 and 2.4 mm is high to very high (frequently more than 2.000/kg and sometimes even more than 10.000/kg). Echinoderm clasts predominate. Ornamented ostracode specimens make up more than 20 % of the ostracode assemblages and often even more than 40 %.

The late Upper Maastrichtian deposits have been observed throughout the region between Aachen and Antwerp, except where they have been eroded after deposition (notably on north-

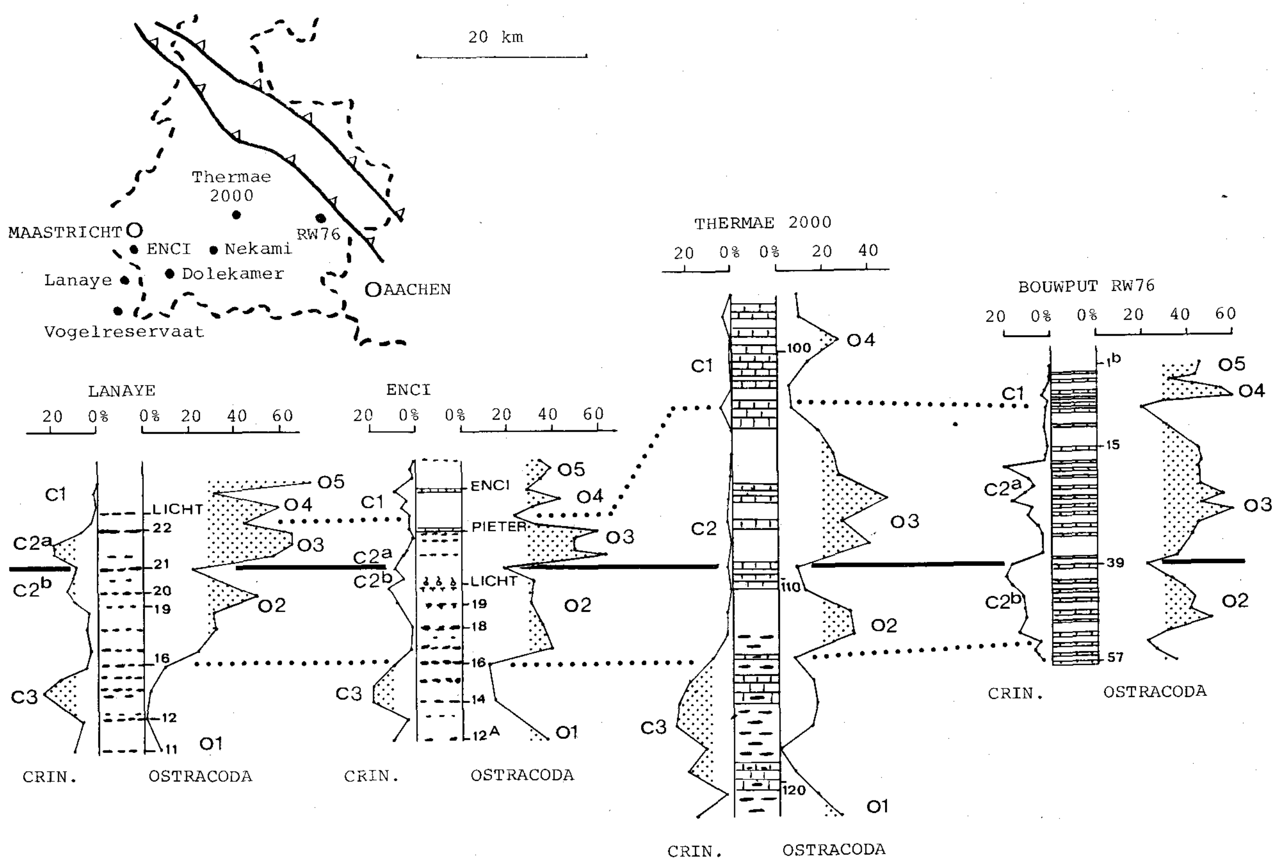

Fig. 6.- Correlation of different lithofacies (Maastricht Chalk with frequent flint layers; Kunrade Chalk with alternation of soft and hard beds) within the middle Upper Maastrichtian by means of ostracodes (percentage of ornamented ostracode specimens shown to the right of lithological columns) and crinoids (percentage of crinoid fragments in bioclast assemblages of sieve fraction 1-2.4 mm shown to the left of lithological columns). Note that the Lichtenberg Horizon in ENCI (type location for base of Maastricht Formation) is not the same as in Lanaye (type location for Lanaye Chalk per definition included in uppermost Gulpen Formation sensu W.M. Felder, 1975).

eastern part of Brabant Massif and in Halembaye area). They also occur north of the Heerlerheide Fault at several places.

3.- SEA LEVEL RISE AND INVERSION TECTONICS

The vertical and lateral changes in the lithofacies and fossil assemblages have been controlled by two simultaneous - but presumably independent - Late Cretaceous processes : inversion of subsidence and eustatic sea level rise.

Since at least the early Carboniferous (and possibly already since the early Devonian) the Rur Valley Graben and the West Netherlands Basin were distinguished from the areas to the south (Brabant Massif and surroundings) by a relatively high rate of subsidence. This resulted in rather thick and more or less uninterrupted sedimentary sequences in the West Netherlands Basin and in the Rur Valley Graben, whereas important gaps (caused by interruption of the deposition and/or by erosion) and condensed sequences characterize the Brabant Massif and its northern border areas.

In the Aachen-Antwerp area this situation persisted until the end of the Santonian. But during this latter timespan the global sea level rise produced an encroachment of the shorelines on the blocks to the south (Kunrade area and eastern Campine Mining District) and to the north (Peel area) of the Rur Valley Graben (fig. 7-8). This gradual transgression is marked by the presence of beach and dune deposits (Aachen sands with drifted wood showing action of marine boring mussels) and local swamps (lignite lenses in Hergenrath clay). Erosion on the southern blocks (a.o. Antwerp Campine, Brabant Massif, Halembaye and Maastricht areas) resulted in local reworking (o.a. mudsands derived from paleosols on top of Dinantian in Valkenburg area; cf. Bless *et al.,* 1986).

The shallow marine Vaals deposits (with a basal conglomerate consisting of locally derived pebbles showing activity of boring sponges) not only occur on top of the Aachen sediments. These also extend southwards and westwards in the Antwerp Campine, on the Brabant Massif and in the Halembaye-Maastricht areas where they overlie Paleozoic rocks. This evidences a further sea level rise during the Lower Campanian period.

The lateral distribution of lithofacies in the Aachen-Antwerp area however cannot be explained by simple sea level rise. The Vaals sediments in the eastern Campine Mining District and in the Kunrade area contain high to very high sand percentages, whereas those in the Antwerp Campine, on the Brabant Massif and in the Halembaye-Maastricht areas are predominantly clayey and silty (fig. 9). This suggests that these deposits were derived from the Rur Valley area to the north. And this implies that inversion of that area started somewhere early in the Lower Campanian. An increased rate of subsidence can be noticed in the Antwerp Campine, where planktonic foraminifera indicate a deeper, more open marine environment than in the Campine Mining District.

Since the Rur Valley area seems too small (maximum 30x100 km) for fluvial erosion during the inversion period, it is assumed that abrasion of the largely unconsolidated Aachen and older sediments on this block was due to interaction of minor drainage systems (mainly tidal gullies and channels), (tidal) waves and wind. The lateral distribution of sediments in the Antwerp-Aachen area may have been the result of sorting by tidal currents and long-shore currents.

The Rur Valley area also acted as a source for clastic sediments during the Upper Campanian to early Upper Maastrichtian (fig. 10). This is indicated by the fact that relatively pure chalk facies (mainly calcisiltites with in the upper half varying amounts of flint) predominate in the southern and western half of the Aachen-Antwerp area (Antwerp Campine, Brabant Massif and Halembaye-Maastricht areas), whereas silty to sandy marls are common in the north-east (eastern Campine Mining District and Kunrade area). However, frequent gaps and an upward diminishing amount of clastics in the sedimentary sequences along the southern border of the Rur Valley area suggest that the uplift rate of the latter was less important than during the Lower Campanian and no longer kept pace with the sea level rise.

Sedimentary gaps occur also in the chalk lithofacies. These indicate a complex cakewalk upwarp and downwarp of individual blocks. Presumably, such gaps may be interpreted by accepting local highs within the reach of storm wave base from where the loose bottom sediment was swept into deeper parts of the basin from time to time. Also the widespread glauconitic layers within the pure chalk facies may represent storm-swept, turbiditic deposits derived either from such local highs (as for instance around Valkenburg during the Upper Campanian and Lower Maastrichtian) or derived from the eastern Campine Mining District and Kunrade area as storm-swept spillover sediments.

Complete relaxation of the inversion movements is assumed for the middle to late Upper Maastrichtian. During the middle Upper Maastrichtian (fig. 11) the Rur Valley area was gradually drowned by the still continuing sea level rise. Only some isolated cliffs of Upper Carboniferous rocks may have served as local sources for minor quantities of clastic debris (quartz, quartzite, shale and coal pebbles occurring in «Kunrade» chalk of eastern Campine Mining District and Kunrade area). But the differentiation into a shallow-marine nearshore Kunrade facies along the border of the Rur Valley area and a slightly deeper marine Maastricht facies in a.o. the Maastricht area and on the Brabant Massif may indicate a slightly higher rate of subsidence for these southern areas. The overall coarser grain-size of the sediment (calcarenites instead of calcisiltites) suggests a gradual shallowing of the environment as compared with that of the Upper Campanian to early Upper Maastrichtian. Remarkable is the frequent occurrence of widespread flint layers in the Maastricht facies and of hardgrounds in the Kunrade facies.

Finally, the late Upper Maastrichtian (fig. 12) is marked by shallow marine calcarenites with local lenses of coarse bioclast accumulations overlying hardgrounds. These extend not only throughout the Aachen-Antwerp area but also overstep the borders of the Rur Valley area. Siliciclastics are practically absent. Apparently the inversion had come to an end. Yet, there are no signs of renewed downwarp for the Rur Valley area. It is presumed that the increased subsidence of that area started only after deposition of the Paleocene sediments (somewhere during the Eocene or Oligocene).

It is likely that the sedimentation rate balanced sea level rise during the late Upper Maastrichtian.

4.- PALEOGEOGRAPHY

The Campanian-Maastrichtian fossil assemblages in the Aachen-Antwerp area show affinities with boreal faunas during the Campanian to early Upper Maastrichtian, and with mediterranean ones during the middle and late Upper Maastrichtian (fig. 13). However, because of its geographically somewhat isolated position (inversion structures in the southern and central Netherlands forming a barrier for many boreal organisms; only at the northernmost edge of the mediterranean realm during the middle-late Upper Maastrichtian) and because of its location near

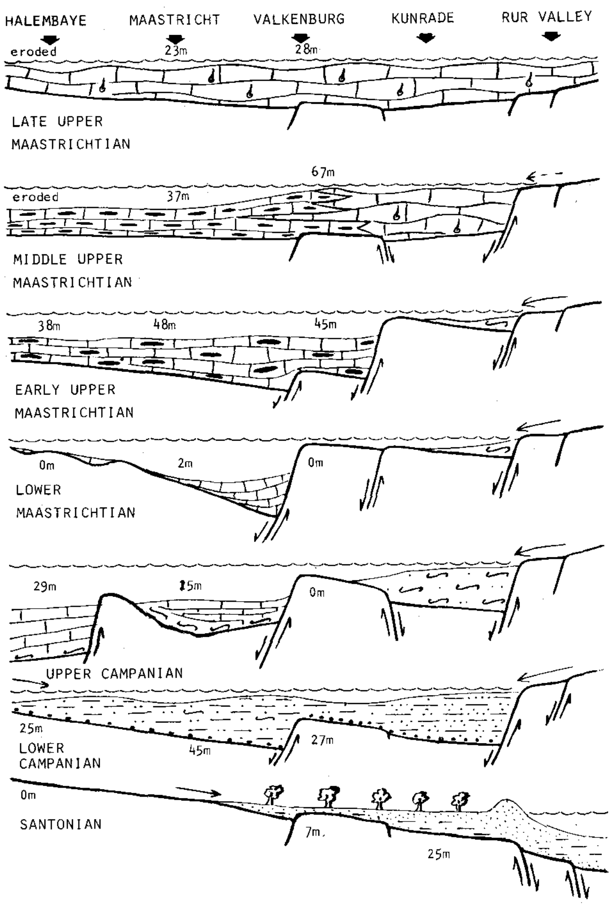

Fig. 7.- Cartoon showing influence of sea level rise and inversion tectonics on late Cretaceous depositional environment in southeastern part of Aachen-Antwerp area. For description of lithofacies see text. Thicknesses for Halembaye area from Halembaye quarry, for Maastricht area from ENCI quarry, for Valkenburg from Thermae 2000 borehole. For Kunrade area and Rur Valley area no thicknesses are indicated with exception of Santonian deposits near Heerlen ((25 m).

regional highs with frequent occurrence of shallow water facies these affinities were never very pronounced, thus complicating long-range correlations with e.g. northern Germany or southern France.

4.1.- BOREAL AFFINITIES

As stated above typical boreal characteristics are largely restricted to the Campanian to early Upper Maastrichtian. Among these the following may be cited :

- frequent occurrence of belemnites permitting relatively detailed correlation with a.o. northern Germany (cf. Robaszynski *et al.*, 1985),
- occurrence of typical «boreal» foraminifer genus *Bolivinoides* (with succession of species *B. strigillata, B. decorata, B. australis, B. draco* and *B. gigantea*) permitting correlation with northern Germany,
- predominance of molluscs amongst bioclasts,
- ostracode assemblages show overall comparison with e.g. Rügen faunas of Herrig (1966) and northern German faunas of Clarke (1982, 1983); some species such as «*Xestoleberis*» *bidentata* are characteristic for «Gulpen» assemblages described by Bonnema (1940-1941) from the northern Netherlands,
- low species diversity for practically all groups.

The predominance of molluscs amongst the bioclasts is matched by their relatively higher diversity. Van der Weyden (1943) listed 146 species of molluscs on a total of 150 fossil species for the Hervian deposits (largely coinciding with the Lower Campanian to early Upper Maastrichtian) of South Limburg. However, a pronounced diversification of molluscs (except for belemnites) only occurred during the middle-late Upper Maastrichtian (see below).

4.2.- MEDITERRANEAN AFFINITIES

Mediterranean organisms invaded the Aachen-Antwerp area only at the onset of the middle Upper Maastrichtian. It may be difficult to pinpoint their appearance in the lithological column. But there are several indications of a rather drastic change in the quantitative and qualitative composition of the fossil assemblages slightly below the Nivelle Horizon. Some obvious characteristics of this mediterranean (or Tethyan) influence are :

- occurrence of large benthic foraminifera such as *Hellenocyclina, Lepidorbitoides, Omphalocyclus, Orbitoides* and *Siderolites* (Hofker, 1966; Villain, 1977),
- (rare) rudists (only in late Upper Maastrichtian when mediterranean influence reached its acme),
- frequent massive presence of serpulids (a.o. *Sclerostyla mosae* in so-called «*Dentalium*» Band) and bryozoans (concentrated in several lenticular «Bryozoan Beds»),
- predominance of echinoderms amongs bioclasts,
- ostracode assemblages include several typical «mediterranean» genera which are rare or absent in the coeval strata of the boreal realm of Northern Germany and which appear in much older deposits in the Iberian Peninsula (Albian-Cenomanian) and in France (Cenomanian) than in the Aachen-Antwerp area (notably *Dumontina* and *Mauritsina;* cf. Babinot *et al.*, 1985),
- pronounced species diversity for practically all groups (with exception of belemnites which tend to be rare and only represented by very few species).

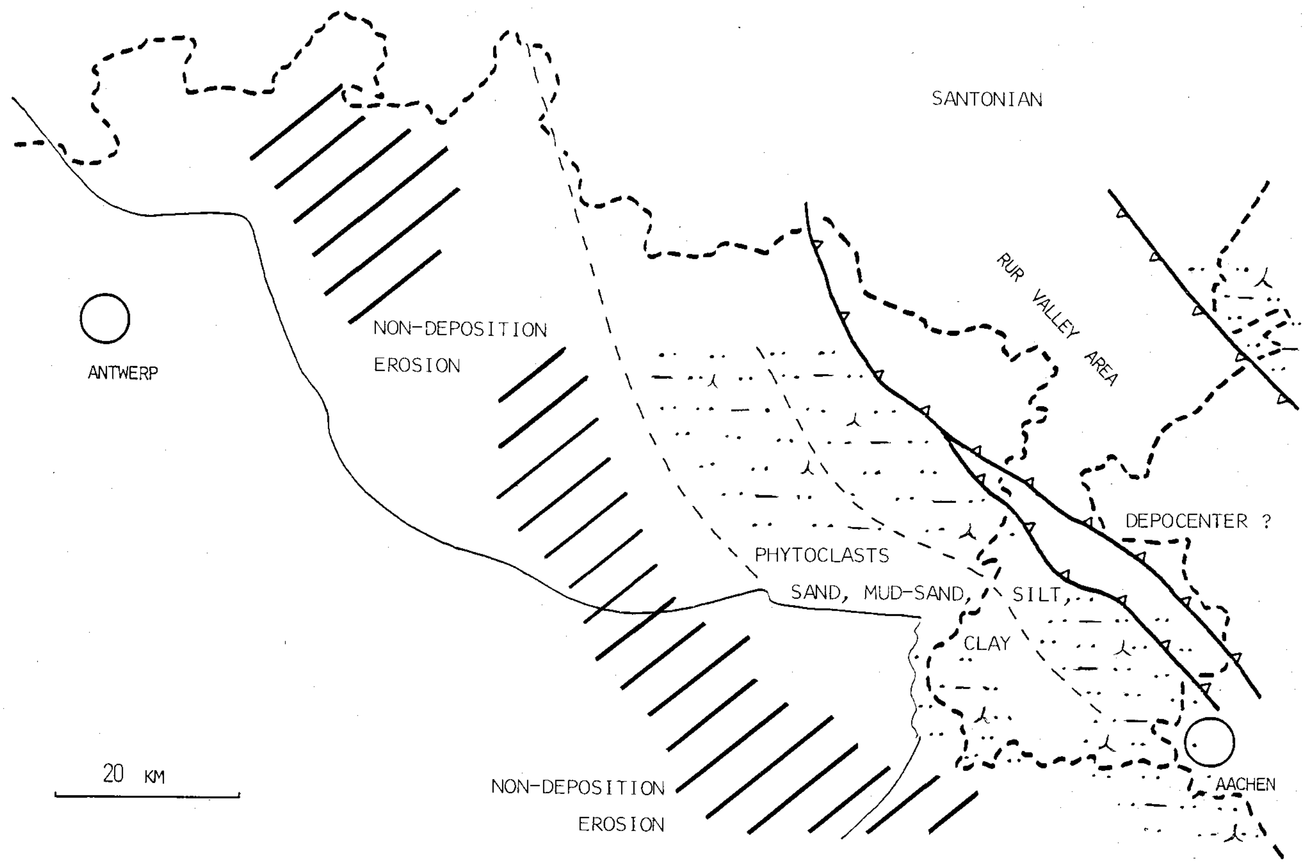

Fig. 8.- Outline paleogeography of Aachen-Antwerp area during Santonian.

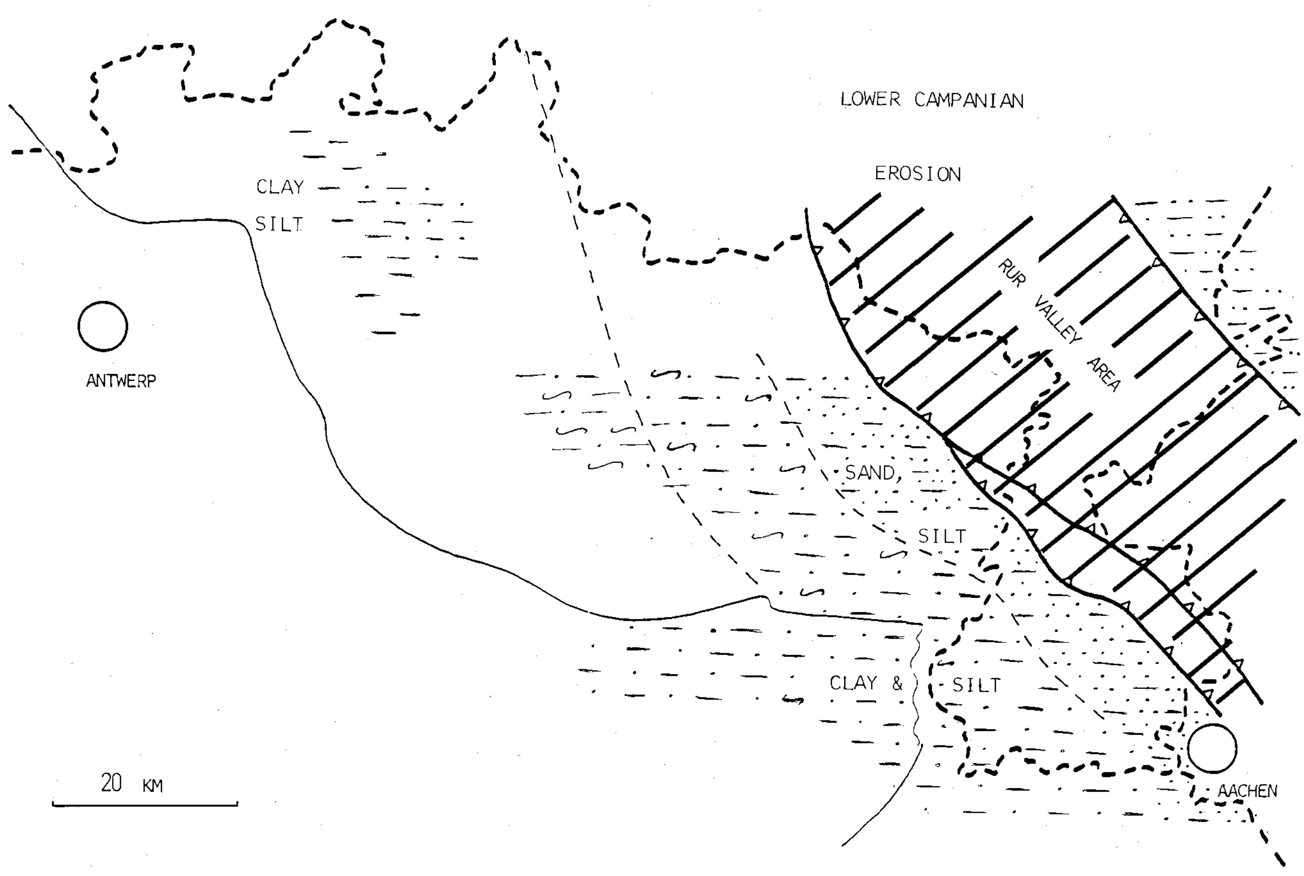

Fig. 9.- Outline paleogeography of Aachen-Antwerp area during Lower Campanian.

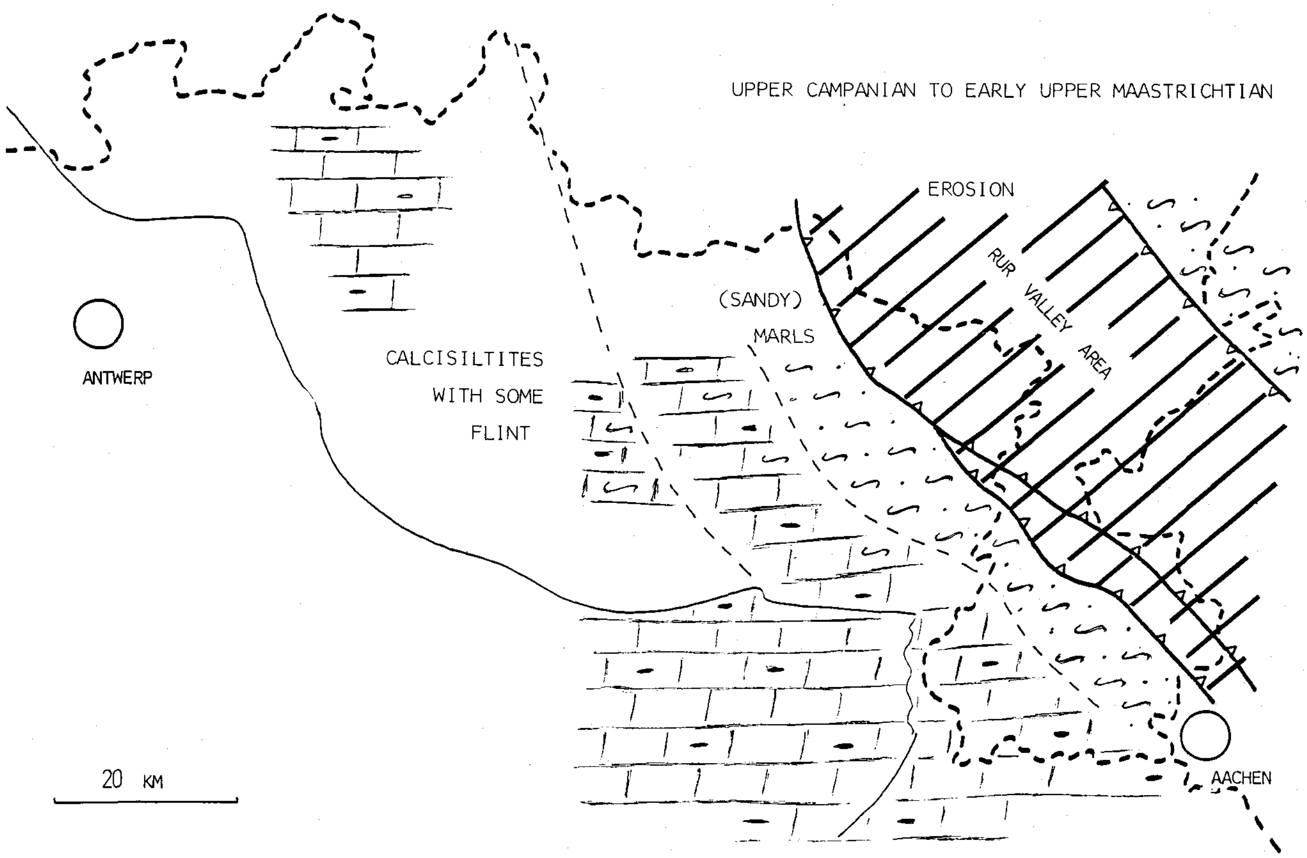

Fig. 10.- Outline paleogeography of Aachen-Antwerp area during Upper Campanian to early Upper Maastrichtian.

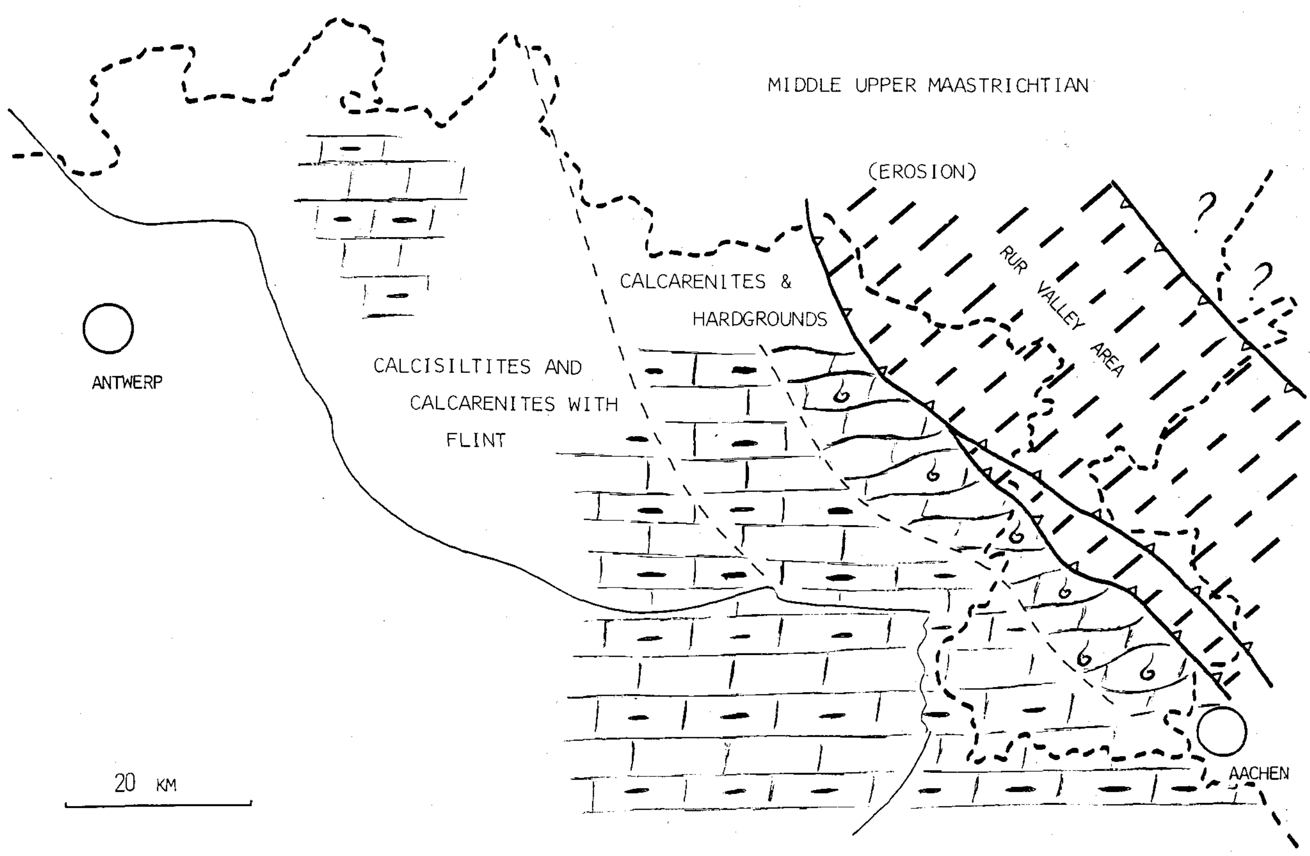

Fig. 11.- Outline paleogeography of Aachen-Antwerp area during middle Upper Maastrichtian.

Maybe, species diversity is the most obvious mediterranean characteristic observed in the middle-late Upper Maastrichtian of the Aachen-Antwerp area. True, diversification in many groups seems to have been a gradual phenomenon reaching its acme only during the late Upper Maastrichtian (serpulids, bryozoans, rudists). However, one should be aware of the fact that most fossil groups have never been treated monographically, thus embarrassing a reliable survey of the available data for the Upper Cretaceous in this region. However, a review of monographs on two groups of microfossils may illustrate this point «à titre d'exemple».

First of all, there are the data on benthic foraminifera (Schijfsma, 1946; Hofker, 1957, 1966; Villain, 1977). Even if we accept that these may need revision, we have to admit that this information shows a general quantitative tendency. The foraminifera of the Vaals or Hervian deposits (largely restricted to the Lower Campanian, but also including Upper Campanian and even younger Lower to early Upper Maastrichtian) have been dealt with by Schijfsma (1946) and Hofker (1957). These authors described respectively 91 and 46 foraminifer species.

Hofker (1966) listed 109 foraminifer species from the Upper Campanian foram zone A, 109 species from the Lower Maastrichtian foram zone B and 159 species from the early Upper Maastrichtian foram zone C. His data on foram zone E are not considered here since this zone bridges the boundary between the early and middle Upper Maastrichtian. In the middle to late Upper Maastrichtian foram zones F to O Hofker distinguished no less than 434 species! This tremendous species diversity in the middle-late Upper Maastrichtian is also corroborated by Romein *et al.* (1977), who mentioned 117 foraminifer species from a single outcrop in the basal portion of the middle Upper Maastrichtian, the highway cutting (RW76) at Benzenrade near Heerlen (section roughly covering foram zones F-H according to Bless *et al.,* 1986).

In the second place there is an excellent monograph on Cytheracean ostracodes by Deroo (1966). His information has been slightly updated by as yet largely unpublished research by the first author. Deroo (1966) cited only 3 species for the Lower Campanian, whereas the first author recognized 10 species. The Upper Campanian yielded 24 species (Deroo, 1966). Although no extensive information has been published on the Lower Maastrichtian (not yet recognized by Deroo for South-Limburg) some 25 to 30 Cytheracean ostracode species can be distinguished (some of these figured in Robaszynski *et al.,* 1985 and in P.J. Felder *et al.,* 1985a). Deroo (1966) listed 36 species for the early Upper Maastrichtian, 123 for the middle Upper Maastrichtian and 116 for the late Upper Maastrichtian. His data for the middle Upper Maastrichtian are confirmed by Romein *et al.* (1977) who figured 114 species from an outcrop in the basal portion of the middle Upper Maastrichtian along the highway cutting (RW76) at Benzenrade near Heerlen (roughly covering foram zones F-H according to Bless *et al.,* 1986).

Of course, these are relative figures which should be appreciated only in a regional context. For example, the data published on Cytheracean ostracode species from the Lower Maastrichtian of the boreal realm in Northern Germany vary strongly from one area to another. Clarke (1983) described 37 species from Lägerdorf-Kronsmoor-Hemmoor, whereas Herrig (1966) mentioned 93 species from the same interval on Rügen. However, in the Aachen-Antwerp area species diversification amongst benthic foraminifera coincides with the appearance of mediterranean elements such as *Siderolites* and *Orbitoidea,* and species diversification amongst Cytheracean ostracodes is matched by the income of mediterranean genera like *Dumontina* and *Mauritsina.*

Finally, it should be noticed that there is no direct correlation between species diversity and relative abundance. For example, the number of ornamented ostracode species is extremely low in the Lower Campanian (only some 10 species amongst *Cytherelloidea* and Cytheracea) of the Aachen-Antwerp area as compared with those in the Upper Campanian to early Upper Maastrichtian (20 to 30 ornamented ostracode species amongst *Cytherelloidea* and Cytheracea). Nevertheless, ornamented ostracode specimens are relatively more abundant in the Lower Campanian (up to 85 % of total number of ostracode specimens) than in the Upper Campanian to early Upper Maastrichtian (usually less than 10 %, occasionally up to 40 % of total number of ostracode specimens). The same is true for the lamellibranchs. This group is highly diverse in the middle-late Upper Maastrichtian where many mediterranean elements can be observed (A.V.J. Dhondt, Koninklijk Belgisch Instituut voor Naturrwetenschappen, Brussels; personal communication d.d. 6-6-1983). However, bivalves make up a relatively small percentage of the total number of bioclasts in this interval. On the contrary, bivalves are relatively abundant in the Lower Campanian to early Upper Maastrichtian although the number of species is distinctly lower during that period.

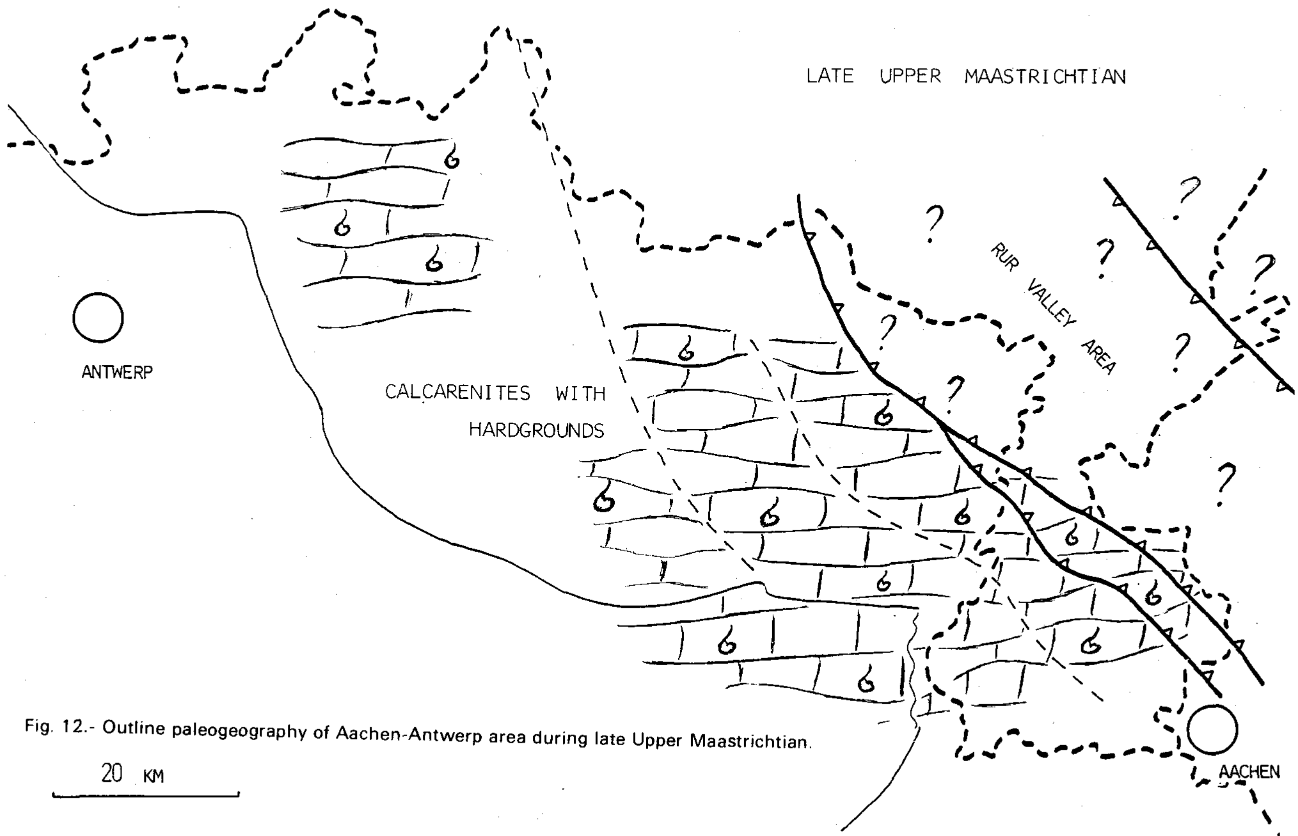

Fig. 12.- Outline paleogeography of Aachen-Antwerp area during late Upper Maastrichtian.

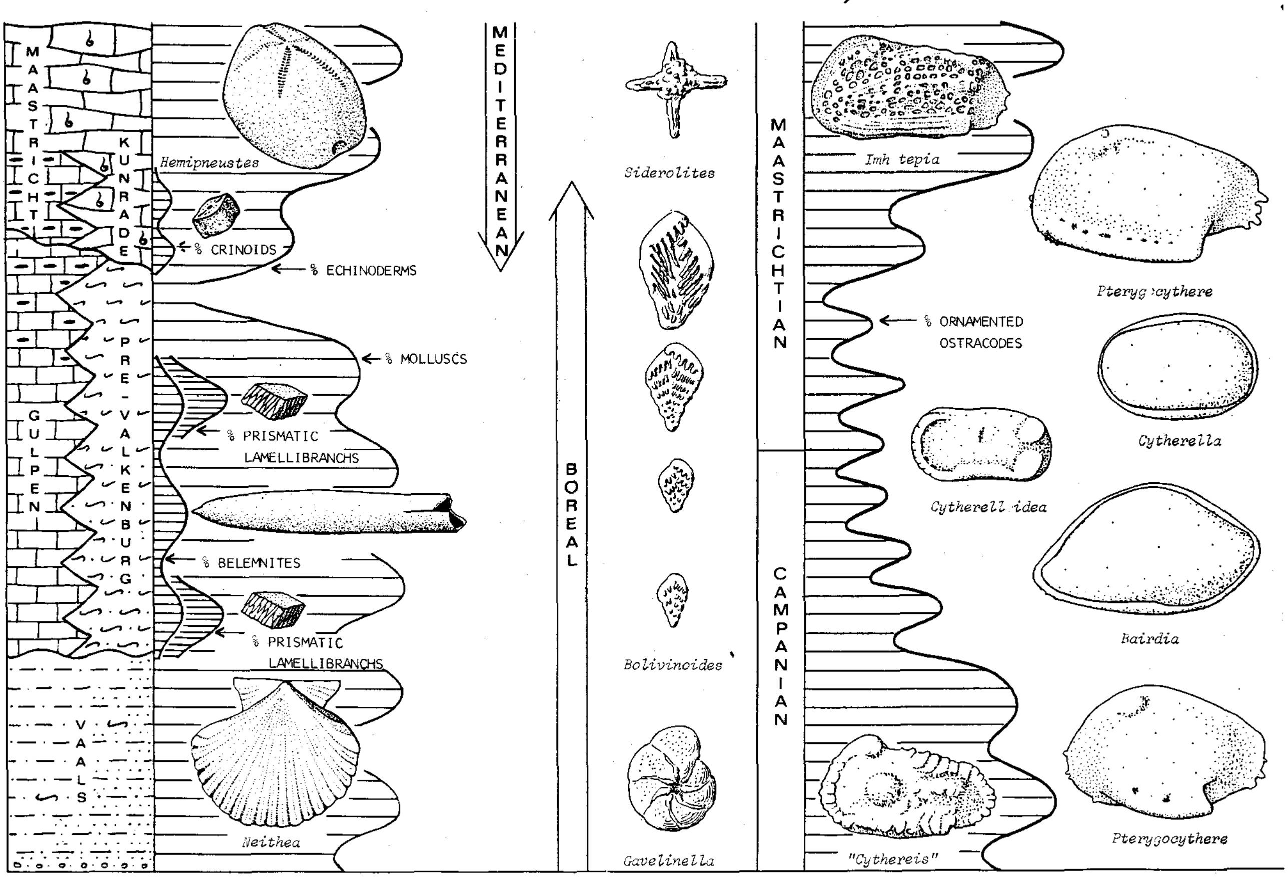

Fig. 13.- Cartoon showing correlation of lithofacies and chronostratigraphy with some selected bioclast assemblages, foraminifera and ostracode assemblages. The onset of the mediterranean influence in the Aachen-Antwerp area is shown by important changes in the quantitative composition of bioclast assemblages (frequent predominance of echinoderms) and ostracode assemblages (increasing number of ornamented ostracode specimens along with sudden diversification of notably the Cytheracea), and by the appearance of many mediterranean foraminifera (among which *Siderolites* and *Orbitoides*).

Table I.- Scheme showing general relationship between age and lithologies for the Upper Cretaceous in the Aachen-Antwerp area.

	ANTWERP CAMPINE, NE BRABANT MASSIF MAASTRICHT & HALEMBAYE AREAS	CAMPINE MINING DISTRICT & KUNRADE AREA
LATE UPPER MAASTRICHTIAN («Mc» & «Md»)	medium- to coarse-grained biocalcarenites (mainly packstones and grainstones, rare floatstones and calcirudites) with frequent hardgrounds; Nekum Chalk and Meerssen Chalk; foram zones K-N.	
	Lava & Laumont hardgrounds with overlying biocalcarenites or biorudites.	
MIDDLE UPPER MAASTRICHTIAN («Cr4» & «Mb»)	flint-bearing fine- to medium-grained calcarenites (packstones, grainstones) with rare hardgrounds; Lanaye Chalk, Valkenburg Chalk, Gronsveld Chalk, Schiepersberg Chalk and Emael Chalk;	rarely flint-bearing fine- to coarse-grained calcarenites with frequent hardgrounds; occasional lithoclasts (shale, quartz, coal pebbles, largely derived from Upper Carboniferous rocks); Kunrade Chalk and Valkenburg Chalk; foram zones J and O
EARLY UPPER MAASTRICHTIAN («Cr3b» pars, «Cr3c»)	flint-bearing coarse-grained calcisiltites (mudstones, wackestones); frequent gaps; Lixhe 1-3 Chalk and Vijlen Chalk; foram zones C-E	sandy and silty glauconitic marls; frequent gaps and condensed sequences; top of Pre-Valkenburg deposits; rare forams sometimes identified as indicating foram zone G
LOWER MAASTRICHTIAN («Cr3b» pars)	sometimes flint-bearing coarse-grained calcisiltites (mudstones, wackestones); frequent gaps; Beutenaken Chalk and Beutenaken Marl; foram zone B	sandy and silty glauconitic marls; frequent gaps and condensed sequences; middle Pre-Valkenburg deposits; rare forams sometimes identified as indicating foram zone B
UPPER CAMPANIAN («Cr3a», «Cr3b» pars)	coarse-grained calcisiltites (mainly mudstones, rare wackestones); rare gaps, Zeven Wegen Chalk; foram zone A	sandy and silty glauconitic marls, locally with intercalated hardgrounds; frequent gaps and condensed sequences; lower Pre-Valkenburg deposits («Benzenrade Chalk»); foram zone A'-upper or A.
LOWER CAMPANIAN («Cr2»)	sandy and silty glauconitic silts, clays and marls; frequently with basal conglomerate of pebbles derived from local sources; Vaals or Herve deposits; foram zone A'-lower; absent on Brabant Massif	
SANTONIAN («Cr1»)	(sometimes variegated) sands, silts, clays and mudstones; locally with abundant phytoclasts; Aachen sands and clays; absent in Antwerp Campine, on Brabant Massif and in Halembaye area	

5.- CONCLUSIONS

1.- The lithostratigraphical subdivision of the Upper Cretaceous in the Aachen-Antwerp area seems to be more complex than hitherto had been accepted. Correlations based on bioclasts, foraminifera, ostracodes, belemnites and petrophysical borehole logs suggest the distinction between a relatively shallow-marine nearshore facies along the southern border of the Rur Valley area during the Upper Campanian to middle Upper Maastrichtian (represented by Pre-Valkenburg strata and Kunrade Chalk) and a relatively deeper, more open-marine environment farther to the south and west (represented by Gulpen Chalk and Maastricht Chalk).

2.- The sedimentary history of the Upper Cretaceous in this area is explained by a more or less continuous sea level rise during the Santonian to late Upper Maastrichtian.

3.- Inversion of subsidence near the Santonian-Campanian boundary caused uplift of the Rur Valley area which became a source of clastic sediments in the following timespan.

4.- Repeated differential warping of blocks to the south and west of the Rur Valley area occurred during the Upper Campanian to early Upper Maastrichtian. These produced several irregularly distributed sedimentary gaps and condensed sequences and at least partly controlled the differentiation into a nearshore and more open-marine depositional environment.

5.- Relaxation of the inversion movements in the Rur Valley area occurred during the middle and late Upper Maastrichtian. Because of the continued sea level rise the Rur Valley area ceased to be a source for clastic material and eventually became a (marine) depositional area during the late Upper Maastrichtian.

6.- The onset of relaxation of the inversion coincides with the invasion of mediterranean organisms in the Aachen-Antwerp area and with a drastic change in the composition of the assemblages. This suggests that relaxation of the inversion in combination with continued sea level rise removed existing barriers which up to then had prevented mediterranean organisms to enter this area. Possibly, similar barriers elsewhere in the Netherlands and in Germany disappeared as well. This may be deduced from the appearance of large benthic foraminifera (a.o. *Lepidorbitoides*) in the Upper Maastrichtian near Hannover (Voigt, 1951) and Berlin (Trümper, 1970), and in Upper Maastrichtian erratic blocks observed near Hamburg and presumably derived from Scandinavia (Voigt, 1963).

7.- The main qualitative and quantitative changes in the fossil assemblages as well as the principal changes in the lithological succession (including gaps and condensed sequences) can be correlated with changes in the tectonic activity. Therefore these may be considered as regional, tectonically induced ecostratigraphical events. Further research is needed to pinpoint these events in terms of chronostratigraphy.

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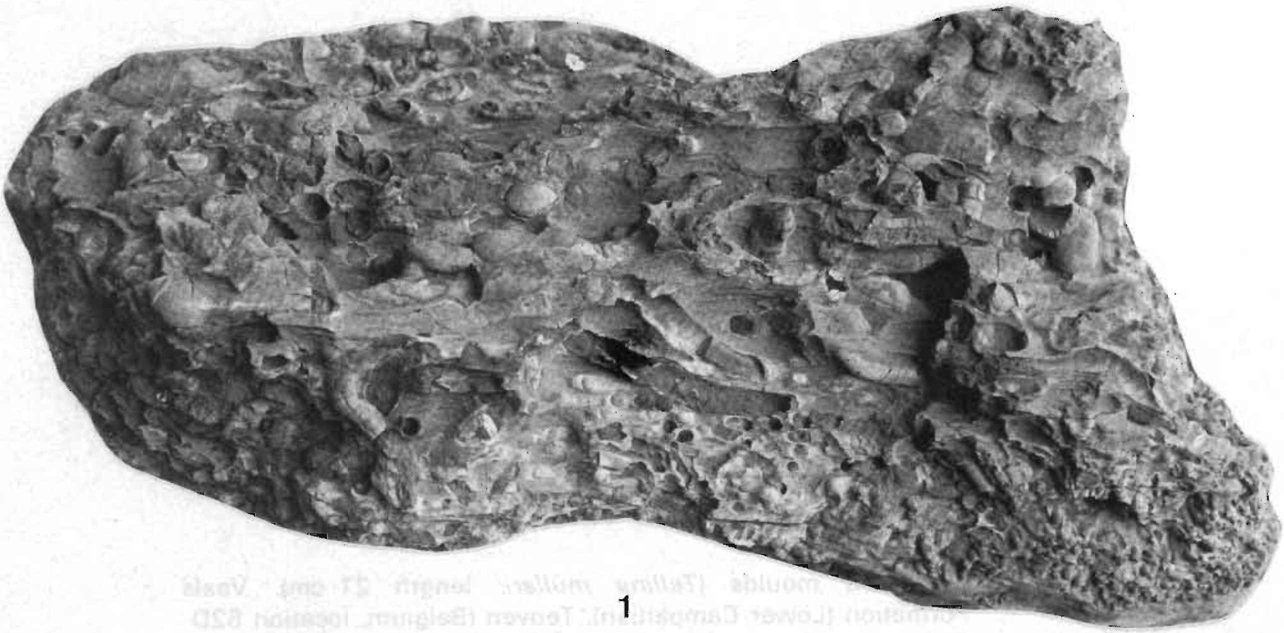
PLATE 1

1. Silicified wood with borings of the mussel *Teredo* sp. (length 53 cm). Aachen Formation (Santonian?), Käskorb Quarry near Kelmis (Belgium, location 62D-74), collection W.M. Felder.

2. Pelecypod moulds (a.o. *Neithea* sp.; length 22 cm). Vaals Formation (Lower Campanian), Cottessen (Netherlands, location 62D-101), collection W.M. Felder.



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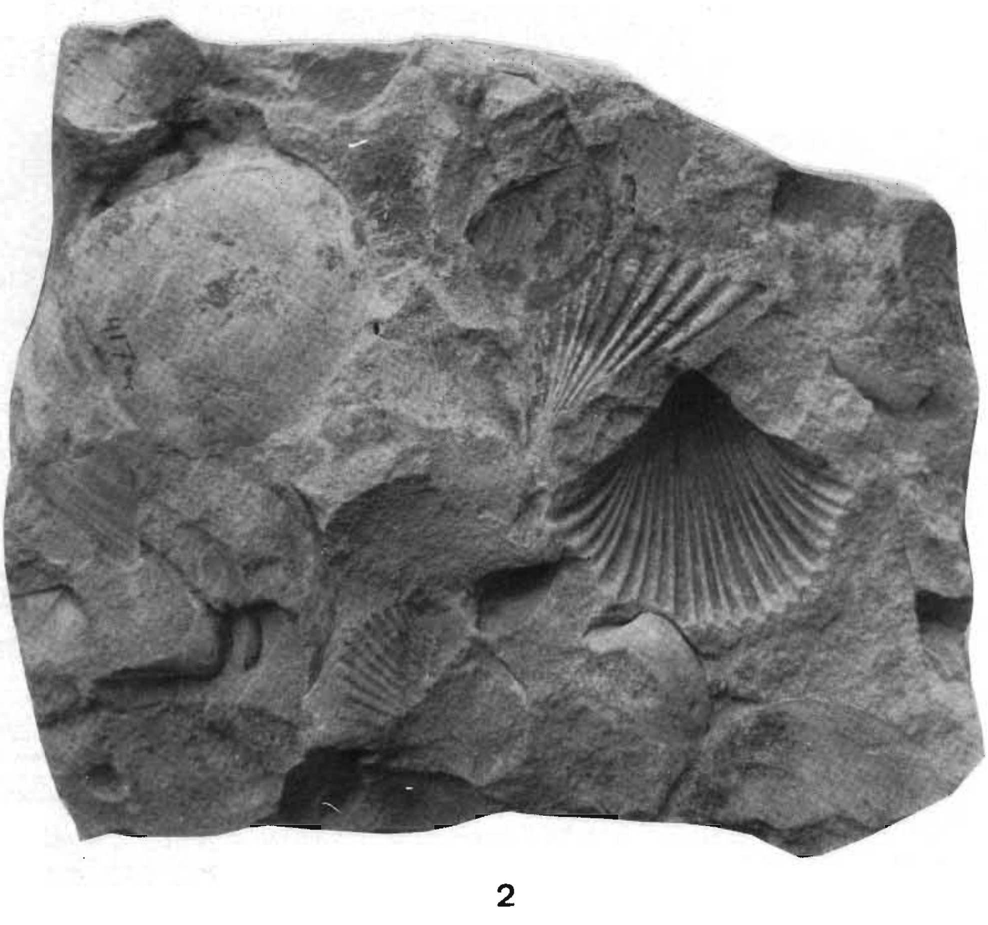

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PLATE 2

1. Pelecypod moulds (*Tellina mülleri;* length 21 cm). Vaals Formation (Lower Campanian), Teuven (Belgium, location 62D-530), collection P. Oei.

2. «Belemnite cemetery» (lenght 46 cm). Gulpen Formation, base of Vijlen Chalk (early Upper Maastrichtian), Beutenaken (Netherlands, location 62C-27), collection Natuurhistorisch Museum Maastricht).

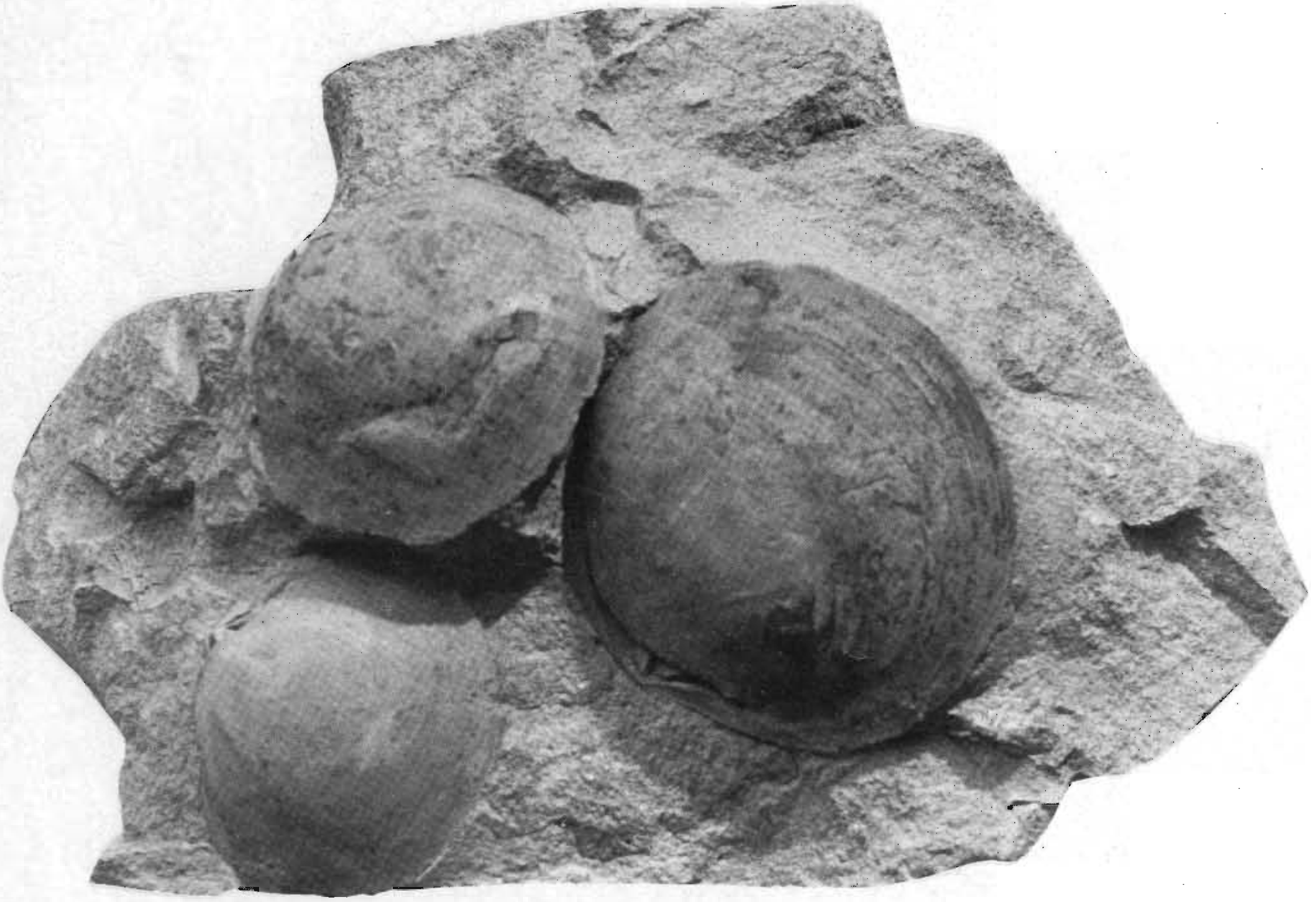

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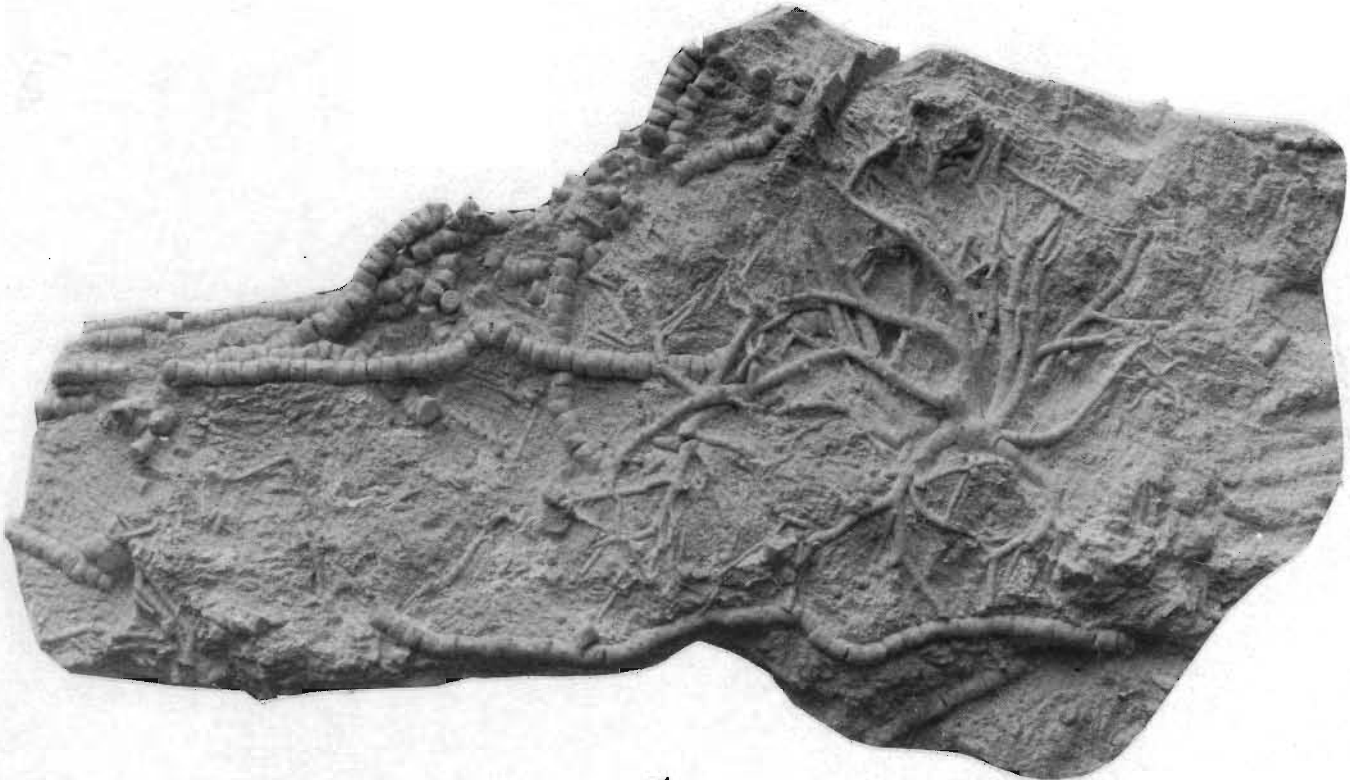
PLATE 3

1. Crinoid (*Bourgueticrinus aequalis;* length 21 cm). Gulpen Formation, Lanaye Chalk, Flint layer 20-21 (sensu W.M. Felder 1975 = Lichtenberg Horizon in ENCI; middle Upper Maastrichtian), Marnebel Quarry (Belgium, location 61H-7), collection T. Lammers.

2. Flint with echinoids (length 24 cm). Maastricht Formation, Schiepersberg Chalk (middle Upper Maastrichtian), Marnebel Quarry (Belgium, location 61H-7), collection W.M. Felder.



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