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STRATIGRAPHY AND CYCLIC NATURE OF LOWER WESTPHALIAN DEPOSITS IN THE BOREHOLES KB174 AND KB206 IN THE BELGIAN CAMPINE

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(6 figures)

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ABSTRACT. Coal and coalbed methane exploration boreholes in the Campine basin (NE Belgium) provided a series of cored sections in the Upper Carboniferous (Westphalian) Coal Measures. Faunal assemblages of Westphalian A/B age have been investigated in detail in two cored sections, KB174 and KB206. The analysis of paleoecological indicators, sedimentary sequences and geophysical well logs within a detailed stratigraphical framework allowed the recognition of various paleoenvironments (euryhaline-brackish-floodplain-swamp) related to relative sea level rise and fall. The cyclic succession of paleoenvironments and coal seams is controlled by transgressive-regressive rhythms of presumed autocyclic nature («Delmer cycles») which could be grouped in larger complex cycles. These have been overprinted by major allocycles of presumably glacio-eustatic origin. The transition from lower to upper delta plain deposits which occurs at the Westphalian A/B boundary and the proposed increase in gradient of the river system may be due to uplift of the hinterland. Marine ingressions on the delta plain formed the decisive factor of the Westphalian A/B paleogeographical evolution.

KEYWORDS: Belgium, Campine, Upper Carboniferous, Westphalian, paleoecology, cyclicity, sequence analysis, coal seams.

RESUME. Stratigraphie et nature cyclique des dépôts du Westphalien inférieur dans les sondages KB174 et KB206 de Campine (Belgique). Les forages d'exploration du charbon et du méthane dans le Bassin de Campine (NE de la Belgique) ont fourni une série de sections carottées du Terrain houiller d'âge Westphalien A/B (Carbonifère supérieur). Des assemblages faunistiques ont été étudiées en détail dans les carottes des sondages KB174 et KB206. L'analyse des indicateurs paléoécologiques, des séquences sédimentaires et des diagraphies géophysiques dans un cadre stratigraphique précis a permis la reconnaissance de plusieurs paléoenvironnements (euryhalin-saumâtre-plaine alluviale-marais) rapportés à des fluctuations relatives du niveau de la mer. La succession cyclique des paléoenvironnements et de veines de charbon est contrôlée par des rythmes transgressifs-régressifs de nature autocyclique probable («Cycles de Delmer», 1952) qui pourraient être groupés en cycles complexes plus longs. Ceux-ci s'intègrent dans un système allocyclique majeur d'origine glacio-eustatique probable. La transition de dépôts de plaine deltaïque basse à haute observée près de la limite du Westphalien A/B et l'accroissement proposé du gradient du système fluviatile peuvent être dû au soulèvement prévarisque de l'arrière pays. Des inondations périodiques de la plaine deltaique ont constitué le facteur déterminant de l'évolution paléogéographique du Westphalien A/B en Campine.

MOTS-CLES: Belgique, Campine, Carbonifère supérieur, Westphalien, paléoécologie, cyclicité, analyse séquentielle, veines de charbon.

1. INTRODUCTION

The cyclic repartition of sediments and fossil assemblages in the paralic Upper Carboniferous basins of northwestern Europe has drawn the attention of many geologists, for instance, Fiege (1937, 1960), Van Leckwijck (1948, 1956, 1960), Delmer (1952), Jessen *et al.* (1952), Fiege *et al.* (1956), Jessen (1961), Böger (1964), Calver (1969) and Ramsbottom (1969).

The ideal sedimentary cycle in the Lower Westphalian coal-bearing strata consists of coal, mudstone, siltstone, sandstone and seatearth or rootlet bed (Calver, 1969). The ideal succession of faunal fossils in the mudstone phase also reveals a cyclic order from non-marine through brackish, marine, brackish and again non-marine assemblages. A further distinction allows the recognition of several marine facies grading from euryhaline «nearshore» to more stenohaline «offshore» environments, each of them characterized by a particular fossil assemblage (Van Leckwijck, 1960; Jessen, 1961; Calver, 1969; Paproth, 1971, 1975). In this way, a clear relationship has been established between major sedimentary and faunal cycles and the cyclic occurrence of (relative) sea level rise and fall, with reference to the concept of genetic stratigraphy.

This theoretical succession of sediments and faunal assemblages is commonly aborted, however, in the non-marine phase, even in the paralic Lower Westphalian coal measures of northwestern Europe. Well-developed marine bands are so rare, that they can be easily identified by their relative position in the sedimentary sequence. The relatively rare occurrence of marine and brackish-water deposits forms, in fact, the basis for the successful correlation of coal-bearing sections by means of geophysical borehole measurements (Schuster, 1968; Schuster & Schmitz, 1991). Practice has shown, however, that well logs must be calibrated from time to time with biostratigraphical (for instance, miospores, macroflora, non-marine bivalves, goniatites) and lithostratigraphical (tonsteins, well-developed marine bands) information derived from cores or cuttings.

Sedimentary and faunal cycles also characterize the Lower Westphalian deposits in the Belgian Campine, where they have been studied in two cored sections from the KB174 (Hechtel-Hoef) and KB206 (Peer) boreholes (locality map on Figure 1). The detailed correlation between these sections and comparison with the standard stratigraphic subdivisions of the Campine and the German Ruhr coal basin is based on non-marine bivalves, tonsteins, marine bands, coal seam characteristics and geophysical well logs, and further supported by microfloral and megafloral assemblages (van Amerom; Loboziak, Streel & Van de Laar; Fairon-Demaret, personal communications).

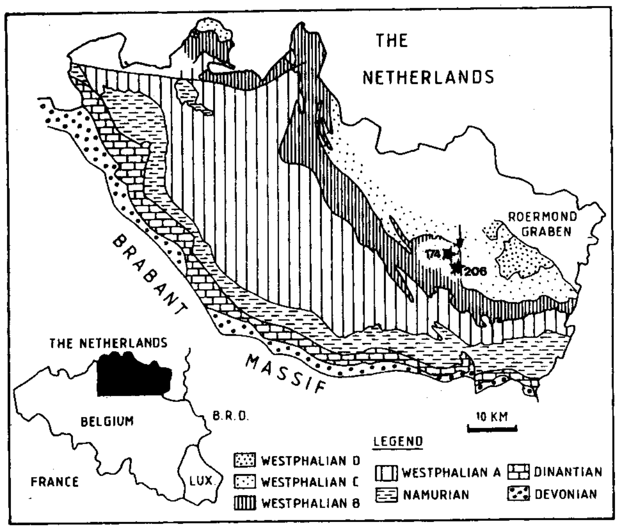


Figure 1. Location map of studied sections KB174 and KB206 in the Campine basin with schematic subcrop of Upper Paleozoic below base Mesozoic (from Langenaeker & Dusar, 1992). The distance between boreholes KB174 and KB206 is 6 km, parallel to the NW-SE regional structural grain. Boreholes in intermediate positions were consulted but not incorporated in the present study because of discrepancies in stratigraphic coverage and/or quality of geophysical well logs. Arrow indicates position of Donderslag lineament, a major transpressional feature with N-S orientation, displaying synsedimentary fault activity.

2. STRATIGRAPHY

2.1. NON-MARINE BIVALVES

Non-marine bivalves occur in a limited number of beds and intervals in the Lower Westphalian of the KB174 and KB206 boreholes (Fig. 5). Three assemblages, closely resembling those described by Calver (1956), are distinguished: an Upper Westphalian A assemblage with *Carbonicola ex gr. cristagalli-oslancis*, a Lower Westphalian B assemblage with *Anthracosia ex gr. ovum-phrygiana*, and a «middle» Westphalian B assemblage with *Anthracosia ex gr. caledonica*.

The assemblage with *Carbonicola ex gr. cristagalli-oslancis* has been recognized between 1433.65 m and 1333.65 m in the KB174 borehole and between 1201.85 m and 1140.25 m in the KB206 borehole. In both boreholes, the top of this assemblage matches the «Schelpenbed», a regionally extended lumachelle-like accumulation of non-marine bivalves above the KS57/2 coal seam (Paproth *et al.*, 1983). *Naiadites ex gr. flexuosus* is common in this assemblage. The *Carbonicola cristagalli* assemblage ranges from the Wellington-1 coal seam to the Gretchen-2 coal seam in the Upper Westphalian A of the Ruhr coal basin and characterizes the lower portion of the Lower Modiolaris non-marine bivalve zone (cf. Jessen *et al.*, 1969). The *Carbonicola cristagalli* assemblage has also been recognized in several British coalfields of Central England and Scotland (cf. Calver, 1956, 1969).

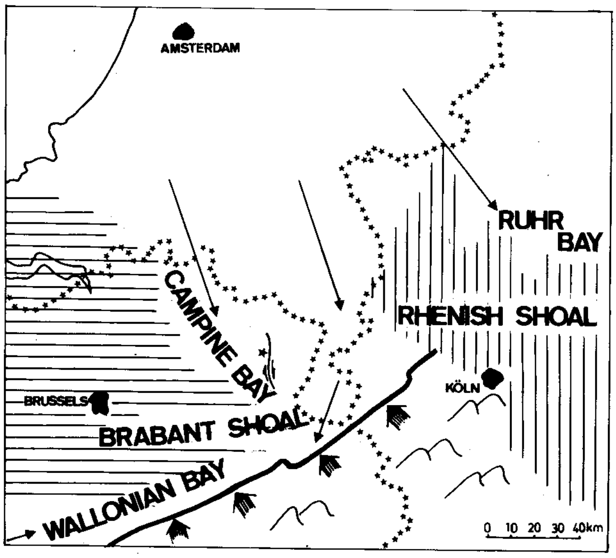


Figure 2. Paleogeography of the Campine coal basin and surrounding areas with direction of marine ingressions during the Early Westphalian. Shoals were occasionally flooded. Incipient variscan uplift and erosion characterizes the area south of the Midi overthrust. Star marks study area to the west of the Donderslag fault.

The *Anthracosia ex gr. ovum-phrygiana* assemblage (Calver, 1956) is common above 1221.40 m in the KB174 borehole (with the exception of an isolated occurrence of *Anthracosia* cf. *ovum* at 1275.00 m) and above 1029.05 m in the KB206 borehole. *Naiadites ex gr. quadratus* is common in this assemblage. The base of the *Anthracosia ex gr. ovum* assemblage is commonly placed at the base of the Westphalian B in Britain and Germany (cf. Calver, 1956, 1969; Jessen *et al.*, 1969), whereas the base of the *Anthracosia ex gr. phrygiana* assemblage occurs slightly higher. A similar observation has been made in the KB174 and KB206 boreholes (Fig. 5). The distinction between *Anthracosia ex gr. ovum* and *Anthracosia ex gr. phrygiana* is, however, not always clear (cf. Paproth *et al.*, 1983). For that reason both assemblages have been combined in this report. The KS50a coal seam at the base of the frequent occurrence of *Naiadites ex gr. quadratus* (1220.10 m in the KB174 borehole and 1029.05 m in the KB206 borehole) is tentatively correlated with the Laura-1 coal seam in the Ruhr coal basin.

The *Anthracosia ex gr. caledonica* assemblage (Calver, 1956) occurs above 1072.60 m in the KB174 borehole (between the KS44 and KS43 coal seams). *Naiadites ex gr. obliquus* is common in this assemblage above 1053.85 m. This assemblage characterizes the lower half of the Lower Similis-Pulchra non-marine bivalve zone. The base of this zone has been placed at the Zollverein-1 coal seam in the Ruhr coal basin (cf. Fiebig, 1969).

2.2. QUAREGNON MARINE BAND

The Quaregnon (= Katharina) Marine Band at the base of the Westphalian B is distinguished in both boreholes by its relative position between the *Carbonicola ex gr. cristagalli-oslancis* and the *Anthracosia ex gr. ovum-phrygiana* assemblages (Fig. 5) as well as by the characteristically rather thick sequence without coal seams (about 35 m in the KB174 borehole and about 26 m in the KB206 borehole) and the typical (although non-marine) log response (Fig. 3). Similarities in log response indicate that the rootlet bed, occurring within this thick sequence at depth 1282.56 m in KB174 does not correlate with coal seams underlying the marine band in other boreholes. It rather forms a local shoal, temporarily occupied by a swamp, within a larger area affected by the relative sea level rise accompanying the Quaregnon Marine Band.

The fauna only consists of non-marine bivalves and the presumably euryhaline ichnofossil *Planolites ophthalmoides* in the KB174 borehole and some unidentified mussel fragments in the KB206 borehole. The absence of a well-developed marine fauna in this band is a common phenomenon, not only in the Campine (cf. Delmer, 1950) but also locally in the Ruhr coal basin (cf. Rabitz, 1964).

At this level there is not only a change in sediment distribution patterns and type of cycles, but also a temporal disruption of coalification trends and a change in coal properties; all these changes may be due to the same origin (change in groundwater chemistry, weathering and preservation?). An abnormal decrease in coalification below the marine horizons of Maurage and Quaregnon was already observed by Pillement (1982) and Veld & Fermont (1990).

2.3. TONSTEINS

Three tonstein horizons, which also occur in the German Ruhr coal basin (cf. Burger, 1985), have been identified in the KB174 borehole: the Zollverein-2 Tonstein in the KS45b coal seam at 1135 m, the Zollverein-8 Tonstein the lower KS48b coal seam at 1195 m, and the Karl Tonstein in the KS70 coal seam at 1452 m (Fig. 5). The Wilhelm Tonstein, recognized in the KS75 coal seam of the Campine coal basin (Paproth *et al.*, 1983), has not been observed in the KB206 borehole. The same holds for the P4 (correlation with O2 tonstein excluded because of arguments forwarded in chapter 2.6.) tonstein in the KS35 coal seam and the Zollverein-3 tonstein in the KS47 coal seam (cf. Paproth *et al.*, 1983).

2.4. PALAEESTHERIA BANDS

The phyllopod *Palaeestheria* occurs at three different depths in borehole KB174: at 1490.70 m immediately above the KS71a coal seam, at 1470.60-1471.15 m above rootlet bed KS70/3, and at 993.20 m within the Eisden (= Domina) Marine Band (some 15 m above the KS39 coal seam) - (Fig. 5).

The *Palaeestheria* bed above the KS71a coal seam at 1490.70 m should perhaps be compared with an isolated occurrence of *Palaeestheria* above the Ida-1 coal seam in the Friedrich Heinrich colliery in the Ruhr coal basin (cf. Bachmann *et al.*, 1970). In the Campine coal basin, borehole KB174 also is the only occurrence where two successive *Palaeestheria* levels are known in the roof of coal seams KS70/3 and KS71a.

The second *Palaeestheria* band at 1470.60-1471.15 m, some 20 m below the KS70 coal seam (with the Karl Tonstein), is typical of the Voort Horizon, a widely extended marker bed in the Campine coal basin (Paproth *et al.*, 1983). This suggests a correlation with the *Palaeestheria* bed above the Blücher-2 coal seam (some 20-30 m below the Karl Tonstein) in the Ruhr coal basin (cf. Bachmann *et al.*, 1970). Pastiels (1964) correlated the Voort Horizon with the Lower Estheria Band of Yorkshire (Central England).

The presence of *Palaeestheria* has only been mentioned by Bouckaert (1958) from the Eisden (= Domina) Marine Band in the Campine coal basin. Farther to the west in the Campine coal basin an additional occurrence of *Palaeestheria* is known above coal seam KS36 (non-published borehole information). In the Campine and Ruhr coal basins, this marine band is commonly characterized by the inarticulate brachiopod *Lingula*. This fits in the scheme of recurrent brackish/marine influence above the Eisden Marine Band (lower portion of complex cycle 10 - Fig.3) and matches a similar succession in coal seam group KS50 above the Quaregnon Marine Band (lower portion of complex cycle 8).

2.5. WIJSHAGEN BAND

The Wijshagen (*Leaia*) Band, commonly found on top of the first rootlet bed above the KS45 coal seam in the Campine coal basin (Paproth *et al.*, 1983) and on top of the GB41/40 coal seam in Southern Limburg (the Netherlands; cf. Van Amerom, 1969), has not been recognized in these boreholes, perhaps because of the fact that the deposits in this interval were rather sandy as is the case in a wider region (Delmer, 1952). The Wijshagen Band has been correlated with a foraminifer-bearing bed above the Zollverein-1 coal seam in the Ruhr coal basin (cf. Van Amerom, 1969; Fiebig, 1969).

2.6. MARINE INFLUENCE ABOVE EISDEN MARINE BAND

The Upper Westphalian B strata above the Eisden (= Domina) Marine Band in the KB174 borehole contain four beds with *Planolites montanus* (locally described as «raindrops») at 868 m, 901 m, 959 m and 985 m. This trace fossil possibly favoured slightly brackish environments (cf. chapter 3.2.). The relative distance of these beds above the Eisden Marine Band (127 m, 94 m, 36 m and 10 m, respectively) suggests a correlation with marine (according to Schuster, 1968), sometimes foraminifer-bearing (according to Fiebig, 1969) beds above the «R», «P», «O» and «M/N» coal seams in the Ruhr coal basin, which are situated at about 150 m, 80 m, 40 m and 20 m above the Domina Marine Band according to data in Schuster (1968) and Fiebig (1969). Correlation of the brackish band at 959 m with the foraminifer-bearing bed above the «O» coal seam in the Ruhr coal basin implies a correlation of the locally tonstein-bearing KS35 coal seam (cf. Paproth *et al.*, 1983) with the tonstein-bearing P4 coal seam in the Ruhr coal basin.

2.7. MARINE INFLUENCE BETWEEN EISDEN MARINE BAND AND WIJSHAGEN BAND

The lower part of the interval between the Eisden Marine Band and the Wijshagen Band contains a cluster of six beds with brackish (*Naiadites*) or euryhaline (*Planolites ophthalmoides* and *Cochlichnus kochi* - possibly better known as «*Beloraphe kochi*» or «*Sinusites*») indicators in the KB174 borehole and one bed with a brackish indicator (*Naiadites*) in the KB206 borehole (Fig. 3). The cluster of six beds in the KB174 borehole possibly matches a similarly clustered occurrence of beds with foraminifers and/or the brackish ostracode *Geisina* above the «A»-«F» coal seams in the Ruhr coal basin (cf. Bachmann *et al.*, 1970).

The single occurrence of the *Planolites montanus* at 1009 m in the KB174 borehole matches perhaps a marine bed with foraminifers above the «H» coal seam in the Ruhr coal basin (cf. Schuster, 1968; Fiebig, 1969; Bachmann *et al.*, 1970).

2.8. MARINE INFLUENCE BETWEEN WIJSHAGEN BAND AND QUAREGNON MARINE BAND

The lower two-thirds of this interval are characterized by the repeated occurrence of beds with brackish (notably *Naiadites*) and euryhaline (*Paraparchites, Cochlichnus kochi* and *Planolites ophthalmoides*) indicators (Fig. 3). The brackish ostracode *Geisina* (common in the interval below the Quaregnon Marine Band) does not occur. It should be emphasized, however, that this absence has also been noticed in the Lower Westphalian B of Britain (Calver, 1969) and the German Ruhr coal basin (cf. Fiebig, 1969). Neither Bachmann *et al.* (1970) nor Fiebig (1969) mention the presence of marine influence above the Katharina Marine Band in the Ruhr coal basin. Schuster (1968), however, recognized at least three marine bands in this interval: above the Viktoria-3 coal seam, above the Laura coal seam and above the Zollverein-7 coal seam. He could trace these bands over considerable distances in NW Germany.

The correlation between the KS48a coal seam and the Zollverein-7 coal seam is based on the oc-

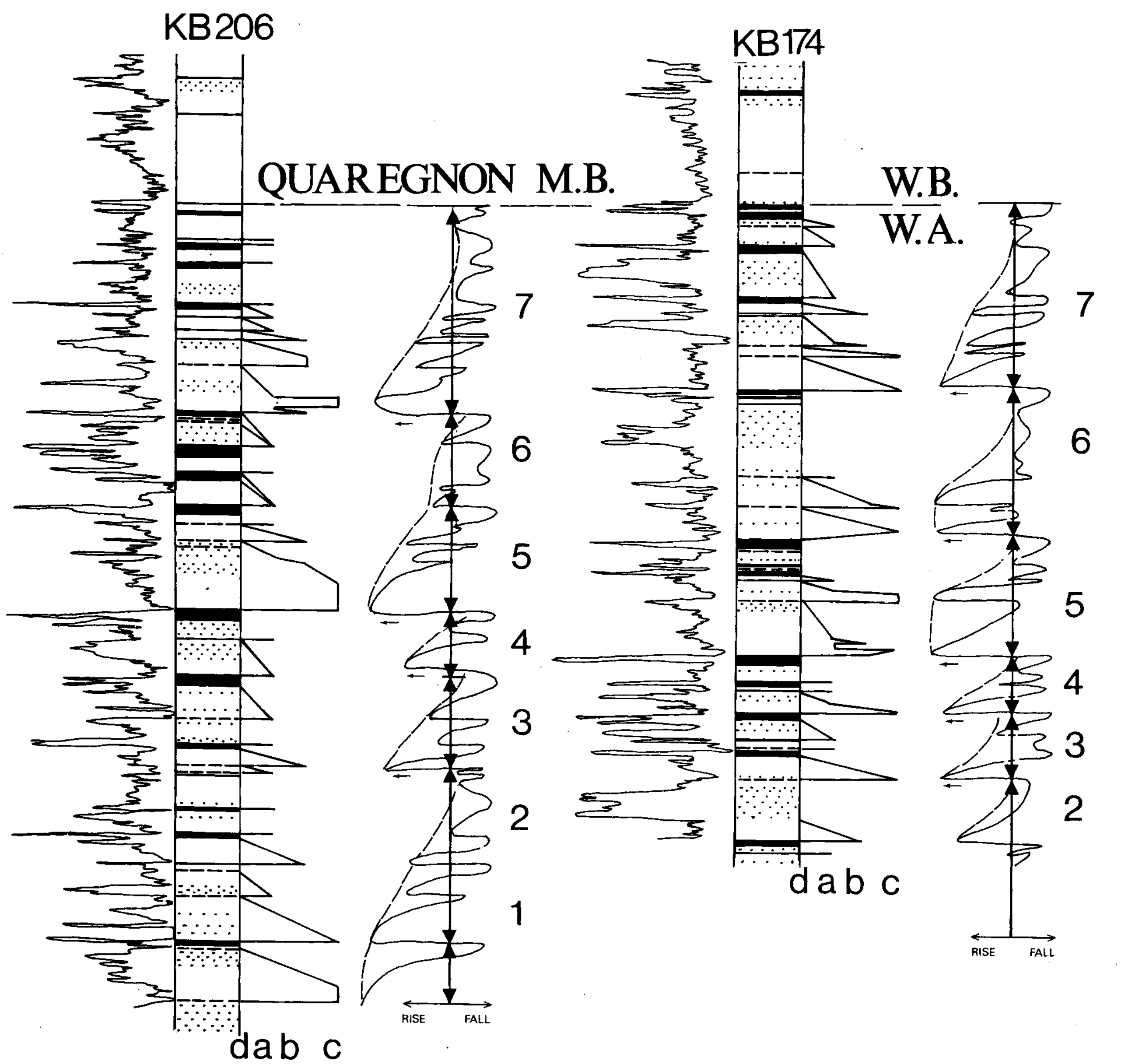


Figure 3.A. Simplified lithologic sequence of boreholes KB174 and KB206 (coal seams, rootlet beds and sandstones indicated), with natural gamma ray log (to the left of litholog; gamma ray range 25-175 API), paleoenvironments based on faunal assemblages (to the right of litholog; swamp = d, floodplain = a, brackish = b, euryhaline = c paleoenvironment) and relative sea level curve (rise to left, fall to right), delimitating basic cycles and complex cycles (interrupted line): Upper Westphalian A interval (below Quaregnon Marine Band.

currence of the Zollverein-8 tonstein in the KS48b coal seam in the KS174 borehole (cf. chapter 3.3). The correlation between the KS50/50a-c coal seams and the Laura-1/3 coal seams roughly matches the base of the common occurrence of *Naiadites ex gr. quadratus* (cf. chapter 2.1, Fig. 5) in the Campine and Ruhr coal basins. The first euryhaline band (capping the KS50/5 coal seam) above the Quaregnon Marine Band has been tentatively correlated with the marine band above the Viktoria-3 coal seam.

2.9. MARINE INFLUENCE BELOW QUAREGNON MARINE BAND

The repeated marine influence in this interval is emphasized by the occurrence of no less than twelve beds with brackish or euryhaline indicators in the 200 m thick sucession between the Quaregnon Marine Band and the KS71 coal seam in the KB174 borehole, whereas an additional number of four beds has been observed in the 60 m thick interval between the KS71 and KS75 coal seams in the KB206

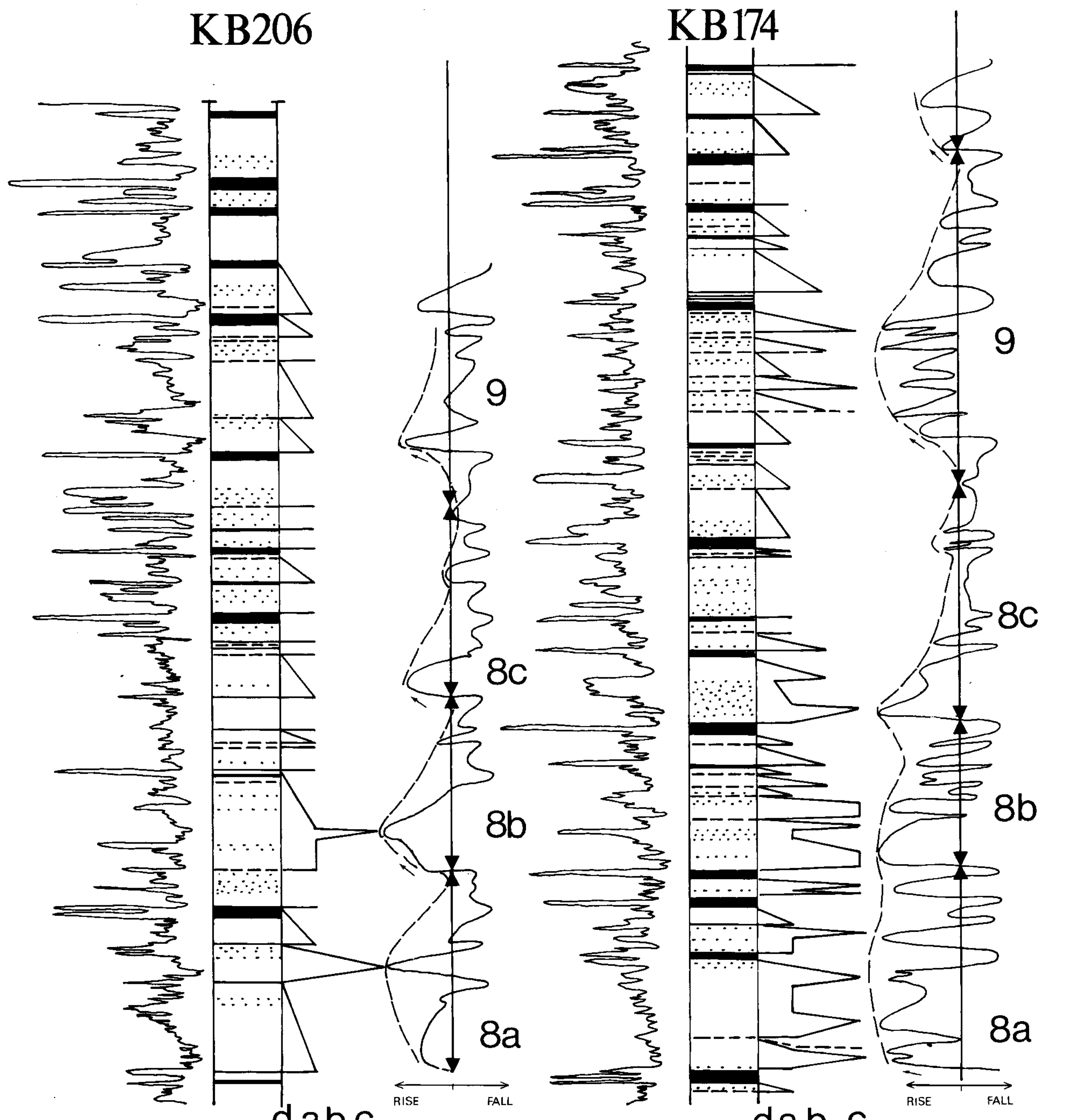


Figure 3.B. Simplified lithologic sequence of boreholes KB174 and KB206 (coal seams, rootlet beds and sandstones indicated), with natural gamma ray log (to the left of litholog; gamma ray range 25-175 API), paleoenvironments based on faunal assemblages (to the right of litholog; swamp = d, floodplain = a, brackish = b, euryhaline = c paleoenvironment) and relative sea level curve (rise to left, fall to right), delimitating basic cycles and complex cycles (interrupted line): Lower Westphalian B interval (between Quaregnon and Eisden Marine bands).

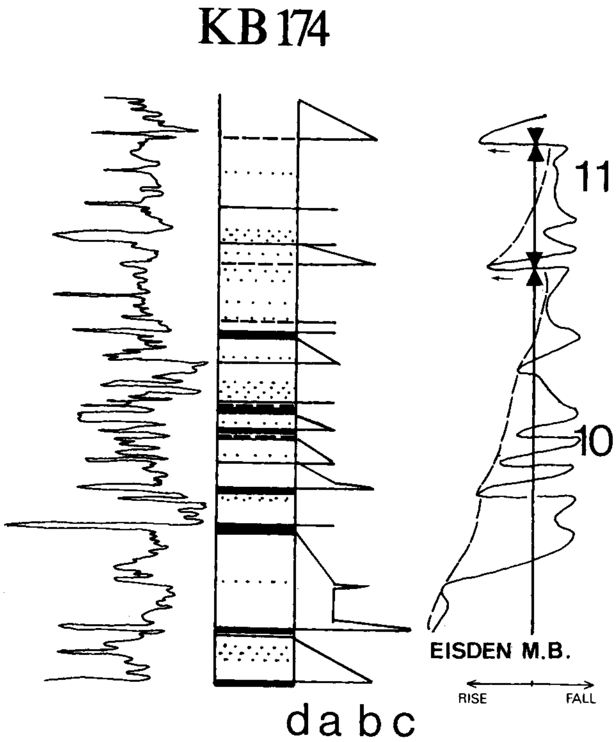


Figure 3.C. Simplified lithologic sequence of borehole KB174 (coal seams, rootlet beds and sandstones indicated), with natural gamma ray log (to the left of litholog; gamma ray range 25-175 API), paleoenvironments based on faunal assemblages (to the right of litholog; swamp = d, floodplain = a, brackish = b, euryhaline = c paleoenvironment) and relative sea level curve (rise to left, fall to right), delimitating basic cycles and complex cycles (interrupted line) : Upper Westphalian B interval (above Eisden Marine Band).

borehole. This large number of brackish/marine bands does not simplify, however, the correlations with the Ruhr coal basin.

Correlation of the KS68 coal seam with the Albert-4 coal seam seems justified because these are the first coal seams overlain by an euryhaline band above the coal seam with the Karl tonstein. Moreover, the euryhaline band above the Albert-4 coal seam is one of the most widely extended in the Ruhr coal basin (Jessen *et al.*, 1969; Knauff & Pieper, 1985). All the other correlations should be regarded as possible ones unless they are based on other evidence (tonsteins or *Palaeestheria* bands).

3. SEDIMENTARY CYCLES

3.1. PALEOENVIRONMENTS

Westphalian deposits in the Campine area are indicative for a fluvial-dominated delta plain complex, that gradually shifted from a lower to upper delta plain. Apparently this shift took place around the Quaregnon Marine Band at the Westphalian A/B boundary (Lorenzi *et al*, 1992; Dreesen *et al.*, 1995).

Four major paleoenvironments «a»-»d» related to relative sea level rise and fall are distinguished in the ideal succession of a sedimentary cycle in the KB174 and KB206 boreholes. The term «relative sea level rise and fall» is used on purpose in order to emphasize that cyclic variations in the environmental conditions are not necessarily due to external causes such as eustatic sea level changes. The internal dynamics of the depositional system (relation between subsidence, sediment supply and paleogeographic position within the sedimentary basin, resulting in episodic fluvial processes) may have been sufficient for the development of autocycles as explained by Delmer (1952). Delmer's concept of autocycles has been adopted here, because it accounts for the frequently limited lateral extension and variability of the 5th and 4th order cycles described in this paper (see also Read, 1995). These autocycles have been overprinted by higher order allocycles of glacio-eustatic origin (Ziegler, 1989, p. 45; Heckel, 1994, p. 83-84), which are bound by the major, widely extended marine bands in northern Europe (possibly related to 3rd order cycles of Posamentier & Weimer, 1993). These are, however, beyond the scope of this paper. Anyhow, Exxon Production Research concepts of sequence stratigraphy are very difficult to apply in fluvial facies associations dominated by autocyclic processes (Read, 1995).

a) Widely extended non-marine floodplains, fluvial channels, crevasse splays and lakes developed at the base of an autocycle. The floodplain deposits, without fauna, consist of frequently fining upward siltstones and silty mudstones with siderite nodules. Fine- to medium-grained sandstone wedges and sheets point to fluvial channel and crevasse splay deposits. Lake deposits are characterized by dark-grey to black, frequently organic-rich, laminated (sometimes silty) mudstones with thin (platy) siderite lenses. Silt (sometimes sand) is introduced by freshwater deltas. Usually, non-marine bivalves (e.g. *Carbonicola, Anthracosia* or *Anthracosphaerium*; cf. Fig. 4a-A/B) predominate the monotonous fossil assemblages of the freshwater delta - lake environment. They may be accompanied or replaced by freshwater ostracodes (*Carbonita*; cf. Fig. 4a-C/D), worms (*Spirorbis*), fish remains (commonly isolated scales; cf. Fig. 4a-F/G) or, in exceptional cases, by merostome arthropods, such as *Adelophthalmus* (cf. Fig. 4a-E and Fig. 4b-A) and *Belinurus*. *Belinurus* has not been recognized in the KB174 and KB206 boreholes. But one single find is here recorded from the late Westphalian A of the KB136 (=KS1) borehole (Fig. 4b-B). The preference of this taxon for freshwater deposits has been postulated by van der Heide (1951, p.63) and Schwarzbach (1962, p.816).

b) The freshwater environment could turn into brackish in case of an open communication with the (distant) sea. In principle, the sediment was similar to that of the freshwater lake deposits. But stagnant water conditions commonly resulted in poorly aerated or even anoxic sediments (black, organic-rich mudstones with dull, framboidal pyrite). The «non-marine» bivalves *Naiadites, Curvirimula* (not observed in the KB174 and KB206 boreholes but occurring elsewhere in the Campine) and *Anthraconaia*, the ostracode *Geisina* (cf. Fig. 4a-H) and the ichnofossil *Planolites montanus* form the principal faunal markers for the brackish water environment. They may occur alone or together with the presumably non-marine taxa. A rather rare brackish water dweller is the malacostracan crustacean *Pyrocephalus* (= «*Anthrapalaemon*») *dubius*. This taxon has not been observed in the

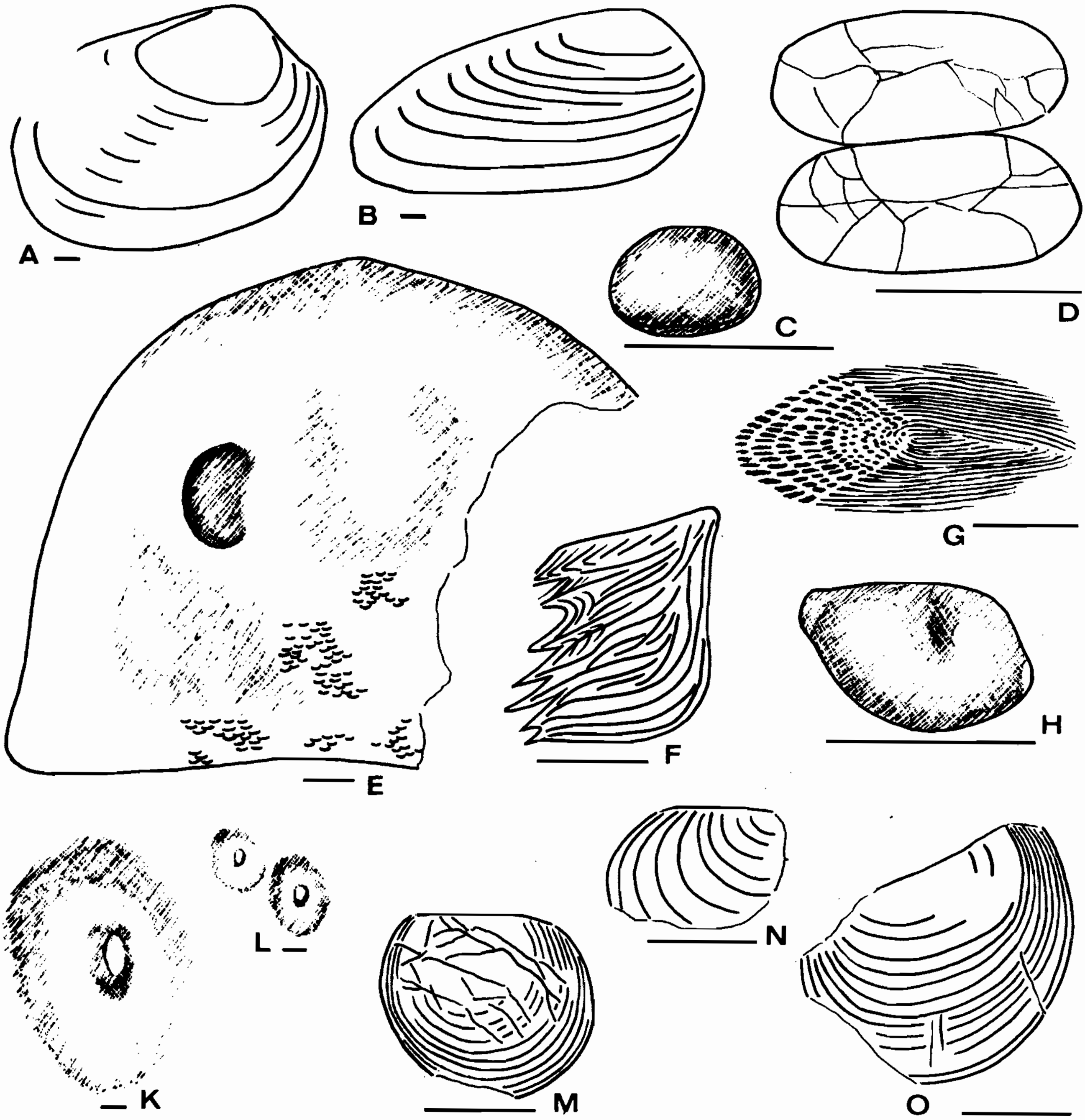


Figure 4.A) Selected taxa which presumably preferred freshwater (A-G), brackish (H) or euryhaline (K-O) conditions in Westphalian A-B times. Examples from the KB174 (Hechtel-Hoef) and KB206 (Peer) boreholes. Bar = 1 mm. A: *Anthracosphaerium* sp., KB206, 864.15 m; B: *Anthracosia* cf. *phrygiana* (WRIGHT), KB206, 865.00 m; C: *Carbonita humilis* (JONES & KIRKBY), KB206, 1151.10 m; D: *Carbonita* cf. *scalpellus* (JONES & KIRKBY), KB174, 1299.30 m; E: *Adelophthalmus imhofi* (REUSS) sensu VAN OYEN 1956, KB174, 1448.90 m; F: *Rhadinichthys* cf. *monensis* (EGERTON), KB174, 1176.95 m; G: *Rhizodopsis sauroides* (WILLIAMSON), KB174, 1077.30 m; H: *Geisina arcuata* (BEAN), KB206, 1131.60 m; K-L: *Planolites ophthalmoides* JESSEN, KB206 (K - 1336.80 m, L - 1211.55 m); M-O: *Palaeestheria* spp., KB174 (M - 993.20 m, N - 1470.60 m, O - 1470.70 m).

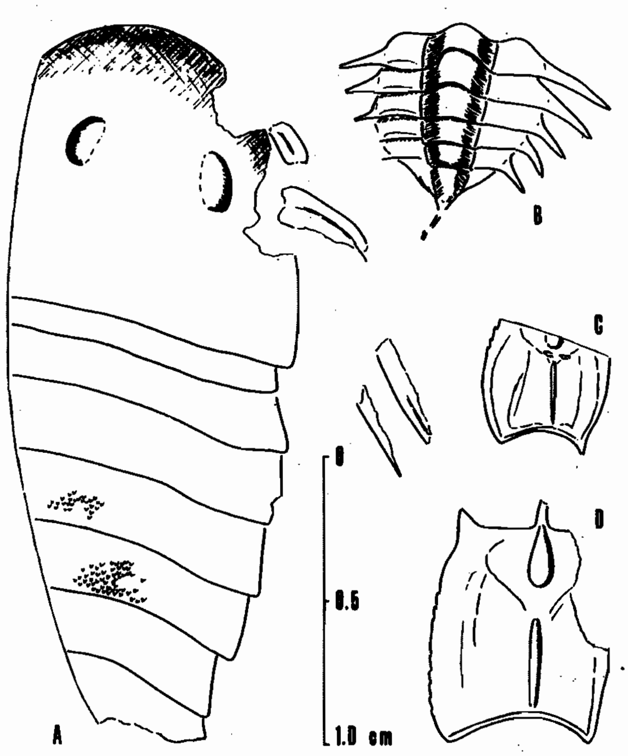


Figure 4.B) Selected Westphalian arthropods from the Campine coal basin which presumably preferred freshwater (A-B) or brackish water (C-D) conditions.
A: *Adelophthalmus imhofi* (REUSS) sensu VAN OYEN, 1956. KB166 (=KS20 Opglabbeek-Biersbeemden borehole, 1031 m, early Westphalian C). Specimen showing part of cephalothorax, abdomen and appendices. In the Campine coal basin, this eurypterid merostome arthropod has also been recorded from the late Westphalian C (cf. Dusar *et al.*, 1987, p.177-179) and late Westphalian A (this report).
B: *Belinurus* sp. KB136 (= KS1 Genk-Schemmersberg borehole, 530.10 m, late Westphalian A). Specimen showing abdomen and part of telson. This is the firstknown specimen of this xiphosurid merostome arthropod in the Campine coal basin.
C-D: *Pyrocephalus dubius* (MILNE-EDWARDS, 1840) sensu VAN DER HEIDE, 1951 (described by van der Heide as *Anthrapalaemon dubius*). Specimens showing part of cephalothorax. Specimen C from KB182 (=KS39 Leopoldsburg-Schrikheide borehole, 993.72 m, early Westphalian C). Specimen D from KB180 (= KS43 Houthalen-De Hutte borehole, 953.20 m, Eisden marine band, late Westphalian B). This malacostracan crustacean arthropod has also been recorded elsewhere in the Westphalian B strata of the Campine coal basin (Pastiels, 1951, Pl. D, Fig. 19 and Pl. F, Figs. 1-3).

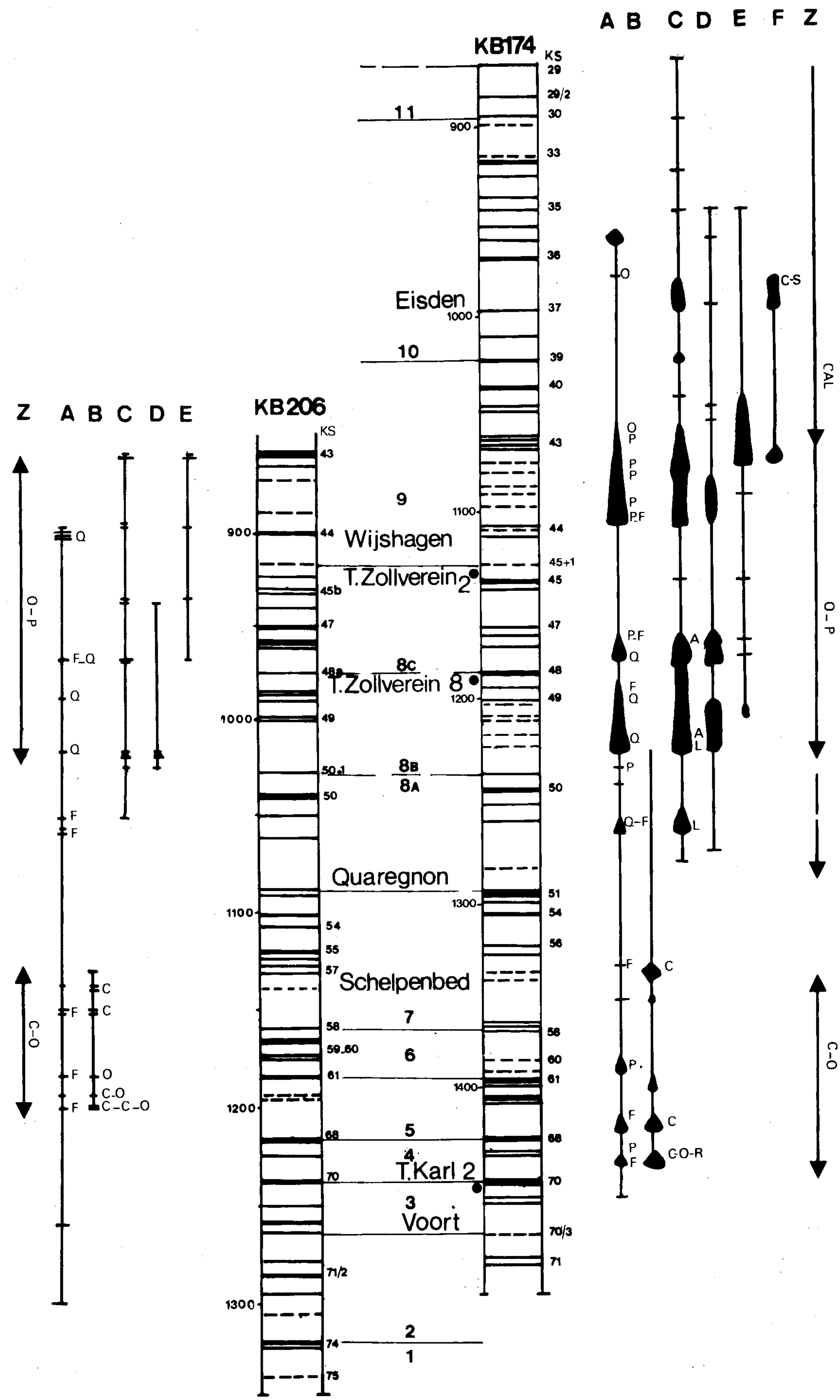
cores from the KB174 and KB206 boreholes, but two specimens are here recorded from the late Westphalian B of the KB180 (= KS43) borehole and the early Westphalian C of the KB182 (=KS39) borehole (Fig. 4b-C-D). *Pyrocephalus* is commonly considered as an inhabitant of freshwater environments, but - as emphasized by van der Heide (1951, p.37) - this taxon preferably occurs in beds with the ostracode *Geisina*.

c) Water conditions could become euryhaline at the acme of the marine ingression. The marine influence could only be deduced from the presence of faunal markers since the sediment closely resembles that of the non-marine and brackish environment (Jessen, 1961). In the KB174 and KB206 boreholes these markers include the ichnofossils *Planolites ophthalmoides (cf. Fig. 4a-K/L)* and *Cochlichnus kochi*, branched pyritized burrows, the phyllopod *Palaeestheria* (cf. Fig. 4a-M/N/O) and the ostracode *Paraparchites*. Elsewhere, euryhaline deposits are characterized by the occurrence of the inarticulate brachiopod *Lingula* and/or agglutinated foraminifera. The slightly marine fauna can be associated with non-marine and/or brackish water representatives. Stenohaline fossil assemblages (with, for instance, myalinid or pectinid lamellibranchs, articulate brachiopods or cephalopods) have not been recognized in the studied sections. In the Campine coal basin these are restricted to lower Westphalian A and base Westphalian C marine bands.

Subsequent relative sea level fall produced a return to brackish and finally freshwater conditions (paleoenvironment types b and a).

d) The non-marine fluvial swamp environment, without fauna but rich in plant remains, displays different facies types, such as paleosols (rootlet beds) and peat-forming swamps and marshes, which are no further commented here (cf. van Amerom & Pagnier, 1990). This environment can be restricted to the coal seam deposit but may reach considerable vertical extension in zones of seam splitting. The top of a coal seam forms the top of an autocycle as defined by Delmer (1952). Subsidence induced by compaction or burning of the organic matter is considered to be the principal cause for drowning of coal seams which generally marks the onset of a new autocycle.

The «a-b-c» succession or transgressive hemicycle developed during relative sea level rise to maximal flooding surfaces, whereas the «c-b-a-d» succession or regressive hemicycle represents the renewed progradation of deltaic facies during relative sea level fall. The ideal succession of paleoenvironments «a-b-c-b-a-d» is practically absent in the KB174 and KB206 boreholes. Marine incursions apparently proceeded so quickly that freshwater and brackish faunas are only rarely recorded in the transgressive hemicycle (cf. Van Leckwijck, 1960; Paproth, 1975). Also the regressive hemicycle is not always complete. Moreover, many cycles were aborted in the non-marine phase (freshwater cycles or «a-d» cycles). Due to seam splitting phenomena, aggradational «a-d» cycles often show limited lateral extent: the number of successive «a-d» cycles does not indicate good correlation potential between boreholes KB174 and KB206 (cf. Dreesen, 1993).


KB174
KB206
KS
Z A B C D E
A B C D E F Z
11
Eisden
10
9
Wijshagen
T.Zollverein 2
8c
T.Zollverein 8
8B
8A
Quaregnon
Schelpenbed
7
6
5
4
T.Karl 2
3
Voort
2
1
900
1000
1100
1200
1300
1400
O-P
C-O
CAL
C-S

For the sake of simplicity the cycles aborted in the brackish phase will be referred to as «b-d» cycles (brackish cycles) and cycles with an euryhaline phase as «c-d» cycles (euryhaline cycles). Analysis of the sections has learned that «c-d» cycles may laterally pass into «b-d» or even «a-d» cycles in accordance with the (varying) paleogeographic position of the boreholes within the continuously evolving sedimentary basin.

The notable decrease in marine influence from KB174 to KB206 possibly fits in the paleogeographical picture for the Campine area: marine influence on the 'Campine bay' is fading from north to south towards the Brabant Massif (Fig. 2). Extensive flooding of the Brabant shoal and thick sediments probably occurred in Westphalian C times only (Van Leckwijck, 1948). The local tectonic situation has possibly reinforced this trend: borehole KB206 is located on the more stable upthrown side of the synsedimentary Donderslag fault block, characterized by slightly reduced subsidence rates and relatively thick (ombotrophic?) coal seams, whereas lacustrine mudstones, overlying thin discontinuous coal seams, prone to salt water intrusion, prevail on the downthrown fault blocks (Dusar, 1989; Dreesen *et al*, 1995; Ferm & Weisenfluh, 1989).

3.2. PALEOECOLOGICAL INDICATORS

The preference and tolerance of the various taxa for a particular paleoenvironment form, of course, open-ended questions. Many «non-marine» bivalves, for example, perhaps never lived in a freshwater habitat. The taxa *Curvirimula* (not recognized in the KB174 and KB206 boreholes), *Naiadites* and *Anthraconaia* possibly favoured «genuine brackish conditions», whereas *Carbonicola, Anthracosia* and *Anthracosphaerium* may have been «euryhaline to limnic brackish water dwellers» sensu Remane (1958, p.21 and 56) according to Paproth (1963, 1971). These suppositions are based on the relative position of these taxa in the ideal faunal succession and the slightly increased boron content of the sediments (Paproth, 1963). Analysis of the thirty-nine beds with *Naiadites* in the KB174 and KB206 boreholes supports the presumed preference of this taxon for brackish environments. Twenty-three beds (59%) have yielded other brackish or euryhaline indicators. *Naiadites* has also been recognized at the position of the (euryhaline) Voort *Palaeestheria* Band in the KB206 borehole at 1267.65 m.

The irregularly distributed fish remains (usually isolated scales) presumably belonged to freshwater dwellers (for instance, *Drydenius, Rhabdoderma, Rhadinichthys, Rhizodopsis*). Van der Heide (1943) emphasized, however, that these may have been marine organisms which entered the freshwater environment only temporarily («adaptées temporellement au milieu d'eau douce»: Van der Heide, 1943, p.62). Remains of fish species, which were considered as «marine» by Van der Heide (1943) have not been recognized in the KB174 and KB206 boreholes.

The long-ranging worm genus *Spirorbis* has an obvious preference for marine environments, but its Late Carboniferous representative *Spirorbis pusillus* presumably lived in brackish and freshwater habitats. It is possible that specimens attached to leaves have drifted into other environments.

The ostracode genus *Carbonita* most likely lived in a freshwater habitat (Van der Heide, 1951; Bless, 1983). In the Campine coal basin the association of *Carbonita, Spirorbis*, non-marine molluscs and fish remains is sometimes found in a thin layer at the base of organic-rich limnic mudstones immediately overlying coal seams. It represents the drowning phase of the peat-forming swamp. These fossils are often pyritized. Anoxic conditions of preservation, recognized by pyrite infilling and replacement, possibly point to intrusion of saline water in a freshwater lake environment, hence to the onset of a transgressive cycle. The occurrence of dull pyrite with otherwise non-marine faunas, as for instance *Spirorbis* or *Carbonita*, is considered as an indication for a weakly brackish environment.

The ostracode species *Geisina* (= «*Jonesina*» or «*Limnoprimitia*», also described as «*Beyrichia*») *arcuata* (BEAN) seems to have favoured brackish environments (Bless, 1983). This is deduced from its common occurrence in the faunal succession in

Figure 5. Bio- and lithostratigraphic synthesis of Westphalian A/B strata in boreholes KB174 and KB206, with non-marine bivalve assemblages and recognized tonstein horizons (marked by black dots). Coal seam numbering corresponds to Campine Collieries 'KS' coal seam succession. Correlation lines along complex cycle boundaries. Westphalian A/B boundary at Quaregnon Marine Band). Note the striking difference between the poorly fossiliferous succession in borehole KB206 and the richer faunal assemblages in borehole KB174.
Z = Non-marine bivalve assemblages zonal extension: C-O = *Carbonicola ex gr. cristagalli-oslancis* assemblage, O-P = *Anthracosia ex gr. ovum-phrygiana* assemblage, CAL = *Anthracosia ex gr. caledonica* assemblage.
A-F = Non-marine bivalves occurrences. A - *Naiadites* spp. [O = *N. cf. obliquus* Dix & Trueman, P = *N. cf. productus* (Brown), F = *N. cf. flexuosus* Dix & Trueman, Q = *N. cf. quadratus* (Sowerby)]; B - *Carbonicola* spp. [C = *C. cf. cristagalli* Wright, C-O = *C. ex gr. cristagalli-oslancis*, O = *C. cf. oslancis* Wright, R = *C. cf. robusta* (Sowerby)]; C - *Anthracosia* spp. [A = *A. cf. aquilina* (Sowerby), I = *A. cf. lateralis* (Brown)]; D - *Anthracosia cf. ovum* Trueman & Weir; E - *Anthracosia cf. phrygiana* (Wright); F - *Anthracosia cf. caledonica* Trueman & Weir [C-S = *A. ex gr. caledonica-simulus* Trueman & Weir]

between typically non-marine and marine assemblages (also cf. Jessen *et al.*, 1952; Fiebig, 1969). The ostracode genus *Paraparchites* commonly occurs in euryhaline or marine nearshore deposits (Bless, 1983). An isolated occurrence of *Paraparchites* sp. at 1022.00 m (above the KS49/5 coal seam) in the KB206 borehole is therefore interpreted as an indication for an euryhaline deposit.

Late Carboniferous and Permian specimens of the merostome genus *Adelophthalmus* have only been recognized in freshwater deposits (Van der Heide, 1951; Van Oyen, 1956; Schwarzbach, 1962).

The paleoenvironmental preference of the phyllopod *Palaeestheria* (= «*Estheria*») is also problematic (cf. Van der Heide, 1951, p.26). This is partly caused by the fact that *Palaeestheria* bands only rarely contain other fossil remains. Calver (1969) stated that «*Estheria* appears to have been dependent on the extension of special conditions into the swamp facies». The same author observed that Lower Westphalian «estheriids commonly precede or follow marine incursions and the inference is that in these measures their favoured environment included a brackish element. However, *Estheria* and related forms are also common in the upper part of the Westphalian C and Westphalian D in which no marine incursions are known, and in this part of the sequence they apparently flourished in a freshwater habitat» (Calver, 1969, p.239). The *Palaeestheria* bands in the KB174 borehole are tentatively interpreted here as euryhaline deposits. The highest one matches the Eisden (= Domina) Marine Band which elsewhere in the Campine area has yielded lingulid brachiopods. The lower two bands (the Voort Horizon at 1470.60-1470.70 m, and an unnamed horizon at 1490.70 m inmediately above the KS71a coal seam) have been correlated with marine foraminifer-bearing bands above the Blücher-2 and Ida coal seams in the Ruhr area, which have also yielded *Palaeestheria* (cf. Bachmann *et al.*, 1970).

A particular problem forms the paleoecological preference of the ichnofossil *Planolites montanus* RICHTER. This taxon is commonly considered as non-marine («extrem nicht-mariner Grabgang» according to Jessen, 1961, p.315). Its distribution in the KB174 and KB206 boreholes suggests, however, that this organism possibly lived in slightly brackish (oligohaline?) water. *Planolites montanus* occurs together with *Cochlichnus* (=*Beloraphe*) *kochi* at 1152.95 m in the KB206 borehole. Of special interest is also the faunal succession above the KS70 coal seam (with the Karl Tonstein) in the KB174 borehole, consisting of (in ascending order) anthracosiids with *Carbonita* sp., *Planolites montanus* with *Naiadites, Planolites ophthalmoides, Planolites montanus* and *Adelophthalmus imhofi*. In this case *Planolites montanus* apparently represents the brackish phase in both the transgressive and regressive hemicycle. Moreover, the four beds with *Planolites montanus* above the Eisden (=Domina) Marine Band in the KB174 borehole are distributed in such a way, that a correlation with the foraminifer-bearing marine bands M/N, O, P and R of the Ruhr area is proposed here. This taxon is therefore considered in this paper as a representative of (slightly) brackish environments.

The ichnofossils *Cochlichnus* (= «*Beloraphe*») *kochi* (LUDWIG) and *Planolites ophthalmoides* JESSEN as well as branched pyritized burrows characterize the incipient euryhaline («estuarine» according to Calver, 1969) environment (cf. Van Leckwijck, 1948; Jessen *et al.*, 1952; Jessen, 1961). These ichnofossils could be released by agglutinating foraminifers and inarticulate brachiopods (*Lingula, Orbiculoides*) if the euryhaline conditions «improved». This is deduced from the observations in, for instance, the Ruhr coal basin (cf. Jessen *et al.*, 1952; Jessen, 1961). These facies transitions have not been recognized, however, in the KB174 and KB206 boreholes.

3.3. GEOPHYSICAL WELL LOG EVIDENCE

Geophysical well logs reflect the lithological composition and contribute to the sedimentological analysis. The cyclic nature of sedimentation is well illustrated by coarsening upward and fining upward sequences as shown by the natural gamma-ray curves. These curves are moreover in good agreement with the distribution of paleoecological indicator fossils (Fig.3). Log responses of particular horizons may be so well individualized that they form reliable criteria for correlation between boreholes, even on interregional scale (Schuster & Schmitz, 1991): the Quaregnon = Katharina Marine Band constitutes a fine example (Fig.3). Nevertheless, the spectralog did not show any indications for sediments of marine origin.

Each cycle is identified by the succession of paleoenvironments, as defined in chapter 3.1. Most cycles start with a transgressive pulse characterized by the maximal flooding of floodplain or swamp and recognised on well logs by low-resistivity high-gamma-ray shale (corresponding to Transgressive Systems Tracts?). This log motif may take a linear form typical for a flooding surface on top of drowned coal deposits or abandoned channels.

The succeeding coarsening upward log motif may represent overbank or crevasse splay progradational deposits formed during floods (corresponding to Highstand Systems Tracts?), until a swamp environment can be established. Small paleofluvial channels and crevasse splays, resulting from channel avulsion, may intervene at all levels during the development of the cycle, and interrupt the general trend observed from the well logs. It should be noted that channels do not incise beyond one associated basic cycle. There is no evidence for incised valleys related to sea level lowstand.

The detrital sediments in freshwater, or floodplain - swamp («a-d») cycles which often occur in closely stacked aggradational successions, again may show fining upward trends, characteristic of a gradual decrease in discharge from distal fluvial systems. Some paleosols display an outstanding natural gamma-ray log response, exceeding the level obtained for the mudstones deposited during the period of maximal flooding.
These fining upward trends may be occasionally interrupted by coarsening upward trends, characteristic of sandy overbank or crevasse splay deposits formed during river floods (cf. Dreesen *et al*, 1995).

High frequency 5th order autocycles or basic cycles may be grouped in series with reinforced coarsening upward or fining upward trends, leading to the recognition of complex, 4th order cycles. The maximum or minimum levels of the natural gamma-ray log response at equivalent positions within successive basic cycles may continue to progress in the same direction for each complex cycle and develop clear trends. Sedimentological trends, derived from well logs, are much better expressed in the Westphalian A deposits. It is not known whether this is due to the more sandy nature of Westphalian B sediments or to an external allocyclic cause.

3.4. COMPLEX CYCLES

The «a-d», «b-d» and «c-d» cycles are not randomly distributed in the KB174 and KB206 boreholes. Simple «a-d» cycles are commonly combined in non-marine «a-d-a-d...» successions, which alternate at irregular intervals with one or more cycles with a brackish («b-d» cycles) or an euryhaline («c-d» cycles) phase, and well in such a way that «complex cycles» are formed with an ideal «c-d-c-d-b-d-a-d-a-d» succession.

Eleven complex cycles (1-11) have been distinguished in the studied interval (Fig. 3). Their description is mainly based on the succession in the KB174 borehole (with the exception of complex cycles 1 and 2) since this sequence has yielded the largest number of fossil assemblages. The definition of complex cycles also takes into account lithological composition and sedimentological trends, illustrated by the natural gamma-ray log motif. The KB206 borehole, with more restricted distribution of faunal elements, allows a better evaluation of the coherency of the complex cycles. Correlations with other boreholes covering the same stratigraphical interval in the Campine coal basin are supporting the subdivision proposed here.

A curve for relative sea level rise and fall is derived from both sedimentary sequences (coarsening and fining upward sequences) and the intensity of flooding (paleoecological indication from fossil assemblages). It thus constitutes a hybridic combination of the Vail and Hallam curves, which cannot be properly applied in this continental environment. The relative sea level curves closely match the succession of complex, 4th order cycles, but also point to discrepancies in facies development between the boreholes, and allow the recognition of higher order megasequences (Fig. 3).

3.4.1. Complex cycle 1

Thickness 19 m; generally thicker in the Campine coal basin. This complex cycle has only been recognized in the KB206 borehole. It comprises the interval between the KS75 and KS74 coal seams (correlated with the interval between Wilhelm and Ernestine/Röttgersbank in the Ruhr coal basin). The sandstone beds traversed in KB206 below coal seam KS75 represent the top of a large sequence, poor in coal, dominated by a euryhaline to brackish environment (cf. Langenaeker & Dusar, 1992).

One coarsening upward «c-d» cycle (with *Planolites ophthalmoides* in the euryhaline phase) can be recognized above the KS75 coal seam. It is succeeded by a thin «a-d» cycle without fauna representing the fining upward branch.

3.4.2. Complex cycle 2

Thickness 52 m. This complex cycle has only been fully recognized in the KB206 borehole; borehole KB174 contains the upper half of this cycle. It comprises the interval between the KS74 and KS70/3 coal seams (correlated with the interval between Ernestine/Röttgersbank and Blücher-2 in the Ruhr coal basin). One «c-d» cycle (with branched pyritic burrows in the euryhaline phase) forms the basal portion of this complex cycle. It is overlain by two «b-d» cycles (with *Naiadites* and *Planolites montanus* in the brackish phase) and capped by two «a-d» cycles without faunal fossils in KB206.

In borehole KB174 a «c-d» (with *Palaeestheria* in the euryhaline phase) replaces the «a-d» cycle on top of coal seam KS71/2, correlated with Ida in the Ruhr coal basin). This level could correspond to a locally developed variation within complex cycle 2. Further marine influence is aborted by channel avulsion and wash outs (coal seam KS71 not present in borehole KB174). However, in the area adjoining the Donderslag fault, this level may take more importance than the succeeding Voort Horizon.

Four cycles display coarsening upward trends; the upper one is terminated by a fining upward spike. This complex cycle is completed by a fining upward branch leading to the succeeding Voort Horizon. The highest natural gamma-ray value observed occurs at the base of this complex cycle.

3.4.3. Complex cycle 3

Thickness 20 m in KB174; 30 m in KB206; thickness difference due to doubling of lower basic cycle in KB206 compared to KB174. This complex cycle comprises the interval between the KS70/3 and KS70 coal seams (correlated with the interval between Blücher-2 and Karl in the Ruhr coal basin). One «c-d» cycle, corresponding to the Voort Horizon (with *Palaeestheria* in the euryhaline phase) is overlain by two «a-d» cycles without faunal fossils. The Voort Horizon forms an excellent marker throughout the Campine coal basin and is characterized everywhere by the presence of *Palaeestheria*. However, the thickness of the faunal band is greatly reduced in the area west of the Donderslag fault: the underlying faunal band may seem to present better conditions for euryhaline organisms.

The natural gamma-ray log shows small coarsening upward sequences for basic cycles within a fining upward envelope, peaking above coal seam KS70/0.

3.4.4. Complex cycle 4

Thickness 18 m in KB174; 21 m in KB206. This complex cycle comprises the interval between the KS70 and KS66-68 coal seams (correlated with the interval between Karl and Albert-4 in the Ruhr coal basin). One «c-d» cycle (with *Planolites ophthalmoides* in the euryhaline phase, and *Planolites montanus* and *Naiadites* in the brackish phase) is succeeded by two «a-d» cycles (with an unidentified fish scale in the lower cycle). Remarkable is the presence of the merostome *Adelophthalmus imhofi* in the freshwater phase of the «c-d» cycle.

A slight upward coarsening trend is continuing from the previous cycle. The natural gamma-ray log shows coarsening upward sequences terminated by a fining upward sequence for KB174 only.

3.4.5. Complex cycle 5

Thickness 36 m in KS174; 32 m in KS206. This complex cycle comprises the interval between the KS66-68 and KS61-62 coal seams (correlated with the interval between Albert-4 and Hugo in the Ruhr coal basin). The base of this complex cycle constitutes a remarkable level in the Campine coal basin; it is characterized by a regular, thick roof for coal seam KS66-68 and widespread faunas. Two «c-d» cycles (with *Planolites ophthalmoides* in the euryhaline phase and *Naiadites* and *Geisina* in the brackish phase) form the lower portion. A minor «b-d» subcycle (with *Planolites montanus* and *Naiadites* in the brackish phase) can be distinguished in the lower «c-d» cycle. They are succeeded by three or four «a-d» cycles without faunal fossils.

The natural gamma-ray is peaking again above coal seam KS68. Coarsening upward trends at large and small scale prevail.

3.4.6. Complex cycle 6

Thickness 53 m in KB174; 31 m in KB206. This complex cycle comprises the interval between the KS61-62 and KS58 coal seams (correlated with the interval between Hugo and Matthias/Mathilde in the Ruhr coal basin). Two «c-d» cycles (with *Planolites ophthalmoides* in the euryhaline phase and *Geisina* and *Naiadites* in the brackish phase) are overlain by three «a-d» cycles without faunal fossils. The smaller thickness in borehole KB206 is compensated by the much greater coal thickness: probably, the thickness difference is due to splitting in the roof of coal seam KS61-62 and wash-outs at the level of coal seam KS59-60 in borehole KB174. Possibly, normal faulting is responsible for some missing sediment around 1175 m.

A succession of two coarsening upward - fining upward sequences can be observed, within an overall coarsening upward trend, continuing from the previous complex cycle. A natural gamma-ray maximum occurs in the middle of the complex cycle, on top of the fining upward sequence (corresponding to euryhaline faunal assemblage in borehole KB174, less developed in KB206 and partly occupied by paleosol of coal seam KS59-60).

3.4.7. Complex cycle 7

Thickness 57 m in KB174; 66 m in KB206. This complex cycle comprises the interval between the KS58 and KS51 coal seams (correlated with the interval between Matthias/Mathilde and Katharina in the Ruhr coal basin). The lower half consists of two «c-d» cycles (with *Planolites ophthalmoides* in the euryhaline phase), succeeded by a (double) «b-d» cycle (with *Naiadites* and *Geisina* in the brackish phase) and again one «c-d» cycle (with *Planolites ophthalmoides* in the euryhaline phase). Four «a-d» cycles (with a single fish scale in one of them) form the upper half of this complex cycle. The coquina horizon «Schelpenbed» (Mussel band), which forms a widely extended marker bed in the Campine coal basin, is also characterized by a natural gamma-ray peak at the base of the «b-d» cycle.

Weakly expressed coarsening upward sequences in the lower part, poor in coal, are terminated by a fining upward branch in the KS55-56 interval. The succeeding «a-d» cycles are marked by the absence of any trends in natural gamma-ray log response, hence in grain-size distribution.

3.4.8. Complex cycle 8

Thickness 175 m in KB174; 169 m in KB206. This complex cycle comprises the interval between coal seam KS51 and rootlet bed KS45+2 or Wijshagen Horizon (correlated with the interval between the Katharina Marine Band and the top of the Zollverein coal seam group in the Ruhr coal basin). The base of this complex cycle is formed by the Quaregnon Marine Band (corresponding to the Katharina Marine Band in the Ruhr). This marine band may be interrupted locally by a rootlet horizon as is the case in KB174. In these conditions the absence of truly marine faunas is not unexpected. No less than ten euryhaline beds (with *Planolites ophthalmoides* and/or *Cochlichnus kochi*) and only one «a-d» cycle (without fauna) occur in the lower half of this succession. The third quarter of this complex cycle consists of six «b-d» cycles (with *Naiadites* in the brackish phase) which alternate with only two «a-d» cycles (one without fauna, one with *Anthracosia* and *Carbonita*). The upper quarter exclusively consists of «a-d» cycles (usually without fauna).

This large complex cycle is marked by an overall regressive trend. Borehole KB206, which contains markedly less faunal evidence for marine ingressions, allows the recognition of three 4th order subcycles within complex cycle 8, of similar scope as the complex cycles defined in the Westphalian A part of the section:

a) Subcycle 8.a (60 m in KB174; 60 m in KB206) comprises the interval between the KS51 and KS50 (50+1) coal seams (correlated with the interval between Katharina and Laura-1 in the Ruhr coal basin). Notwithstanding the equal thickness for this complex cycle, the top of coal seam KS50 in KB206 shows a sandy-silty intercalation, attaining 12 m in thickness, and representing abandoned channel fills without fauna in the swamp environment «d». Such an intercalation is irregularly distributed in the western Campine coal basin.

The natural gamma-ray log response is characterized by an overstepped coarsening upward sequence in the lower part, succeeded by a fining upward trend in the overlying coal-bearing cycles (corresponding to the Viktoria-3 - Laura-1 interval).

b) Subcycle 8.b (44 m in KB174; 52 m in KB206) comprises the interval between the KS50 (50+1) and KS48 (48a) coal seams (correlated with the interval between Laura-1 and Zollverein-7 in the Ruhr coal basin). The roof of the KS50 (locally KS50+1) coal seam is typically characterized by *Planolites* («raindrops» horizon). The thickness difference may again be due to the presence of an additional silt-rich seam split without fauna at the top of the complex cycle in borehole KB206.

The natural gamma-ray log is much better expressed in KB174. Just as for complex cycle 6, a repetition of a coarsening upward and a fining upward sequence is observed within an overall coarsening upward envelope, terminated by a fining upward branch.

c) Subcycle 8.c (71 m in KB174; 57 m in KB206) comprises the interval between coal seam KS48 (48a) and rootlet bed KS45+2 or Wijshagen Horizon (correlated with the interval between Zollverein-7 and Zollverein-1 in the Ruhr coal basin). The roof of the KS48 (locally KS48a) coal seam is well developed and characterized by *Planolites* («raindrops» horizon), similar to the roof of coal seam KS50. Thickness differences due to seam splits and sandstone intercalations, which affect all basic cycles, compensate for the differences observed in the previous cycle.

Again, the natural gamma-ray log in much better expressed in KB174. Coarsening upward sequences succeed within an overall coarsening upward trend, started already in the previous complex cycle, until coal seam KS45b (correlated to Zollverein-2 in the Ruhr coal basin). A fining upward branch terminates this part of the cycle.

The Wijshagen (*Leaia*) Horizon above coal seam KS45+2 (locally KS45) is not recognized as a particular faunal band in either borehole. During the time of deposition of the Wijshagen Horizon, the area west of the Donderslag fault was occupied by river systems, leaving an extensive sand load possibly causing relief inversion. However, the rootlet bed

KS45+2 marks a flexure point in the relative sea level curve, indicating the onset of a transgressive sequence.

3.4.9. Complex cycle 9

Thickness 72 m in KB174; 66 m in KB206. This complex cycle comprises the interval between rootlet bed KS45+2, corresponding to the Wijshagen (*Leaia*) Horizon, and coal seam KS39 (correlated with the interval between Zollverein-1 and «H»? in the Ruhr coal basin). Elsewhere in the Campine coal basin, the Wijshagen Horizon clearly marks the onset of this complex cycle; the roof of coal seam KS44 there constitutes a recurrence of the brackish environment established by the Wijshagen Horizon. The specialized *Leaia* fauna of the Wijshagen Horizon possibly testifies of the harsh ecological circumstances caused by a marine ingression after a long period of relative sea level fall.

Coal seam KS39 is probably the most regular thick seam in the Campine coalfield. It is underlain by a well developed, widespread megaflora zone. In general the interval KS43 - KS39 is composed of a succession of thick coals, deposited on the progradating delta plain during a period of relative sea level fall. The succeeding coal seams in the next complex cycle, immediately below the Eisden Marine Band always remain thinner.

As explained above, the base of this complex cycle is locally marked by two «a-d» cycles, up to coal seam KS44. The following facies succession is very regular and similar all over the western Campine coal basin. The lower half of the complex cycle, up to coal seam KS43, is dominated by half a dozen cycles with a brackish (with *Naiadites* and a single *Anthraconaia*) or an euryhaline (with *Planolites ophthalmoides* or *Cochlichnus kochi*) phase, which alternate with some thin «a-d» cyles, developed as rootlet beds only. *Planolites* («raindrops» horizons) laterally continue up to the coal seam KS41. The upper half consists of coal-rich «a-d» cycles (sometimes with *Anthracosia*, *Carbonita* or fish scales). The slight transgressive trend in the basal portion of this complex cycle becomes clearly regressive in the upper half of the succession. The natural gamma-ray curve does not show an overall trend, notwithstanding the predominance of coarsening upward cycles in the lower half and fining upward cycles in the upper half of the sequence.

3.4.10. Complex cycle 10

This complex cycle with thickness 120 m has only been recognized in the KB174 borehole. It comprises the interval between the KS39 coal seam and the rootlet bed KS32 (correlated with the interval between «H»? and «P» in the Ruhr coal basin). The interval between the KS39 and KS39/1 coal seams with a thickness of 12 m is perhaps associated with the underlying complex cycle 9 since brackish to euryhaline faunas only start above this level. However, this interval is locally composed of a small channel followed by proximal crevasse splays, unsuitable for the establishment of faunas.

One «a-d» cycle (perhaps due to an unfavourable environment as explained above) is found at the base. Three «b-d» cycles (with *Planolites montanus* and *Naiadites* in the brackish phase) and one «c-d» cycle (Eisden Marine Band with *Palaeestheria* in the euryhaline phase) dominate the lower half, wherein only one «a-d» cycle without fauna has been recognized. The Eisden Marine Band is typically characterized by frequent fish remains in the Campine coal basin.

The third «b-d» cycle above coal seam KS35/5 is highly variable in the Campine coal basin. Laterally, the level corresponding to the brackish phase may be occupied by a megaflora horizon in the eastern part of the coal basin, or by a *Palaeestheria* bed in the western Campine coal basin (correlated with «O» in the Ruhr coal basin). The upper half exclusively consists of «a-d» cycles (sometimes with *Anthracosia*, *Carbonita* or fish scales). Within the western Campine coal basin, a fauna minimum can be discerned for these levels, possibly corresponding to a lengthier relative sea level lowstand.

The complex cycle starts with two coarsening upward cycles, followed by two, rather unusual fining upward branches reaching a maximum in the Eisden Marine Band. This indicates that the Eisden Marine Band does not coincide with the onset of the transgression or relative sea level rise; it rather marks the maximal flooding surface. Coarsening upward sequences combined with overall coarsening upward trends predominate in the upper half of this complex cycle which has again become richer in coal seams. Fining upward sequences, marked by high gamma-ray readings in the root zone of coal seams KS35/5 and KS34 interrupt the coarsening upward trends.

3.4.11. Complex cycle 11

This complex cycle with thickness 31 m minimum has only been recognized in the KB174 borehole. It comprises the interval between the KS32 and the KS29b rootlet beds (correlated with the interval between «P» and «R» in the Ruhr coal basin). One «b-d» cycle (with *Planolites montanus* in the brackish phase) at the base is succeeded by two «a-d» cy-

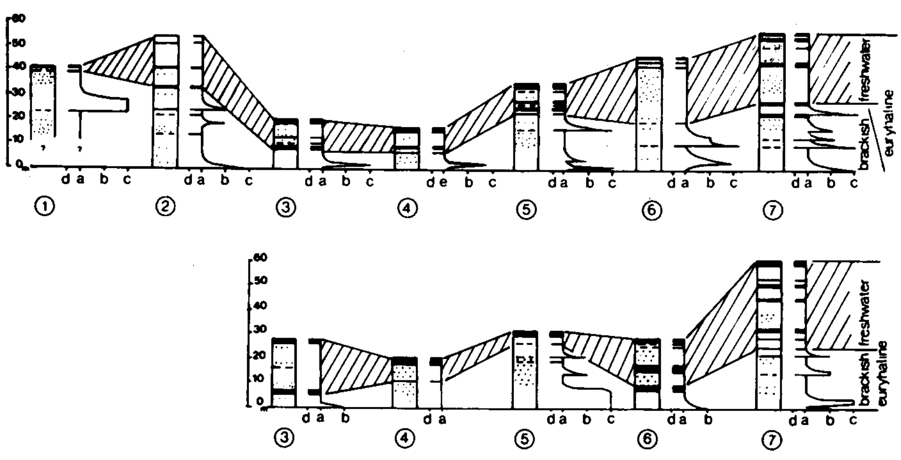


Figure 6. Evolution of complex cycles 1-7 in the Upper Westphalian A for boreholes KB174 (upper row, complex cycles 3-7) and KB206 (complex cycles 1-2; lower row): increasing relative/absolute thickness of freshwater clusters with time, indicating the development of an Upper Westphalian A megacycle with overall regressive trend. For legend: see Fig. 3.

cles (without fauna). The «b-d» cycle on top of the KS29b rootlet bed is provisionally considered as the base of the next complex cycle.

An overall coarsening upward trend can be discerned in this complex cycle, which is composed by a succession of coarsening upward cycles.

3.5. COMPARISON BETWEEN COMPLEX CYCLES

3.5.1. Complex cycles 1-7 (Upper Westphalian A)

The cyclic succession in the complex cycles 1-7 is extremely uniform (Fig. 6). Brackish to euryhaline clusters of one to four «c-d»/«b-d» cycles are succeeded by freshwater clusters of one to four «a-d» cycles. Rootlet beds, sometimes capped by a thin coal seam, separate the «c-d»/«b-d» cycles in the lower cluster, whereas workable coal seams only occur in the uppermost cycle of the brackish to euryhaline cluster or in the upper freshwater cluster. The lower cluster with (repeated) brackish to euryhaline influences might represent a paralic estuarine regime with rather ephemeral vegetations, whereas the upper cluster possibly reflects lower delta plain conditions with widely extended freshwater swamps. The non-marine clusters display an upward trend of becoming thicker and relatively more important between complex cycle 1 and complex cycle 7. The overall coal content is evidently following the same trend. Based on the succession of coal seam groups and the quality of their roofs or on the relative sea level curve, complex cycles 1-2, 3-4 and 5-6 may be combined. The resulting thickness of the combined cycles attains respectively 71, 51, 63 and 66 m for KB206; in KB174 this regular thickness distribution is disrupted by the anomalous development at the level of coal seam KS59-60, which is the scene for widespread seam splitting in the Campine coal basin.

It is therefore suggested that these complex cycles belong to an Upper Westphalian A megacycle «1-7» with an overall regressive trend. Both the complex cycles and the here suggested megacycle may be higher order autocycles in the sense of Delmer (1952) which were the result of minor changes in the paleogeographic setting of the sedimentary basin. There is no obvious need to invoke external causes such as eustatic sea level changes for their development. Most likely, however, these autocycles have been overprinted by higher order glacio-eustatic allocycles, which produced the major marine bands in northern Europe, as, for instance, the Quaregnon/Katharina Marine band and the Eisden/Domina Marine band.

3.5.2. Complex cycles 8-11 (Westphalian B)

The complex cycles 8-11 are distinghuished from the complex cycles 1-7 by the rather large number of small cycles (average thickness 7 m) and the presence of workable coal seams in between the «c-d»/«b-d» cycles of the lower brackish/euryhaline clusters. The occurrence of workable coal seams in the brackish/euryhaline clusters may be due to the assumed gradual progradation of the upper delta plain regime, accompanying a raising surface gradient of the delta plain from the Westphalian A-B boundary onwards (cf. Dreesen, 1993). The increase in gradient is not only deduced from the higher sand/silt content of the Westphalian B sediments but also from the slower rate of marine ingression. Maximal flooding, characterized by the most marine-influenced fossil assemblages, is no longer attained with the first transgressive sequence or bounding surface at the base of a complex cycle, as was the case in the Westphalian A: marine bands (e.g. Eisden Marine Band) are delayed compared to the transgressive base of complex cycles (Fig. 3). Incipient uplift of the Variscan hinterland is regarded as the principal cause for this important paleogeographic shift (see Fig. 2). Delta progradation is also indicated by the upward decreasing number of brackish/euryhaline bands and the increasing relative thickness of the upper freshwater clusters (25% of total thickness in complex cycle 8, 40% in complex cycle 9 and 50% in complex cycle 10). Differences between the successive complex cycles perfectly match Delmer's (1952) model of autocycles in a continuously evolving sedimentary basin.

Complex cycle 11 possibly fits in a model of increasing brackish/euryhaline influence in the Upper Westphalian B, culminating in the Lanklaar Horizon (level not attained in the studied boreholes). At the same time widespread paleofluvial channels prevent reliable regional correlation (a concentration of paleofluvial channels toward the western margin of the Donderslag fault was already noticed by Dreesen, 1993 for the Westphalian A). Cyclicity in the Upper Westphalian B strata remains of local importance. In these conditions no workable coal seams developed in the western Campine coal basin during the Upper Westphalian B.

The sedimentary architecture of the Upper Westphalian B remains rather enigmatic. The single brackish bands above the Eisden Marine Band fit the trend of a reduced marine influence during continued progradation (also marked by an increased sand content). Cyclic development does no longer show long-lasting trends allowing recognition of larger cycles; thick coal seams do not develop. Furthermore paleoenvironments show limited lateral extent. However, brackish/euryhaline clusters will take more amplitude again in the upper part of the Upper Westphalian B.

4. CONCLUSIONS

Autocyclic sedimentation of coal-bearing delta plain deposits of Westphalian A/B age in the Campine coalfield is controlled by the internal dynamics of the depositional system (relation compaction/subsidence - fluvial system/sediment supply). Basic, 5th order autocycles, which are here named 'Delmer cycles' after the eminent geologist who devised this system, normally range from the roof of a coal seam to the top of the next seam. No evidence for allocyclic development due to eustatic sea level rise and fall could be discerned for these cycles.

The cyclic nature of the Westphalian sediments, progradating on the delta plain, can be explained in terms of relative sea level rise and fall vs. elevation and paleogeographic architecture of the delta plain. Ingression of salt water in the delta plain supposedly coincided with periods of relative sea level rise, marking the cycle's basis (corresponding to Transgressive Systems Tracts?). Thick continuous coal seams mostly developed during periods of relative sea level fall, coinciding with the cycle tops. However, genetic sequence stratigraphy is not readily applicable in this non-marine setting.

Four major paleoenvironments related to relative sea level rise and fall are distinguished: 1) non-marine swamps rich in plant remains, containing the coal seams; 2) non-marine floodplains, with fluvial channels and lakes; 3) brackish water floodplains under influence of distant marine ingressions; 4) euryhaline floodplains and lakes at the acme of marine ingressions. Fully marine beds are not present; all delta plain sediments are supplied by the paleofluvial system.

Consequently, the transition from freshwater to marine environments can be recognized unequivocally from faunal assemblages only. Sedimentary features nor well logs can provide the same paleoecological information in such boreholes. The following gradation is recognized: 1) non-marine swamp environment without fauna; 2) non-marine floodplain fauna characterized by fresh water molluscs, simple bioturbations, *Carbonita*, fish, *Spirorbis*; 3) brackish fauna characterized by *Naiadites, Anthraconaia*, *Geisina*, *P. montanus*; 4) euryhaline fauna characterized by *P. ophthalmoides, C. kochi, Paraparchites*, branched pyritized burrows.

Marker beds of the Campine coal basin such as the Voort, Schelpenbed, Wijshagen Horizons do not have the same importance as the traditional marine bands which provide the framework for the stratigraphic subdivision of the Westphalian. These marker beds generally coincide with saltwater ingressions at times of pronounced sea level fall. Faunal assemblages colonizing the floodplains under such conditions appear to be more specialized, with few dominant species.

Transition between successive non-marine bivalve assemblage zones does not show discrepancies between the Campine and Ruhr or Pennine coalfields. As could be expected, the occurrence and evolution of non-marine bivalves or other non-marine faunas, is hardly influenced by the marine ingressions.

The decrease in marine influence from KB174 in the northwest to KB206 in the southeast possibly fits in the overall paleogeographical picture: stronger marine influence is present in NW direction, away from the Brabant shoal in the south (extensive flooding and thick sediments - now eroded - on the eastern part of the Brabant shoal did not occur before the Westphalian C; cf Van Leckwijck, 1956).

Local tectonic conditions may reinforce this gradation: borehole KB206 is located on the stable upthrown side of the Donderslag fault block. Persistence of paleofluvial channels in this area reduces the available space for paleoenvironments favouring preservation of faunal assemblages.

Well-developed autocycles start with a transgressive pulse, containing most fauna horizons, at least in the Westphalian A, followed by a regressive (coarsening upwards) branch and terminate with a fining upwards branch and coal; paleofluvial sandstone deposits may intervene at all positions (and interrupt well log trends). Many basic cycles are, however, aborted in the non-marine floodplain - swamp environment. Successive basic cycles may display coarsening upwards or regressive trends which can be grouped into complex, 4th order cycles. Complex cycles may have been overprinted by 3rd order glacio-eustatic allocycles, which build the classic stratigraphic framework of the Coal Measures, characterised by marine bands at the base of each subdivision. Marine bands are regarded as maximum flooding surfaces. The onset of relative sea level rise occurs earlier, depending on the rapidity of the marine ingression over the delta plain.

All complex cycles start with a rise of the relative sea level. In the Westphalian A the stage of maximal flooding seems to be attained very fast, in any case within the first basic cycle of a complex cycle (resulting in a seasaw pattern of the relative sea level curve, bounded by regionally extensive low-resistivity high-gamma-ray shale). In the Westphalian B the stage of maximal flooding is apparently more delayed (resulting in a sinuous pattern of the relative sea level curve). A tentative explanation for this difference may be a tectonic event causing uplift and increased erosion of the Variscan hinterland, starting at the Westphalian A/B boundary. Probably, higher hydrographic gradients slowed down the rate of ingression of salt water in the delta plain during the Westphalian B. Uplift of the hinterland may also be responsible for the higher sand/silt content of the Westphalian B sediments and the poorer preservation potential of fossils. Moreover, disruption of coalification trend and changes in coal properties, observed at the Westphalian A/B boundary, may result from a change in groundwater chemistry and weathering, caused by such uplift. Due to higher hydrographic gradients and raised freshwater tables, the swamp environment could locally persist in floodplains: salt water ingressions followed the fluvial system and bypassed the coal-forming swamps. This was notably the case in the transgressive sequence of the Lowermost Westphalian B (KS50 seams). Otherwise there is no evidence for a decrease of marine influence during the Westphalian B as opposed to the Westphalian A. These arguments further support the differentiation between lower and upper delta plain sedimentary regime around the Westphalian A/B boundary.

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