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Late Cretaceous unconformities in the Subhercynian Cretaceous Basin (Germany)

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ABSTRACT:

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In the Subhercynian Cretaceous Basin, six Upper Cretaceous angular unconformities can be observed. The first unconformity, at the base of the Cenomanian transgressive deposits, is not related to the development of the basin. While the second (Lower to Middle Coniacian) unconformity is almost limited to the northern basin margin, four unconformities are developed at the Harznordrand Thrust and span the short period from the Middle Santonian to the late Early Campanian (about 3 Ma). The intra-Coniacian unconformity at the northern basin margin proves tilting of the basin floor to the south-east and is possibly related to the development of the thrust too. The Santonian to Campanian unconformities at the Harznordrand Thrust reflect the formation of a continuously growing fault-propagation fold. Deposition above unconformities occurred when the rate of eustatic sea-level rise exceeded thrusting rate. Transgressions occurred in the earliest Middle Santonian, in the Late Santonian (intra-*Marsupites* Zone), in the earliest Campanian (*granulataquadrata* Zone) and in the late Early Campanian (*Offaster pilula* Zone). The ages of unconformities correlate well with the transgressive pulses proved in Western and Middle Europe and are not related to discrete deformational events.

Key words: Upper Cretaceous, Central Europe, Subhercynian Cretaceous Basin, Intraplate Deformation, Harznordrand Thrust, Unconformities.

INTRODUCTION

The Subhercynian Cretaceous Basin in central Europe is one of the classic places where Late Cretaceous intraplate deformation and basin formation were studied (e.g. VOIGT 1929, VOIGT 1963, WUNDERLICH 1953, MORTIMORE & *al*. 1998). Like other basins in western and central Europe which developed during the Late Cretaceous, the basin was filled with several hundred metres of clastic and carbonate sediments and later overthrusted by the adjoining source areas (ZIEGLER 1987). In contrast to other basins, the situation after deposition and thrusting was nearly completely preserved, including syntectonic sediments close to the thrust front. Neither major erosion nor subsequent deposition changed the situation after the Early Campanian. Based on several unconformities exposed at the southern basin margin in front of the Harznordrand Thrust, STILLE (1924) defined several tectonic phases which are believed to be relevant at least on a regional and perhaps global scale (MORTIMORE & *al*. 1998). These unconformities, especially their timing and relations to tectonic processes became the subject of an intensive discussion (e.g. VOIGT 1929, WUNDERLICH 1953, WREDE 1988, FRANZKE & SCHMIDT 1995).

Detailed mapping, compilation of borehole data and outcrop stratigraphy allow us to review the development of the Harznordrand Thrust and related Late Cretaceous unconformities. The aim of this paper is to summarise and compare all available data concerning the unconformities of the Subhercynian Cretaceous Basin and to develop a coherent model of the tectono-sedimentary evolution of that area.

GEOLOGICAL SETTING OF THE SUBHERCYNIAN CRETACEOUS BASIN

Basin structure

The Subhercynian Cretaceous Basin (Text-fig. 1) is about 90 km long and in its present shape only 15 km wide. It represents a narrow, NW-SE striking graben-like structure within the Niedersachsen Basin (KOCKEL 1996). Several changes in the tectonic style, related to the onset of rift basin formation at the eastern margin of the Atlantic Ocean and convergence of the alpine orogenic belt at the northern margin of the Tethys, caused a very complex basin history (ZIEGLER 1990, BALDSCHUHN & *al.* 1991). After a long-lasting period of extension, the Niedersachsen Basin was affected by crustal shortening during the Late Cretaceous and the earliest Tertiary (e.g. KOSSOW & KRAWCZYK 2002). Both extension and compression were strongly influenced by the presence of thick Upper Permian salt deposits, which formed a decollement horizon between the basement (which was deformed during the Carboniferous) and the thick Mesozoic sedimentary cover (e.g. KOCKEL & *al.* 1996) The presence of thin Triassic evaporites caused a layering of competent and incompetent strata which supported folding and shearing along bedding planes during deformation. Intrusion of Upper Permian salt into Upper Buntsandstein evaporites caused decoupling of the Lower and Middle Buntsandstein (BALDSCHUHN & *al.* 1991). Diapirs and salt-injected anticlines were active in different stages of the tectonic development (STACKEBRANDT & FRANZKE 1989, SCHECK & *al.* 2003). The most pronounced changes of the basin structure and the strongest deformation occurred during a short period during the Late Cretaceous (VOIGT 1963, STACKEBRANDT & FRANZKE 1989).

To the south, the basin is bounded by the Harznordrand Fault, which is one of the major fault zones in Central Europe and has a vertical displacement of at least 4, and according to fission track data even 7-10 km (THOMSEN & *al.* 1997). This fault is only a part of a broader zone of significant crustal shortening at the southern margin of the Niedersachsen Basin (KOCKEL 1996). The Harznordrand Fault is a reverse fault which dips 45-60° SSW based on data from the Schöth 1 Borehole, which recovered Lower Buntsandstein below Devonian base-

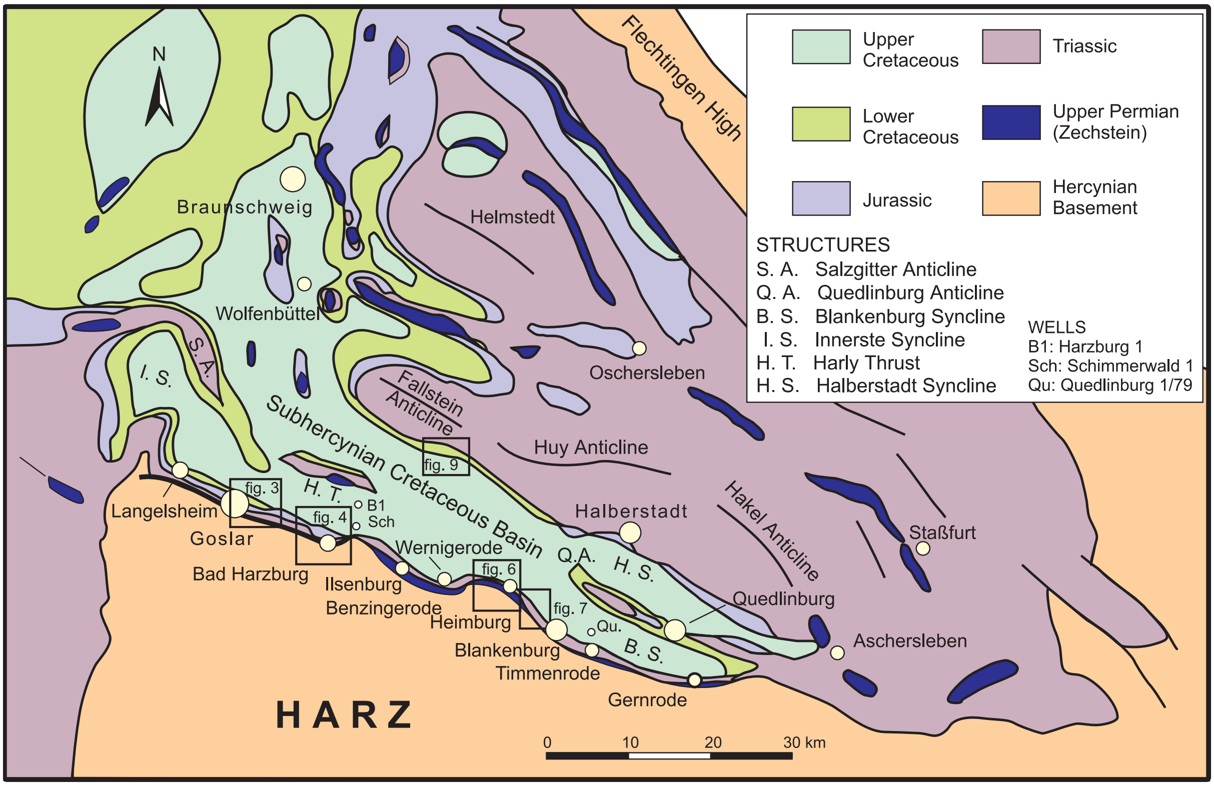

Fig. 1. The Harz Massif and the Subhercynian Cretaceous Basin with main localities mentioned in the text. The locations of detailed maps are indicated by black boxes

ment more than 2 km south of the surface outcrop of the fault (FRANZKE & SCHMIDT 1995). At the southern basin margin, the basin fill and the 1000-2000 m thick Mesozoic succession below the Cretaceous deposits was tilted and partly overthrust by Devonian to Lower Carboniferous sediments deformed during the Variscan Orogeny and Upper Carboniferous intrusions which form the basement in the whole of Central Europe.

At the north-eastern basin margin, three large anticlines (Fallstein, Huy, and Hakel), form the boundary of the basin, while to the northwest a gradual transition to the Niedersachsen Basin can be observed (e.g. KOCKEL 1996).

The internal structure of the Subhercynian Cretaceous Basin (Text-fig. 1) is complicated by the south-directed Harly Thrust (H.T.), the Westerhausen Thrust (W.T.) at the southern flank of the Quedlinburg Anticline (Q.A.), and the complex Salzgitter Anticline (S.A.), which runs mainly in a N-S direction (JUBITZ 1957, KOCKEL 1996). The elongated Halberstadt Syncline (H.S.) and Blankenburg Syncline (B.S.), separated by the narrow Quedlinburg Anticline (Q.A.), modify the eastern part of the basin. The Salzgitter Anticline separates the Innerste Syncline (I.S.) in the west from the Wernigerode Syncline (W.S.) within the central part of the basin in the east.

Depositional style of the basin fill

The Cretaceous history of the Subhercynian Cretaceous Basin is characterised by a long-lasting period of thermal subsidence from the Albian until the Turonian, followed by rapid tectonically induced subsidence from the Turonian to the Campanian (KÖLBEL 1944, VOIGT 1963, BALDSCHUHN & *al*. 1991) which occurred contemperaneously with the uplift of the southern basin margin (VOIGT 1963).

The onset of basin development is not easy to define precisely due to a limited database concerning the Cenomanian to Coniacian stratigraphy in the deeper parts of the basin. Whilst VOIGT (1931) believed that the basin was initiated at the Albian-Cenomanian boundary, strong variations of facies and thickness of the Upper Turonian and Lower Coniacian (KÖLBEL 1944, KARPE 1973, ERNST & WOOD 1995) indicate that the initiation of differential subsidence started later in the Turonian. Although Early Cretaceous and Cenomanian deposits are present at the base of the basin-fill, the distribution and thickness of these deposits show no relationship to the later NW-SE striking basin structure (WILMSEN 2003).

The syntectonic basin-fill (Turonian to Campanian) starts with pelagic limestones which become progressively replaced by terrigenous deposits, which were nearly completely deposited in a shallow marine environment (TRÖGER 1995). The greatest thicknesses occur at the southern basin-margin, where a maximum 2000 m of marine sediments (only Coniacian and Santonian) were cored (ROLL 1953, WUNDERLICH 1953). According to stratigraphical and seismic data, the thickness of Late Cretaceous deposits might even exceed 3000 m in the central part of the basin (KOCKEL 1996). Only a few boreholes (Harzburg B1, Schimmerwald 1, Quedlinburg Hy1/79, for location see Text-fig. 1) were investigated in detail in this part of the succession. Due to different definitions of the stage boundaries (for review see TRÖGER 2000 and NIEBUHR 2000) and the monotonous marlstones which contain only few fossils, correlation of these sections is difficult. Using the inoceramid stratigraphy of SEITZ (1965) and TRÖGER (2000), correlation can be made between the Harzburg 1, Schimmerwald 1, and Quedlinburg Hy1/79 boreholes and some formerly existing surface outcrops. The boreholes are situated near the subsidence axis of the Subhercynian Cretaceous Basin and are characterised by surprisingly thick and complete marl successions. All biozones of the Coniacian and Santonian were recognized in the western part (see ROLL 1953 for Schimmerwald 1 and Harzburg B1), and in the Quedlinburg Hy 1/79 (TRÖGER, pers. comm., hitherto unpublished).

Facies distribution during the Turonian and Coniacian is characterised by a coarsening-upward sequence starting with hemipelagic limestones, passing first into marls and then followed by marine sandstones which were shed from the northeast (e.g. SCHRÖDER & BÖHM 1909, VOIGT 1929, TRÖGER 1995). Progradation of these sandstones did not reach the southwestern part of the basin.

During the Santonian, the east-west facies trend is even clearer, as is reflected by a complete facies profile starting from coastal plain facies with rootlet beds, thin coal seams and tidal flat deposits, followed by an extended belt of cross-bedded shallow marine sandstones. These tidally transported sandstones pass first into fine-grained bioturbated sandstones and are finally replaced by bioturbated marls of the offshore facies (TRÖGER 1995). It must be emphasised that the position of the Coniacian and Santonian facies belts does not correspond to the recent borders of the Subhercynian Cretaceous Basin or to the WNW-ESE striking zone of maximum subsidence.

Starting with the Santonian, a second source area is indicated by the occurrence of conglomerates of Jurassic limestones and Triassic rocks (Muschelkalk limestones and sandstones of the Buntsandstein) at the southern basin margin (e.g. SCHROEDER, 1927). Facies distribution of the Campanian is characterised by calcareous lithic sandstones at the southern basin margin, which pass into sponge-rich marls and bioclastic carbonates to the north. Large clasts of Lower Carboniferous greywackes and cherts in Lower Campanian deposits immediately north of the thrust prove the exhumation of the basement south of the Harznordrand Thrust.

UNCONFORMITIES IN THE SUBHERCYNIAN CRETACEOUS BASIN

The most striking evidence for tectonic processes in Central Europe during the Late Cretaceous is given by angular unconformities developed at the southern margin of the Niedersachsen Basin. Most of them were observed north of the Harznordrand Thrust, where an upturned and well exposed Mesozoic succession is overlain by Cretaceous deposits which were partly also affected by later rotation (e.g. VOIGT 1929).

The Santonian to Campanian succession, in particular, is characterised by several strongly developed unconformities. At the southern basin margin, several hundred metres of sediments were eroded. The Santonian to Campanian marine deposits cover erosion surfaces which cut down to Triassic and Permian units. The unconformities disappear towards the basin axis. Deposits spanning the Coniacian-Santonian transition (marls with *Magadiceramus subquadratus* and *Cladoceramus undulatoplicatus*) are extremely rare and are known solely from the boreholes mentioned above and from some surface outcrops near Goslar (MORTIMORE & *al.* 1998). At the northern basin margin, erosion removed Santonian and Campanian deposits, but on the flank of the Fallstein Anticline an unconformity between Upper Turonian limestones and marly sandstones of the Lower Campanian was observed (BEHREND 1929).

Later, condensed sections and hiatuses were found in the Turonian and Coniacian at the north-eastern basin margin (VOIGT 1929, KARPE 1973, TRÖGER 1998, MORTIMORE & *al.* 1998). Reworked Albian to Turonian rocks in adjacent Coniacian sections point to uplift and erosion in this area.

Some of these unconformities were already described before the beginning of the last century (EWALD 1862), and attributed to the uplift and tilting of the southern basin margin (VOIGT 1929, SCHROEDER 1909, CLOOS 1917). Later they were believed to be the expression of regional and even global tectonic phases (STILLE 1924), all grouped together into the "Subhercynian tectonic period" (MORTIMORE & *al.* 1998). In the following part, the distribution and expression of all known unconformities within the Subhercynian Cretaceous Basin will be described in detail.

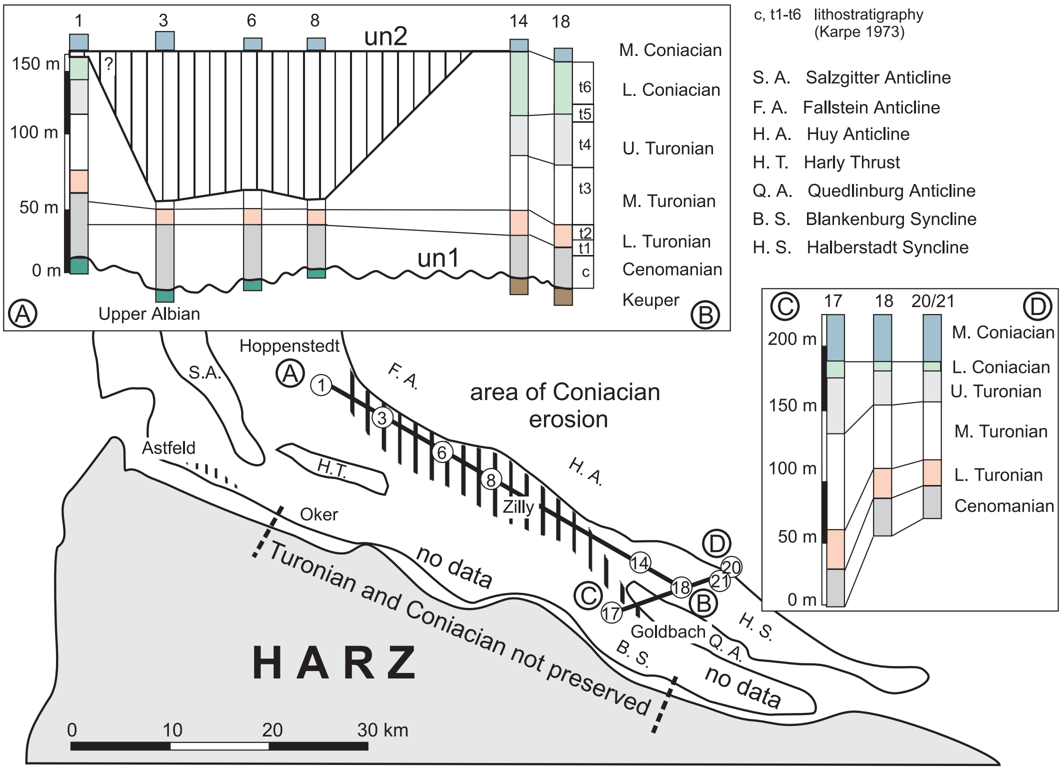

Fig. 2. Unconformity 1 at the base of the Cenomanian transgression is of regional distribution in the whole Subhercynian Cretaceous Basin. Unconformity 2 is developed within the Lower Coniacian and limited to the northern margin of the Subhercynian Cretaceous Basin. According to log correlation of boreholes by KARPE (1973), about 80 m of Turonian deposits were removed before deposition of Middle Coniacian *koeneni* Marls. Evidence for a hiatus at the southern basin margin in the same position was given by MORTIMORE & *al.* 1998 and TRÖGER 1999. Increasing thickness of Turonian and Lower Coniacian deposits to the south indicate tilting of the basin floor starting during the Early Turonian. Numbers of boreholes and thicknesses refer to KARPE 1973; biostratigraphic correlation was modified according to WIESE & *al.* 2000, KAPLAN 2000 and NIEBUHR & *al.* 2001)

Unconformity 1 (Base Cenomanian)

The first, almost basin-wide unconformity is developed at the base of the Cenomanian. While the Cenomanian rests with only a small hiatus on Late Albian deposits in the western part of the basin (ERNST & *al*. 1983, NIEBUHR & *al*. 2001), the extent of the hiatus increases to the east, reflected by the rapidly decreasing thicknesses of Albian deposits, which are not preserved east of a line marked by Oker and the southeastern margin of the Fallstein Anticline. East of this area, the base of the Cenomanian rests mostly on Late Triassic claystones (Middle Keuper). This general pattern is complicated by several N-S striking structures, filled with Upper Keuper sandstones and Lower Jurassic claystones, which were formed in a period between the Early Jurassic and the Cenomanian (HEIMLICH 1956). The most prominent pre-Cenomanian structure is a NW-SE striking graben limited to the recent Quedlinburg Anticline (KOCKEL 1996) and preserving Hauterivian and Barremian deposits. Although the hiatus between the Upper Triassic and Cenomanian spans a period of 135 Ma, the angle of unconformities is much less than 1° and can be observed only at a regional scale. Due to the significance of the Cenomanian transgression throughout the Subhercynian Cretaceous Basin, it is referred to as unconformity 1 in this paper (Text-fig. 2).

Unconformity 2 (Middle Coniacian)

Following the Cenomanian transgression, sedimentation in the Subhercynian Cretaceous Basin continued until the Late Turonian. Minor condensation and stratigraphic gaps occurred during the Middle and Upper Turonian and were attributed to eustatic sea-level changes (WIESE & KRÖGER 1998). Synsedimentary tectonism during the Turonian is indicated by slumps, reworked clasts (NIEBUHR & *al*. 2001) and strongly varying thicknesses (KÖLBEL 1944, KARPE 1973). The thickness maps of KARPE (1973) and KÖLBEL (1944) display a distinct trend, reflecting a subsidence axis in front of the later Harznordrand Thrust (Text-fig. 2). The increase in thickness affected possibly all Turonian units, but certainly started from the Middle Turonian. The amount of additional thickness is in the order of 50 m in the section C-D shown in Text-fig. 2.

Along the strike of the Subhercynian Cretaceous Basin the thickness of the Turonian remains more or less constant (Text-fig. 2), as was shown by KARPE (1973). Only at the northeastern margin of the central Subhercynian Cretaceous Basin is the succession incomplete. As pointed out already by VOIGT (1929), a significant hiatus is developed at the southern margin of the Quedlinburg Anticline (Goldbach section near Langenstein), where the Middle Coniacian marls rest presumably on the Upper Turonian hardground followed by a strongly condensed succession. The number of the stratigraphic gaps was discussed again by TRÖGER & ULBRICH 1970 and MORTIMORE & *al*. 1998. For a summary of the stratigraphy of this section see MORTIMORE & *al*. 1998. Unfortunately, the section is in a very bad condition and revision of the biostratigraphy is no longer possible. A similar situation was observed by KÖLBEL and SEITZ (in KÖLBEL 1944) north of Zilly, 15 km northwest of the Goldbach section, where surface outcrops and boreholes proved rapid thinning and sharp contact of Coniacian Emscher Marls to Upper Turonian limestones.

Careful well-log correlations (self potential, resistivity log), calibrated with index fossils in cored boreholes, were carried out by KARPE (1973) who investigated the distribution of this hiatus. He was able to differentiate between 6 litho-units (t1 to t6), comprising the uppermost Cenomanian from the "Facies Change" (lower part of t1), the whole Turonian (upper part of t1 to lower part of t5), Lower Coniacian, including the "Grauweisse Wechselfolge", the "Upper Limestone Unit" and the "Transitional Unit" sensu NIEBUHR & *al*. 2001 (upper part of t5 and t6) and possibly the Middle Coniacian (t6?). The biostratigraphy, sedimentary succession and (to a minor degree) the resistivity log pattern correlate with the intensively investigated successions of the adjoining Salzgitter area (NIEBUHR & *al*. 2001). Although the calibration is a little bit crude, especially in the Coniacian, there is clear evidence for deep erosion in an area between the southeastern margin of the Fallstein Anticline and the southwestern Quedlinburg Anticline. Surprisingly, this stratigraphic gap disappears to the northeast (Halberstadt Syncline).

In Text-fig. 2, a map of the unconformity (un2) and two cross-sections are shown. The successions of the Halberstadt Syncline and the Blankenburg Syncline seem to be almost complete on the basis of the rich inoceramid assemblages found in the boreholes (KARPE 1973). Even deposits containing *Mytiloides scupini*, a unit that was found to fall often into a sequence boundary in major parts of the Niedersachsen Basin and elsewhere in Europe (WIESE & KRÖGER 1998), were proved by TRÖGER (1999) near Hoppenstedt. Lower Coniacian inoceramid assemblages (*Cremnoceramus waltersdorfensis*, *Cremnoceramus rotundatus* [*Cremnoceramus deformis erectus*], *Cremnoceramus deformis*) are characteristic of the succession (upper part of the "Grauweisse Wechselfolge" and "Upper Limestone Unit") in both the Halberstadt Syncline and the central Blankenburg Syncline (KARPE 1973), indicating a complete succession across the Turonian-Coniacian transition. This changes to the north, where Emscher Marls rest directly on the Middle Turonian limestones along the southwestern flank of the Fallstein Anticline and the western margin of the Huy Anticline. The Emscher Marls are poorly fossiliferous and no index fossils were found in the boreholes investigated by KARPE (1973), but yielded the Middle Coniacian index *Volviceramus koeneni* some metres above the contact in a borehole near Zilly (KÖLBEL 1944) and in the outcrops near Langenstein (SCHROEDER 1927). Most of the Middle Turonian, the whole Upper Turonian and probably the lower part of the Lower Coniacian were eroded before deposition of the Emscher marls. In this context, the occurrence of sandy event-beds in the higher Lower Coniacian, following a complete basal Coniacian succession north of the Harly Thrust (road section near Vienenburg, ERNST & *al*. 1997), must be reinterpreted, as assumed already by MORTIMORE & *al*. (1998). The pebble composition (phosphorites, Cenomanian and Turonian limestone clasts) and the high maturity of the terrigenous material (as in the Coniacian sandstones to the northeast) indicate transport from the adjoining area north of the Harly (Fallstein Anticline), about 6 km distant.

The cored sections at the northern basin margin prove about 80 m of erosion, but reworked Cenomanian and Albian fossils in the Middle Coniacian of Zilly (VOIGT 1929) point to sustained removal of at least 150 m of Cretaceous deposits north of the recent margin during the Coniacian.

At the southern basin margin, a similar situation can only be presumed, because pre-Middle Santonian erosion removed all deposits younger than Early Cretaceous and obliterated a possible unconformity. MORTIMORE & *al*. (1998) mentioned a minor hiatus in a comparable stratigraphic position near Astfeld, which was observed in some discontinuous exposures (Text-fig. 2). This hiatus could be of only local extent, because a complete succession from the Turonian to the Upper Coniacian (including the Grauweisse Wechselfolge) was observed by SCHRÖDER (1927) and MORTIMORE & *al*. (1998) in the Petersberg and Paradiesgrund section near Goslar, which are closer to the Harznordrand Thrust. Considering the whole Coniacian, a strong thickness trend from north to the south is obvious: whereas the northeastern sections reach thicknesses up to 200 m (Halberstadt Syncline), the marls in the southern parts of the basin reflect progressively increasing thicknesses up to more than 700 m (Quedlinburg Hy 1/79 Borehole). There is no evidence for redeposited Cretaceous rocks in the thick Coniacian succession north of the Harznordrand Thrust, so it must be emphasised that the existence of an Early Coniacian unconformity at the southern basin margin remains unclear.

The existing biostratigraphic data (summarized in MORTIMORE & *al* 1998) and thickness data of KARPE (1973) indicate Early Coniacian erosion of older deposits at the northern basin margin accompanied by simultaneous southward tilting of the basin floor. The erosion surface is covered by undated Lower or Middle Coniacian marine sandy marls (MORTIMORE & *al*. 1998).

Unconformity 3 (Middle Santonian)

At the southwestern margin of the Subhercynian Cretaceous Basin, an upturned Mesozoic succession is exposed which shows a stratigraphic gap at the base of the Middle Santonian which increases from northwest to northeast. This is the most distinct angular unconformity of the Subhercynian Cretaceous Basin and is described as unconformity 3 in this paper.

Whereas near Langelsheim and Goslar the Turonian limestones are overlain by an almost complete succession from the Coniacian to the Santonian (except the incomplete sections mentioned above), sandy deposits of the Middle Santonian rest on an erosion surface that cuts down through most of the Coniacian north of Oker (Text-fig. 3). Unfortunately this area is poorly exposed, so that structural relationships and the amount of erosion are unknown (for detailed discussion see MORTIMORE & *al*. 1998). The deposits above the unconformity consist of sandy marlstones with intercalated conglomeratic quartz sandstones and contain a typical Middle Santonian fauna (*Actinocamax verus*, *Gonioteuthis westfalica*). This succession is called the Sudmerberg Formation (FRANK 1981). The conglomerates derived mainly from Jurassic limestones and to a minor degree also from Early Cretaceous sandstones.

A few kilometres to the southeast, at the Langenberg and Scharenberg, the erosion surface at the base of the Middle Santonian deposits cuts down to the Upper Jurassic, removing at least 300 m of older deposits (estimated from complete sections in the west and the northern basin parts). This unconformity is well exposed in some old quarries between Oker and Harzburg (Langenberg 2 and 3). The angle of unconformity can be determined to be of the order of 45°. The find of a *Gonioteuthis granulata* in the transgressive bioclastic deposits above the unconformity give evidence of the Upper Santonian. This is in contrast to published data (VOIGT 1929) pointing to Middle Santonian age. This difference can possibly be explained by occurrence of an only 4 m thick cover of overturned Middle Santonian deposits dipping with 60° to the south followed by a vertical succession of Upper Santonian sandstones. The contact between both units is not exposed and the occurrence of an additional unconformity remains open.

Unconformity 3 can be traced along the Butterberg west of Bad Harzburg, cutting down progressively to the Lower Jurassic (Text-fig. 3). Both at the Butterberg section and at the Scharenberg a Middle Santonian age of the overlying sequence is proven by the occurrence of *Gonioteuthis westfalica* (VOIGT 1929).

At the western edge of the Schimmerwald Sporn (marked by the Uhlenköpfe in Text-fig. 3), where Palaeozoic rocks of the Harz are displaced to the northeast,

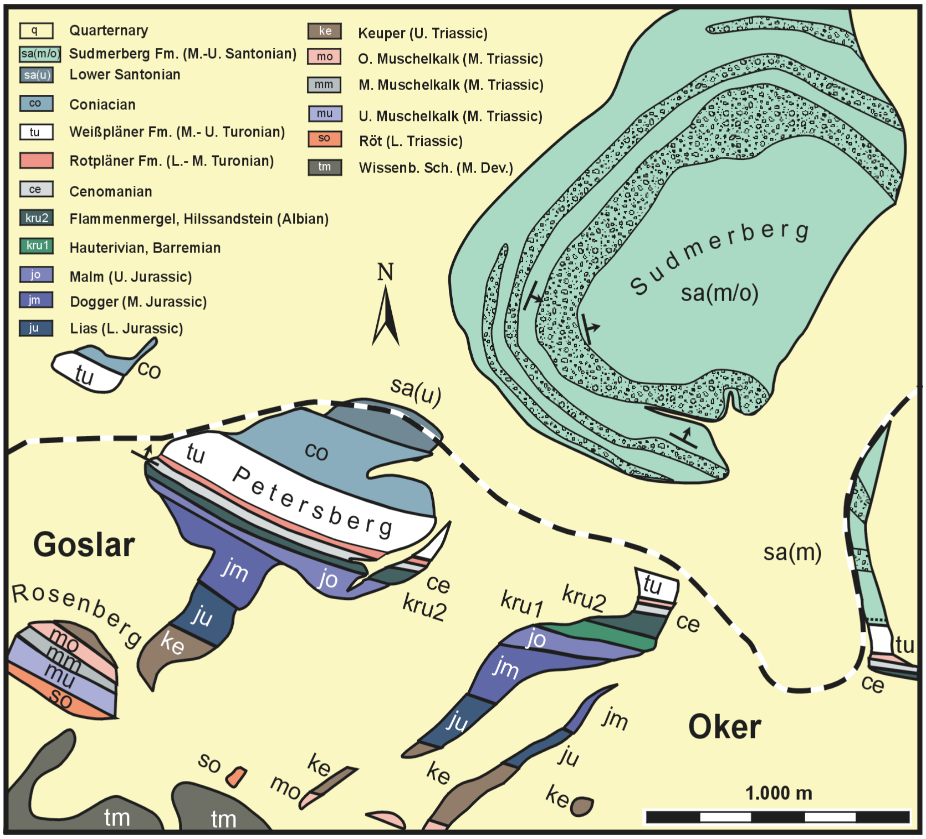

Fig. 3. The poorly exposed sections near Goslar display the change from the complete and undisturbed succession of the Cenomanian to Santonian in the west to the unconformable succession to the southeast. While the succession between Petersberg and Sudmerberg seems to be almost complete as is indicated by Upper Coniacian and Lower Santonian index fossils reported by SCHROEDER 1913, Middle Santonian sandy marlstones and conglomeratic sandstones resting on Upper Turonian limestones north of Oker point to erosion before the deposition of the Middle Santonian. Sandy marlstones and conglomeratic cross-bedded sandstones of the Sudmerberg Formation form a flat syncline at the Sudmerberg. Younger deposits are not preserved

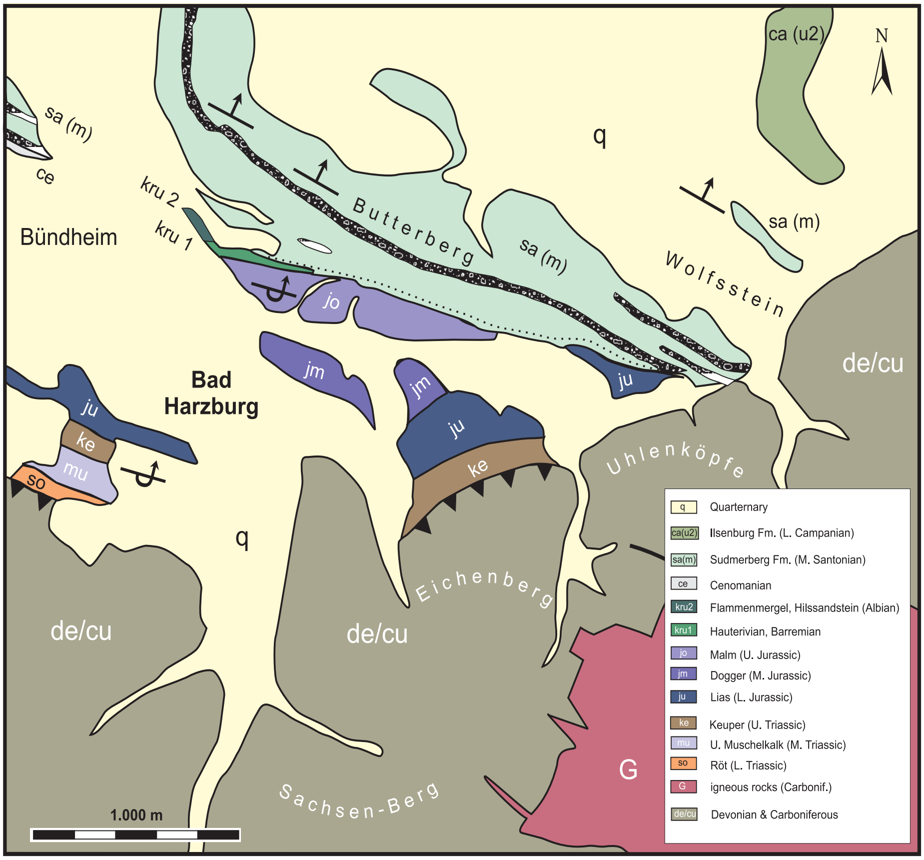

Fig. 4. The upturned Triassic to Cenomanian succession in front of the Harznordrand Thrust between Oker and Bad Harzburg is overlain by conglomeratic sandstones which contain a fauna of Middle Santonian age. The transgressive surface cuts down from the Cenomanian in the west to the Lower Jurassic in the east. While the Jurassic deposits below the transgressive surface are now in an overturned position, the steep northeast-dipping Sudmerberg Formation at the Butterberg and at the Wolfsstein is covered by marls and conglomerates of the Ilsenburg Formation dipping at10-20° northeast. To the east, at the foot of the Uhlenköpfe, the Palaeozoic is believed to be thrust even over the Middle Santonian Sudmerberg Formation

unconformity 3 disappears below younger deposits. The Santonian, which dips at 50-60° to the northeast, is covered by Lower Campanian deposits dipping at 10-20° to the north (Text-fig. 3). The borehole Bettingerode 1, drilled 1500 m north of the Butterberg, recovered 1800 m of marly Coniacian to Campanian deposits containing a rich inoceramid fauna indicating a complete succession, including Late Coniacian and Early Santonian species [*Sphenoceramus cardissoides* and *Cladoceramus undulatoplicatus* (KÖLBEL 1944)]. No unconformity was observed. KÖLBEL (1944) constructed a realistic model of the stratigraphic relationships which is displayed with few modifications in thickness and stratigraphic descriptions in Text-fig. 4.

In the central part of the Subhercynian Cretaceous Basin, thick Lower Campanian marls with intercalated conglomeratic sandstones cover almost the whole upturned succession along a distance of 22 km of the southern basin margin. Because of this cover, no data relating to unconformity 3 have been obtained to date.

In the eastern part of the Subhercynian Cretaceous Basin, unconformity 3 is not well exposed because Middle Santonian marls overlie soft claystones of the Middle Keuper. This part of the succession is almost covered by Quaternary deposits. In contrast to the spectacular outcrops of unconformity 3 in the western parts of the basin, this unconformity never attracted the same attention. Only SCHROEDER (1927, 1930) and KURZE & TRÖGER (1976) published data about this important structural feature.

In fact, the structural situation mirrors the pattern in the western part of the basin: Near Gernrode, a 250 m thick succession of Middle Coniacian sandstones grades upward into sandy marls of Santonian age. Although the occurrence of the Upper Coniacian and of the Lower Santonian is not proven due to the scarcity of index fossils, no noticeable hiatus in the sedimentary record can be recognized. Upper Coniacian and Lower Santonian inoceramids were recovered in the Quedlinburg Hy 1/79 Borehole (TRÖGER pers. comm.). This situation changes rapidly to the northwest. The top of the Coniacian succession is eroded progressively and overlain by the Middle Santonian Salzberg Formation containing a very rich inoceramid assemblage (TRÖGER & ULBRICH 1971) verifying both the *cordiformis* and the *pinniformis* zones in most of the sections. This unconformable succession was first observed at the Kucksgrund section near Timmenrode (SCHROEDER 1927) and can be traced to the railway-cutting northeast of Timmenrode, where it was described by the same author (SCHROEDER 1927). Thin conglomerates at the base of the fine-grained sandy marls of the Salzberg Formation contain mostly reworked Coniacian marlstones. The unconformity cuts down into Turonian (Cenomanian?) deposits a few kilometres to the west at the Jordan-Tal and the adjacent Sautrog section, where the situation was complicated by later thrusting (SCHROEDER 1930, KURZE & TRÖGER 1976). The composition of the conglomerates is characterised by micritic limestones of Cenomanian and

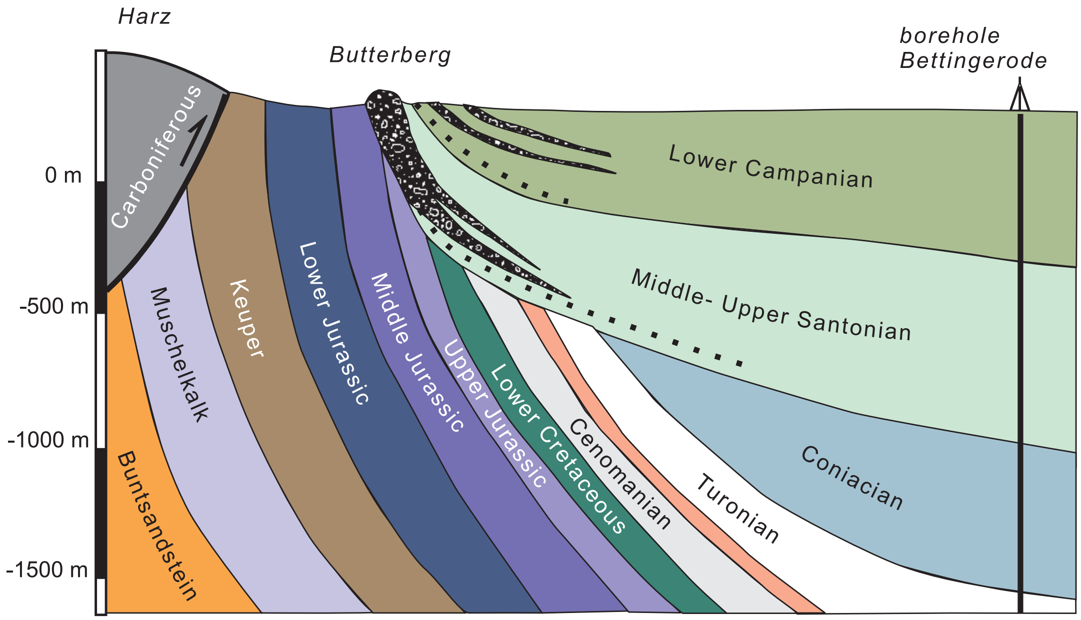

Fig. 5. Cross-section of the southwestern margin of the Subhercynian Cretaceous Basin east of Bad Harzburg. The upturned succession from Upper Permian (Zechstein) to Middle Jurassic is thrusted by Variscan basement. The first Late Cretaceous unconformity is underneath Middle Santonian quartz sandstones and was also upturned. Deposits of the Lower Campanian follow above a second unconformity to the north. Both unconformities disappear in basinward direction. The Bettingerode Borehole recovered nearly 2000 m of a continuous succession of Late Cretaceous sediments

Turonian age, but also fossiliferous limestones of the Muschelkalk (Middle Triassic) have been observed. The unconformity is covered by Lower Campanian sands and marls in the area of the town of Blankenburg, but five kilometres to the west, the upturned Permian to Santonian succession comes up again (Text-figs 5-6). Between the villages of Michaelstein and Heimburg, the Middle Santonian rests on the Upper Triassic (Middle Keuper). The whole Cretaceous succession from the Cenomanian to the Coniacian had been removed before. Like in the western part of the Harznordrand Fault, the succession was upturned to a vertical position or even overturned. The removed thickness below this unconformity can be estimated only imprecisely to be in the range of 300-1000 m due to an unknown original thickness of Coniacian deposits. The unconformity is poorly exposed at the Mönchemühlenteich near Oesig and in the valley of the Teufelsbach (Text-fig. 6). Due to the monotonous, fine-grained succession and significant ductile deformation, it is not easy to determine the angle of the unconformity, which fluctuates between 10 and 30°. Detailed investigations at the slope of the Teufelsbach valley showed that the basal Salzberg Formation is separated by a thrust fault from Lower Keuper claystones in this outcrop. In a road-cutting west of Heimburg, a strongly deformed section of the Cenomanian and probably the Lower Turonian can be observed. At the base of the Cenomanian, glauconitic sands with phosphorite concretions rest on a steeply dipping transgressive surface above red Middle Keuper claystones and represent unconformity 1 (Text-fig. 5). A similar isolated occurrence of Cenomanian deposits has been observed around the village of Benzingerode. The pelagic limestones of the Cenomanian and Turonian

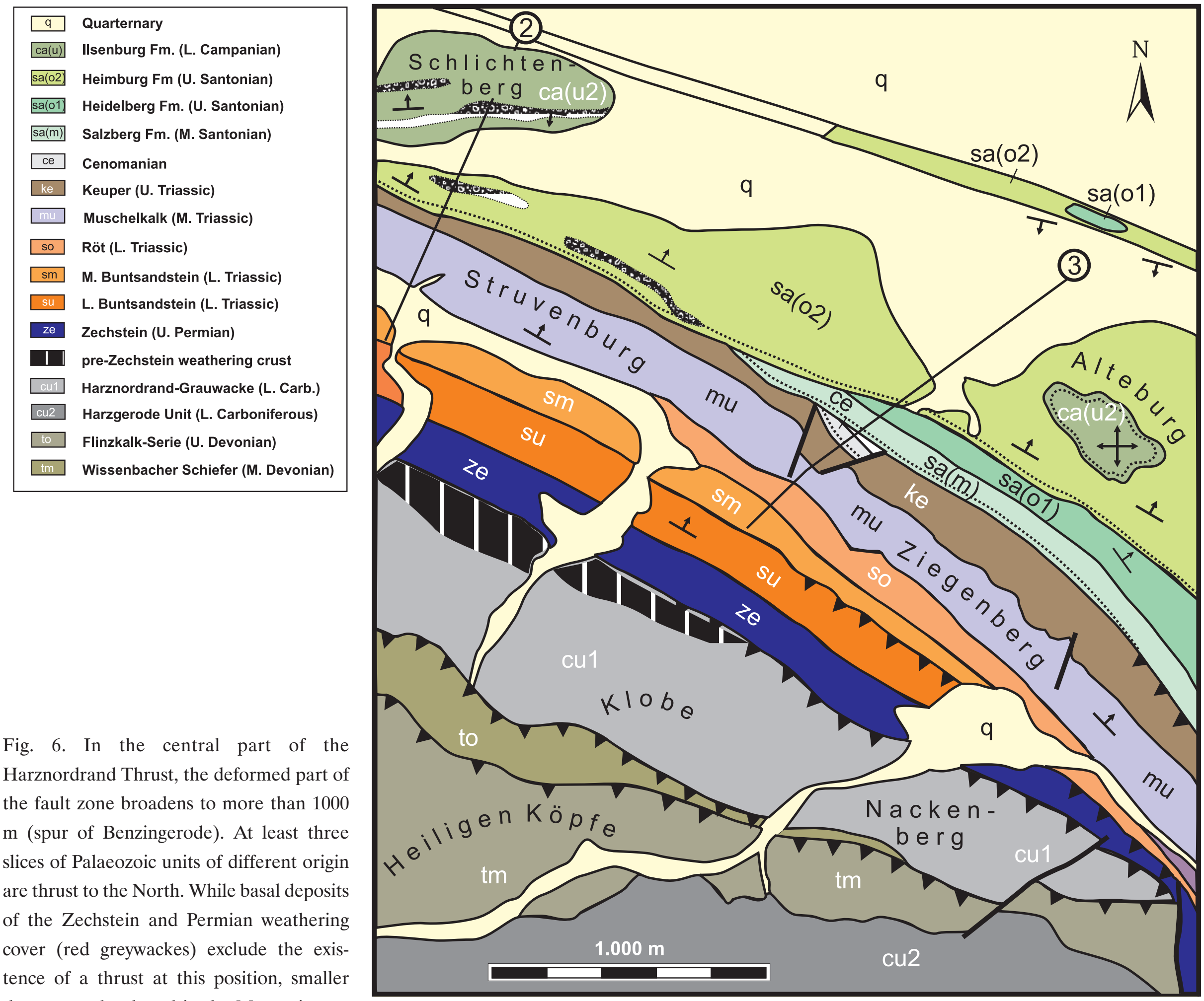

Fig. 6. In the central part of the Harznordrand Thrust, the deformed part of the fault zone broadens to more than 1000 m (spur of Benzingerode). At least three slices of Palaeozoic units of different origin are thrust to the North. While basal deposits of the Zechstein and Permian weathering cover (red greywackes) exclude the existence of a thrust at this position, smaller thrusts are developed in the Mesozoic succession to the southeast. Four Late Cretaceous unconformities were recognized in this small area: The basal Cenomanian unconformity is exposed at the Ziegenberg and only preserved in a pre-Santonian graben. At the base of the Salzberg Formation and at the base of the Heimburg Formation, two Santonian unconformities were mapped. The Lower Campanian Ilsenburg Formation rests unconformably on Triassic to Late Santonian deposits. In Text-figs 7 and 12, a suggestion for the development of these complicated structural relationships is given

were preserved in two small NE-SW striking graben structures which were formed before the Middle Santonian transgression. The basal conglomerate of the Middle Santonian Salzberg Formation contains both clay pebbles derived from the Middle Keuper and limestone clasts of the Cenomanian and Turonian (SCHROEDER 1927). On the northern slope of the Struvenburg hill, unconformity 3 disappears below a thin cover of the Upper Santonian Heimburg Formation, shown on Text-fig. 5.

Unconformity 4 (Upper Santonian)

The Upper Santonian of the Subhercynian Cretaceous Basin is represented by two formations. The Heidelberg Formation, which contains *Sphenoceramus pinniformis* and *Gonioteuthis granulata* in its lower part and *Sphenoceramus patootensiformis* and *Marsupites testudinarius* in the upper, comprises mainly marine sandstones which contain terrigenous claystone and sandstone horizons (rootlets, lateritic soils) in the eastern part of the basin and passes laterally into marls towards the west. Normally, this formation is overlain conformably by the Heimburg Formation (*Marsupites/granulata* Zone) which is composed of fine-grained sandstones with intercalated conglomerates and strongly cemented, calcareous, fossil-rich sandstones.

In a limited area west of Heimburg an unconformity (un4) can be mapped where vertical sandstones of the Heidelberg Formation disappear below a cover of Heimburg sandstones which dip at only 30° to the north. (Text-fig. 6). Unconformity 4 can be traced on the northern slope of the Struvenburg hill, where nearly the whole upper Triassic disappears below yellowish, calcareous sandstones containing Upper Santonian inoceramids (*Sphenoceramus patootensiformis*, TRÖGER pers. comm.). Thick conglomerate beds, intercalated in this succession, contain mainly limestones and dolomites of the Middle Triassic, but occasionally also red oolith-bearing sandstones, indicating the appearance of Lower Buntsandstein (Lower Triassic) above the erosion level in the adjoining source area. The unconformity un4 is traceable in a SE direction along the Harznordrand Thrust: North of the Mönchemühlenteich in the Goldbach valley, vertical, partly silicified sandstones of the Heidelberg formation are followed by calcareous sandstones with intercalated conglomerates (Heimburg Formation). The bedding planes in the few outcrops of the Heimburg Formation are nearly horizontal and indicate an unconformity. Due to missing outcrops in the critical position a conformable succession which flattens gradually cannot be excluded completely.

The structural relationships change rapidly; only 1000 m to the north, temporary exposures in a road-cutting showed a gradual transition and no difference in dip (Text-figs 5-6). Because the upper parts of the Heidelberg Formation contain the index fossil *Marsupites* (SCHROEDER 1927, VOIGT 1929) which also occurs frequently in the Heimburg Formation, VOIGT (1929) was able to place unconformity 4 within one biozone.

Unconformity 5 (basal Lower Campanian)

The Lower Campanian of the Subhercynian Cretaceous Basin is represented by two formations: The lowermost Campanian comprises the Blankenburg Formation, which contains a rich fauna with *Gonioteuthis granulataquadrata* (TRÖGER 2000). The Blankenburg Formation is of very limited areal extent (southern limb of the Blankenburg Syncline) but the same stratigraphic interval is represented by monotonous sandy marls in the centre of the basin (ULBRICH 1971). The higher Lower Campanian (*Offaster pilula* Zone) is represented by the Ilsenburg Formation, which fills the central part of the Wernigerode Syncline. Both the Blankenburg Formation and the Ilsenburg Formation rest with angular unconformities (un5 and un6) on overturned deposits (Zechstein to Upper Santonian).

A section near Blankenburg (Teufelsbachtal) shows marly, slightly glauconitic sands on overturned Upper Muschelkalk. A thin conglomerate sheet 1 m above the transgressive surface contains small limestone pebbles derived from the Lower Muschelkalk. A poor fauna (with the index fossil *Gonioteuthis granulataquadrata*) and the lithostratigraphical correlation prove an Early Campanian age of the deposits above the unconformity. Several thrusts developed along the bedding planes of the Triassic limestones and also affected the Campanian succession (CLOOS 1917). Like in the outcrops at the Langenberg, these deformation structures were formed during continuous rotation of the succession after deposition.

The Lower Campanian fine-grained sands can be traced along the slope of the Muschelkalk Probstberg hill. A second outcrop near the ponds of the Mönchemühle exposes a similar contact between the Lower Muschelkalk and the Blankenburg Formation. These sections have been repeatedly described (CLOOS 1917, VOIGT 1929, SCHROEDER 1909) and were chosen by STILLE (1924) to define the Wernigerode tectonic phase. The thin cover of Blankenburg Formation between Teufelsbachtal and Blankenburg is the relict of a 100-200 m thick succession preserved in a narrow, only 200 m wide NW-SE graben-like structure. To the southeast (town of Blankenburg), the whole succession from Lower Buntsandstein to Upper Santonian is covered by Lower Campanian deposits of the Blankenburg Formation (Text-fig. 6).

Unconformity 6 (higher Lower Campanian)

A similar basal unconformity is traceable at the base of the Ilsenburg Formation, which covers the upturned older succession in the central section of the thrust zone. This unconformity is referred to as unconformity 6. The Ilsenburg Formation consists of whitish sandy marlstones containing thick conglomeratic, partly cross-bedded sandstones. These clastic deposits are composed of quartz, feldspar and rounded fragments of calcareous red algae. A significant proportion of the clasts was derived from Carboniferous and Devonian rocks which are recently exposed in the adjacent mountains of the Harz. Cobbles up to 30 cm have been found in these sandstones, and indicate a strong gradient between source rocks and depositional area. All sections show that transgressive deposits of the *pilula* Zone form the base of the Ilsenburg deposits (ULBRICH 1971). The best exposures of the Ilsenburg Formation in the marginal facies are situated north of the village of Benzingerode, where sandstones and marls were quarried on the slopes of the Austberg and the Schlichtenberg (Text-fig. 6). Unconformity 6 covers

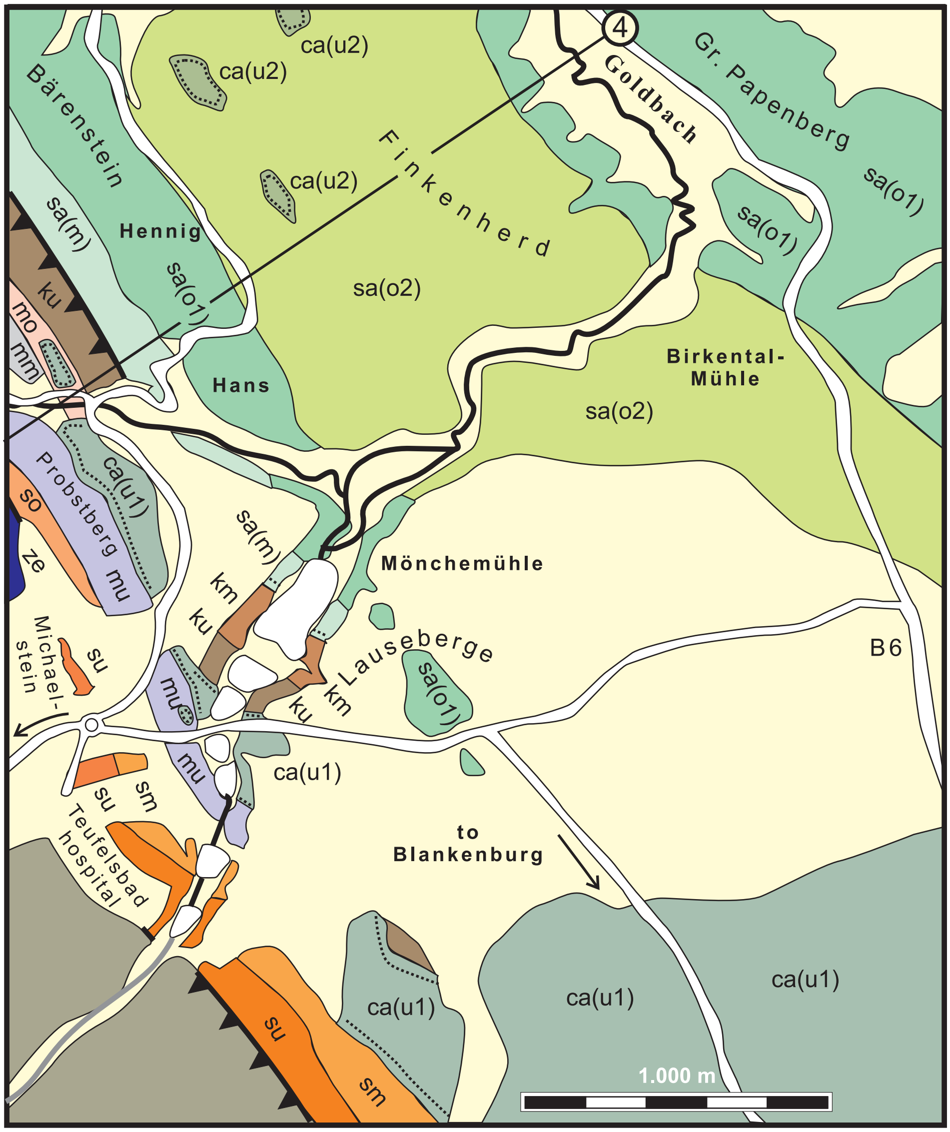

Fig. 7. The map of the Harznordrand fault at the southeastern edge of the Benzingerode Spur near Blankenburg shows that the generally WNW-ESE striking Harznordrand Fault turns into a NNW-SSE direction. This part is accompanied by additional thrusts which affected Middle Buntsandstein, Zechstein and the Middle Santonian. Three Cretaceous unconformities can be observed: The Middle Santonian Salzberg Formation overlies Upper Triassic. The nearly horizontal Lower Campanian Blankenburg Formation covers several Triassic units in a NW-SE striking graben and probably the whole succession (including the steeply-dipping Santonian) in the southern part of the map. Conglomeratic, bioclastic sandstones with Palaeozoic clasts belong to the higher Lower Campanian (Ilsenburg Formation) which covers the Upper Santonian Heimburg Formation in the centre of the Blankenburg Syncline

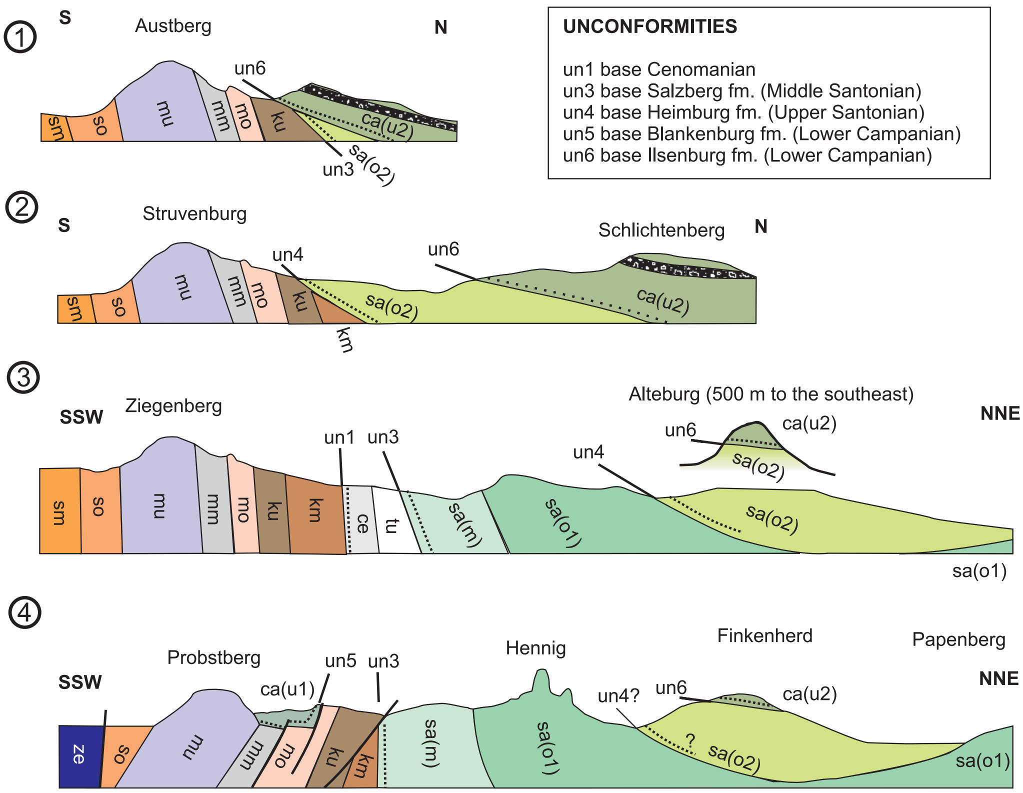

Fig. 8. Four cross-sections of the southern margin of the Subhercynian Cretaceous Basin between Benzingerode and Heimburg (Text-figs 6-7). The Triassic succession dips steeply to the north in the westernmost cross-section and becomes progressively overturned to the east. Five Cretaceous unconformities are developed on the northern slope of the Muschelkalk-hills. They show decreasing dip angles with decreasing age. Unconformity 5 at the base of Blankenburg Formation is preserved only in a NW-SE striking graben (northern slope of the Probstberg). Deposits of the Blankenburg Formation were eroded before formation of unconformity 6 (base Ilsenburg Formation) in the displayed area. They are widespread to the southeast (Blankenburg)

Upper Santonian deposits of the Heimburg Formation and Upper Triassic rocks in this area. West of Benzingerode, all of the Cretaceous disappears below the Campanian deposits. The unconformity cuts progressively down the stratigraphy, so that Ilsenburg Formation covers Lower Buntsandstein east of Wernigerode (Vossberg) and even the upturned Zechstein (exposed south of Ilsenburg and in the Ecker valley near Bad Harzburg). Although unconformity 6 is the last clear evidence for synsedimentary deformation in the Subhercynian Cretaceous Basin, the strongly varying orientation of bedding planes of the Ilsenburg Formation indicates later tectonic processes (Text-fig. 8).

The structural relationships at the base of the Ilsenburg Formation can be best observed between Blankenburg and Benzingerode, where older Cretaceous deposits disappear gradually below the Ilsenburg Formation (Text-figs 6-7).

The slope of the Altenburg hill, north of the village of Heimburg, exposes sandstones of the Upper Santonian Heimburg Formation dipping at 20°-25° to the northeast. The top of the hill is formed by typical black and white speckled sandstones and whitish marls of the Ilsenburg Formation. At the base of the succession, a conglomerate bed can be observed which consists exclusively of sandstone pebbles of the underlying Heimburg Formation. The angular unconformity was excavated by BOSSE & FREIBERG (1962) and described by TRÖGER & ULBRICH (1971), but is no longer exposed. The last remnants of the Ilsenburg Formation can be traced towards the southeast, where the hilltops of the Finkenherd are covered with conglomerates containing rock fragments of the slates and greywackes of the Hercynian basement (Text-fig. 7).

Text-fig. 8 shows four cross-sections related to the maps displayed in Text-figs 6-7. The cross-sections are orientated perpendicular to the Harznordrand Thrust and show the complex pattern of Cretaceous unconformities expressed in this area. The tendency of the unconformities to flatten, from the vertical position of unconformity 1 to the nearly flat unconformity 6, is clearly seen.

At the northern basin margin, deposits of the Ilsenburg Formation overlie steeply dipping Upper Turonian (Text-fig. 9). On the slope of the Grauentalsberg, north of Zilly, calcareous glauconitic sandstones cover white micritic limestones. This locality was described by BEHREND (1929) and detailed mapping

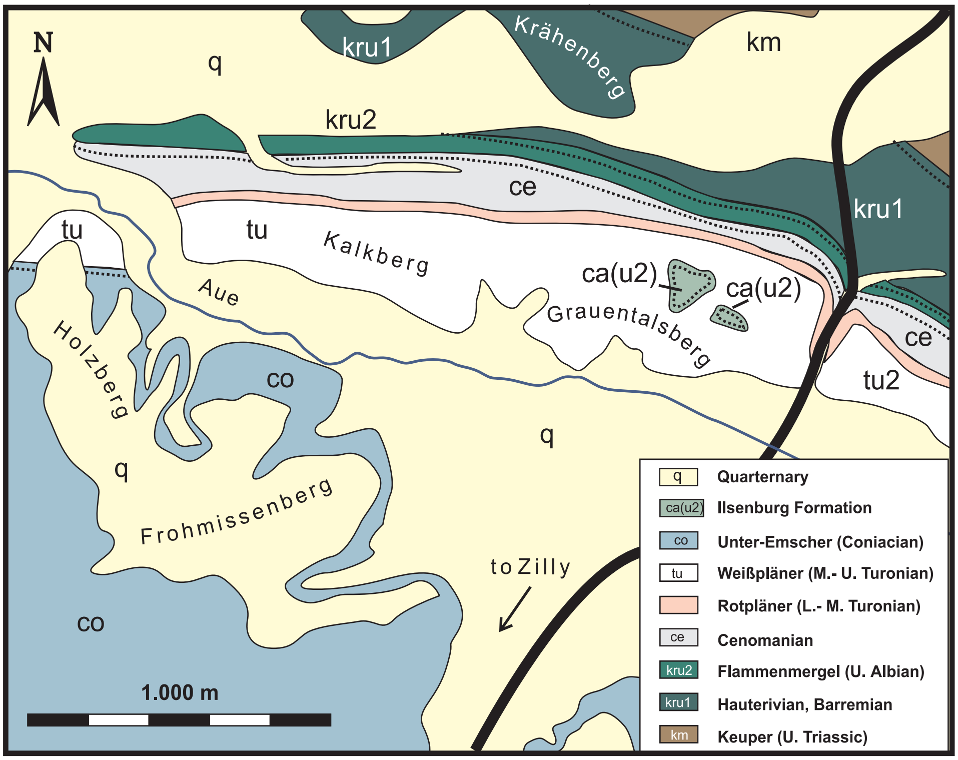

Fig. 9. The large Fallstein Anticline forms the recent northern margin of the Subhercynian Cretaceous Basin. Regional weak unconformities can be observed at the base of the Hauterivian, Albian and Cenomanian (un1). The stratigraphic gaps are not related to activity of the NW-SE striking Fallstein Anticline regarding to a general E-W facies- and thickness-trend of Cretaceous deposits. A significant hiatus leading to the erosion of about 80 m of Middle to Upper Turonian deposits can be observed at the base of the Lower Coniacian (un2) resulting from the uplift of the northern basin margin. Transgressive marlstones and fine-grained sandstones of the Ilsenburg Formation are preserved on the slope of the Grauentalsberg. These deposits, resting on steeply-dipping Upper Turonian, prove uplift and erosion between Santonian and Campanian, as at the southern basin margin.

has confirmed his results. The unconformity is not exposed, but a small excavation gave the opportunity to measure the dip of the covering sandy succession (6°/176). The underlying Turonian limestones dip at 30-42° in the same direction. The stratigraphic position of the sandy unit is not very clear, because only a small fragment of a belemnite was found (*Gonioteuthis* sp.). The sharp contrast between the glauconitic whitish sands and the dark-grey marls of the Santonian, which are exposed in a conformable position above the Coniacian 2 km to the south, allows a lithostratigraphic correlation with the Ilsenburg Formation.

RESULTS AND DISCUSSION

Dating and Geometry of Late Cretaceous unconfonformities

Biostratigraphy is essential for dating of unconformities. However, the lack of outcrops and index fossils in some parts of the succession makes unequivocal zonation difficult. Mortimore & *al* (1998) collected all the available biostratigraphic data from a vast amount of published und unpublished literature and discussed the dating of tectonic events in the Late Cretaceous of Western Europe. A modern overview of the biostratigraphy of the German Upper Cretaceous was published by the "Stratigraphische Kommission Deutschlands" (ed., 2000). We refer mostly to these publications and feel unable to discuss the detailed biostratigraphy of the sections in question, particularly as it is often based on data published at the beginning of the last century, which can no longer be proved.

Biozones of the Coniacian and Santonian in northern Germany span mostly not more than a few hundred thousand years. Thus, the Coniacian lasted 3.2 Ma and includes 9 biozones (Kaplan 2000), while the Santonian comprises 6 biozones and spans only 2.3 Ma (Ernst & Wood 2000). For that reason the precision of dating is high in comparison to over Cretaceous deposits, despite the fact that some deposits above the unconformities are not dated with the accuracy of one biozone. In some critical cases, especially concerning the intra-Upper Santonian unconformity, the age of tilting, erosion and renewed deposition was determined extremely precisely, as is shown by the occurrence of the same index fossils below and above the unconformity.

In the Subhercynian Cretaceous Basin, six syndepositional unconformities were recognised. While the base-Cenomanian unconformity reflects a transgression over a large peneplain that underwent a long-lasting tectonic history and 30-45 Ma erosion, the five other unconformities reflect a short period of synsedimentary tectonic activity. Unconformity 2 near the base of the Middle Coniacian is known only from the northern margin of the basin and reflects, together with the observed thickness trend, the tilting of the basin floor to the south. The situation near Astfeld at the northwestern margin of the Harz, provides evidence that this unconformity could also have been expressed at the southern basin margin, but it was obliterated by deep erosion below unconformity 3 along the strike of the Harznordrand fault.

The formation of the following four unconformities spans the period from the Middle Santonian to Early Campanian. According to the global time scale of GRADSTEIN & OGG (1996) this period comprises not more than 3 Ma.

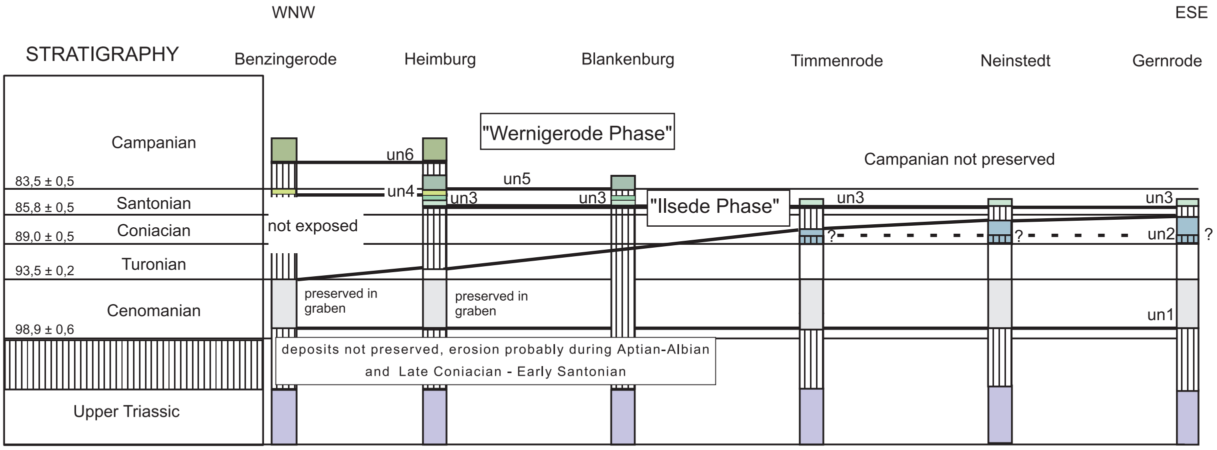

Fig. 10. Chronostratigraphic diagram of Late Cretaceous unconformities in the eastern part of the Subhercynian Cretaceous Basin. Jurassic and Early Cretaceous deposits are missing in the eastern part of the Harznordrand Thrust. Cenomanian deposition starts above Middle Keuper (Upper Triassic) after a regional hiatus. The unconformity below the Middle Santonian marlstones and conglomerates represents an angular unconformity (up to 10°). It cuts progressively into older deposits from east to west. The preservation of pelagic Cenomanian and Turonian in some graben-like structures and Coniacian marls near Blankenburg proves post-Coniacian tectonic activity. Possibly, a minor unconformity exists near the base of the Coniacian, because there is no evidence of Early Coniacian index fossils in the sections.

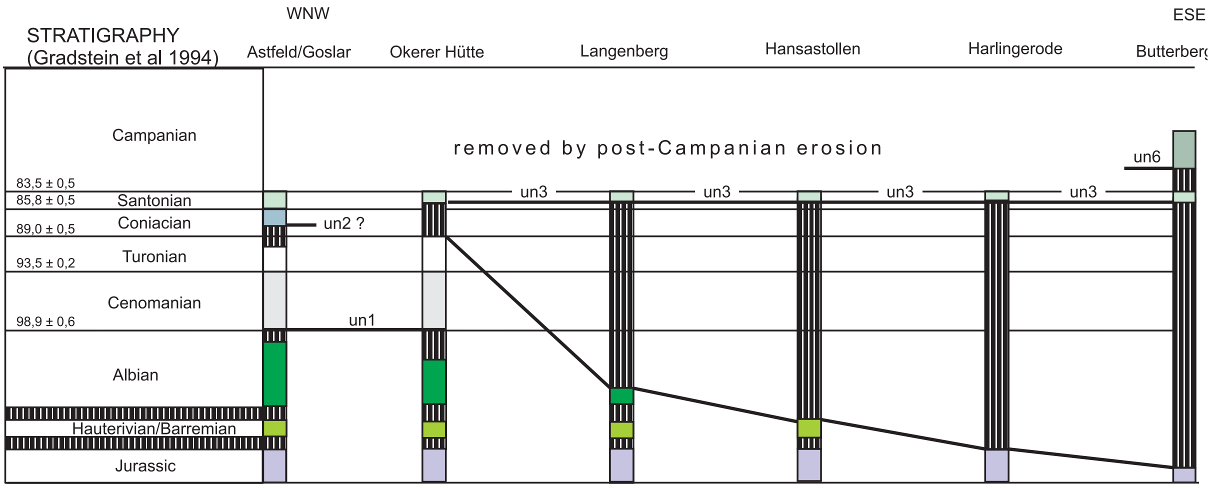

Fig. 11. Chronostratigraphic diagram of Jurassic to Late Cretaceous unconformities in the western part of the Subhercynian Cretaceous Basin. While the stratigraphic gaps from Upper Jurassic to Coniacian are of regional extent and were caused mainly by low sea level or regional uplift, the Middle Santonian transgressive surface cuts deeply into older deposits. The basal conglomeratic sandstones of the Santonian were deposited above an angular unconformity which grows from west to east (maximum 30°). The preservation of Cenomanian to Coniacian pelagic limestones and marls in the west indicates a Late Coniacian to Early Santonian age of tectonic movements.

The Middle Santonian unconformity (un3) was first recognised in the western part of the basin and correlated with the section at Gross-Ilsede in Lower Saxony, where Middle Santonian iron-ores rest unconformably on steeply dipping Albian claystones (RIEDEL 1938, ERNST 1968). At that locality, the "Ilsede phase" was defined (STILLE 1924), although the tilting had occurred sometime in the long period between the Albian and Middle Santonian (15 Ma). The chosen area is, therefore, not suitable to define a deformation event and a lot of confusion was caused by this decision. A summary and detailed discussion of the resulting problems was given by MORTIMORE & *al* (1998).

The timing of tilting both of the successions at the anticlines and the Harznordrand Thrust can be defined much more closely if the surrounding sections are taken into consideration. Cross-sections based on borehole data obtained by oil companies in the last century (BETTENSTAEDT & DIETZ 1957, BALDSCHUHN & *al*. 1991) and outcrop studies (ERNST 1968, 1975) show clearly that at least the Turonian limestones are affected by the same deformation event like the Albian mudstones at Groß-Ilsede. The monotonous bioturbated marls of the Coniacian and Santonian ("Emscher-Mergel") normally lack any bedding planes so that hiatuses can only be recognized by detailed biostratigraphical investigations. Stratigraphic gaps between the Coniacian and Middle Santonian were reported by ERNST (1968) ("*undulatoplicatus* regression"). While the unconformity in the Middle Santonian marls which cover the erosion surface in the eastern part of the Subhercynian Cretaceous Basin is well defined by index fossils such as *Gonioteuthis westfalica*, *Hauericeras clypeale*, *Sphenoceramus pinniformis* and *Cordiceramus cordiformis* (ULBRICH 1971, TRÖGER 1995), dating of the conglomerates and sandstones in the western Subhercynian Cretaceous Basin is more questionable as it was emphasized by MORTIMORE & *al*. 1998 in view of a specimen of a Late Santonian *G. granulata* at Langenberg Quarry which was believed to be exclusively of Middle Santonian age. Nevertheless, if the determination of some *G. westfalica* specimen reported by SCHROEDER (1927) and VOIGT (1929) from the Butterberg and the Langenberg near the base of the transgressive surface (Text-fig. 4) is correct, the formation of the erosion surface can be unequivocally dated as pre-Middle Santonian.

To define the age of unconformity 3, two chronostratigraphic diagrams were drawn which cover the area in front of the Harznordrand Thrust between Benzingerode and Heimburg (Text-fig. 10) and between Astfeld and Bad

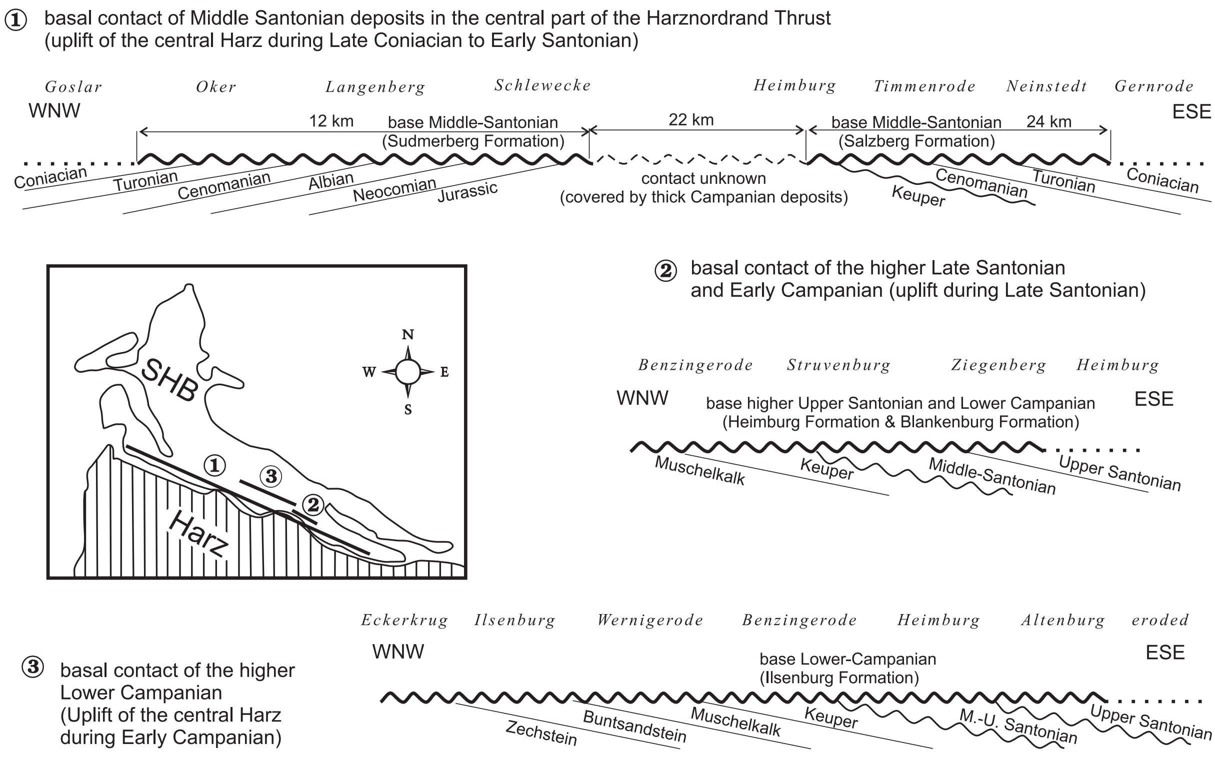

Fig. 12. Structural relationships of Late Cretaceous transgressive deposits at the southeastern border of the Subhercynian Cretaceous Basin: Continuous onlap on older deposits towards the central part of the Subhercynian Cretaceous Basin reflects nearly symmetric uplift, with the highest rates in the central section of the fault, and decreasing rates to the east and west, where the unconformities disappear. The different phases of uplift can be recognized better in the eastern part of the basin, because all deposits younger than Middle Santonian had been removed by later erosion in the western basin parts

Harzburg (Text-fig. 11). Both diagrams indicate an erosion event during the Late Coniacian and Early Santonian (< 1 Ma) which affected only the central part of the of the later thrust fault. There is no significant difference in age and only a minor difference in the amount of erosion in the eastern and western part of the basin. The growing hiatus towards the central segment of the thrust zone points to stronger uplift and even deeper erosion between Bad Harzburg and Benzingerode, where the unconformity is concealed by Campanian deposits (Text-fig. 12).

Rapid facies- and thickness-changes of the Coniacian in the Subhercynian Cretaceous Basin were interpreted to be the result of the same tectonic event that created the unconformities at the base of the Middle Santonian (MORTIMORE & *al*. 1998). However, the lack of evidence for an unconformity at the southern basin margin and the provenance of coarse-grained Middle Coniacian sediments from the northern basin margin even close to the Harznordrand Thrust (TRÖGER 1995) do not support this conclusion.

Unconformities 4-6 seem to be restricted to the eastern part of the Subhercynian Cretaceous Basin, leading to the often reiterated interpretation of VOIGT (1929), that the Middle Santonian unconformity ("Ilsede Phase") dominates in the west and the Lower Campanian unconformities ("Wernigerode Phase") reflect the major uplift in the east. VOIGT (1929) also emphasized a different structure of the fault zone east and west of the Schimmerwald Sporn (Text-fig. 4), but this is caused by the thick Campanian sediments covering the upturned Mesozoic succession in the central parts of the Subhercynian Cretaceous Basin.

Actually, there is also no reason to suppose a different development of the eastern thrust segment. We think that there are several reasons why the unconformities are obscured in the western segment. This part of the basin was strongly affected by Cenozoic erosion which removed all deposits younger than Santonian between Langelsheim and Bad Harzburg. Remains of Upper Santonian deposits occur only in a distance of at least 3 km north of the thrust, but all Santonian and Campanian unconformities disappear in a basinward direction (compare Text-figs 5 and 8), so that the probability of finding any trace of them is low in this position. Lastly, the sandy and conglomeratic, highly variable deposits in the eastern part of the basin allow easy recognition of unconformities, while the marly succession of the western basin is very homogeneous and mostly covered by Quaternary deposits. The following description deals, therefore, with the area between Blankenburg and Wernigerode, where five of the six unconformities are recognized.

Unconformity 4 at the base of the Heimburg Formation is of very limited extent and developed in the very short period of a single biozone (*Marsupites* Zone) of the Late Santonian. The maps displayed in Text-figs 6 and 7 cover the whole area where the unconformity is developed. The deposits of the Heimburg Formation cover a transgressive surface that cuts from Upper Santonian (Heidelberg Formation) down to the Upper Muschelkalk between Heimburg and Benzingerode (Text-fig. 12). A hiatus in the same stratigraphic interval, eventually connected with a weak unconformity was demonstrated by ERNST (1975) from a marl pit near Hannover-Misburg. He verified the indistinct hiatus by detailed biostratigraphic investigations and proved a gap in the evolution of the *Gonioteuthis*-lineage.

The area between Blankenburg and Bad Harzburg was chosen by STILLE (1924) to define the Wernigerode Phase, which is based on the unconformities developed north of the Harznordrand Thrust, and the appearance of conglomerates with Palaeozoic clasts within the Ilsenburg Formation. He dated the unconformities as forming during the Late Santonian. In fact, as emphasised by MORTIMORE & *al* (1998), two separate unconformities have to be distinguished, both dated as Early Campanian. Unconformity 5 is followed by a succession containing *Gonioteuthis granulataquadrata*, while the succession above unconformity 6 starts within the *Offaster pilula* Zone of the Lower Campanian.

Unconformity 5, at the base of the Blankenburg Formation, extends from the village of Wienrode near Blankenburg to the Teufelsbachtal near Heimburg. The generally flat-lying succession covers the whole upturned succession from the Buntsandstein to the Upper Santonian. Folds and thrusts within the Blankenburg Formation prove later deformation (JUBITZ 1957).

Unconformity 6, at the base of the Ilsenburg Formation, covers the central segment of the upturned Mesozoic succession between Heimburg and Bad Harzburg. It cuts down from the Upper Santonian to the Keuper over the short distance of 3 km between the Altenburg hill near Heimburg and the Austberg, west of Benzingerode. Near Wernigerode and Ilsenburg, Campanian deposits cover nearly the whole older succession, except for some hills consisting of Lower Buntsandstein and Lower Muschelkalk (Triassic). Between Ilsenburg and Bad Harzburg the deposits of the *pilula* transgression even rest on the Upper Permian (Zechstein). This pattern was interpreted as reflecting the sea bottom topography during the Campanian, including small islands and stacks (SCHROEDER 1927), but it is more likely that this distribution of the Campanian deposits was caused by strain partitioning during continuous rotation of the upturned succession, as was already pointed out by CLOOS (1917).

Formation of unconformities by thrusting

In the last century, an intensive discussion started about the tectonic structure and development of the

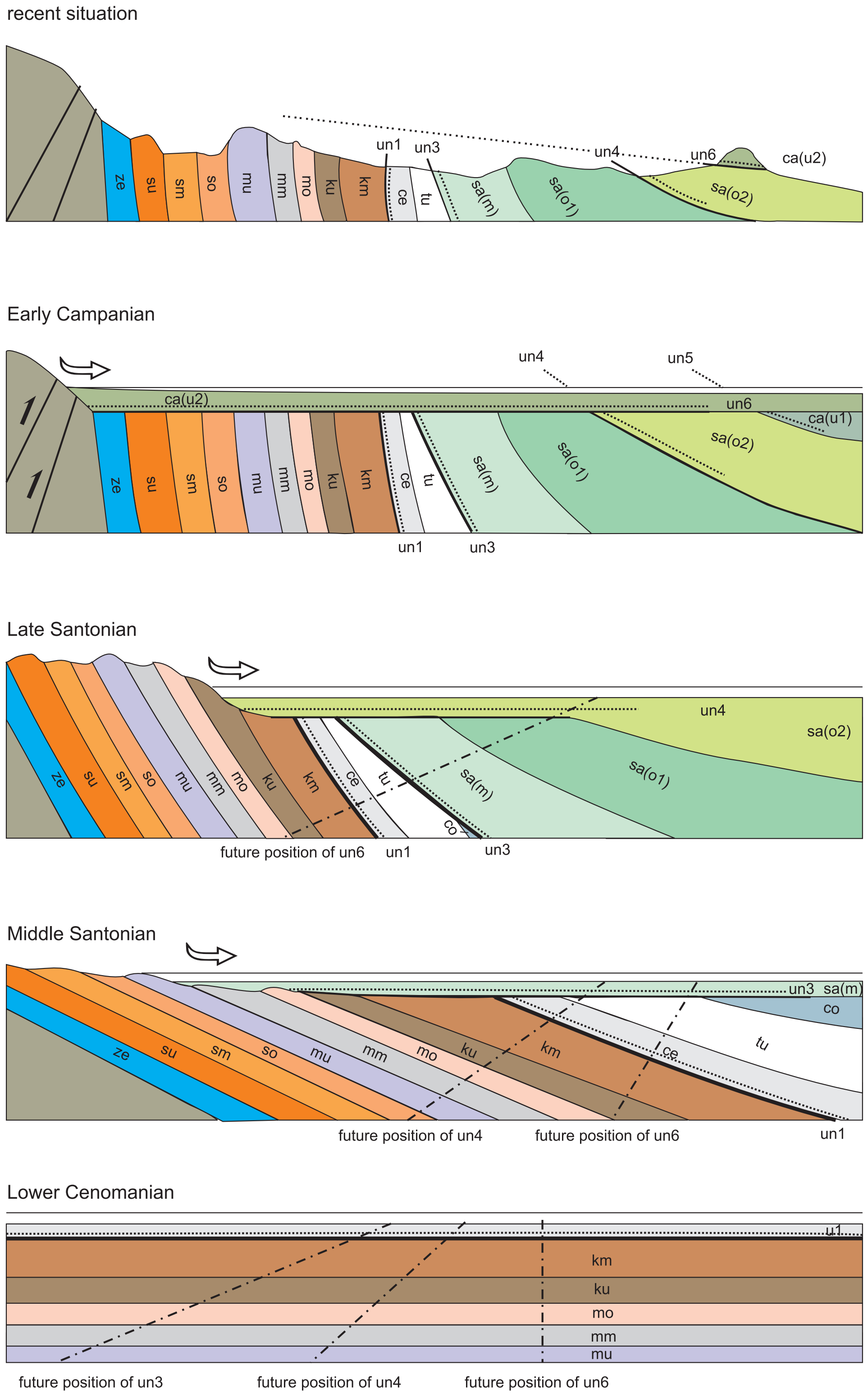

Fig. 13. Development of the southern margin of the Subhercynian Cretaceous Basin (Blankenburg area) during the Late Cretaceous. Progressive tilting of the succession started before the Middle Santonian and was nearly finished in the early Campanian. Transgressions during the Middle Santonian, Late Santonian and Early Campanian produced at least four unconformities, which disappear in basinward direction. For better orientation, the position of future unconformities is indicated. Unconformity 2 (Coniacian) and unconformity 5 (earliest Campanian) were not observed in this area. The figure is highly schematic because thrusts, backthrusts and shearing along the bedding planes accompanied rotation of the succession.

boundary of the Harz basement and the Subhercynian Cretaceous Basin (e.g. VOIGT 1929, WUNDERLICH 1953, VOIGT 1963, WREDE 1988, STACKEBRANDT & FRANZKE 1989). Different models were developed, which explain the Harznordrand Fault as a frontal basement thrust (STACKEBRANDT & FRANZKE 1989), a gravitational collapse structure (WUNDERLICH 1953) or a transpressional horst within a flower structure (WREDE 1988). A similar discussion was provoked about the timing of the Harz basement uplift. This problem was probably solved by fission track data provided by THOMSEN & *al.* (1997), which point to very rapid cooling of the basement and uplift of at least 5 km around 85 Ma.

To understand the causes of the Harz uplift, it is necessary to take both structural and sedimentary data into consideration. One of the main arguments to support or exclude different models is timing and spatial distribution of unconformities in front of active thrusts (e.g. BURBANK & REYNOLDS 1988, SUPPE & *al.* 1992).

Unconformities 3-6 are arranged in an area, striking northwest-southeast, in front of the recent thrust zone and disappear in basinward direction. The stratigraphical relationships display a progressive upturning (rotation) of older deposits in front of the recent thrust fault. Text-fig. 13 shows the development of the unconformity in front of the Harznordrand Thrust reconstructed from the slightly idealised cross-section of Text-fig. 8. The sequence was constructed by means of step-by-step rotation of the respectively youngest unconformity into a horizontal position.

This pattern of stepwise rotation of unconformities can be attributed to the development of a growing anticline. Such structures develop very often above thrust faults, and were described from different areas of foreland deformation, such as in the Rocky Mountain foreland and in the Pyrenean fold-and-thrust belt (SPANG & EVANS 1988, MEIGS 1997). Observations on numerous basement thrusts reaching the overlying sedimentary sequences showed that the focused deformation of the basement fault is mostly distributed to the sedimentary cover, leading to the development of fault propagation folds (SPANG & EVANS 1988, SUPPE & MEDWEDEFF 1990, ALMENDINGER 1998). If thrusting rates are higher than the rate of accommodation, these folds will be eroded continuously, but if rising base-level or decreasing tectonic activity provide accommodation space at the fold margins, rotating unconformities will be produced (SPANG & EVANS 1988). Stratal geometries across unconformities preserve the tilt of beds established prior to deposition above the unconformity. Thus, a complex, but completely redeformable series of angular relationships will be preserved across the unconformities.

The overlying transgressive deposits above the unconformities near the Harznordrand Thrust reflect a situation

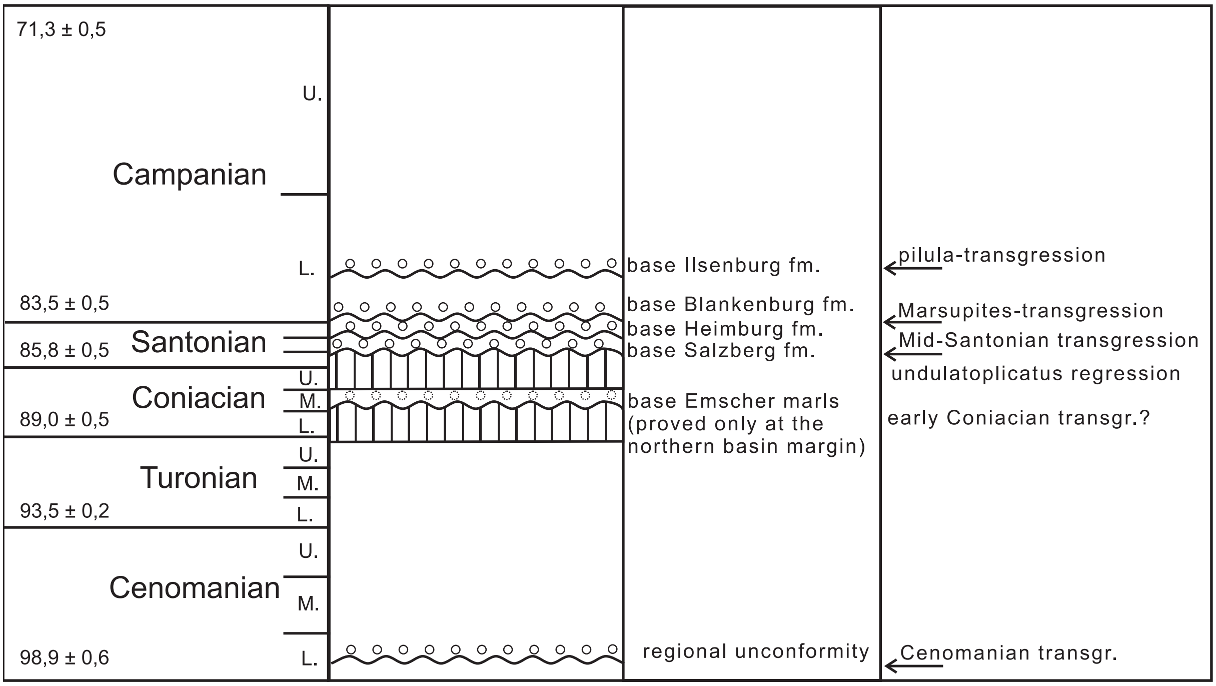

Fig. 14. The Santonian to Campanian unconformities developed at the southern margin of the Subhercynian Cretaceous Basin are related to the development of the Harznordrand Thrust. Three of the four observed unconformities span a short timespan of only 2 million years. The fourth unconformity, at the base of the Ilsenburg Formation, was formed in the Early Campanian, but refers to the same tectonic setting (movement of the thrust). The timing of the unconformities shows a very good correlation with the transgressions and regressions during the Santonian and Campanian recognized by NIEBUHR (2000) in the North German Basin. Deposition on top of the active thrust occurred when the rate of sea-level rise exceeded uplift rate

where the increase in accommodation space keeps pace or exceeds the rate of thrust movement. This can be caused either by decreasing thrusting rates or by rising sea-level. In times with decreasing accommodation potential, the uplifting units in front of the thrust zone were eroded and redeposited north of the fault. The preservation of several unconformities in a very close position to the active thrust demonstrates that the thrust developed rapidly from its blind stage (fault propagation fold) to a nearly stationary active thrust, which caused only minor rotation of the footwall. The formation of a rolling hinge in the foreland syncline can be excluded, because the unconformities were preserved close to the propagating thrust.

The two major transgressions that can be traced along the whole thrust fault occurred at the beginning of the Middle Santonian (*Gonioteuthis westfalica* Zone) and in the late Early Campanian (*Offaster pilula* Zone). They correlate well with the major transgressions in the Cretaceous of northern Germany (Text-fig. 14) published by NIEBUHR (1995) and could correlate to the global sea-level cycles 3.3 and 3.5 of HAQ & *al*. (1987). The transgressions in the Late Santonian (intra-*Marsupites* zone) and at the base of the Campanian (*Gonioteuthis granulataquadrata* zone), which were found only in a limited area north of the Harznordrand Thrust were detected by ERNST (1965) at the same stratigraphical position in Hannover Misburg and verified by NIEBUHR (1995) in the whole southern Niedersachsen Basin. The ages of the deposits above the unconformities probably reflect global sea-level rises because they correlate well with transgressive pulses in other basins (HANCOCK 1989). Nevertheless, these transgressions are not displayed in the global cycle chart of HAQ & *al*. (1987), which seems to be rather imprecise in the Late Cretaceous (HANCOCK 1989, NIEBUHR 1995).

Based on the correlation of the deposits above the unconformities with transgressive deposits in areas of tectonic quiescence, we conclude that there was relatively continuous activity of the thrust, and concomitant rotation of the foreland succession. Eustatic sea-level fluctuations seem to be the main controlling factor for the formation of the unconformities (Text-fig. 14). While erosion both of the hanging wall and of the upturned limb of the foreland syncline occurred during low sea level, deposition above the erosion surface started with rising sea level. There is no need to assume polyphase deformational events attributable to discrete tectonic pulses.

This interpretation is supported by the pattern of facies-changes at the northeastern basin margin, which was not influenced by the active fault. The transition from mixed shallow-marine to coastal plain facies of the Upper Santonian Heidelberg Formation to the subtidal bioturbated sandstones of the Heimburg Formation indicates a transgression, as does the transition from the sandy Upper Santonian to sponge-rich Lower Campanian marls in the western basin.

The symmetric distribution pattern of unconformities and the observed thickness trends exclude the vertical uplift model and the following gravitational collapse proposed by WUNDERLICH (1953). The strike-slip model of WREDE (1988) is not justified by the structural data (FRANZKE & SCHMIDT 1995) and is also not supported by the symmetric and time-specific unconformity pattern in the adjacent Subhercynian Cretaceous Basin. The tectonic structure of the North German Basin (BALDSCHUHN &

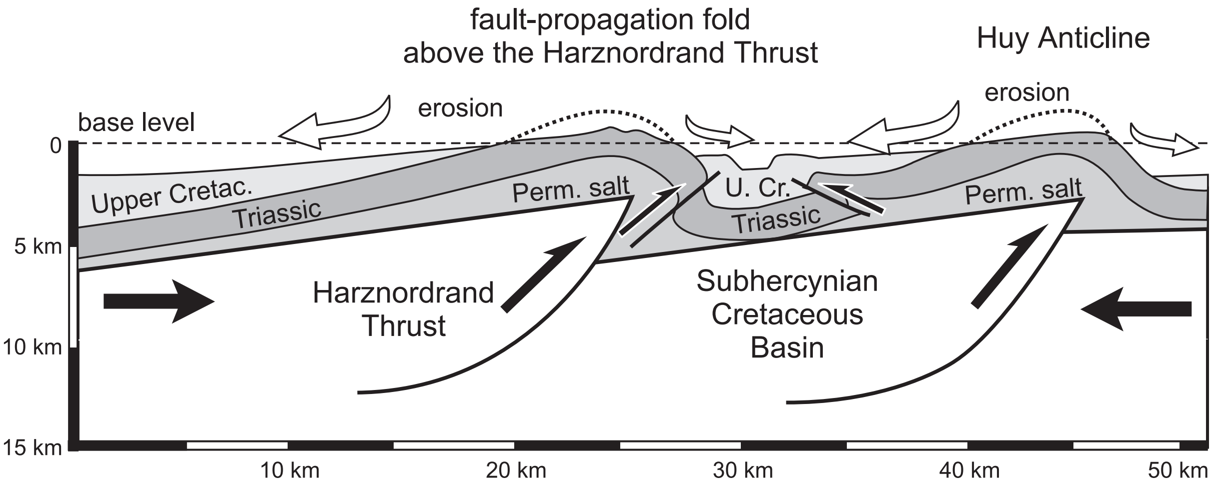

Fig. 15. Reconstruction of the Harznordrand Thrust and the Subhercynian Createous Basin during the Santonian. A large anticline (fault-propagation fold) develops above a steep basement thrust which flattens in a depth of about 10 km (Harznordrand Thrust). Thick Permian evaporites form the decollement between the brittle basement and the stratified and ductile deformed Triassic succession. A second thrust below the Huy Anticline is of minor importance but leeds to the rotation of the basinfloor of the Subhercynian Cretaceous Basin which is filled by syntectonic deposits, eroded from the growing anticlines. Minor thrusts and back-thrusts (Westerhausen Thrust) modify the internal structure of the basin

al. 1991) and the interpretation of recently obtained seismic data (KRAWCZYK & *al*. 1999, KOSSOW & KRAWCZYK 2002) proved the existence of basement thrusts leading to considerable shortening at the southern margin of the NE German Basin during the Late Cretaceous. A reconstruction of the Harznordrand Thrust and the adjoining basins during the Santonian based on seismic data, thickness distribution and conglomerate provenance of the Cretaceous deposits is shown in Text-fig. 15.

The observed development of unconformities is in very good agreement with both the fission-track data of THOMSEN & *al*. (1997) and the published structural data (STACKEBRANDT & FRANZKE 1989) indicating a frontal thrust. The origin of the unconformities reflects the continuous development of a large fault propagation fold above a basement thrust in a short period from the Coniacian to the Early Campanian.

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