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High-resolution sequence stratigraphy of the Lower Triassic 'Buntsandstein' in the Netherlands and northwestern Germany

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Abstract

Detailed log correlations of the largely fluvio-lacustrine Lower Triassic 'Buntsandstein' (Late Permian-Early Anisian), carried out on 80 wells in the Dutch onshore and offshore areas, can be linked to northwest-German high-resolution sequence stratigraphy. The correlations show that cyclic sedimentation occurred in large parts of the basin. Seven 1st-order sequences are recognised, namely the Main Claystone, Rogenstein, Volpriehausen, Detfurth, Hardegsen, Solling and Lower Röt Sequences. They are overlain by the lower part of the Upper Röt–Lower Muschelkalk Sequence. Distinct sequence boundaries have been identified at the bases of four sequences: Volpriehausen, Detfurth, Solling and Upper Röt. The higher-order sequences consist of fining-upwards cycles with a thickness of up to tens of metres. The sequences are laterally persistent and have a characteristic expression on gamma-ray and sonic logs. In the Lower Buntsandstein, they display a uniform character throughout most of the area, with only minor differences in thickness or lithology. NNE-oriented lows and swells were formed during deposition of the Volpriehausen, Detfurth and Hardegsen Sequences. Uplift prior to the deposition of the Solling Sequence caused deep erosion on the swells in the basin and minor erosion in the lows. The high-resolution sequences probably represent alternating, relatively wet and dry climatic periods, with a periodicity of about 100 000 years. An analysis of the sequences suggests that their reduced thickness on the swells is mainly the effect of erosion. This is supported by analyses of the accumulation patterns and rates.

Introduction

The Buntsandstein forms the lower, mainly clastic, part of the Germanic Trias. It was deposited during the Late Permian to Early Anisian in a large intracratonic basin in a fluvio-lacustrine environment, with marine influences restricted to the upper part (Aigner & Bachmann 1992, Van Adrichem Boogaert & Kouwe 1994, Ziegler 1990). The thickness of the complete succession typically lies between 500 and 1000 m, but occasionally reaches up to 4000 m in grabens in northwest Germany (Röhling 1991a). The Buntsandstein is traditionally subdivided into a fine-grained Lower Buntsandstein, comprising several characteristic oolite beds, a Middle or Main Buntsandstein in which sheet sandstones alternate with oolitic claystones, and an Upper Buntsandstein composed of evaporites and claystones. The tripartite subdivision has not only been used lithostratigraphically, but also chronostratigraphically, since it has been maintained in sand-prone areas near the basin margin. The succession is almost completely devoid of fossils, and typically shows extensive soft-sediment deformation, mud cracks, and secondary reddening and reduction. The carbonate oolites in the Lower and Middle Buntsandstein formed in a brackish water environment (Peryt 1975, Brüning 1986). The sediments in the study area, which comprises the Netherlands and northwest Germany, were supplied from the south (Geluk et al. 1996, Röhling 1991a). The lithostratigraphic subdivision of the Buntsandstein is shown in Table 1.

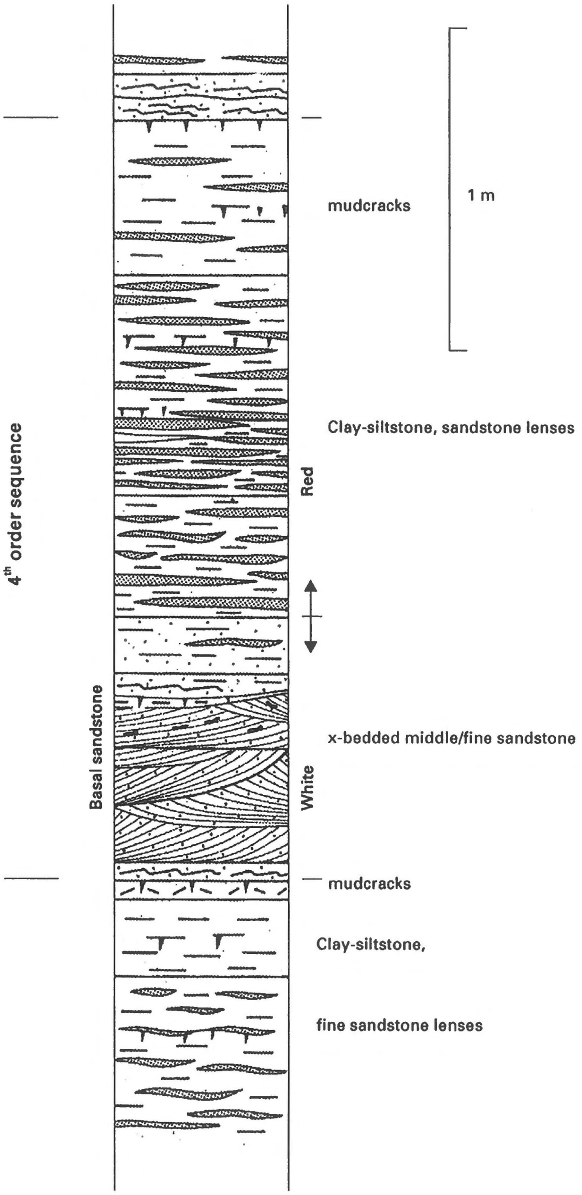

Figure 1. Sedimentological log of a 4th-order sequence in the Volpriehausen Sequence on Helgoland (after Binot & Röhling 1988).

In the Netherlands, a large number of oil and gas wells penetrated the Triassic. In many cases, the Buntsandstein was the target and several important discoveries were made in sandstones of the Main and Upper Buntsandstein over the last decades (e.g. Fontaine et al. 1993, Geluk et al. 1996, Roos & Smits 1983, Winstanley 1993). Furthermore, locally leached oolite beds of the Lower Buntsandstein Formation have reservoir qualities in the eastern Netherlands (Gdula 1983). Correlation of the Main Buntsandstein Subgroup in the western offshore area of the Netherlands with the classic German subdivision of Boigk (1959) has been speculative for a long time, and was only fully understood during the revision and update of the stratigraphic nomenclature of the Netherlands (Van Adrichem Boogaert & Kouwe 1994, Section E). The work presented in this paper underlies this update of the nomenclature.

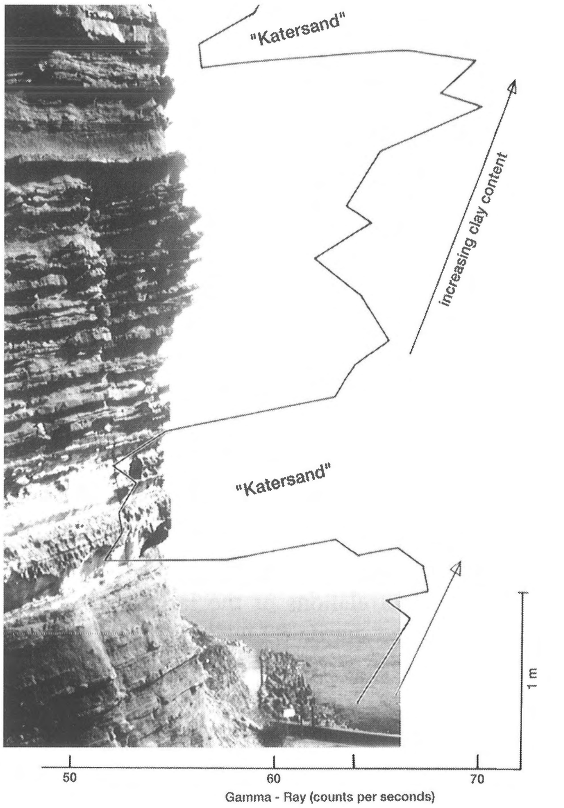

Figure 2. Correlation of lithology and natural gamma radiation of a 4th-order sequence as shown in Figure 1 of the Volpriehausen Sequence on Helgoland (after Binot & Röhling 1988). 'Katersand': basal sandstone of a 4th-order sequence.

Sequence stratigraphy, originally defined in sedimentary successions deposited in a passive margin setting (Van Wagoner et al. 1990, and many others), has been successfully applied over the last decade to deposits in continental basins (e.g. Aigner & Bachmann 1992, Clemmensen et al. 1991, Intergeos 1989, Yang & Baumfalk 1991). Cyclicity in continental basins may be independent of sea-level fluctuations; most likely, cyclicity patterns are related to 'Milankovitch' climate cycles (Perlmutter & Matthews 1990).

In the last decade several studies have been made concerning the cyclicity of the Lower and Middle Buntsandstein in northwest Germany (Brüning 1986, Röhling 1991a, b) and the Netherlands (Intergeos 1989). High-resolution sequences were identified and correlated on wireline logs throughout the northwest-German onshore and offshore area (Röhling 1991a, b). Insight into the cyclicity was essential to outline the Lower Triassic structural units and their subsidence history.

The purpose of this paper is:

1. to make a comparison between the lithostratigraphic nomenclatures used for the Buntsandstein in the Netherlands and Germany,
2. to discuss the origin of the cyclicity,
3. to analyse the development of the Buntsandstein in the Netherlands from a sequence-stratigraphic point of view,
4. to demonstrate that the cyclicity of the Buntsandstein as recognised in Germany (Brüning 1986, Röhling 1991a, b) is applicable to the North Sea, and to establish correlations with the outcrop areas in Germany as described by Boigk (1959, 1961),
5. to characterise the development of the Early Triassic structural elements in the Netherlands.

The Buntsandstein cyclicity

The Buntsandstein is composed of a hierarchical system of sequences of varying magnitude. The cyclicity of the lower part of the Buntsandstein was first described in a systematic way by Brüning (1986) from the southern part of Lower Saxony. Röhling (1991a, b) showed that these cycles are persistent throughout the Northwest German Basin, and established a subdivision for the Rogenstein, Volpriehausen, Detfurth and Hardegsen Sequences. In order of increasing importance, the following sequences have been recognised (Röhling 1991b, Binot & Röhling 1988):

5th-order sequences are centimetre to decimetre-thick fining upwards cycles, composed of sandstone and clay-siltstone.

4th-order sequences, of decimetre to metre thickness, are built up of several 5th-order sequences. A typical 4th-order sequence starts with a basal sandstone, which is oolitic in several sequences, covered by an alternation of sandstone, siltstone and claystone (Figures 1, 2). The number of sandstone beds and the sandstone percentage decrease upwards. Ideally, these sequences are topped by an up to several decimetres thick clay- and siltstone, clearly expressed by high gamma-ray readings (Figure 2).

3rd-order sequences comprise a varying number of 4th-order sequences. They generally reach a thickness of between 5 and 25 m (sometimes more), and their bases are characterised by the coarsest and thickest clastic deposits of a group of 4th-order sequences. This type of cyclicity is identified on wireline logs and can be correlated over great distances. It is the main topic of this paper and it is referred to as high-resolution cyclicity. The M1 to M4 and R5 to R8 sequences are good examples of this cyclicity (Figures 4, 5). Below the basal clastic deposits, some truncation of the underlying sequence is occasionally observed on log correlations.

2nd-order sequences comprise three to five 3rd-order sequences, with a similar lithological composition, such as the group of sequences R5 to R7, which stand out because of their thick basal oolite beds (Figures 4, 6, 7, 10).

1st-order sequences comprise a group of 2nd-order sequences, for instance the group formed by the sequences R1 to R14 (Figures 6, 7). They have thicknesses of up to several hundreds of metres.

Data-base and working method

For the offshore area of the Netherlands, exploration data older than 10 years are officially released. For the onshore area, a special agreement exists between the oil industry and the Netherlands Institute of Applied Geoscience TNO (NITG-TNO), allowing publication of interpretations of older confidential data. On this basis, over 80 wells were selected with a complete Lower Buntsandstein Formation and/or Main Buntsandstein Subgroup (Figure 3). Of the Upper Buntsandstein, here taken as the Solling and Röt Formation together, only the lower part was studied. Furthermore, some released Danish wells, situated on the southern flank of the Ringkøbing-Fyn High, have been analysed (R-1, Grindstedt-1, Løgumkloster-1).

The sequences as defined by Brüning (1986) and Röhling (1991a, b) have been coded in order to avoid confusion between lithostratigraphy and sequence stratigraphy. For the identification of the Buntsandstein cyclicity, gamma-ray and sonic logs were used by preference, although in some instances also spontaneous-potential, induction and resistivity logs were used successfully. A 1:1000 log-scale supplied enough detail to establish the correlations. The method implies the

Table 1. Lithostratigraphic nomenclature of the Lower Triassic Buntsandstein in the Netherlands and Germany (Van Adrichem Boogaert & Kouwe 1994; Röhling 1991a, b, 1993), together with the sequences proposed in this paper and their ages. V, D, H and R indicate important sequence boundaries. Numbers of 3rd-order sequences are presented between brackets.

AGE	THE NETHERLANDS Group	Subgroup/Form.		Member	SEQUENCE		NORTHWEST-GERMANY		
Anisian	**Upper Germanic Trias Group**	Muschelkalk Fm.		Lower Musch. Mb.	**Lower Musch.**		**Muschelkalk**	Unterer Muschelkalk Folge	
		Röt Fm.[1]		Upper Röt Clayst. Mb.	**Upper Röt** ∼∼∼∼∼R		**Oberer Buntsandstein**	Pelitröt -Folge	Grauviolette Serie Rotbraune Serie
				Upper Röt Evap. Mb. Interm. Röt Clayst. Mb. Main Röt Evap. Mb.	**Lower Röt**			Salinarröt -Folge	Oberes Rötsalinar Rötsalinar-Zwischenschichten Unteres Rötsalinar
Scythian		Solling Fm.[1]		Solling Claystone Mb. Bas. Solling Sst Mb.	**Solling** ∼∼∼∼∼H	(4)		Solling -Folge[2]	
	Lower Germanic Trias Group	**Main Buntsandstein Subgroup**	Hardegsen Fm.		**Hardegsen**	(20)	**Mittlerer Buntsandstein**	Hardegsen -Folge	Hardegsen-Abfolge 5 Hardegsen-Abfolge 4 Hardegsen-Abfolge 3 Hardegsen-Abfolge 2 Hardegsen-Abfolge 1
			Detfurth . Fm.	Detfurth Claystone Mb.	**DC**	(2)		Detfurth -Folge	Detfurth-Wechselfolge
				Lower Detfurth Sst. Mb.	**DS1-2** ∼∼∼∼∼ D	(2)			Detfurth-Sandstein
			Volpriehausen Fm.	Volprieh. Clay-Siltstone Mb.	**VA1-8**	(8)		Volprie hausen - Folge	Volp.-Aviculaschichten
					VW1-7	(7)			Volp.-Wechselfolge
				Lower Volpr. Sst. Mb.	**VS** ∼∼∼∼∼ V	(1)			Volp.-Sandstein
					VVS	(2)			
		Lower Buntsandstein Fm.		Rogenstein Mb.	**R1-14**	(14)	**Unterer Buntsandstein**	Bernburg -Folge	Obere Wechselfolge Kalkoolithschichten Oolithische Wechselfolge
				Main Claystone Mb.	**M1-10**	(10)		Calvörde -Folge	sandig-oolith. T.-sch. Oolithschichten Oolith. Sdst.-Tst.-sch sandig-tonige Basissch.
? **Late Permian**				(Upper Bröckelsch.)[3]	**Br**	(1)			
	Zechst.	Ze. Upper Claystone Fm.					**Zechstein**	Zech. Übergangsfolge	

[1]: Solling and Röt Fm. together correspond to the informal 'Upper Buntsandstein'.
[2]: Regional subdivisions (see Röhling 1991a).
[3] No formal unit in the Netherlands, belongs to the Main Claystone Mb.

recognition on well logs of patterns such as breaks, peaks and trends. The Buntsandstein succession is composed of a stacking of these patterns, which can be correlated from well to well. The extensive lateral distribution of these patterns from basin centre to basin margin and their independence of lithofacies form in our view the proof that these patterns represent sequences of an extrabasinal origin. Examples of these patterns are the base of the M3 sequence, characterised by a double peak on the sonic log, and the R5 to R8 sequences, characterised by thick oolite beds with low gamma radiation (Figures 4, 5). For correlation, four reference wells for the various structural settings were used: Blijham-1 for the eastern onshore area, Rustenburg-1 for the central onshore area, L2-1 for the Off Holland Low, and Strijen-West-1 for the basin-fringe area (Figures 6–8). Logs of these wells on a 1:2000 scale have been published by Van Adrichem Boogaert & Kouwe (1994) and RGD (1993).

For all wells, the depths of the bases of the sequences were stored in an Excel spreadsheet, and used to calculate average thicknesses and net accumulation rates. This is discussed in Appendix 1. The averages are based on present-day thicknesses and show differences not only due to depositional causes, but also to compaction. The effects of compaction can, however, be ruled out in this regional study by applying a contour interval of 5 cm/ka. This was documented

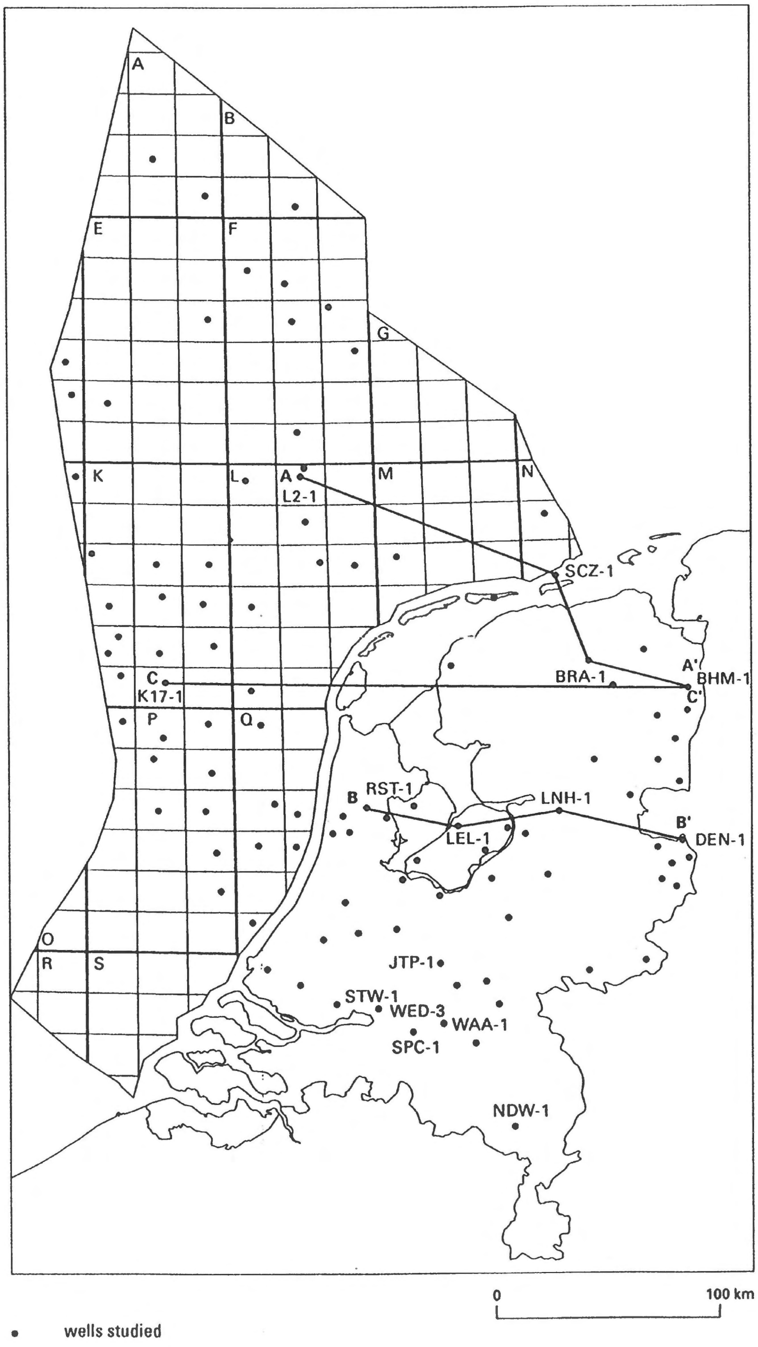

Figure 3. Well data-base and locations of the cross sections of Figures 6, 7 and 10. Specific wells discussed in the text and not shown in the cross-sections are: JTP-1: Jutphaas-1; NDW-1: Nederweert-1; SPC-1: Sprang-Capelle-1; STW-1: Strijen West-1; WAA-1: Wijk-Aalburg-1; WED-3: Werkendam-3.

by the analysis of the Buntsandstein in the Jutphaas-1 well, where, as a result of Late Cretaceous reversed faulting, the entire Lower Buntsandstein section was encountered twice, viz. at 1181–1563 m and at 2807–3150 m. The depositional situation of these intervals is assumed to have been identical. Analyses of the sonic-log velocities indicated a difference in maximum burial depth of 2200 m between these two intervals (Bulat &

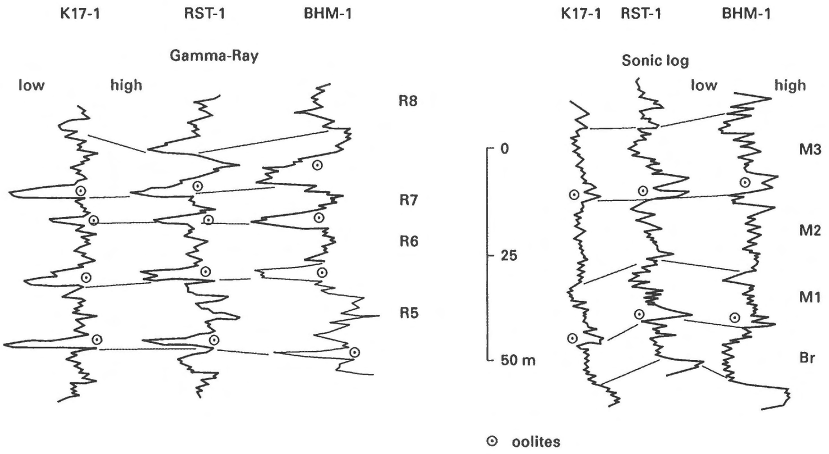

Figure 4. Detailed correlation of the oolite beds of the R5 to R8 sequences on gamma-ray logs and of the Br to M3 sequences on sonic logs in the wells K17-1, Rustenburg-1 (RST-1) and Blijham-1 (BHM-1). The well locations are shown in Figure 3 and the stratigraphy in Table 1.

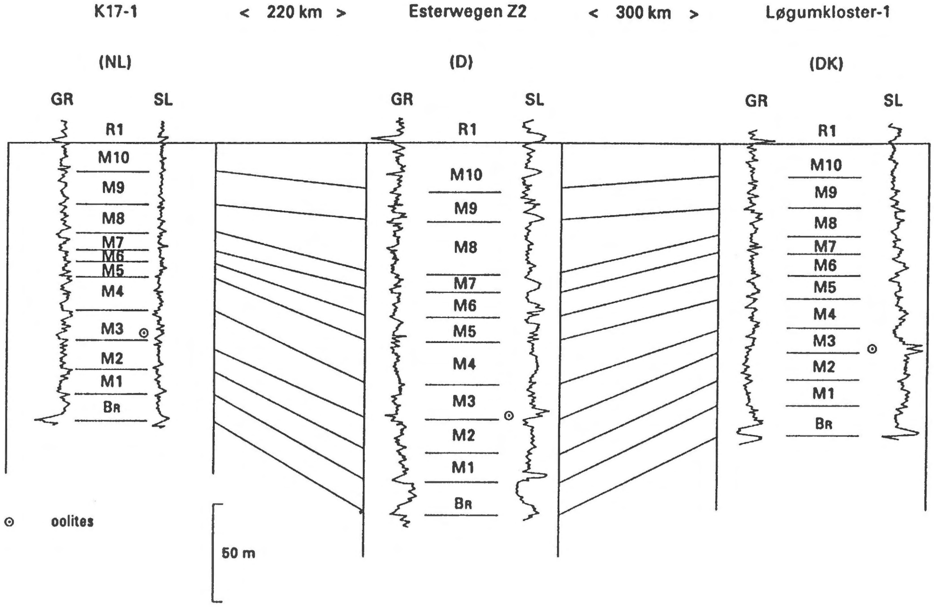

Figure 5. Correlation of the Main Claystone Sequence between wells in the Netherlands (K17-1), northwest Germany (Esterwegen Z2) and Denmark (Løgumkloster-1). Note the comparability of the 3rd-order Br and M1 to M10 sequences over the distances indicated.

Stoker 1987). Despite this large difference, the average thicknesses of the high-resolution sequences showed a close similarity between the two intervals and the maximum difference was 10% or less.

The Zechstein/Buntsandstein boundary

Between the Netherlands, Germany and surrounding countries, there is a difference in the definition of the boundary between the Zechstein and the Buntsandstein. There is general agreement, however, that this boundary does not represent the Permian/Triassic boundary. The latter boundary is situated within the Lower Buntsandstein (Van Adrichem Boogaert & Kouwe 1994).

In the Netherlands, the base of the Triassic is placed at the base of the Upper Bröckelschiefer, since this sequence forms a good marker bed throughout both the onshore and offshore areas. The sequence is con-

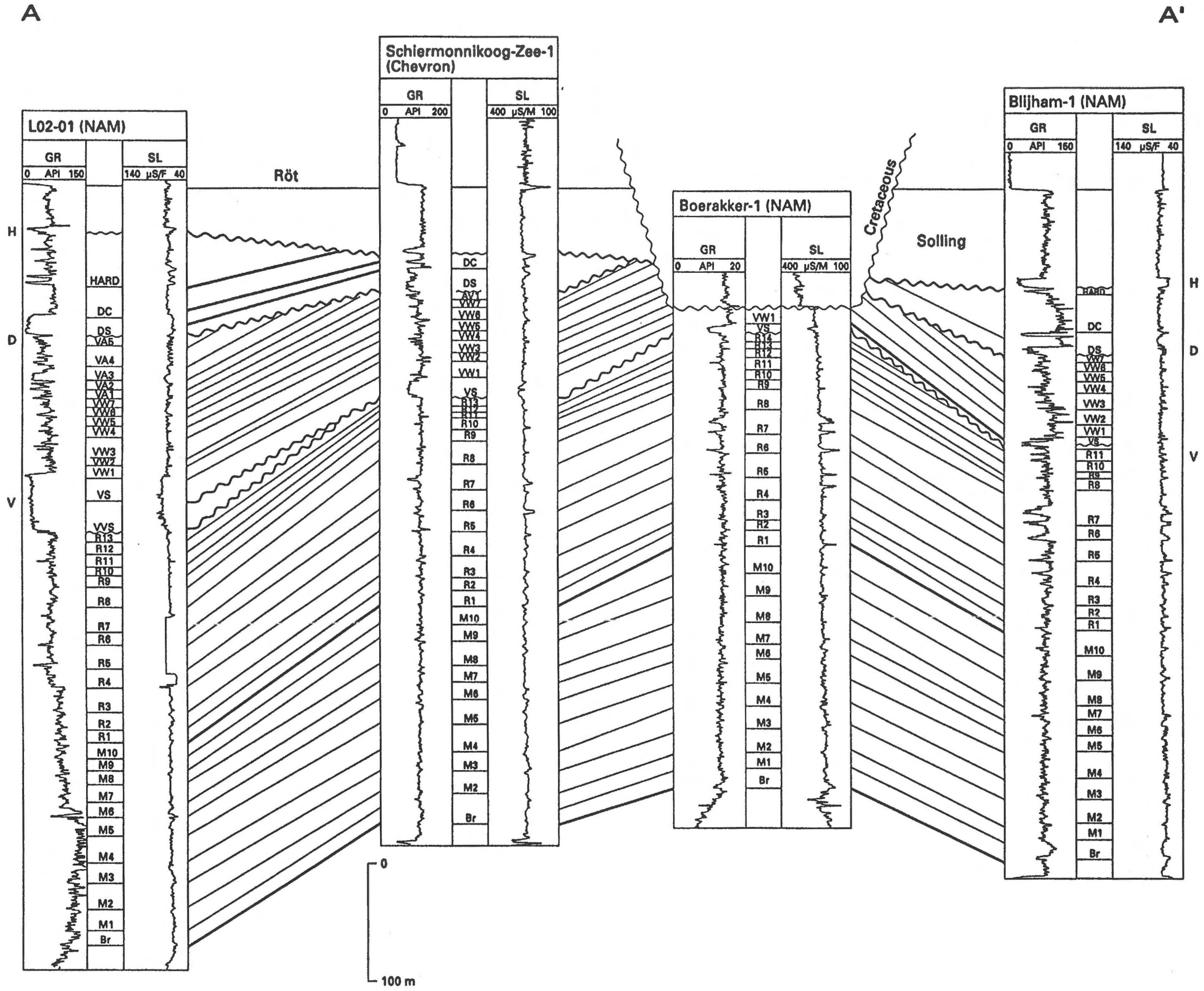

Figure 6. Section A–A', L2-1 – Blijham-1. The development of the Br, M1 to M10 and R1 to R14 sequences does not show any influence by the Netherlands Swell. Note the eastward thinning of the VS Sequence. For location see Figure 3 and for stratigraphy Table 1. The datum level is the base of the Lower Röt Sequence.

sidered to form the basal transgressive unit of the Lower Buntsandstein (Van Adrichem Boogaert & Kouwe 1994). The Upper Bröckelschiefer rests with a minor hiatus on the Zechstein Upper Claystone Formation.

In Germany, the sediments of the Upper Bröckelschiefer are often anhydrite and halite-bearing and therefore are regarded to belong to the Zechstein (Best 1989, Röhling 1991a, b, 1993). The lower boundary of the Buntsandstein is defined at the base of the first intercalations of oolitic sandstones above the Zechstein Übergangsfolge (= Zechstein transitional sequence).

In the UK and Denmark, the Zechstein/Buntsandstein boundary is taken at the base of the Zechstein Upper Claystone Formation (= base Zechstein Übergangsfolge), and as such lies considerably lower than the boundaries in the Netherlands and Germany.

Lithostratigraphic nomenclature of the Buntsandstein

In the Netherlands and northwest Germany, recent updates of the lithostratigraphic nomenclature have been published by Röhling (1991a, b, 1993) and Van Adrichem Boogaert & Kouwe (1994). There is, however, a major difference in the approach. In the Netherlands, the rules of Hedberg (1976) are applied, whereas in Germany by tradition a chronostratigraphic

(= sequence-stratigraphic) approach is followed. The implications are that in the Netherlands, lithostratigraphic units may be diachronous, whereas in Germany they are considered as isochronous units. Despite this fundamental difference, the nomenclatures of the two countries show a close correspondence, as the Triassic has a pronounced layer-cake character and the formations almost represent time-slices (Van Adrichem Boogaert & Kouwe 1994). There are some slight differences between the boundaries and units in the Netherlands and Germany, which are explained below (Table 1).

In the Netherlands, the Lower Buntsandstein Formation and Main Buntsandstein Subgroup together form the Lower Germanic Trias Group; the Solling and Röt Formations belong to the Upper Germanic Trias Group. The Main Buntsandstein Subgroup in the Netherlands is equivalent to the Middle Buntsandstein as defined in eastern Germany (Dockter et al. 1980), but differs from the Middle Buntsandstein in western Germany (Boigk 1956, 1961, Röhling 1991a, b) by taking the 'H' or Base Solling Unconformity rather than the base of the Röt Formation as the base of the Upper Buntsandstein (Table 1). In the Netherlands, the Solling and the Röt Formations are informally referred to as the Upper Buntsandstein. A similar proposal for Germany was published by Backhaus (1994).

High-resolution sequence stratigraphy

Lower Buntsandstein Formation (Late Permian-Scythian)

In the Netherlands as well as in Germany a twofold lithostratigraphic subdivision is applied in the Lower Buntsandstein Formation (Table 1). The units are the Main Claystone and the Rogenstein Members in the Netherlands and the Calvörde-Folge and Bernburg-Folge in Germany (Subkommission Perm-Trias 1993; Röhling 1993). The distinction is made on the basis of the predominance of thick oolitic sandstone beds in the Rogenstein Member and Bernburg-Folge.

The Lower Buntsandstein Formation forms a single megasequence, bounded by unconformities. This megasequence can be subdivided into two 1st-order sequences, the Main Claystone (M) and Rogenstein (R) Sequences, which coincide with the lithostratigraphic subdivision. In the sequences, together up to 400 m thick in central parts of the basin, no major breaks in sedimentation were identified based on well log correlation. On seismics, the megasequence forms a transparent unit with a constant thickness. No synsedimentary faulting occurred (Van Adrichem Boogaert & Kouwe 1994).

The sedimentary conditions of the Lower Buntsandstein Formation range from fluvial in the Roer Valley Graben (Geluk et al. 1996) to lacustrine in the basin centre. At the end of its deposition, lacustrine conditions prevailed throughout the study area.

Main Claystone Sequence

In the Main Claystone Sequence, 11 high-resolution, 3rd-order sequences (Br, M1–M10) have been recognised (Brüning 1986, Röhling 1991a, b). The Main Claystone shows an increasing thickness from southwest to northeast from 100 to over 200 m. Despite this thickening, the character of the 3rd-order sequences remains more or less the same. The lower sequences, up to M4, show thickness variations, and probably are somewhat reduced in the basin-fringe area. The M5 to M10 sequences, however, show a more sheetlike development.

The Br (Upper Bröckelschiefer) sequence at the base shows a considerable variation in thickness and development in the Netherlands. Its basal sandstone is often anhydritically cemented. Only in the basin-fringe area there is evidence (logs, cores) indicating a minor hiatus at the base. The disconformable contact is, however, more pronounced in Germany (Röhling 1993). The M1 sequence is characterised by the first development of oolitic sandy sediments (Röhling 1991a). In the M2 sequence, claystones with high gamma-ray readings form a good correlation marker. Throughout the area, the base of the M3 sequence forms a good reference horizon (Figures 4–7); it is characterised by a sharp double peak on the sonic log, caused by a sandy oolitic development. In the western offshore area, a sand bed forms the base of this sequence. The M4 and M5 sequences also show the same character over the entire area. The upper high-resolution sequences, M6–M10, display a higher clay content and they may be difficult to distinguish in some wells. The M10 sequence often displays peaky high gamma-ray readings in its uppermost part, possibly reflecting minor erosion below the R1 sequence.

In the Roer Valley Graben, an almost completely sandy Lower Buntsandstein Formation is present. The onset of the sand influx lies at the base of the M3 sequence, but owing to lack of well information, no further sequences have been identified here.

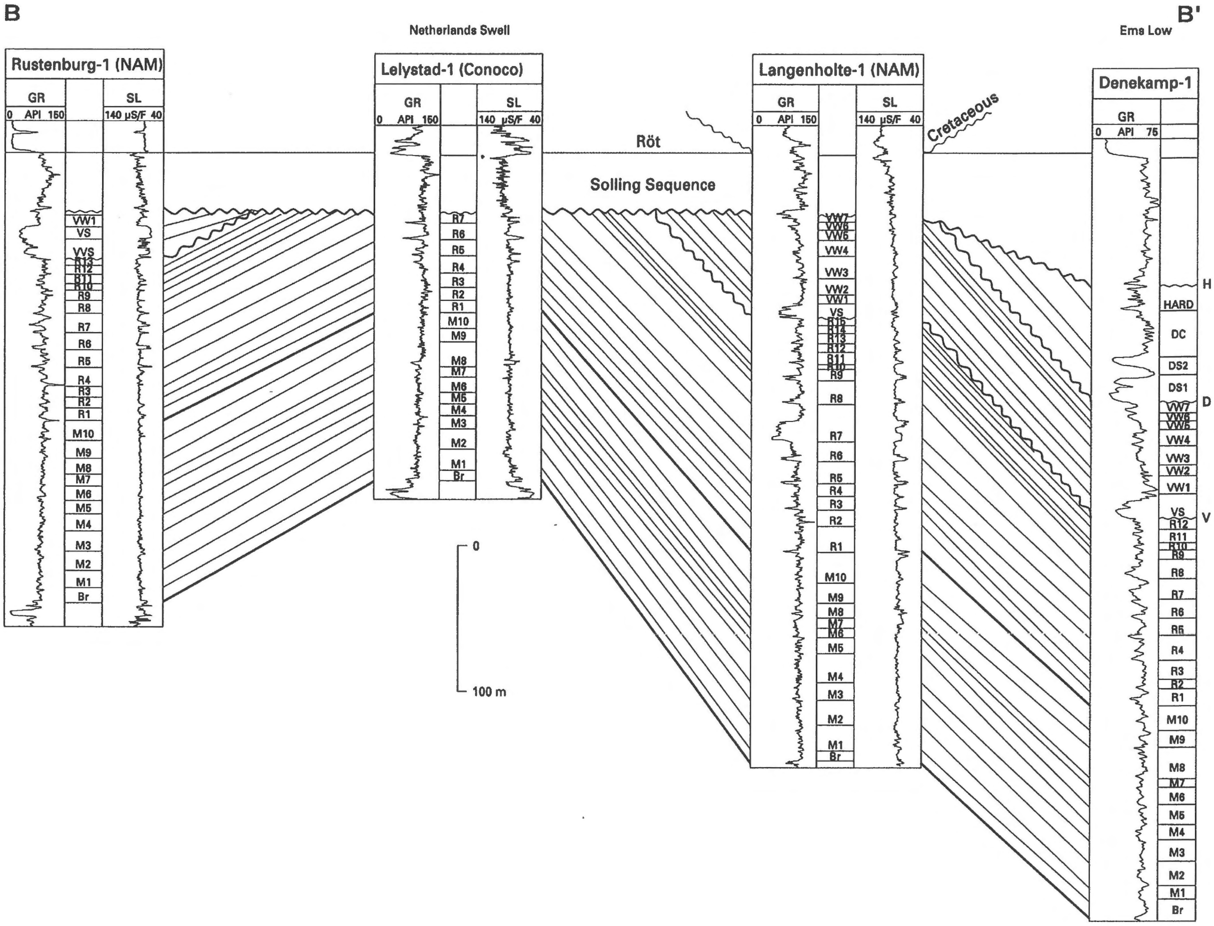

Figure 7. Section B–B', Rustenburg-1 – Denekamp-1. Note the strong increase in thickness of the Buntsandstein from Lelystad-1 towards Denekamp-1, in the Ems Low. Lelystad-1 is on the Netherlands Swell, where the Rogenstein Sequence has a reduced thickness below the H-Unconformity. The datum level is the base of the Röt Sequence. For location see Figure 3 and for stratigraphy Table 1.

Rogenstein Sequence

In the Rogenstein Sequence up to 14 high-resolution sequences (R1 to R14) have been identified in outcrops and on logs (Röhling 1991a, b). The 'V' or Volpriehausen Unconformity forms the boundary with the overlying Volpriehausen Sequence. The Rogenstein Sequence is almost 200 m thick in the lows (Figures 6, 7). It has a reduced thickness on the Hunte and Eichsfeld-Altmark Swells in northwest Germany (see Figure 9 for location). The thickness of the individual high-resolution sequences is identical on the highs and in the lows, but the number of sequences is reduced on the highs. This indicates that a post-Rogenstein but pre-Volpriehausen uplift and erosion took place. In northwest Germany, the Volpriehausen Sequence unconformably overlies the sequences R7 to R14 (Röhling 1991a, b). In the Netherlands no pre-Volpriehausen uplift occurred; only two to three sequences have been found missing, but not on any specific structural unit. The swells subtly influenced sedimentation, as is shown by the fact that the thickest oolitic layer on top of the Eichsfeld-Altmark Swell is situated in the R5 sequence, while towards the basin the maximum oolitic thickness moves into the R6 sequence (Röhling 1991a, b, 1993). The Netherlands Swell also influenced sedimentation. The development of the Rogenstein Sequence shows a good correlation between northwestern Germany and the Ems Low; but west of this low the lower part of the sequence loses its oolitic character (Figures 6, 7). A slight decrease in thickness accompanies this facies change. For this reason, the base of the Rogenstein Member was traditionally picked too high, namely at the base of the R5 sequence.

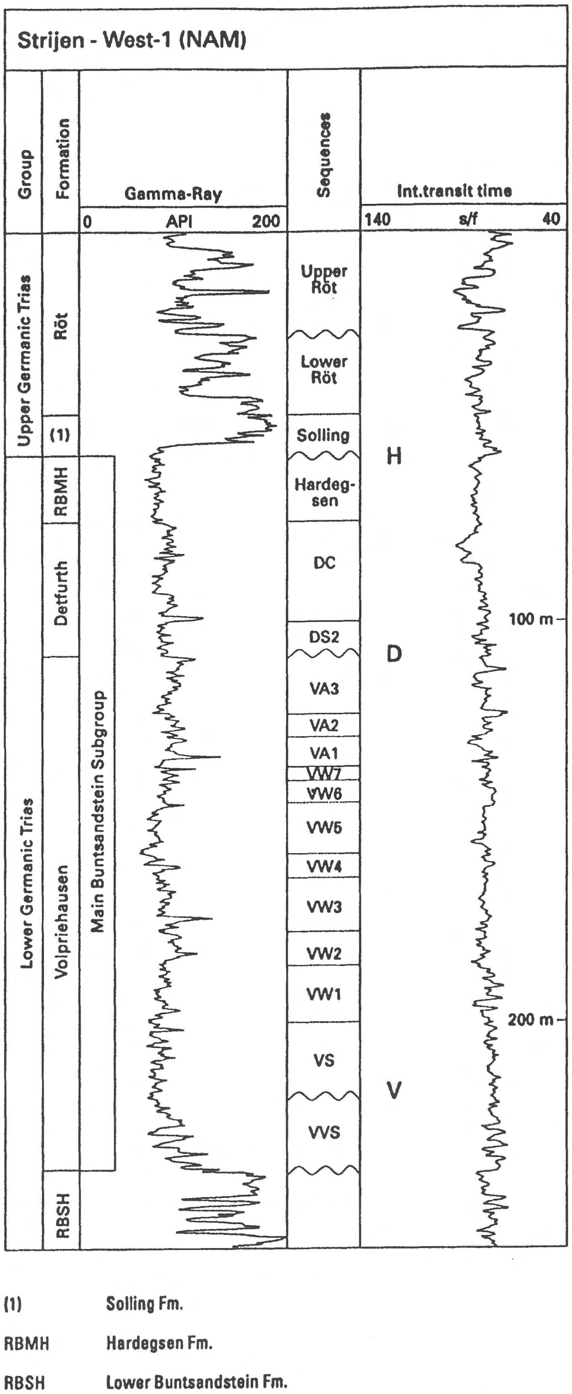

Figure 8. High-resolution 3rd-order sequences in the sandy Main Buntsandstein Subgroup, well Strijen-West-1. For location see Figure 3 and for stratigraphy Table 1.

At the base of the Rogenstein, a sharp lithological break indicating a sequence boundary was found only in the southeastern part of the West Netherlands Basin. Here the R1 sequence shows a thick (10–15 m), massive basal sandstone bed, below which some erosion into the underlying sequences has been observed (wells Wijk-Aalburg-1, Werkendam-3, Sprang-Capelle-1). This boundary can be correlated with the conformable base R1 boundary in other areas (Figures 6, 7).

The thickest oolitic sandstones in the Rogenstein Member occur in the sequences R4 to R8. Either the R5 or the R6 sequence shows the thickest oolitic development. In the northern foreland of the Harz Mountains, the so-called 'Rogensteine' of these sequences become dominant, forming massive pisolitic, sandy carbonate beds about 10 m thick in which pisoliths of up to 10 cm occur.

In the sequences R9 to R14, oolitic sandstones are less pronounced. These sequences are composed predominantly of claystones and the clayey facies persist far south in the basin-fringe area as is observed in the Nederweert-1 well, where they rest upon the sandy R1 to R8 sequences. The R9 to R14 sequences indicate a marked expansion of lacustrine facies. They are thinner (5–10 m) than the underlying sequences R4 to R8 (13–20 m; see Appendix 1).

The most continuous sedimentary record from the Rogenstein into the Volpriehausen Sequence occurs in the Off Holland Low, where, based on the wireline log patterns, a more gradual transition occurs between these sequences than in the Ems Low (Figure 10).

Main Buntsandstein Subgroup (Scythian)

Within this subgroup, three formations are distinguished, namely the Volpriehausen, Detfurth and Hardegsen Formations (Table 1). The subgroup is thickest in isolated grabens. It reaches up to 3500 m in the Glückstadt Graben and the Horn Graben (Röhling 1991a). These complete successions, however, are undrilled and only known from seismic data.

Within the subgroup, three 1st-order sequences can be distinguished: the Volpriehausen, the Detfurth and the Hardegsen Sequence. The upper boundary is formed by a major sequence boundary at the base of the Solling Sequence, the Hardegsen or 'H'-Unconformity (Aigner & Bachmann 1992; Röhling 1991a, b).

For the Main Buntsandstein, a high-resolution sequence-stratigraphic framework was proposed by Intergeos (1989). The model as presented in this paper differs in several aspects from the Intergeos model. The main difference is the fact that the unconformity at the base of the Detfurth Formation was not recognised by Intergeos (1989).

Volpriehausen Sequence

The 'V' Unconformity (Trusheim 1961) at the base of the Volpriehausen Sequence is recognised in the northwest-German onshore and offshore areas, where it truncates up to 50 to 60 m (Röhling 1991a, b). By contrast, only 5 to 20 m of the Rogenstein Sequence were eroded in the Netherlands. The Volpriehausen Sequence comprises four 2nd-order sequences, from bottom to top the VVS, VS, VW and VA Sequences (Table 1). There is generally good correlation with the sequences identified in the lower part of the Volpriehausen by Intergeos (1989).

The distribution of the VVS Sequence is mainly limited to the lows, particularly in the western offshore area of the Netherlands (Figures 6–8, 10, 11D). The VS and VW Sequences, however, are widely distributed in the study area. The 'V'-Unconformity is composed of two unconformities, situated at the bases of the VVS and VS Sequences respectively (Röhling, 1991a, b). The most important of these is that below the VS Sequence, as it truncates the VVS Sequence (Figure 10).

The *VVS Sequence* or 'Volpriehausen Precursor Sandstone' (Röhling 1991a, b) comprises an alternation of sandstone and siltstone beds. The sandstones are rich in carbonate and claystone material, which was reworked from the underlying deposits. The sandstones have been deposited in a fluvial environment, whereas the siltstones represent lacustrine deposits (Geluk et al. 1996). In the northern offshore of the Netherlands, VVS sands were deposited in an aeolian setting (Fontaine et al. 1993: figure 10, unit 1).

The VVS Sequence is widely present to the south and west of the Netherlands Swell and in the North German Basin, but only in a limited number of wells in the Ems Low (Figures 6, 7, 9, 11D). It reaches a maximum thickness of up to 60 m in the Off Holland Low, and displays rapid lateral thickness variations. Some of these variations indicate fault activity. On the Cleaver Bank High the sequence reaches a thickness of 20 m. This distribution outlines the area of earliest Volpriehausen Sequence deposition (Figure 11D). This area is not related to pre-Volpriehausen erosion and is assumed to be fault-controlled (Figure 10). The western extent of this sequence is unknown. It is notable that the Cleaver Bank High did not yet form a positive relief (Figure 12).

The *VS Sequence* or 'Volpriehausen Sandstone' (Röhling 1991a, b) marks the expansion of the sedimentation over the Netherlands Swell. The base of the sequence is a major sequence boundary, the 'V' Unconformity (Figures 5–7, 10). The sequence forms a thick, massive sandstone (15–25 m) in the Ems Low and Off Holland Low, and a thin silty to clayey transgressive sandstone (<1 m) on the Netherlands Swell. It is of fluvial origin (Ames & Farfan 1996, Geluk et al. 1996), but in the northern Off Holland Low, aeolian sandstones occur (Intergeos 1989, Fontaine et al. 1993: figure 10, unit 2). Towards the basin centre it passes into an alternation of metre-thick sandstone and claystone beds (Röhling 1991a, b).

The *VW Sequence* marks the change to fine-grained lacustrine deposition. This change occurred diachronously in the study area. In northwest Germany and in the northern offshore and eastern onshore areas of the Netherlands, this change was abrupt and occurred during deposition of the VW1 3rd-order sequence. Towards the southwest, the deposition of fine-grained material started much later. In the northern Off Holland Low sands dominate up to the top of the VW3 sequence and in the central P-blocks even as far up as the top of the VW5 sequence (Figure 11C). In the southern Off Holland Low and the adjacent part of the West Netherlands Basin, fluvial sandstones dominate the entire VW Sequence (Figure 8). The fine-grained VW sequences consist of lacustrine sediments (Van Adrichem Boogaert & Kouwe 1994), and their expansion is considered to represent a gradually rising water-table. Anomalously high gamma-ray readings in sequences VW2, VW3 and VW5 (Figures 6–8) serve for correlation purposes since they are very persistent in the sandy fringe setting. They represent very thin (0.5–1 m) lacustrine deposits (Geluk et al. 1996).

The *VA Sequence* forms the uppermost 2nd-order sequence of the Volpriehausen Sequence. The complete sequence displays in its basal parts predominantly sandy sediments, grading upward into argillaceous sediments (Röhling 1991b). Within the Dutch area, only the lower, more sandy 3rd-order sequences have been preserved beneath the Detfurth Unconformity in the northern Ems Low, Central Graben, Off Holland Low and Roer Valley Graben (VA1–5; Figures 6, 7, 10). Oolite beds frequently occur in the VA Sequence. At the base of the VA3 sequence, a porous sandstone with a typical expression on wireline logs occurs, named 'Görtelsandstein' in Germany and 'Avicula Sandstone

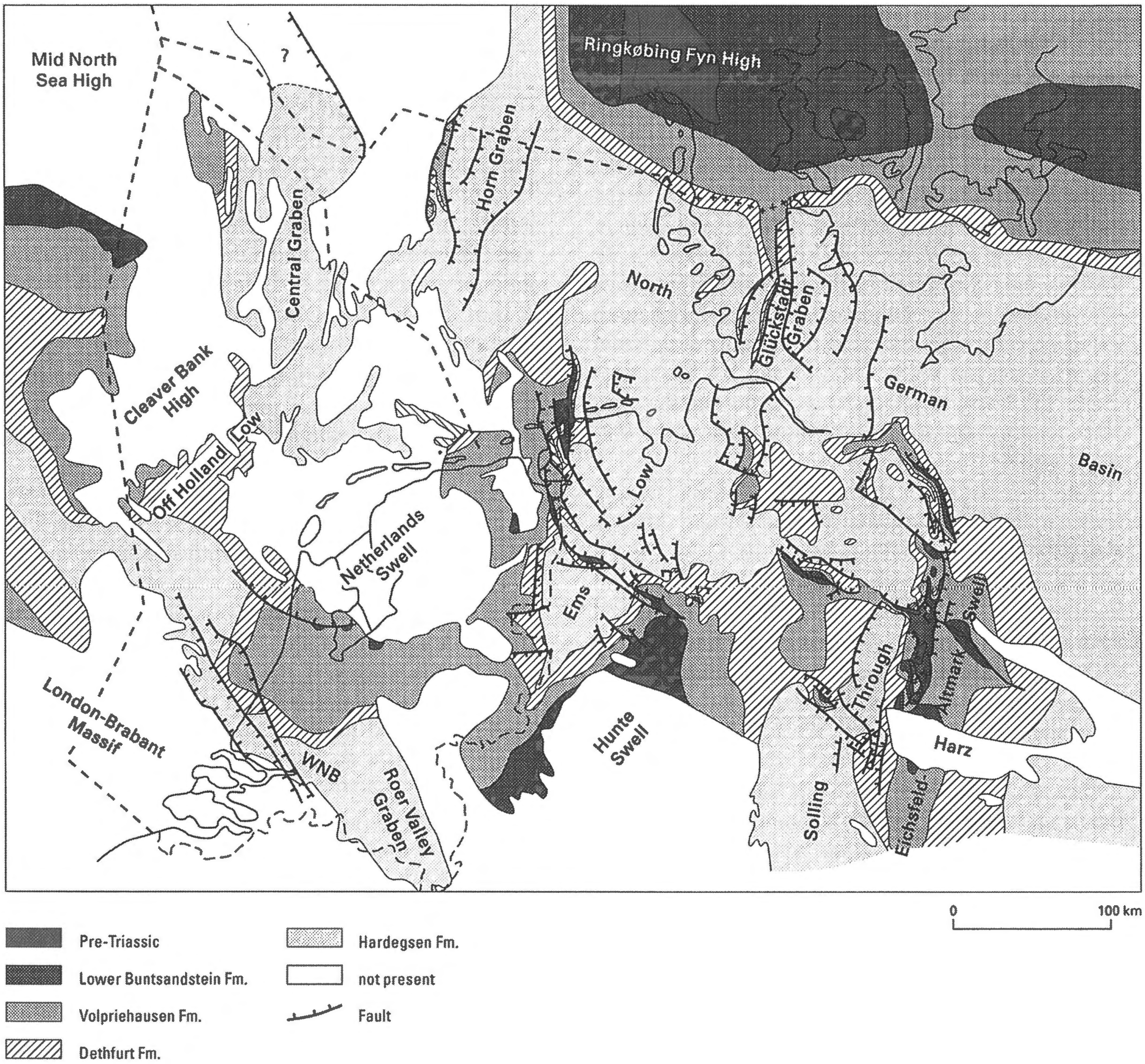

Figure 9. Geological map of the H (= Hardegsen = base Solling) Unconformity, showing the main structural elements discussed in the text. Compiled from literature (Bertelsen 1980; Cameron et al. 1992; Röhling 1991a; Van Adrichem Boogaert & Kouwe 1994) and released well-data. WNB: West Netherlands Basin.

Bed' in the Netherlands (well L2-1, Figure 6). This can be traced over great distances into the basin-fringe area (Figures 6, 8).

The Volpriehausen Sequence was originally deposited in the entire basin, with a slightly reduced thickness on the swells (Figure 12). In northwest Germany the individual VW sequences decrease up to 15% in thickness from the lows towards the swells, but they never pinch out (Röhling 1991a, b). The analysis of the thicknesses in the Netherlands shows the same results. After deposition, the Volpriehausen Sequence became subject to two phases of uplift and erosion, the first prior to deposition of the Detfurth–Hardegsen Megasequence, and the second prior to the Solling transgression.

Detfurth–Hardegsen Megasequence

No erosional boundary has been observed between the 1st-order Detfurth and Hardegsen Sequences, and therefore these sequences have been grouped together

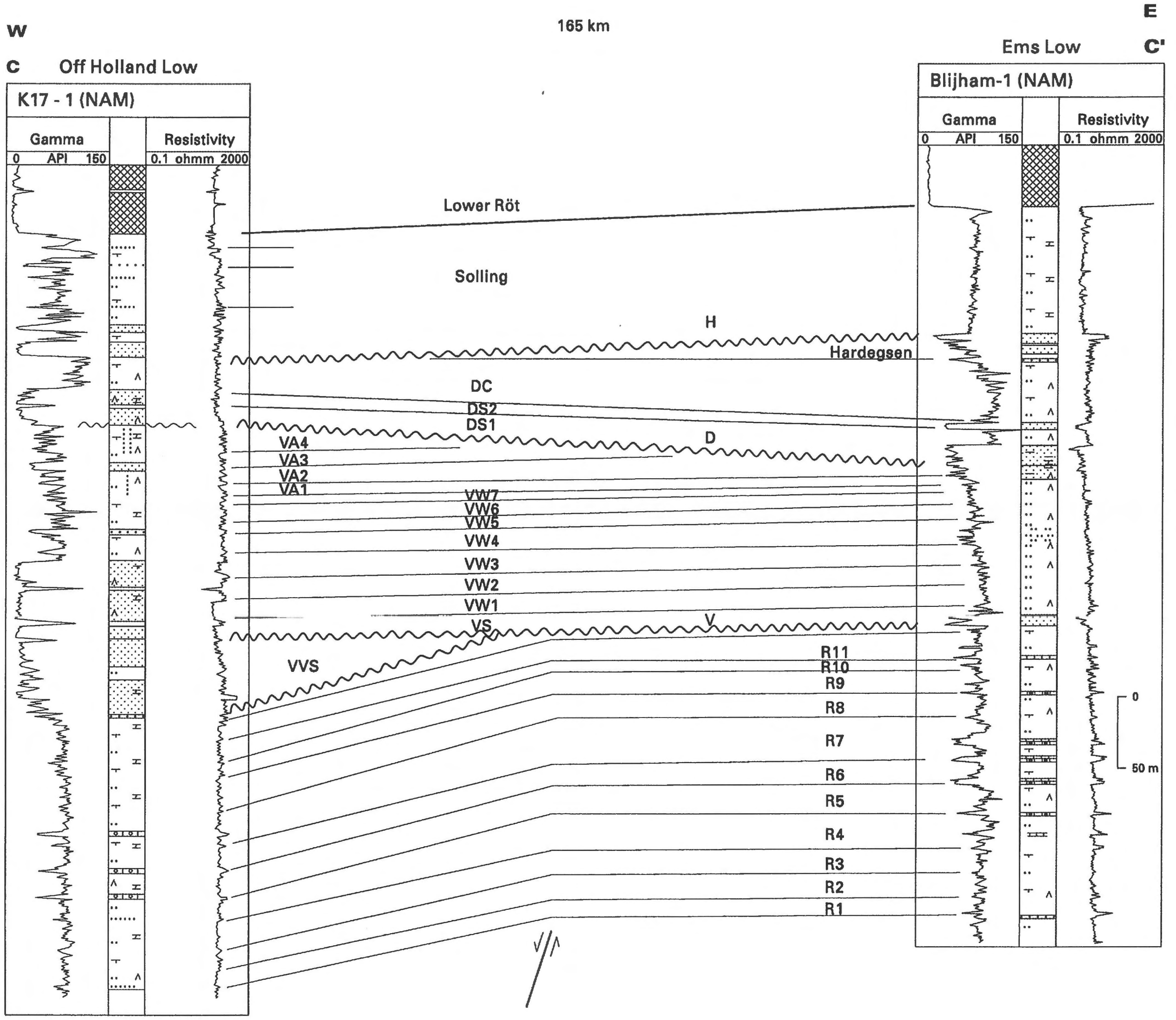

Figure 10. Section C–C', showing the development of the Rogenstein, Volpriehausen, Detfurth–Hardegsen and Solling Sequences in the Off Holland Low (K17-1) and the Ems Low (Blijham-1). Note that, although the amount of pre-Volpriehausen erosion is the same in these two lows, the development of the VVS and VS Sequences is different. This is attributed to the infilling of relief created by extensional tectonics. For location see Figure 3 and for stratigraphy Table 1.

into one megasequence, which comprises from bottom to top the 2nd-order DS, DC, and Hardegsen 1 to 5 Sequences. The megasequence has been found complete only in northwest Germany (Röhling 1991a). In the Netherlands most of the Hardegsen Sequence has been eroded. This study revealed that deposits in the K, L and northern P and Q quadrants, considered as Hardegsen Formation by Van Adrichem Boogaert & Kouwe (1994), belong most likely to the Solling Formation (compare K17-1 in Figure 10 with annex E-1 of Van Adrichem Boogaert & Kouwe 1994).

The *DS Sequence,* the 'Detfurth Sandstone' of Röhling (1991a, b), marks a sharp lithological break with the underlying deposits. Above a widely recognised unconformity ('D'-Unconformity sensu Trusheim 1961, Röhling 1991a, b, Geluk et al. 1996) this sandstone rests on either the VW or VA Sequences. The amount of erosion varies from several tens of metres in the lows to 100 m on the swells. This unconformity is considered to represent a sequence boundary. The sandstones are of fluvial and aeolian origin.

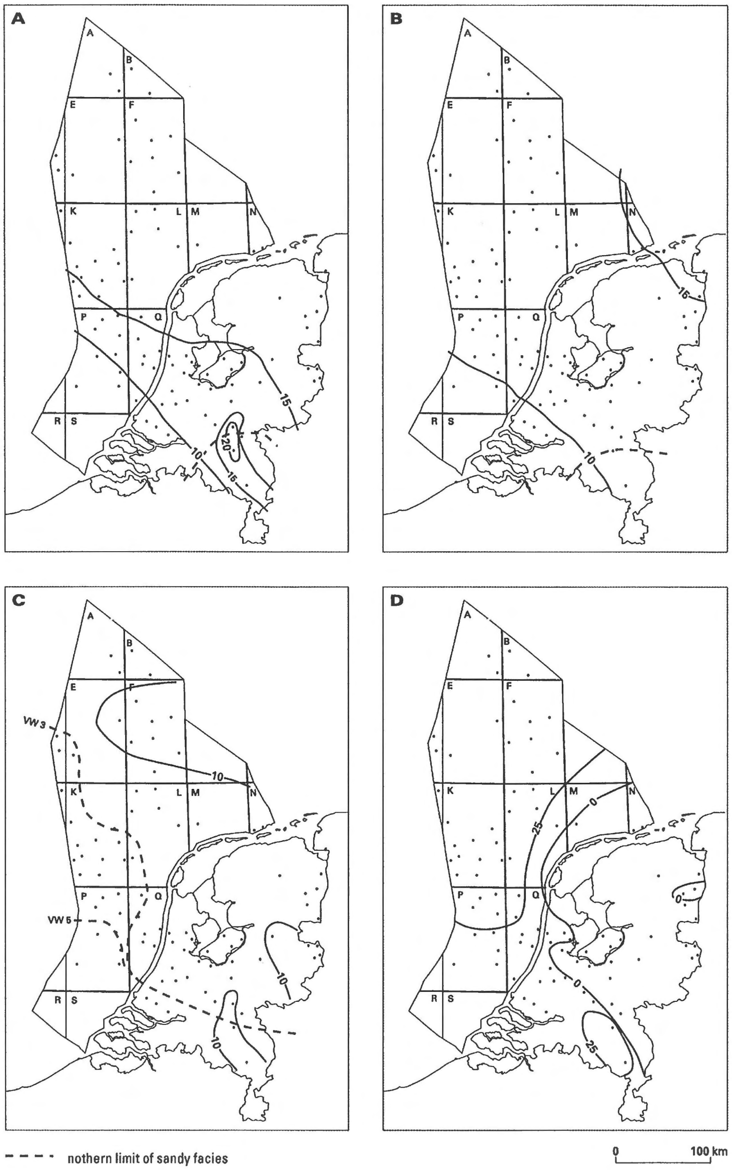

Figure 11. Net accumulation rates (cm/ka) and sandstone distribution of various Buntsandstein sequences in the Netherlands. A) Main Claystone Sequence. The northern extent of the sandy facies is indicated. B) Rogenstein Sequence. The northern extent of the sandy facies is indicated. C) Volpriehausen Sequence. The northern extent of the sandy facies in two sequences, VW3 and VW5, is indicated. D) Distribution and thickness (m) of the VVS Sequence.

In the Ems Low, the DS Sequence displays two well-developed 3rd-order sandstone-claystone sequences, DS1 and DS2; Figures 6, 7, 10). This character is also typical of northwest Germany (Röhling 1991a). In the Off Holland Low, the West Netherlands Basin and the Roer Valley Graben, however, the DS Sequence appears as a massive sandstone (Figure 10), like in southern or southeastern Germany (Röhling 1991a). In the western Netherlands offshore area, log correlation indicates that the claystone bed at the boundary of DS1 and DS2 has been eroded. In the West Netherlands Basin and on the flanks of the Cleaver Bank High, only the DS2 sequence appears to be present; it displays generally a well-recognisable fining-upwards trend.

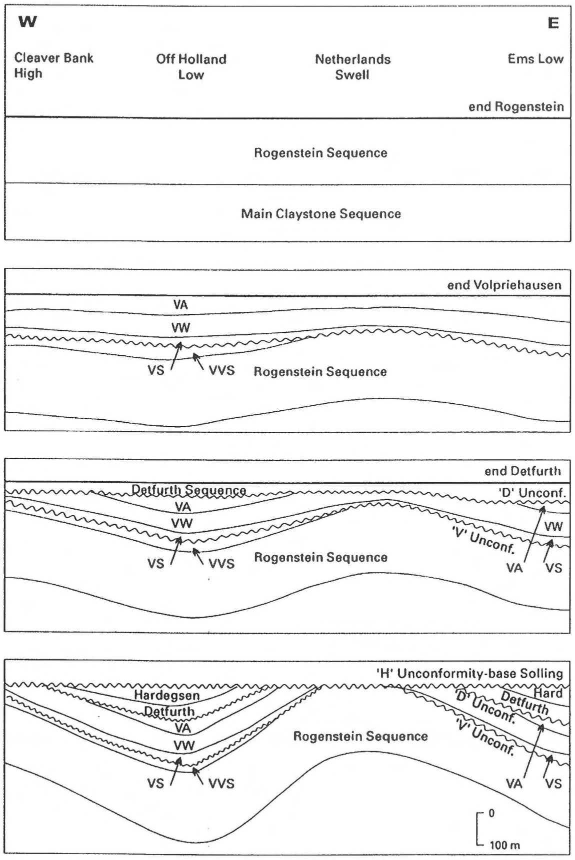

Figure 12. Schematic development of structural elements during the Early Triassic along a section from the Cleaver Bank High to the Ems Low. Length of section is approximately 300 km.

The DS Sequence in the Netherlands represents a palaeovalley fill, with the thickest sandstone development limited to structural lows, and with a thinning and onlap of the sequence towards the bordering Cleaver Bank High and Netherlands Swell. On the crests of these swells, sandstones have probably not been deposited. With respect to the Volpriehausen Sequence, the main area of subsidence had shifted to the Ems Low (Geluk et al. 1996). In northwest Germany, however, the deposition of the DS Sequence was not confined to the lows and occurred sheet-like over the entire area.

The *DC Sequence*, the Detfurth Claystone of Röhling (1991a, b), forms a good correlation marker. It has characteristic high gamma readings with a block-like appearance (Figures 6, 7, 10). These readings reflect a higher clay content with respect to the underlying VW Sequence. The DC Sequence is of lacustrine origin (Röhling, 1991b). In the southern Off Holland Low and the West Netherlands Basin it includes an alternation of fluvial and aeolian sandstones and lacustrine deposits. No regional correlatable high-resolution sequences could be identified.

The *Hardegsen Sequence* rests conformably on the DC Sequence. Its distribution is shown in Figure 9. In the Netherlands, generally only the basal part of the sequence is present. More complete successions occur locally in the Off Holland Low and the Central Graben. A complete section of the sequence has up to now only been observed in the central parts of the North German Basin and in local subsidence centres or grabens in Germany, e.g. in the well Sagermeer Z12 (Röhling 1991a: pl. 7), situated in a graben on the western flank of the Hunte Swell. In such subsidence centres the Hardegsen Sequence attains a thickness of more than 200 m. The sequence consists here of, altogether, five 2nd-order fining-upward sequences, Hardegsen 1 to 5, each comprising four 3rd-order fining-upward sequences (Röhling 1991a, b).

Uplift and erosion after deposition of the Hardegsen Sequence accentuated the swells which had already developed prior to the deposition of the Detfurth Sequence (Figure 12). The movements were apparently stronger in Germany, where the Solling Sequence locally rests upon the Zechstein, than in the Netherlands, where erosion on the swells only very locally cut into the Rogenstein Sequence (Figure 7). The erosion amounts to up to several hundreds of metres on the swells. The question where the eroded material has been deposited remains unanswered; the most likely locations are graben systems like the Horn Graben and the Glückstadt Graben, both with a thick undrilled Buntsandstein succession.

'Upper Buntsandstein' (Scythian-Early Anisian)

Solling–Lower Röt Sequence

The 1st-order *Solling Sequence* marks an important transgression above a sequence boundary (Aigner & Bachmann 1992, Röhling 1991a, b), which is recognised basin-wide as the 'H' or Hardegsen Unconformity. The transgression took place from east to west. The sequence onlaps onto different deposits of the Main Buntsandstein Subgroup, the Lower Buntsandstein Formation and the Zechstein Group, and on the Ringkøbing-Fyn High even upon basement (Danish well Grindstedt-1). The base of the sequence becomes progressively younger to the southwest, accompanied by a marked decrease in the sequence thickness from 125 to 10 m.

The organisation of the high-resolution sequences within the Solling Sequence is not yet fully understood, and appears to vary considerably laterally. In the basin, the sequence is developed entirely in a clay- to siltstone facies; individual high-resolution sequences are difficult to identify. Only in the basin margin areas, where the lithological diversity is greater, can four such sequences be identified (Dutch K, P and Q quadrants; Figure 10).

The deposition of the sequence marks a change in the subsidence pattern in the Netherlands. The subsidence of the E–W trending Central Netherlands Basin clearly differs from that of the NNE-trending Main Buntsandstein lows. The North German Basin and Ems Low continued to subside, but previous areas of subsidence such as the Roer Valley Graben, West Netherlands Basin and Off Holland Low had become part of a platform area (Geluk et al. 1996). On this platform, the Solling Sequence is thin (8–25 m) but always present.

The sequence was followed without a break by the evaporitic 1st-order *Lower Röt Sequence*. Two evaporite and claystone sequences characterise the Lower Röt and have a wide distribution, being present both in the basin and on the swells. In the lows the evaporites are composed of halite, and on the swells of anhydrite. The Lower Röt Sequence was deposited during a period of sea-level highstand, as is shown by its extensive distribution. In the basin-fringe area, evaporites grade into strongly cemented sandstones (Geluk et al. 1996). During the deposition of the Lower Röt, the strongest subsidence took place in the Roer Valley Graben, the Central Netherlands Basin and the Ems Low. The sequence reaches its greatest thickness in the Ems Low, where it exceeds 175 m. The West Netherlands Basin continued to be a platform area. In the Off Holland Low, the Lower Röt Sequence is absent below the Upper Röt–Lower Muschelkalk Sequence.

Upper Röt–Lower Muschelkalk Sequence

An important sequence boundary at the base of this sequence, the 'R'-Unconformity (Table 1), is marked by thick basal sandstones in the basin-fringe area of the Netherlands, and by only a thin (1–2 m) sandstone bed in the basin centre. In the southwestern offshore area of the Netherlands the Upper Röt Sequence rests upon the Solling Sequence; the Lower Röt Sequence has been eroded here (Geluk et al. 1996). The deposition of the Upper Röt Sequence marks a major transgression. The sequence was deposited as a sheet of 50 to 70 m thickness over the entire area, and heralded the flooding by the Muschelkalk sea from the east (Ziegler 1990). The erosion prior to the deposition of this sequence amounts to up to some 50 m.

Origin of the cyclicity

This study documents that cyclicity occurs in Buntsandstein deposits in a large part, at least 500 000 km^2, of the northwest-European Triassic basin. Furthermore it shows that the cyclicity is facies-independent, as it occurs both in the fine-grained basinal facies and in the sandy facies at the basin margin in the southwestern Netherlands. Therefore, it is attributed to extra-basinal factors. Three candidates for these factors are sea level oscillations, tectonics and climatic variations.

Most of the Buntsandstein is made up of continental, mainly fluvio-lacustrine deposits, which virtually rules out cyclic variations in relation to sea level. Only in the Röt Formation some marine influences occur. Tectonics is not considered either, in view of the very uniform character of the sequences over a wide area. Over the last years, a number of studies have pointed to climatic cycles as being responsible for cyclic patterns in continental basins (Perlmutter & Matthews 1990, Intergeos 1989, Yang & Baumfalk 1991). In view of the large area where the cyclicity is developed, the Buntsandstein cycles probably reflect climatic variations.

Three types of solar-induced climatic cycles exist, namely precession, obliquity and eccentricity (Berger et al., 1989), of which the latter cycle, with a periodicity of 100 000 years, has been shown to be the most prominent in continental deposits (Yang & Baumfalk 1991).

Within the Buntsandstein succession up to the base of the Röt Formation (= base Anisian), a total of 71 third-order sequences has been identified (Table 1). This succession corresponds to the Late Permian to Scythian (Van Adrichem Boogaert & Kouwe 1994). The exact location of the Permo-Triassic boundary within the Lower Buntsandstein Formation is unknown, but based upon recent investigations in Poland it is assumed to be situated in the lowermost part of the formation, in the M1 or M2 sequence (R. Wagner, pers. comm.). This leaves 69 to 70 sequences of Scythian age. There is some debate concerning the duration of the Scythian (Menning 1995), but this

Table 2. Estimated minimum durations of the 1st-order sequences of Scythian age in the Netherlands.

1st-order sequence	Duration (Ma)	
	This study	Menning (1995)
Solling	1.0	1.0
hiatus	*1.5*	
Hardegsen	2.0	2.0
Detfurth	0.5?	1.0
hiatus	*0.5*	
Volpriehausen	1.8	1.6
hiatus	*0.5*	
Rogenstein	1.4	1.6
Main Claystone	0.8*	1.6

* Total duration 1.2 Ma; partly Late Permian.

stage is now generally considered to represent 10 Ma. The average duration of the sequences would then be 130 000 years. Taking into account observed erosional hiatuses, this average duration would most likely correspond to the 100-ka eccentricity cycles, in which case 70% of the Scythian would be represented by sediments. There are no data on the durations of the hiatuses below the Volpriehausen, Detfurth and Solling Sequences, but based upon the thicknesses of eroded sequences, it is estimated that the hiatus between the Hardegsen and Solling Sequence is the longest (Table 2).

It is also possible to calculate the duration of the other sequences; the 100-ka or 3rd-order sequences are grouped into 2nd-order sequences, with a duration of 400 to 500 ka. According to Berger et al. (1989) these would also be attributed to variations in the eccentricity. The 1st-order sequences range from a questionable 0.5 to 2 Ma (Table 2). The 4th and 5th-order sequences probably reflect obliquity (35 and 44.3 ka) and precession (17.6 and 21 ka), but there is not enough data to prove this.

There is generally good agreement between the 1st-order sequence durations presented in Table 2 and the time scale published by Menning (1995). Note that these durations represent minimum values only, based upon the number of 3rd-order sequences, whereas Menning's results were obtained in an integrated time analysis, comprising the hiatuses.

The 100-ka sequences correspond to variations in humidity (Perlmutter & Matthews 1990). The claystones reflect humid periods, with maximal extension of the lake and coarse clastic input only at the basin margins. The sandstones were deposited during dry periods, when clastics built out towards the centre of the lake. This is documented by the widespread occurrence of aeolian sandstones in central parts of the basin, notably in the VVS, VS and DS Sequences.

Lower and Middle Buntsandstein tectonics

Although the study was not focused upon an interpretation of the tectonics influencing the Buntsandstein deposition, some important observations can be made. During the deposition of the Lower Buntsandstein Formation, no faulting took place in the study area, and subsidence was most likely of thermal origin. During the deposition of the Main Buntsandstein Subgroup and the Solling Formation, the so-called Hardegsen Phase led to the formation of a pronounced relief of swells and lows (Figures 9, 12). This phase is actually made up of three rifting pulses, prior to the deposition of the Volpriehausen, Detfurth and Solling Sequences, respectively (Figure 12). The last pulse was the strongest and caused deep erosion on the swells. Between these rifting pulses, thermal subsidence prevailed, as is indicated by the uniform thickness development.

Accumulation rates

Based upon an average duration of the 3rd-order sequences of 100 ka discussed above, the accumulation rates of the sequences in the Netherlands can be calculated. The accumulation rates of the Main Claystone Sequence (Figure 11A) show an increase from less than 10 cm/ka in the southwest (basin-fringe area) to over 15 cm/ka in the northeast; the highest rates of over 20 cm/ka occurred in the Roer Valley Graben. Note that there is no influence yet of the Netherlands Swell. The accumulation rates of the lower sequences (M1–M4) show more variation than these of upper sequences. The lower sequences are probably somewhat reduced in thickness in the basin-fringe area.

The accumulation rates for the Rogenstein Sequence (Figure 11B) show a gradual increase from less than 10 cm/ka in the southwest to over 15 cm/ka in the northeast. In the upper part of this sequence, the rates decreased to less than 10 cm/ka.

The VS and VVS Sequences of the Volpriehausen Sequence show a large variation in accumulation pattern, which was probably controlled by erosion and faulting. Accumulation during deposition of the VW and VA Sequences is generally less than 10 cm/ka, but shows a more differentiated pattern than during the Main Claystone and Rogenstein Sequences, with higher subsidence rates in the Roer Valley Graben and the Ems Low than on the Netherlands Swell (Figure 11C). The database of this study did not comprise enough data on the Detfurth and younger sequences to calculate their accumulation rates.

Compared to other continental deposits (cf. Yang & Baumfalk 1991), the accumulation rates calculated for the pre-Detfurth part of the Buntsandstein can be considered as slightly lower than average values, which lie around 20 cm/ka.

Conclusions

The conclusions of this study can be summarised as follows:

1. The cyclic character of the fluvio-lacustrine Buntsandstein allows a very good correlation between the Netherlands and Germany. The observed high-resolution, 3rd-order, sequences most likely correspond to the 100-ka cycles, and reflect variations in humidity.
2. Prominent sequence boundaries exist at the bases of the Volpriehausen, Detfurth, Solling and Upper Röt Sequences. They have been identified on the basis of truncation of the underlying sequences and associated widespread deposition of sands.
3. During deposition of the Main Claystone Sequence, the Netherlands Swell had not yet come into existence as a separate positive element. The greatest subsidence took place in the Roer Valley Graben and Ems Low. The central and western parts of the Netherlands onshore and adjacent offshore area subsided at a lower rate. The area of lesser subsidence encompassed the Off Holland Low.
4. During the deposition of the Rogenstein Sequence the Netherlands Swell subtly influenced the facies distribution. In the Ems Low, brackish-water oolites occur already in the R1 sequence, whereas on the central part of the swell and to the west of it, the first oolites occur in the R5 sequence.
5. The updoming of the Netherlands Swell post-dates the deposition of the Volpriehausen Sequence. The first upward movements occurred prior to the Detfurth Sequence, while the strongest movements occurred prior to the Solling Sequence (Figure 12).
6. During the deposition of the Main Buntsandstein Subgroup, the Netherlands Swell formed a positive element on which, due to the erosion phases corresponding to the well-developed 'V', 'D' and 'H' Unconformities, only reduced thicknesses of stratigraphically incomplete Buntsandstein sections can be observed.
7. The relatively great subsidence of the Roer Valley Graben, West Netherlands Basin and Off Holland Low post-dates deposition of the Rogenstein Sequence. The great thicknesses of sandstones in these lows occur in the VVS, the VS and the lower part of the VW Sequence. These lows formed fluvial palaeovallies, in which thick sandy deposits were laid down. The eastern boundary of the palaeovalley was structurally controlled and was formed by the Netherlands Swell.
8. The accumulation rates calculated for the pre-Detfurth part of the Buntsandstein are slightly lower than the average of about 20 cm/ka calculated for continental deposits by Yang & Baumfalk (1991).

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Appendix 1

Statistical analysis of thicknesses (m) of Buntsandstein sequences below the Hardegsen Sequence.

	Total Netherlands (n = 80)		Ems Low (n = 10)	
Sequence	Mean	Stand. dev.	Mean	Stand. dev.
DC*	25.5	12.6	25	6.2
DS*	19.5	10.8	29.3	5.2
VA5	8.9	3.6		
VA4	12.2	6.7		
VA3	12.2	4.8		

Statistical analysis of thicknesses (m) of Buntsandstein sequences below the Hardegsen Sequence.

	Total Netherlands (n = 80)		Ems Low (n = 10)	
Sequence	Mean	Stand. dev.	Mean	Stand. dev.
VA2	7.5	3.4		
VA1	8.3	1.6	7.1	1.3
VW7	6.7	1.8	7.7	1.8
VW6	7.9	2.0	9.1	1.5
VW5	7.9	1.8	7.9	1.1
VW4	9.7	2.7	10.3	1.7
VW3	15.0	3.1	15.6	1.7
VW2	9.4	3.4	10.7	3.8
VW1	12.7	2.8	12.6	2.2
VS*	17.4	11.0	14.4	6.7
VVS*	26.0	12.2	–	–
R14				
R13	5.7	1.7	5.7	1.9
R12	9.2	2.9	9.1	3.9
R11	9.9	2.6	11.5	1.9
R10	7.7	2.3	8.2	2.5
R9	8.9	2.2	9.0	1.9
R8	13.0	3.1	15.3	2.1
R7	20.6	6.7	26.9	5.6
R6	13.5	5.3	11.5	2.2
R5	16.2	3.5	18.7	2.7
R4	15.4	4.9	18.4	2.9
R3	12.1	4.3	15.7	4.0
R2	9.7	4.0	11.1	4.7
R1	10.6	4.0	12.4	3.3
M10	19.6	5.3	24.0	3.2
M9	16.2	4.2	17.5	1.8
M8	16.0	6.0	19.8	3.5
M7	13.0	2.8	13.5	1.7
M6	10.8	2.8	11.9	2.0
M5	11.5	3.0	13.8	3.0
M4	16.8	4.9	18.8	3.4
M3	17.4	6.5	20.1	4.1
M2	16.1	5.0	17.7	1.0
M1	14.4	4.0	14.2	3.4
Br	14.4	5.3	16.3	3.3

Sequences listed are 3rd-order sequences, except for sequences marked with an asterisk *, which are 2nd-order sequences. The stratigraphy of these sequences is shown in Table 1. Thickness data have been calculated directly in the spreadsheet and average values and standard deviations were calculated for the total database of 80 wells. The results show the highest standard deviations in the sandstone deposits, reflecting the great differences in thickness between the lows and the swells. The total database comprises wells from the basin margin with reduced sequences and wells from the lows with more complete sequences. To test the effects of different settings a subset of data from the Ems Low (10 wells) was also worked out. The general trend derived from this is, that for approximately 85% of the sequences the standard deviation is equal to or lower, sometimes much lower, than for the entire dataset, as one would expect. For the remaining 15%, four cases, the standard deviation is higher than in the complete dataset. In the case of the R12 and R13 sequences this can probably be attributed to the erosional effect below the Volpriehausen Unconformity. For the other two sequences, VW2 and R2, the higher standard deviation is caused by one well, where these sequences are much thicker. This probably reflects local effects on the accommodation, either caused by erosion or by subsidence.

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