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The northern Upper Rhine Graben: basin geometry and early syn-rift tectono-sedimentary evolution

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Abstract A large-scale transfer zone subdivides the northern parts of the Upper Rhine Graben into a northern and a southern sub-basin. These sub-basins display the geometry of asymmetric half-grabens with opposing tilt directions. The transfer zone connects the western master fault of the northern half-graben with the eastern master fault of the southern half-graben. In the northern Upper Rhine Graben early syn-rift sedimentation (Late Priabonian to Late Rupelian) was controlled by the tectonically induced subsidence of these half-grabens (autogenetic), as well as by regional third-order sea level variations (allogenetic). Within the graben, lateral changes in subsidence rates (in dip and strike direction of fault blocks) controlled the development of accommodation space and thus, sediment thickness and facies. Furthermore, a low-displacement segment along the western border fault acted as a sediment entry point. Tectonics controlled the distribution of early syn-rift deposits and the palaeogeography of the northern Upper Rhine Graben.

Keywords Upper Rhine Graben · Transfer zone · Early syn-rift stage · Tectonics · Sedimentary cycles

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Introduction

Several generations of workers have analysed the structure and sedimentary fill of the Upper Rhine Graben from various points of view (e.g. Doebl and Malz 1962; Schad 1962; Illies 1965, 1981; Martini 1973; Teichmüller and Teichmüller 1979; Sittler and Schuler 1988; Mauthe et al. 1993; Gaupp and Nickel 2001).

This paper integrates new tectonic interpretations and high-resolution sequence stratigraphy to bring new insight into the evolution of the northern parts of the Upper Rhine Graben. Such an approach is required as today mechanisms of rifting and sedimentary models for extensional basins are better understood based on the analysis of ancient and recent graben systems, such as the Gulf of Corinth (Gawthorpe et al. 1994), continental rift systems (Lambiase and Bosworth 1995; Howell and Flint 1996), and individual oil fields in the Norwegian offshore (Badley et al. 1984).

The objective of this study on the northern parts of the Upper Rhine Graben is the analysis of its structural configuration and evolution and their effects on syn-rift sedimentation throughout Cenozoic time. We specifically focus on the early syn-rift stage that lasted from Late Eocene to Early Oligocene. For this phase, key structural elements are identified and integrated into a tectonic model. The structural control on sediment transport and deposition is interpreted in term of third-order eustatic cyclic sedimentation. It will be shown that an understanding of the early syn-rift tectonic framework of the northern Upper Rhine Graben is fundamental to the interpretation of depositional environments of its basin fill during the above time span, as well as to the identification and prediction of potential reservoir rocks.

Field of study and data base

This study focuses on the northern parts of the Upper Rhine Graben that are bounded to the West by the

Mainz Basin and to the East by the Odenwald Massif (Fig. 1).

Our interpretations are based on the analysis of about 300 km of 2D reflection-seismic profiles that cover much of the study area and that were generously made available by the German oil industry. As these seismic lines were recorded to 3s two-way-travel time (TWT), they permit to study the entire Cenozoic syn-rift succession, as well as part of the pre-rift strata. Most of the seismic sections (with some exceptions) were not migrated. The seismic data were primarily used for structural analyses and secondarily for the definition of the seismic facies.

Wireline logs, descriptions of cores and cuttings, and palaeontological informations from about 77 oil wells were used in addition to the seismic sections. All wells reached the base of the Cenozoic. Self-potential (SP), resistivity (RES), and caliper (CAL) logs were available for all wells, whereas gamma ray (GR) and sonic logs (SN) were recorded only in some of them. These wells provided lithologic and stratigraphic information, and allowed a sequence stratigraphic interpretation of the sedimentary fill of the northern Upper Rhine Graben. In some of the wells, check-shots and synthetic seismograms permitted to calibrate the seismic profiles.

Time-equivalent sediments to those penetrated by the wells were studied in outcrops on the Mainz Block and in the southern parts of the Upper Rhine Graben in an effort to improve the sedimentologic interpretation of well logs and to understand lateral facies variations within the northern parts of the basin.

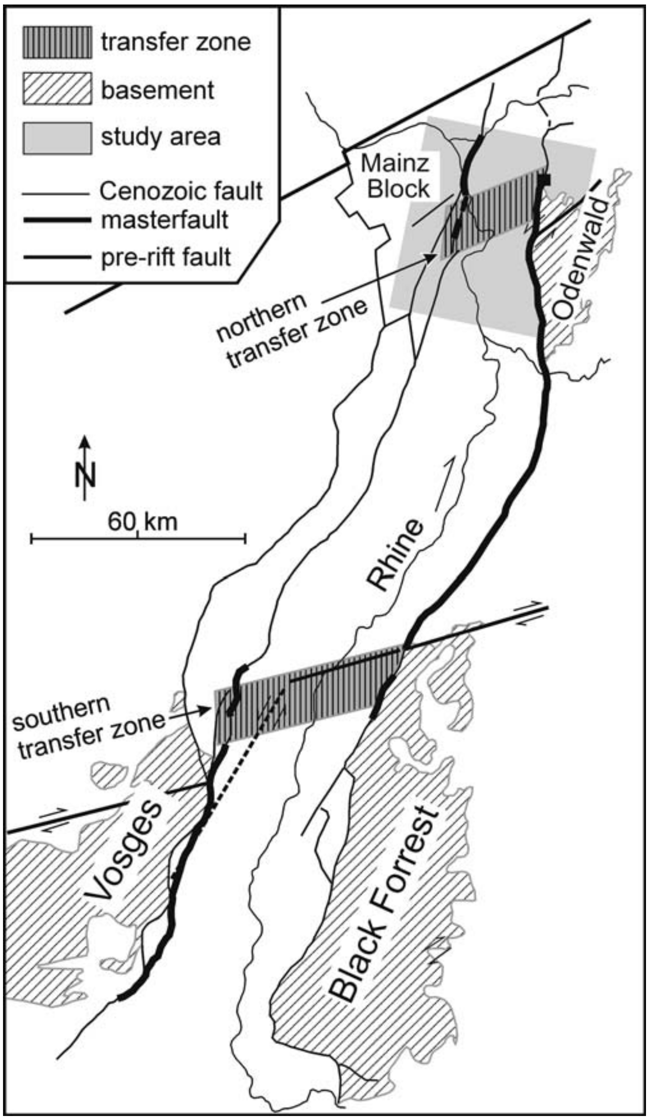


Fig. 1 The study area in the Upper Rhine Graben (*shaded rectangle*). Location of the northern (Derer et al. 2003) and southern transfer zone (interpreted from Mauthe et al. 1993). Note how the masterfault switches side at the transfer zones

Methods

Our sequence stratigraphic concept applied to the northern Upper Rhine Graben combines the "base-level approach" of Wheeler (1964) – updated and condensed for practical use by Cross and Homewood (1997), Cross and Lessenger (1998), Homewood et al. (2000), and Schäfer (2004) – and structural models for extensional basins of Gawthorpe and Hurst (1993), Gawthorpe et al. (1994, 1997), Lambiase and Bosworth 1995, and Howell and Flint (1996).

Lithological and wire-line logs of several wells were used in the interpretation of sedimentary facies. Combined with palaeontologic and palaeoecologic data, these provided the means for stratigraphic and sedimentologic interpretations.

The seismic sections were primarily used for the analysis of structural features at different scales. Moreover, as they revealed to be of fundamental importance for the interpretation of sedimentary sequences in the extensional basins, they were also used for the definition and identification of early syn-rift sediments. In this respect, seismic data were calibrated with well data, using velocity information from check-shots for the identification of seismic reflectors and lithologic markers.

In sedimentary basins, the stratigraphic base-level is an abstract (non-physical), continuous surface, that rises and falls with respect to the Earth's surface (Wheeler 1964). Sediment accumulation occurs only when between the base-level and the surface of the solid Earth accommodation space is available. If the base-level is below the surface of the Earth, sediment will be eroded and transported downhill (down-gradient) to the next location, where accommodation space is available (where the base-level is above the Earth's surface).

In this sense, within the sedimentary basins, the up- and downward movements of the base-level produce the sedimentary record. When base-level rises (base-level rise hemicycle), its intersections with the seaward-tilted surface of the Earth move up-gradient (uphill). Thus, it creates more accommodation space, in both marine and continental environments (Cross and Homewood 1997). In this accommodation space, sediment will be deposited, if available. When the base-level falls (base-level fall hemicycle), accommodation space decreases and sediment is eroded, when the base-level falls below the Earth's surface.

During base-level cycles (one cycle consists of one rise plus one fall hemicycle) the depositional environments (i.e. facies tracts) move uphill and downhill (up-gradient and down-gradient). They generate associated vertical successions of facies bounded by unconformities (i.e. Walther's law of the correlation of facies; Cross and Homewood 1997). Consequently, the sedimentary record of a base-level cycle contains vertical successions of facies interrupted by surfaces of unconformity.

The stratigraphic base-level describes the relationship between processes which create and remove accommodation space, and processes which bring sediment to or remove sediment from this accommodation space (Cross and Homewood 1997). Thus, for practical reasons, the movements of the base-level are explained by the interaction between the variation of accommodation space (A, space available for sedimentation in a certain time interval) and sediment supply (S, volume of sediments available in the same time interval). It is the ratio between accommodation space and sediment supply (A/S ratio), that controls the build-up of sedimentary sequences (e.g. Cross and Lessenger 1998).

The creation of accommodation space is a function of the interplay between subsidence of the basin floor (tectonics, isostatic response to water and sediment loads, compaction), sea-level fluctuations, or lake and groundwater level fluctuations in continental settings.

During a base-level rise hemicycle, the creation of accommodation space exceeds the sediment supply. In this case, the depositional environments move up the depositional gradient (distal environments move into more proximal positions). They form an associated vertical rock succession in which facies becomes more distal towards the top (e.g. deepening upward successions in marine settings, or meandering river deposits on top of braided river deposits in continental settings).

During a base-level fall hemicycle, the creation of accommodation space cannot keep pace with the sediment supply. Thus, the accommodation space will be filled and sediment bypassing and even erosion occurs, while the depositional environments move down the depositional gradient. The associated vertical rock succession has more proximal facies towards the top and is characterised by surfaces of unconformity (e.g. shallowing upward succession in marine settings). In extreme cases, no sedimentary record is preserved due to bypassing and erosion.

When the creation of accommodation space keeps pace with the sediment supply, sediments may accumulate at different rates, creating a complete rock record with conformable strata.

The transition from a base-level rise to a base-level fall hemicycle (called rise-to-fall turnaround) is characterised by the maximum A/S ratio. The rise-to-fall turnaround corresponds to a condensed section in distal marine settings and to the maximum flooding surface in marginal marine environments (in terms of the sequence stratigraphic nomenclature, e.g. Van Wagoner et al. 1990; Coe et al. 2003).

The minimum of the A/S ratio is recorded at the change from a base-level fall to a base-level rise hemicycle (called fall-to-rise turnaround). It displays an incomplete depositional record. If it is a major erosion surface it could be interpreted as sequence boundary (in terms of the sequence stratigraphic nomenclature), provided it has a clear regional significance.

The correlation of base-level cycles in the northern Upper Rhine Graben was only possible after its structural configuration was understood. Lateral variations in accommodation space and sediment supply were, to a large extent, controlled by the subsidence pattern of its individual fault blocks, as evident also in other extensional basins (see the above references). The complex

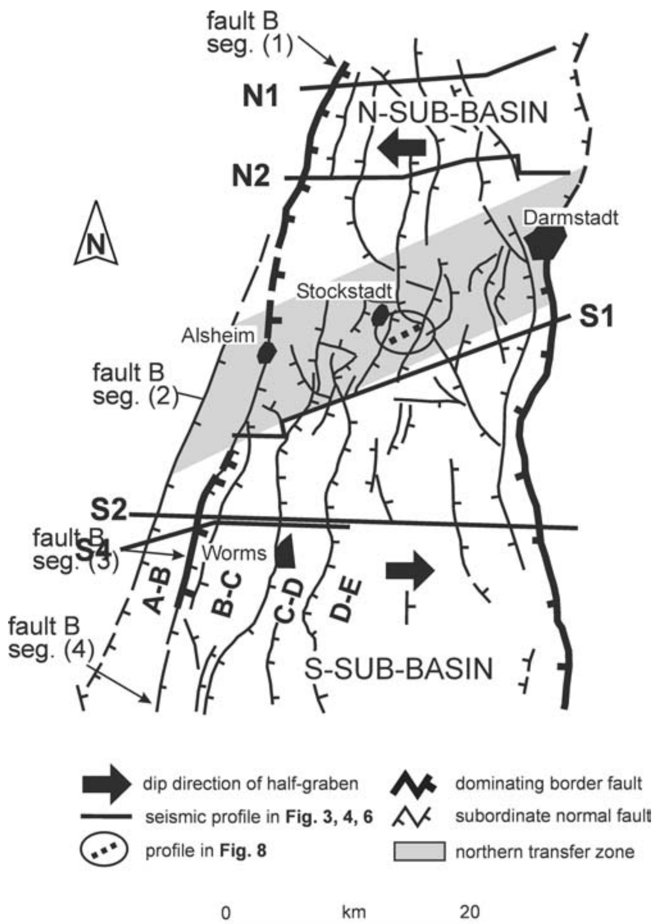


Fig. 2 Structural map of the northern Upper Rhine Graben, modified from Andres and Schad (1959), Straub (1962), Stapf (1988), Durst (1991), Plein (1992), Mauthe et al. (1993), and Jantschik et al. (1996). The northern transfer zone separates two half-grabens with opposite tilt directions. The seismic sections N1, N2, S1, and S2 are shown in Fig. 3, the seismic section S4 and its depth converted interpretation in Fig. 4

basin geometry, and particularly lateral subsidence variation in depositional strike and dip directions has to be taken into consideration. On the other hand, Rupelian eustatic sea level fluctuations, as discussed by Sissingh (1997, 1998, 2003) and Schäfer et al. (2005; this volume), gave rise to a base-level cyclicity that can be resolved in the Upper Rhine Graben by our base-level approach. In this sense, the rise-to-fall turnarounds at different scales allowed correlations of sedimentary sequences.

Tectonic settings

Following its initiation during the Late Eocene, the northern Upper Rhine Graben underwent three main subsidence episodes during the Late Eocene to Early Oligocene, Latest Oligocene to Early Miocene, and Pliocene to Quaternary (Illies 1965, 1978; Teichmüller and Teichmüller 1979; Pflug 1982; Meier and Eisbacher 1991; Schumacher 2002). A major transfer zone, here referred to as the northern transfer zone, had a bearing on the structural configuration of the northern parts of the Upper Rhine Graben during its entire Cenozoic evolution (Derer 2003; Derer et al. 2003). Along the Darmstadt–Stockstadt–Alsheim transect, this transfer zone strikes NE–SW. It subdivides the northern parts of the Upper Rhine Graben into a northern and a southern half-graben with opposite polarity (Figs. 2 and 3). Whereas the depocentre of the northern sub-basin is located adjacent to the western border fault of the graben, the depocentre of the southern sub-basin is associated with its eastern master fault. This transfer zone, an antithetic interference zone after the geometric nomenclature of Gawthorpe and Hurst (1993), influenced the geometry of the northern Upper Rhine Graben throughout its entire evolution. It corresponds to a structurally elevated domain and, at times, a palaeotopographic barrier between the northern and southern sub-basins (Derer 2003; Derer et al. 2003; also see below).

The NE–SW striking (Variscan strike) northern transfer zone (Fig. 1) is located in the vicinity of a Variscan shear zone (Krohe 1992), near the boundary

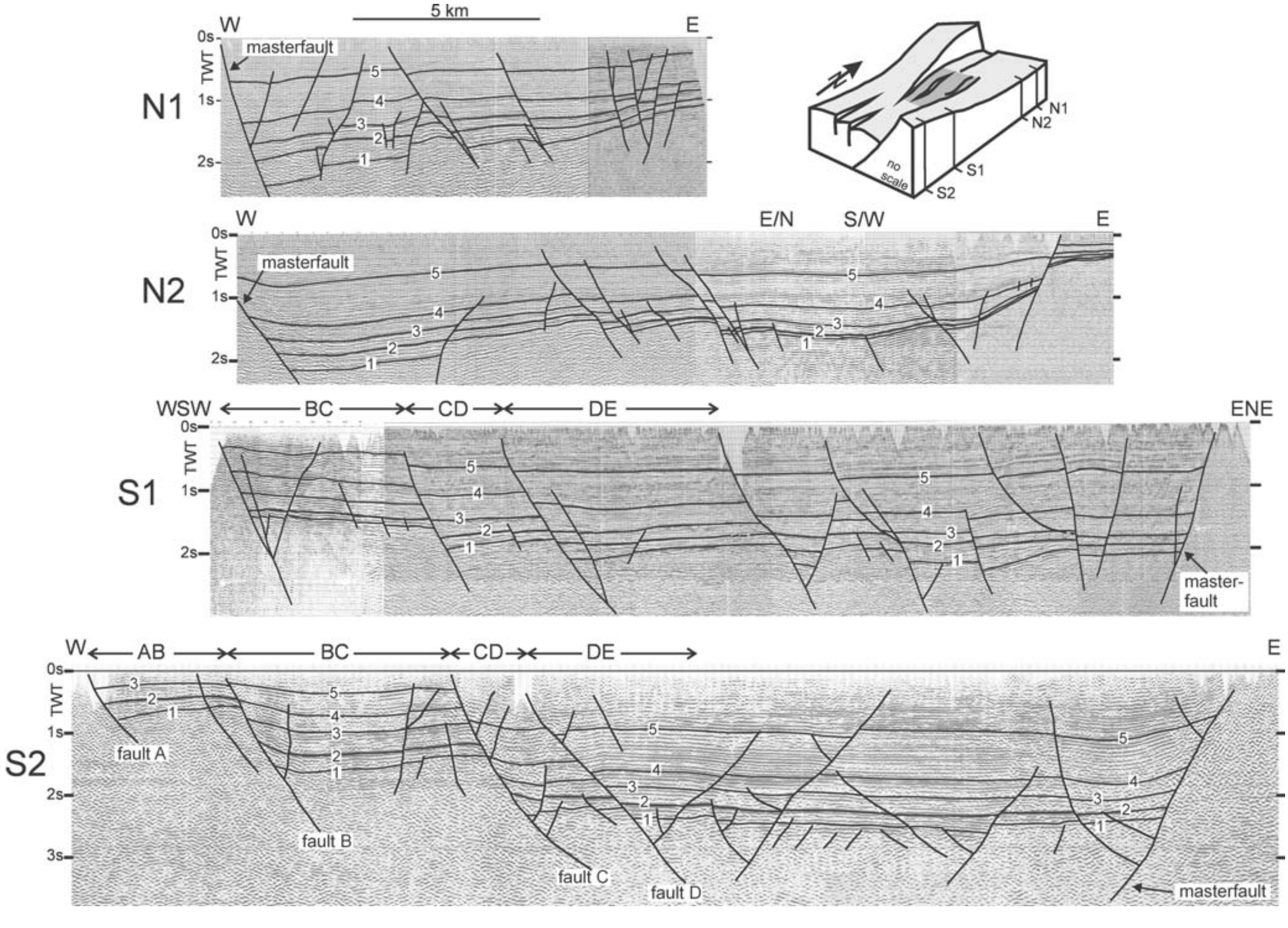


Fig. 3 Interpreted seismic sections across the northern Upper Rhine Graben, showing opposing tilt of the northern (N1 and N2) and southern sub-basins (S1 and S2); the location of the sections is shown in Fig. 2. *Vertical scale* in seconds two-way travel time. The *3D-block* gives a simplified model of the transfer zone and the two half-grabens. The stratigraphy is as in Fig. 5: *1* top pre-rift, *2* top Rupel Clay, *3* top Niederrödern Layers, *4* top Corbicula Beds, and *5* top Hydrobia Beds. Seismic section S2 (part of DEKORP 9N) is based on data from the GeoForschungsZentrum Potsdam

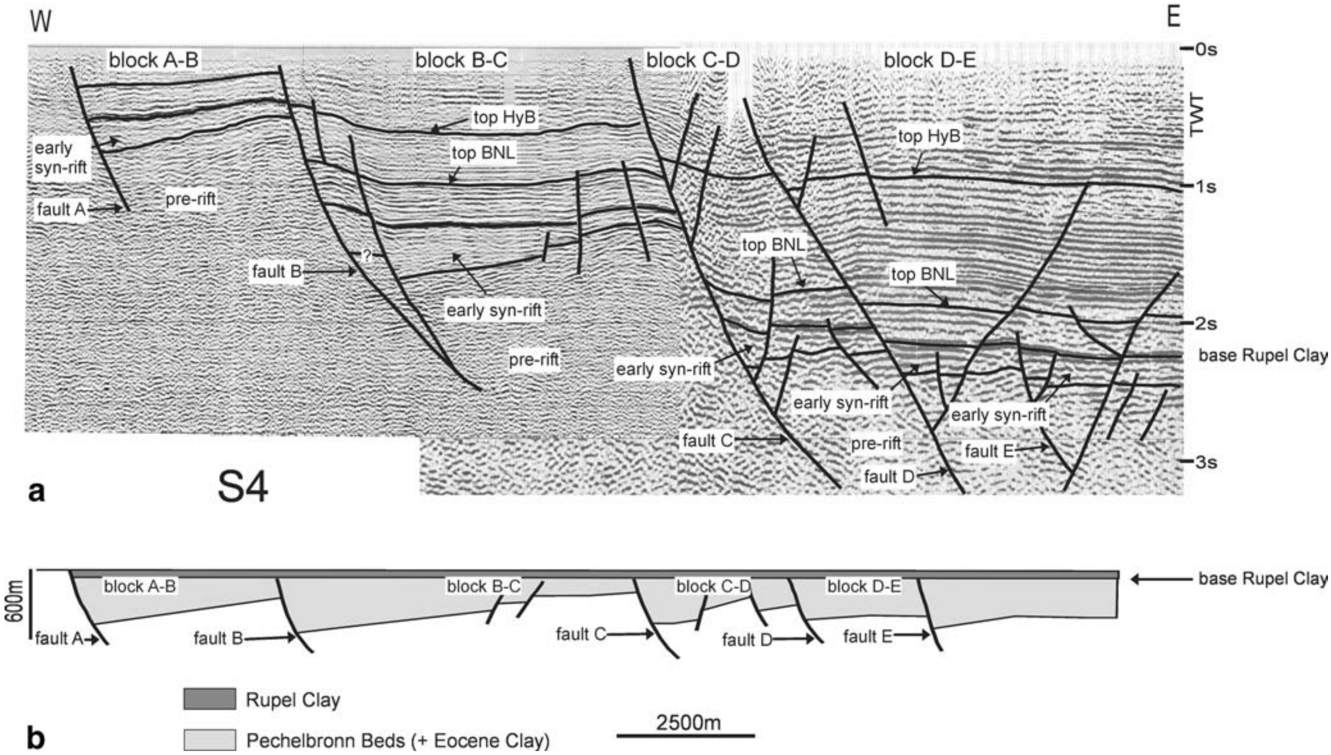


Fig. 4 Composite seismic section S4. **a** Several intermediate-scale tilted fault blocks are bounded by growth faults (TWT two-way travel time in seconds). *BNL* Niederrödern Layers, *HyB* Hydrobia Beds. Location in Fig. 2. **b** Palinspastically restored and depth-converted cross section of the early syn-rift graben fill, derived from the seismic section S4 (restoration datum is base of Rupel Clay). Note the half-graben geometry of the individual depocentres

between the Permo-Carboniferous Saar-Nahe Basin and the Odenwald-Spessart High (Schäfer and Korsch 1998). Consequently, development of this transfer zone probably involved the reactivation of an inherited Late Palaeozoic structure (Derer 2003).

A similar transfer zone is evident in the southern parts of the Upper Rhine Graben, across which the master fault shifts from the eastern to the western graben margin (Pflug 1982; Mauthe et al. 1993; Schumacher 2002) (Fig. 1). As this southern transfer zone is associated with the Variscan Baden-Baden-Lalaye-Lubine fault zone, reactivation of Variscan structures had apparently also in the southern parts of the Upper Rhine Graben a bearing on its geometry (Mauthe et al. 1993; Schumacher 2002).

At a subordinate scale, the half-grabens and the transfer zone of the northern Upper Rhine Graben are characterised by synthetic and antithetic faults, sub-parallel to the graben shoulders. These faults delimit intra-basinal fault blocks (Figs. 2 and 3), and are associated with minor depocentres that formed isolated basins during the early stages of graben formation (see below).

The initial Late Priabonian to Rupelian subsidence phase of the northern parts of the Upper Rhine Graben (early syn-rift stage) was controlled by a pulse of approximately WNW–ESE directed extension (Illies 1978; Meier and Eisbacher 1991; Schumacher 2002), initiating the subsidence of minor half-grabens. These early syn-rift deposits are bounded by horizons 1 and 2 (Fig. 3). A left-lateral strike–slip regime controlled the subsequent (post-Rupelian) main subsidence episodes of the graben (Illies 1978; Schumacher 2002) during which Late Eocene to Early Oligocene faults were selectively reactivated. In the process of this the graben narrowed, as evident by the abandonment of some of the western marginal half-grabens (blocks A–B and partly B–C in section S2) and the continued subsidence of the segment between fault C and the eastern master-fault (Fig. 3).

The character of the postulated strike–slip regime has been subject of debate. Bergerat (1987) assumed that steeply dipping faults behaved during the Aquitanian as right-lateral strike–slip faults, whereas Meier and Eisbacher (1991) described a rotation of the extension direction from WNW–ESE during the Rupelian to NE–SW during the Aquitanian. This probably fits with the average NNW-strike direction of the normal faults that were active during the Late Chattian to Aquitanian or Burdigalian (Cerithium to Hydrobia Beds; Schad 1964; Illies 1974; Manfred Lutz personal communication 2004).

Early syn-rift stage of the northern Upper Rhine Graben

The Late Priabonian to Late Rupelian early syn-rift stage of the northern Upper Rhine Graben, as defined in this study, was controlled by WNW–ESE directed extension. In the study area, the geometry of early syn-rift depocentres and of their sedimentary fill was defined on the basis of seismic lines and calibrating well control. The early syn-rift depocentres are located on the dip-slopes of rotated fault blocks that are bounded by growth faults and thus are contained in half-grabens (Fig. 4). The sedimentary fill of these half-grabens is wedge-shaped with thickness increasing and internal reflectors diverging towards the fault scarp of the adjacent footwall block. This implies syn-sedimentary fault activity and hanging-wall rotation. The early syn-rift units include the Eocene Clay, the Pechelbronn Beds (Late Priabonian to Early Rupelian), and the Rupel Clay (Late Rupelian, Fig. 5) (Derer 2003). In the following discussion we will mainly consider the last two units, as the occurrence of the Eocene Clay is too isolated to permit a sequence stratigraphic analysis.

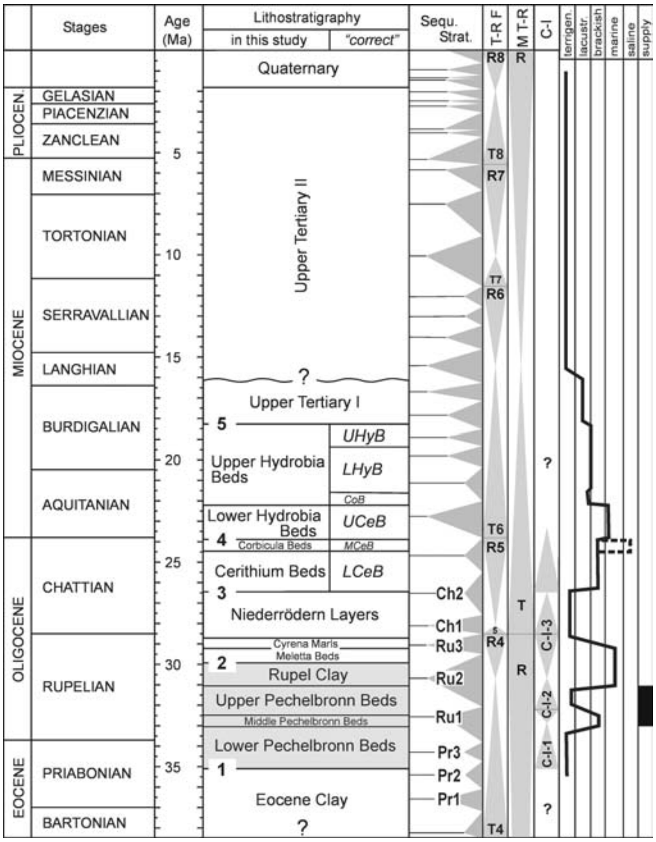


Fig. 5 Cenozoic stratigraphy in the northern Upper Rhine Graben, as from German Stratigraphic Commission (2002). The Miocene lithostratigraphic units used in this study correspond to the oil industry classification, which differs from the actual "correct" stratigraphy. *LCeB*/*MCeB*/*UCeB* Lower/Middle/Upper Cerithium Beds, *CoB* Corbicula Beds, *LHyB*/*UHyB* Lower/Upper Hydrobia Beds. The columns 'Sequence Stratigraphy', 'T–R F' (transgressive–regressive facies cycles) and 'M T–R' (major transgressive–regressive cycles) are according to Hardenbol et al. (1998). Base-level cycles are interpreted by Derer (2003), Derer et al. (2003), and in this study. *Bold numbers 1– 5* correspond to horizons of Fig. 3. The early syn-rift succession is in the Pechelbronn Beds and Rupel Clay. The early syn-rift brackish and marine events of the graben probably had the same regional causes as the Ru 1 and Ru 2 floodings. 'Supply' (*black*) marks the interval of sediment input through the low-relief zone of the western border fault

In most of the study area, early syn-rift sedimentation commenced with the Pechelbronn Beds, which unconformably rest on Permian pre-rift strata. The early syn-rift succession of the Pechelbronn Beds and Rupel Clay can be subdivided into two large-scale base-level cycles referred to as C-I-1 and C-I-2 (Fig. 5; Derer 2003; Derer et al. 2003). These cycles, which can be correlated across the entire study area, mark major reorganisations in the depositional history and the palaeogeographic framework of the northern Upper Rhine Graben. In terms of their time span, these cycles reflect a third-order stratigraphic cyclicity (0.5–3Ma according to Duval et al. 1998).

Cycle C-I-1 is a rise-asymmetric cycle and comprises the Lower Pechelbronn Beds and the lower part of the Middle Pechelbronn Beds. The Lower Pechelbronn Beds consist of fluvial, interfluvial, and lacustrine sediments (e.g. Gaupp and Nickel 2001; Derer et al. 2003). During the Early Rupelian, these deposits were transgressed and covered by the Middle Pechelbronn Beds which were deposited in a brackish lake, with variable salinity, that covered almost the entire Upper Rhine Graben (e.g. Doebl and Malz 1962; Duringer 1997; Gaupp and Nickel 2001). It is still controversial, whether open communication existed between this lake and a marine basin, such as the Molasse Basin to the South (Duringer 1997; Sissingh 1998). However, this Early Rupelian rise in base-level is time-equivalent to the third-order Ru 1 flooding, that is evident in several European basins (Fig. 5) (Schäfer et al. 2005). Hence, it is probable that a eustatic rise in sea level (Ru 1), combined with tectonic subsidence, induced this rise of the base-level in the Upper Rhine Graben, probably involving a rise of the ground water level (Grimm et al. 2000). In the study area, the Middle Pechelbronn Beds are represented by fluvial/alluvial, brackish shoreface, and offshore systems. The turnaround between cycle C-I-1 and C-I-2 (located within the Middle Pechelbronn Beds) records conditions of maximum flooding and the availability of maximum accommodation space.

Cycle C-I-2 consists of a base-level fall and a base-level rise hemicycle (Fig. 5). The fall hemicycle (upper part of the Middle Pechelbronn Beds) records a general retreat of the brackish environments and the progradation of shorelines, up to subaerial exposure. During the C-I-2 rise hemicycle, the fluvial and interfluvial sediments of the Upper Pechelbronn Beds accumulated, they interfinger in local depocentres with remnant brackish deposits. During the Late Rupelian transgression, the open-marine shales of the Rupel Clay covered these sediments. This transgression corresponds to the Ru 2 flooding (Grimm et al. 2000; Derer 2003) that is also recorded in other European basins. During this time, the Upper Rhine Graben corresponded to an intermittent seaway that connected the marine Molasse and North Sea Basins (e.g. Doebl 1967; Berger 1996; Sissingh 1998). The upper boundary of cycle C-I-2 is located within the Rupel Clay.

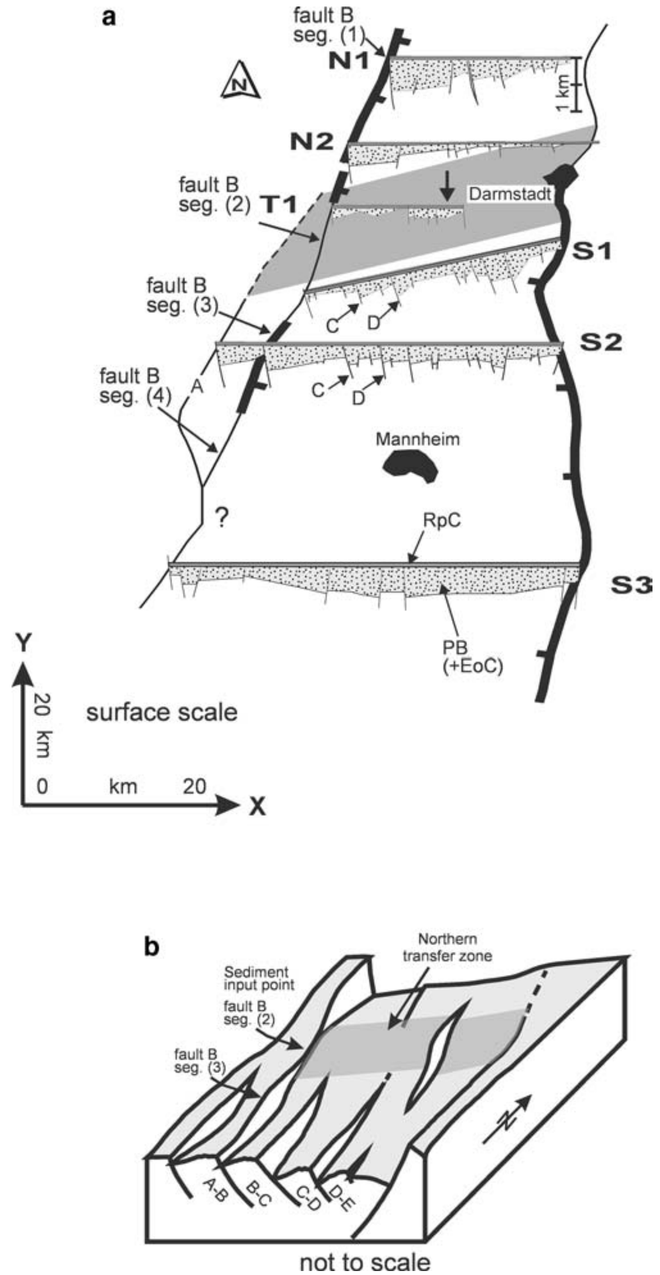


Fig. 6 Palinspastically restored cross-sections, depth-converted, and with a restoration datum at the top of the early syn-rift stage, i.e. the base of the Rupel Clay (modified from Derer 2003). **a** In the northern sub-basin the depocentre is close to the western border fault, whereas in the southern sub-basin it is close to the eastern border fault. Cross-sections N1, N2, T1, S1, and S2 are constructed under use of the industry seismic profiles, in part shown in Fig. 3, yet follow their positions only roughly. Cross-section S3 is derived from Doebl and Teichmüller (1979). Note, the surface scale of the figure is extended in the *X* direction (E–W). The vertical scale valid for all cross-sections is given at N1. The eastern part of the cross-section T1 (*arrow*) is explained with greater details in Fig. 8. **b** The *block diagram* gives a simplified model of part of the Upper Rhine Graben with the fault blocks A–B, B–C, C–D, and D–E at the western part of the southern sub-basin, during the early syn-rift stage. Input of sediment is rich at the position of fault B (seg. 2), at the southwestern end of the northern transfer zone

▶

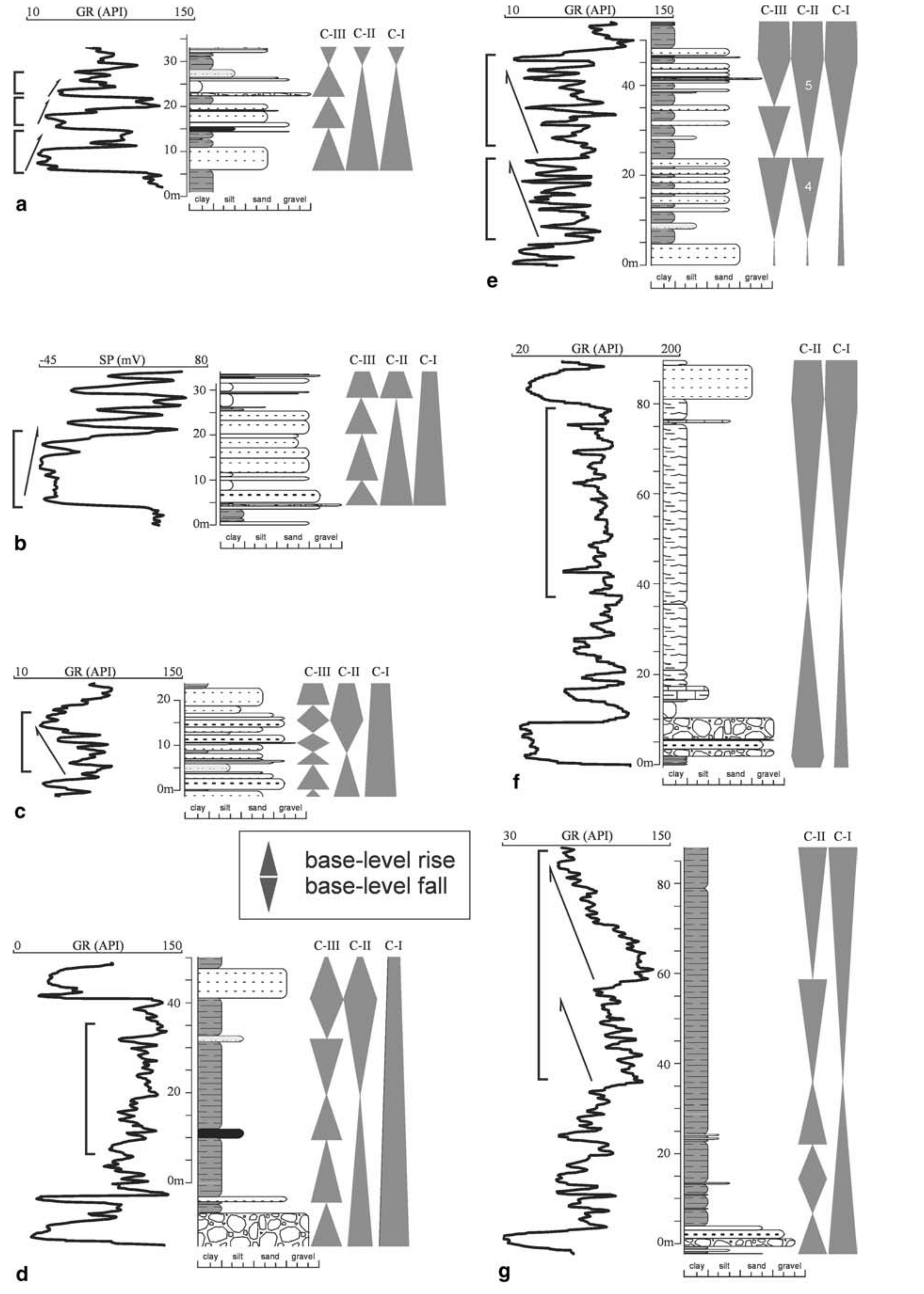
Fig. 7 Early syn-rift facies associations and their possible relation to base-level cycles (C-III small-scale cycles, C-II intermediate-scale cycles, and C-I large-scale cycles). A *bar* marks one single facies association and an *arrow* the fining-up or coarsening-up depositional trend. The logs are gamma ray (GR) or self-potential (SP). Modified from Derer (2003). **a** Fluvial channel/overbank facies association of three superimposed single channels, and the interpreted stacking pattern of base-level cycles. **b** Fluvial facies association of a multi-storey (stacked) channel complex, and the interpreted stacking pattern of base-level cycles. **c** Alluvial fan facies association, prograding and waning, and the interpreted stacking pattern of base-level cycles. **d** Interfluvial/lacustrine facies association (*marked by a bar*), and the interpreted stacking pattern of base-level cycles. The two C-III fall cycles represent splay deposits. **e** Two superimposed delta/shoreface facies associations (*brackish/marine*) and the interpreted stacking pattern of base-level cycles. The intermediate-scale C-II-4 fall cycle was exclusively controlled by increased sediment supply, as it occurs within a large-scale rise cycle. The C-II-5 cycle was controlled both by decreasing accommodation space (recorded also by the large-scale fall) and increasing sediment supply. **f** Offshore brackish/marine facies association (*marked by a bar*) in the Middle Pechelbronn Beds. The small-scale cyclicity in the clay/mudrocks cannot be defined. **g** Offshore marine prograding facies association of the Rupel Clay, deposited in about 100–200 m water depths. The base-level rise-to-fall turnaround could be a condensed

It can be concluded that the two large-scale base-level cycles were – directly or indirectly – related to third-order eustatic sea-level fluctuations, which are evident in several European basins (Derer 2003; Schäfer et al. 2005, this volume). Yet, within the Upper Rhine Graben, the distribution of depositional environments and their stacking during these cycles was essentially tectonically controlled (Derer 2003; Derer et al. 2003), although climatic effects might have played a role as well (Duringer 1997; Gaupp and Nickel 2001).

Early syn-rift tectonic settings

Three main structural elements characterise the early syn-rift basin geometry of the northern parts of the Upper Rhine Graben. These are: (1) the northern transfer zone, (2) a low-displacement segment along the western border fault (fault B), and (3) adjacent subordinate tilted-blocks/halfgrabens (Fig. 6). Interpretation of the early syn-rift structural framework has to take into account that during the Miocene and Plio-Quaternary strike slip regime Late Eocene to Early Oligocene faults were partly reactivated. Nevertheless, most of the early syn-rift structural geometries were preserved.

1. The northern transfer zone, separating the northern from the southern sub-basin, came already into evidence during the early syn-rift stage. It marks the shift of the depocentre from the western to the eastern graben margin (as seen on the restored sections in Fig. 6). Subsidence rates were higher in these sub-basins as compared to the transfer zone that formed a structural and palaeogeographic high. Major axial



a
10 GR (API) 150
C-III C-II C-I
clay silt sand gravel
b
-45 SP (mV) 80
C-III C-II C-I
clay silt sand gravel
c
10 GR (API) 150
C-III C-II C-I
clay silt sand gravel
d
0 GR (API) 150
C-III C-II C-I
clay silt sand gravel
base-level rise
base-level fall
e
10 GR (API) 150
C-III C-II C-I
5
4
clay silt sand gravel
f
20 GR (API) 200
C-II C-I
clay silt sand gravel
g
30 GR (API) 150
C-II C-I
clay silt sand gravel

depositional gradients developed, dipping away from this transfer-zone into the sub-basins, controlling the sediment distribution (Derer et al. 2003).
2. During the early syn-rift stage, displacements along the western border fault (fault B) of the northern Upper Rhine Graben varied along strike (Fig. 6). As fault segment 2 was characterised by reduced displacements as compared to adjacent fault segments to the South and North (Derer 2003), it formed a low-relief zone across which sediments were shed into the graben. This is particularly evident during the upper C-I-1 and the C-I-2 cycles (time of deposition was during the Middle and Upper Pechelbronn Beds).
3. Subordinate growth faults subdivided the transfer zone and the sub-basins into tilted blocks/half-grabens (Fig. 4) forming the basic tectonic building blocks of the northern Upper Rhine Graben. The width and length of these tilted blocks ranges between 2–5.5 km and up to 14 km, respectively. Half-grabens associated with these fault blocks formed minor depocentres. From the leading edge of such footwall blocks accommodation space expanded down-dip towards the adjacent block, thus creating subordinate depositional gradients perpendicular to the graben axis. In such half-grabens, the un-decompacted sediment thickness is variable, but reaches a maximum of ca 500m. The overall arrangement of tilted blocks striking parallel to the graben margins speaks for typical extensional basins.

The combination of these three structural elements generated a complex basin physiography, which influenced the local development of accommodation space. This is, for instance, the case for the tilted-block/half-graben C–D, which is particularly important in the study area (Figs. 2, 4, and 6). From the leading edge of this block accommodation space increased down-dip towards fault C that bounds it to the West (Fig. 4b). The displacement along this fault increased towards the South (Fig. 6), away from the transfer zone. Consequently, subsidence of Block C–D increased in the same direction, creating an axial depositional gradient. Correspondingly, this block formed a ramp-like structure, which dipped southward, away from the transfer zone. On this ramp, sediments were transported into the southern sub-basin. Lateral variations in subsidence rates, both in dip and strike direction, have to be considered in a study addressing the sedimentation history in the northern Upper Rhine Graben – as was done in field studies in the Gulf of Corinth by Gawthorpe et al. (1994) and in the North Sea Graben by Howell and Flint (1996).

Early syn-rift facies associations

In the Pechelbronn Beds and Rupel Clay of the northern Upper Rhine Graben, six key facies associations were identified on the basis of well logs and calibrated by core data (Fig. 7). GR and of SP logs display characteristic shapes (Asquith and Gibson 1983; Cant 1992; Hatsch 1994; Rider 1996) for particular depositional environments of the early syn-rift sediments and reflect specific accommodation space and sediment supply conditions.

Single-storey channels (Fig. 7a)

The single-storey channel facies is composed of a succession of alternating fluvial channels and overbank deposits. The channels have an erosive base and are filled with fine- to medium-grained sandstones (sometimes with subordinate conglomerates). Channel fill and overbank deposits display a fining-upward trend. This association was deposited by low-energy fluvial systems (meandering rivers) with a low sediment load under high rates of accommodation space development. Thus, thick overbank sediments were deposited and preserved.

Multi-storey channels (Fig. 7b)

The multi-storey channel facies is associated with channel amalgamation, which inhibits the preservation of overbank deposits. Stacked channels are the result of low accommodation space development and a large supply of coarse-grained sediments, characteristic for high-energy fluvial systems (braided rivers). Transitional members between the multi-storey and single-storey channel complexes have been observed.

Alluvial fans (Fig. 7c)

Alluvial fan facies associations are characterised by a coarsening upward trend, with grain size increasing from silty mudstones to coarse-grained sandstones and fine-grained conglomerates. From base to top, alluvial fans record an increase in sediment supply and a decrease in accommodation space.

Interfluvial plains and lakes (Fig. 7d)

The interfluvial and lacustrine facies association consists of overbank and lake mudstones and silty mudstones. These are locally bioturbated or contain desiccation structures. Intercalated siltstones and fine-grained sandstones represent splay deposits (which locally form minor coarsening-upward trends). The interfluvial flood plains and lake environments reflect high rates of accommodation space development and a low sediment input.

Delta and shoreface (Fig. 7e)

Coarsening and shallowing upward successions represent delta and shoreface systems. Lithologies gradually change upward from bioturbated mudstone to siltstone to fine- and medium-grained sandstone (sometimes to fine-grained conglomerate). The ratio between accommodation space and sediment supply decreases from base to top of this facies association (either due to decreasing accommodation space or due to extremely high sediment input). Delta and shoreface systems occur in the brackish Middle Pechelbronn Beds. Here, the ostracod association consisting of *Quadracythere* sp., *Cytheridea* sp., *Schuleridea* sp., *Hemicprideis* sp. is typical (Reiser 1992). Delta and shoreface systems occur locally also in the Upper Pechelbronn Beds at the beginning of the second Rupelian transgression which gave rise to the deposition of the Rupel Clay.

Offshore brackish deposits (Fig. 7f)

The brackish facies association occurs exclusively in the Middle Pechelbronn Beds. It represents the distal equivalent of a prograding brackish delta and shoreface systems and contains the same faunal assemblage. This facies association consists of bioturbated mudstones and marlstones with rare thin siltstone and fine-grained sandstone intercalations. It reflects mainly low-energy conditions below storm-wave base, owing to the availability of a large accommodation space. Deposition was

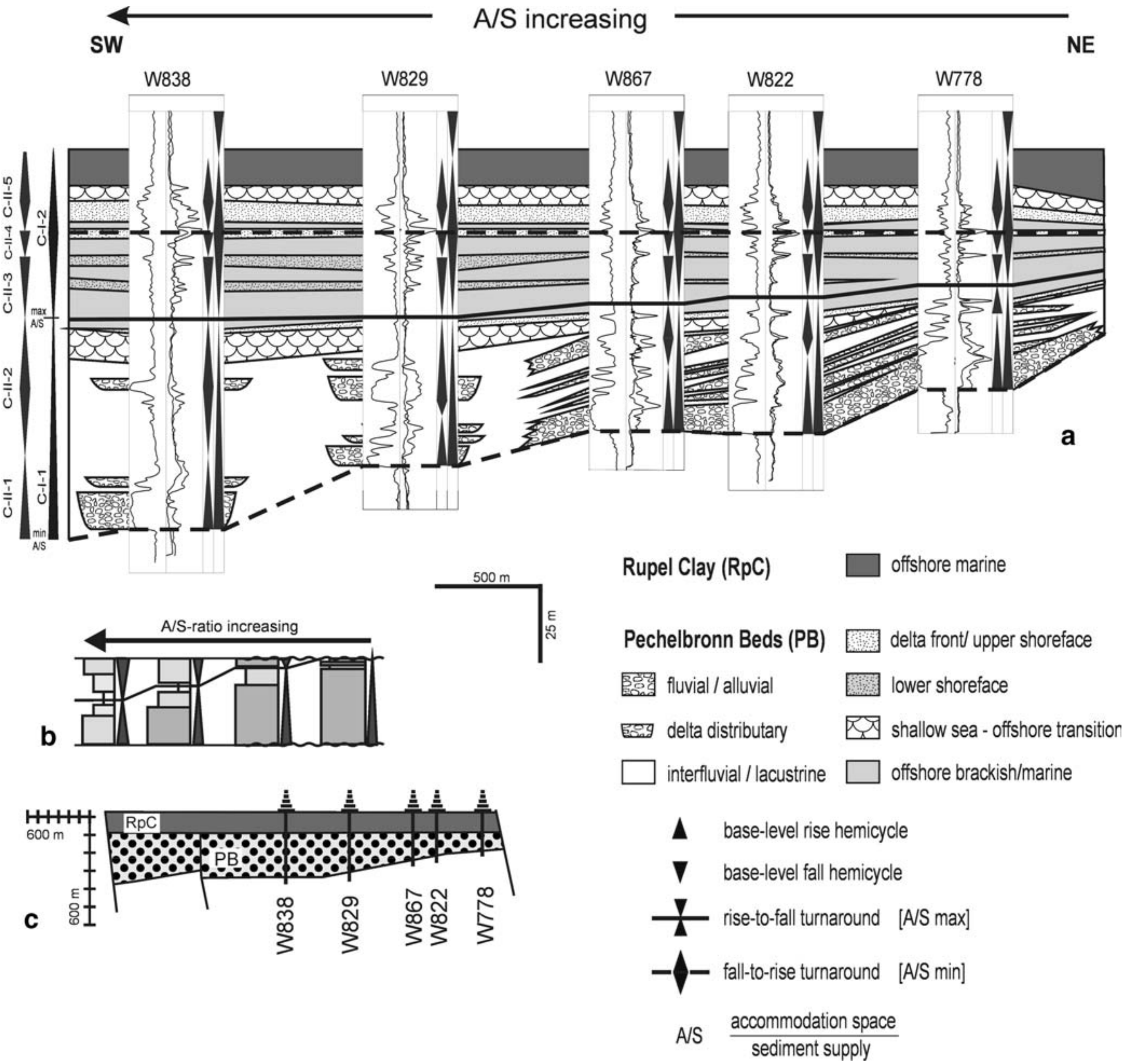
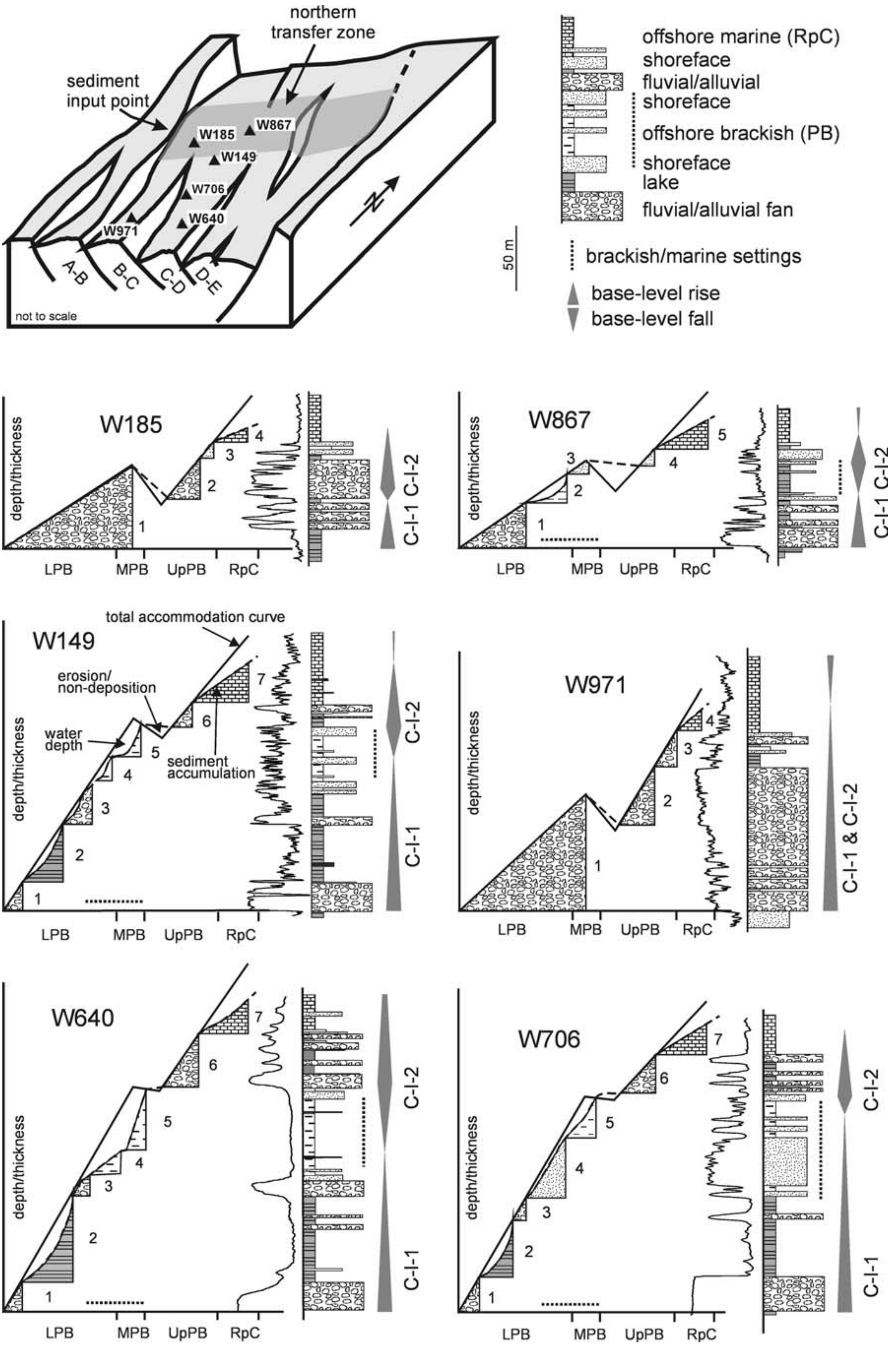


Fig. 8 Interpreted part of the cross-section T1, showing a half-graben on the transfer zone; modified from Derer (2003). **a** A depositional gradient is along the section from NE to SW, as the A/S ratio increases from the leading edge of a central block of the transfer zone towards the SW. The section datum is given by the gamma-ray maximum in the offshore shales of the Rupel Clay; this is interpreted as the A/S max. The location of the cross-section is in Figs. 2 and 6a. **b** Conceptual model showing changes in cycle symmetry as observed for cycle C-I-1. **c** Projected locations of the wells on the palinspastically restored fault block (*arrow* on profile T1 in Fig. 6a)



northern transfer zone
sediment input point
W185
W867
W149
W706
W640
W971
A-B
B-C
C-D
D-E
not to scale
offshore marine (RpC)
shoreface
fluvial/alluvial
shoreface
offshore brackish (PB)
shoreface
lake
fluvial/alluvial fan
50 m
brackish/marine settings
base-level rise
base-level fall
depth/thickness
LPB
MPB
UpPB
RpC
C-I-1
C-I-2
total accommodation curve
erosion/ non-deposition
water depth
sediment accumulation
C-I-1 & C-I-2

◀

Fig. 9 Early syn-rift stage in the northern Upper Rhine Graben: the total accommodation space and the sediment supply varied with respect to the position in its tectonic framework. The accommodation and sediment accumulation curves are qualitative. The *horizontal axis* represents time (*LPB* Lower Pechelbronn Beds, *MPB* Middle Pechelbronn Beds, *UpPB* Upper Pechelbronn Beds, *RpC* Rupel Clay; the *numbers* mark the depositional units interpreted). The total accommodation curve includes the sinusoidal allogenetic variation of the accommodation space and the autogenetic linear subsidence. With increasing subsidence the downshift of the accommodation curve is suppressed

mainly from suspension, interrupted by only minor traction and turbidity currents (of a low sediment supply). Lampe (2001) suggested a maximum palaeo-water depth of about 40m.

Offshore marine deposits (Fig. 7g)

The offshore marine facies association occurs exclusively in the Rupel Clay that was deposited at a time when marine conditions dominated the Upper Rhine Graben area, as evidenced by the occurrence of a foraminifera association of *Bathysiphon* sp., *Cibicides* sp., *Cyclammina* sp., *Gyroidina* sp., *Bolivina* sp. (Elstner 1985). The locally bioturbated open-marine shales of the Rupel Clay, that were deposited from suspension in water depths of 100–200m (Rothausen and Sonne 1984; Grimm 1991), generate to a distinct marker in well logs and seismic sections that can be recognised across the entire study area.

Sedimentation on a tilted-block/halfgraben

The interplay between extensional tectonics and sedimentation is exemplified by a cross-section across a tilted-block/halfgraben in the southern parts of the northern transfer zone of the Upper Rhine Graben (Fig. 8, for location see Fig. 6). This block was tilted to the West owing to growth along a fault that sub-parallels the graben. As the displacement along this fault increases southwards, this block also tilted in this direction. Therefore, accommodation space on this block increased both in the dip and strike direction. The NE–SW oriented cross-section illustrates the sedimentation conditions along the dip of the block. As the interpreted cross-section is located in central parts of the northern Upper Rhine Graben, sediment supply was only moderate in a down-dip direction.

Cycle C-I-1

Owing to a low A/S ratio, cycle C-I-1 commenced with single-storey fluvial channels that can be attributed to a south to southwest directed drainage system (Gaupp and Nickel 2001; Derer et al. 2003). The accommodation space increased away from the leading edge of the block and controlled the lateral extent of the depositional systems. At the crest of the block, multi-storey channel facies associations predominate with overbank/lacustrine facies playing a subordinate role (e.g. wells W778, W822). Down-dip, the thickness of overbank and lacustrine facies increases progressively, although single-storey channels still occur (e.g. wells W829, W838). Thus, the preservation potential of over-bank and lacustrine deposits increased away from the edge of the block.

In the upper part of C-I-1 cycle, the fluvial and interfluvial systems were flooded and offshore brackish conditions controlled deposition of the Middle Pechelbronn Beds. This is attributed to the Early Rupelian rise in sea level (Ru 1, Fig. 5). Similar as the overbank and lacustrine successions, also the thickness of the brackish offshore facies associations increases down-dip from the leading edge of the block.

Cycle C-I-2

The C-I-2 fall (shallowing upward) hemicycle is represented by fine-grained prograding delta/shoreface systems. The clastic material was probably derived from areas to the north or northwest of the transfer zone (cf. Gaupp and Nickel 2001). The studied fault block was distal relative to the sediment input point along the western border fault, and no important sediment source was active in the immediate vicinity of this block.

Within the C-I-2 fall-hemicycle, repeated shoreface progradations represent fall-asymmetric C-II intermediate-scale cycles. The C-II-3 fall (Fig. 8) starts with offshore shales that gradually pass upward into fine-grained lower shoreface sands. After a subordinate transgression, the following C-II-4 fall ends within upper shoreface sands. In most of the wells, these upper shoreface sands have a sharp base. This could imply that the C-II-4 base-level fall was mainly triggered by a decrease in accommodation space and not by an increasing sediment supply. Thus, erosion occurred at the base of the shoreface sands.

As the northern transfer zone was generally characterised by low accommodation space, only thin sediment layers could be deposited and preserved during the subsequent C-I-2 base-level rise that was mainly triggered by the Late Rupelian marine transgression (Ru 2, Fig. 5) and during which a delta and shoreface system developed. The latter was drowned, and at its top a marine ravinement surface developed. Subsequently, offshore marine shales of the Rupel Clay covered the coastal environment deposits.

Early syn-rift tectono-sedimentary model

Based on the above observations, we present a comprehensive tectono-sedimentary model for the early syn-rift stage of the northern parts of the Upper Rhine Graben. This model illustrates the effects of structural control on lateral variations in depositional environments (for further detail see Derer 2003; Derer et al. 2003).

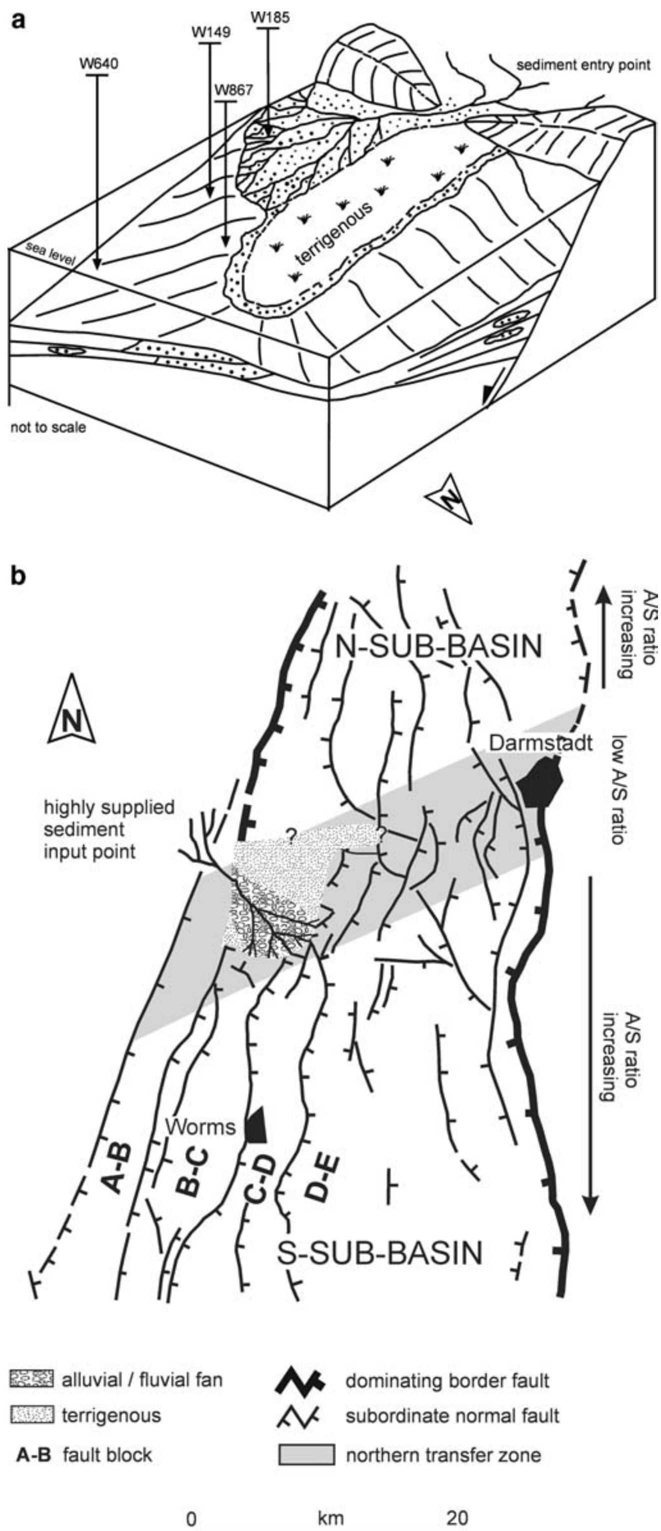


Fig. 10 **a** Palaeogeographic setting of the northern Upper Rhine Graben during the Early Rupelian (brackish lakes cover almost the entire graben surface, while the Middle Pechelbronn Beds were deposited). Low accommodation space is on the northern interbasin transfer zone. High sediment supply through a low-displacement fault segment at the western graben shoulder built an alluvial/fluvial fan protruding into the basin. The northern and southern sub-basin had high A/S ratios. The transfer zone partially separated the northern and southern sub-basins. A communication between the two sub-basins was probably open only in the central and eastern part of the transfer zone. **b** Idealized block showing the environmental setting ontop of the northern interbasin transfer zone, close to the western graben fault (view from the NE). The terrigenous area is bounded at its South by an alluvial/fluvial fan protruding into the southern sub-basin. Four of the wells that were discussed in Fig. 9 are located

Figure 9 illustrates contemporaneous A/S conditions (expressed as the ratio between accommodation space vs sediment supply; Cross and Lessenger 1998) in the area of the northern transfer zone and the southward adjacent sub-basin. The A/S conditions, the symmetries of the related base-level cycles, and the distribution of depositional environments vary as a function of the structural position with the evolving extensional basin.

The curves, which reflect variations in total accommodation space and sediment accumulation, were derived from interpreted well logs at locations which are included in a basin-wide sequence stratigraphic model proposed for the Upper Rhine Graben by Derer (2003) and Derer et al. (2003).

The accommodation curves of all wells show two characteristic rising limbs that correspond to the regional third-order Rupelian transgressions Ru 1 and Ru 2 (Fig. 5). It is interpreted that the accommodation curves for the northern Upper Rhine Graben are influenced by allogenetic causes from outside the basin, as the slopes of the individual curves depend on the setting of the respective control point within the tectonic framework of the basin. Thus, it is assumed that they depend on subsidence rates which are controlled by autogenetic causes inherent in the basin. Hence, we conclude that the accommodation curves reflect the sum of the allogenetic sinusoidal accommodation variation and the autogenetic linear subsidence (see for example, Jervey 1988; Howell and Flint 1996).

On individual fault-blocks, subsidence rates increased down-dip from their leading edge towards the adjacent growth fault. At a regional scale, subsidence rates increased away from the transfer zone towards the southern sub-basin. This tendency was specifically observed on block C–D to the south of the transfer zone, where it could be shown that subsidence rates gradually increased along strike owing to increasing displacements along fault C (Derer 2003).

Increased subsidence caused a minor decrease of space on the falling limb of the allogenetically driven accommodation curve. Consequently, in the northern Upper Rhine Graben, the shape of the accommodation curve varies primarily as a function of tectonic subsidence. Similar mechanisms have been suggested for other extensional basins such as the Gulf of Corinth (Gawthorpe et al. 1994) and the North Sea Graben (Howell and Flint 1996).

As mentioned before, a marine transgression into the Upper Rhine Graben during the first Early Rupel flooding (Ru 1) is still controversial (in contrast to the second flooding Ru 2). Consequently, we suggest the term ‘‘allogenetic accommodation variation’’ to describe the change in accommodation that cannot be attributed without doubts to a sea level rise. This term only implies that development of accommodation space within the basin depended on an external mechanism.

Sediment supply to the control points discussed depended to a large extent on their location with respect to the sediment entry point on the western border fault (Figs. 6b and 9). Increased supply of coarse-grained material was confined to the vicinity of this entry point, whilst the grain-size and volume of sediments reaching more distal positions was reduced. Certainly, sediment sources, such as the leading edges of fault-blocks, occurred in the interior of the basin, but their importance was confined to local areas.

The interbasin northern transfer zone represented a structural and palaeotopographic high on which accommodation space was reduced owing to moderate to low subsidence rates (W185, W867). Hence, following rapid infilling of the available accommodation space (allogenetic cause), the area of the transfer zone was subjected to significant erosion and bypassed by sediments.

The main difference in sedimentation conditions between location of W185 and W867 was the sediment supply. As the well W185 is located in the vicinity of the sediment entry point on the low-displacement segment of the western border fault, sediment supply quickly outpaced the development of accommodation space. Consequently, sediment bypassing and amalgamation occurred even during the development of further accommodation space, and sediments were transported southward into the southern sub-basin. Alluvial fans and stacked fluvial channels formed during times of increasing accommodation space (W185 in Fig. 9). Thus, the westward prograding Upper Pechelbronn alluvial fans (Plein 1992; Gaupp and Nickel 2001) resulted from sediment over-supply through this slowly subsiding zone.

Well W867 was located further away from the sediment entry point. Correspondingly, the sediment supply could not keep pace with the generation of accommodation space and brackish offshore conditions developed during the deposition of unit 2 (Fig. 9, Middle Pechelbronn Beds). However, this brackish offshore facies association was gradually replaced by prograding delta and shoreface systems during the deposition of unit 3. These systems are time-equivalent to the alluvial fans active in the vicinity of the sediment input point near well W185.

The southern flank of the transfer zone was associated with a major axial depositional gradient that dipped into the southern sub-basin. The wells W185, W149, and W640 are located on the ramp-like fault block C–D that formed part of this gradient (Fig. 9). Subsidence rates increased towards the South, away from the transfer zone, concomitant with a displacement increase along fault C. The southward increase in subsidence rates implies a progressively smaller decrease in accommodation space during the falling limb of the allogenetic curve. Consequently, development of accommodation space increased away from the transfer zone. Comparing the accommodation curves of wells W185, W149, and W640, it is evident that during the allogenetic accommodation decrease, sediment bypassing and erosion played down-gradient and southward a progressively smaller role.

Sediments supplied through the entry point on low-relief zone of the western border fault largely bypasses well W185 and were deflected southward down the axial gradient. In the southern sub-basin, proximal to the transfer zone, prograding delta/shoreface systems accumulated during units 4 and 5 in well W149 (Fig. 9), suggesting proximity of a coastline during the brackish conditions of the Middle Pechelbronn Beds. The delta and shoreface facies of unit 4 continued to prograde into the basin despite the ongoing creation of accommodation space. Thus, deposition of this unit was exclusively controlled by the balance between sediments supplied through the low-relief zone and the development of accommodation space.

In contrast, the delta and shoreface unit 5 reflects an increased sediment supply and a resulting decrease in accommodation space. Owing to continued subsidence, the decrease of accommodation space during the sea level fall at the end of unit 5 was as severe in well W149 as in well W185 on the transfer zone (Fig. 9). Nevertheless, in W149 subaerial erosion and bypassing occurred at the top of unit 5. And during the second increase of accommodation, thin single-storey systems aggraded in unit 6.

The amount of sediments reaching well W640, located distal with respect to the transfer-zone, was subordinate and could not keep pace with the development of accommodation space during the initial subsidence phase of the basin. Consequently, the Middle Pechelbronn series are developed in brackish offshore facies associations that are time-equivalent to the prograding delta and shoreface systems of well W149 (see dashed lines in Fig. 9). As in well W640 high subsidence rates compensated the allogenetic decrease in accommodation space, erosion at the fall-to-rise turnaround of cycle C-I-2 was not so significant, and a thicker pile of single-storey channels (unit 6) accumulated during the second subsidence phase.

At a subordinate-scale, tilted-blocks and half-grabens controlled sedimentation. For instance, in well W971, which is located near the leading edge of fault block B–C, sediment supply outpaced the development of accommodation space, as is evident by the accumulation of stacked channel deposits. Owing to moderate to low subsidence rates, erosion and incision occurred at this location during the falling limb of the allogenetic part of the accommodation curve. Due to sediment amalgamation, cycles C-I-1 and C-I-2 cannot be differentiated.

On the other hand, in well W706, which is located on the hanging wall of block C–D next to the growth fault bounding block B–C, the development of accommodation space was directly linked to activity along this fault. As subsidence rates were high, the accommodation space increased towards the end of the brackish conditions of the Middle Pechelbronn Beds (C-I-1 rise) and was only partly balanced by an increased sediment influx from the leading edge of block B–C. This resulted in the accumulation of a thick unit 4 succession of aggrading shallow water deposits, time-equivalent to the prograding delta and shoreface systems of well W149 (dashed line) and the offshore units of well W640 (dashed line). Furthermore, owing to high subsidence rates, a drastic decrease of accommodation space due to allogenetic causes was inhibited, and the duration of subaerial exposure and bypassing was relatively short.

These examples demonstrate the variability of sedimentation conditions within the northern parts of the Upper Rhine Graben during its early syn-rift stage.

Palaeogeographic reconstruction

The evolution of the northern Upper Rhine Graben started with the development of minor half-grabens. By the Early Rupelian, these subordinate depocentres presumably coalesced, thus forming the major depocenters of the northern und southern sub-basin, which accommodated the brackish environments of the Middle Pechelbronn Beds (result of the first Rupelian transgression). During this time, the palaeogeographic setting was controlled by the northern transfer zone and by an increased sediment supply through the low-relief zone along the western border fault, resulting in the build-out of a fan complex into the graben (Fig. 10). As this alluvial fan was deflected to the South, delta and shoreface systems prograded at the transition between the northern transfer zone and the southern sub-basin into the latter. A connection between the southern and the northern sub-basin probably existed in the central and eastern part of the northern transfer zone. After the retreat of the brackish environments, it probably functioned as sediment barrier between the two sub-basins. During the second Rupelian transgression, which controlled the deposition of the open-marine Rupel Clay, drowning of the northern transfer zone established a connention between the northern and southern sub-basins.

Conclusions

This paper integrates a structural interpretation of the early syn-rift development of the Upper Rhine Graben with a high-resolution sequence stratigraphic analysis. This resulted in an integrated tectono-sedimentary model, which considers the fundamental large-scale structural features of this extensional basin and their intimate link to the development of sedimentary systems.

We show that, already during its early stage the northern part of the Upper Rhine Graben corresponded to a typical extensional basin. Its large-scale structure was dominated by the northern transfer zone that linked two half-grabens with opposing polarity to its south and north. At a smaller scale, depositional gradients developed away from this transfer zone in conjunction with the subsidence along tilted fault blocks in the northern and southern sub-basins. These controlled the dispersal of clastics and thus the deposition of early syn-rift sequences. In this respect, the early stage Upper Rhine Graben shows remarkable similarities with other rifted basins, such as the East African Rift (Morley et al. 1990; Rosendahl et al. 1986) or the North Sea Graben (Morley et al. 1990; Scott and Rosendahl 1989). In all cases, the presence of transfer zones across which the rift polarity of graben changes along trend, exerts a strong control on sedimentation. In the East African rift, Lake Albert is confined to a single half-graben, whereas Lake Tanganyika extends over several sub-basins and drowned transfer zones (Lambiase and Bosworth 1995).

In the northern parts of the Upper Rhine Graben, the northern transfer zone functioned as a sediment barrier until it was partially or totally drowned by two Rupelian base-level rises during which communications between the two sub-basins were established. Moreover, intrabasinal tilted fault blocks, forming subordinate building blocks of the graben, are typical for rifted basins (Badley et al. 1984; Scott and Rosendahl 1989; Morley et al. 1990; Steel and Ryseth 1990).

Lateral subsidence and fault displacement changes controlled the sediment entry point at the western border fault of the northern Upper Rhine Graben. At this entry point, alluvial/fluvial fans prograded into the graben. Similar cases are recorded along the eastern border fault of the Gulf of Suez where submarine fans formed in front of several low-displacement segments of this fault (Gawthorpe and Hurst 1993).

An understanding of the early syn-rift structural configuration of the graben permitted to apply high-resolution sequence stratigraphic concepts to the initial syn-rift deposits. These could be subdivided into correlative base-level cycles that were controlled, at different scales, by allogenetic factors (eustasy and regional variations in the sea level) and autogenetic factors (the intragraben tectonic structure and its subsidence).

The recognition of the allogenetic control on cycle development permitted a regional correlation between the different sub-basins in the northern parts of the Upper Rhine Graben. Moreover, this allowed for an analysis of the effects the Rupelian Ru 1 and Ru 2 transgressions had on sedimentation in the Upper Rhine Graben. The correlation of the Ru 1 transgression with the C-I-1 to C-I-2 rise-to-fall turnaround suggests a common regional causality, although an open communication between the Upper Rhine Graben and other basins is still controversial. With this approach, correlations between the depositional sequences of the Upper Rhine Graben and those of adjacent basins (e.g. Molasse Basin, North Sea Basin, Lower Rhine Basin) may be possible, provided reliable time stratigraphic control is available.

The use of well information for sequence stratigraphic interpretation of the Late Eocene to Early Oligocene sediments was facilitated by a relatively good data quality available in the northern Upper Rhine Graben as compared to its other parts. As the early synrift deposits in this area consist mainly of clastics they could be interpreted on the basis of well logs. By contrast, a well log based sequence stratigraphic approach to the Miocene series would meet with difficulties as these consist of a ‘‘monotonous’’ succession of marlstones, mudstones, and evaporitic intercalations.

Consequently, only the early syn-rift stage of the northern Upper Rhine Graben is suitable for the construction of a tectono-sedimentary model.

The construction of such a model permits to predict depositional systems, and facies variations along depositional strike and dip. This plays a major role in the hydrocarbon exploration. In the North Sea Graben, several oil fields are located on transfer zones (Morley et al. 1990). In the Gulf of Suez, the submarine fans related to sediment entry points form important reservoir rocks (Morley et al. 1990; Gawthorpe and Hurst 1993).

Similarly, in the northern parts of the Upper Rhine Graben the bulk of oilfields that are reservoired in Pechelbronn Beds (Durst 1991) are located on the transfer zone and in the vicinity of the sediment entry point. The transfer zone was not only a structural high and created structural traps but represented also zone with a low ratio of accommodation space to sediment supply. This, combined with the sediment entry point permitted deposition and preservation of coarse-grained reservoir-quality sands.

However, models do not prove anything. If they are correct, they may suggest a certain degree of predictability in exploration.

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