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The Upper Cretaceous succession (Cenomanian – Santonian) of the Staffhorst Shaft, Lower Saxony, northern Germany: integrated biostratigraphic, lithostratigraphic and downhole geophysical log data

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ABSTRACT:

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The Cenomanian to Santonian succession of the Staffhorst shaft, ca. 50 km south of Bremen, because of its structural position in the northern German Upper Cretaceous basin, is intermediate in character and fossil content between the pelagic sediments characterizing the Pompeckj Block in the north and the proximal sediments of the Lower Saxony Block in the south. The biostratigraphic subdivision of the shaft is based on inoceramids, echinoids, belemnites and foraminifera. The various biozonations and zonal boundaries used in the Boreal Realm are compared and applied to the zonation of the shaft succession, and the biostratigrapy of the individual fossil groups is described. A new inoceramid zone, that of *Inoceramus gibbosus*, is proposed for the topmost Lower Coniacian; and an echinoid assemblage zonation is introduced. The existing benthic foraminiferal zonation of the Middle Turonian to Santonian has been modified, with changed age assignments based on the macrofossil zonation. The proposed basal stage boundary criteria of the "Second International Symposium on Cretaceous Stage Boundaries" (Brussels, 1995) could be applied only in some cases. The proximity of the Staffhorst shaft to the trial borehole, situated only 39 m away, has permitted the Self Potential (SP) and Resistivity (R) logs to be uniquely directly calibrated against the lithostratigraphical and biostratigraphic succession of the shaft. The previous identification of some stage and substage boundaries on the logs of northern German boreholes based on foraminiferal zonation will need to be shifted by several tens of metres as a result of this calibration.

Key words: Upper Cretaceous, Northern Germany, structural geology, electric borehole logs, stratigraphy, inoceramids, belemnites, echinoids, foraminifers.

Contents

1. HISTORY (B. NIEBUHR)

The Staffhorst shaft is situated at the boundary of the Lower Saxony and Pompeckj blocks ca. 50 km south of Bremen on the ordnance survey map sheet 3219 (Affinghausen). Boreholes drilled by the German oil/gas companies (Staffhorst 2 and 3 boreholes) proved the Staffhorst Dogger iron ore deposit in 1954. In order to investigate this deposit in detail, the Staffhorst trial borehole was drilled in September 1960 at grid reference 34 $^{92\ 152}$/58 $^{44\ 943}$. One year later the excavation of the 6.75 m wide shaft was started, 39 m south of the Staffhorst trial borehole at grid reference 34$^{92\ 152}$/58$^{44\ 904}$. The Barbara Erzbergbau GmbH (now Barbara Rohstoffbetriebe GmbH) was able to prove reserves of oolitic iron ores of the phosphorite-rich chamositic-sideritic type of ca. 500 Mio. tonnes over an area of ca. 60 km^2 (THIENHAUS 1960). Because of the technical problems involved in mining this deposit, the pilot plant was abandoned in August 1965 and the Staffhorst shaft was closed (RÖHRS 1992).

We are grateful for permission to use the logging data and fossil content of the shaft of the Barbara Rohstoffbetriebe GmbH (Porta Westfalica). The fossil and lithologic material was collected by SPIEGLER & SPIEGLER (1964) from the heaps of rock excavated from the shaft, but not directly from the shaft itself. Normally each unit of excavated material spanned about 4-7 m of strata. The collections of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and the Niedersächsisches Landesamt für Bodenforschung (NLfB), Hannover, contain the inoceramids and the microfauna. The supplementary fauna (ammonites, bivalves, brachiopods, corals, sponges) is incorporated into the collection of the University of Hamburg. The echinoids and belemnites also belong to the collection of the University of Hamburg, but are temporarily on loan to G. ERNST, Berlin, for further investigation.

Part of the Staffhorst shaft Upper Cretaceous succession (Middle Turonian to Lower Coniacian) was already illustrated by WOOD & *al.* (1984). Stratigraphic data were published by ERNST & *al.* (1983). FRIEG & *al.* (1989) worked on the Albian/ Cenomanian boundary succession and calibrated the aranaceous microfauna against the electric borehole logs. By means of the boreholes of the Staffhorst area, KOCKEL (1998) demonstrated certain effects of the northern German inversion tectonics in the Coniacian to Santonian. BALDSCHUHN & *al.* (1998a) dealt with salt intrusions into the bedrocks.

2. OBJECTIVES (B. NIEBUHR)

This paper deals with the Upper Cretaceous succession of the shaft, which spans the interval from ca. 240 – 790 m. Because of its structural position, the section mediates between the different facies areas of the "proximal" Lower Saxony Block, to the south, and the "pelagic" Pompeckj Block, to the north. Due to the close proximity of the shaft and the the trial borehole, Staffhorst provides a unique opportunity, using a variety stratigraphic methods (1) to investigate the appplicatbility to the shaft succession of the Stage and Substage boundary criteria that were proposed at the Second International Symposium on Cretaceous Stage Boundaries, Brussels, 8-16 September, 1995 (Cenomanian: TRÖGER & KENNEDY

1996; Turonian: BENGTSON 1996; Coniacian: KAUFFMAN & *al.* 1996; Santonian: LAMOLDA & HANCOCK 1996); (2) to calibrate the electric logs of the trial borehole against the lithostratigraphy and biostratigraphy of the shaft; (3) to apply the recalibrated electric logs to the interpretation of the electric logs of the numerous other north German boreholes.

This recalibration will be of particularl value to the German oil/gas companies, since the Upper Cretaceous in the older boreholes was almost invariably never cored and the positioning of the Stage and Substage boundaries was mostly based on electric logs calibrated by means of foraminiferal biostatigraphy, using now outdated stage concepts. In chapter 4, "Borehole log peak stratigraphy and lithostratigraphy", the previously applied (BALDSCHUHN & JARITZ 1977; KOCH 1977a) and the herein revised Stage and Substage boundaries are shown (*see* Text-fig. 5) to the left and right of the SP log of the Staffhorst trial borehole respectively. In chapter 10, "Mulstistratigraphic correlation and conclusions" the interpretation of the stratigraphy and the rationale behind the revised positioning of the Stage and Substage boundaries is comprehensively discussed.

3. STRUCTURAL DEVELOPMENT IN THE STAFFHORST AREA (R. BALDSCHUHN)

The Staffhorst shaft is situated on the lower northern flank of the Staffhorst inversion and thrust structure (Text-figs 1-2), which continues towards the east into the Blenhorst structure and towards the west into the Scholen structure. This elongated structure is part of a thrust fold belt 70 km long and 15-20 km wide, on the northern margin of the invert-

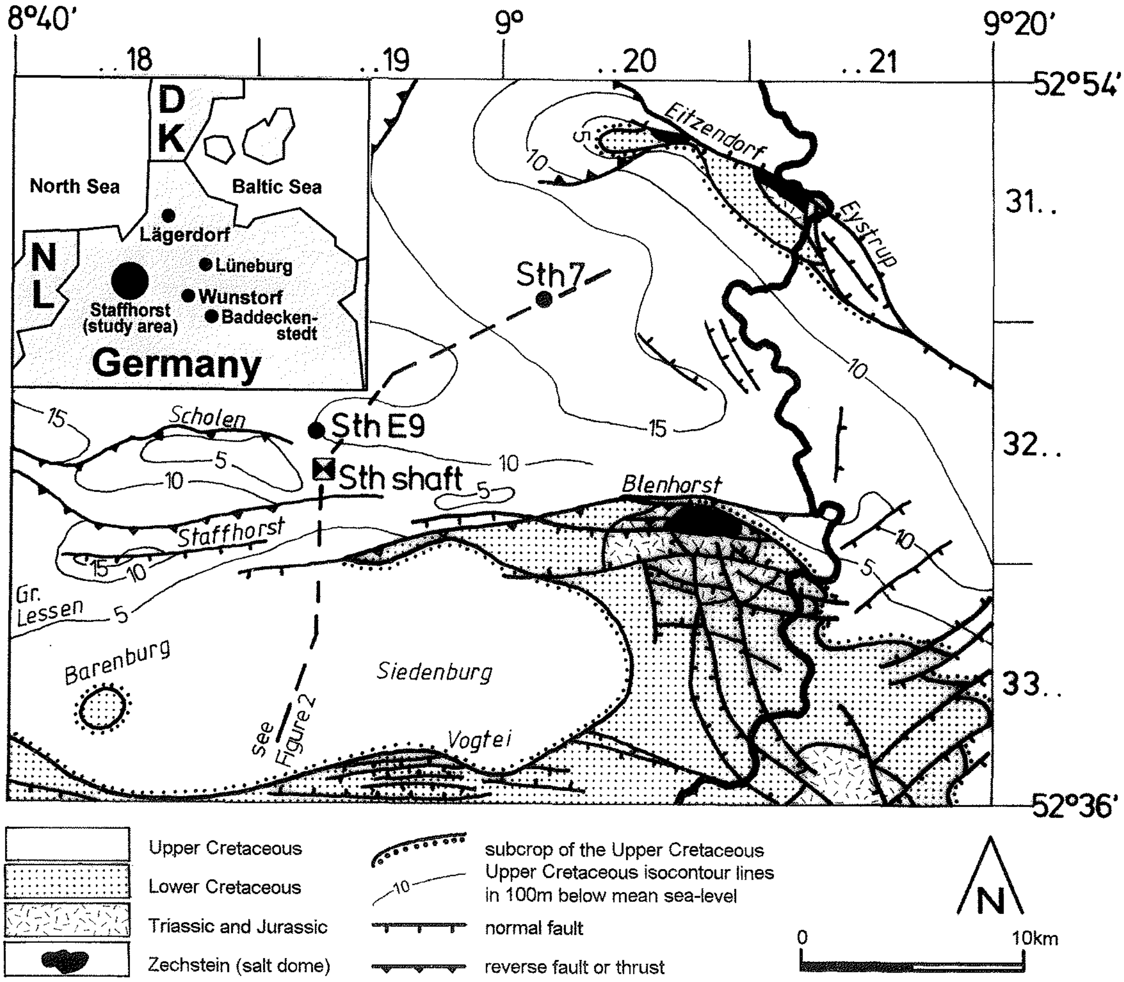

Fig. 1. Structural location map of the Staffhorst area, Lower Saxony

ed western Lower Saxony Basin, which can be followed from the Steinhuder Meer lineament at the Weser river in the east to the Cloppenburg area in the westnorthwest (BALDSCHUHN & KOCKEL 1998). A system of basement faults at the base of the Upper Permian Zechstein, the so-called Goldenstedt – Blenhorst lineament, separates the Lower Saxony Basin in the south from the Pompeckj Block in the north. The southern margin of the Pompeckj Block is subdivided into the Southern Oldenburg and Hoya blocks, and is characterized by deep marginal troughs with Upper Cretaceous sedimentary infill.

The inversion structures, including the Staffhorst structure, which form the northern margin of the above-mentioned thrust fold belt, are characterized by intrusions of Zechstein salt into the level of the Upper Buntsandstein ("Röt") evaporite layer, and by subhorizontal detachment planes which partly root in thrusts within the basement and cut through the entire pre-Upper Cretaceous overburden. These thrusts had been formerly normal faults and were reactivated as thrusts during the Late Cretaceous (*see* Text-figs 1-2).

The structural development of the Staffhorst structure, like all other inversion structures in the western Lower Saxony Basin, follows a cycle with a duration of 70 my, which can be subdivided into four genetic stages (BALDSCHUHN & *al.* 1991).

The first genetic stage commenced with the taphrogenetic development of the Lower Saxony rift basin, which started in the Late Jurassic, and during which rapidly subsiding synsedimentary troughs, grabens and half-grabens formed.

The second genetic stage comprised the Albian, Cenomanian and Turonian ages. The tectonic activities decreased, the depocentres were gradually filled without faulting and sedimentation extended over the basin margins.

The third genetic stage, the inversion of the Lower Saxony Basin, started in the basin centre in the Coniacian and proceeded during the Santonian towards the margins of the basin. During this stage, the entire basin was uplifted, as well as the individual component troughs and grabens. The former normal faults became reversely reactivated and changed to reverse faults or thrusts.

During the fourth and final genetic stage, which lasted from the Campanian until the Maastrichtian according to the distance from the basin centre, *i.e.* the former North Westphalia – Lippe trough, the nonruptural and flexural uplift of the structures gradually ceased, accompanied by deep erosion of the structural crests and infill of the marginal troughs.

The structural development began as early as the Triassic. In Middle Buntsandstein and Lower Gipskeuper (km1) times, an active synsedimentary, longitudinal W-E striking, north-dipping fault developed along the southern margin of the present day Staffhorst structure (BALDSCHUHN & *al.* 1998b). This fault bordered a half-graben, which in Liassic and Middle Jurassic times developed towards the north into a graben with synsedimentary active listric boundary faults rooting in the Röt evaporites. Following regional erosion during the Early Kimmeridgian, transgressive Middle Kimmeridgian, Portlandian and Berriasian sediments were deposited in the Staffhorst graben.

The northern graben shoulder was situated during the Late Jurassic and Berriasian in the area between the boreholes Mellinghausen 1 and Staffhorst E 14, which today is the most uplifted part. During the Early Cretaceous (Hauterivian to Aptian) this area was incorporated into the complex Staffhorst graben in the course of the progressive enlargement of the Lower Saxony Basin towards the north.

The northernmost block of the Staffhorst structure in which the Staffhorst shaft is situated remained in the position of a graben shoulder until the Late Aptian. During the Early and Middle Albian it was also incorporated into the Lower Saxony Basin along a marginal flexure zone. The Albian transgression, caused by an eustatic sea level rise, flooded the southern fringe of the Pompeckj and south Oldenburg blocks, including the Asendorf salt pillow. This area had been uplifted during the Late Jurassic taphrogenesis and subsidence of the Lower Saxony Basin and eroded down to the Lower Middle Jurassic.

The interval from the end of the Albian until the Turonian was tectonically quiet. This is also confirmed by SPIEGLER & SPIEGLER (1964) for the Staffhorst shaft. In the Early Coniacian the subhercynian inversion of the Lower Saxony Basin (Ilsede phase of STILLE 1924) was initiated. The centre of the inversion and uplift was the axis of the North Westphalian – Lippe trough, which transformed into the North Westphalian – Lippe swell. The basement underneath this swell became uplifted by several thousand metres (BALDSCHUHN & KOCKEL 1997a, b). The Staffhorst graben, together with the Siedenburg structure, became uplifted and inverted to a much lesser extent, due to the external position at the northern margin of the Lower Saxony Basin. The basement beneath the Siedenburg structure was thrust onto the Staffhorst Block. SPIEGLER & SPIEGLER (1964) described evidence of tectonic influence on the Lower Coniacian to Santonian sed-

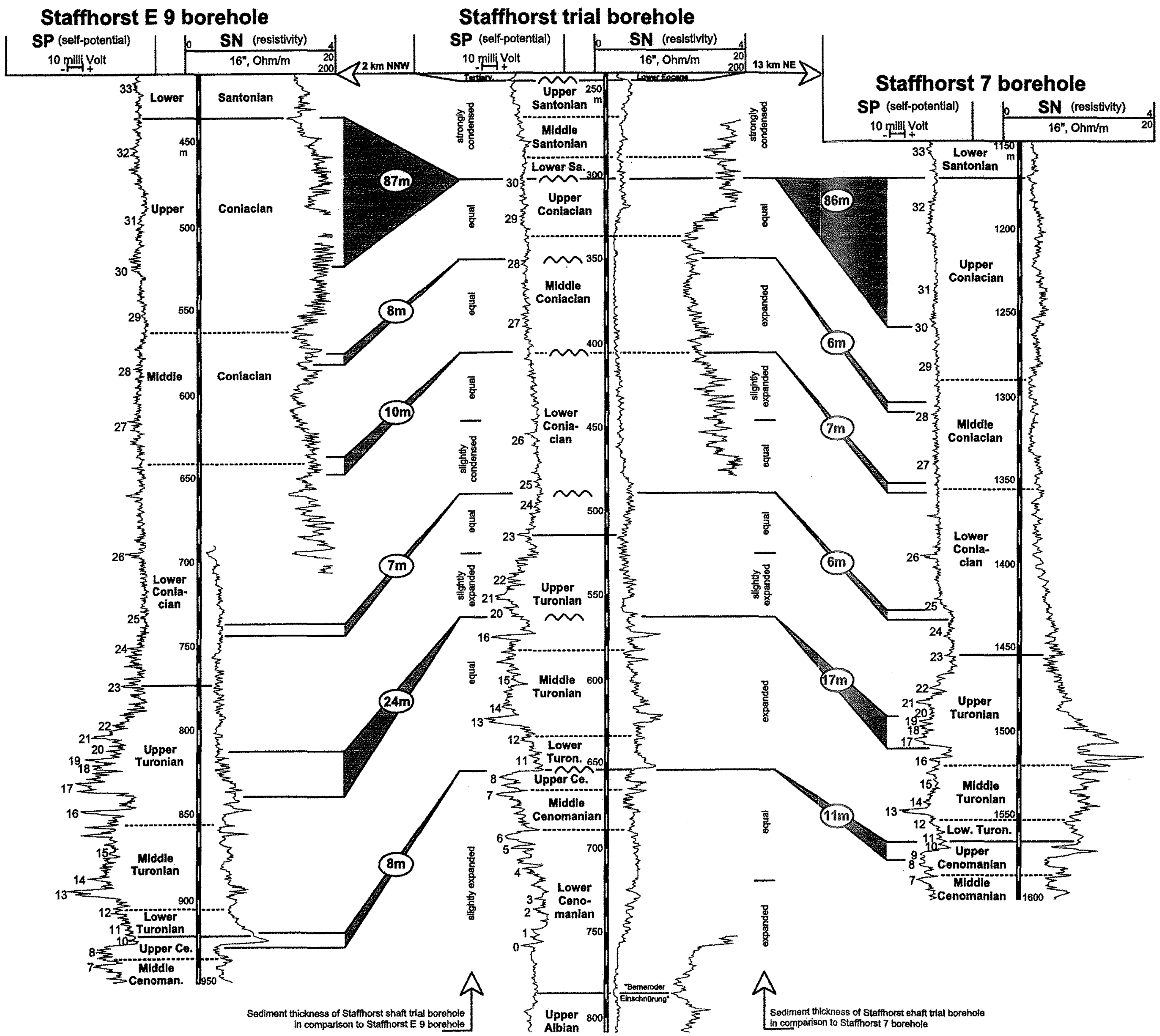

Fig. 3. SP and SN log correlation of the Staffhorst trial borehole in comparision to Staffhorst 7 and E 9 boreholes

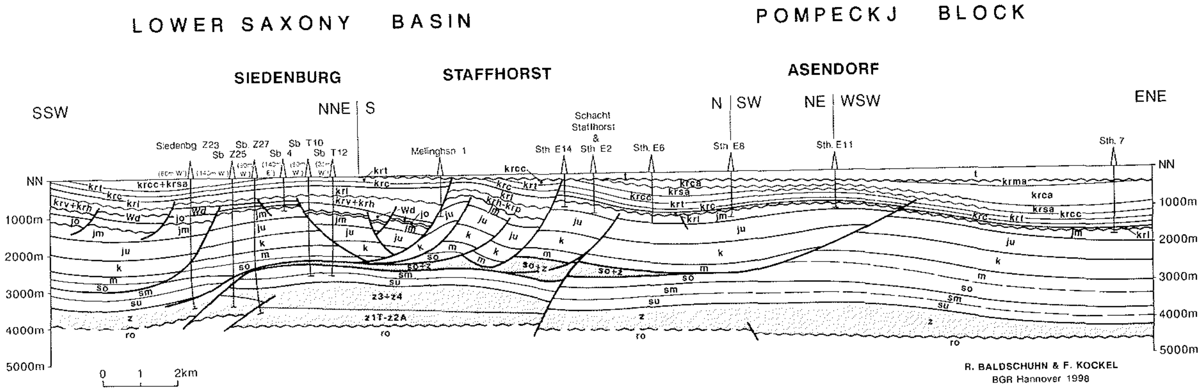

Fig. 2. SSW to ENE section of the Staffhorst area through the boundary region between the Lower Saxony Basin in the south and the Pompeckj Block in the north

iments from ca. 460 m depth in the Staffhorst shaft.

The former normal faults in the basement, as well as the south-dipping parallel faults in the post-Zechstein sedimentary pile, became reversely reactivated in the compressional stress field and became thrusted against the Pompeckj Block in the north. The thrust front of the detachment plane in the Röt evaporites reached the Asendorf salt pillow in the north. Zechstein salt became mobilised and intruded into the Röt evaporites at the boundary faults of the uprising Staffhorst graben and the South Oldenburg Block in the north. The South Oldenburg Block itself subsided synsedimentarily and, over its southern margin, a system of marginal troughs (VOIGT 1963) developed, which received the eroded material from the southern inversion structures.

Erosion of the crests of the inversion structures started already in Coniacian and Santonian times. On the northern flank of the structure are found onlap unconformities of the transgressive Santonian as well as Lower and Upper Campanian that are similar to those observed by NIEBUHR (1995) in the eastern Lower Saxony Basin. The transgressions were caused by eustatic events which interfered with the final stages of the inversion. During the Late Campanian and Maastrichtian, beds of Early Campanian age became uplifted on the northern flank of the structure.

Following the regressions in Maastrichtian and, especially, in Middle Palaeocene times, linked to eustatic sea level changes (GRAMANN & KOCKEL 1988), the crest of the structure became eroded down to the Turonian and Cenomanian. This peneplain was flooded by the Late Palaeocene – Early Eocene sea, with further transgressions taking place at the beginning of the Middle Oligocene and in the Early Miocene (MURAWSKI & *al.* 1983). These Tertiary sediments were partly removed in Pliocene times when the Lower Saxony mountainous area became uplifted in compensation to the subsidence of the North Sea Basin.

4. BOREHOLE LOG PEAK STRATIGRAPHY AND LITHOSTRATIGRAPHY (B. NIEBUHR)

Geophysical methods

The wireline logs investigated comprise the Spontaneous or Self-Potential (SP) logs, expressed in millivolts, and the Resistivity or Normal (N) logs, expressed in ohmmetres.

The SP logs primarily reflect the lithology, and the resistivity of the formation waters, and not the permeability (NORTH 1985; HATZSCH 1994). They are particularly valuable for distinguishing between shale and non-shale rocks. The highest (right-handed = positive) SP values correspond to the highest clay contents and, due to the absence of sandy intercalations within the Upper Cretaceous carbonates, the lowest (left-handed = negative) SP values correspond to the sediments with the highest carbonate content.

The N logs were used to differentiate the specific resistivities of the layers penetrated, as well as to specify the lithologies and geophysical properties of the rocks. They also allow the recognition of bedding planes. The logging procedure usually comprises the short normal (SN), with 16" separation of the electrodes, and the long normal (LN) with 64" separation. However, the LN log has not been figured here since, due to the massive lithology of the Upper Cretaceous rocks, it shows only minor excursions.

SP and SN log correlation

The geophysical data have proved to be the most reliable tool for correlation (*see* ALBERTI 1968). Consequently, a log peak stratigraphy for the Late Cretaceous of northern Germany was established by BALDSCHUHN & JARITZ (1977) and calibrated against the microfossil biostratigraphy of KOCH (1977a). The log peak stratigraphy was based on distinctive negative SP peaks, which were continuously numbered from the base (Cenomanian) to the top (Maastrichtian). The Late Cretaceous standard SP logs (BALDSCHUHN & JARITZ 1977) were subdivided into 84 correlatable units, defined by SP log peaks 0-83.

In the SP log of the Staffhorst trial borehole the SP peaks 0-8, 11-16 and 20-30 were proved, representing the newly interpreted stratigraphic interval from the Albian/Cenomanian boundary to the lower Upper Coniacian. A log peak stratigraphy of the Santonian is not possible because of the numerous hiati and the strong condensation in the Staffhorst trial borehole succession.

The stratigraphic completeness of the Upper Cretaceous succession of the Staffhorst area increases from S to N (Text-fig. 2), whereas the thickness remains constant or is slightly reduced (Text-fig. 3). A comparison with the stratigraphically more complete electric borehole logs of the Staffhorst 7 (Sth 7, ca. 13 km NE of the Staffhorst trial borehole) and Staffhorst E 9 (Sth E 9, ca. 2 km NNW of the Staffhorst trial borehole) boreholes (*see* Text-fig. 1) by means of log peak stratigraphy reveals the following hiati within the Upper Cretaceous succession of the Staffhorst trial borehole (Text-figs 3-4):

654 m: Cenomanian/Turonian boundary – 11 m (to Sth 7) with SP peaks 9 + 10;
563 m: lower Upper Turonian – 17 m (to Sth 7), 24 m (to Sth E 9) with SP peaks 17-19;
491 m: lower Lower Coniacian – 6 m (to Sth 7), 7 m (to Sth E 9);
407 m: Lower/Middle Coniacian boundary – 7 m (to Sth 7), 10 m (to Sth E 9);
357 m: Middle Coniacian – 6 m (to Sth 7), 8 m (to Sth E 9);
303 m: Upper Coniacian – 86 m (to Sth 7), 87 m (to Sth E 9) with SP peaks 31 + 32;
243 m: Upper Santonian to basis of Tertiary – ca. 700 m (to Sth 7) with SP peaks 36-66.

The Cenomanian to Upper Coniacian strata of Staffhorst dip at ca. 10°N-NE. Due to the location of the trial borehole 39 m to the north of the shaft, a correlation value of +7 m for a correlation from the shaft to the trial borehole, and -7 m from the trial borehole to the shaft has to be used (*see* Text-fig. 5). Two separate depth values are therefore given in the chapters "Borehole peak stratigraphy and lithostratigraphy" and "Multistratigraphic correlation and conclusions", the first of which is the shaft depth and the second (in brackets) is the trial borehole depth. Upsection of 303 m depth, above a major hiatus of ca. 90 m in the Upper Coniacian, the Santonian sediments are apparently flat-lying and no correlation factor is needed. SPIEGLER & SPIEGLER (1964) also recognized a dip only well below the prominent hiatus at 379 m shaft depth.

The bedding of the intervals 243-388 m (243-394 m) of the Upper Santonian to Middle Coniacian and 411-453 m (418-460 m) of the Lower Coniacian was described by SPIEGLER & SPIEGLER (1964) as "tectonically disturbed", this being linked to the inversion of the Staffhorst graben in the Early Coniacian (BALDSCHUHN & *al.* 1985, 1991). Due to the following progressive uplift and erosion, the sections are generally incomplete. Only the Santonian transgressions overlap the inversion structure.

Litho- and log peak stratigraphy

The lithostratigraphic investigation of the Staffhorst shaft (Text-fig. 5) was carried out using the material in the collections of the BGR/NLfB, Hannover. In this way, it was possible to check and, where necessary, to revise the descriptions given by SPIEGLER & SPIEGLER (1964). For a definition of the related litho-units and events *see* ERNST & *al.* (1979, 1983), WOOD & *al.* (1984) and ERNST & WOOD (1995).

The **Albian/Cenomanian boundary** lies in the Bemeroder Schichten (KEMPER 1973) and is lithologically poorly characterized. In the electric borehole logs it is taken at a marked negative SN peak at 779 m shaft (786 m trial borehole), the so-called "Bemeroder Einschnürung" (Bemerode constriction), biostratigraphically defined by the associated (second) occurrence of the ostracod *Physocythere steghausi* (FRIEG & *al.* 1989).

Lower Cenomanian: The Bemeroder Schichten of the basal Cenomanian, between 753-779 m (760-786 m), are marly with fine silty concretions and streaks and lithologically scarcely distinguish-

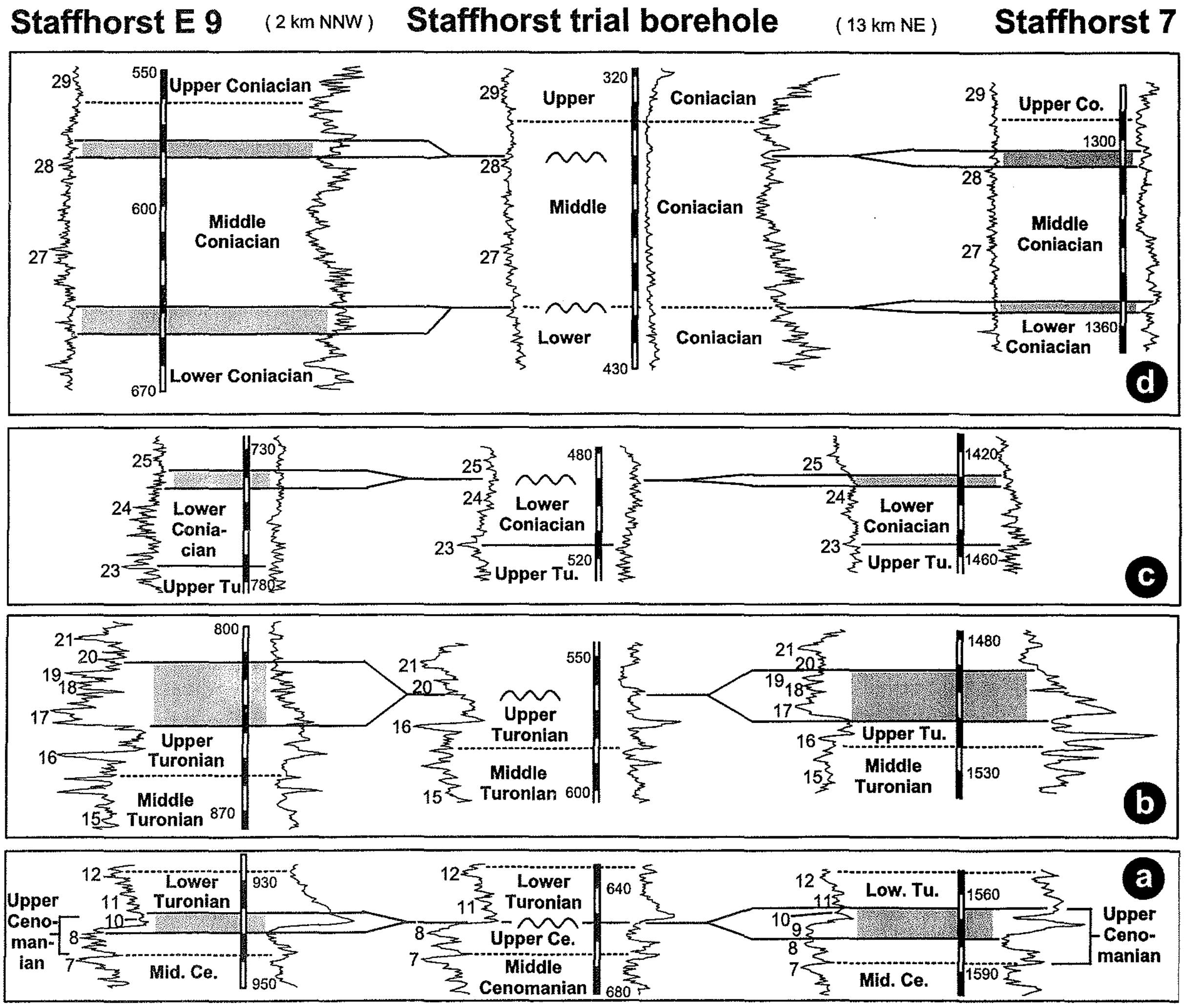

Fig. 4. Hiati in the Staffhorst trial borehole section in comparision to Staffhorst 7 and E 9 boreholes

able from the Upper Albian. These are interpreted in a sequence stratigraphic context as a shelfal lowstand sediment beneath the Lower Cenomanian transgression horizon. In northern Germany, the Bemeroder Schichten, with a maximum thickness of up to 40 m, are only locally developed; in many places, as in the Salzgitter area, the sediments of the Lower Cenomanian transgression lie directly on the Flammenmergel (FRIEG & *al.* 1989).

The most important marker horizon, SP peak 0 at 750 m (757 m) with distinctly more negative (= more calcareous) SP values, is the sediment of the Lower Cenomanian transgression, which here, as locally in England (WOOD, *pers. comm.*) is composed of massive hard glauconitic limestone. Upsection there is a distinct facies change to glauconitic marlstones with inoceramid debris. From here on the SP und SN logs show relative high values. Two inoceramid debrites in this marl unit at 730-735 m (737-742 m) and 722-726 m (729-733 m) respectively may represent sequence boundaries. Within the uppermost Lower Cenomanian sequence III the glauconite content gradually decreases and the carbonate content concomitantly gradually increases. Up to 683 m (690 m) the sediment consists of calcareous marlstones. Intervals with distinct alternations between calcareous and marly beds, thus with high SP and SN values, occur between 683-707 m (690-714 m) at the level of SP peaks 4-6. This lithological and sequence development of the Lower Cenomanian is comparable with that found in more proximal depositional areas around Salzgitter, southern Lower Saxony (*cf.* WILMSEN, *in*: NIEBUHR & *al.*, *in prep.*); however, in Staffhorst the uppermost Lower Cenomanian sequence III (*Mariella* sequence of ERNST & REHFELD 1997) is two to three times thicker.

Middle Cenomanian: A particularly marked glauconitic marl bed with high SP values is found at the base of the Middle Cenomanian above SP peak 6 at 682 m (689 m), and marks a sequence boundary. Associated with this sequence boundary is a debrite composed of abundant comminuted irregular echinoids at 678 m (685 m). The Mid-Cenomanian event between 676-678 m (683-685 m) is developed as a bioturbated nodular calcareous marlstone, associated as usual, with the occurrence of *Holaster subglobosus* (*cf.* ERNST & *al.* 1983; ERNST & REHFELD 1997). After increasing carbonate content to SP peak 7 at 662 m (669 m) the dark marly and glauconitic sequence boundary of the *Pycnodonte* event at 659 m (666 m) is indicated by a marked positive SP peak. This sequence IV of the Middle Cenomanian is thus expressed in the SP log in exactly the same way as sequence III of the upper Lower Cenomanian: above a marly-glauconitic sequence boundary with an abrupt, positive SP peak, the increase in carbonate content is expressed by a falling SP trend. The top of the sequence, at SP peak 6 for sequence III, and at SP peak 7 for sequence IV respectively, shows the lowest SP values in each case. Thus presumably completely developed sequences in this lithology are expressed in the SP logs by typical "saw-tooth" signatures (*see* Text-fig. 5).

Upper Cenomanian: Of the overlying sequence V of the Upper Cenomanian Arme *rhotomagense* Kalke (STROMBECK 1857), only the basal part up to the *Amphidonte* event could be proved. In contrast to the Söhlde section, near Salzgitter (*see* ERNST & *al.* 1998b), the upper ca. 15 m of the Arme *rhotomagense* Kalke, the *plenus* Bed and the lowest 4 m of the Turonian are all missing. Compared to the Staffhorst 7 borehole on the pelagic Pompeckj Block, in which all the SP peaks of the Cenomanian/Turonian boundary interval are demonstrable, 17 m of sediment are missing here (Text-figs 3-4). In Staffhorst, SP peaks 9 + 10 are absent at the omission surface with *Amphidonte* and phosphorites at 647 m (654 m). The base of SP peak 10 of the Staffhorst 7 and E 9 boreholes within sequence VI corresponds to the *plenus* Bed (*see* Text-fig. 4; *cf.* NIEBUHR, *in*: NIEBUHR & *al.*, *in prep.*).

Lower Turonian: From 641-647 m (648-654 m) appear reddish and greenish coloured calcareous marlstones, the so-called Lower Rotpläner of the Lower Turonian. The base of the Rotpläner is composed of greenish-grey, followed by reddish-brown, marly limestones. The reddish coloration passes upwards into grey (SPIEGLER & SPIEGLER 1964). In the overlying beds with SP peaks 11 + 12, the sediment becomes increasingly calcareous and paler.

Middle Turonian: The so-called Weiße Grenzbank is represented by a well defined limestone bed at the top of sequence VII (ERNST & WOOD 1995), at the level of SP peak 13, between 614-621 m (621-628 m). This peak is one of the most conspicuous Upper Cretaceous peaks in the SP and SN borehole logs of the Lower Saxony Block (*see* Text-fig. 3) and is also easily identifiable in the borehole logs of the Pompeckj Block (*see* BALDSCHUHN & JARITZ 1977). The Weiße Grenzbank terminates in the sequence boundary of the marl bed M_0 at 614 m (621 m) and the corresponding marked positive SP peak. This spectacular dark grey marl layer with included inoceramid debris appears to be of allochthonous origin. ERNST & REHFELD (1998) postulated an hiatus at the horizon of marl bed M_0.

Disturbed alternations of calcareous marlstones and marly limestones with intercalated, mostly allochthonous, marl beds mark the 587-602 m (594-609 m) interval. The red coloration of the sediments of the Middle and Upper Rotpläner of the more proximal depositional area near Salzgitter (ERNST & *al.* 1998b) is not developed in Staffhorst. Between 575-587 m (582-594 m) the limestones exhibit omission surfaces. These limestones terminate in a debrite with inoceramid debris at 573 m (580 m), which can be interpreted as a sequence boundary between sequences VIII and IX.

Upper Turonian: At 556 m (563 m) log peak correlation indicates an hiatus comprising SP peaks 17-19 (Text-figs 3-4), which can be assigned to the lower part of the Upper Turonian. Above the hiatus the sediment in the following Lower Limestone Unit becomes increasingly more calcareous. At 534-537 m (541-544 m) an alternation of hard, splintery white limestones with dark grey marls could correspond to the stratigraphic level of the *Hyphantoceras* event (*see* chapter 6). Between SP peaks 22 + 23 at ca. 520 m (ca. 527 m) there is a distinct facies change from the Lower Limestone Unit into massive greenish-grey marlstones, which represent the stratigraphic equivalent of the Grauweiße Wechselfolge, and are expressed by uniform small-scale changes in SN values ranging from low to medium levels. ALBERTI (1968) had already distinguished this stratigraphic interval as a conspicuous marker in electric borehole logs of the boreholes of the Pompeckj Block.

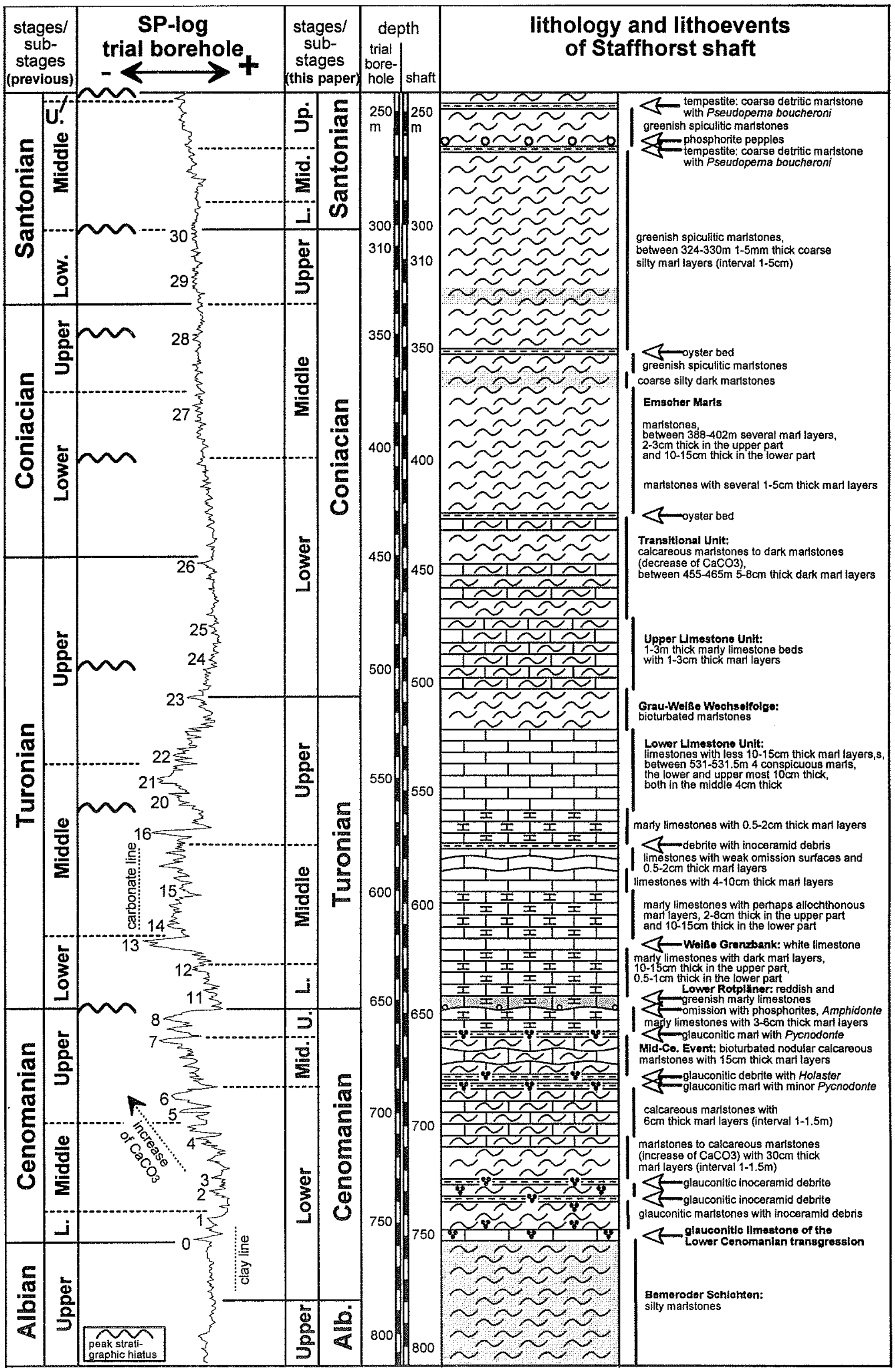

Fig. 5. SP log of the Staffhorst trial borehole and lithology of the Staffhorst shaft. Note the 7 m correction factor between shaft and trial borehole as well as the previously applied (BALDSCHUHN & JARITZ 1977; KOCH 1977a) and newly interpreted stage and substage boundaries (*this paper*)

Lower Coniacian: In the lowermost Coniacian, above SP peak 23 at 504 m (511 m), the massive marlstones pass up into the marly limestones of the following Upper Limestone Unit. The equivalent of the Grauweiße Wechselfolge would thus have in Staffhorst a ca. 14 m thick "Turonian part" and a ca. 2 m thick "Coniacian part". This ca 7 : 1 ratio is very similar to the 6 : 1 ratio found in the Salzgitter-Salder area (WOOD & ERNST 1998, p. 95). According to the electric borehole logs, the Upper Limestone Unit probably extends up to above the SP peak 25 at 473 m (480 m). However, it is lithologically not clearly separable from the overlying Transitional Unit, since this contains repeated calcareous intercalations in the basal part.

Above 453 m (460 m) the boreholes can be correlated only by means of SN logs. This facies change shows the onset of inversion tectonics in the Lower Coniacian on the Lower Saxony Block (BALDSCHUHN & *al.* 1991; *see* chapter 3).The SP logs of boreholes on both the Lower Saxony and Pompeckj blocks exhibit relatively small values on a low level. Between 413-483 m (420-490 m) alternations of bioturbated marlstones and calcareous marlstones occur, with the alternation being particularly strikingly developed between 443-447 m (SP peak 26 at 450-454 m in the trial borehole). Above an oyster bed at 426 m (434 m), in the upper Lower Coniacian, the sediment is even more uniform, comprising dark marlstones with less calcareous layers, and representing the stratigraphic equivalent of the Emscher Marls.

Middle Coniacian: The onset of distinctly more negative SP values, approximately marking the end of the typical Emscher Marls, appears at SP peak 28 in the Middle Coniacian on the "pelagic" Pompeckj Block (*see* BALDSCHUHN & JARITZ 1977), on the Lower Saxony Block, however this monotonous marly facies may locally continue up into the Lower Campanian. In Staffhorst, according to log correlation, two small hiati occur within the Emscher Marls of the Middle Coniacian at 350 m (357 m) and 400 m (407 m) respectively, but these cannot be identified biostratigraphically. At 352 m (359 m) another oyster bed is found.

Upper Coniacian: In the Staffhorst area, the Upper Coniacian succession is marked by the renewed intercalation of gradually paler and more calcareous portions. At 303 m in the shaft and trial borehole (Coniacian/Santonian boundary) log peak correlation identifies a distinct hiatus, which in the Staffhorst trial borehole is expressed by the absence of some 90 m, corresponding to SP peaks 31 + 32 (*see* Text-fig. 3). This hiatus comprises the middle and upper Upper Coniacian, since above the hiatus basal Lower Santonian has been proved (*see* chapter 5).

Santonian: The Santonian of Staffhorst is condensed and full of hiati; consequently no attempt has been made to number the log peaks of the trial borehole. This situation relates to the structural position of the Staffhorst area on the top of the inversion structure (*see* chapter 3). The Lower and Middle Santonian succession is developed as spiculitic marlstones with pigment-glauconite, and is scarcely distinguishable lithologically from the underlying Upper Coniacian. Here again there are some more calcareous layers. At 268-271 m and 249-253 m in the shaft and trial borehole coarse detrital, bioclast-rich marlstones with mass occurrences of *Pseudoperna boucheroni* are interpreted as tempestites. Between 261-263 m, centimetre-sized phosphorites were found, indicating a distinct hiatus with an associated transgression horizon.

The Late Cretaceous succession in both shaft and trial borehole is truncated at 242 m by the Lower Eocene transgression (SPIEGLER & SPIEGLER 1964; KOCH 1977b).

5. INOCERAMID STRATIGRAPHY
(I. WALASZCZYK & C.J. WOOD)

The Staffhorst shaft provides extremely rich and taxonomically diverse inoceramid material, allowing precise stratigraphic subdivision of the succession in terms of the existing zonal scheme (Text-fig. 6). However, as in the case of the other macrofossils, the inoceramid samples generally represent intervals that are several metres thick, so that only a broad picture of the succession of assemblages and the location of critical event beds can be obtained. It must also be emphasised that much of the material is to a greater or lesser extent distorted through compaction.

In the Cenomanian and Turonian parts of the succession, the inoceramid record is surprisingly incomplete, but it is unclear whether or not this is a result of the collection method from heaps of rock excavated from the shaft (the Halde, in German) or of selective collecting of particular fossil groups. With the exception of some event occurrences, the available material is not particularly impressive. However, the inoceramids can be used to locate the approximate position of most of the stage and substage boundaries.

The Coniacian assemblages are of particular importance in that they permit a further elaboration of

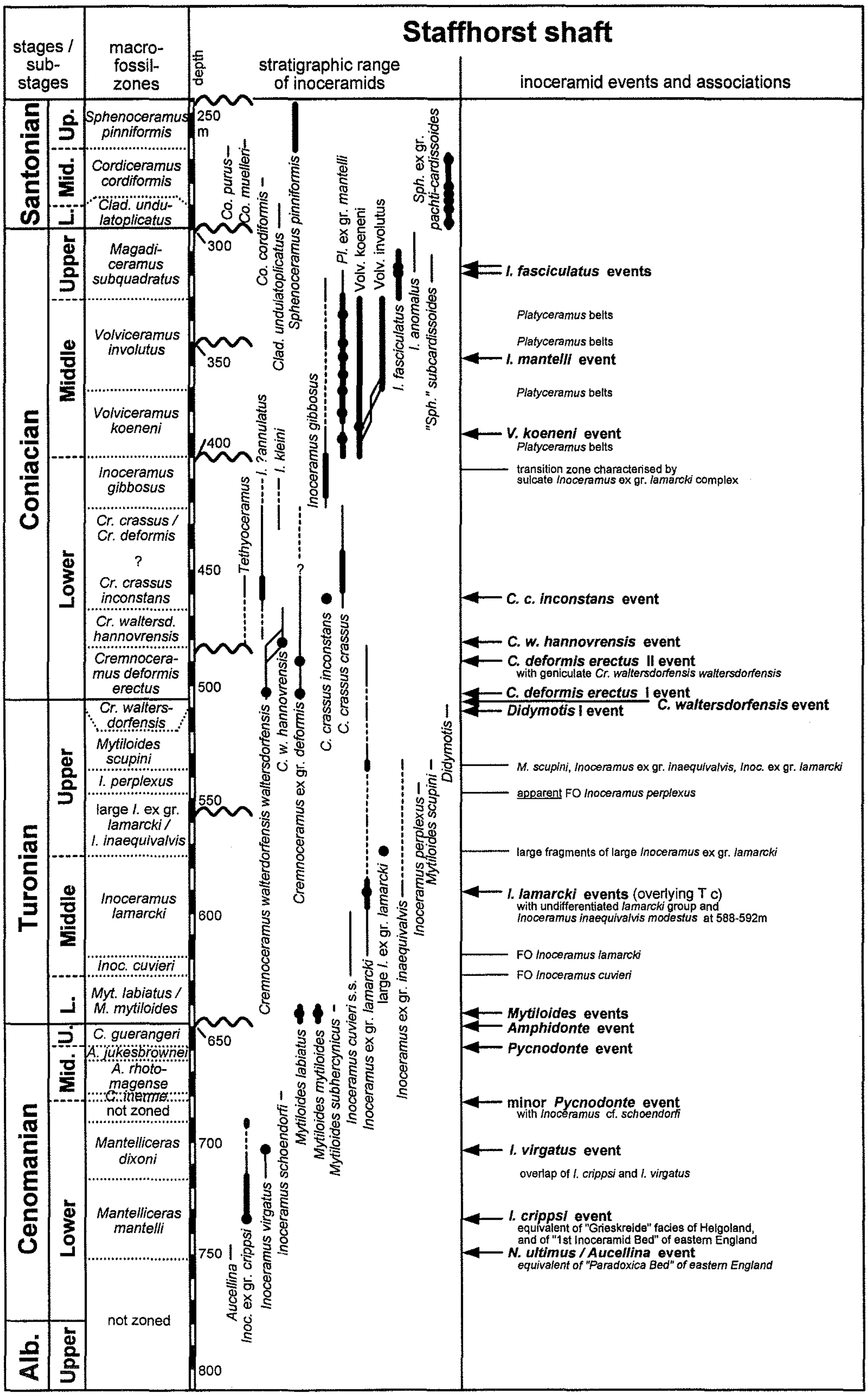

Fig. 6. Vertical ranges and abundances of inoceramids in the Upper Cretaceous of the Staffhorst shaft

the present inoceramid zonal scheme that is applicable at least in the European Province. A new upper Lower Coniacian inoceramid zone, that of *Inoceramus gibbosus*, is proposed for the interval between the last cremnoceramids (the group characterising the greater part of the Lower Coniacian) and the entry of volviceramids at the base of the Middle Coniacian. The Middle Coniacian assemblages permit morphological changes within the volviceramids to be investigated and correlated with horizoned material collected by HEINZ from the marly chalk facies of the former Lüneburg quarries (*cf.* HEINZ 1926). The diverse Upper Coniacian assemblages include four of the five new species that were originally documented by HEINE (1929) in his work on the Emscher inoceramids of the Westphalian coal-shaft successions, but which have subsequently been only sporadically reported and usually without detailed stratigraphic data. The higher Upper Coniacian assemblages appears to be absent as the result of an hiatus.

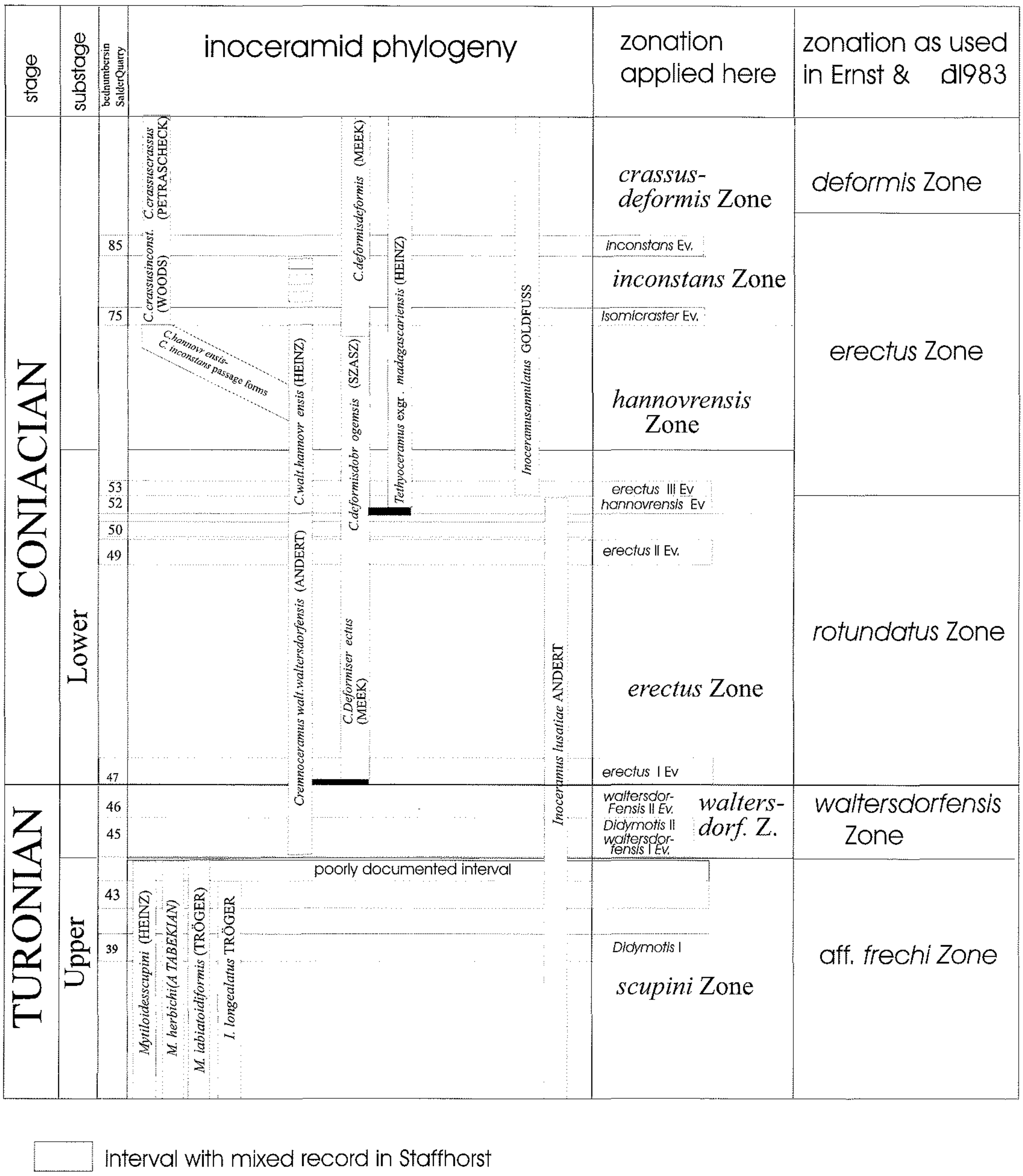

Fig. 7. Inoceramid succession, phylogeny, and zonation at the Turonian/Coniacian boundary in comparison to the Salzgitter-Salder quarry, Lower Saxony

The Santonian assemblages are dominated by sphenoceramids.

A detailed palaeontological description of the Coniacian inoceramids and full discussion of the new biostratigraphic results will be presented in a separate paper following further investigation of the Staffhorst material and comparative material from other shaft and outcrop successions (WALASZCZYK & WOOD, *in prep.*).

Cenomanian

The available inoceramid material provides only a surprisingly incomplete record of the stage. On the other hand, some of the main inoceramid events are well represented. *Inoceramus* ex gr. *crippsi*, including *I. crippsi crippsi* MANTELL, occurs in abundance in the 715-735 m interval. The basal sample (731-735 m), in which the inoceramids are present in rock-forming quantities, both as shell fragments and complete valves, is lithologically comparable with the 1st *Inoceramus* bed of the eastern England succession, which is usually attributed to the *Sharpeiceras schlueteri* Subzone (GALE 1995) of the Lower Cenomanian *Mantelliceras mantelli* Zone. The overlying samples with *I.* ex gr. *crippsi*, including material preserved in pale coloured limestones, could belong either to this subzone or to the overlying *Mantelliceras saxbii* Subzone. The occurrence of *I. virgatus* SCHLÜTER in association with *I.* ex gr. *crippsi* in the 706-715 m interval suggests the basal part of the *Mantelliceras dixoni* Zone. The intra-*M. dixoni* Zone *I. virgatus* event (ERNST & *al.* 1983) is well represented in the 702-706 m interval, occurring as usual in limestones. This event marks the top of the lowest of the three parts into which GALE (1995) divided the *M. dixoni* Zone.

The occurrence of *Inoceramus schoendorfi* HEINZ in the 678-682 m sample indicates the lower Middle Cenomanian *Cunningtoniceras inerme* or *Acanthoceras rhotomagense* zones. There is no evidence for the beds with *Inoceramus atlanticus* at the base of the terminal Middle Cenomanian *Acanthoceras jukesbrownei* Zone, although the immediately overlying oyster-rich *Pycnodonte* event is well represented at 659 m.

Turonian

The **base of the Turonian** is taken at the appearance of *Mytiloides* ex gr. *labiatus* (SCHLOTHEIM), which is present in rock-forming quantities in orange-brown sediments (Rotpläner lithology) in the 641-647 m sample, constituting the Lower Turonian *Mytiloides* event(s) of the standard event scheme. Morphotypes present include forms referable to *M. labiatus* and *M. mytiloides* (MANTELL). The absence of the earliest Early Turonian mytiloids, *i.e. M. hattini* ELDER and *M. kossmati* (HEINZ), indicates an hiatus comprising the Cenomanian/Turonian boundary interval and the basal Lower Turonian.

The *transiens* morphotype of *Mytiloides subhercynicus* (SEITZ) is found in the topmost part of the 641-647 m sample in pale green limestones, associated with *M.* ex gr. *labiatus-mytiloides*. This form has its FO in the upper part of the Lower Turonian, but it ranges up into the basal Middle Turonian (*see* TRÖGER 1989, HARRIES & *al.* 1996).

Middle Turonian: The base of this substage is taken at the first appearance of small *Inoceramus cuvieri* (J. SOWERBY) at 628 m. However, the substage base may actually lie some distance below this level. As currently defined, in terms of inoceramid stratigraphy, the boundary is drawn at the FO of *Mytiloides hercynicus* (PETRASCHECK). However, as in the case of other condensed northern German successions, *M. hercynicus* is also missing here. Since this datum cannot be recognised in the Staffhorst succession, the substage boundary is drawn only approximately, somewhere in the interval between the highest *M. subhercynicus* and the lowest *I. cuvieri*.

The first unequivocal *Inoceramus lamarcki* PARKINSON appear higher, at 619 m. *I. lamarcki* and related forms occur in mass abundance (the *I. lamarcki* events of the outcrop successions) in the 586-598 m interval. Unfortunately, current knowledge of this group is inadequate to allow it to be used for a more refined subdivision of this part of the Turonian.

Upper Turonian: In Europe, the base of the Upper Turonian was traditionally placed at the FO of *Inoceramus costellatus* WOODS. It appears, however, that forms commonly referred to WOODS' species are different from the English type (WALASZCZYK & WOOD 1999) and are conspecific with the North American species *Inoceramus perplexus* WHITFIELD (*see* WALASZCZYK & COBBAN, *in press*). *I. costellatus* (of authors, non *I. costellatus* sensu WOODS) thus falls into synonymy of WHITFIELD's species, which consequently becomes the Middle/Upper Turonian boundary marker, as provisionally adopted at the Brussels Symposium (*see* BENGTSON 1996). Accordingly, the boundary event, formerly referred to as the *Mytiloides costellatus/Sternotaxis plana* event becomes the *Inoceramus perplexus/Sternotaxis plana* event, and the basal Upper Turonian *M. costellatus*/large *I. cuvieri/I. lamarcki stuemkei/I. inaequivalvis* Zone becomes the *I. perplexus*/large *I. cuvieri/I. lamarcki stuemkei/I. inaequivalvis* Zone.

The apparent FO of *Inoceramus perplexus* WHITFIELD occurs in the 543-548 m interval. However, the occurrence, in the 572-575 m interval, of fragments of large *Inoceramus* ex gr. *lamarcki*, a characteristic feature of the basal Upper Turonian *Inoceramus perplexus*/large *I. cuvieri/I. lamarcki stuemkei/I. inaequivalvis* Zone in northern Germany (ERNST & *al.* 1983; WOOD & *al.* 1984), suggests that the base should be taken at the base of this interval. This is supported by the fact that below this level in the shaft inoceramids are rare, and represented by single moderately sized *I. lamarcki* forms, these being features which are characteristic of the upper Middle Turonian succession of central Europe.

There is no inoceramid material indicative of the succeeding *Mytiloides labiatoidiformis/"Inoceramus" striatoconcentricus* Zone of the ERNST & *al.* (1983) scheme, *i.e.* the level of the main *Hyphantoceras* events. *Mytiloides scupini* (HEINZ), the zonal index of the penultimate Late Turonian inoceramid zone (the *I.* aff. *frechi* Zone of earlier zonal schemes), first appears in the 534-537 m interval, associated with large *Inoceramus* ex gr. *lamarcki* and *I.* ex gr. *inaequivalvis*. In the absence of other data, the base of the *M. scupini* Zone is taken at 537 m. The association with large *I.* ex gr. *lamarcki* supports assignment to the lower part of the *M. scupini* Zone.

Coniacian

The zonation of the Lower Coniacian follows the one recently worked out by WALASZCZYK & WOOD (1999; *see also* KAUFFMAN & *al.* 1996), comprising, in ascending order, the *Cremnoceramus deformis erectus* Zone, *C. hannovrensis* Zone, *C. crassus inconstans* Zone and *C. crassus crassus/C. deformis deformis* Zone. This scheme consists of a sequence of interval range zones, and differs markedly from the traditional scheme based on the *C. rotundatus-erectus-deformis* lineage (*see e.g.* KAUFFMAN & *al.* 1978; HERM & *al.* 1979; ERNST & *al.* 1983; WOOD & *al.* 1984). The two schemes are shown side by side for comparison (Text-fig. 7). For the terminal Lower Coniacian, a new zone, that of *Inoceramus gibbosus* is proposed herein. We likewise follow here the revised event terminology proposed in the same paper. In ascending order these are (with the old name, where different, in parentheses): *Didymotis* I event, *C. waltersdorfensis* I event, *Didymotis* II event, *C. waltersdorfenis* II event (the three latter events were formerly referred to as the *C. waltersdorfensis/Didymotis* II and *C. waltersdorfensis* events), *C. erectus* I (= *C. rotundatus*) event, *C. erectus* II (= *C. brongniarti*) event, *C. hannovrensis* (= *C. waltersdorfensis hannovrensis*) event, and *C. erectus* III (*C. erectus*) event.

Lower Coniacian: The base of this substage is taken here at the FO of *Cremnoceramus deformis erectus* (MEEK), which was recently shown (WALASZCZYK & COBBAN, *in press*) to be a senior synonym of *C. rotundatus* (TRÖGER *non* FIEGE), the inoceramid marker of the base of the Coniacian following the Brussels decision (KAUFFMAN & *al.* 1996). In the shaft succession, this datum is drawn in the middle part of the interval (504-509 m) that includes the inoceramid assemblages of the Turonian/Coniacian boundary transition. The inoceramids from this interval are dominated by *C. waltersdorfensis waltersdorfensis* (ANDERT) and *C. deformis erectus* (MEEK). Mass-ocurrences of these taxa characterize the boundary itself, ANDERT's form occurring immediately below the boundary in the *C. waltersdorfensis* I and *C. waltersdorfensis* II events (*see* WOOD & *al.* 1984; KAUFFMAN & *al.* 1996; WALASZCZYK & WOOD 1998), with *C. deformis erectus* dominating the basal Coniacian assemblage.

In the candidate basal boundary stratotype Salzgitter-Salder section (WOOD & *al.* 1984; KAUFFMAN & *al.* 1996), the *C. erectus* I (= *C. rotundatus*) event closely follows the *Didymotis* II and *C. waltersdorfensis* II events, and its base is taken as the base of the Coniacian. In more expanded successions, *e.g.* the Vistula section in Poland, both these events are even more distinctly separated than at Salzgitter-Salder, and the *C. erectus* event is actually situated slightly above the FO of *C. deformis erectus*. In the Staffhorst succession, *Didymotis* appears to be missing from the terminal Turonian *C. waltersdorfensis waltersdorfensis* assemblage. The only record of *Didymotis* is an unornamented form from the 509-514 m interval, differing significantly from the radially ornamented morphotype that characterizes the *Didymotis* II event, and corresponding to the morphotype characterizing the *Didymotis* I event of the *M. scupini* Zone.

From the base of the Coniacian up to 484 m, the inoceramids are dominated by representatives of the *Cremnoceramus deformis* lineage, comprising the subquadrate, upright forms of the chronosubspecies *erectus* with subordinate small *C. waltersdorfensis*

waltersdorfensis. This association suggests still a very low position in the Coniacian, *i.e.* below the *C. hannovrensis* event (bed 52) of the Salzgitter-Salder succession (*see* WOOD & *al.* 1984; WALASZCZYK & WOOD 1999).

The inoceramid assemblage from the succeeding samples, up to the 463-467 m interval, shows much greater diversity and includes *C. waltersdorfensis hannovrensis* (HEINZ), *C.* spp. of the *deformis* lineage, *Tethyoceramus* ex gr. *madagascariensis* (HEINZ) and *Inoceramus ?annulatus* GOLDFUSS. Situated above an interval dominated by *C. deformis erectus*, and below the FO of *C. crassus inconstans* (WOODS), this interval represents the *C. hannovrensis* Zone. However, the absence of any evidence for the interval dominated by *C. waltersdorfensis hannovrensis* at the base of this zone, a conspicuous level in every complete succession in central Europe, suggests an hiatus corresponding to the *C. hannovrensis* event and probably also to the *C. erectus* III event.

The appearance of *C. crassus inconstans* in the 463-467 m interval marks the base of the *C. c. inconstans* Zone, and equates in part with the *C. c. inconstans* event (of WOOD & *al.* 1984). Other inoceramids from the same interval include *C. waltersdorfensis hannovrensis, C.* sp. of the *deformis* lineage, *Tethyoceramus* ssp., and *C. crassus crassus* (PETRASCHECK), as well as non-sulcate forms of the *I. lamarcki* group, provisionally referred here to *I. annulatus* GOLDFUSS. The co-occurrence of forms referable to *C. crassus crassus* and *C. crassus inconstans*, interpreted here as two successive chronosubspecies (*see* WALASZCZYK & WOOD 1999), may possibly indicate condensation, but could equally well have resulted from the sampling method. The *C. c. inconstans* and *C. c. crassus/C. d. deformis* zones are, consequently, not distinguished as separate zones in this account.

We have included within our concept of *C. crassus crassus* the morphotype referred by FIEGE (1930) to the new subspecies *Inoceramus inconstans woodsi*, which he documented from the Westphalian shaft successions. FIEGE's morphotype is characterized by the earliest ontogenetic ornament of typical *C. crassus crassus* extending further onto the disc than usual. Some of the stratigraphically highest Staffhorst material includes several specimens that match FIEGE's morphotype, and we cannot exclude the possibility that this form represents a late cremnoceramid development with some biostratigraphic significance. This problem requires further investigation.

Of particular importance in the Staffhorst succession is the succeeding interval, comprising the terminal Lower Coniacian, which shows the manner in which the diverse, albeit *Cremnoceramus*-dominated, assemblages are replaced by *Inoceramus* assemblages comprising representatives of the *I. lamarcki* group, prior to the entry of volviceramids at the base of the Middle Coniacian. This interval, and its inoceramids, appears to be better developed here than in any other European succession known at present. Above the last cremnoceramids and below the FO of *Volviceramus koeneni* (MÜLLER), there is an interval characterized by both non-sulcate and sulcate large- and medium-sized representatives of the *I. lamarcki* group, together with extremely rare *I. kleini* MÜLLER and *I.* cf. *kleini*. The non-sulcate *I. lamarcki* group forms are provisionally referred to *I. annulatus*, as in the case of the forms of this type from the underlying undivided *C. c. inconstans/C. c. crassus* Zone. Non-sulcate representatives of the *I. lamarcki* group first become common, albeit irregularly, even lower. Already in the 460-463 m interval, *i.e.* only some metres above the *C. c. inconstans* event, an assemblage is found that is dominated by *Inoceramus annulatus*. The sulcate forms are collectively referred here provisionally to *Inoceramus gibbosus* SCHLÜTER, the earliest available name for these forms (*see* discussion below).

The interval between the LO of the genus *Cremnoceramus* and the FO of *Volviceramus koeneni* is proposed herein as a separate inoceramid zone characterized by *Inoceramus gibbosus*. Since the index taxon ranges into the basal Middle Coniacian *Volviceramus koeneni* Zone, *i.e.* well above the FO of *V. koeneni,* the new zone has the status of an interval range zone. The use of the name *I. gibbosus* must be provisional at present, since there are currently four morphologically similar and, at least in part, probably conspecific, taxa known from the terminal Upper Coniacian and basal Middle Coniacian of the European area. These are: *Inoceramus gibbosus* SCHLÜTER, 1877 from the Emscher Marl facies of Westphalia; *I. lezennensis* (DECOCQ, 1874) (BARROIS 1878, 1879) from the chalk facies of northern France; *I. percostatus* MÜLLER, 1888 from the Middle Coniacian *V. koeneni* Zone "Form Sands" of the Subhercynian Cretaceous Basin, and *I. russiensis* NIKITIN, 1888 from the chalk facies of Russia. Apart from *I. percostatus*, which is represented by rich and well preserved three-dimensional material, in association with *Inoceramus kleini* and *Volviceramus koeneni*, all the other taxa are based either on a single (*I.*

russiensis, I. gibbosus) or a few specimens (*I. lezennensis*), which precludes detailed study of population and intra-specific variability. The possible relationship between the first three taxa was briefly discussed by SEITZ (1962, pp. 355-356, footnote). Although we have provisionally chosen *I. gibbosus* as the zonal index, it is actually possible that the DECOCQ (1874) description of his new species is valid and available – it describes the main morphological characters well, but lacks an illustration; however, this description appears in a report of a paper read by DECOCQ, and not in an actual paper. BARROIS (1878) gave a more detailed description and, one year later, in another paper (BARROIS 1879), he repeated the 1878 description word for word, but with the addition of a figure. Furthermore, the Staffhorst material assigned here to *I. gibbosus* displays an increasing degree of sulcation up-section, culminating in the distinctive *I. gibbosus s.s.*, above which the degree of sulcation appears to reduce again. It may eventually prove necessary to recognize an additional chronosubspecies for the earlier, less strongly sulcate forms that characterize the terminal Lower Coniacian.

Middle Coniacian: The base of this substage is well documented by the appearance of *Volviceramus koeneni* in the 397-400 m interval. Immediately below this, in the 400-406 m interval, two specimens of an inoceramid with a rounded, internally striate right valve umbo, may represent a possible *Volviceramus* precursor but require further investigation. *Volviceramus* is particularly well represented in the Staffhorst collections, and includes specimens of all sizes, many preserving the shell, and fully articulated. A strongly developed *V. koeneni* event is located somewhere in the 387-393 m interval. Every morphological gradation between typical *V. koeneni* and the inrolled *V. involutus* (J. DE C. SOWERBY) is present in Staffhorst, showing the general trend within the population to flattening of the initial distinctive, highly elevated, right valve umbo of *V. koeneni*. The relationship between some of these morphotypes and the North American taxa *Volviceramus umbonatus* (MEEK) and *V. exogyroides* (MEEK) is unclear, and requires further investigation. The *Volviceramus* morphotypes match quasi-horizoned material collected by HEINZ (1926) from the former Lüneburg quarries. In the higher part of the succession (330-333 m), immediately below the entry of inoceramids of Upper Coniacian aspect, a morphotype with a large, flat, antero-posteriorally elongated right valve is found together with *V. involutus*. This morphotype, which is possibly the *V. grandis* of American authors, occurs commonly, together with subordinate *V. involutus s.s.* in the white chalk facies in England, at the top of the beds with abundant *Volviceramus*.

Apart from *Volviceramus*, *Inoceramus gibbosus* and rare small questionable early *Cordiceramus* sp., the Middle Coniacian of Staffhorst is characterized by common *Platyceramus*. There is a tendency for *Platyceramus*-dominated assemblages to alternate with assemblages dominated by *Volviceramus*. The *Platyceramus* predominantly comprise the morphotypes referred by SEITZ (1962) to the subspecies *Platyceramus mantelli mantelli* (DE MERCEY) and *P. mantelli angustus* (SEITZ), the latter subsequently renamed by SEITZ (1965) *P. mantelli beyenburgi*. These two morphotypes are respectively thick and thin-shelled, quite apart from differing in the hinge and in the shape of the growth trace on the disc. Other morphotypes cannot be assigned satisfactorily to either of these forms, and may possibly include forms close to *P. mantelli subrhenanus* (SEITZ).

Upper Coniacian: Following the Brussels criterion (KAUFFMAN & *al.* 1996), the base of this substage is drawn at the entry of *Magadiceramus subquadratus* SCHLÜTER. TRÖGER (1989) recognised two *Magadiceramus*-dominated inoceramid assemblages (assemblages 23 and 24 of TRÖGER 1989) within the Upper Coniacian, the lower containing late *Volviceramus*, and the higher, in which this genus is absent.

In Staffhorst, the index Upper Coniacian inoceramid is extremely rare and, moreover, TRÖGER's two assemblages cannot be distinguished at all. Although a twofold subdivision of the Upper Coniacian by means of inoceramids is possible, the observed inoceramid assemblages are different from those distinguished by TRÖGER (1989). This is also the case in certain other shaft sections (*e.g.* Ickern IV), in which the lower Upper Coniacian is represented by a taxonomically rich assemblage without *Magadiceramus*, while the upper Upper Coniacian is characterized by an almost monospecific *Magadiceramus subquadratus* assemblage. It is possible that the pattern of vertical distribution of magadiceramids follows the facies characteristics of the region in question, and has no general biostratigraphic significance, but this needs further investigation. The only unequivocal *Magadiceramus*, apart from an anomalous (and possibly displaced) specimen from the 412-416 m interval of the Middle Coniacian, is a single specimen from the 311-313 m interval. In the absence of *Magadiceramus*-dominated assemblages, the base of the substage is taken at the appearance of other typically Upper Coniacian forms, notably *"Sphenoceramus"* *subcardissoides* (SCHLÜTER) and four of the new species described by HEINE (1929) from the Westphalian coal shafts: *Inoceramus fasciculatus, I. latisulcatus, I. canaliculatus* and the volviceramid-like *I. anomalus*. The assemblage also includes *I. gibbosus* that are less strongly sulcate than the forms in the beds below. *I. fasciculatus* occurs in flood abundance in the 315-319 m and the 319-321 m intervals. The absence of *Magadiceramus*-dominated assemblages strongly suggests a significant hiatus involving the higher part of the Upper Coniacian. The existence of an hiatus is further supported by the absence of the terminal Coniacian (formerly basal Santonian) *Sphenoceramus* Teilzone, with the first *Sphenoceramus* ex gr. *pachti – cardissoides*, which was documented by SEITZ (1961) from the Westphalian coal-shafts.

Santonian

According to the Brussels proposals (LAMOLDA & HANCOCK 1996) the base of the stage is taken at the FO of *Cladoceramus undulatoplicatus* (ROEMER). This taxon is relatively uncommon in the Staffhorst material, being first noted as single specimens in the 303-300 m interval, and also in the 292-290 m interval. This sparse *Cladoceramus* record matches the rare occurrences of the genus in the Lägerdorf standard section (ERNST & SCHULZ 1974). In both intervals, the dominant inoceramids are *Sphenoceramus* ex gr. *pachti – cardissoides*. Sphenoceramids of this group range throughout the remainder of the Santonian part of the shaft succession. The upper limit of the higher interval with *Cladoceramus* is taken here, in the absence of other data, as the base of the Middle Santonian. The Middle Santonian assemblages are, as in the case of the Lower Santonian assemblages, dominated by *Sphenoceramus* ex gr. *pachti – cardissoides*, although rare *Cordiceramus* cf. *purus* (SEITZ) and *Platyceramus* sp. were also noted. The base of the Upper Santonian is taken here at the FO of *Sphenoceramus pinniformis* (WILLETT) at 265 m. This datum approximates to the FO, in the 263-265 m interval, of *"Inoceramus" muelleri* PETRACHECK, a taxon known to appear close to the Middle/Upper Santonian boundary (*see* TRÖGER 1989; OPPERMANN 1996).

6. ECHINOID STRATIGRAPHY (G. ERNST)

In the chalk facies of England and France irregular echinoids were used from an early date for zonation and, in part, for the designation of stratigraphic units, *e.g.* the *Holaster subglobosus, Sternotaxis plana, Micraster cortestudinarium*, and *Micraster coranguinum* zones (*see* ROWE 1899; LAMBERT 1903a, 1903b; CAYEUX 1965, 1966, 1967). In contrast, the echinoid stratigraphy of the lower Upper Cretaceous (Cenomanian – Coniacian) of northern Germany is still rather underdeveloped, and is invariably used only as a supplementary stratigraphy or parastratigraphy. The last attempts to establish an echinoid zonal scheme for the Boreal German Upper Cretaceous are now several decades old (ERNST 1970a, 1970b; ERNST & SCHULZ 1974; ERNST & SEIBERTZ 1977). In these schemes it was mainly the higher Upper Cretaceous that was considered, apart from discussing concepts and methodology relating to the application of echinoids to biostratigraphy in general. For the Cenomanian – Coniacian interval no single usable independent echinoid zonal scheme existed.

In marked contrast with the situation in the chalk facies of the Boreal white chalk sea, the potential disadvantages of an echinoid-based zonal scheme are much more apparent in the variable lithotopes of the Lower Saxony and Westphalian Upper Cretaceous. Ecomorphological reactions and the link to definite facies-belts lead, in many cases, to a regional restriction of the echinoid distribution and, thereby, to marked small-scale endemism. On the other hand, this sensitivity to facies makes the echinoids useful for palaeoecological and sequence stratigraphic interpretations (ERNST & WOOD 1996). In particular, they have proved their worth in the development of an event stratigraphic scheme for the lower part of the Upper Cretaceous and they are used as eponymous marker fossils for eustatic- and bioevents (for example, the *M. cortestudinarium* and *Isomicraster* events of ERNST & *al.* 1983).

Absence of space here for detailed discussion of the complex palaeoecological and sequence stratigraphic questions, and for the treatment of certain nomenclatorial und taxonomic problems, makes it necessary for the rich echinoid fauna of the Staffhorst shaft to be treated in a separate paper (ERNST, *in prep.*).

Cenomanian

In comparison to the nearest exposures (Wunstorf and Misburg), Staffhorst has provided only few Cenomanian echinoids, with only three species having been recognised.

Lower Cenomanian: The *Mantelliceras dixoni* Zone of the higher Lower Cenomanian has yielded single examples of *Holaster bischoffi* from the 695-702 m interval and a questionable *Sternotaxis* ex gr. *gregoryi – trecensis* from the 702-706 m interval. In comparative sections (Baddeckenstedt, Hoppenstedt) *H. bischoffi* is typical of the basal *Mariella* sequence of the lower *M. dixoni* Zone (ERNST & REHFELD 1997).

Middle Cenomanian: The 673-676 m interval has yielded three test fragments of *Holaster subglobosus*. Although this species actually has a greater vertical range, its dependency on facies results in it occurring commonly only in the region of the Mid-Cenomanian event (ERNST & *al.* 1983) of the middle Middle Cenomanian, or immediately above. The occurrrence of the species at this horizon in the so-called *H. subglobosus* bioevent has an inter-regional value in an event stratigraphic scheme (ERNST & WOOD 1995), and the species is used in western Europe as an index fossil of the upper Middle Cenomanian (CAYEUX 1965).

In the 676-678 m interval is found a tempestite-like accumulation of thin-tested echinoid debris, which may well consist of *S.* ex gr. *gregoryi – trecensis*. Both these *Sternotaxis* morphotypes are used, for example in England, as indicators for the Middle and Upper Cenomanian (OWEN & SMITH 1987).

Upper Cenomanian: The limestones typical of the Arme *rhotomagense* Kalke of the lower Upper Cenomanian are virtually devoid of echinoids in outcrop sections. This interval in Staffhorst has also yielded no echinoids.

Turonian

Lower Turonian: There are also no echinoids from this level in Staffhorst. It is only in the boundary transition to the Middle Turonian in extensive outcrop sections that the first small irregular echinoids appear.

Middle Turonian: Echinoids remain extremely rare. An isolated *Echinocorys* morphotype (*E.* aff. *sphaerica* in Text-fig. 8) from the 593-602 m interval is of interest but, due to the lack of comparative material, provides no stratigraphic information.

Upper Turonian: This is the substage that is richest in echinoids in Staffhorst. According to ERNST & *al.* (1998b), this abundance reflects an alteration in ecological conditions documented by starved sedimentation, condensation und substrate-hardening, which was linked to a shallowing phase and to cold water influences.

The FO of *Sternotaxis plana* in the 559-562 m interval could mark a sequence stratigraphically significant horizon. This occurrence may represent the equivalent of a firmground with echinoids in the top part of the Upper Rotpläner in the Söhlde section (Lesse Syncline) in eastern Lower Saxony (ERNST & *al.* 1998b). *S. plana* is used in England and France as an index fossil for the *Sternotaxis (Holaster) plana* Zone, which equates with the Upper Turonian in France, and with the higher part of the Upper Turonian in England respectively (LAMBERT 1903a; CAYEUX 1966; FOURAY & POMEROL 1985).

A suite of *Echinocorys,* comprising some 20 examples, which was found above the hiatus recognized using log peak stratigraphy (*see* chapter 4) in the 543-553 m interval, is also of stratigraphic interest. The morphotype in question possesses characters intermediate between those of the Cenomanian *E. sphaerica* and the Upper Turonian *E. gravesi* (*E.* m.f. *sphaerica – gravesi* in Text-fig. 8). In the Wüllen (Westphalia) section this morphotype characterizes an hardground succession downsection of an hiatus in the Middle/Upper Turonian transition (ERNST & *al.* 1998a).

On the basis of biostratigraphically significant echinoids, the Middle/Upper Turonian boundary should be drawn at 548 m, above the hiatus identified by means of log peak stratigraphy (*see* chapter 4), because in the 543-548 m interval *Sternotaxis plana* occurs together with the FO of the inoceramid *Inoceramus perplexus* (= *Inoceramus costellatus* of authors, *see* WALASZCZYK & WOOD 1999 and chapter 5). The two in combination could mark the *I. perplexus*/*S. plana* event, which is currently the preferred choice for the substage basal boundary in northern Germany. However, this echinoid-based interpretation is disputed on inoceramid evidence by WALASZCZYK & WOOD (*see* chapter 5), who draw the boundary much lower, at the base of the 572-575 m interval, below an occurrence of large fragments of large *Inoceramus* ex gr. *cuvieri*.

Immediately above this there is a distinct turnover in the echinoid assemblages, which probably reflects another hiatus. In the lower *E. gravesi* Zone, the characteristic *Echinocorys gravesi* splits off from the above-mentioned transitional form *E.* m.f. *sphaerica-gravesi*. At the same horizon are found the first transitional forms from *Sternotaxis plana* to *S. placenta* and the immigration of the first primitive *Micraster, M. (Roweaster) borchardi* also takes place. All three forms together characterize, in

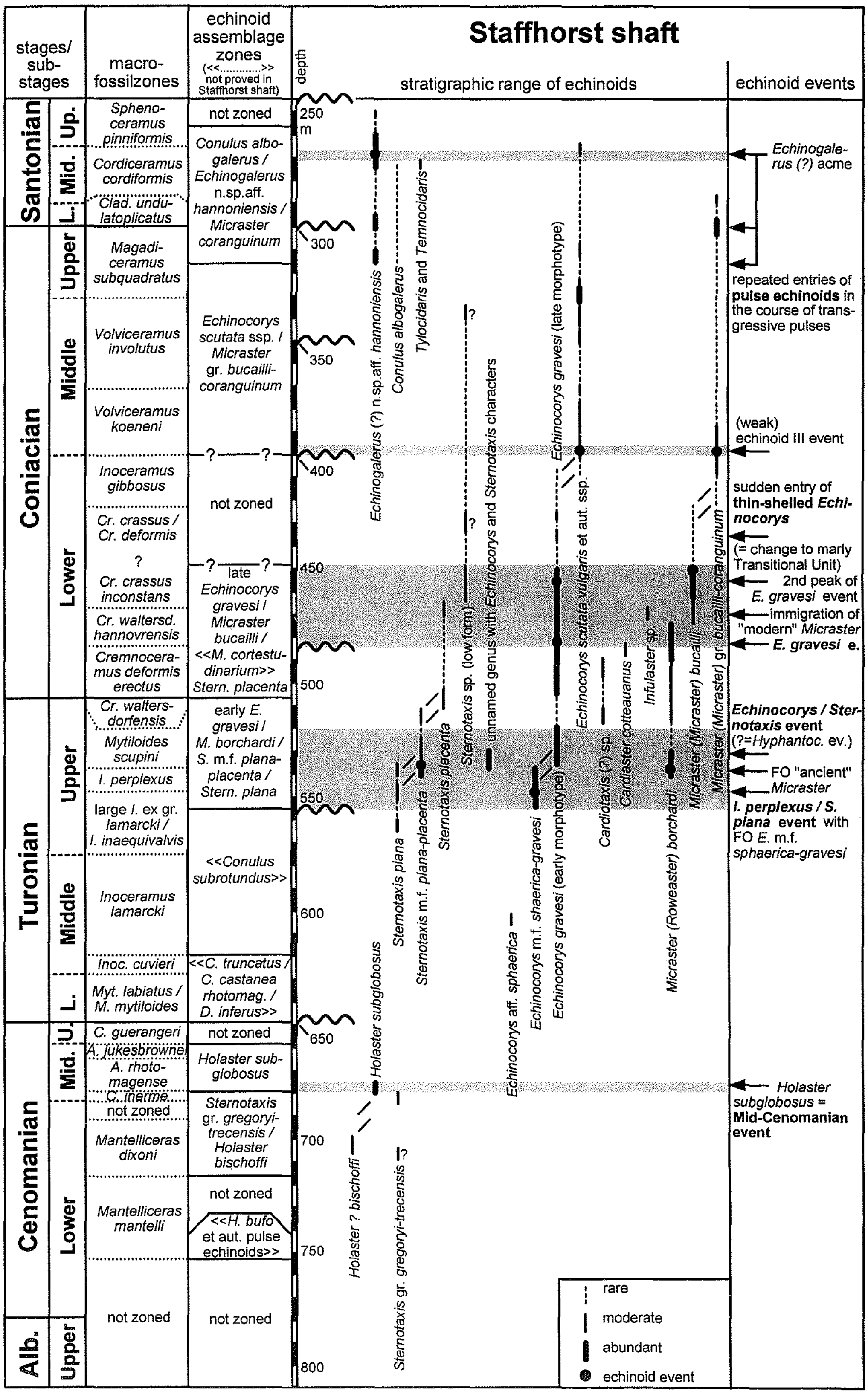

Fig. 8. Vertical ranges and abundances of echinoids in the Upper Cretaceous of the Staffhorst shaft

northwest German outcrop sections, the middle Upper Turonian interval between tephroevents T_E to T_F, including the *Hyphantoceras* event. The latter event has recently been taken (ERNST & *al.* 1998a) as the beginning of a new sedimentary sequence, and is usually marked by condensation, as it is here in Staffhorst.

In the 514-521 m interval echinoids temporarily disappear completely, probably due to the onset of the clayey-marly sedimentation of the Grau-Weiße Wechselfolge. Right up to the Turonian/Coniacian boundary, in the 504-509 m interval, the characteristic Upper Turonian assemblage comprising *Echinocorys, Sternotaxis* and *Micraster* is impoverished. The LO of *Sternotaxis* m.f. *plana – placenta* is provisionally placed in this interval. A single poorly preserved small-sized representative of the *Cardiaster/Cardiotaxis* group in the 509-514 m interval is noteworthy.

Coniacian

The echinoid stratigraphy of this stage is poorly known and, moreover, the clayey-marly facies of the Emscher Marls in the Middle and Upper Coniacian (*see* chapter 4) is unsuitable for echinoids. Only the carbonate richer sediments of the Lower Coniacian have yielded relatively abundant finds in Staffhorst.

Lower Coniacian: The Turonian/Coniacian stage boundary in the 504-509 m interval is marked by the FO of *Sternotaxia placenta*. This species also characterizes the Turonian/Coniacian transition in England and northern Spain (Barranca) and it is therefore introduced here as the zonal marker for the lower Lower Coniacian. In LAMBERT's echinoid scheme for northern France this species is used as a zonal guide fossil for the Middle Coniacian (*Volviceramus involutus* Zone), in the upper *Micraster decipiens* Zone (FOURET & POMEROL 1985). Associated with *S. placenta* in Staffhorst are *Micaster (R.) borchardi* and the last representatives of *Echinocorys gravesi* (early morphotype).

At 484 m is found another change in the echinoid assemblage, which coincides with another hiatus recognized by means of log peak stratigraphy (*see* chapter 4). With 36 examples, *Echinocorys* reaches its absolute abundance maximum in the 480-484 m interval. The Upper Turonian forms referred to *E. gravesi* (early morphotype) are replaced here by morphotypes which already show characters reminiscent of the later *E. scutata*. However, since the *stratum typicum* of *E. gravesi* (DESOR) is the *Micraster decipiens* Zone, *i.e.* lower Lower Coniacian (LAMBERT 1903b), the species name *E. gravesi* must be retained for the forms of this age (*E. gravesi,* late morphotype). The index taxon *Micraster cortestudinarium* is absent in Staffhorst. However, a single find of a *Cardiaster cotteauanus* in the 480-480 m interval is noteworthy, since its morphological characters show it to be a precursor of the Santonian *Cardiaster jugatus*.

In the 463-467 m interval *M. (Roweaster) borchardi* is replaced by the "modern" *Micraster (M.) bucailli*. *Sternotaxis* simultaneously exhibits certain apparent changes in morphology, but the extremely poorly preserved nature of the material does not permit these changes to be clearly identified. The high forms of *S. placenta* disappear in favour of sporadic flat forms. Rare *Cardiotaxis* sp. and *Infulaster* sp. also occur.

The 447-467 m interval is characterized by a last flourishing phase of *E. gravesi* (late morphotype) and *Micraster (M.) bucailli*. Above this lies an over 30 m thick succession that is devoid of echinoids. The disappearance of echinoids at 447 m clearly documents, on the basis of echinoid ecological criteria, the top of the Upper Limestone Unit and the beginning of the Transitional Unit.

Middle Coniacian: In the Lower/Middle Coniacian transition, echinoids of the genera *Micraster* and *Echinocorys* become temporarily more abundant. *Micraster (M.)* m.f. *bucailli – coranguinum* already appears beneath the hiatus identified by means of log peak stratigraphy at the substage boundary in the 400-413 m interval (*see* chapter 4), *Echinocorys* of the *scutata* group is found just above, in the 393-397 m interval.

Upper Coniacian: Echinoids are also under-represented in this substage in Staffhorst. In addition to a few *Echinocorys sulcata* ssp., there are (initially sporadic) occurrences of *Echinogalerus*(?) sp. aff. *hannoniensis*. In the 311-313 m interval, an abundance of this latter taxon, as so-called "pulse echinoids", clearly marks an early Late Coniacian transgressive pulse.

Santonian

The genera *Echinocorys* and *Micraster*, which are abundant in the Santonian chalk facies of Lägerdorf (ERNST & SCHULZ 1974), are scarcely represented in the marl facies of Staffhorst. On the other hand, the holectypoidea, represented by *Echinogalerus*(?) and *Conulus*, are commoner.

Lower Santonian: The Early Santonian transgressive pulse in the 295-300 m interval, which is also documented by the pulse-like occurrrence of the belemnite *Gonioteuthis* (*see* chapter 7), is indicated by a second, short-lived appearance of *Echinogalerus*(?) sp. aff. *hannoniensis*, associated with a few small *Micraster* of the *coranguinum* group; *Echinocorys* is missing.

Middle Santonian: Only in the middle part of the substage, in the 260-274 m interval, which in the Lägerdorf standard section corresponds to the *M. coranguinum/G. westfalica* Zone, do echinoids reappear, as a result of the Middle Santonian transgression. *Echinogalerus*(?) sp. aff. *hannoniensis* reaches its abundance maximum at this level. There are in addition a few fragments of *Echinocorys scutata* ssp.. Also indicative of this transgressive pulse are occurrences of the regular echinoids *Tylocidaris clavigera* and *Temnocidaris sceptrifera* in the 265-271 m interval.

The position of the three *Conulus albogalerus* collected from Staffhorst cannot be reconstructed because the specimens in question have been mislaid. Since *Conulus* is an excellent example of a pulse echinoid, these specimens are likewise probably also attributable to the Santonian transgressive pulses. *C. albogalerus* is used in the French echinoid scheme as an indicator of the Santonian (FOURAY & POMEROL 1985), but it already appears in the higher Coniacian of northern France (CAYEUX 1967). In Lägerdorf it is found in the Grabganglagen (bioturbated horizons) G251 and G252, at the base of the Middle Santonian *M. rogalae/G. westfalica* Zone (ERNST & SCHULZ 1974).

Upper Santonian: Echinoids cannot be employed to determine whether or not the Upper Santonian is present – particularly in view of the fact that *Micraster rogalae,* which is used in Lägerdorf for the zonation of the Santonian, has not been found in Staffhorst.

7. BELEMNITE STRATIGRAPHY (G. ERNST)

Neither the *Neohibolites ultimus/Aucellina gryphaeoides* event of the transgressive Lower Cenomanian, nor either of the two *Praeactinocamax* events (Middle Cenomanian *P. primus* event and Upper Cenomanian *P. plenus* event respectively) can be confirmed in Staffhorst at their presumed stratigraphic position on the basis of belemnite finds. However, the marls of the Upper Coniacian and Santonian have provided almost 100 representatives of the *Gonioteuthis* lineage, as well as 3 specimens of *Actinocamax verus*. In this interval *Gonioteuthis* traditionally possesses a high stratigraphic resolution potential (*see* ERNST 1964). In particular, *Gonioteuthis* offers the possibility of correlation between Staffhorst and the stratigraphically continuous Lägerdorf standard section on the Pompeckj Block in the north, which has provided extensive and well studied material of this lineage (*see* ERNST 1966; ERNST & SCHULZ 1974).

Gonioteuthis lineage

The discontinuous record of abundances of *Gonioteuthis* in the Staffhorst succession is closely related to the transgressive pulses of the Upper Coniacian and Santonian. This is evidenced by the regional distribution pattern in northern Germany, which demonstrates that *Gonioteuthis* preferentially occupied proximal, near-shore facies zones (ERNST 1964). *Gonioteuthis* thus constitutes a further characteristic element of the so-called pulse fauna in the course of eustatic movement in the sense of sequence stratigraphy. Following two short-term occcurences in the Upper Coniacian and Lower Santonian, *Gonioteuthis* finally became established in Staffhorst, as in Lägerdorf, in the course of the later Middle Santonian transgression. The maximum abundance, represented by 22 specimens, is found in the 254-256 m interval which, significantly, is closely followed by an oyster bed at 251-253 m.

Preservation: The majority of rostra are represented by fragments, which can be treated statistically only in the abundance curve (Text-fig. 9a). Proximal fragments preserving the pseudoalveolus are evaluated as far as possible (Text-fig. 9c). However, of these, only 17 specimens (17.5 %) were sufficiently complete to allow the stratigraphically significant RIEDEL Quotient and RIEDEL Index to be measured (Text-figs 9d-e).

Morphologic and morphometric development of *Gonioteuthis*

Biostatistic methods have been applied to the *Gonioteuthis* lineage for several decades in order to obtain stratigraphic data (*e.g.* ERNST 1964). This particularly applies to the Santonian, when the evolution of the statistically relevant characters took place very rapidly. Following the methodology introduced by ERNST & SCHULZ (1974), the ratios (RIEDEL Index, RIEDEL Quotient) of certain parameters (length of rostrum, depth of pseudoalveolus) are of greater stratigraphic significance than the absolute values of the parameters themselves. Of the two RIEDEL values, the RIEDEL Index, *i.e.* the depth of the pseudoalveolus expressed as a percentage of the rostrum length, is better suited for demonstrating evolution than the RIEDEL Quotient, which is derived by dividing the rostrum length by the depth of the pseudoalveolus.

Length of rostrum (Text-fig. 9b): No stratigraphically significant changes in this parameter can be observed in the Staffhorst material. Variation in the mean values, which range between 50-60 mm, is probably controlled by the fluctuating proportion in the population of immature individuals.

Depth of pseudoalveolus (Text-fig. 9c): Analysis of the section of the curve for this parameter above 272 m, with almost 50 individual values, reveals a discontinuous distribution pattern. Mean values of 4-5 mm in the 256-272 m interval are followed by values of 6-7 mm in the 245-254 m interval. This relatively abrupt change in the mean values points to a break in the *Gonioteuthis* record in the Santonian and, consequently, to a significant hiatus.

RIEDEL Index (Text-fig. 9d): The division of the mean values curve for the depth of the pseudoalveolus into two distinct parts is particularly strongly expressed by this ratio. The lower interval (259-272 m) yields mean values of 8-9 %, while in the higher interval (245-256 m) the mean values are 11-12 %. According to the standard Lägerdorf curve (ERNST & SCHULZ 1974, Fig. 15), the former values fall within the Lower *Gonioteuthis westfalica* Zone and the latter in the *G. westfalicagranulata* Zone, respectively.

RIEDEL Quotient (Text-fig. 9e): The distribution of mean values for this ratio is similar to that for the RIEDEL Index. The lower interval (259-272 m) is characterized by mean values of 11-13, the higher interval (245-256 m) by values of 8-9.

Surface ornament: The strength of longitudinal striation and granulation cannot be analysed quantitatively without the expenditure of considerable time and effort. All that is possible is a subdivision into broad classes based on a subjective assessment of the relative strengths of these characters (ERNST & SCHULZ 1974). In Staffhorst, only longitudinal striation was observed up to a depth of 25 m, with only a few specimens exhibiting a mostly only weakly developed granulation. Above the hiatus at 256 m, the granulation of the rostra becomes stronger, but the longitudinal striation does not completely disappear.

Gonioteuthis stratigraphy and regional correlations

In the Santonian of the Boreal European subprovince, *Gonioteuthis* stratigraphy maintains its position as a practicable biostratigraphic method next to the inter-regionally more widely applicable inoceramid stratigraphy. From the Upper Coniacian to the Santonian/Campanian boundary, a kind of phylostratigraphy can be established, comprising, in ascending order, the following four phylozones: *G. praewestfalica*, *G. westfalica*, *G. westfalicagranulata* and *G. granulata* zones. On the basis of proportions the *G. westfalica* and *G. granulata* zones are each subdivided into Lower and Upper subzones.

G. praewestfalica Zone (296-311 m): This zone has been recognised up to now only in Lägerdorf, where apart from isolated records of the index taxon in the underlying *Volviceramus involutus*/*Micraster bucailli* Zone, it corresponds to the upper assemblage zone of the higher, strongly condensed, Coniacian (*Micraster bucailli*/*G. praewestfalica* Zone), with the index inoceramid *Inoceramus fasciculatus* (ERNST & SCHULZ 1974, Figs 4-5). In Staffhorst, *G. praewestfalica* enters just above several *I. fasciculatus* events (*see* chapter 5). The initial transgressive pulse is additionally emphasized by the ocurrence of pulse echinoids at 311-314 m (*see* chapter 6). Due to the absence of belemnites at Lägerdorf, it is not possible to establish whether or not the lower part of the succeeding *Sphenoceramus pachti*/*Cladoceramus undulatoplicatus* Zone of the Lower Santonian also belongs to the *G. praewestfalica* Zone. In Staffhorst, however, the second pulse of *Gonioteuthis,* documented at 296-298 m by 5 fragments which presumably belong to *G. praewestfalica,* clearly lies above the *C. undulatoplicatus* trangression, and thus falls in the basal Lower Santonian.

Above this follows in Staffhorst, as in Lägerdorf, a ca. 25 m thick packet of strata that has not yielded *Gonioteuthis*, designated the "*Gonioteuthis* depleted interval" (*see* Text-fig. 9).

G. westfalica Zone (256-271 m): The third strong *Gonioteuthis* pulse in the Middle Santonian, at 256-271 m, marks the base of the *G. westfalica* Zone. It can be assumed that this reappearance of *Gonioteuthis* in Staffhorst was contemporaneous with that at Lägerdorf and that it falls, consequently, at the base of the *Micraster coranguinum*/*G.*

westfalica Zone. The fairly constant mean values for the depth of pseudoalveolus, RIEDEL Index and RIEDEL Quotient clearly show that in Staffhorst essentially only the Lower *G. westfalica* Zone is present, with its upper limit marked by an hiatus. The position of the hiatus must lie at about 256 m, as shown by the shift in the *Gonioteuthis* morphometric data, but no sedimentary expression for an hiatus has been detected (*see* chapter 4). Above the hiatus, a renewed transgressive pulse can be inferred, the base being marked by the absolute abundance maximum of *Gonioteuthis*. In Lägerdorf, this event is documented in the G251/G252 interval by the occurrence of diverse pulse echinoids in association with abundant belemnites (ERNST & SCHULZ 1974). The base of the lower Middle Santonian *M. rogalae/G. westfalica* Zone, or of the Upper *G. westfalica* Zone, is drawn at this level. On the basis of the correlation with Lägerdorf, the hiatus in Staffhorst therefore spans most of the Upper *G. westfalica* Zone.

G. westfalicagranulata Zone (245-256 m): On the basis of *Gonioteuthis* morphometric data, this interval clearly belongs to the *G. westfalicagranulata* Zone, or to the *M. rogalae/G. westfalicagranulata* Zone of the upper Middle Santonian and basal Upper Santonian. However, the *Gonioteuthis* morphometric means derived from the belemnite fauna of bed G236 (which marks the FO of *Uintacrinus*, and hence, by definition, the base of the Upper Santonian) in the middle *M. rogalae/G. westfalicagranulata* Zone of Lägerdorf (ERNST & SCHULZ 1974, Fig. 15) are not realized in Staffhorst. Consequently, the presence of Upper Santonian sediments cannot be proved by means of belemnite stratigraphy.

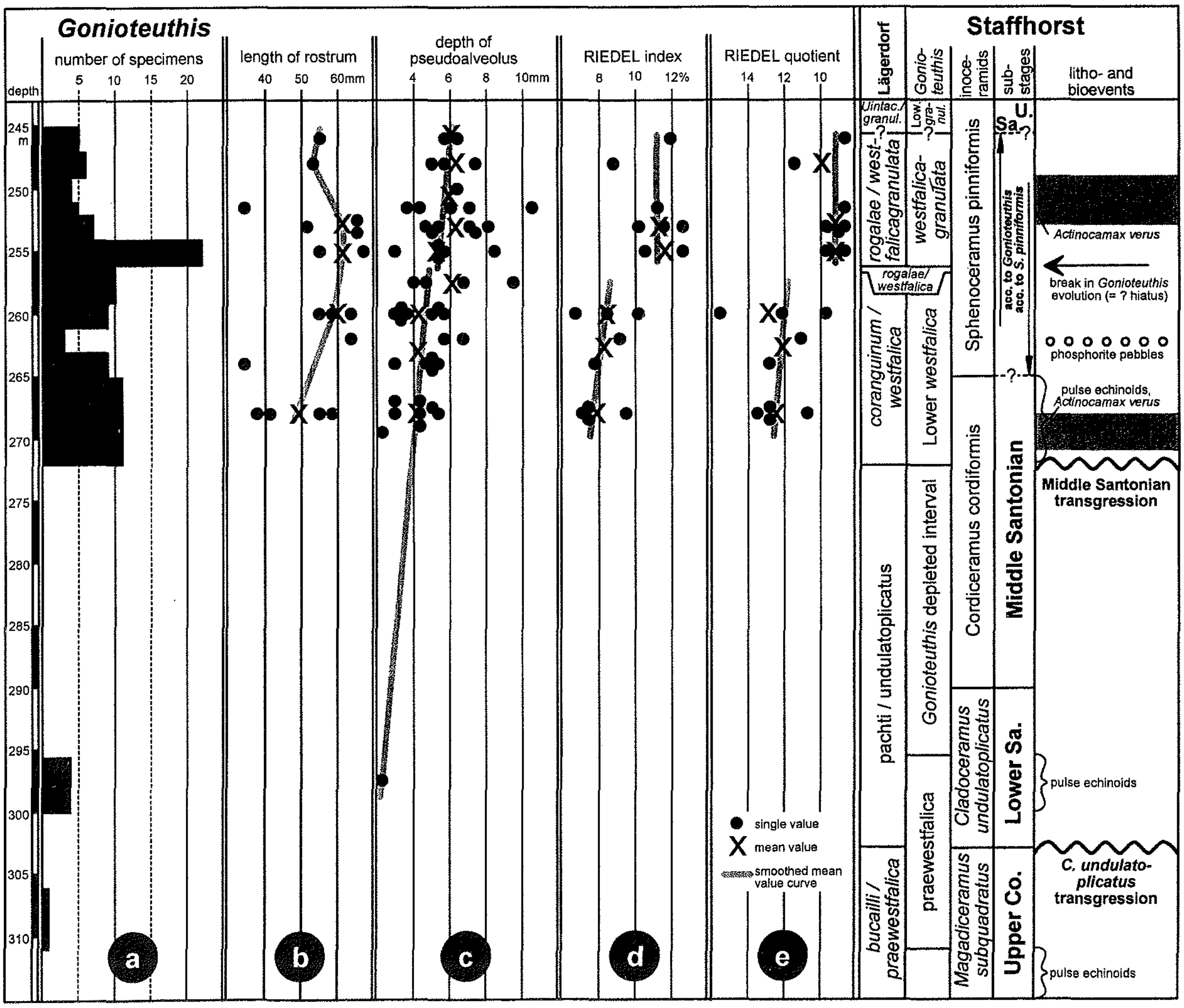

Fig. 9. Biostatistic morphometry and zonation of the Upper Coniacian and Santonian *Gonioteuthis* lineage of the Staffhorst shaft

Actinocamax verus

In the belemnite assemblages of the Santonian, *Actinocamax verus* is usually associated with *Gonioteuthis*. It is proportionally most abundant in nearer-shore, transgressive sediments. *Actinocamax* accordingly reacts much more strongly to transgressive pulses than *Gonioteuthis* (pulse belemnite). Only 3 specimens have been collected from Staffhorst (Text-fig. 9), which suggests that the depositional area at that time occupied a relatively distal position. The first rostrum is associated with the Middle Santonian trangressive pulse at 265-272 m. The two remaining specimens come from the oyster bed at 251-252 m, in which the pulse echinoid *Echinogalerus*? sp. aff. *hannoniensis* appears again after an hiatus (*see* chapter 6).

8. SUPPLEMENTARY FAUNAL RECORD (C.J. WOOD)

Apart from inoceramids, irregular echinoids and, at some levels, belemnites, the fauna of the Staffhorst succession is of surprisingly low diversity. The main additional faunal groups recognised are sponges, corals, serpulids, brachiopods, ammonites, bivalves, gastropods, asteroids, crinoids and regular echinoids. This material is housed in the collections of the University of Hamburg and was cursorily examined by the author in 1980.

Sponges

The Middle and Upper Coniacian of Staffhorst are characterized by an abundance of sponges recorded as "massive cylindrical sponges" without further attempt at determination. A more delicate, funnel shaped sponge from the 321-324 m interval (Upper Coniacian) has been tentatively determined as *Rhizopoterion* sp. and there are several possible *Sporadoscinia* sp. in the 324-330 m interval (Upper Coniacian), as well as a *Sporadoscinia* type sponge with a very coarse meshwork in the 492-500 m interval (Lower Coniacian).

Corals

As would be expected in view of the comparatively argillaceous lithofacies, corals are poorly represented in the Staffhorst faunas. Two small single corals with strongly ribbed calyces from the 268-271 m interval (Santonian) are reminiscent of *Parasmilia fittoni* from the Santonian white chalk of southern England. It should be noted that the taxonomy of all Chalk corals is in urgent need of revision, and that this determination should not be regarded as definitive. Nevertheless it is interesting to see this white chalk morphotype in time-equivalent beds in the Staffhorst succession. Single corals attributed to *Parasmilia*, are much commoner in the white chalk facies of the Lägerdorf standard section, where ERNST & SCHULZ (1974, Fig. 4) record them as ranging from the top of the Coniacian to the equivalent of the top of the Staffhorst succession.

Brachiopods

A medium-sized terebratulid was noted from the 251-252 m interval and an unidentified *Orbirhynchia* is not uncommon in the 265-271 m interval (Santonian). The occurrence of *Orbirhynchia* may match minor acme-occurrences of this genus in the Middle Santonian of Lägerdorf (ERNST & SCHULZ 1974, Fig. 4). Additional noteworthy records are a large *Kingena* sp. from the 277-279 m interval (Middle Santonian) and a *Gibbithyris* or *Concinnithyris* with straight commissure from the 467-473 m interval (Lower Coniacian).

Ammonites

Several ammonites collected from the Cenomanian were removed for examination from Hamburg by the late Professor J. WIEDMANN, and are presumably at present in Tübingen. According to KAPLAN & *al.* (1998) these mainly, perhaps exclusively, comprised *Schloenbachia varians* at 682 m. Additional specimens of *Schloenbachia varians* were mentioned by SPIEGLER & SPIEGLER (1964) between 711-735 m. A single specimen of *Schloenbachia* sp. and *Turrilites* sp. at 673-676 m are also present in the BGR/NLfB collection.

One of the most remarkable features of the Staffhorst material is the unexpected complete absence of any ammonites from the broadly conceived Scaphiten-Schichten of the traditional German stratigraphic scheme and, specifically, from the otherwise ammonite-rich *Hyphantoceras* events (ERNST & *al.* 1983; KAPLAN & KENNEDY 1996). This absence is particularly surprising in view of the fact that the level of the *Hyphantoceras* events can be inferred on the basis of the echinoid faunas (see chapter 6). It is unlikely to be attributable to facies control, for the ammonites of the *Hyphantoceras* events are found throughout northern Europe in lithofacies ranging from coccolith/calcisphere chalks, through Pläner limestones to mudstones. However, the absence of ammonites is paralleled by the equally remarkable virtual absence of the rich inoceramid assemblages of the *Hyphantoceras* events.

There is extensive ammonite material from the top beds of the Lower Coniacian upwards. This comprises predominantly flattened, weakly pyritised, composite moulds. Most of the forms recorded are smooth and/or unornamented, with some indications of constrictions. These have been listed broadly as *Puzosia* or puzosiid, although this should not be taken to imply that the genus *Puzosia* is actually present. It is probable that this relatively poorly preserved material includes several generic and/or specific taxa. In addition, there is one specimen of a tuberculate ammonite (presumably a texanitid) from the 265-268 m interval, and fragments of ribbed heteromorphs in the 321-324 m (Upper Coniacian), 400-406 m and 416-420 m (Lower Coniacian) intervals.

Bivalves

The Santonian part of the succession is characterized by limacean bivalves such as *Plagiostoma cretacea* and *P. hoperi*. The *P. cretacea* are predominantly of small size in comparison with specimens from the white chalk facies, but the *P. hoperi* include relatively large-sized, albeit rather thin-shelled, individuals. It should be noted that large specimens of *P. hoperi* are particularly characteristic of the Santonian chalks of southern England.

The occurrence of beds of thin-shelled oysters (*Pseudoperna boucheroni* and, possibly also *Acutostrea* sp.) in rock-forming quantities towards the top of the Santonian succession (268-271 m and 249-251 m intervals) is noteworthy. These beds are reminiscent of the Grobkreide lithofacies that spans the terminal Upper Santonian – basal Lower Campanian interval in the Lägerdorf standard section and in correlative successions throughout Europe. A comparable approach to Grobkreide facies is found in the lower part of the basal Upper Santonian *Uintacrinus socialis* Zone in Yorkshire, eastern England.

Crinoids

The record of a columnal of *Austinocrinus granulata*? from the 400-406 m interval (basal Middle Coniacian) is of interest. This genus has previously been recorded from the Middle Santonian *Micraster rogalae*/*Gonioteuthis westfalicagranulata* Zone of the Lägerdorf standard section (Ernst & Schulz 1974, Fig. 4) and from the white chalk facies (inferred Santonian) of Helgoland (Wood & Schmid 1991).

An echinoderm plate from the 251-252 m interval (Santonian) was tentatively identified as *Uintacrinus* and used to assign this interval to the Upper Santonian *Uintacrinus socialis* Zone. The specimen in question has been re-examined for this paper and proves not to belong to *Uintacrinus*.

Regular echinoids

Regular echinoids are represented by isolated spines of *Hirudocidaris hirudo*, *Temnocidaris sceptrifera* and *Tylocidaris clavigera*. All three taxa occur together in the Santonian in the 265-271 m interval. *Temnocidaris sceptrifera* and *Tylocidaris clavigera* are also recorded from the Upper Coniacian in the 319-321 m and 315-319 m intervals respectively.

These three taxa are common in the white chalk facies (Coniacian – Santonian) *Micraster coranguinum* Zone of southern England, and the first two are recorded (Wood & Schmid 1991) from the white chalk (inferred Santonian) of Helgoland.

9. FORAMINIFERAL STRATIGRAPHY
(W. Weiss)

The re-investigation of the microfaunas from the Staffhorst section is based on earlier studies (*see* above). Preliminary micropaleontogical results were summarized in an internal BGR short report by Koch (1977a). For the study presented here foraminiferal microfaunas were studied stratigraphically from about 350 samples which were collected from the 243.25-813 m interval more or less continuously in units of about 2 m throughout the sequence.

The microfaunas found in the slides of the Staffhorst collection consist mainly of planktic and benthic foraminifers; ostracods and mesofaunal fragments are rare. The planktic foraminiferal component yields specimens from different groups, such as hedbergellids (*H. delrioensis, H. brittonensis, H. paradubia, H. simplex*), whiteinellids (*W. baltica*), archaeoglobigerinids (*A. cretacea*), praeglobotruncanids (*P. stephani, P. gibba*), dicarinellids (*D. imbri-*

cata, D. hagni) and double-keeled marginotruncanids (*M. marginata, M. paraventricosa, M. coronata, M. pseudolinneiana, "M. lapparenti", M.* cf. *fornicata*); specimens of the heterohelicids (*H. reussi, Pseudotextularia* cf. *elegans*) occur very rarely and are often absent. The benthic foraminiferal component is composed of specimens of the genera *Stensioeina, Neoflabellina, Bolivinoides* (see below), *Gavelinella* (*G. cenomanica, G. baltica, G. thalmanni*) and of agglutinated specimens (*i.e. Marssonella trochus, Spiroplectinata jaeckeli*). The general composition of the microfauna indicates an epicontinental palaeoenvironment which is located roughly between an outer-shelf to middle part of the sublittoral.

The preservation of the microfaunas is generally poor. The tests are often covered by sediment overgrowth due to slight secondary recrystallisation, which tends to prevent exact taxonomic assignment. It has therefore proved impossible to produce a complete faunal list of all the species present. Text-fig. 10 shows the distribution of those stratigraphically important taxa that were positively identified.

Stratigraphic ranges

In this study special emphasis was laid on the first and last occurrences (FO and LO) of well-known index markers of the Boreal Upper Cretaceous (planktic foraminifers, *Stensioeina, Neoflabellina* and *Bolivinoides* taxa). These were used to establish a new and revised foraminiferal zonation for the Staffhorst succession. The new zonation was then correlated with the zonations and biostratigraphic assignments based on macrofossils.

The succession of important taxa and of the foraminiferal zones presented here conforms approximately to the general succession of *Stensioeina* and *Neoflabellina* foraminiferal zones established earlier by KOCH (1977b) for northern Germany. However, the succession of index marker zones has been further refined. Subsequent changes in stage concepts, and changed stratigraphic interpretations based on a reassessment of the Staffhorst macrofaunas (*see* chapter 5), have necessitated a reassessment of the microfossil zones of KOCH (1977b) in relation to the biostratigraphic framework used today. The succession of the foraminiferal zones identified in Staffhorst is as follows:

Interval not zoned from 683.5-778.5 m: Base = FO of *Physocythere steghausi* at 778.5 m; Top = FO of *Rotalipora reicheli* at 683.5 m; Stratigraphic position according to macrofossils = Lower Cenomanian.

Remarks: The Albian/Cenomanian boundary is defined by the (second) occurrence of the ostracod marker *Physocythere steghausi* (confirmed by LUPPOLD, *pers. comm.*), which has its FO in the upper part of the Upper Albian (*see* KEMPER 1989; FRIEG & *al.* 1989). *Rotalipora globotruncanoides* (= *R. brotzeni*), the basal boundary marker taxon for the Cenomanian stage according to the Brussels conclusions, was not observed. *R. appenninica* is rare in the 727.5-755.5 m interval. Within the 725-727.5 m interval there are rare specimens of planoconvex rotaliporids which might be assigned to *Rotalipora micheli*.

Single specimens of *Rotalipora appenninica* are typical of the Boreal Lower Cenomanian. The exact stratigraphic assignment of the species is therefore often difficult. In the Boreal Realm the species is known from the Upper Albian to Lower Cenomanian of northern Germany (KOCH 1977b), and from the Lower Cenomanian to lower Middle Cenomanian (*R. appenninica* and *R. reicheli* zones) of England (HART & *al.* 1989). *R. micheli* was not known hitherto from the Boreal Realm.

Rotalipora reicheli (interval) Zone from 668.5-683.5 m: Base = FO of *Rotalipora reicheli* at 683.5 m; Top = FO of *Rotalipora cushmani* at 668.5 m; Stratigraphic position according to macrofossils = terminal Lower Cenomanian to lower Middle Cenomanian.

Remarks: *R. reicheli* was not recorded previously from this northern region of Germany. It is rare in the Lower/Middle Cenomanian boundary interval (*e.g.* the Mittellandkanal section of the Hannover area, ROHDE & BECKER-PLATEN 1998) and is also recorded from Baddeckenstedt (WOOD, *pers. comm.*).

From the Albian/Cenomanian boundary to the base of the *Rotalipora cushmani* Zone of the Middle Cenomanian of the Staffhorst section, gavelinellids such as *G. cenomanica* and *G. baltica*, are not suitable as zonal index markers (*cf.* KOCH 1977b).

Rotalipora cushmani (total range) Zone (*pars*, lower part only) from 650-668.5 m: Base = FO of *Rotalipora cushmani* at 668.5 m; Top = LO of *Rotalipora cushmani* at 650 m; Stratigraphic position according to macrofossils = upper Middle Cenomanian to lower Upper Cenomanian.

Remarks: The upper part of the Upper Cenomanian is missing. This is inferred from the

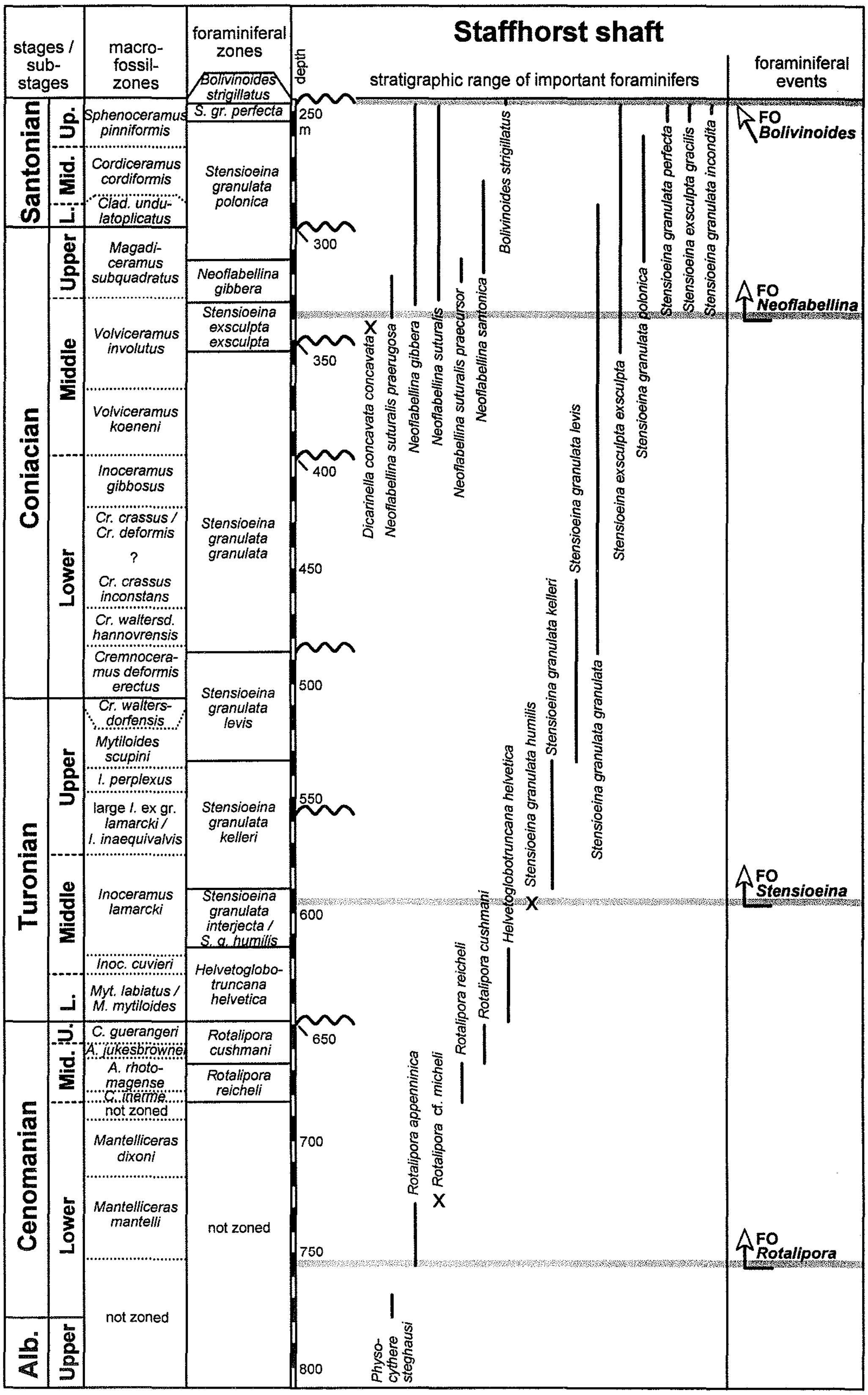

Fig. 10. Vertical ranges of important foraminifera in the Upper Cretaceous of the Staffhorst shaft

fact that species normally accompanying *R. cushmani*, such as *R. greenhornensis* and *R. deeckei* in the upper Upper Cenomanian, have not been found together with *R. cushmani* in Staffhorst.

The *Whiteinella archaeocretacea* Zone of the Cenomanian/Turonian boundary interval is suspected either to be present in the short 647.1-650 m interval, or the zone is completely missing. The index marker was not observed in the only sample from this interval, at 648.5 m.

Helvetoglobotruncana helvetica (total range) Zone from 617-647.1 m: Base = FO of *Helvetoglobotruncana helvetica* at 647.1 m; Top = LO of *Helvetoglobotruncana helvetica* at 617 m; Stratigraphic position according to macrofossils = Lower Turonian to basal Middle Turonian.

Remarks: This single-keeled, planoconvex species was hitherto not reported from northern Germany. The chambers of the final whorl on the ventral side of the specimens found are not so strongly inflated as is typical for Tethyan specimens, but the Boreal specimens show the typical rugose ornamentation on the ventral side of the chambers.

Stensioeina granulata interjecta/*Stensioeina granulata humilis* Zone from 589.5-617 m: This zone is inferred to be present over this interval, and it is definitely proved by the occurrence at 595 m of single specimens of *Stensioeina granulata humilis*. Stratigraphic position according to macrofossils = Middle Turonian.

Stensioeina granulata kelleri (total range) Zone from 534-589.5 m: Base = FO of *Stensioeina granulata kelleri* at 589.5 m; Top = LO of *Stensioeina granulata kelleri* at 534 m; Stratigraphic position according to macrofossils = terminal Middle Turonian to upper Upper Turonian.

Remarks: *Stensioeina granulata kelleri* was previously used as the index marker of the upper part of the Middle Turonian (KOCH 1977b), *i.e.* Upper Turonian in modern terms. Within the 585.5-588 m interval planktic foraminifers are strongly reduced, whereas *Stensioeina* specimens are become dominant for the first time. At 581 m both planktic foraminifers and *Stensioeina* specimens show significant carbonate dissolution.

Stensioeina granulata levis (interval) Zone from 487-533 m: Base = FO of *Stensioeina granulata levis* at 533 m; Top = FO of *Stensioeina granulata granulata* at 487 m; Stratigraphic position according to macrofossils = upper Upper Turonian to basal Lower Coniacian.

Remarks: The FO of *Stensioeina granulata levis* was used by KOCH (1977b) to define the base of the Upper Turonian micropalaeontologically [*i.e.* Lower Coniacian in modern terms]. Within the 492.5-521 m interval planktic foraminifers, such as praeglobotruncanids and double-keeled marginotruncanids, are common. Lithologically, this part coincides with the Grauweiße Wechselfolge and the Upper Limestone Unit (*see* Text-fig. 5).

Stensioeina granulata granulata (interval) Zone from 355.2-487 m: Base = FO of *Stensioeina granulata granulata* at 487 m; Top = FO of *Stensioeina exsculpta exsculpta* at 355.2 m; Stratigraphic position according to macrofossils = Lower Coniacian and lower Middle Coniacian.

Remarks: According to KOCH (1977b) this index marker has its FO in the upper part of the Upper Turonian, *i.e.* within the Lower Coniacian in modern terms.

Stensioeina exsculpta exsculpta (interval) Zone from 334-355.2 m: Base = FO of *Stensioeina exsculpta exsculpta* at 355.2 m; Top = FO of *Neoflabellina gibbera* at 334 m; Stratigraphic position according to macrofossils = upper Middle Coniacian.

Remarks: According to KOCH (1977b), who used a twofold subdivision of the Coniacian, the index marker has its first occurrence in the upper part of the Lower Coniacian, *i.e.* upper Middle Coniacian in modern terms. Within this zone one true specimen of *Dicarinella concavata*, a Tethyan planktic foraminiferal species, was observed at 343 m.

Neoflabellina gibbera (interval) Zone from 315.5-334 m: Base = FO of *Neoflabellina gibbera* at 334 m; Top = FO of *Stensioeina granulata polonica* at 315.5 m; Stratigraphic position according to macrofossils = terminal Middle Coniacian and lowermost Upper Coniacian.

Remarks: The FO of *Neoflabellina gibbera* has hitherto been used to define the base of the Lower Santonian micropalaeontologically (KOCH 1977b).

Stensioeina granulata polonica (total range) Zone from 260-315.5 m: Base = FO of *Stensioeina granulata polonica* at 315.5 m; Top = LO of *Stensioeina granulata polonica* at 260 m; Stratigraphic position according to macrofossils =

lower Upper Coniacian to Middle (or basal Upper) Santonian.

Remarks: According to CHRISTENSEN & SCHULZ (1997, p. 10) the FO of *Stensioeina granulata polonica* does not coincide with the base of the *Sphenoceramus pachti/Cladoceramus undulatoplicatus* Zone defining the base of the Santonian, it is within the *Volviceramus koeneni* Zone of the Middle Coniacian.

Stensioeina granulata perfecta (interval) Zone from 244.2-255 m: Base = FO of *Stensioeina granulata perfecta* at 255 m; Top = FO of *Bolivinoides strigillatus* at 244.2 m; Stratigraphic position according to macrofossils = Middle (or basal Upper) Santonian to Upper Santonian.

Remarks: The FO of *Stensioeina granulata perfecta* was used by KOCH (1977b) to define the base of the upper part of the Middle Santonian.

Bolivinoides strigillatus Zone from 242.25-244.2 m (last sample studied): Base = FO of *Bolivinoides strigillatus* at 244.2 m; Stratigraphic position of the base according to macrofossils = Upper Santonian.

General remarks

During the later Early Cenomanian the Tethyan influence increased, as indicated by the occurrence of planktic foraminifers such as *R. appenninica, R.* cf. *micheli, R. reicheli, R. cushmani* and *Helvetoglobotruncana helvetica*. The planktic foraminiferal zonation used in the Tethys is applicable for this part of the Staffhorst sequence.

For the interval from the upper Middle Turonian to the Upper Santonian the Boreal benthic foraminiferal zonation established by KOCH (1977b) for northern Germany can be broadly applied, albeit with considerable modifications, necessitated by changed stage boundary concepts, as well as revised stratigraphic positions based on macrofossils, event stratigraphy and hiati (*cf.* Text-fig. 11).

Planktic foraminifers from the Tethyan Realm have not been found throughout this part of the succession. Rare specimens of Tethyan species are present, as is indicated by the occurrence of *Dicarinella concavata* at 343.5 m which, according to the macrofossils, falls in the upper part of the Middle Coniacian.

The first occurrences of key benthic foraminiferal index taxa are related to three separate levels:

The FO of specimens of the *Stensioeina granulata kelleri – levis – granulata* group is at 595 m in the lower Middle Turonian.

The FO of *Neoflabellina* (*Neoflabellina suturalis* group, *N. gibbera, N. santonica*) is at 340 m in the terminal Middle Coniacian.

The FO of *Bolivinoides* (*Bolivinoides strigillatus*) is at 244 m within the Upper Santonian.

These first occurrences indicate the onset of a significant change in the paleoenvironmental depth, which becomes shallower.

A remarkable hiatus is present from the upper part of the Upper Cenomanian on. It includes the Oceanic Anoxic event at the Cenomanian/Turonian boundary. There is no significant change in composition of the microfossil assemblages; the microfacies and the planktic foraminiferal composition is similar below and above the hiatus. The reason for this similarity is unclear.

10. MULTISTRATIGRAPHIC CORRELATION AND CONCLUSIONS

Albian/Cenomanian boundary

Proposal in Brussels (*see* TRÖGER & KENNEDY 1996): FO (first occurrence) of the planktic foraminifer *Rotalipora globotruncanoides*.

This paper: The FO of *R. globotruncanoides* cannot be used because of the absence of the taxon in the Boreal. The Albian/Cenomanian boundary in Staffhorst is defined by the re-entry (= second occurrence) of the ostracod *Physocythere steghausi* at 779 m shaft (786 m trial borehole), which is accompanied by a conspicuous negative SN peak, the so-called Bemeroder Einschnürung (Bemerode constriction) within the clayey-marly Bemeroder Schichten (KEMPER 1973; FRIEG & *al.* 1989).

Lower Cenomanian

The most important marker bed is the Lower Cenomanian transgression horizon of SP peak 0 at 750 m (757 m) which corresponds to the *Neohibolites ultimus/Aucellina* event. In marginal sections, the transgressive deposits onlap older strata with a gap and consequently this horizon is used to mark the Albian/Cenomanian boundary on geological maps (= "base of the Upper Cretaceous"). In the

Staffhorst area, the transgression horizon is located ca. 30 m upsection of the Albian/Cenomanian boundary defined by microfossil biostratigraphy and log peak stratigraphy. At 755m (762m) the first keeled planktic foraminifera (*Rotalipora appenninica*) appear.

The Lower Cenomanian can be divided into three sequences (*see* Text-fig. 11). Two stratigraphically important inoceramid events can be observed. The *I. crippsi* event of the *Mantelliceras mantelli* Zone in the 715-735 m (722-742 m) interval marks the sequence boundary between sequence I and II below SP peak 2, and the *I. virgatus* event of the *Mantelliceras dixoni* Zone in the 702-706 m (709-713 m) interval appears in the middle part of sequence III at a conspicuous positive SP peak upsection of SP peak 4.

Lower/Middle Cenomanian boundary

Proposal in Brussels (*see* TRÖGER & KENNEDY 1996): FO of the ammonite *Cunningtoniceras inerme,* with the entry of the inoceramid *Inoceramus schoendorfi* and the planktic foraminifer *Rotalipora reicheli* as secondary markers.

This paper: *C. inerme* cannot be proved in Staffhorst, and therefore the secondary markers were used. In Staffhorst, *I. schoendorfi* is first proved in the 672-682 m (679-689 m) interval. This correlates well with the FO of *R. reicheli* at 683 m (690 m). Above SP peak 6 a distinct positive SP peak occurs at 682 m (689 m in the log of the Staffhorst trial borehole). This "marl peak" = minor *Pycnodonte* event at the base of the Middle Cenomanian, is interpreted as a sequence boundary with a major hiatus (*C. inerme* hiatus of ERNST & REHFELD 1997), and it probably correlates with the marl layer M II of Baddeckenstedt. Because of the *C. inerme* hiatus, the FO of *C. inerme* lies directly below the *P. primus* event in Wunstorf (Lower Saxony) (MEYER 1990). In more complete sections, the *P. primus* event correlates with the base of the succeeding *Acanthoceras rhotomagense* Zone (PAUL & *al.* 1994).

Middle Cenomanian

In Staffhorst, the Mid-Cenomanian event in the 676-678 m (683-685 m) interval is a bioturbated nodular calcareous marlstone, as usual associated with the occurrence of *Holaster subglobosus* (*cf.* ERNST & *al.* 1983; ERNST & REHFELD 1997).

Middle/Upper Cenomanian boundary

Proposal in Brussels (*see* TRÖGER & KENNEDY 1996): No agreement was reached.

This paper: In northern Germany, the *Pycnodonte* event can usually be used as the boundary marker (*cf.* ERNST & *al.* 1983). In Staffhorst, it appears at 659 m (666 m). In the electric borehole logs it correlates with a distinct positive SP peak upsection of SP peak 7 within the *Acanthoceras jukesbrownei* and lower *Rotalipora cushmani* zones respectively.

Upper Cenomanian

In Staffhorst, only the lower part of the typical Arme *rhotomagense* Kalke is developed, *i.e.* the interval from the *Pycnodonte* event up to the *Amphidonte* event; the *Metoicoceras geslinianum* and *Neocardioceras juddii* zones are completely missing. Likewise, only the lower part of the *Rotalipora cushmani* Zone is proved. This situation is similar to that in the Sarstedt section, where the Upper Cenomanian Arme *rhotomagense* Kalke are also only a few metres thick (ERNST & SCHMID 1984).

Cenomanian/Turonian boundary

Proposal in Brussels (*see* BENGTSON 1996): FO of the ammonite *Watinoceras devonense*.

This paper: In the Staffhorst section, the Cenomanian/Turonian boundary falls into an hiatus, which covers more than three macrofossil zones. Compared to the succession in Baddeckenstedt (ERNST & REHFELD 1997), the upper half to two-thirds of the Arme *rhotomagense* Kalke, the Facies Change, the *plenus* Bed and the *Mytiloides hattini* events are missing. Likewise, the planktic foraminifer *Whiteinella archaeocretacea* of the Cenomanian/Turonian boundary interval is also absent. In the Staffhorst trial borehole the SP peaks 9 (upper Arme *rhotomagense* Kalke) and 10 (*plenus* Bed, topmost Cenomanian) are not recorded.

Lower Turonian

The Lower, not basal, Turonian of Staffhorst starts with the *Mytiloides* events, which correlate with the end of the Oceanic Anoxic event II (ERNST & *al.* 1983). The FO of *Helvetoglobotruncana helvetica*, the index of the second Turonian foraminifer zone,

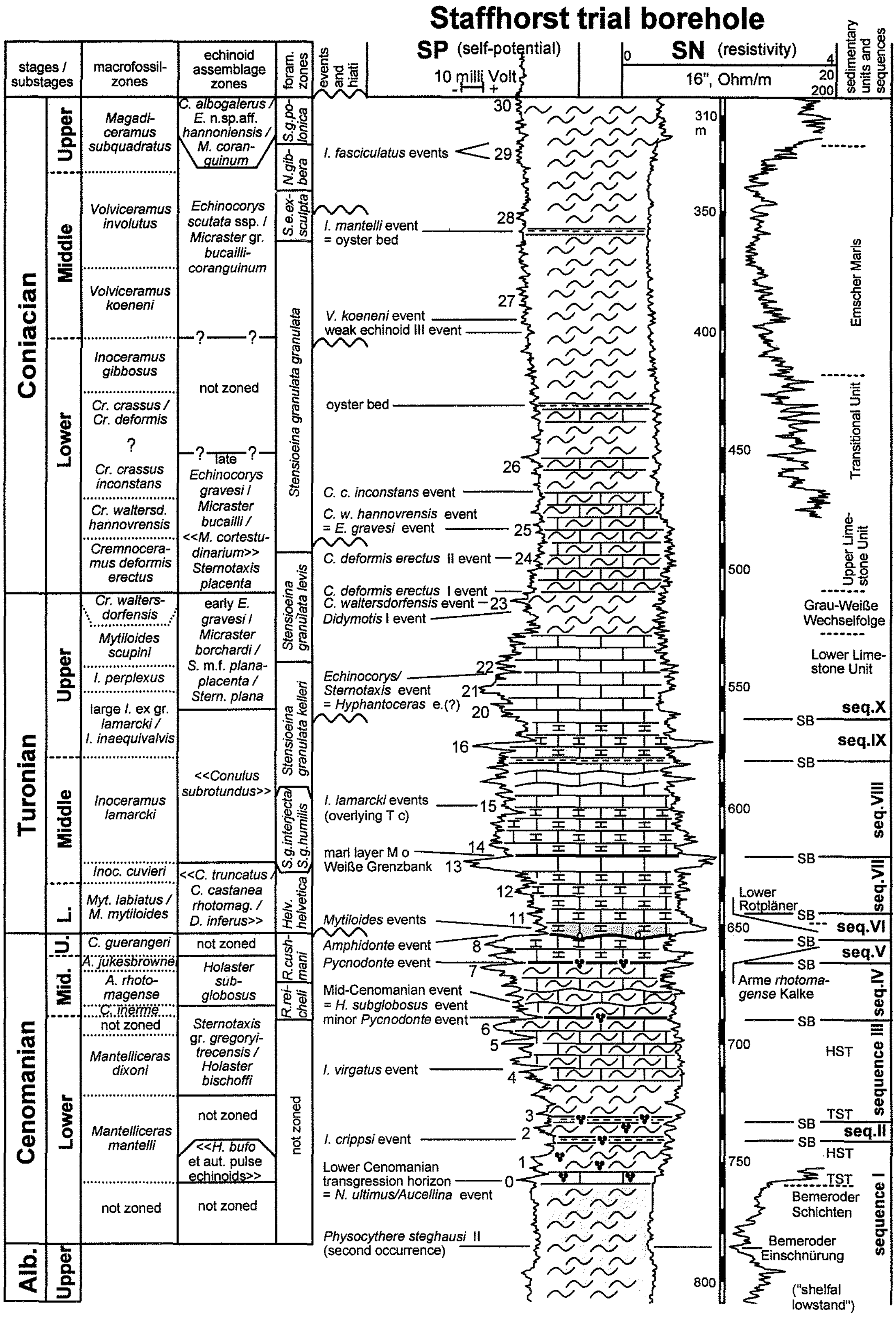

Fig. 11. Multistratigraphical chart of the Albian/Cenomanian boundary to Upper Coniacian succession of the Staffhorst trial borehole using inoceramids, echinoids, foraminifera, bioevents, and lithounits

lies at 647 m (654 m). From 641-647 m (648-654 m), the section is developed in Rotpläner facies.

Lower/Middle Turonian boundary

Proposal in Brussels (*see* BENGTSON 1996): FO of the ammonite *Collignoniceras woollgari*.

This paper: In northern Germany the time-equivalent FOs of the inoceramids *Inoceramus cuvieri* und *Mytiloides hercynicus* can be used (*see* KAUFFMAN & *al.* 1996). In the Staffhorst shaft the FO of *I. cuvieri* at 628 m (635 m) is recorded in the upper part of SP peak 12, *M. hercynicus* is missing.

Middle Turonian

A characteristic lithologic feature of the lower Middle Turonian is the increasing carbonate content, accompanied by decreasing SP values, up to the Weiße Grenzbank at SP peak 13 in the 614-621 m (621-628 m) interval. Within the Weiße Grenzbank, the FO of unequivocal *Inoceramus lamarcki* is recorded at 619 m (626 m) and the LO (last occurrence) of *Helvetoglobotruncana helvetica* is recorded at 617 m (624 m).

The distinct positive SP peak of the dark marl bed at the top of the Weiße Grenzbank at 614 m (621 m) is interpreted as a sequence boundary and may correspond to the marl bed M_O of Söhlde (*cf.* ERNST & WOOD 1995). The subdivision of the remainder of the Middle Turonian is scarcely possible; only the *I. lamarcki* events, which lie in outcrop sections above tuff layer T_C (*cf.* ERNST & *al.* 1998a) are recorded in the 586-598 m (593-605 m) interval. The FO of benthic foraminifers of the *Stensioeina granulata kelleri-levis-granulata* group at 595 m (602 m) indicates the first observable change to shallower environments in the Staffhorst area.

Middle/Upper Turonian boundary

Proposal in Brussels (*see* BENGTSON 1996): No agreement was reached.

This paper: Following the traditional European concept the FO of the inoceramid *Inoceramus perplexus* WHITFIELD (= *Inoceramus costellatus* of authors, non *I. costellatus* WOODS) can be used, which in northern Germany corresponds to the *I. perplexus*/*Sternotaxis plana* event. In Staffhorst an apparent FO of *I. perplexus* is noted in the interval 543-548 m (550-555 m), where it also co-occurs with the echinoid species *Sternotaxis plana*. However, based on the occurrence of large representatives of *I.* ex gr. *lamarcki*, characterizing the basal Upper Turonian zone of *Inoceramus perplexus*/large *I. cuvieri*/*I. lamarcki stuemckei*/*I. inaequivalvis*, in the 572-575 m (579-582 m) interval, the actual FO of *I. perplexus* and, accordingly, the base of the Upper Turonian may lie as low as 575 m (582 m). At 573 m (580 m) the limestones terminate in a debrite with inoceramid debris, which can be interpreted as a sequence boundary. In the SP log this event lies just above SP peak 16.

Upper Turonian

In the lower Upper Turonian, compared to the Staffhorst 7 and E 9 boreholes, there is clear evidence of an hiatus in the Staffhorst trial borehole at 556 m (563 m), comprising SP peaks 17-19. The inoceramid association characteristic of the *Hyphantoceras* event was not found. However, within the *Echinocorys*/*Sternotaxis* event of the 534-537 m (541-544 m) interval, an echinoid association appears which is typical of the stratigraphic position of the *Hyphantoceras* event. *Mytiloides scupini* has its FO at the same level, correlating well with the FO of *Stensioeina granulata levis* at 533 m (540 m). This event-bundling shows the pronounced condensation of the Staffhorst section in comparision to Salzgitter-Salder, where ca. 40 m of sediments are intercalated between the *I. perplexus*/*S. plana* event and the *Hyphantoceras* event, and ca. 20 m between the *Hyphantoceras* event and the FO of *M. scupini* respectively (*see* HORNA & WIESE 1997). In the Staffhorst shaft, the *Hyphantoceras* event (as defined by the echinoid assemblage) and FO of *M. scupini* are in the same interval and only ca. 11-14 m above the apparent *I. perplexus*/*S. plana* event. This situation is also found in the Staffhorst 7 and E 9 boreholes, and consequently stratigraphic condensation in this interval may characterize the whole Staffhorst area.

Condensation und event-bundling upsection of the hiatus support the interpretation of a distinct sequence boundary and condensation within the succeeding TST. After an abrupt facies change from white chalky limestones of the Lower Limestone Unit at 521 m (528 m) between SP peaks 22-23, this condensation continues into the Grauweiße Wechselfolge. At 509-514 m (516-521 m), the *Didymotis* I and *C. waltersdorfensis* events of the terminal Turonian are found.

Turonian/Coniacian boundary

Proposal in Brussels (*see* KAUFFMAN & *al.* 1996): FO of the inoceramid *Cremnoceramus rotundatus,* which appears to be a junior synonym of *Cremnoceramus deformis erectus* (MEEK).

This paper: The proposal of the Brussels symposium can be applied. In Staffhorst *C. deformis erectus* has its FO in the 504-509 m (511-516 m) interval at SP peak 23 within the Grau-Weiße Wechselfolge.

Lower Coniacian

The exact position of the top of the Grauweiße Wechselfolge and its transition into the overlying Upper Limestone Unit is not fully agreed between the authors of this paper, but is nevertheless well defined. However, according to the lithological characters, the transition into the Upper Limestone Unit occurs at 504 m (511 m), thereby giving the Grauweiße Wechselfolge its characteristic ratio of 6-7 "Turonian parts" to 1 "Coniacian part" (*cf.* WOOD & ERNST 1998, p. 95). According to faunistic markers, the Grauweiße Wechselfolge comprises the interval up to the hiatus at 484 m (491 m). Directly above this hiatus, within the 447-484 m (454-491 m) interval, the *Echinocorys gravesi* event is recorded, marked by the absolute frequency maximum of *Echinocorys* within the succession, and the immigration of the first "modern" *Micraster* at 467 m (454 m). At the same time, inoceramids of the *Cremnoceramus crassus inconstans* group have their first occurrences in the 463-467 m (470-474 m) interval, indicating either a co-migration event or an hiatus. The FO of *Stensioeina granulata granulata* is situated a short distance above the hiatus at 487 m (494 m).

Lower/Middle Coniacian boundary

Proposal in Brussels (*see* KAUFFMAN & *al.* 1996): FO of the inoceramid *Volviceramus koeneni.*

This paper: The proposal of the Brussels symposium can be applied. *V. koeneni* appears in Staffhorst above a subordinate hiatus within the Emscher Marls at 400 m (407 m). In the 400-406 m (407-413 m) interval a possible evolutionary precursor of *Volviceramus* was found.

Middle Coniacian

Directly above the Lower/Middle Coniacian boundary within the Emscher Marls below the SP peak 27 a subordinate echinoid III event occurs in the 393-397 m (400-404 m) interval; it is followed by the *Volviceramus koeneni* event at 387-393 m (394-400 m).

In the terminal Middle Coniacian, rare planktic foraminifers of the Tethyan Realm, *Dicarinella concavata,* were found at 343 m (350 m). The FO of the benthic foraminifer *Neoflabellina* at 340 m (347 m) indicates a second noticeable change to shallower environments.

Middle/Upper Coniacian boundary

Proposal in Brussels (*see* KAUFFMAN & *al.* 1996): FO of the inoceramid *Magadiceramus subquadratus.*

This paper: In Staffhorst the boundary definition using the FO of *M. subquadratus* is difficult, because this species is extremely rare. In the absence of *Magadiceramus*-dominated assemblages, the base of the substage is taken at the appearance of other inoceramids characteristic of the Upper Coniacian, notably *"Sphenoceramus" subcardissoides, Inoceramus fasciculatus, I. latisulcatus, I. canaliculatus* and the volviceramid-like *I. anomalus.* In Staffhorst this assemblage first appears at 330 m (337 m) within the *Neoflabellina gibbera* Zone. The FOs of *N. gibbera* at 334 m (341 m) and *Neoflabellina suturalis* at 332 m (339 m) can consequently be used as secondary markers.

Upper Coniacian

In Staffhorst only the lower Upper Coniacian is represented. The *I. fasciculatus* mass-occurrence is found in the 315-322 m (322-329 m) interval. The FO of *Stensioeina granulata polonica* is situated at 315 m (322 m). In the electric borehole logs, the SN values start to increase at this depth, which is probably related to the gradual upper transition into the Emscher Marls.

In the 306-311 m (313-318 m) interval occurrences of *Gonioteuthis* and *Echinogalerus* (?) document a Late Coniacian transgressive pulse. According to belemnite stratigraphy, the *Gonioteuthis praewestfalica* Zone starts at this level.

Coniacian/Santonian boundary

Proposal in Brussels (*see* LAMOLDA & HANCOCK 1996): FO of the inoceramid *Cladoceramus undulatoplicatus*.

This paper: The proposal of the Brussels symposium can be applied. In Staffhorst *C. undulatoplicatus* appears directly above the conspicuous hiatus at 303 m, where, according to log peak correlation with the Staffhorst 7 and E 9 boreholes, ca. 90 m are missing. Upsection from the base of the Santonian, the sediments are apparently flat-lying and no correlation factor of 7 m between shaft and trial borehole is necessary.

Lower Santonian

In the 296-300 m interval occurrences of *Gonioteuthis* and *Echinogalerus*(?) document a transgressive pulse of the Early Santonian *C. undulatoplicatus* transgression (Text-fig. 9). Some of the *Gonioteuthis* from this level are corroded. According to belemnite stratigraphy, the *C. undulatoplicatus* transgression also falls into the top of the *G. praewestfalica* Zone. This zone, therefore, spans the middle and upper Upper Coniacian, as well as the basal Santonian, including the major hiatus in the late Late Coniacian. In the more complete Staffhorst E 9 borehole, where no hiatus is developed, the *G. praewestfalica* Zone would comprise more than 100 m and the *Stensioeina granulata polonica* (total range) Zone, which also crosses the major hiatus in the Staffhorst shaft, would be more than 140 m thick.

Lower/Middle Santonian boundary

Proposal in Brussels (*see* LAMOLDA & HANCOCK 1996): LO of the inoceramid *Cladoceramus undulatoplicatus*.

This paper: The proposal of the Brussels symposium can be applied. The LO of the inoceramid *C. undulatoplicatus* in Staffhorst is at 290 m. According to belemnite stratigraphy, the boundary lies within the "*Gonioteuthis*-depleted interval", which in the Lägerdorf standard section covers the *Sphenoceramus pachti*/*Cladoceramus undulatoplicatus* Zone of the lower Lower Santonian (*see* ERNST & SCHULZ 1974).

Middle Santonian

In the 265-271 m interval, the occurrence of *Gonioteuthis* and *Echinogalerus*(?) documents the main transgressive pulse of the Middle Santonian transgression. According to belemnite stratigraphy, it lies at the base of the lower *G. westfalica* Zone and, therefore, at the base of the *Micraster coranguinum*/*G. westfalica* Zone of Lägerdorf (*see* ERNST & SCHULZ 1974, there: upper Lower Santonian).

Middle/Upper Santonian boundary and Upper Santonian

Proposal in Brussels (*see* LAMOLDA & HANCOCK 1996): FO of the crinoid *Uintacrinus socialis*.

This paper: The occurrence of *U. socialis* in Staffhorst cannot be proved. An echinoderm plate from the 251-252 m interval in the Hamburg University material was originally identified as *Uintacrinus* and used to assign this interval (WOOD, *unpubl. report*) to the Upper Santonian *Uintacrinus socialis* Zone. The presumed original specimen, consisting of a tempestite with a mass occurrence of *Pseudoperna boucheroni*, contains crinoid and other echinoderm fragments, but the crinoids appear not to belong to *Uintacrinus*. It must be emphasized that, although no specimens of *Uintacrinus* have been identified from Staffhorst, the foraminiferal evidence unequivocally proves that the *Uintacrinus* Zone is present. *Uintacrinus* is extremely rare in the lower part of its range, and otherwise typically occurs in floods, separated by intervals with few or no occurrences. In this paper the following possible boundary markers are discussed:

inoceramids: FO of *Sphenoceramus pinniformis* at 266 m; FO of *"Inoceramus" muelleri* at 266 m;
foraminifers: FO of *Stensioeina granulata perfecta* at 255 m; FO of *Bolivinoides strigillatus* at 244 m;
belemnites: FO of *Gonioteuthis granulata*, not recorded up to 245 m.

In the Text-figures of this paper the Middle/Upper Santonian boundary is defined according to the FOs of the inoceramids *"I." muelleri* and *S. pinniformis* at 266 m. *"I." muelleri* is a Middle/Upper Santonian boundary marker in northern Spain, where *S. pinniformis* has not been recorded (OPPERMANN 1996). In the Lägerdorf standard section, *"I." muelleri* has not been found; here, the FO of *S. pinniformis* (and only horizoned record) is located significantly lower, within the Middle Santonian *Micraster rogalae/Gonioteuthis westfalica* Zone, with presumed occurrences extending up to above the FO of *Uintacrinus* in bed G236 (ERNST & SCHULZ 1974, Fig. 4). This relatively low placing of the boundary in Staffhorst is possibly supported by the occurrence of phosphorite pebbles at 261-263 m, which could be inferred to document the Late Santonian transgression. However, on the basis of the *Gonioteuthis* morphometric data, the overlying 245-256 m interval still clearly belongs to the *G. westfalicagranulata* Zone (*see* Text-fig. 9). If one were to take the FOs of *S. pinniformis* and *"I." muelleri* at 266 m as the base of the Upper Santonian, the entire *G. westfalicagranulata* Zone would, both in Staffhorst and in Lägerdorf, fall by definition into the Upper Santonian, but such an interpretation would be completely at variance with standard practice in Germany.

The mass-occurrence of *Pseudoperna boucheroni* associated with echinoderm debris in the 251-252 m interval may equate with the *Ostrea* bed recorded by ERNST (1963: 106) in Lägerdorf immediately overlying F232, close to the base of the *Uintacrinus socialis/Gonioteuthis granulata* Zone. A comparable oyster-rich event with *P. boucheroni* and *Sphenoceramus pinniformis* is also known from eastern England, in the lower part of the *Uintacrinus socialis* Zone, and ca. 1 m beneath an occurrence of *Uintacrinus*. The FO of *Uintacrinus* in Lägerdorf is actually located ca. 4.5 m below the base of the *Uintacrinus/G. granulata* Zone in bed G236 (SCHULZ & *al.* 1984) and, therefore, in the middle of the ca. 10 m thick *M. rogalae/G. westfalicagranulata* Zone. The higher part of the *M. rogalae/G. westfalicagranulata* Zone thus falls, by definition, into the basal Upper Santonian.

At 255 m a break is found in the *Gonioteuthis* evolution, which is probably connected with an hiatus. At the same level, *Stensioeina granulata perfecta* first appears. In Lägerdorf this FO falls within the *Micraster rogalae/Gonioteuthis westfalicagranulata* Zone, but only a short distance (ca. 1 m) below the FO of *Uintacrinus* in bed G236. The FO of *Bolivinoides strigillatus* in Staffhorst is at 244 m. The FO of *B. strigillatus* in Lägerdorf is in the F226-F227 interval (SCHÖNFELD 1990), in the higher part of the *Uintacrinus socialis/G. granulata* Zone (*cf.* section details *in*: ERNST 1963).

The stratigraphic levels at Lägerdorf of these two foraminiferal FOs with respect to the macrofossil biostratigraphy also agrees well with unpublished data from current investigations of the Seaford Head section in the white chalk of southern England.

To summarize, the evidence for placing the base of the Upper Santonian is, admittedly, contradictory, with perhaps the strongest evidence being provided by the foraminifera. According to the foraminiferal biozonation, the presence of Upper Santonian in Staffhorst is unequivocally proved by the FO of *Bolivinoides strigillatus* at 244 m, and almost equally certainly indicated by the FO of *Stensioeina granulata perfecta*, 11 m lower, at 255 m. However, it is unclear whether or not this represents the true FO of *S. granulata perfecta*, since this apparent FO is associated with an hiatus. The apparent absence of *Uintacrinus* in Staffhorst is explicable in view of the rarity of this crinoid towards the base of its range, and by the fact that it typically occurs in discrete levels of relative flood abundance, and is never conspicuous. The oyster-rich horizon in the 251-252 m interval actually supports taking the base of the Upper Santonian near the FO of *S. granulata perfecta*. Although there is definite evidence of a significant inoceramid turnover at 266 m, it must be accepted that the FO of *Sphenoceramus pinniformis* at Lägerdorf, if correctly interpreted, clearly falls in the higher part of the Middle Santonian. This inoceramid FO and associated inoceramid turnover should perhaps not be used as a definitive criterion for identifying the base of the Upper Santonian, and more reliance should be placed instead on the foraminiferal evidence. For the reasons discussed above, two possible interpretations of the base of the Upper Santonian are shown in the Text-figures of this paper. The entirely contradictory nature of the evidence provided by the *Gonioteuthis* lineage, which indicates that both of these interpretations are impossible, cannot readily be resolved.

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