TECTONO-SEDIMENTARY EVOLUTION OF THE NORTHERN UPPER RHINE GRABEN (GERMANY), WITH SPECIAL REGARD TO THE EARLY SYN-RIFT STAGE

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1. INTRODUCTION

1.1 Aims of the study

The aims of this study are:
1) An overview on the overall Cenozoic syn-rift evolution of the northern Upper Rhine Graben, in terms of tectonic framework, subsidence, and depositional history.
2) A detailed analysis of the early syn-rift depositional history (late Eocene-early Oligocene) of the northern Upper Rhine Graben, studying the interplay between tectonics and sedimentation and using a sequence stratigraphic approach.

For deciphering the sedimentation history it is essential to first understand the basin dynamics. In extensional settings, like the Upper Rhine Graben, tectonic influence can overprint all other sedimentation controls (e.g. variations of sea-level, climate, etc.), leading to complex depositional patterns. This study aims to improve the understanding of the depositional history in the northern Upper Rhine Graben.

1.2 General overview on the Upper Rhine Graben

The Upper Rhine Graben (URG) belongs to the European Cenozoic rift system (e.g. Illies, 1970; Prodehl *et al.*, 1992; Ziegler, 1992; Ziegler, 1994) and is limited by the Rhenish Massif to the north and the Jura Mountains to the south. It has a NNE-SSW strike and extends 300 km in length and 30-40 km in width (**Fig. 1.1 a, b**).

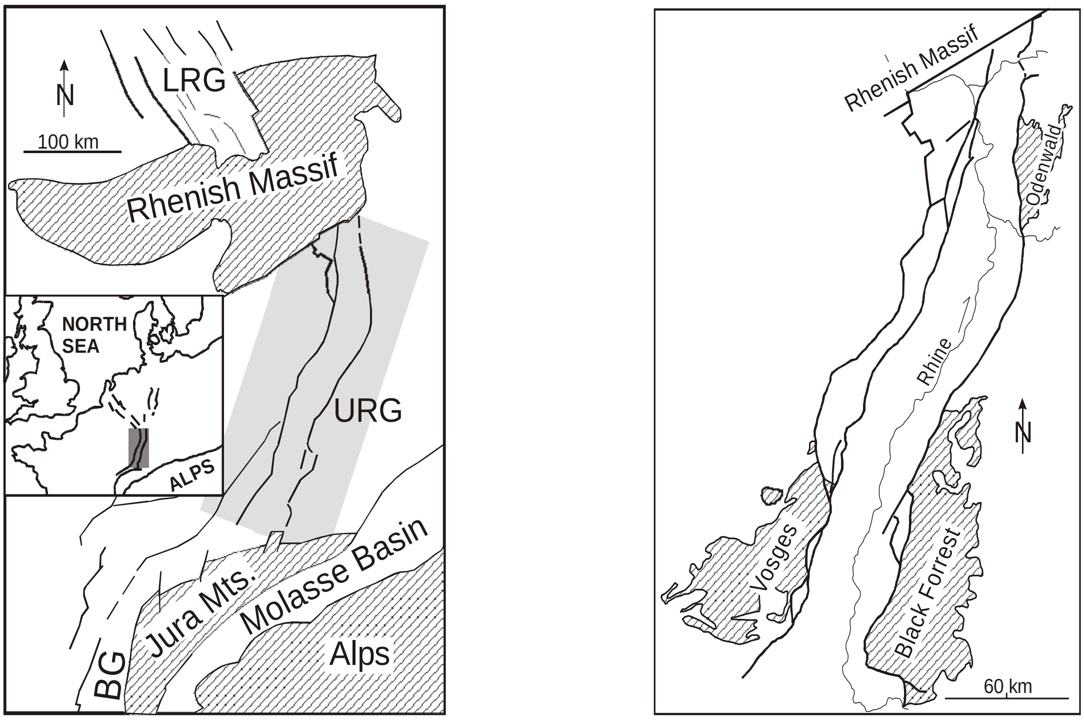


Fig. 1.1a, b The Upper Rhine Graben (URG, shaded area), as part of the European Cenozoic rift system. LRG-Lower Rhine Graben; BG-Bresse Graben.

The formation of the Upper Rhine Graben was, in a broad sense, synchronous with the collisional events of the Alpine orogen, and its evolution shows a polyphase tectonic history. Subsidence commenced in the middle (?) to late Eocene, and the Cenozoic graben fill has a maximum thickness of more than 3000 metres (Doebl & Olbrecht, 1974), even though there are important thickness variations, especially between the southern and northern part.

1.2.1 PRE-RIFT SETTINGS

The pre-rift settings of the Upper Rhine Graben area, and their possible influence on the Cenozoic formation and evolution of the graben were recently summarised by Schumacher (2002).

The pre-rift history started with the Variscan orogeny in Palaeozoic and early Permian times. The most important structures are NE to ENE striking Variscan dislocation zones such as the South Hunsrück-Taunus Borderzone (separating the Rhenohercynian in the north from the Saxothuringian domain, in the central part), the Baden-Baden-Lalaye-Lubine fault zone (forming the limit between the Saxothuringian and the Moldanubian domain in the very south (e.g. Wickert *et al*., 1990), and the Badenweiler-Lenzkirch fault zone (Krohe & Eisbacher, 1988) located within the Moldanubian area (**Fig. 1.2**). During early Carboniferous to early Permian times, a NNE sinistral shear fault system and intrusive bodies of the Vosges, Black Forest and the Odenwald were set in place.

Late Hercynian wrench tectonics (Stephanian-Autunian) formed a system of Permo-Carboniferous troughs and highs, which followed the ENE structural grain of the Variscan fold belt (Ziegler, 1990). In the URG area they are: Saar-Nahe Trough, Odenwald-Spessart High, Kraichgau Trough, Northern Black Forest High, Villé-Offenburg Trough, Main Upper Rhine High, the Burgundy-Schramberg Trough, and the Main Southern German High (Boigk & Schoeneich, 1970) (**Fig. 1.2**).

During the post-variscan Permian time, erosion and infilling of the troughs occurred, thus, the transgressive Mesozoic sediments rest discordantly on the Permo-Carboniferous series. In the URG area, only Triassic to late Jurassic (Kimmeridgian) deposits are preserved (e.g. Pflug, 1982) and it is unsure whether late Cretaceous sediments were eroded or not deposited at all (Ziegler, 1990). This hiatus is attributed to the uplift of the “Rhenisch Shield” (Cloos, 1939), which started at the end of Jurassic (Illies, 1975; Walter, 1995). Ziegler (1990) suggests that the uplift (late Jurassic to early Cretaceous) was compensating the extension in the North Sea region and the Atlantic shelves. In late Cretaceous times volcanic activity took place in the area of the shield (Lippolt *et al*. 1974 *fide* Pflug, 1982; Illies, 1975).

The actual subcrop pattern of the Upper Rhine Graben comprises Permian to Kimmeridgian strata. These pre-rift series form in northern URG a southward dipping monoclinal structure. In the southern URG, the Mesozoic cover shows anticline-syncline structures, which apparently mould the Burgundy Trough/Kraichgau Trough and Northern

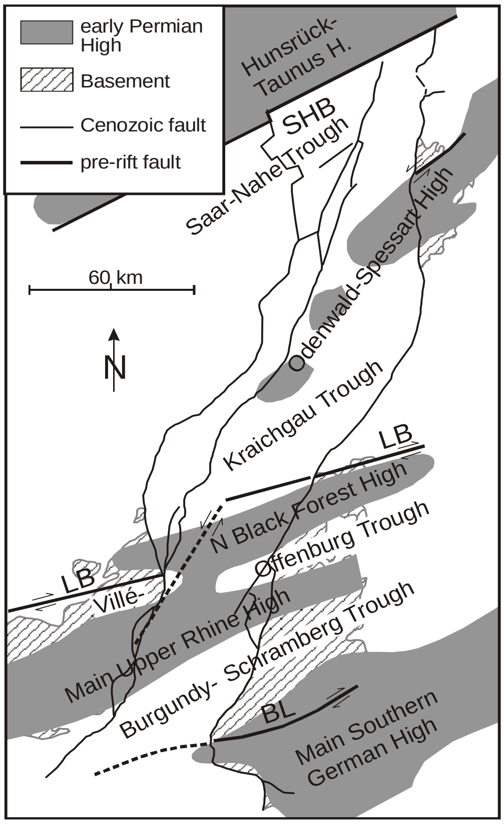


Fig. 1.2 The pre-rift structural features across Upper Rhine Graben area. Modified from Boigk & Schoeneich (1970); Schumacher (2002). SHB South Hunsrück Borderzone; LB Lalaye-Lubine-Baden-Baden zone; BL Badenweiler-Lenzkirch zone.

Black Forest High/Main Upper Rhine High respectively (Illies, 1965; Pflug, 1982; Sittler, 1969; Schumacher, 2002).

However, the Variscan NNE striking shear zones and the ENE trending Permo-Carboniferous troughs and highs dominate the URG area at crustal level. They probably had an influence on the formation and structural evolution of the Upper Rhine Graben during the Cenozoic (Schumacher, 2002).

1.2.2 SYN-RIFT EVOLUTION

The formation of the Upper Rhine Graben started in the middle (?) to late Eocene (yet, due to dating uncertainties the beginning of rifting is still controversial). Its evolution shows several changes in stress regime, which led to different subsidence and uplift phases (e.g. Illies, 1975; Illies, 1978; Teichmüller & Teichmüller, 1979; Villemin *et al.*, 1986; Ziegler, 1992; Sissingh, 1998; Schumacher, 2002).

In the early Rupelian, a first major subsidence phase occurred (Illies, 1975; Illies, 1978; Schumacher, 2002; Sissingh, 1998; Villemin & Coletta, 1990) due to a WNW-ESE oriented extension (Meier & Eisbacher, 1991; Schumacher, 2002).

The reorientation of the stress field in early Miocene times (Aquitanian) led to the second major subsidence phase, which was confined mainly to the northern URG. Starting with the middle Miocene, the southern graben was uplifted (Illies, 1975; Illies, 1978; Teichmüller & Teichmüller, 1979; Villemin & Coletta, 1990; Schumacher, 2002). Beginning with the middle Miocene and continuing in the Quaternary the graben was subjected to sinistral shear. As a consequence, the northern and southern part subsided, and the central part acted as a restraining bend (Illies, 1975; Illies, 1978; Teichmüller & Teichmüller, 1979; Villemin & Coletta, 1990; Meier & Eisbacher, 1991; Schumacher, 2002).

Sedimentation in the Upper Rhine Graben started in the middle (?) to late Eocene. The distribution and the thickness of the Cenozoic graben fill is closely linked to the tectonic evolution and migration of depocentres (e.g. Illies, 1965; Sissingh, 1998; Schumacher, 2002). In the Eocene, an early syn-rift volcanic phase was active (Lippolt *et al.*, 1974; Gaupp & Nickel, 2001). In the northern URG, sediment thickness reaches a maximum of 3300 metres (Doebl & Olbrecht, 1974), while the deposition of up to 2000 metres of sediment took place during the Miocene. In the southern graben, sediments are up to 2500 metres thick. These were probably generated only during Eocene and Oligocene times, as in the Miocene uplift occurred. This uplift (reaching up to 1500 metres, Brun *et al.*, 1992) was accompanied by erosion, nondeposition and volcanism (the latter generated the Kaiserstuhl). During the Quaternary, deposition was again active almost all over the graben (Bartz, 1974).

Multiple, laterally linked and vertically stacked sedimentary environments (ranging from terrestrial to brackish, evaporitic, and marine) controlled the deposition of the Cenozoic infill of the graben. Several major marine transgressions took place during the Cenozoic, connecting the Upper Rhine Graben to adjacent marine basins such as the Molasse Basin and the North Sea Basin (e.g. Doebl, 1967; Doebl, 1970; Pflug, 1982; Sissingh, 1998; Reichenbacher, 2000).

1.3 Previous research

Research in the Upper Rhine Graben started already in the 19th century and the term “graben” was first introduced for this structure by Suess (1885). Cloos (1939) tried to explain the genesis of the graben with an analog model and defined the “Rhenish Shield” with the Upper Rhine Graben at its apex.

Since the sedimentary fill of the graben is poorly exposed, only extensive well and seismic investigations, related to hydrocarbon exploration, provided more details about the basin evolution. Results on the pre-rift settings, taphrogenesis, tectonic framework, lithology, facies and stratigraphy are summarised by Sauer (1964); Rothe & Sauer (1967); Illies & Mueller (1970); Illies & Fuchs (1974); Pflug (1982). However, stratigraphic and lithostratigraphic correlations were made, between the Cenozoic deposits of the URG and the Mainz Block (Mainz Basin), with emphasis on palaeogeographic and environmental reconstructions (Prell-Müssig, 1965; Best, 1975; Martini, 1978; Grimm, 1994; Reichenbacher, 1998; Reichenbacher, 2000; Grimm, 2002). Environmental interpretations were also performed by Nickel (1996), Schwarz (1997), Gaupp & Nickel (2001). Reflection seismic and well information also enabled the construction of structural maps and the interpretation of the Cenozoic subsidence history of the Upper Rhine Graben (e.g. Andres and Schad, 1959; Illies, 1975; Illies, 1978; Villemin *et al.*, 1986; Villemin & Coletta, 1990; Lampe, 2001). Geothermy in the graben area was investigated and modelled by Doebl & Teichmüller (1979); Teichmüller & Teichmüller (1979); Lampe (2001).

The graben fill is subdivided into lithostratigraphic units, which can easily be recognised in subsurface data and correlated with the successions cropping out on the Mainz Block. However, Durst (1991) used genetic criteria and subdivided the Cenozoic sediments into three marine and one clastic cycle. Sissingh (1998) defined eleven correlative sequences, on the basis of unconformities, lithofacies boundaries and areal extent, and correlated them to neighbouring basins. The concept of sequence stratigraphy was used by Jantschik *et al*. (1996), for the correlation at small scale of late Eocene to early Oligocene sand bodies.

1.4 Study area, database and methods

This study will concentrate on the northern Upper Rhine Graben (**Fig. 1.3**), an area extending approximately from the Main River in the north to the city of Mannheim in the south. To the west, the northern URG is limited by the Mainz Block (Mainzer Becken) and to the east by the Odenwald massif.

Within the northern part of the graben the Cenozoic deposits do not crop out thus, subsurface information were used. The database consists of several reflection seismic profiles and a multitude of well information (generously made available by German oil companies **Fig. 1.3**).

The well log data (especially GR-gamma ray, SP-self potential, CAL-caliper and resistivity measurements), palaeontologic data, description of cores and cuttings, seismic facies and information from literature provided the basis for a stratigraphical, lithological, depositional and plaeo-environmental interpretation of the strata. Well information and the stratigraphic framework were also integrated in a subsidence analysis of the northern URG. The sedimentological interpretation, the vertical and lateral stacking of depositional environments formed the basis for a sequence stratigraphic interpretation at a smaller scale in the Eocene-Oligocene sediments. Time-equivalent deposits were studied in outcrops on the Mainz Block and in the southern Upper Rhine Graben, in order to facilitate the sedimentological interpretation of well logs and to understand lateral facies variations between the basin centre and its margin.

The seismic data were primarily used for the analysis of the tectonic structure at different scales, which is fundamental for the understanding of the deposition of sedimentary sequences in extensional settings. They were also used for the definition and identification of the early syn-rift stage of the graben formation. Interpretation of seismic data was based on the correlation with the well information. Significant surfaces identified in wells were tied to the seismic lines using velocity data.

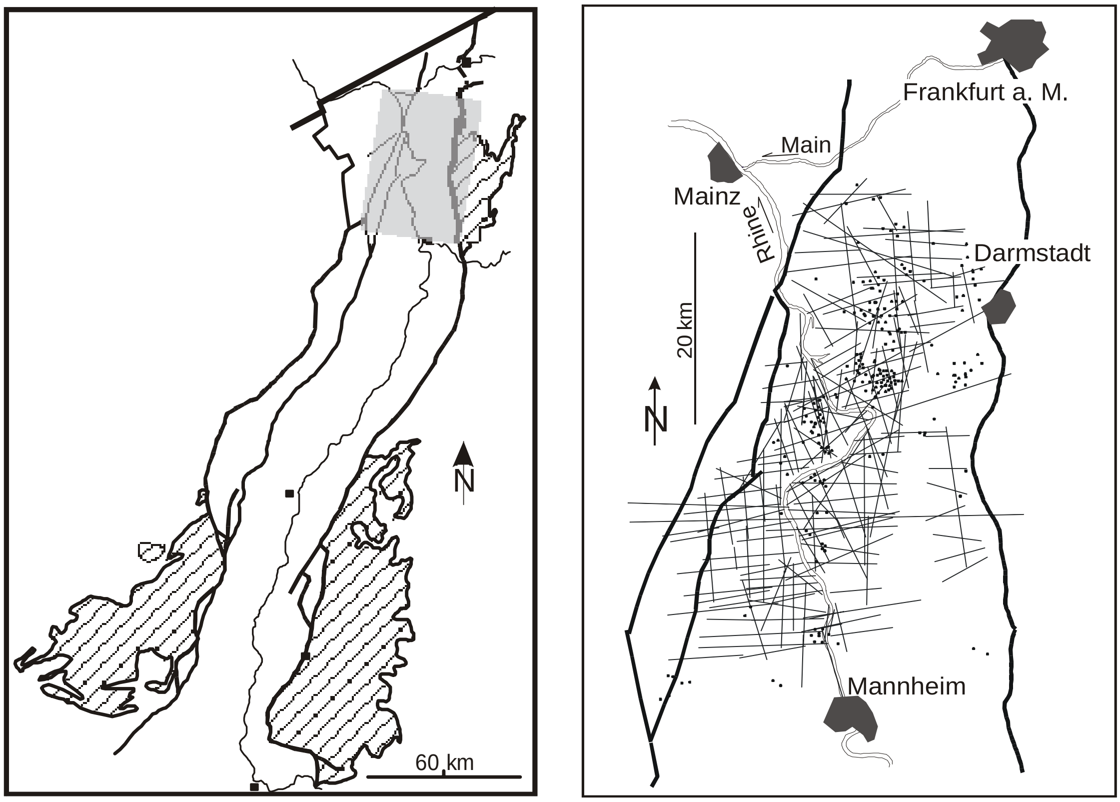


Fig. 1.3 a) Location of the study area of the northern Upper Rhine Graben (shaded area).
b) The database for this study within the northern Upper Rhine Graben. Seismic sections are represented by lines and wells by dots.

2. THE CENOZOIC SYN-RIFT EVOLUTION OF THE NORTHERN UPPER RHINE GRABEN

The aim of this chapter is to highlight aspects concerning the tectonic settings and sedimentation for the syn-rift stage of the northern Upper Rhine Graben, interpreted from subsurface data. The syn-rift fill, as defined for this study, comprises the Cenozoic sediments (from late Eocene to Quaternary), as subsidence in the northern graben was active for this period, even though at various rates and with changing stress regimes.

2.1 Methodology and concepts

2.1.1 SUBSIDENCE ANALYSIS

Subsidence analysis represents a method to reconstruct the subsidence history of a location within the basin by using the information contained in the sedimentary column. It was performed for one well within the central northern Upper Rhine Graben in order to identify major subsidence episodes. The analysis used standard techniques (e.g. Steckler and Watts, 1978; Sclater & Christie, 1980; Bond & Kominz, 1984; van Wees & Stephenson, 1995) with the program WHIZMOD. The reconstruction of the subsidence history consists of two steps.

1) The geohistory analysis (Van Hinte, 1978) aims the reconstruction of the total (composite) subsidence curves through time. This is done by the reconstruction of the sediment and estimated water column for a number of time steps during the evolution of the basin, including the decompaction of the individual sediment packages to their original palaeo-thicknesses. In this study, the time steps are represented by the difference between the ages of the lithostratigraphic boundaries of the graben fill (see **chapter 2.2 Syn-rift stratigraphy**).

2) The calculation of the air- and water-loaded tectonic subsidence (backstripping) is done by removing the isostatic response of the lithosphere to the sediment load from the total subsidence of the basin. Airy isostasy is assumed, meaning, that any vertical column of load is compensated locally. This assumption was already tested for rift basins (e.g. Kooi *et al*., 1989; Barr, 1991). Local isostasy implies that the lithosphere has no strengths to support the load.

Several corrections and limitations have to be taken into account when studying the subsidence history. These are:

Palaeobathymetry: The palaeobathymetry was estimated from sedimentary facies, faunal data and literature information. Depositional depth never reached values over 200 metres, mostly much shallower depth prevailed.

Eustasy: Eustatic sea-level fluctuations were not incorporated to the analysis.

Compaction: Decompaction was performed for the individual lithostratigraphic units, in order to correct their progressive loss of porosity with depth of burial. Each lithostratigraphic unit between two chronostratigraphic horizons has been assigned a sand, silt, shale, carbonate, anhydrite and halite percentage, with each lithology responding to its own compaction scheme. Mean standard exponential variations and material parameters were used (cf. Sclater & Christie, 1980). Lithologies were taken from descriptions of cores and cuttings, and from interpretation of well logs.

Dating: The determination of the stratigraphic ages has a major influence on the subsidence curves. The stratigraphy and absolute ages will be discussed in the **chapter 2.2 Synrift stratigraphy**. Tectonic subsidence and subsequent uplift, associated with a possible erosional hiatus were not considered.

2.1.2 APPLIED STRATIGRAPHIC PRINCIPLES

For the correlation and interpretation of the studied sedimentary successions, a sequence stratigraphic approach is used. The method combines the “base-level approach” of Wheeler (1964); Cross & Lessenger (1998) with the accommodation models for extensional basins of Gawthorpe *et al*. (1994); Howell & Flint (1996). The application of the base-level approach is only reasonable if the tectonic framework of the basin is known.

The “base-level approach” (Wheeler, 1964; Cross & Lessenger, 1998) takes into account that the deposition of sedimentary sequences is controlled by accommodation space (A, volume available for sedimentation in a certain time interval) and sediment supply (S, volume of sediment delivered in the time interval). It is the variation of the accommodation space to sediment supply ratio (A/S ratio), equivalent to the upward and downward movement of the base level (*sensu* Wheeler, 1964), which leads to the formation of cycles (**Fig. 2.1**). A base-level cycle is composed of two hemicycles: during a base-level rise hemicycle (accommodation space to sediment supply ratio increasing) the capacity of the basin to store sediment increases. During a base-level fall hemicycle (accommodation space to sediment supply ratio decreasing) the capacity of storing sediment moves down-gradient, leading to sediment bypassing and erosion. The transition between hemicycles is characterised by turnarounds: fall-to-rise (minimum A/S) and rise-to-fall (maximum A/S).

A distinction may be made between symmetric cycles (where rise and fall hemicycles have similar thickness) and asymmetric cycles (where sediment thickness of one of the hemicycles dominates). In addition to the symmetry of the cycles, the preservation potential of sedimentary facies and environments changes. At a position on the gradient with a minimum A/S ratio, the preservation potential is low and a hiatus forms as a result of bypassing. At a position with a maximum A/S ratio, a hiatus can occur due to starvation. Thus, the preservation potential and the diversity of depositional elements are maximal only when the creation of accommodation space and sediment input are in equilibrium.

The base-level cycles and turnarounds at different scales can only be correlated if they will respond to the same causes, which influenced accommodation and sediment supply. This condition applies if: 1) The causes (e.g. subsidence/uplift, rise/fall of relative sea level) will have a regional character and will overprint subordinate factors (e.g. fault blocks, topography). 2) The deposits to correlate will belong to the same depositional gradient. These limitations have especially to be considered in extensional basins, where sedimentation is controlled by transfer zones, strike and dip variations of accommodation space, different sediment fluxes (axial, footwall- and hangingwall-derived fluxes) and a complex basin physiography (Gawthorpe *et al*., 1994; Lambiase & Bosworth, 1995; Howell & Flint, 1996). If these conditions are fulfilled (i.e. verified by comparative well log and seismic interpretation), then it can be assumed that the rise-to-fall turnarounds represent timelines. Certainly, stratigraphic dating is important.

In the northern Upper Rhine Graben the combination of the two methods was primarily used for the reconstruction of the early syn-rift conditions (late Priabonian to early Rupelian), when tectonics was controlled by extension (see **chapter 3**).

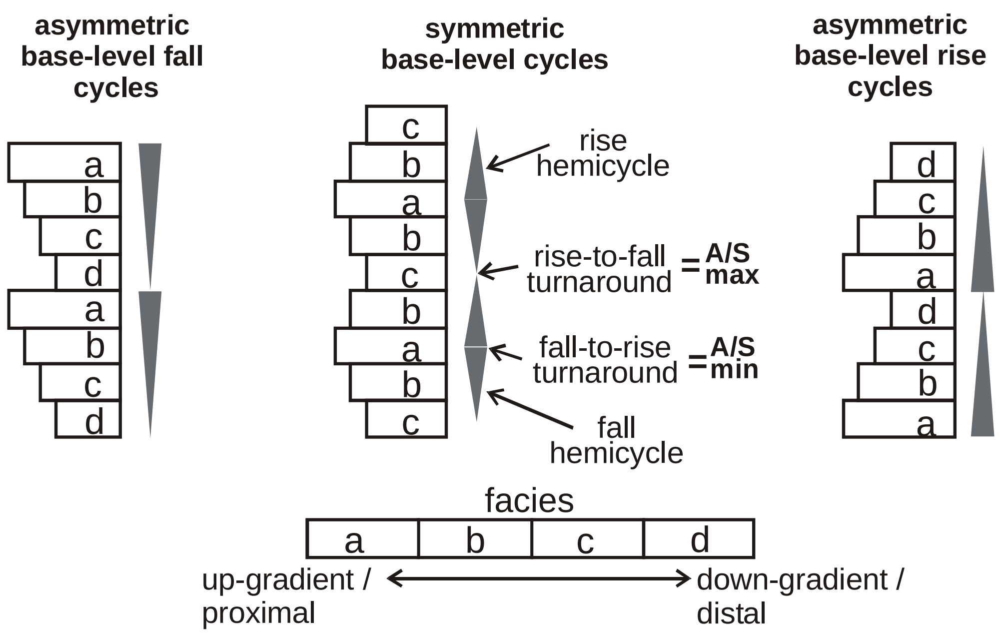


Fig. 2.1 Definition of the base-level cycles and their symmetry. Base-level cycles are defined by the sediment accumulated and preserved during periods of base-level fall and rise. Asymmetric fall and rise cycles contain sediments predominantly deposited during base-level fall or rise respectively. Symmetric cycles contain comparable proportions of sediment deposited during base-level fall and rise. Modified from Cross & Lessenger (1998).

2.1.3 CYCLE HIERARCHY

In the northern Upper Rhine Graben, a threefold hierarchy of stratigraphic cycles is recognised (C-I, C-II, C-III). Criteria for the recognition of cycles include facies changes both within and between individual depositional systems, changes of depositional systems in the stratigraphic section, and the areal extent of cycle recognisability.

Small-scale cycles (C-III) are 3 to 15 metres thick and record minor lateral facies shifts within a depositional system. They can be confidently correlated only locally.

The thickness of the intermediate-scale cycles (C-II) varies between 15 and 50 metres; they can be recognised and correlated over a part of the basin. These cycles reflect an up- or down-gradient shift of depositional systems.

The large-scale cycles (C-I) have a thickness span of 25 to 600 metres. They can be traced and correlated throughout the basin and are generated by major and basin-wide changes in sedimentation. The large-scale cycles correspond to some extent to the lithostratigraphic units. Yet, the sequence stratigraphic approach used in this study redefines boundaries and symmetries of the units within the area of study.

The variations in accommodation space and sediment supply, controlling the deposition of the stratigraphic cycles are influenced both by local and regional factors. In order to differentiate between basin-internal and basin-external causes, attempts were made, to correlate the large-scale cycles with sequence stratigraphic classifications in other basins. For correlation, the “Transgressive/Regressive Facies Cycles” (TRF Cycles) and “Sequence Cycles” (*sensu* Jaquin & de Graciansky, 1998a; Jaquin & de Graciansky, 1998b) from other European basins are used (Hardenbol *et al*., 1998). These are related to relative sea-level changes, triggered by tectono-eustatic events.

2.2 Syn-rift stratigraphy

For the subdivision of the Cenozoic syn-rift sedimentary fill of the northern Upper Rhine Graben, the lithostratigraphic classification is used (**Fig. 2.2**). The lithostratigraphy corresponds to the classification established by the oil industry (based on micro-palaeontology and well logs). For the post-Rupelian time, this classification differs from the actual Upper Rhine Graben stratigraphy, correlated to the Mainz Basin (e.g. Prell-Müssig, 1965; Best, 1975; Reichenbacher, 2000). The present study uses the industrial classification, as the database was made available by the oil industry, and since these lithostratigraphic units can often be recognised in well logs and in seismic sections.

The oldest sediments encountered in the study area (pre-Pechelbronn Beds) will be called Eocene Clay (**Fig. 2.2**), as a more precise identification is not possible due to the scarce palaeontological data.

For the subsidence analysis, the lithostratigraphic units were correlated with the “Stratigraphic Table of Germany 2002” (German Stratigraphic Commission, 2002), which considers the chronostratigraphic ages of Berggren *et al*. (1995). Due to the scarcity of the dating, the absolute ages at the boundaries of the lithostratigraphic units may vary considerably. This implies some uncertainties for the subsidence analysis. However, it does not change the qualitative characteristics of the subsidence curves.

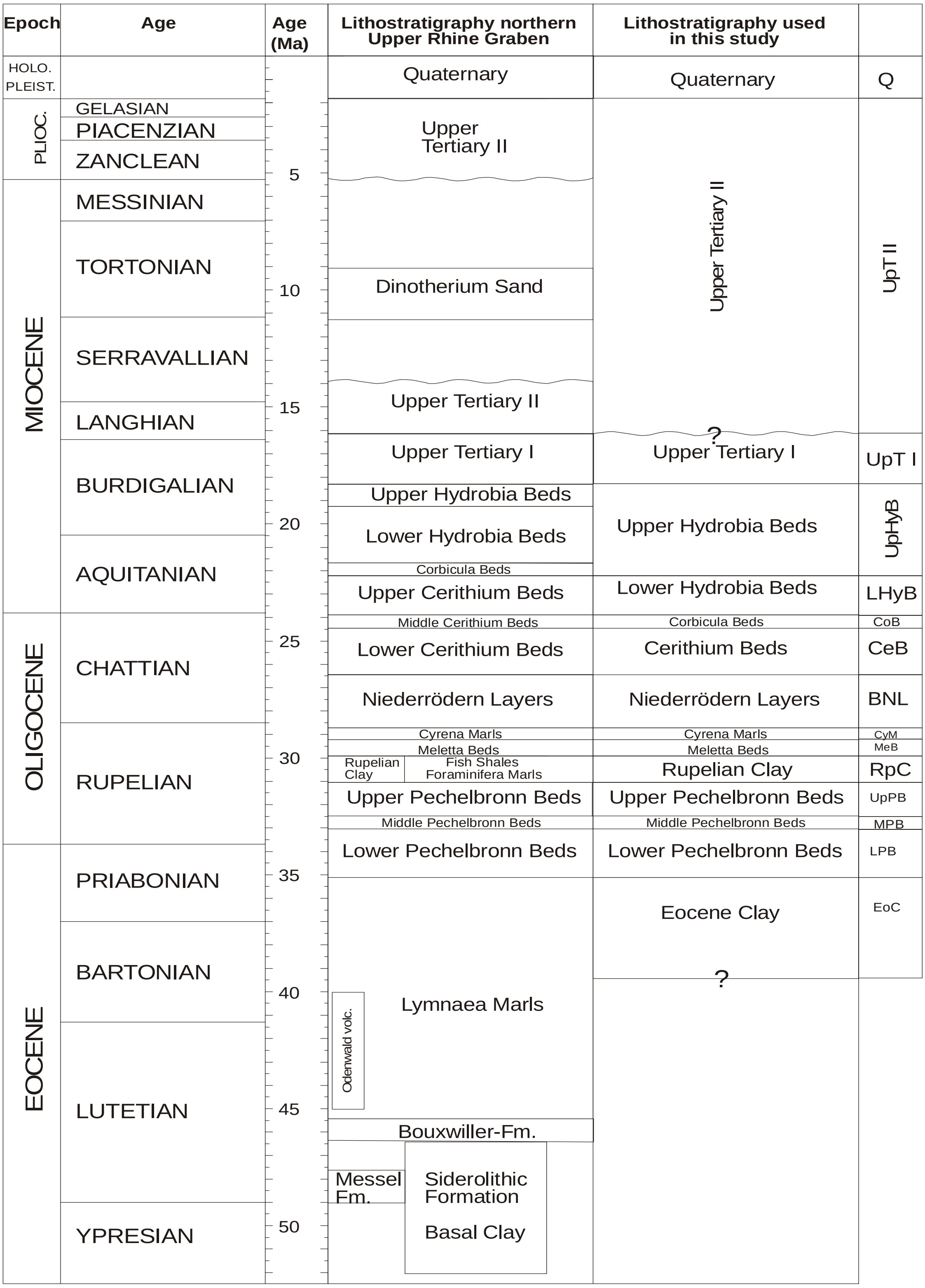


Fig. 2.2 Lithostratigraphic chart of the northern Upper Rhine Graben. Modified from the German Stratigraphic Commission (2002). Chronostratigraphy after Berggren *et al* . (1995). The post-Rupelian lithostratigraphic units used in this work correspond to the classification of the oil industry. Note the difference between the two classifications for the post-Rupelian time.

2.3 Syn-rift tectonic settings

The syn-rift tectonic settings of the northern Upper Rhine Graben are characterised by a multiphase subsidence history, with selective reactivation of pre-existing structures (e.g. Schumacher, 2002), under a repeatedly changing stress field, and by the resulting changes in rift geometry during Cenozoic times.

2.3.1 GRABEN GEOMETRY

The rift structure of the northern Upper Rhine Graben can be differentiated from a dimensional point of view into large- and intermediate-scale geometry. The importance of these two geometry types varied during the Cenozoic evolution of the northern URG.

The large-scale structure is dominated by a northeast-southwest oriented interbasin transfer zone (between Darmstadt and Alsheim), which subdivides the northern URG in two halfgrabens (i.e. a northern and a southern sub-basin) with opposing tilt directions (**Fig. 2.3a, b**; Derer *et al*., 2003). This antithetic interference zone (after the geometric nomenclature of Gawthorpe & Hurst (1993)) connects the western master fault of the northern halfgraben with the eastern master fault of the southern halfgraben. Thus, from north to south, the depocentre axis shifts from the western to the eastern graben margin (**Fig. 2.3a, b**). The transfer zone represented during the Cenozoic graben evolution a structural high and, at times, a palaeotopographic barrier between the northern and southern sub-basins. The southern end of the southern halfgraben is represented by the Baden-Baden-Lalaye-Lubine zone (outside the study area **Fig. 2.4**). This structure represents also a transfer zone. This southern transfer zone connects the eastern masterfault of the southern sub-basin with the western masterfault of the southernmost part of the Upper Rhine Graben. As a consequence, the depocentre axis shifted again, from the eastern graben margin to the western graben margin (Pflug, 1982; Mauthe *et al*., 1993; Schumacher, 2002) (**Fig. 2.4**).

The northern transfer zone is placed in the vicinity of a Variscan shear zone (Krohe, 1992), and in the boundary area between two inherited Permo-Carboniferous structures. These structures are the Saar-Nahe Trough in the north and the Odenwald-Spessart High in the south (**Fig. 2.4**). The location and the southwest-northeast “Variscan” strike of the transfer zone could imply an influence of the pre-existing Paleozoic structural grain of the area on the Cenozoic syn-rift tectonics, as suggested for other URG structures by Schumacher (2002). The migration of the depocentres in the northern Upper Rhine Graben from the western to the eastern master fault (considered by Derer *et al*. (2003) and in this study as the result of a large scale transfer zone) was previously discussed by Straub (1962) and Doebl (1967).

At subordinate scale, the halfgrabens and the transfer zone are characterised by faults, sub-parallel to the graben shoulders. The fault planes are often listric and delimit fault blocks (**Fig. 2.3a, b**). The blocks created minor depocentres which, especially during the early stage of graben formation, acted as isolated basins. Good examples are fault blocks A-B, B-C, D-E of the southern sub-basin, related to faults A, B, C, and D respectively (**Fig. 2.3a** and **profile S2** in **figure 2.3b**). The evolution of these blocks will be discussed in more detail in **chapter 2.3.2**. Fault B corresponds to the "Grünstadt Oppenheim Fault" (Lampe, 2001). Fault C corresponds to the "Western Main Fault" ("westliche Rheingrabenhauptstörung") (Stapf, 1988; Lampe, 2001). Fault D corresponds to the "Hofheim Fault" (Lampe, 2001).

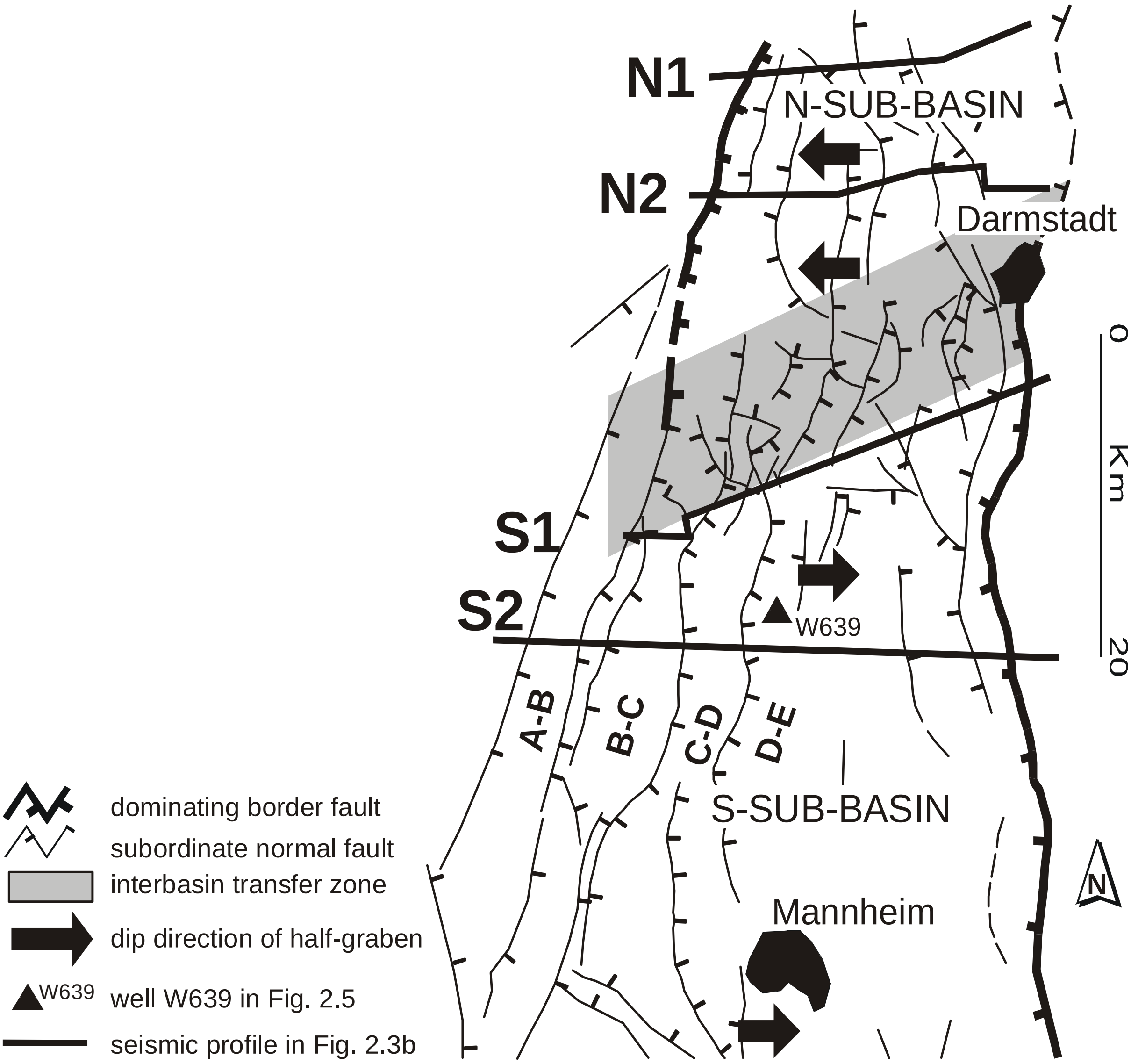


Fig. 2.3a The northern Upper Rhine Graben. The large-scale transfer zone separates two halfgrabens with opposing tilt directions. The seismic sections N1, N2, S1, S2 are shown in **Fig. 2.3b**. Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996). The structural level of the fault pattern is top Rupelian Clay.

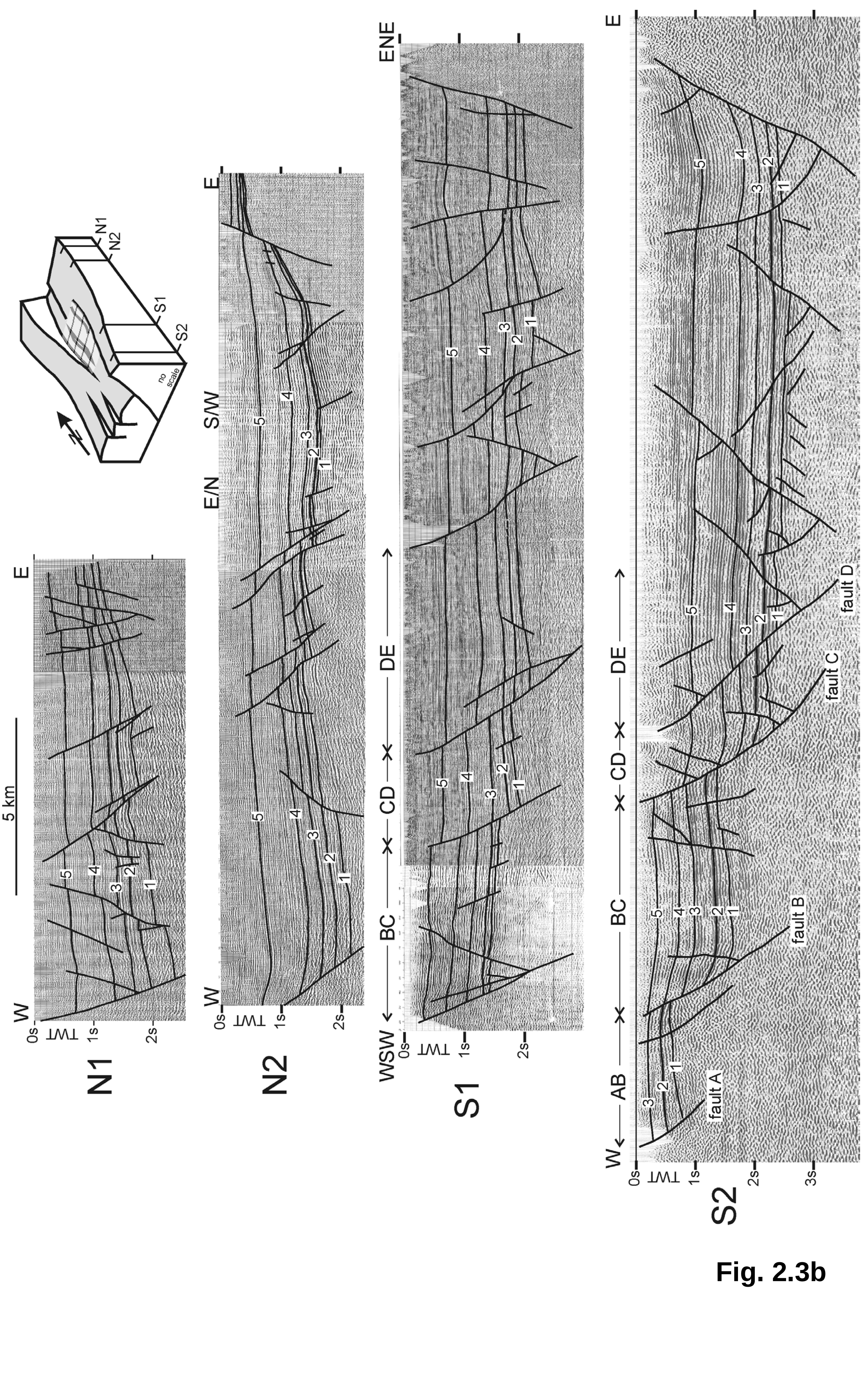

N1
N2
S1
S2
5 km
no scale
W
E
WSW
ENE
E/N
S/W
TWT
0s
1s
2s
3s
AB
BC
CD
DE
fault A
fault B
fault C
fault D

Fig. 2.3b

Fig. 2.3b (previous page) Interpreted seismic sections across the northern Upper Rhine Graben, showing opposing tilt of the northern and southern sub-basins. Vertical scale is two-way travel time in seconds. Location in **Fig. 2.3a**. The 3D-block shows a simplified model of the transfer zone and the two halfgrabens. 1 top pre-rift (base Cenozoic); 2 top Rupelian Clay; 3 top Niederrödern Layers; 4 top Corbicula Beds; 5 top Hydrobia Beds. Sections N1, N2, S1 with the kind permission of the Wirtschaftsverband Erdöl- Erdgasgewinnung e.V. Section S2 (DEKORP 9N), data from the GeoForschungsZentrum Potsdam with the kind permission of the GeoForschungsZentrum Potsdam.

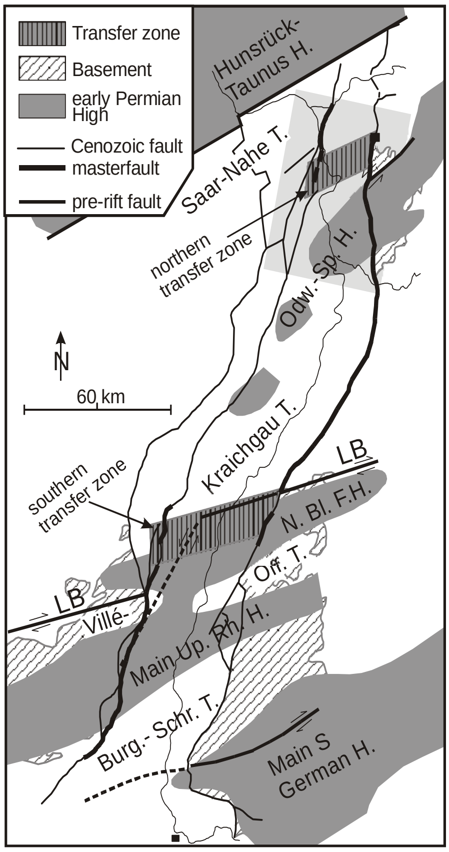


Fig. 2.4 The location of the northern (Derer *et al*., 2003) and southern transfer zone (interpreted from Mauthe *et al*. (1993)) within the Upper Rhine Graben. Their existence could be influenced by pre-rift Paleozoic structures (from Boigk & Schoeneich (1970); Schumacher (2002)). Study area marked by the shaded rectangle. LB-Baden-Baden-Lalaye-Lubine zone.

2.3.2 GRABEN SUBSIDENCE AND EVOLUTION

The northern Upper Rhine Graben was subjected, after its initiation in the middle (?) to late Eocene, to three main subsidence phases: (I) late Eocene - early Oligocene, (II) latest Oligocene - early Miocene, and (III) Pliocene - Quaternary (Illies, 1978; Teichmüller & Teichmüller, 1979; Meier & Eisbacher, 1991; Ziegler, 1992; Schumacher, 2002).

Subsidence analysis was performed with the backstripping method for one well (W639) located in the southern sub-basin (**Fig. 2.5**, location in **Fig. 2.3a**). This well is especially suited for this investigation, as it penetrates almost the complete Cenozoic succession. The curves represent (1) air-loaded tectonic subsidence; (2) water-loaded tectonic subsidence, (3) total basement subsidence (non-decompacted), (4) total basement subsidence (decompacted). Palaeodepositional depth (5), but no sea level changes were considered. On the palaeo-waterdepth curve (5), the maximum bathymetries correspond to the boundaries of the lithostratigraphic units. This is not the case in reality, but imposed by software limitations. Due to dating uncertainties, the interpretation of these curves (in the interval between the Pechelbronn Beds and the Hydrobia Beds) is qualitative. Especially the dating of the Upper Tertiary I and II, and Quaternary is highly problematic, thus this curve segment will not be considered.

On the tectonic subsidence curves (1) and (2) three steep inflections are recognised, representing periods of accelerated subsidence. The ones during the deposition of the Middle Pechelbronn Beds and the Rupelian Clay/Meletta Beds/Cyrena Marls belong to the early Oligocene tectonic stage. The inflection during the (Cerithium)/Corbicula/Hydrobia Beds is the result of the early Miocene subsidence phase. The results of the backstripping were compared with the interpreted seismic sections across the graben (**Fig. 2.3b**).

(I) <u>The first major subsidence episode</u> of the northern URG was the result of an extensional, maybe initially transtensional, phase with a WNW-ESE oriented least principal stress axis (Meier & Eisbacher, 1991; Schumacher, 2002). This episode first created incipient, partly isolated halfgrabens, where the Eocene Clay and the terrestrial Lower Pechelbronn Beds accumulated. By early Rupelian, most of these small depocentres must have coalesced, as the Middle Pechelbronn Beds were deposited in brackish/marine settings covering almost the whole graben area. The Middle Pechelbronn Beds are marked on the subsidence curves by a steep inflection.

The geometry of the depocentres of the Pechelbronn Beds is in harmony the synsedimentary WNW-ESE extension. Graben-parallel, listric growth faults, associated with the syn-sedimentary rotation of the hangingwall, generated a series of subordinate tilt blocks/halfgrabens (**N1, S1, S2** in **Fig. 2.3b**, between horizons 1 and 2). On the hangingwall, the deposits are wedge-shaped, with the thickness increasing toward the growth fault. Reflectors diverge towards the fault plane, reflecting block rotation during deposition. Especially fault blocks A-B and B-C of the southern sub-basin display the pronounced halfgraben asymmetries (**profile S2** in **Fig. 2.3b**). This halfgraben configuration, controlled by growth faults, was significant only for the early syn-rift stage, during the deposition of the Pechelbronn Beds (latest Priabonian to lower Rupelian).

The transfer zone was also active during this phase, and separated the northern and the southern depocentre. Within the transfer zone itself, the Pechelbronn Beds are very thin or absent. The Rupelian Clay, Meletta Beds and Cyrena Marls were sedimented partly in deep marine conditions across the entire graben. Thus, during the upper Rupelian, the northern URG acted as one depozone, sporadically connecting the Molasse Basin and the North Sea Basin (e.g. Berger, 1996).

During the Chattian, a phase of decreased subsidence is recorded in the northern Upper Rhine Graben (**Fig. 2.5**), when the Niderrödern Beds were deposited. They have a relative constant thickness over the study area.

(II) During the second major subsidence phase (late Oligocene-early Miocene), the thickest pile of the basin fill in the northern Upper Rhine Graben was deposited (between horizons 3 and 5 in **Fig. 2.3b**). This phase is reflected by an inflection on the subsidence curves (**Fig. 2.5**). At the same time uplift and erosion occurred in the southern URG (e.g. Teichmüller & Teichmüller, 1979; Ziegler, 1992; Schumacher, 2002). During this subsidence phase the Cerithium-, Corbicula- and Hydrobia Beds were deposited. Schumacher (2002) suggests for this stage an overall left-lateral transtension and Gaupp & Nickel (2001) mention post-early Oligocene sinistral strike-slip faults.

During this subsidence phase, some of the Eocene-Oligocene faults were reactivated and new faults formed. In the southern sub-basin, on **profile S2** in **figure 2.3b** between faults A, B, and C the degree of reactivation from west to east can be observed. Fault A shows very little subsidence in the time after the deposition of the Niederrödern Layers (horizon 3 in **Fig. 2.3b** is top Niederrödern Layers). Consequently, Miocene reactivation was minimal or absent. On fault B Miocene reactivation occurred, whereas the maximum Miocene subsidence was accommodated by fault C. Across fault C high thickness variations occur, especially within the Hydrobia Beds. Fault blocks A-B and B-C, characterised during late Eocene-early Oligocene by important subsidence, were not so active during the Miocene stage, in contrast to the blocks more to the east (D-E, etc.). Consequently, an eastward shift of the depocentre can be assumed for the southern sub-basin.

In W-E seismic sections, at intermediate scale, no syn-tectonic sedimentary wedges are observed at the faults active during the second subsidence phase. Abrupt changes in seismic facies across the faults and flower structures may result from strike slip movements. The master faults on both sides of the transfer zone were active and the Miocene fill of the two halfgrabens reflects pronounced asymmetries (**Fig. 2.3b**). Especially at the western border fault of the northern sub-basin syn-tectonic sedimentary wedges are present. The subsidence pattern was controlled at regional scale by the northern transfer zone and locally, within the sub-basins, by variable subsidence rates between the different fault blocks.

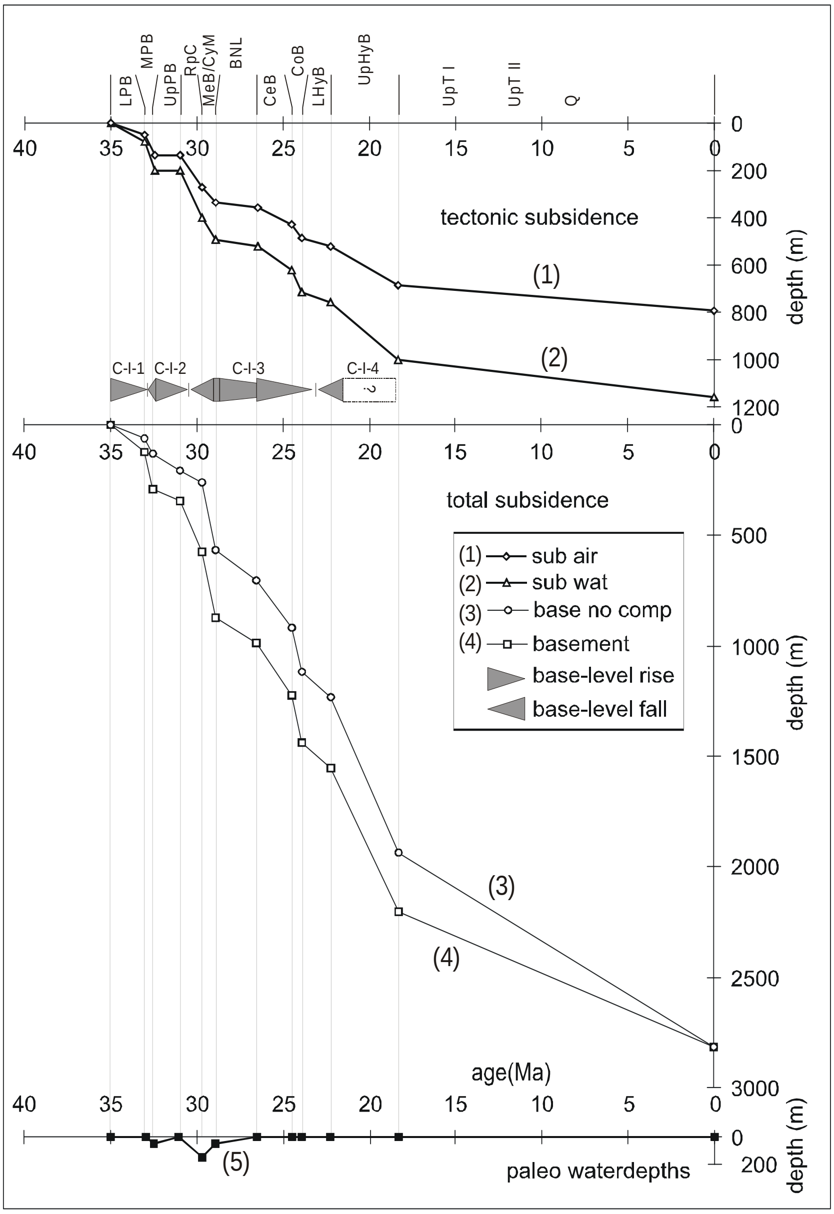


Fig. 2.5a Subsidence curves of well W639. Location in **Fig. 2.3a**. (1) air-loaded tectonic subsidence, (2) water-loaded tectonic subsidence, (3) total basement subsidence (non-decompacted), (4) basement subsidence (decompacted), (5) palaeo-water depth (due to software limitations maximum bathymetries are plotted at lithostratigraphic boundaries; this does not correspond to reality). Lithostratigraphic units and large-scale base-level cycles (as interpreted in this study) are shown. LPB Lower Pechelbronn Beds, MPB Middle Pechelbronn Beds, UpPB Upper Pechelbronn Beds, RpC Rupelian Clay, MeB Meletta Beds, CyM Cyrena Marls, BNL Niederrödern Layers, CeB Cerithium Beds, CoB Corbicula Beds, LHyB Lower Hydrobia Beds, UpHyB Upper Hydrobia Beds, UpT I Upper Tertiary I, UpT II Upper Tertiary II, Q Quaternary.

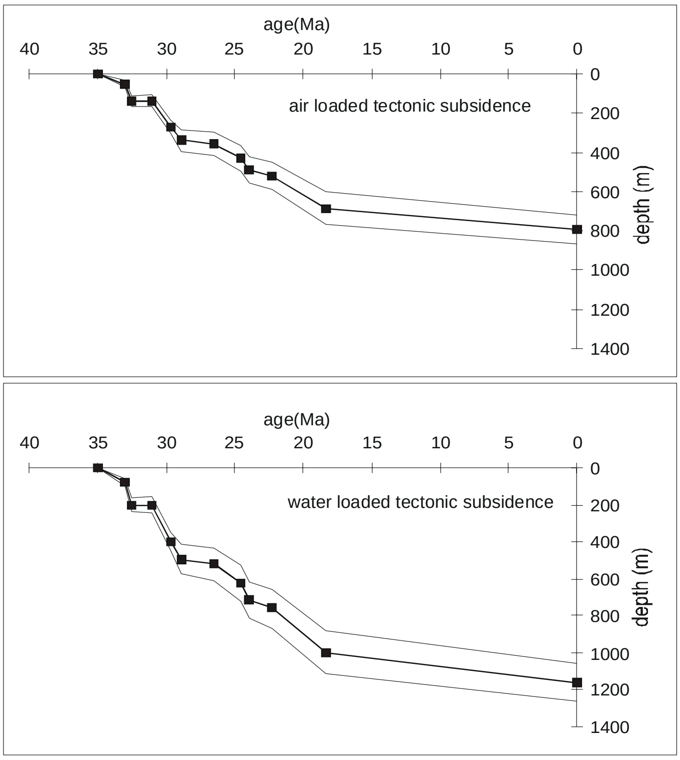


Fig. 2.5b Tectonic subsidence of well W639 with the variation range due to lithologic uncertainties.

(III) The third subsidence phase (Pliocene to Quaternary) was triggered by a sinistral shear regime (Illies, 1978; Ziegler, 1992; Schumacher, 2002). In the seismic sections of the northern sub-basin, the Pliocene-Quaternary fill shows a wedge-structure with westward increasing thickness, and in the southern sub-basin an eastward increasing thickness (**Fig. 2.3b**). This opposing asymmetry reflects the active role of the transfer zone in influencing the deposition. The master faults of the sub-basins and several reactivated late Eocene-early Oligocene faults show activity signs till in the uppermost Plio-Quaternary layers. At subordinate-scale, graben-interior faults (e.g. fault C in **profile S2** in **Fig. 2.3b**) led to thickness variations of these sedimentary successions (above horizon 5 in **Fig. 2.3b**).

The structural configuration of the northern Upper Rhine Graben (depocentres and faults) changed during the syn-rift evolution. In the early stages of rifting, the sedimentation of the Eocene Clay and Pechelbronn Beds was controlled by local fault movements, which created small halfgrabens spread over a larger area, and not by absolute subsidence of one large depozone. The northern URG, as a major depocentre was probably accomplished at the end of the early Rupelian, when the basin was formed, which allowed the formation of the marine conditions of the Rupelian Clay. In the southern sub-basin, during the Miocene and Plio-Quaternary evolution, subsidence decreased or even ceased for some of the initial subordinate halfgrabens located at the western margin (as is the case for block B-C and A-B respectively, **Fig. 2.3b**). Meanwhile the major depocentre migrated eastward and the maximal subsidence was accommodated on a narrower area within the graben (e.g. on profile S2 between fault C and the eastern masterfault, **Fig. 2.3b**). The eastward shift of the depocentres through Cenozoic time is in accordance with the eastward propagation of the fault system, as mentioned by Lampe (2001).

2.4 The syn-rift sedimentary fill: seismic and wire-line log response

The lithologic, depositional and palaeoenvironmental characteristics of the Cenozoic sedimentary fill of the northern Upper Rhine Graben were interpreted in this study from wire-line logs, descriptions of cores and cuttings, palaeontologic information and reflection seismic data. Completion reports and literature were consulted. In addition, outcrops with the equivalent deposits were studied. The well logs used were natural gamma ray (GR), self potential (SP), caliper (CAL), resistivity and sometimes sonic. The characteristics of fluids (e. g. salinity) contained in the porous units are highly variable, thus the sedimentologic interpretation of the resistivity tool is limited. The resistivity response will be mentioned when it is important for the scope of the study.

Abrupt lateral changes in facies occur due to syn-depositional tectonics and related depositional conditions, which vary laterally. Consequently, the interpretation provides only an overview on the dominating sedimentary environments in the axial area of the northern Upper Rhine Graben (**Tab. 2.1**). The discussion will consider the classic lithostratigraphic units, as they can be easily recognised in well logs and sometimes in reflection seismic sections (**Fig. 2.6 a, b, c; Fig. 2.7**).

During the early rift-stage (latest Priabonian to early Rupelian), sediments were deposited in a series of partly isolated basins, thus the variable seismic and well-log response reflect the local sedimentation conditions. Starting with the late Rupelian, the northern URG acted more like one single depocentre. Sedimentation conditions became more uniform across the basin, thus the seismic facies can be correlated over larger areas and in both N-S and W-E directions.

The oldest Tertiary deposits of the northern URG are of Eocene age (the **Eocene Clay**) (Doebl, 1967; Gaupp & Nickel, 2001). These overlie uncomformably the Permian strata. Due to lack of palaeontologic data, a more precise dating was not possible. They only occur locally, but can reach a thickness of ca. 100-150 metres. These Eocene sediments were identified with certainty in only two wells, in the very north of the study area. They mainly consist of mudstones and siltstones (often reddish in colour), characterised by low resistivity and positive SP values (**Fig. 2.6b**). Sandstones and conglomerates occur in fining- or coarsening-upward trends (bell- and funnel-shaped SP signals) within the fine-grained sediments. The seismic facies of this lithostratigraphic unit consists of moderate amplitudes, variable frequencies, a low continuity and reflection pattern which varies from chaotic to subparallel and oblique. The reflection characteristics reflect a rapid lateral change of sedimentation condi-

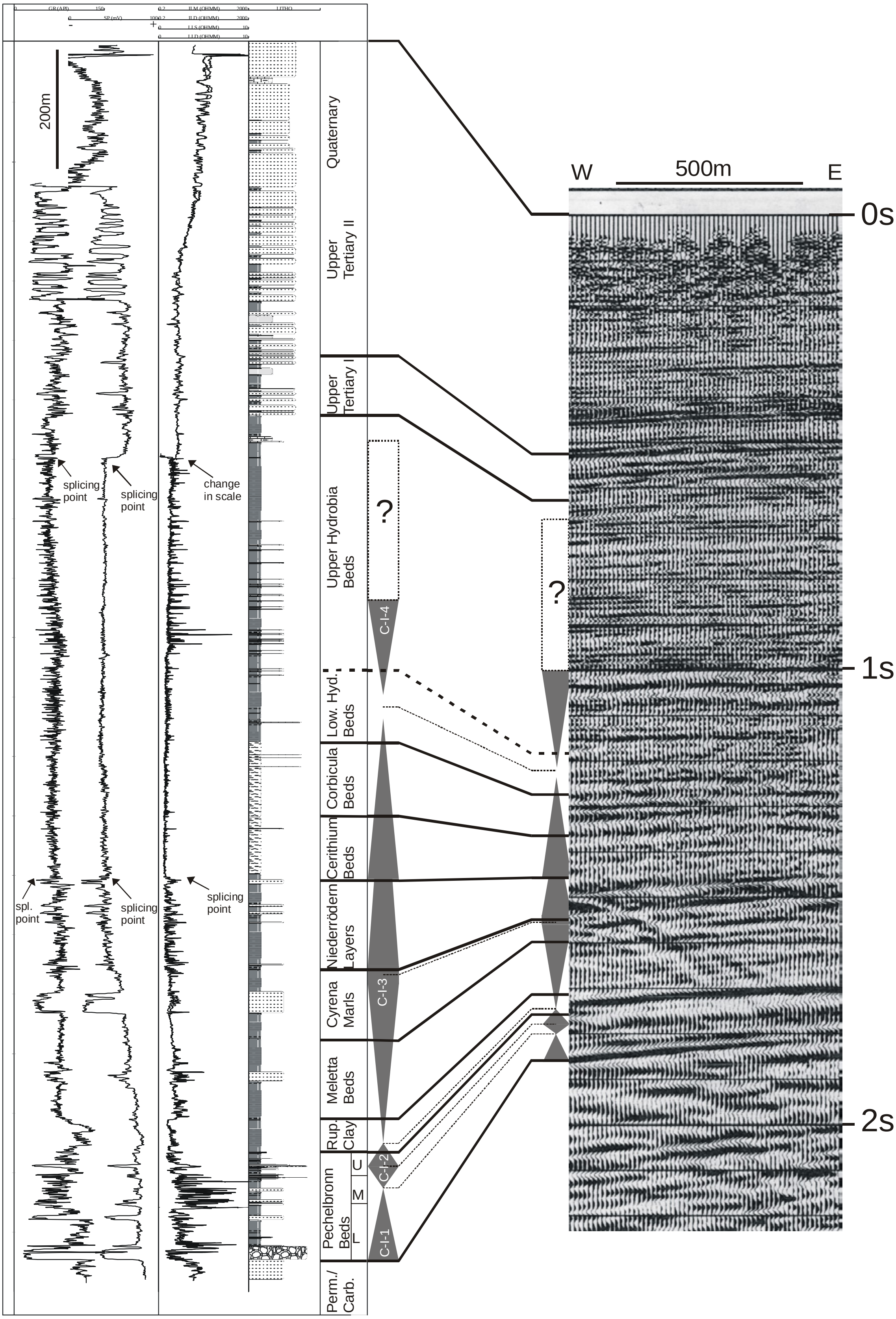


Fig. 2.6 a Lithology and wire-line log response of the Cenozoic fill of the northern Upper Rhine Graben in a composite log. Its correlation with the seismic facies. Interpreted large-scale base-level cycles. Seismic facies from section S1 (**Fig 2.3a**). Legend in **Fig. 2.6b**.

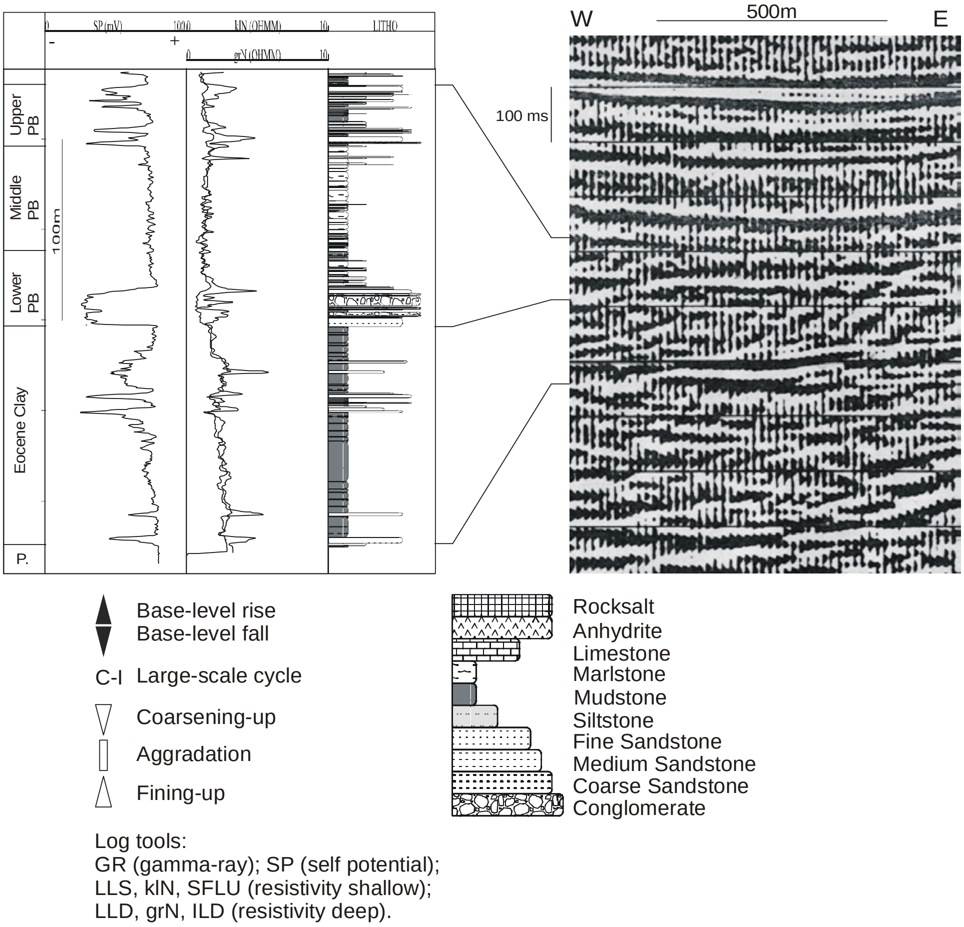


Fig. 2.6 b Lithology, wire-line logs response and seismic facies of the Eocene Clay and Pechelbronn Beds (PB). P Permian.
Legend for **Fig. 2.6a, b, c** and **Fig. 2.7**. GR and resistivity values increasing towards the right. SP values: left negative, right positive.

tions. Gaupp & Nickel (2001) call these deposits "Red Bed"-facies ("Rotfazies"). They may be interpreted as generated in terrestrial environments: interfluvial, lacustrine, small fresh-water deltas (e.g. **Fig. 2.6 b**), fluvial channels and splays.

The **Pechelbronn Beds (PB)** have a far larger areal extent in the northern URG. In most cases, they directly overlie the Permian pre-rift deposits. In the study area, their depositional pattern is very diverse and their thickness varies between zero and 250 metres. A detailed interpretation and discussion of the Pechelbronn Beds is presented in **chapter 3**.

Based on lithostratigraphy, biostratigraphy and palaeoecology they were divided into **Lower**, **Middle** and **Upper Pechelbronn Beds** (Schnaebele, 1948) (**Fig. 2.6a, 2.6b**). This differentiation is possible in most of the wells, but the vertical seismic resolution does not allow it for the seismic data. The **Lower Pechelbronn Beds (LPB)** usually have a sharp base, characterised by fluvial sandstones with negative SP and low GR values. Often these sandstones display a blocky pattern as a result of channel amalgamation. Up in section they alternate with lacustrine/interfluvial mudstones and swamp deposits (e.g. Plein, 1992; Nickel, 1996; Gaupp & Nickel, 2001; Derer *et al*., 2003), with positive SP pattern and higher GR signals. The **Middle Pechelbronn Beds (MPB)** are represented by offshore mudstones in depocentres (**Fig. 2.6b**) and prograding fine-grained delta/shoreface sandstones in landward positions (**Fig. 2.6a**, Gaupp & Nickel, 2001; Derer *et al*., 2003), formed under brackish-marine conditions of a sea advancing from the south (e.g. Doebl, 1967; Gaupp & Nickel, 2001). The positive SP, high GR and low resistivity of the mudstones represent a good correlation marker. The prograding units appear as coarsening-upward trends (funnel-shaped SP and GR response). Martini (1973) attributed the MPB to the nannoplankton zone NP 22 (earliest Rupelian). In the **Upper Pechelbronn Beds (UPB),** coarse-grained sandstones and conglomerates of fluvial origin alternate with interfluvial/lacustrine mudstones and siltstones (Gaupp & Nickel, 2001, Derer *et al*., 2003). These packages interfinger with mudstones and fine-grained sandstones of the remnant brackish/marine settings in the depocentres (Gaupp & Nickel, 2001). On top, a second marine transgression occurred with the sea advancing from the north. In general, the porous and permeable fluvial sandstones and conglomerates of the Upper Pechelbronn Beds appear as relatively isolated negative SP and low GR peaks. These represent single-storey fluvial channels embedded in overbank fines.

The seismic facies of the Pechelbronn Beds is highly variable but its main characteristics are a moderate to high amplitude, low frequency and a low continuity. It reflects the dominant terrestrial systems with a rapid lateral change in sedimentation style.

The following **Rupelian Clay (RpC)** (**Foraminifera Marls** and **Fish Shale**) has a uniform facies, which covers almost the entire Upper Rhine Graben. The Upper Rhine Graben probably had, at its time of deposition (upper Rupelian), temporary marine communication with the North Sea Basin and the Paratethys (Molasse Basin) (e.g. Doebl, 1967; Berger, 1996). The **Foraminifera Marls** consist of offshore marine shales and marls, which become bituminous in the **Fish Shale**, due to oxygen depletion of the bottom water layer (Doebl & Malz, 1962; Grimm, 1991). The two units cannot be differentiated on the basis of well logs. The thickness of the Rupelian Clay in the study area varies between 50 and 100 metres. It displays a characteristic log pattern, with extreme positive SP, two maximum GR peaks and a relative low resistivity signal (**Fig. 2.6.a**). The seismic facies of the Rupelian Clay usually consists of a very thin package of high amplitude, low-moderate frequency and high continuity parallel reflectors, representing an excellent seismic marker horizon within the entire study area. The high amplitudes are given by the strong acoustic impedance contrast between the well-stratified shales and marls of the Rupelian Clay and the sandstones of the Upper Pechelbronn Beds and the weakly bedded marls and siltstones of the Meletta Beds.

The maximum water depth was estimated at about 150-200 metres for the Foraminifera Marls (Rothausen & Sonne, 1984) and at about 100 metres for the Fish Shale (Grimm, 1991). The coastal equivalents of the Rupelian Clay can be found on the Mainz Block (Mainzer Becken) as the **Lower Marine Sand** (Doebl, 1967; Hartkopf & Stapf, 1984; Grimm, 1998), which displays shoreface and deltaic facies.

The Rupelian Clay is followed in continuity of sedimentation by the **Meletta Beds** (**MeB**), which have a thickness of about 100 metres. Their dominant component consists of weakly stratified marls with positive SP response and relative high GR values (**Fig. 2.6.a**). The resistivity signal is variable. However, there is a clear contrast of wire-line log pattern to the subjacent Rupelian Clay. Subordinate, siltstones and fine-grained sandstones occur in coarsening-upward trends, creating funnel-shaped SP and GR pattern (10 to 30 metres thick). The reflection characteristics display very low amplitude, moderate frequency, moderate-low continuity and a parallel to subparallel reflection configuration.

During the deposition of the Meletta Beds, the environment became aerated again (Doebl, 1967), and the decrease of salinity led to brackish conditions (Schwarz, 1997). The sedimentary environment was dominated by deep-water conditions. The marls are offshore successions, deposited below wave-base, whereas the subordinate coarsening upward silt- and sandstones represent the distal parts of delta/shoreface systems (minor gravity flows on the lower shoreface, prodelta deposits?). The proximal, coastal facies of the Meletta Beds is again known from the Mainz Block, as the uppermost part of the **Lower Marine Sand** and the **Upper Marine Sand** (Rothausen & Sonne, 1984).

Up in stratigraphic section, and in continuity of sedimentation, the **Cyrena Marls** (**CyM**) were deposited with a thickness of ca. 100 metres. The lithologic and wire-line log characteristics are similar to the Meletta Beds, but the content of fine- to medium-grained sandstones increases upward, especially in the upper parts of the Cyrena Marls (**Fig. 2.6a**). The sandstones create an overall thickening and coarsening-upward trend. The increase in sand content can be sometimes recognised in the gradual upward change of the seismic facies from the Meletta Beds to the Cyrena Marls. The reflection pattern of the Cyrena Marls has higher amplitudes, moderate frequency, moderate-low continuity and parallel to subparallel reflection configuration. The establishing of an exact boundary between the Cyrena Marls and the subjacent Meletta Beds was not possible. It is neither in well logs and seismic lines, nor with available palaeontologic data possible. Thus a transitional boundary zone is considered.

The salinity of the depositional environment decreased continuously, forming brackish/ lacustrine conditions (Schwarz, 1997; Reichenbacher, 2000). The shaly marls may represent the fine-grained offshore sedimentation, which is increasingly disturbed by more proximal prograding delta/shoreface systems. However, the marly offshore sedimentation dominates the successions till in the upper parts of the CyM, where the increased input of coarse material form delta/shoreface systems occurred.

The **Niederrödern Layers (BNL)** have a thickness between 100 and 250 metres. They consist of an alternation of marls/shaly marls and fine- to medium-grained sandstones. The BNL can easily be recognised in well logs, as all curves (SP, GR, resistivity) display a very irregular signal (**Fig. 2.6.a**). Both coarsening- and fining-upward trends are present at small scale, but no overall tendency can be recognised. The seismic facies usually shows high amplitude, medium frequency, low-moderate continuity, and various reflection configurations (subparallel, hummocky, etc.). Due to high contrast in acoustic impedance, the boundary between the sandstone/marl alternation of the Niederrödern Beds and the overlying predominant marly Cerithium Beds often represents a good seismic marker horizon. Due to the scarce dating, the position of the lower boundary of the BNL is uncertain. However, from sedimentological and depositional points of view, the lower part of the Niederrödern Layers belongs to the continuous shallowing upward transition, which started in the Meletta Beds.

The Niederrödern Layers were generated in terrestrial, fresh-water conditions (Doebl, 1967; Mauthe *et al*., 1993; Schwarz, 1997; Reichenbacher, 2000), at a time when the Upper Rhine Graben was an isolated basin. The marls and shaly marls are interfluvial and lacustrine sediments (displaying continuous seismic reflection pattern), whereas river channels and crevasse splays have deposited the sandstone bodies (with a low continuity seismic reflection pattern). Locally, towards their top, a gradual increase of brackish influences is observed (Schwarz, 1997).

On top of the Bunter Niederrödern Beds follow the **Cerithium Beds** (**CeB**). These consist of about 100 metres of poorly stratified shales and shaly marls, locally containing anhydrite concretions and thin limestone beds. The well logs show “smooth” curves of positive SP (which could represent the “shale-line”), high GR and low resistivity values (**Fig. 2.6a**). In seismic profiles, the Cerithium Beds display very low amplitudes, moderate frequency, and a relative continuous parallel to subparallel reflection configuration. All geophysical patterns reflect widespread low energy sedimentation, with a low input of clastic material. Brackish lakes dominated the environmental conditions, with an increasing salinity in time due to evaporation (Prell-Müssig, 1965; Schwarz, 1997).

The sedimentation of the **Corbicula Beds** (**CoB**) was similar to the sedimentation of the Cerithium Beds, but under conditions of higher salinity. In the northern part of the study area (north of Worms), the CoB are mainly represented by 150 to 200 metres of bituminous shales and shaly marls, often with anhydrite intercalations. The wire-line log response is similar to that of the Cerithium Beds, but the seismic facies displays higher amplitudes (**Fig. 2.6a**).

In the southern part of the study area (south of Worms), in several intervals, rock salt is interbedded with the marls over a thickness of several tens of metres (**Fig. 2.6c**). The rock salt is clearly seen as low-value GR peaks (the SP measurement is useless due to the salt- and oil-based drill fluid), and by higher resistivity signals, especially for the deep-measuring device. A good identification of the salt layers is also possible with the sonic-log (showing characteristic interval transit times of 220-225 msec/m) and the caliper. The seismic facies is dominated by the high acoustic impedance contrast between the salt and the marls, displaying very high amplitudes, moderate to low frequency, very high continuity and parallel reflector configuration. The deposition took place in a brackish environment of high planktonic production, interrupted by hypersaline episodes when salt precipitated (Prell-Müssig, 1965; Doebl, 1967). At that time, the Upper Rhine Graben was an isolated basin (Prell-Müssig, 1965; Reichenbacher, 2000). The lithological and geophysical facies reflect low energy lakes of important areal extent.

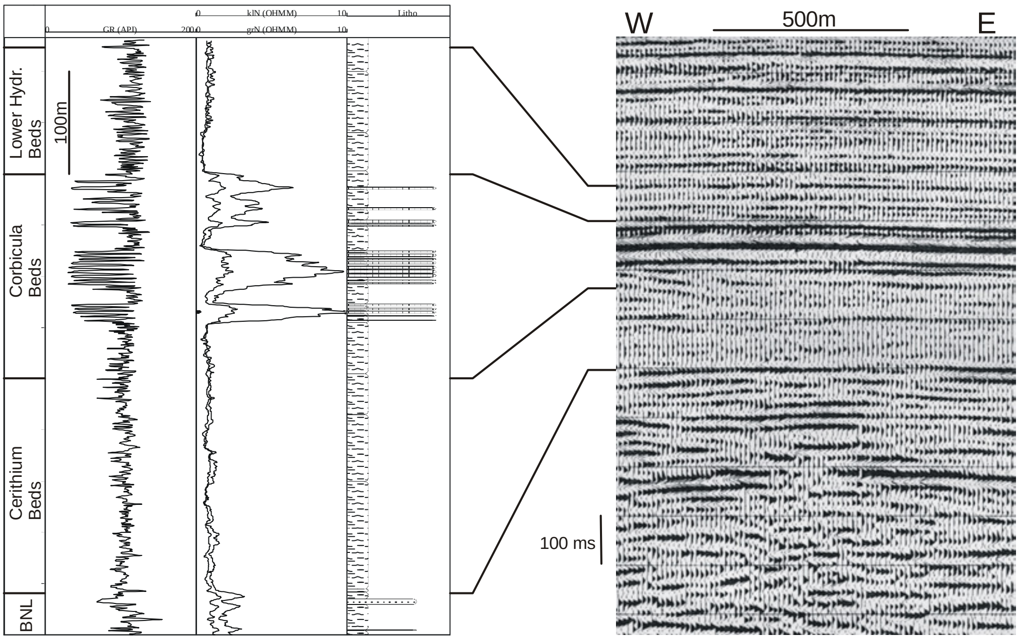


Fig. 2.6 c Lithology, wire-line logs response and seismic facies of the saliferous Corbicula Beds. Note the low-value GR peaks of the rock salt, and the high reflection amplitudes due to high acoustic impedance contrast. Legend in **Fig. 2.6b**.

Communications between the Upper Rhine Graben and neighbouring marine basins opened again during the deposition of the **Hydrobia Beds** (**HyB**) (Prell-Müssig, 1965; Doebl, 1967; Sissingh, 1998; Reichenbacher, 2000). Based on micropalaeontology they were divided into **Lower** and **Upper Hydrobia Beds**. The distinction between the Lower and Upper Hydrobia beds on the basis of lithology or geophysical data is not possible. The Hydrobia Beds are between 600 and 800 metres thick and consist of shales, shaly marls and marls with anhydrite intercalations. In some intervals, frequent thin limestone and dolomite layers are present. These intercalations are traceable in both well logs and seismic. The wire-line log facies displays more irregularity that the one of the Cerithium and Corbicula Beds (**Fig. 2.6a**). The positive SP (close to “shale line”), high GR and low resistivity trend of the shales and marls is disrupted by thin, more resistive peaks with negative SP and low GR values of the limestone and dolomite layers. The seismic facies displays high frequency, moderate to high continuity and a parallel to subparallel configuration. The amplitudes vary between moderate and high, depending on the occurrence of the lime-/dolostone intercalations.

The depositional environments consisted of extended brackish lakes, influenced by marine conditions during the sporadic communications with the North Sea Basin (via the Lower Rhine Embayment) and possibly with the Mediterranean region (via the Rhone-Bresse Graben, Schad, 1964; Prell-Müssig, 1965; Doebl, 1967; Best, 1975; Martini 1981; Sissingh, 1998; Reichenbacher, 2000). The most prominent marine influence occurred in the Lower Hydrobia Beds (e.g. Hüttner, 1991; Schwarz, 1997; Sissingh, 1998).

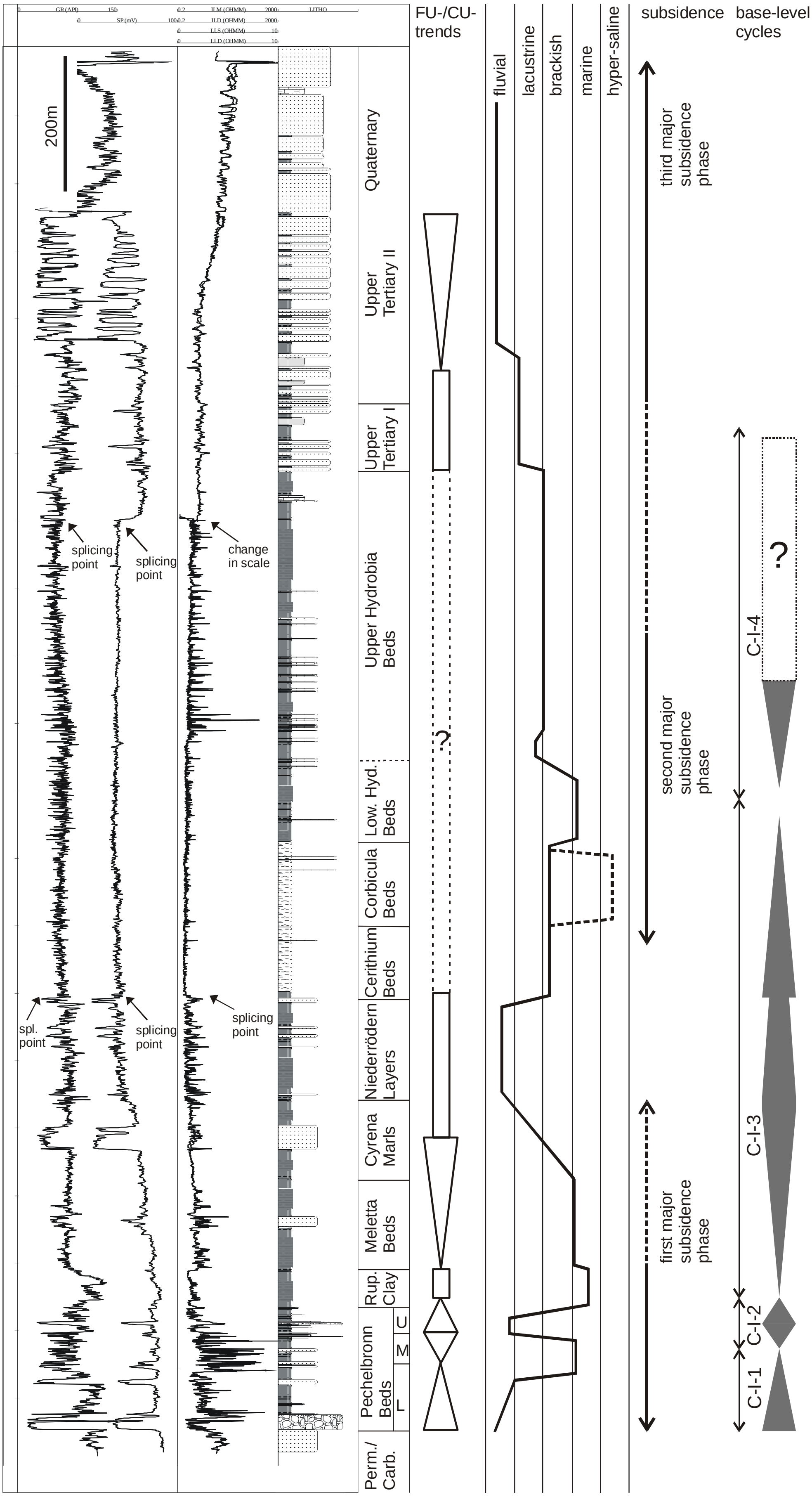
The deposition of the **Upper Tertiary I** (100-150 metres thick) took place under fresh water conditions (Doebl, 1967; Schwarz, 1997; Reichenbacher, 2000). They consist of shales with few sandstone and conglomerate intercalations. Sparse isolated negative SP and low GR peaks interrupt the positive SP and high GR values of the shales (**Fig. 2.6a**). The resistivity curves are variable, but have a higher signal than the subjacent Hydrobia Beds, allowing the distinction of the two units. The sandstones and conglomerates probably represent fluvial channels and splays, which are embedded in the fine-grained material of lacustrine/ interfluvial environments. The relative low amount of channels implies a low energy system with scarce input of clastic sediment. The seismic facies displays similar characteristics as the Hydrobia Beds, with slightly higher amplitudes.

The sediments of the **Upper Tertiary II** and the **Quaternary**, with a thickness of about 500 metres, capped the Upper Tertiary I. The Quaternary cannot be differentiated from the Upper Tertiary II due to the lack of dating and the quality of the seismic sections. The deposits predominantly consist of fluvial sands and gravels of negative SP and low GR values, with few intercalations of interfluvial/lacustrine shales (**Fig. 2.6a**). The resistivity curve is characterised by high values. The seismic features of the Upper Tertiary II are variable amplitudes, moderate to high frequency, parallel to subparallel reflectors of low continuity. The succession contains small-scale fining-upward trends, overprinted by an overall coarsening- and thickening-upward tendency, representing the final stages of basin infill. In contrast to the unit below, high-energy sedimentation conditions and rapid lateral change of depositional style prevail. On the studied seismic profiles no major unconformity could be observed at the boundary between Upper Tertiary I and II, as mentioned by Doebl & Teichmüller (1979); Hüttner (1991); Sissingh (1998). However, south of Landau and Bruchsal (middle Upper Rhine Graben), the Upper Tertiary II rests unconformably on the underlying strata (Schad, 1964; Schad, 1965).

Fig. 2.7 (page 32) Interpretation of the Cenozoic fill of the northern Upper Rhine Graben Stacking pattern, depositional environments and base-level cycles correlated with the subsidence phases. Subsidence from backstripping (**Fig. 2.5**) and from Illies (1978); Teichmüller & Teichmüller (1979); Ziegler (1992); Schumacher (2002). Environments interpreted from well data and literature (Schwarz, 1997; Reichenbacher, 2000). Legend in **Fig. 2.6b**.

	Lithostratigraphic unit	Reflection characteristics	Environment
12	Upper Tertiary II (UT II)	amplitude: variable (moderate) frequency: moderate-high continuity: low-moderate configuration: parallel-subparallel	fluvial/interfluvial
11	Upper Tertiary I (UT I)	amplitude: moderate-high frequency: high continuity: moderate-high configuration: parallel-subparallel	lacustrine/fluvial
10	Hydrobia Beds (HyB)	amplitude: variable frequency: high continuity: moderate-high configuration: parallel-subparallel	UpHyS: lacustrine/brackish low energy LHyS: brackish/marine low energy
9	Corbicula Beds (CoB) (rock salt, south of Worms)	amplitude: high frequency: moderate-low continuity: high configuration: parallel	hypersaline low energy
8	Corbicula Beds (CoB) (north of Worms)	amplitude: moderate frequency: moderate continuity: moderate-high configuration: parallel	brackish low energy
7	Cerithium Beds (CeB)	amplitude: low frequency: moderate continuity: moderate-high configuration: parallel-subparallel	brackish low energy
6	Niederrödern Layers (BNL)	amplitude: high frequency: moderate continuity: low-medium configuration: variable	fluvial/interfluvial
5	Cyrena Marls (CyM)	amplitude: moderate frequency: moderate continuity: moderate-low configuration: parallel-subparallel	offshore-shoreface brackish
4	Meletta Beds (MeB)	amplitude: low frequency: moderate continuity: moderate-low configuration: parallel-subparallel	offshore marine
3	Rupelian Clay (RpC)	amplitude: high frequency: moderate-low continuity: high configuration: parallel	offshore marine
2	Pechelbronn Beds (PB)	amplitude: moderate-high frequency: low continuity: low configuration: variable	UpPS: fluvial/interfluvial MPS: brackish/marine LPS: fluvial/interfluvial
1	Eocene Clay (Eoc)	amplitude: moderate frequency: variable (moderate) continuity: low configuration: variable	fluvial/interfluvial

Tab. 2.1 Seismic facies of the lithostratigraphic units in the central northern Upper Rhine Graben and their environmental interpretation.



FU-/CU-trends
fluvial
lacustrine
brackish
marine
hyper-saline
subsidence
base-level cycles
200m
splicing point
change in scale
spl. point
Quaternary
Upper Tertiary II
Upper Tertiary I
Upper Hydrobia Beds
Low. Hyd. Beds
Corbicula Beds
Cerithium Beds
Niederrödern Layers
Cyrena Marls
Meletta Beds
Rup. Clay
Pechelbronn Beds
U
M
L
Perm./Carb.
third major subsidence phase
second major subsidence phase
first major subsidence phase
C-I-1
C-I-2
C-I-3
C-I-4
?

Fig. 2.7

2.5 Syn-rift depositional cycles: a possible interpretation

The Cenozoic sedimentary fill of the northern Upper Rhine Graben displays a complex evolution and, in certain time intervals, a rapid lateral facies change caused by tectonics (e.g. Schad, 1962; Jantschik *et al*., 1996; Gaupp & Nickel, 2001; Derer *et al*., 2003). However, looking at a large scale, it is possible to group strata into base-level cycles of gradually changing depositional conditions (such as accommodation space, sediment input, and depositional energy). These large-scale base-level cycles (C-I) were generated by the interplay of tectonic activity of the URG and major tectono-eustatic events of European basins. The correlation between the subsidence curves and the cyclicity has some limitations. This is because as the lithostratigraphic boundaries (used for the subsidence analysis) do not correspond to the genetic stratigraphic boundaries of the base-level cycles (turnarounds).

Earlier attempts of classification of the Cenozoic graben fill in cycles were made by Durst (1991) and Sissingh (1998). For the discussion of the base-level cycles **figure 2.5a, figure 2.7** and **figure 2.8** will be considered.

The **first cycle** (**C-I-1**, asymmetric base-level rise cycle) comprises the Eocene Clay (where deposited), the Lower Pechelbronn Beds and the lower part of the brackish/marine Middle Pechelbronn Beds (Derer *et al*., 2003). The deposition was characterised by an overall increase in accommodation space after rift initiation. Amalgamated fluvial channels (blocky GR and SP) are gradually replaced upward in the section by lacustrine and coastal deposits, and finally by the offshore shale of the Middle Pechelbronn Beds, where a turnaround zone is located. Sediment supply was variable, but generally decreased from base to top of the cycle. Creation of accommodation space was predominantly tectonic-controlled: the subsidence curves of the Middle Pechelbronn Beds show a steep inflection (**Fig. 2.5**). Due to active rifting, most isolated depocentres for the Eocene Clay and the Lower Pechelbronn Beds coalesced by early Rupelian (Schumacher, 2002). They formed the northern and southern sub-basin, where the brackish/marine settings of the Middle Pechelbronn Beds dominated. However, interplay with the global tectono-eustatic sea level rise is probable (Grimm *et al*., 2000), which led to the transgression of the brackish/marine conditions of the Middle Pechelbronn Beds (NP 22).

The **second cycle** (**C-I-2**) starts with a gradual decrease of accommodation space and increase of the sediment supply. Delta/shoreface systems of the upper part of the Middle Pechelbronn Beds prograded into the basin (coarsening-upwards units), and facies became more proximal. The fall-to-rise turnaround zone is located at the base of the Upper Pechelbronn Beds (Derer *et al*., 2003) and correlates with a decrease of the subsidence rate. The following rise in base-level created accommodation space for aggrading terrestrial deposits (fluvial, lacustrine of the Upper Pechelbronn Beds), which were drowned and capped by the offshore marine shales of the Rupelian Clay (rise-to-fall turnaround zone). At the time of deposition of the Rupelian Clay the maximum palaeo-waterdepth was recorded. 150-200 metres are interpreted for the Foraminifera Marls (Rothausen & Sonne, 1984), and not at the top of the SpT, as shown in curve (5) of **figure 2.5**. Sedimentation from suspension dominated, and the basin centre was sediment-starved.

The turnaround zone within the Rupelian Clay (nannoplankton zone NP 23) coincides with the peak of the transgression T4 of the T-R facies cycles (Hardenbol *et al*., 1998; **Fig. 2.8**). Grimm *et al*. (2000) mentioned it for the Mainz Block. It also coincides with a new steepening on the basement subsidence curves. Thus, creation of accommodation space due to tectonic subsidence of the basin was superimposed on creation of accommodation space generated by the regional transgression, triggered outside the graben.

The base-level fall of the **third cycle** (**C-I-3**) includes the upper part of the Rupelian Clay, the Meletta Beds, Cyrena Marls, up to the lower boundary of the Niederrödern Layers. The tectonic subsidence curves suggest for these units an important tectonic component. The total subsidence during this time was also strongly influenced by the sediment load of the Meletta Beds and the Cyrena Marls, which filled the marine basin (the total basement curve has a steeper trend, relative to the Rupelian Clay segment, than the tectonic one). The overall coarsening- and thickening upward trend evidence, in spite of ongoing tectonic subsidence, the increase of sediment input into the basin and the decrease of accommodation space. The sedimentary environment changed from offshore to coastal systems, increasing the depositional energy. The Niederrödern Layers were generated under general high-energy conditions and contain stacked fluvial channels and interfluvial/lacustrine sediments (Doebl, 1967; Mauthe *et al*., 1993). For the deposition of the Niederrödern Layers, the curves show a decreased subsidence. The fall-to-rise turnaround is located within a zone between the upper part of the Cyrena Marls and the lower Niederrödern Beds, at the transition between upper shoreface and terrestrial sediments. Its location corresponds approximately to the beginning of decreased subsidence. However, the main part of the fall hemicycle of C-I-3 (MeB and lower part of CyM) was controlled by offshore sedimentation, which is in accordance to an active subsiding basin. Only in the upper Cyrena Marls, the transition to higher sediment input and depositional energy accelerated and delta/shoreface systems occurred. The base-level fall of C-I-3 could have been induced by the regional fall of relative sea-level fall (probably corresponding to the regressive facies cycle R4 at the Rupelian/Chattian boundary of Hardenbol *et al*. (1998), **Fig. 2.8**), and eventually by the uplift of the southern Upper Rhine Graben (Schumacher, 2002).

The subsequent base-level rise includes the Niederrödern Layers, Cerithium Beds, Corbicula Beds, and brackish/marine Lower Hydrobia Beds. It could be possible that the tectonic uplift, creating the intra-Chattian unconformity on the Mainz Block (Rothausen & Sonne, 1984; Sissingh, 1998; Schumacher, 2002), has also induced a minor base-level fall at the top of the Niederrödern Layers in this area. The available data cannot give more details on the existence of this event within the graben. However, at local scale, within the northern

URG, the transition from the Niederrödern Layers to the Cerithium Beds is accompanied by a gradual increase of salinity (from fresh to brackish, Schwarz, 1997), which may suggest a continuous sedimentation (?).

The brackish/lacustrine and hypersaline intervals of the Cerithium and Corbicula Beds were characterised by low depositional energy, a decreased input of clastic material and, locally, by *in situ* sediment production (evaporites). The depositional pattern was probably aggradational. Accommodation space was tectonically created, as the subsidence curves show for the Cerithium Beds and especially for the Corbicula Beds an increased subsidence (belonging to the late Oligocene-early Miocene phase). For the Lower Hydrobia Beds, marine conditions influenced the deposition in the northern URG, according to palaeontologic data and literature (Schwarz, 1997; Reichenbacher, 2000). In this interval, the rise-to-fall turnaround zone is probably located.

The **forth cycle** (**C-I-4**) is formed by the brackish/lacustrine deposits of the Lower and Upper Hydrobia Beds. It is known from available data and literature (Hüttner, 1991; Schwarz, 1997; Sissingh, 1998; Reichenbacher, 2000), that the Lower Hydrobia Beds are followed by a general decrease of marine influence (with minor exceptions, Reichenbacher, 2000). The low-energy sedimentation was restricted to input of suspended load and *in situ* production (carbonates) in an aggradational style.

The northern Upper Rhine Graben experienced in the late Oligocene-early Miocene a second major subsidence episode (Illies, 1975; Illies, 1978; Villemin & Coletta, 1990; Sissingh, 1998; Schumacher, 2002). Thus, the creation of accommodation space for the deposition of the Upper Hydrobia Beds was controlled by tectonics, while there the sea retreated from the Upper Rhine Graben.

For a more precise characterisation of the fourth cycle, a detailed palaeontologic study would be necessary, which is beyond the scope of this work.

The dating of the late Miocene (Upper Tertiary I and II) to Quaternary deposits, their internal stratigraphic continuity and their stratigraphic relation to the subjacent Hydrobia Beds is still highly problematic. Thus, an interpretation in terms of base-level cycles would be too speculative. However, the rise in base-level necessary for the deposition of the thick Quaternary series (up to 380 metres in the Heidelberg area) was possible due to a new pulse of subsidence, triggered probably by the left-lateral strike-slip regime (Illies, 1978; Schumacher, 2002).

The Cenozoic syn-rift sedimentation of the northern Upper Rhine Graben displays a complex pattern. This was influenced by the interaction between the graben tectonics and major tectono-eustatic events recorded in several European basins.

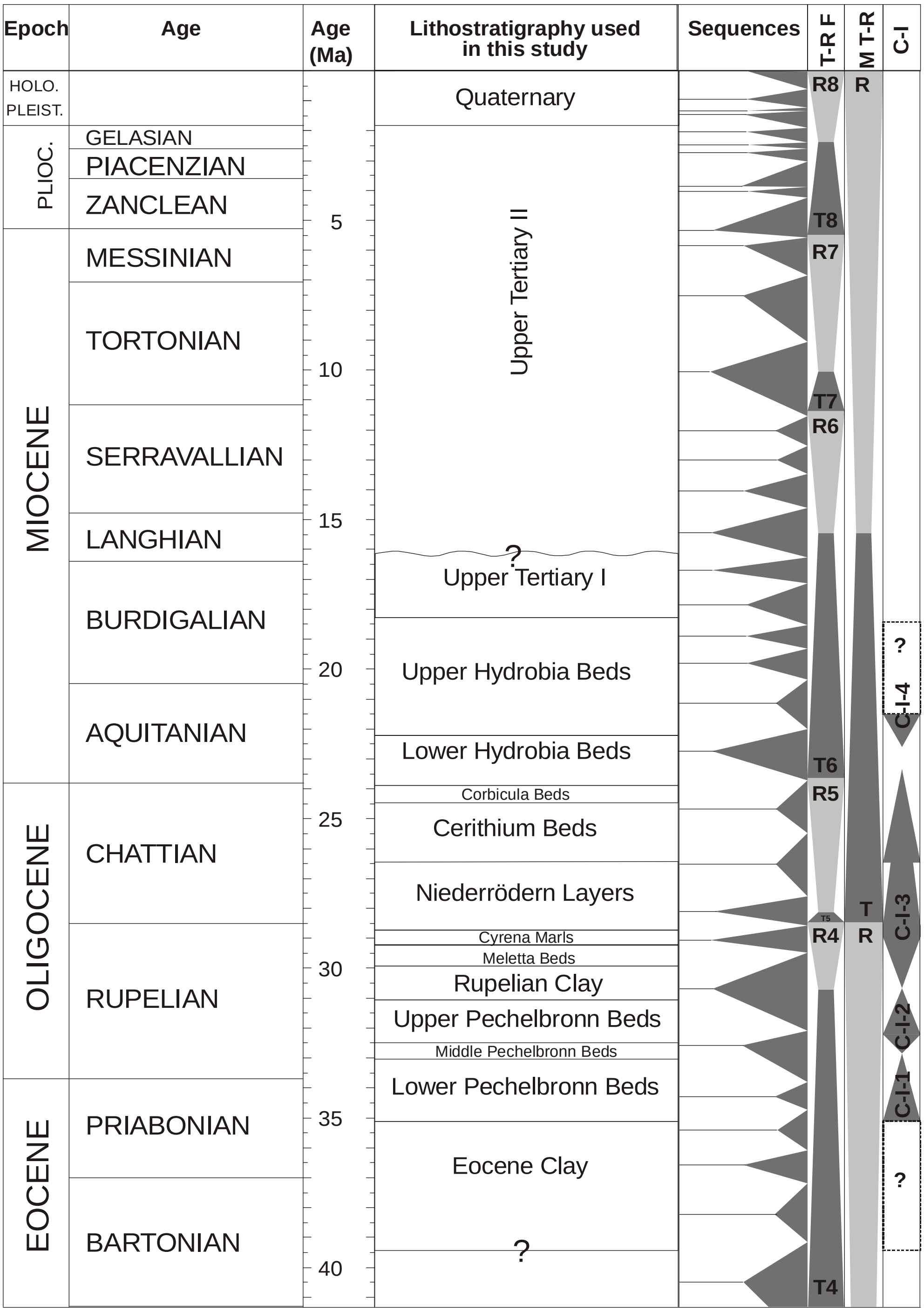


Fig. 2.8 Lithostratigraphy of the northern Upper Rhine Graben correlated with the sequence chronostratigraphy of the Cenozoic (Hardenbol *et al*., 1998) and the base-level cyclicity interpreted in this work. T-R F transgressive-regressive facies cycles, MT-R major transgressive-regressive cycles (Hardenbol *et al*., 1998). C-I large scale base-level cycles used in this study.

3. EARLY SYN-RIFT TECTONO-SEDIMENTARY EVOLUTION OF THE NORTHERN UPPER RHINE GRABEN

The aim of this chapter is the detailed examination of the interplay between tectonics and sedimentation during the early syn-rift stage of the northern Upper Rhine Graben (**Fig. 3.1**). This implies the understanding of the spatial and temporal evolution of depocentre geometries and their related depositional systems.

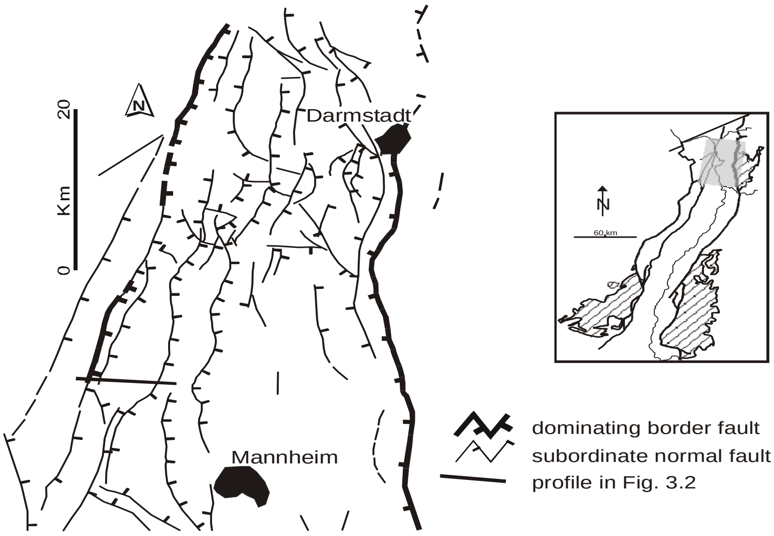


Fig. 3.1 Structural map of northern Upper Rhine Graben. Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996). The structural level of the fault pattern is top Rupelian Clay.

3.1 Early syn-rift sedimentary succession: identification and overview

3.1.1 DEFINITION AND IDENTIFICATION

Initial subsidence in the northern Upper Rhine Graben was triggered by an approximate WNW-ESE oriented extension (Illies, 1978; Meier & Eisbacher, 1991; Schumacher, 2002). Within the study area, the early syn-rift sedimentary infill is defined and identified by seismic stratigraphy constrained with stratigraphic well control. The early syn-rift succession was deposited in basins, which have in W-E direction, parallel to the extension, typical asymmetric halfgraben geometry. The halfgrabens are bounded by growth faults (**Fig. 3.2**, see **chapter 3.2** for detailed explanations). The sediment fill includes the lithostratigraphic units of the Eocene Clay, Pechelbronn Beds and Rupelian Clay (**Fig. 3.3**).

In the hangingwall of the growth faults, the external seismic geometry of the early syn-rift deposits is wedge-shaped, with the thickness increasing toward the fault plane (**Fig. 3.2**). The internal seismic facies displays reflectors diverging toward the fault plane, indicating syn-sedimentary fault activity and block rotation. The most significant reflectors, bounding and subdividing the early syn-rift fill are: top pre-rift (base Cenozoic), top Pechelbronn Beds, top early syn-rift (top Rupelian Clay).

The top pre-rift does not always appear as a clear boundary. When it does, it occurs as a reflector, which dips toward the fault plane. It separates the Permo-Carboniferous seismic facies (high-amplitude, low-continuity) from the early syn-rift seismic reflection configuration (lower-amplitude, divergent reflectors, **Fig. 3.2**). Locally, this boundary truncates the pre-rift strata. In the literature sometimes there is a discrepancy between the identification of the top pre-rift unconformity from well and seismic information. This can happen due to an unclear seismic response, or due to an erroneous interpretation of the base Cenozoic in some wells (Gaupp & Nickel, 2001).

The top of the syn-rift, corresponding to top Rupelian Clay, is a high-amplitude reflector, which represents an excellent marker horizon in the study area (**Fig. 3.2**). It is given by the high acoustic impedance contrast between the well-stratified shales and marls of the Rupelian Clay (with low internal velocity) and the weakly bedded marls and siltstones of the Meletta Beds (with higher internal velocity).

The top Pechelbronn Beds can only be recognised if well information are used. It displays a relative strong reflection that is caused by the strong impedance contrast between the low-velocity Rupelian Clay and the high velocity Pechelbronn Beds (**Fig. 3.2**).

The westward or eastward dipping halfgraben geometry, perpendicular to the rift axis, was generated mainly in the early syn-rift stage (Priabonian-early Rupelian, including the Eocene Clay, the Pechelbronn Beds and the Rupelian Clay). Younger series, deposited during the Miocene tectonic phase, especially the Cerithium Beds and younger strata, display in W-E direction mainly parallel reflectors (sometimes with drag-folds). They do not exhibit in W-E direction syntectonic wedges. This confirms, the change in stress regime at the end of the Oligocene (cf. Meier & Eisbacher, 1991 and Schumacher, 2002).

3.1.2 LITHOSTRATIGRAPHY

The early syn-rift succession in the northern Upper Rhine Graben starts with the **Eocene Clay**, which is uncomformably overlying pre-rift Permian strata. It occurs only locally and was confidently identified in two wells only. Its thickness varies between 100-150 metres. Due to the lack of palaeontologic data, a precise dating was not possible. The Eocene Clay is dominated by reddish mudstones and siltstones with subordinate sandstones and fine-grained conglomerates. The sediments were deposited in terrestrial environments: interfluvial, lacustrine, minor fresh-water deltas, fluvial channels and splays.

This study will mainly focus on the **Pechelbronn Beds** (van Werveke, 1904). In most of the northern Upper Rhine Graben they unconformably rest directly on the Permian series. The age of the Pechelbronn Beds is late Priabonian to early Rupelian (Nickel, 1996; German Stratigraphic Commission, 2002) (**Fig. 3.3**). The thickness of the Pechelbronn Beds is up to 250 metres. Based on lithological and biostratigraphical criteria, Schnaebele (1948) divided

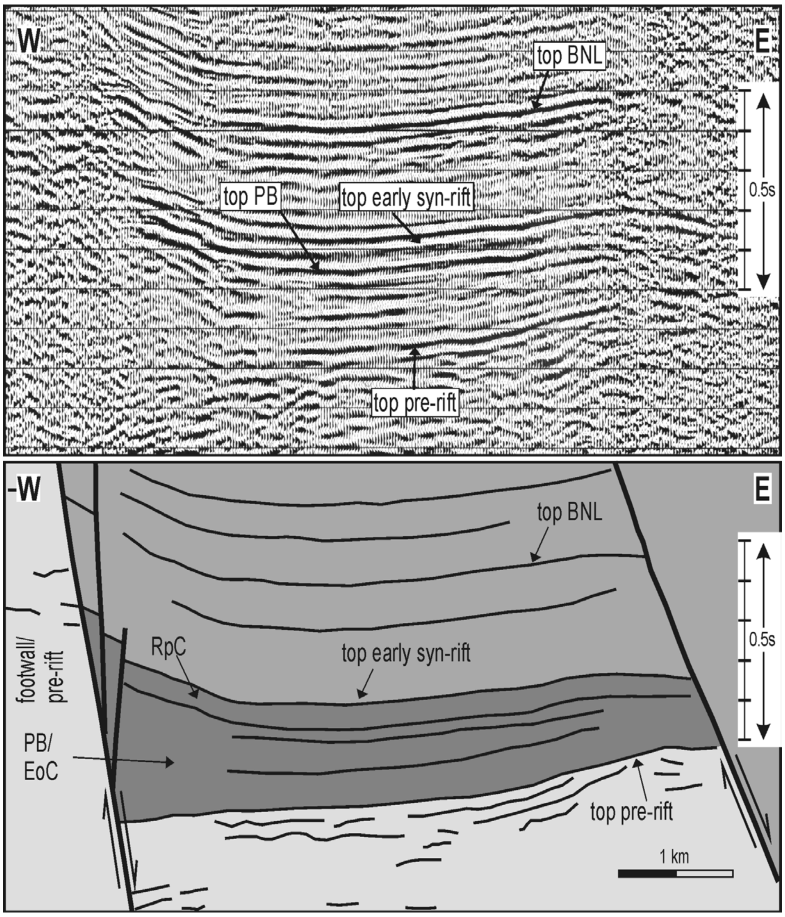


Fig. 3.2 W-E seismic section and its interpretation showing the early syn-rift geometry. Note the asymmetric halfgraben geometry, bounded by growth faults. The reflectors diverge towards the fault plane, showing that sedimentation was time-equivalent to fault activity and block rotation. Pre-rift strata are truncated. Location in **Fig. 3.1**. Vertical scale is two way travel time in seconds. EoC Eocene Clay, PB Pechelbronn Beds, RpC Rupelian Clay, BNL Niederrödern Layers.

the Pechelbronn Beds into three lithostratigraphic subunits: Lower, Middle and Upper Pechelbronn Beds.

The deposition of the **Lower Pechelbronn Beds** took place under terrestrial conditions, where alluvial systems alternated with interfluvial/lacustrine and swamp environments (Gaupp & Nickel, 2001; Derer *et al*., 2003). The main drainage direction of the fluvial systems was probably toward the south to southwest (Gaupp & Nickel, 2001; Derer *et al*., 2003). The deposits vary from high-energy conglomerates and sandstones to organic-rich mudstones. Plein (1992) and Gaupp & Nickel (2001) also note the presence of a volcanoclastic layer, which probably was derived from the Eocene alkali basaltic volcanism of that area. Towards the top of the Lower Pechelbronn Beds brackish influences became dominant (Gaupp & Nickel, 2001).

During the period of deposition of the **Middle Pechelbronn Beds**, the sea advanced from the South (Doebl, 1967) creating brackish/marine environments in the northern Upper Rhine Graben (Gaupp & Nickel, 2001). A brackish/marine fauna is mentioned in some of the

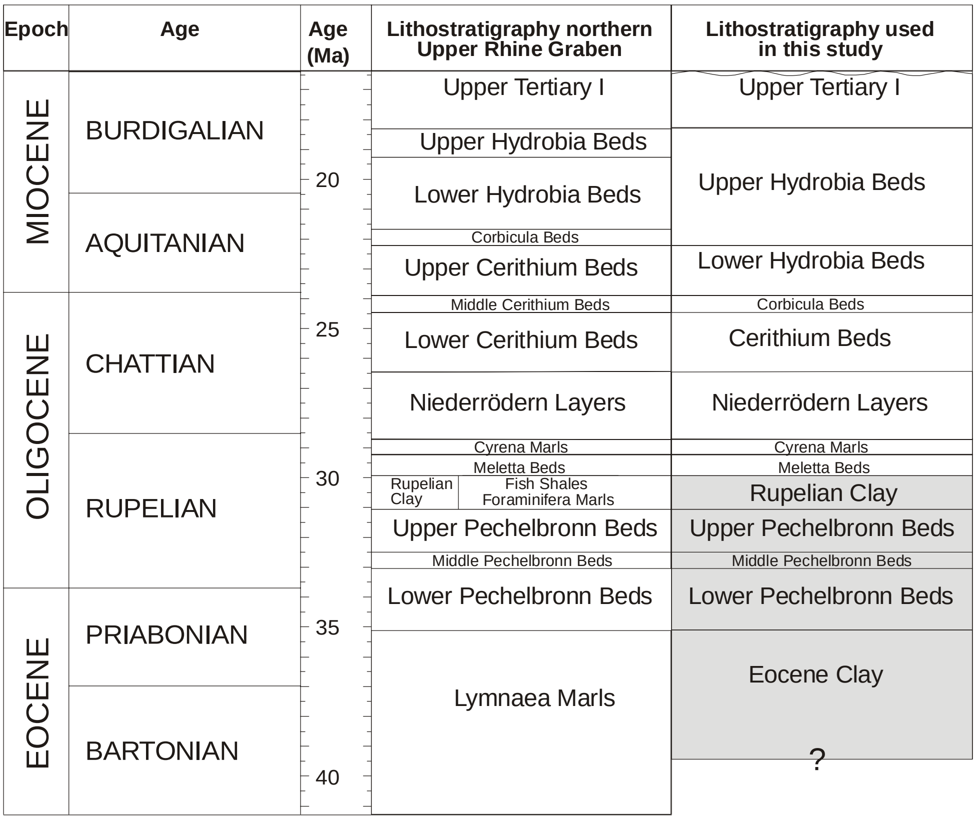


Fig. 3.3 Lithostratigraphic chart (Eocene-Miocene) of the northern Upper Rhine Graben. Modified from the German Stratigraphic Commission (2002). The shaded area marks the early syn-rift units.

wells. Based on nannofossils, Martini (1973) attributed the Middle Pechelbronn Beds to the nannoplankton zone NP 22 (earliest Rupelian). At this time, offshore shale was deposited in the depocentres, whereas fine-grained coastal and deltaic sands occurred in landward positions (Gaupp & Nickel, 2001; Derer *et al*., 2003).

The **Upper Pechelbronn Beds** were deposited in terrestrial environments (alluvial fans, fluvial/interfluvial, lacustrine, Gaupp & Nickel, 2001; Derer *et al*., 2003). The sediments advanced from the west and interfingered with the remnant brackish/marine settings (lagoons?) of the graben centre and its eastern border (Plein, 1992; Gaupp & Nickel, 2001). The terrestrial deposits consist of conglomerates, lithic sandstones, and mudstones. Mudstones and fine-grained quartz sandstones alternate in the brackish/marine settings. The Upper Pechelbronn Beds gradually pass upwards into offshore-marine deposits of the Rupelian Clay (late Rupelian **Fig. 3.3**). Due to palaeogeographic and depositional conditions in the study area, the Lower, Middle, and Upper Pechelbronn Beds cannot always be differentiated (see **chapter 3.3**).

While the Lower and Middle Pechelbronn Beds were deposited, humid tropical to subtropical conditions dominated in the northern Upper Rhine Graben. The palaeoclimate became cooler and dryer during the formation of the Upper Pechelbronn Beds (Schuler, 1990; Nickel, 1996).

The **Rupelian Clay** (**Foraminifera Marls** and **Fish Shale**) is characterised by off-shore shales deposited in fully marine environments (due to oxygen depletion bituminous for the Fish Shale, e.g. Doebl & Malz, 1962; Grimm, 1991). The Rupelian Clay belongs to the nannoplankton zone NP 23 (Müller, 1988). It was deposited while the Upper Rhine Graben might have been temporarily connected to the North Sea Basin and the Paratethys (Molasse Basin, e.g. Doebl, 1967; Berger, 1996). The maximum water depth was estimated to be about 150-200 metres in the Foraminifera Marls (Rothausen & Sonne, 1984) and at about 100 metres in the Fish Shale (Grimm, 1991). The thickness of the Rupelian Clay varies between 50 and 100 metres in the study area.

3.1.3 SEISMIC AND WIRE-LINE LOG FACIES

The majority of the early syn-rift halfgrabens strike approximately N-S, parallel to the rift axis. Thus, the external wedge geometry and the diverging internal reflectors mostly occur in E-W direction (**Fig. 3.2, Fig. 3.4a**). In N-S sections the sheet form and parallel to sub-parallel reflection configuration prevail (**Fig. 3.4b**). Due to a complex fault pattern and the strike slip tectonics during the Miocene, the initial geometry of the early syn-rift series cannot be always recognised.

The Eocene Clay and Pechelbronn Beds can be differentiated only with well control. They display both in E-W and N-S directions a facies with low frequency and variable amplitudes (high amplitude reflectors of low continuity embedded within a low amplitude zone). This facies mirrors the high lateral variability of the early syn-rift sedimentation conditions for these units. The Rupelian Clay was deposited in deep marine settings and shows parallel reflectors of high continuity, high amplitude, and low-moderate frequency.

The Eocene Clay is usually characterised by low resistivity and positive SP curves, with some fining- and coarsening-upward trends (**Fig. 3.5**). The Pechelbronn Beds and Rupelian Clay can easily be recognised in well logs, when they display the complete and “classical” succession. The high GR and positive SP pattern of the shaly brackish/marine Middle Pechelbronn Beds (locally with coarsening upward trends) often represent a good correlation marker. It separates the coarser-grained Lower Pechelbronn Beds from the Upper Pechelbronn Beds. The Rupelian Clay typically displays very high GR and positive SP values, which can be identified in the whole the study area. However, the log pattern varies considerably within the northern Upper Rhine Graben, as a function of the depositional environments, which are dependent on the palaeogeographic position in the basin.

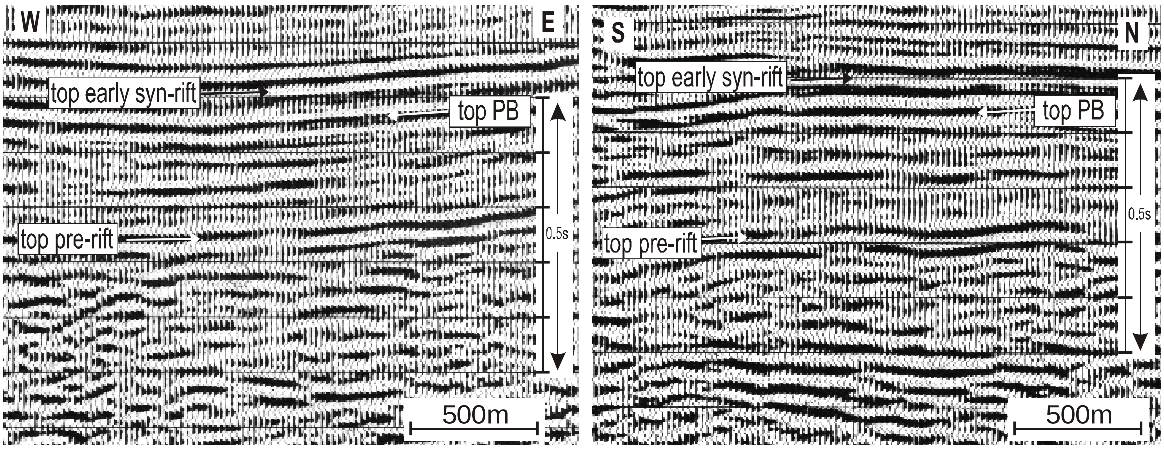


Fig. 3.4 Seismic facies of the early syn-rift succession in W-E **(a)** and S-N **(b)** direction.
The Eocene Clay and Pechelbronn Beds display reflectors with variable amplitudes and low continuity. The Rupelian Clay is represented by high amplitude, high-continuity reflectors. Vertical scale is two way travel time in seconds.

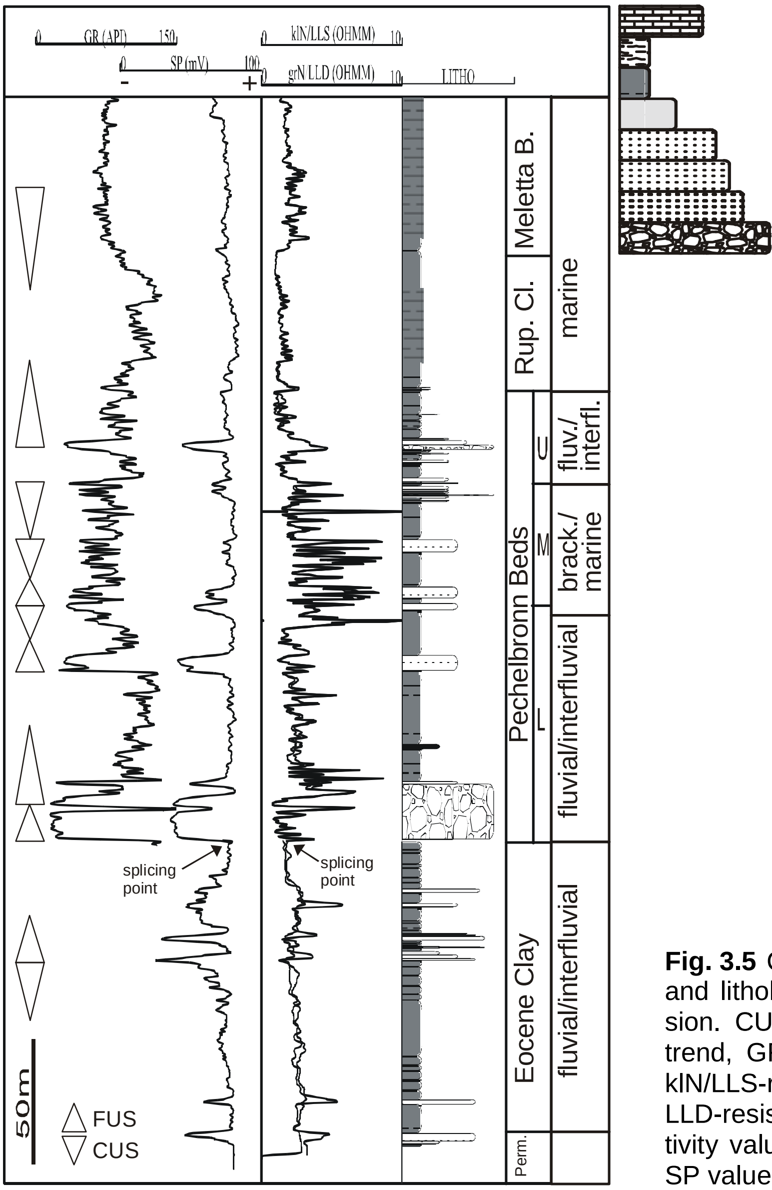


Fig. 3.5 Composite wire-line log response and lithology of the early syn-rift succession. CUS/FUS coarsening/fining-upward trend, GR-gamma ray, SP-self potential, klN/LLS-resistivity shallow device, grN/LLD-resistivity deep device. GR and resistivity values increasing towards the right. SP values: left negative, right positive.

3.2 Early syn-rift tectonic structure and evolution

In this chapter the structural aspects of the northern Upper Rhine Graben will be considered, which are important for the interpretation of the early syn-rift sedimentation history, in terms of accommodation space and sediment supply. This includes the reconstruction of the early syn-rift structural geometry at different scales and its temporal evolution.

The tectonic framework of the earliest rift stage was created by a WNW-ESE directed extension (Illies, 1978; Meier & Eisbacher, 1991; Schumacher, 2002). However, it has to be taken into account, that the initial tectonic features were partly modified by the late Oligocene-early Miocene and Pliocene-Quaternary strike slip regime (see **chapter 2.2**).

3.2.1 LARGE-SCALE INTERBASIN TRANSFER ZONE

A NE-SW striking large-scale transfer zone (between Darmstadt and Alsheim) controlled during the early syn-rift stage the basin physiography of the northern Upper Rhine Graben (Derer *et al*., 2003). It separated two individual halfgrabens (sub-basins), in the north and in the south, which had opposing subsidence patterns and tilt directions (**Fig. 3.6**). The transfer zone is an interbasin transfer zone (after the nomenclature of Gawthorpe & Hurst (1993)), taking into account the dimensions of the halfgrabens (tens of kilometres in length and width). **Figure 3.6** shows palinspastically-restored cross-sections of the early syn-rift graben fill (Eocene Clay, Pechelbronn Beds, Rupelian Clay). The sections were derived from seismic profiles (profiles N1, N2, S1, S2 in **Fig. 2.3b** in **chapter 2**), which were depth-converted and restored for the end of the deposition of the Rupelian Clay (restoration datum is the top Rupelian Clay, i.e. top early syn-rift). The sediment thickness is not decompacted. The opposing asymmetry of the sedimentary fill of the two sub-basins implies a syn-sedimentary subsidence of both depocentres. It is also a proof for the existence of this transfer zone already in the early stage of rifting. The location of the transfer zone is in accordance with the isopach map of Doebl (1967) (**Fig. 3.7**). The isopach distribution shows the two main depocentres and the reduced thickness of the Pechelbronn Beds within the area of the interpreted transfer zone.

The transfer zone (antithetic interference zone, after the geometric classification of Gawthorpe & Hurst (1993)) enabled the shift of the major depocentre from the western master fault in the northern halfgraben to the eastern master fault in the southern halfgraben. In the northern sub-basin, the depocentre is located proximal to the active master fault. In the southern sub-basin, in the proximity of the transfer zone, the main depocentre is located away from the eastern master fault. Toward the south, the depocentre gradually migrates toward the eastern master fault, and reaches it outside the study area (**Fig. 3.6**, **Fig. 3.7**).

Within the transfer zone, subordinate faults, sub-parallel to the border faults, formed a series of tilt-blocks and horst structures (**Fig. 3.8, Fig. 3.9**). Normal faulting is common for the transfer zone. It could not be established, whether the faults also had an oblique-slip component during the early syn-rift stage. The sub-basins are also characterised by a series of subordinate faults oriented mainly sub-parallel to the graben axis. Within the northern sub-basin, these subordinate faults are both synthetic and antithetic to the western master fault (**Fig. 3.6**, **Fig. 3.8**). The southern sub-basin is characterised within the study area mainly by eastward dipping faults, antithetic relative to the eastern master fault (**Fig. 3.6**, **Fig. 3.8, Fig. 3.9**). However, more to the south, outside the study area in the profile S3 (**Fig. 3.6**), both antithetic and synthetic faults are interpreted. The importance of these subordinate faults will be discussed in **chapter 3.2.3**.

The transfer zone represented during the deposition of the Pechelbronn Beds a structural and palaeotopographic high. It acted as a sediment barrier between the sub-basins and partly as a source area (Gaupp & Nickel, 2001; Derer *et al*., 2003). It created large-scale axial depositional gradients, dipping away towards the sub-basins (Derer *et al*., 2003), directing the sediment flux. The transfer zone, in combination with the intermediate-scale block C-D created an important major depositional gradient. This gradient displays a ramp geometry dipping into the southern sub-basin (see **chapter 3.2.3**).

The existence of two different depocentres in the northern Upper Rhine Graben (first mentioned by Straub (1962)) is the result of the interbasin transfer zone (Derer *et al*., 2003).

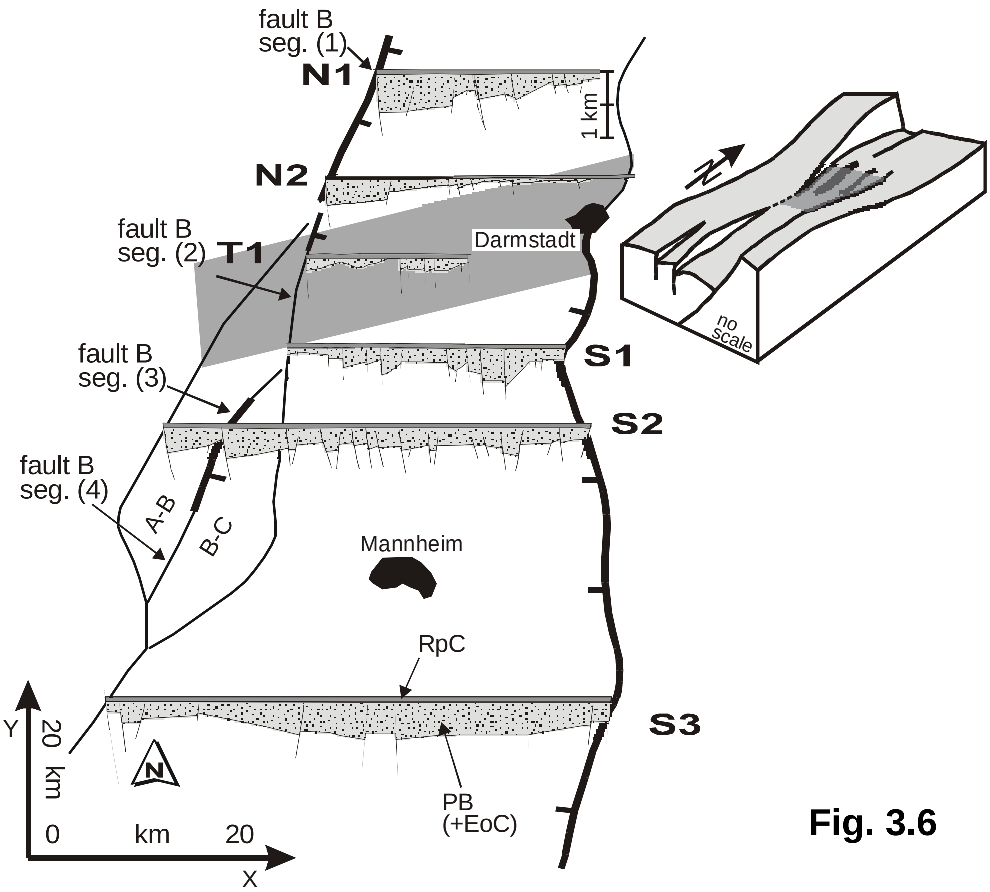


Fig. 3.6

Fig. 3.6 (previous page) Early syn-rift geometry of the northern Upper Rhine Graben. Due to the interbasin transfer zone the depocentre shifted from the western border fault of the northern sub-basin to the eastern border fault of the southern sub-basin (illustrated by palinspastically restored cross sections, depth-converted, restoration datum top early syn-rift). Cross sections N1, N2, T1, S1 are derived from industry seismic profiles. S2 from seismic profile DEKORP-9N. S3 is derived from cross section 1 of Doebl & Teichmüller (1979). The figure is distorted in the Y direction.

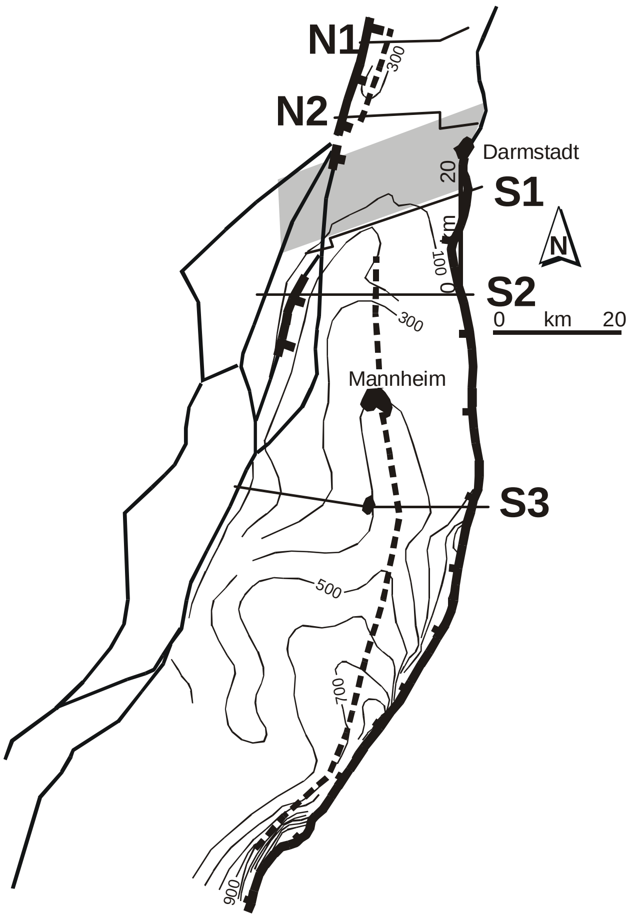


Fig. 3.7 Isopach map of the Pechelbronn Beds in metres (Doebl, 1967). The minimum thickness corresponds to the location of the transfer zone interpreted in Derer *et al.* (2003) and in this study.

3.2.2 STRIKE VARIATIONS OF FAULT DISPLACEMENT

In rift basins, fault growth starts with initially small fault segments with minor displacements. The maximum displacement (maximum hangingwall subsidence and footwall uplift) is in the centre of the fault segment, and decreases toward the tips of the fault (Gawthorpe *et al*., 1994). During further extension, these fault segments propagate and can connect (e.g. Gawthorpe & Leeder, 2000).

For the early syn-rift stage, the western border fault (fault B) of the northern Upper Rhine Graben was composed of four main fault segments of variable displacements (**Fig. 3.6, Fig. 3.8**). **(1)** The **northern segment of fault B** is the master fault in the northern sub-basin, with a maximum throw of about 650 metres (measured on the non-decompacted restored section, **cross section N1 in Fig. 3.6**). The throw decreases toward the south, reaching in the **(2) second segment** about 160 metres (**cross section S1 in Fig. 3.6**). This second segment corresponds to the western margin of the interbasin transfer zone. **(3)** The **third segment** of fault B has a length of about 6 kilometres and is located in the southern sub-basin. Its throw increased relative to the previous segment and measures ca. 300 metres (**cross section S2 in Fig. 3.6**). On this segment, fault B has even a higher throw than the eastern master fault (**cross section S2 in Fig. 3.6**). **(4)** Further to the south, outside the study area, the displacement of fault B decreases again and the eastern master fault becomes dominant (**cross section S3 in Fig. 3.6**). The block diagrams shown in **figures 3.6 and 3.8** are simplified models of the structural geometry of the study area. They show the two opposing halfgrabens and the displacement variation along the strike of fault B.

The low-displacement **second segment** of fault B corresponds to the zone where the transfer zone intersects the western border fault. This fault segment has a low footwall elevation and hangingwall subsidence compared with the segments to the north and to the south. Thus, it formed a low-relief zone with a subordinate depositional gradient, which enabled sediment to enter the graben through drainage systems. This structure could explain the fans of the Upper Pechelbronn Beds prograding from the western graben shoulder (Plein, 1992; Gaupp & Nickel, 2001).

The existence of segmented faults and the variations of displacement along their strike directly influenced the sediment input to the depocentres and the creation of accommodation space.

3.2.3 INTERMEDIATE-SCALE TILT-BLOCKS/HALFGRABENS

Due to the density and the quality of the data, this study focuses mainly on the transfer zone and the southern sub-basin (**Fig. 3.9**). However, when possible, also the northern sub-basin will be discussed.

A series of subordinate normal growth faults, sub-parallel to the graben axis, were active during the early syn-rift stage. They subdivided the sub-basins and the transfer zone into tilted fault blocks. The fault planes are often listric and are associated with the rotation of the hangingwalls.

The tilt-blocks represent subordinate halfgrabens with wedge-shaped sedimentary fill. The reflectors diverge toward the fault plane, demonstrating their syn-sedimentary subsidence and rotation (**Fig. 3.10, Fig. 3.2**). The halfgrabens have in the study area a width of 2 to 5.5 kilometres, and a length of up to 14 kilometres. This structural geometry, with tilt-blocks striking parallel to the graben margins, was created by the WNW-ESE extensional episode. Even though the Miocene transtension reactivated some Eocene-Oligocene faults, most parts of the early syn-rift structural geometry are preserved.

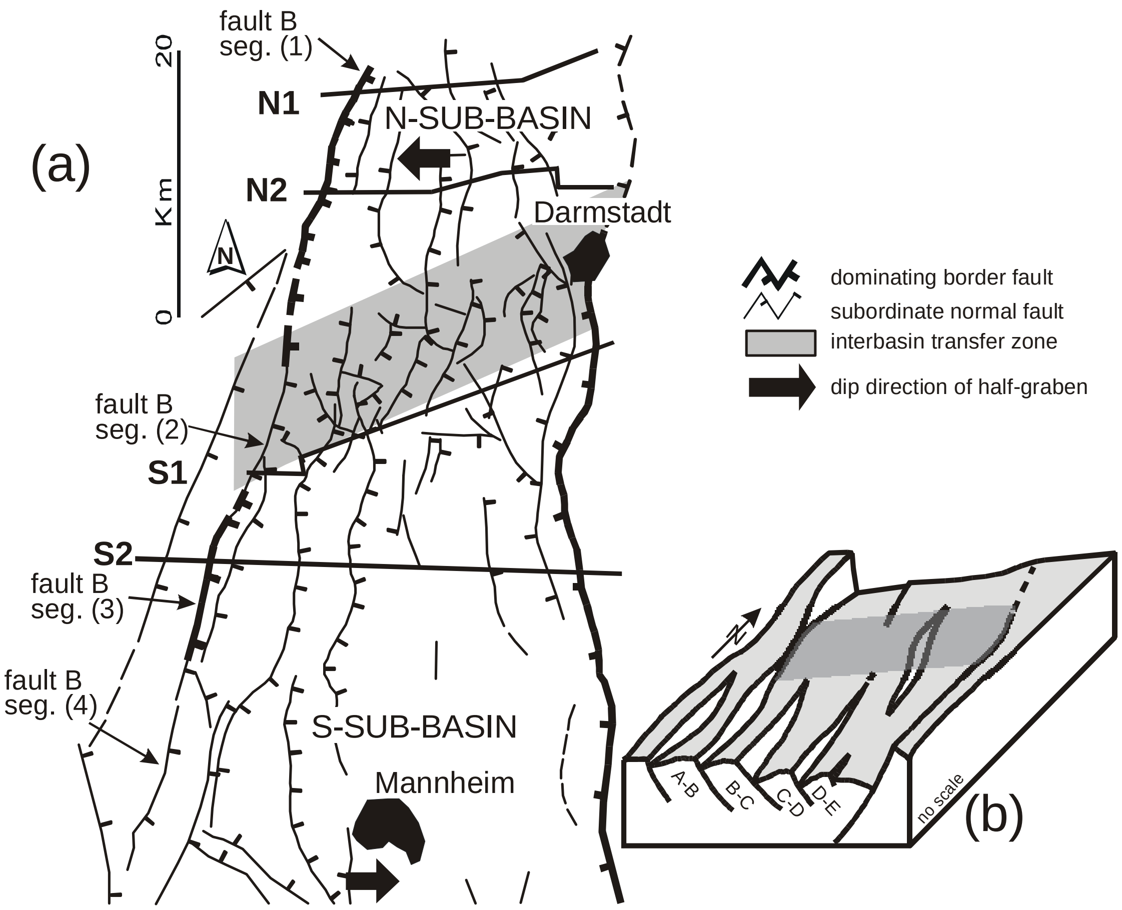


Fig. 3.8 Structural map of the study area showing the transfer zone and the two associated sub-basins. Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996).
Fig. 3.8b Simplified block diagram showing the three main tectonic features of the studied northern Upper Rhine Graben: interbasin transfer zone, strike variation of fault displacement, and intermediate tilt blocks/halfgrabens.

The non-decompacted sediment thickness within these subordinate halfgrabens is variable, but can reach a maximum of about 550 metres (**Fig. 3.6, 3.10**). Locally, the halfgrabens formed important depocentres, although with a relatively reduced length. Within the southern sub-basin, faults A, B, and C (creating the subordinate halfgrabens A-B, B-C and C-D respectively, **Fig. 3.9, 3.10**) have approximately equal displacements. However, these local depocentres were only significant during the early syn-rift stage. During the younger tectonic activity (Miocene phase), the displacement partitioning is abandoned in favour of fault C, where most of the deformation was accommodated (see also **chapter 2.3.2**).

The intermediate-scale geometry of the northern Upper Rhine Graben is thus, determined by a series of minor halfgrabens, striking mainly parallel to the general trend of the graben. The tilt of these fault blocks is controlled both by the dip direction of the bounding growth fault and the existence of the interbasin transfer zone. The blocks C-D and D-E of the southern sub-basin (**Fig. 3.9**) dip toward their bounding faults in the W, and toward the S due to the structurally and palaeotopographic elevated transfer zone. Block C-D forms a ramp, which tilted from the transfer zone toward the south.

The subordinate halfgrabens formed in the transfer zone and the southern sub-basin intermediate-scale depocentres. They also created depositional gradients with footwall and hangingwall derived sediment flux.

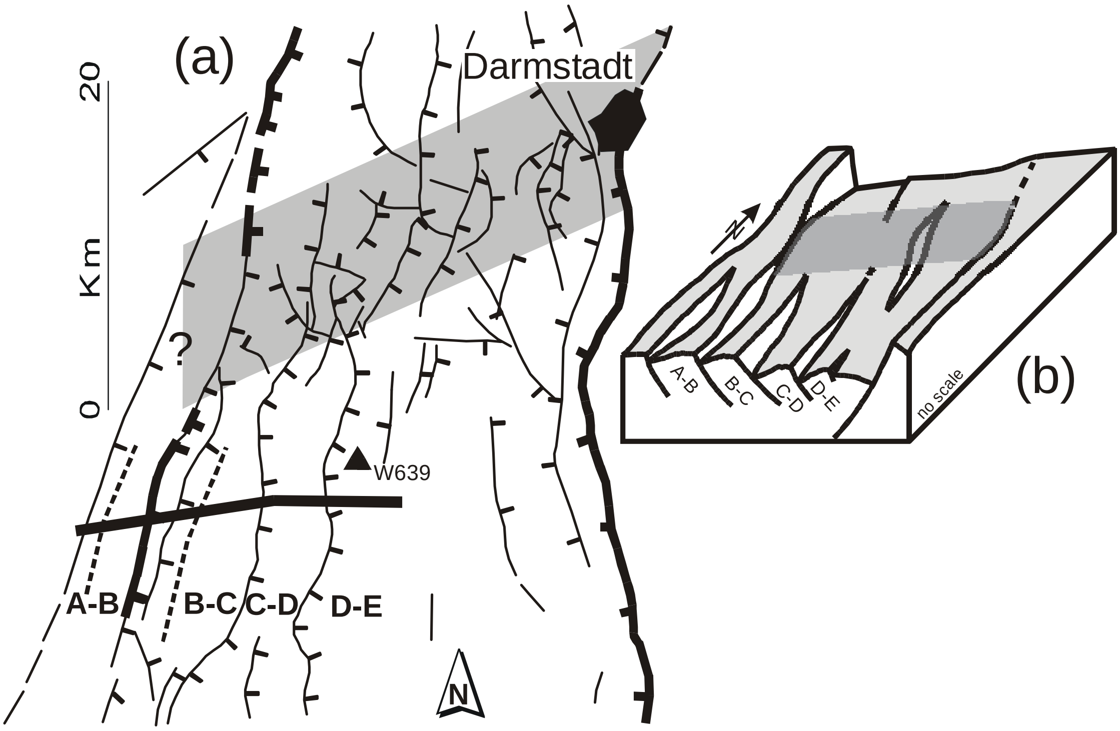


Fig. 3.9 a) Structural map of the transfer zone and the southern sub-basin. The discussed faults are A, B, C and D, which delimit blocks A-B, B-C, and D-E respectively. Location of profile of **figure 3.10** (black line). Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996). Legend in **Fig. 3.8**. **b)** Simplified block diagram.

3.2.4 SUBSIDENCE AND EVOLUTION OF THE STRUCTURAL GEOMETRY

Rift initiation started in the middle (?) to late Eocene and initially created small-scale isolated halfgrabens. Within these depocentres the terrestrial Eocene Clay and partly the Lower Pechelbronn Beds were deposited. The tectonic subsidence curves in **Fig. 3.11** show a strong inflection for the time of deposition of the Middle Pechelbronn Beds. By that time, most of the isolated basins probably coalesced, and formed the two major depocentres of the northern and southern sub-basins. Thus, subsidence acted on larger depozones and the brackish/marine settings of the Middle Pechelbronn Beds could cover the southern and northern sub-basins. Tectonic subsidence decreased during the deposition of the Upper Pechelbronn Beds, and the transfer zone functioned as a sediment barrier between the northern and southern sub-basin, and partly as source area. The northern Upper Rhine Graben acted as one depozone for the subsidence phase during the deposition of the Rupelian Clay. At that time, deep marine conditions controlled the whole area. The thickness of the Rupelian Clay cannot be used for subsidence reconstruction, as it is partly pelagic sediment, deposited from suspension. However, tectonic subsidence was superimposed upon the creation of accommodation space due to a general rise of the relative sea level (a palaeo-waterdepth of up to 200 metres was reconstructed for the Foraminifera Marls, Rothausen & Sonne, 1984).

The syn-sedimentary tectonic settings of the early rift stage of the northern Upper Rhine Graben reveal a complex geometry. This geometry was controlled by the presence of the large-scale interbasin transfer zone and a series of subordinate fault blocks, which were bounded by active faults with displacement variations along their strike (**Fig. 3.8**). These features exercised a significant control, at different scales, on the creation of accommodation space and the coeval sediment supply.

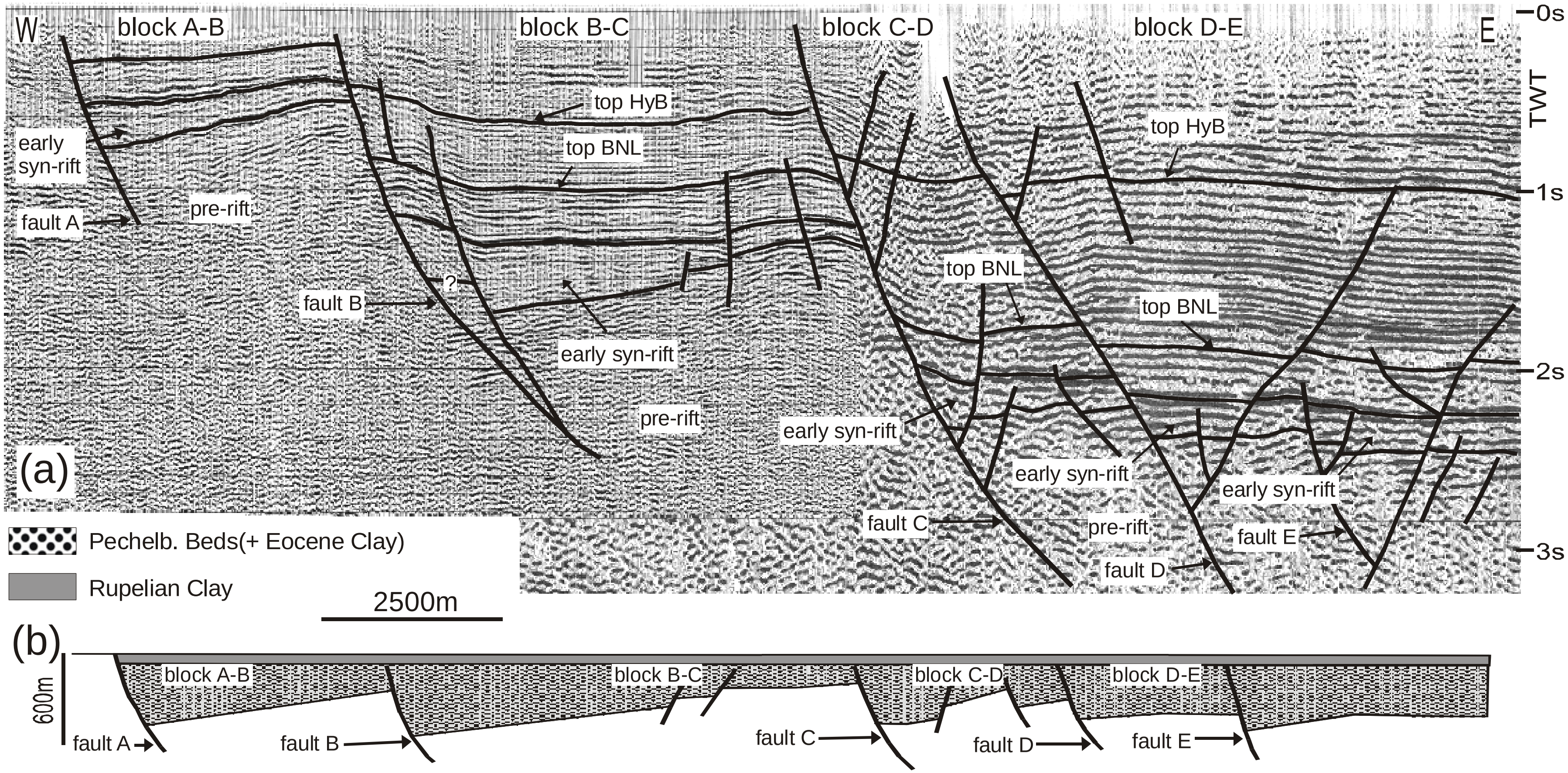


Fig. 3.10a Interpreted composite seismic section showing several intermediate-scale tilted fault blocks bounded by growth faults. TWT two-way-travel time in seconds. Location in **Fig. 3.9**. Modified from Derer *et al*. (2003). BNL Niederrödern Layers, HyB Hydrobia Beds.

Fig. 3.10b Palinspastically restored cross section of the early syn-rift graben fill, derived from the seismic section of **Fig. 3.10a** (restoration datum top early syn-rift, thickness is not decompacted). Note the halfgraben geometry of the depocentres.

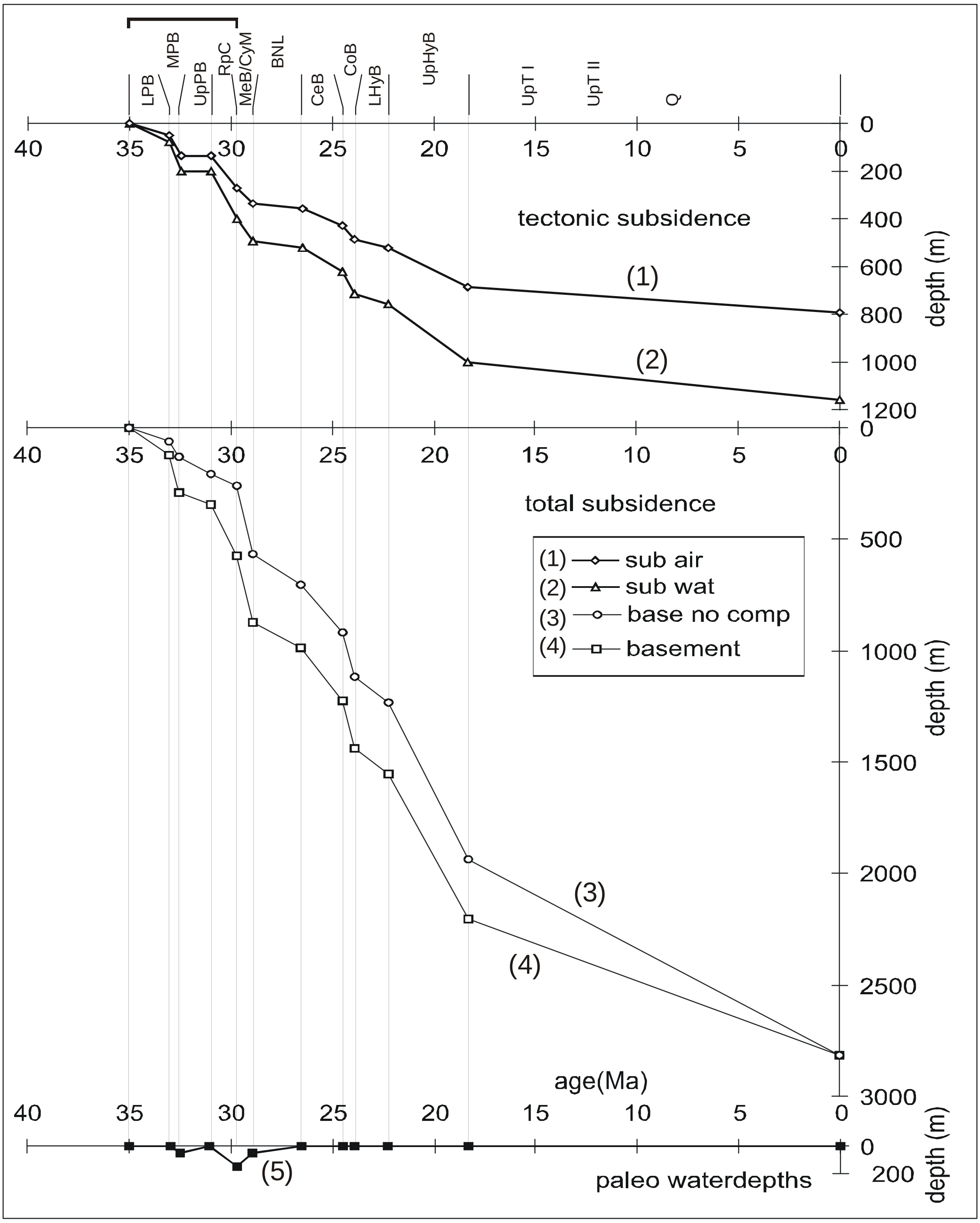


Fig. 3.11 Subsidence curves of well W639. Location in **Fig. 3.9**. (1) air-loaded tectonic subsidence, (2) water-loaded tectonic subsidence, (3) total basement subsidence (non-decompacted), (4) basement subsidence (decompacted), (5) palaeo-water depth (due to software limitations maximum bathymetries are plotted at lihostratigraphic boundaries, this does not correspond to reality). Note the increased subsidence during the MPB and RpC. The early syn-rift succession is marked by a horizontal bar. LPB Lower Pechelbronn Beds, MPB Middle Pechelbronn Beds, UpPB Upper Pechelbronn Beds, RpC Rupelian Clay, MeB Meletta Beds, CyM Cyrena Marls, BNL Niederrödern Layers, CeB Cerithium Beds, CoB Corbicula Beds, LHyB Lower Hydrobia Beds, UpHyB Upper Hydrobia Beds, UpT I Upper Tertiary I, UpT II Upper Tertiary II, Q Quaternary.

3.3 Depositional elements and base-level cycles: identification and hierarchy

The sedimentation history of the early syn-rift stage in the northern Upper Rhine Graben is interpreted by using the genetic stratigraphic approach of base-level cycles (Cross & Lessenger, 1998, presented **in chapter 2.1.2**), and the accommodation models for extensional basins of Gawthorpe *et al*. (1994) and Howell & Flint (1996). The base-level method reflects the variations of accommodation and sediment supply in space and time. The interpretation will mainly consider the Pechelbronn Beds and the Rupelian Clay, as the occurrence of the Eocene Clay is isolated.

3.3.1 DEPOSITIONAL ELEMENTS

The identification of cycles implies a detailed sedimentological analysis of the well data (see Homewood *et al*. (1992) and Kerans & Tinker (1997) for a detailed explanation of the working method). For this purpose, the wireline logs were calibrated with the available descriptions of cores and cuttings, and with palaeontologic information. This calibration allows the sedimentological interpretation of logs, when cores and cuttings are not available.

The sedimentological interpretation consists of the definition and identification of depositional elements of different orders: facies and facies associations. These elements are interpreted in terms of depositional conditions (e.g. depositional energy, bathymetry) and thus, represent the building blocks for the reconstruction of depositional environments, respectively depositional systems.

The lithologic characteristics of the Pechelbronn Beds and Rupelian Clay from cores and cuttings were grouped into six major facies types and classified in terms of depositional energy (**Tab. 3.1**). The facies are grouped into facies associations ("groups of facies genetically related to one another and which have some environmental significance" Collison, 1969 *fide* Walker, 1992). After log calibration it is possible to identify facies associations (e. g. channel/overbank facies association, alluvial fan facies association, etc.) in logs with no core data.

The interpretation of facies, facies associations and depositional environments leads to a sedimentological model, and to the construction of ideal proximal-distal depositional gradients, on which the depositional elements are positioned.

3.3.2 CYCLE HIERARCHY

Base-level cycles group strata that record the rise and fall of the base level. This implies the variation of depositional conditions in time and their shift on the depositional gradient. The cycles are bounded by rise-to-fall turnarounds. For the Pechelbronn Beds and Rupelian Clay three different ranks of stratigraphic cycles are identified. Criteria for establishing the cycle hierarchy include facies changes both within and between individual depositional

Facies	Dep. energy	Grain size	Sedimentary structures
F1	decreasing	gravel/coarse sand	massive, cross bedding
F2		coarse-medium sand	massive, cross bedding
F3		medium-fine sand	massive, cross bedding
F4		sand/silt	flaser bedding, cross lamination, bioturbation
F5		mud/sand	lenticular bedding, cross lamination, bioturbation
F6		mud (marl)	massive, parallel lamination, bioturbation, (locally peat)

Tab. 3.1 Facies identified in the Pechelbronn Beds and the Rupelian Clay

environments, changes of depositional environments in stratigraphic section, and the areal extent of cycle recognisability.

Small-scale cycles (C-III) are 3 to 15 metres thick and record minor lateral facies shifts within a depositional system. They can be confidently correlated only locally.

The thickness of the **intermediate-scale cycles (C-II)** varies between 15 and 50 metres. They can be recognised and correlated over parts of a sub-basin. These cycles reflect up- or down-gradient shifts of depositional systems. The intermediate-scale cycles usually consist of sediments of one depositional system and its transitions to the adjacent next-proximal and next-distal system on the depositional gradient.

The **large-scale cycles (C-I)** are between 25 and 200 metres in thickness. They can be traced and correlated at basin-wide scale and are generated by major changes in sedimentation. The large-scale cycles typically consist of sediments of several laterally linked depositional systems. The C-I cycles are delimited by turnarounds that reflect major reorganisations in the depositional history and in the palaeogeographic framework of the basin. The C-I cycles would correspond, from the point of view of the time span, to the 3rd order stratigraphic cyclicity (sequence cycles 0.5-3 My, Duval *et al*., 1998). However, in this study only the above-defined relative hierarchy will be used.

3.3.3 CYCLE IDENTIFICATION

The large-scale base-level variations are composed of the base-level variations of intermediate- and small-scale. The high-frequency variations of base-level (generating small-scale cycles) impose changes of the depositional energy within a depositional environment. The low-frequency base-level variations (generating large-scale cycles) generate a shift of environments on the depositional gradient. **Figures 3.12** to **3.14** show the cycle stacking pattern, and the identification of the high-order cycles (C-II and C-I).

In wells with sufficient core data, facies plots (with the facies classified from the point of view of the depositional energy) are calculated for each small-scale cycle (**Fig. 3.12**). The relative importance of a facies, corresponding to an energy domain, varies in stratigraphic section and reflects the higher-order cyclicity. The second method is the stacking pattern diagram (e.g. Homewood *et al*., 1992), which is mainly used for wells with scarce core data. It represents the shift, at different scales, of the sedimentation conditions on the depositional profile (**Fig. 3.12a**, **Fig. 3.14**).

An ideal depositional gradient for the early-syn rift environments of the northern Upper Rhine Graben is shown in **figure 3.13**. The terrestrial and marines environments are each located on a separate gradient. However, when looking at a large scale, the grouped terrestrial units represent the proximal equivalent of the marine successions. For the characteristics of these sedimentary successions see **chapter 3.4**.

The fall-to-rise of the cycles marks the maximum depositional energy and most-proximal position on the depositional gradient. The rise-to-fall turnarounds mark the minimum depositional energy and most-distal position on the depositional gradient. The turnarounds are not necessarily represented by a surface. When the exact position of turnaround cannot be identified in the sedimentary succession, a turnaround zone is considered. Within this zone the ratio between accommodation space to sediment supply changes (e.g. C-II and C-I fall-to-rise turnaround in **Fig. 3.12a**).

Two large-scale turnarounds (which represent timelines) correspond to widespread marker horizons in the study area. They are represented by 1) the offshore shale of the Rupelian Clay, and 2) the offshore shale of the brackish-marine Middle Pechelbronn Beds. The former covers the entire study area, the latter is missing in parts of transfer zone.

Fig. 3.12a (top of next page) Example of interpretation of cycles stacking pattern. In wells with sufficient core data, facies plots can be calculated for each C-III cycle. The variation of facies in stratigraphic section indicates the trends of C-II cycles. The stacking pattern diagram (Fisher plot) is shown parallel to the facies plots. The diagram reflects the shift of environments on the depositional gradient through time. An ideal depositional gradient for the early syn-rift sedimentary succession is illustrated in **Fig. 3.13**. The first fall-to-rise turnaround of the C-II and C-I cycles is represented by a zone and not by a surface. F1 to F6 facies described in **Tab. 3.1**.

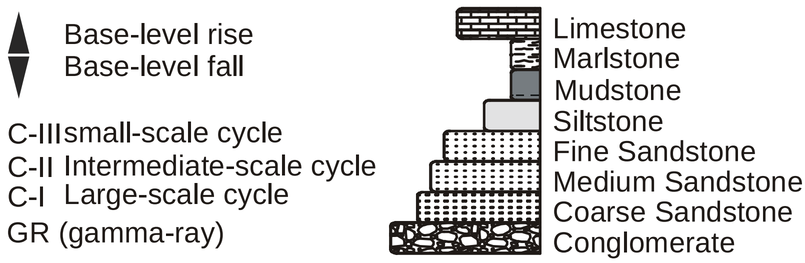


Fig. 3.12b Legend for **figures 3.12-3.21**.

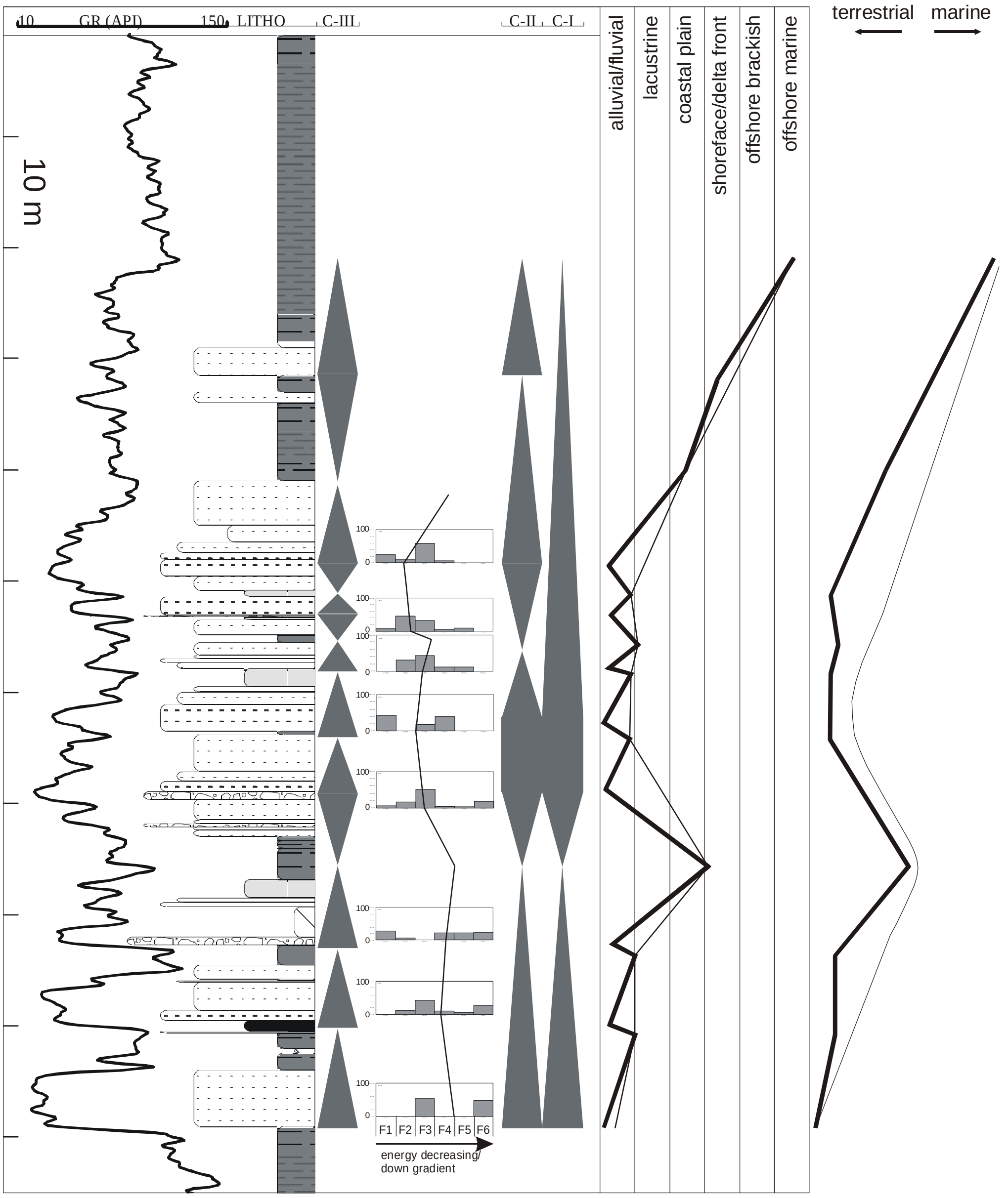


Fig. 3.12a

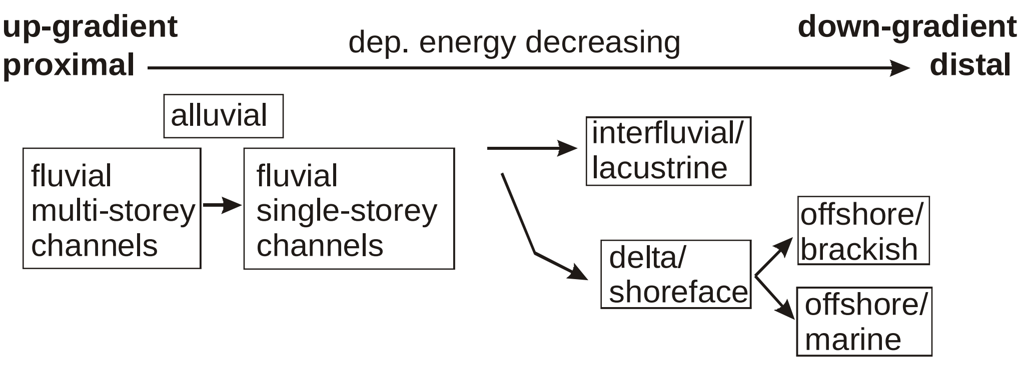


Fig. 3.13 Ideal depositional gradient showing the lateral distribution of the early syn-rift environments of the northern Upper Rhine Graben.

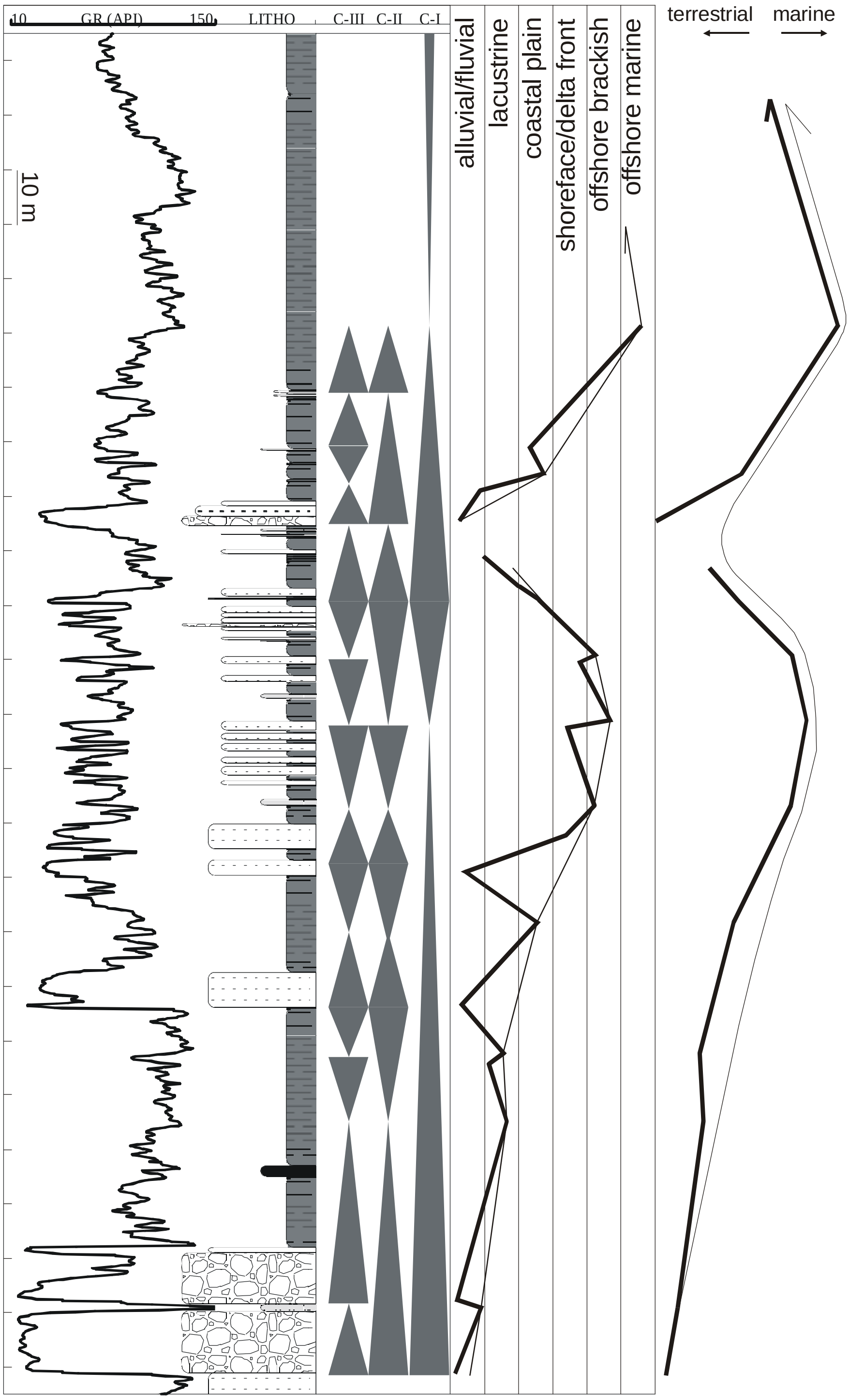


Fig. 3.14 Example of interpretation of cycles stacking pattern with the stacking pattern diagram. This method is used in most of the wells (due to scarce core data). The diagram reflects the shift of environments on the depositional gradient through time. An ideal depositional gradient for the early syn-rift sedimentary succession is illustrated in **Fig. 3.13**.
Legend in **Fig. 3.12 b**.

3.4 Key facies associations

Six key facies associations, which are characteristic for particular depositional environments, were identified within the Pechelbronn Beds and the Rupelian Clay of the northern Upper Rhine Graben. These facies associations are characterised at different scales in terms of depositional conditions and their relation to base-level variations (variations of the accommodation space to sediment supply ratio -A/S-).

3.4.1 CHANNEL/OVERBANK (**Fig. 3.15, 3.16**)

The channel/overbank facies association is composed of a succession of alternating fluvial channels and overbank deposits. The channel/overbank unit occurs within the transfer zone, and in the Lower and Upper Pechelbronn Beds of the southern sub-basin. The channels display an erosive base, sometimes with rip-up clasts or a conglomeratic lag. The channel fill usually consists of coarse- to fine-grained sandstones (sometimes with fine-grained conglomerate), with grain size decreasing from base to top. Often plant debris is present. At the top, the channel fill passes over to overbank fines, and both form a fining upward succession (small-scale C-III cycle). The overbank deposits consist of mudstones and silty mudstones. These locally display bioturbation, desiccation cracks and soil structures. From the point of view of the vertical stacking pattern of the channels, two end members are identified.

1) Single-storey channels (**Fig. 3.15**) are represented by isolated channel fills embedded in overbank fines. Deposition was characterised by low supply of coarse-grained sediment and by high rates of accommodation space creation, which increased the preservation potential of overbank fines. Single-storey channels are generated by low-energy fluvial systems (e.g. meandering river systems).

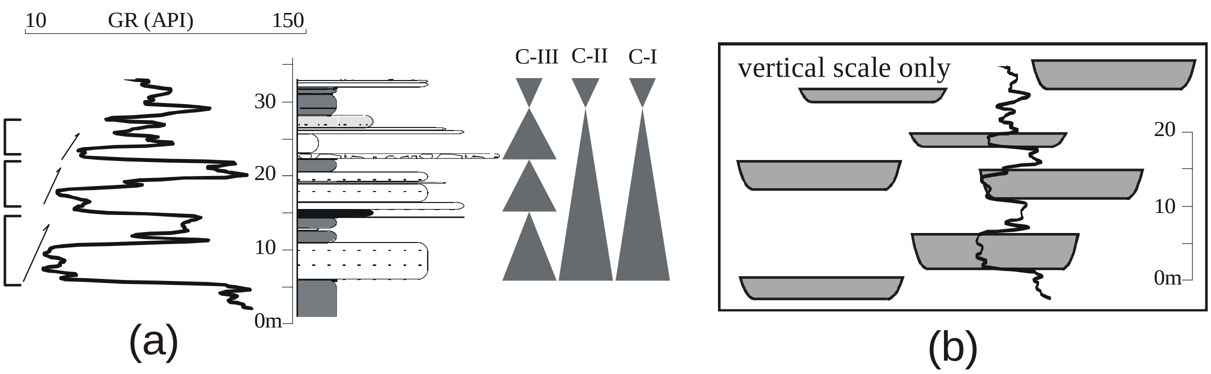


Fig. 3.15 a) Three superimposed channel/overbank facies associations within a single storey channel complex, and the interpreted stacking pattern of base-level cycles. A bar marks a single facies association. SP self potential, GR gamma ray, C-III small-scale cycles, C-II intermediate-scale cycles, C-I large-scale cycles. Legend in **Fig. 3.12 b**.
b) Conceptual panel of a single storey channel complex and the typical GR-log response.

2) Multi-storey (stacked) channels (**Fig. 3.16**) are associated with channel amalgamation, which inhibits the preservation of overbank deposits. Stacked channels are the result of a high input of coarse-grained sediment and low accommodation space conditions. These conditions impose the lateral migration of channels that is usually characteristic for high-energy fluvial systems (e.g. braided river systems).

Within the study area, also transitional members between the multi-storey and single-storey channel complex occur. Multi-storey channel complexes are more frequent in the Lower Pechelbronn Beds, where also a coarser average grain size than in the Upper Pechelbronn Beds is present. In the southern sub-basin, the syn-rift deposition usually starts with the stacked channels of the Lower Pechelbronn Beds, reflecting low accommodation conditions during the very beginning of the rifting. Within the Upper Pechelbronn Beds mainly single storey channels occur. The occurrence of multi-storey channels within the Upper Pechelbronn Beds is controlled by local block tectonics.

The channel/over bank facies associations correspond to C-III base-level rise hemicycles. These facies associations are included in C-II and C-I rise hemicycles (which reflect an overall increase of the accommodation space to sediment supply ratio).

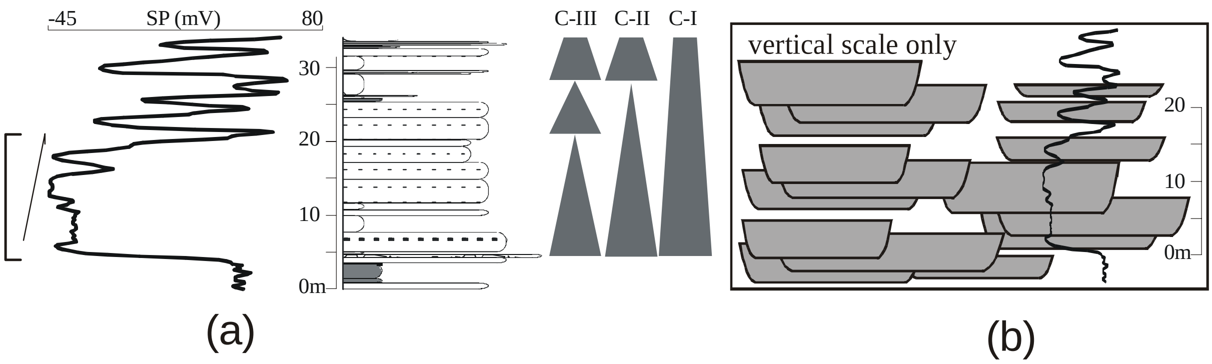


Fig. 3.16 a) Channel/overbank facies association within a multi-storey (stacked) channel complex (marked by a bar). The interpreted stacking pattern of base-level cycles.
b) Conceptual panel of a multi-storey channel complex, and the typical SP-log response. Legend in **Fig. 3.12 b**.

3.4.2 INTERFLUVIAL/LACUSTRINE (**Fig. 3.17**)

The interfluvial/lacustrine facies association consists of overbank and lake mudstones and silty mudstones. The fine-grained sediments can display bioturbation and desiccation features, and are sometimes interrupted by splay siltstones and fine-grained sandstones. Even swamp deposits are intercalated. The interfluvial/lacustrine units occur within the Lower and Upper Pechelbronn Beds and are exclusively located within the sub-basins. The overbank fines and lake sediments display a higher thickness in the Lower Pechelbronn Beds than in the Upper Pechelbronn Beds. The interfluvial/lacustrine deposition reflects high accommodation space conditions (available within the sub-basins and not in the topographically elevated transfer zone) and low sediment input. The interfluvial/lacustrine facies associations contain both C-III fall- and rise-hemicycles, represented by crevasse splays and channels respectively. Within the Lower Pechelbronn Beds, they also comprise the rise-to-fall turnarounds of C-II cycles. The interfluvial/lacustrine units, in both cases (Lower Pechelbronn Beds and Upper Pechelbronn Beds), are part of higher-ranking C-I rise hemicycles.

Depending on the ratio between distributary channels and overbank fines/limnic deposits, a transition exists between the channel/overbank and interfluvial/lacustrine units.

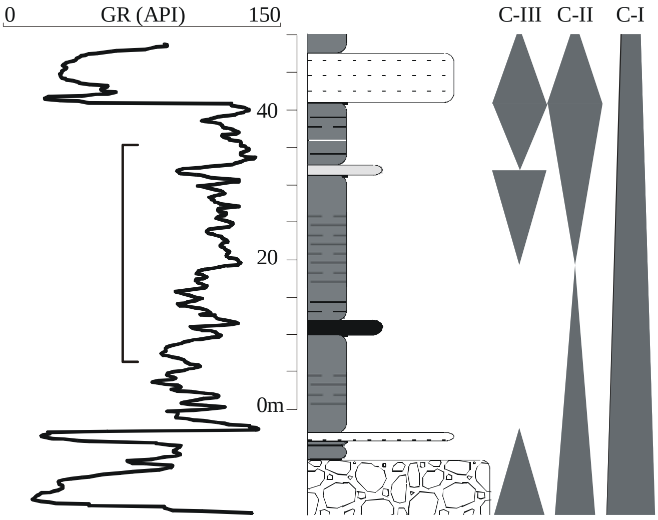


Fig. 3.17 Interfluvial/lacustrine facies association (marked by a bar). The interpreted stacking pattern of base-level cycles. The C-III fall cycles represent splay deposits. Legend in **Fig. 3.12 b**.

3.4.3 ALLUVIAL FAN (**Fig. 3.18**)

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. Often plant debris occurs in the sandy layers. Alluvial fan facies associations occur within the transfer zone (where the Pechelbronn Beds cannot be differentiated) and on the crests of subordinate tilt-blocks, where the A/S ratio was relatively low. Alluvial fans record, from base to top, an increase of sediment supply and a decrease of accommodation space at intermediate scale (C-II fall hemicycles). They consist of several small-scale fall- and rise-hemicycles (C-III) and are included within both higher-ranking fall and rise C-I hemicycles. Within the transfer zone, the alluvial fans pass laterally into fluvial systems.

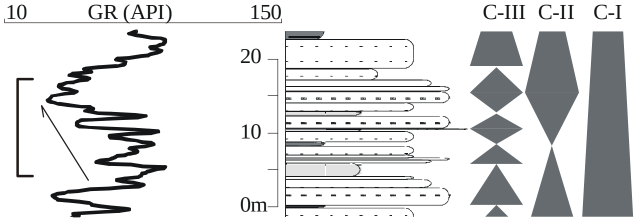


Fig. 3.18 Alluvial fan facies association (marked by a bar). The interpreted stacking pattern of base-level cycles. Legend in **Fig. 3.12 b**.

3.4.4 BRACKISH-MARINE DELTA/SHOREFACE SYSTEM (**Fig. 3.19**)

This facies association occurs in the Middle Pechelbronn Beds, at the transition between the transfer zone and the southern sub-basin. It is also encountered in the central transfer zone where A/S conditions were favourable. However, its thickness in the transfer zone is reduced. Palaeontological data suggest a brackish/marine environment (e.g. ostracod association: Quadracythere sp., Cytheridea sp., Schuleridea sp., Hemicyprideis sp.; e.g. Reiser, 1992). The delta/shoreface systems represent overall coarsening upward successions with grain size gradually increasing from mudstone to siltstone and fine- to medium-grained sandstone (sometimes to fine-grained conglomerate). The mudstone is often bioturbated and contains shell fragments (Mytilus sp., e.g. Wirth *et al*., 1952). Locally lags of Mytilus fragments occur in sand layers (e.g. Wirth *et al*., 1952), which might represent storm events.

The delta/shoreface unit records the shallowing upward trend from offshore (below storm wave base) to the upper shoreface. It corresponds to an intermediate-scale C-II base-level fall, and contains several minor C-III base-level falls.

Within the offshore mudstones, usually the large-scale rise-to-fall turnaround is located. Thus, the delta/shoreface C-II cycles occur within a large-scale C-I fall cycle (e.g. C-II-5 in **Fig. 3.19**). In this case, the C-II fall cycles were created by increased sediment supply and by the decrease of accommodation space, due to the regression of the sea of the Middle Pechelbronn Beds. However, in some particular cases, the prograding delta/shoreface systems are included in a C-I rise cycle (e.g. C-II-4 in **Fig. 3.19**). These C-II cycles were exclusively controlled by a locally increased sediment input derived from the transfer zone. Thus, local sediment supply outpaced the overall increase of accommodation space (C-I rise) imposed by the transgression, which created the brackish/marine settings of the Middle Pechelbronn Beds.

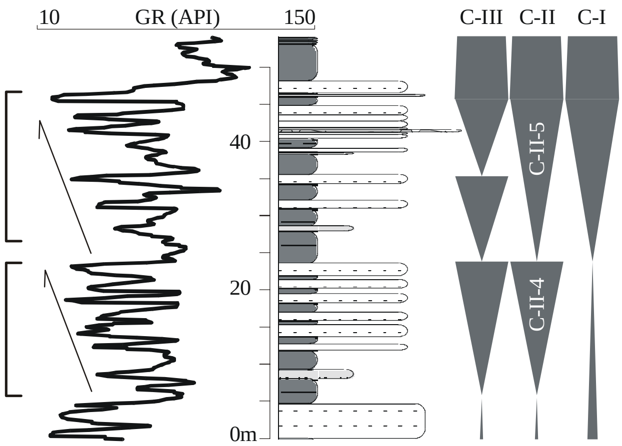


Fig. 3.19 Two superimposed brackish/marine delta/shoreface facies associations (marked by a bar). The interpreted stacking pattern of base-level cycles. The intermediate-scale C-II-4 fall cycle was exclusively controlled by increased sediment supply, as it occurs within a large-scale rise cycle. The C-II-5 cycle was controlled by both decreasing accommodation space (recorded also by the large-scale fall) and increasing sediment supply. Legend in **Fig. 3.12 b**.

3.4.5 OFFSHORE BRACKISH/MARINE (**Fig. 3.20**)

The brackish/marine offshore facies association is characterised by the same faunal association as the delta/shoreface systems. It also exclusively occurs in the Middle Pechelbronn Beds and represents the distal equivalent of the prograding delta/shoreface systems. The unit was identified in both southern and northern sub-basin and the central transfer zone. It consists of mudstones and marlstones with rare thin siltstone and fine-grained sandstone intercalations. The mud- and marlstones are often bioturbated. Similar macrofauna as in the delta/shoreface unit (Mytilus sp.) occurs. This facies reflects predominant low-energy conditions, present below storm-wave base. Deposition was from suspension and was interrupted by minor traction and turbidity currents. Lampe (2001) suggests a palaeo-waterdepth of about 40 metres. Within this unit, the rise-to-fall turnaround of intermediate- (C-II) and large-scale (C-I) cycles is located. Thus, the turnaround represents a time line valid for the entire study area. It also allows correlation between the northern and southern sub-basin, across the transfer zone.

In the southern sub-basin, in a transfer zone distal position, fluctuations in base level were controlled by variation of the accommodation space only. This was because sedimentation at this location was not directly linked to shoreface progradation (the coarse-grained sediment delivered by the transfer zone did not reach far into the basin).

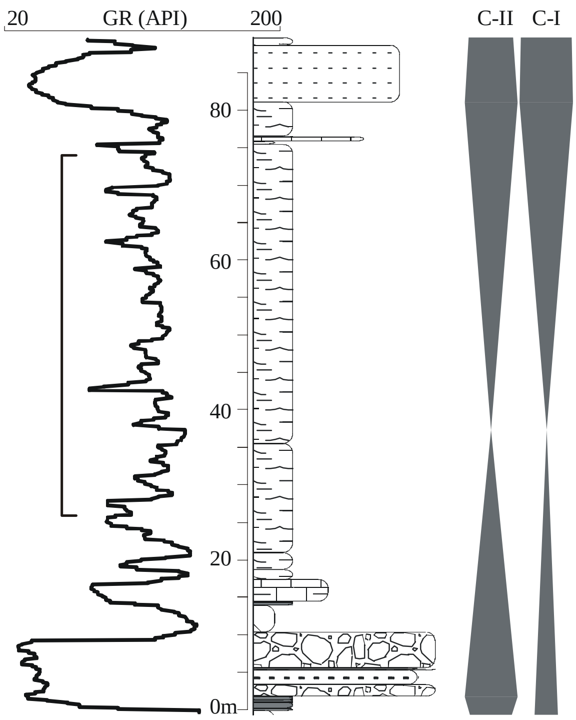


Fig. 3.20 Offshore brackish/marine facies association (marked by a bar) in the Middle Pechelbronn Beds. The small-scale cycles cannot be defined. Legend in **Fig. 3.12 b**.

3.4.6 OFFSHORE MARINE (**Fig. 3.21**)

The offshore marine facies association exclusively occurs in the Rupelian Clay. It was deposited at a time when marine conditions controlled the entire Upper Rhine Graben area (e.g. foraminfera associations like: Bathysiphon sp., Cibicides sp., Cyclammina sp., Gyroidina sp., Bolivina sp., e.g. Elstner, 1985). It consists of locally bioturbated shale, deposited from suspension in an offshore environment. The water depth varied between 100 and 200 metres (Rothausen & Sonne, 1984; Grimm, 1991). The transition from the terrestrial Upper Pechelbronn Beds to these offshore conditions consists of an alternation of mudstones and thin rippled siltstones and fine-grained sandstones. Gaupp & Nickel (2001) suggest tidal influences for this transition.

The offshore shales of the Rupelian Clay can be recognised as marker in the entire study area. The offshore marine unit contains the rise-to-fall turnaround of C-I and C-II cycles, which, consequently, represents a basin wide time line usable for correlation.

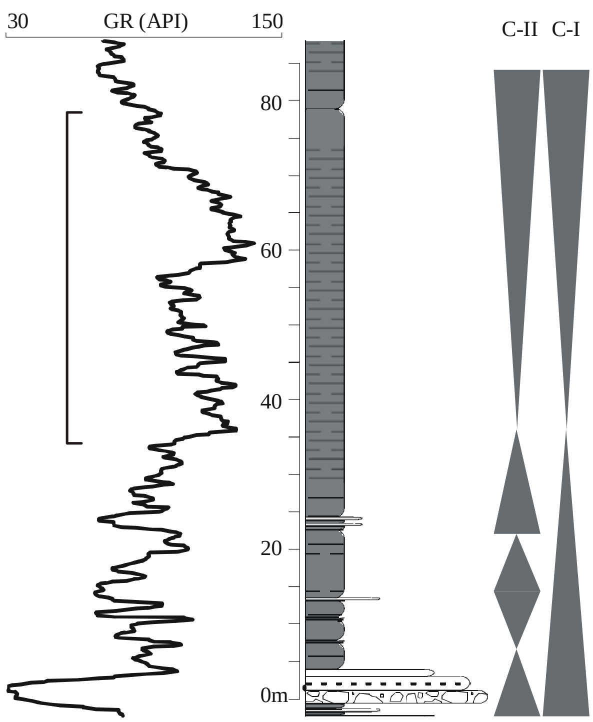


Fig. 3.21 Offshore marine facies association of the Rupelian Clay (marked by a bar). Legend in **Fig. 3.12 b**.

3.5 Base-level cycles and their palaeogeographic variability

Two large-scale cycles (C-I-1 and C-I-2, in **Fig. 3.22**) are identified within the discussed early syn-rift succession (Pechelbronn Beds and Rupelian Clay) of the northern Upper Rhine Graben. The occurrence of the Eocene Clay is too isolated in order to allow a reasonable sequence stratigraphic interpretation. The characteristics of the two identified cycles, such as accommodation space, sediment supply, and the included intermediate C-II cycles, vary considerably as a function of the palaeogeographic position within the basin. The basin physiography and the sediment supply at different scales are mainly controlled by the tectonic framework (**Fig. 3.23**).

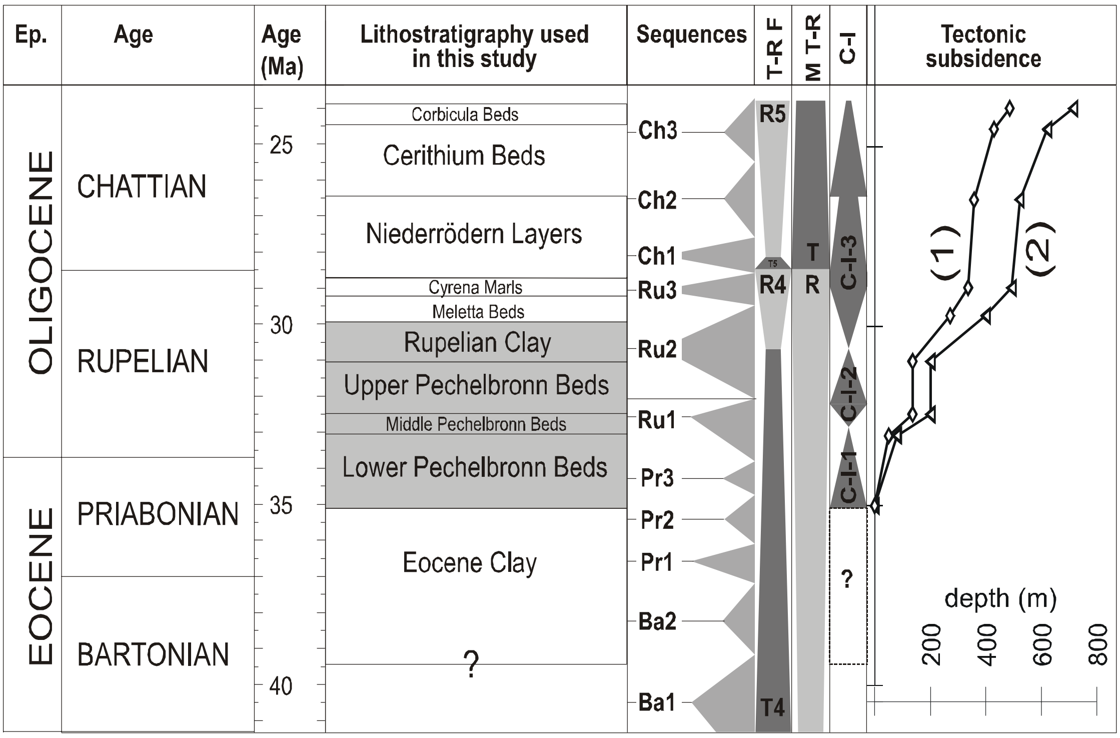


Fig. 3.22 The early syn-rift succession of the northern Upper Rhine Graben (shaded area). Lithostratigraphy is correlated with the base-level cycles, the tectonic subsidence, and the sequence chronostratigraphy of other European basins. Lithostratigraphy from the German Stratigraphic Commission (2002). Base-level cycles as interpreted in Derer *et al*. (2003) and in this study. Subsidence curves of well W639 (location in **Fig. 3.9**); (1) air-loaded tectonic subsidence, (2) water loaded tectonic subsidence. Cenozoic sequence chronostratigraphy from Hardenbol *et al*. (1998). T-R F transgressive-regressive facies cycles, M T-R major transgressive-regressive cycles; Ba1, Ba2, etc. maximum flooding surfaces.

(1) The large-scale interbasin transfer zone influenced both accommodation space and sediment dispersal by separating two main depocentres (as are the northern and the southern sub-basins, **Fig. 3.23**). It also created major axial depositional gradients dipping away from it. The topographically elevated transfer zone was generally characterised by low accommodation space and high sediment input. This led to low sediment preservation conditions, and the clastic material was transported into the sub-basins, along the axial depositional gradi-

ents. Consequently, in some areas of the transfer zone, the Pechelbronn Beds are very thin or even absent. This means that in some areas of the transfer zone C-I-1 and C-I-2 were not able to develop as two distinct cycles.

In contrast to the situation in the transfer zone, higher accommodation space and decreased sediment supply occurred in the two sub-basins, which allowed the formation and preservation of both cycles (C-I-1 and C-I-2). These deposits, with a total thickness of more than 200 metres, onlap onto the margins of the transfer zone.

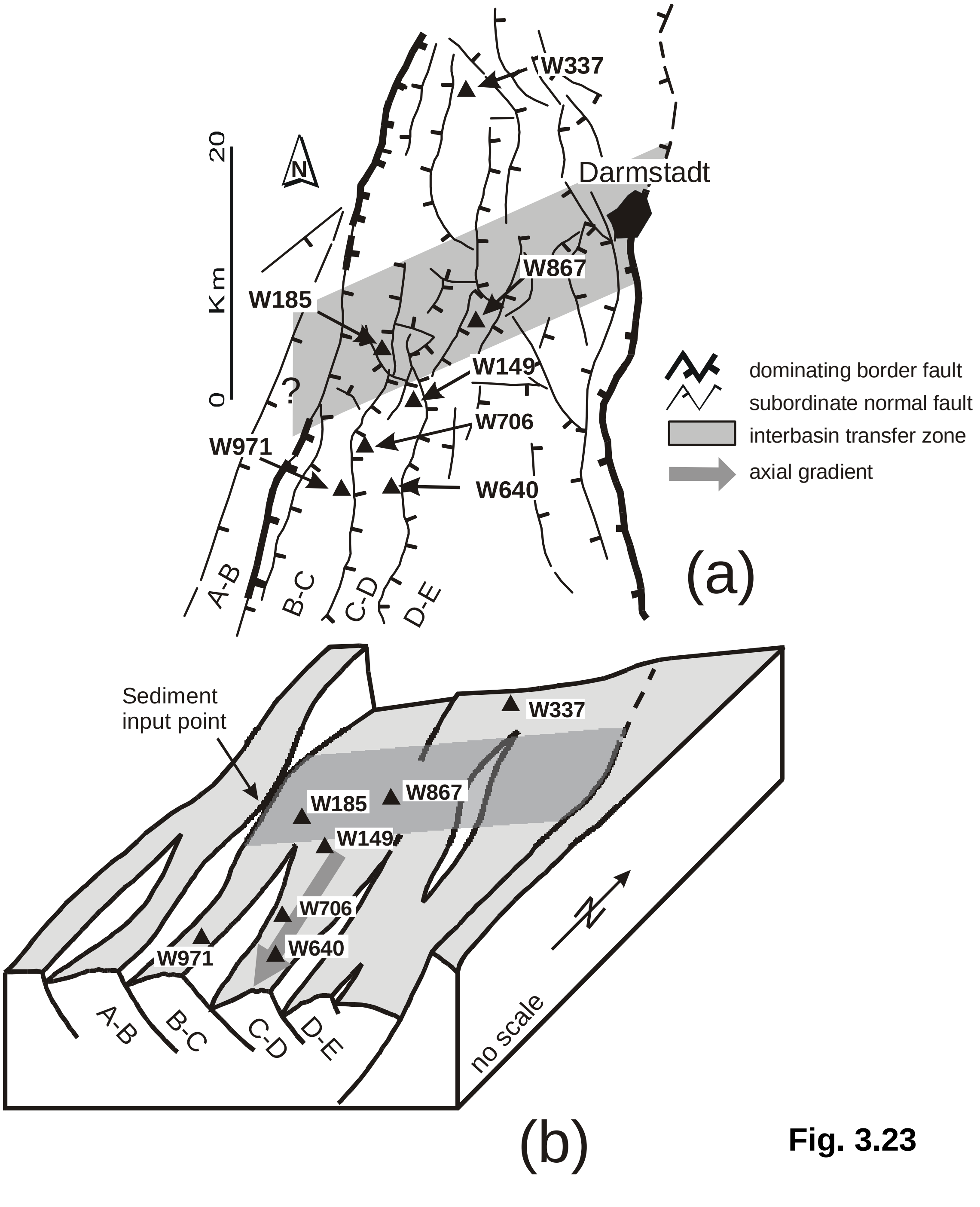


Fig. 3.23

Fig. 3.23 (previous page) Structural map and simplified block diagram of the northern Upper Rhine Graben. They illustrate the interbasin transfer zone, the low-displacement segment of the western border fault and subordinate tilt-blocks. These tectonic features influenced sedimentation during the early syn-rift stage. Location of the wells discussed in the text. Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996). The structural level of the fault pattern is top Rupelian Clay.

(2) Within the interbasin transfer zone and the southern sub-basin, active tilted fault blocks and horst structures formed, at a subordinate scale, an intrabasinal palaeotopography, which controlled deposition (**Fig. 3.23**). The fault block crests had low accommodation conditions and moderate sediment input. At times, especially during falls in base-level, they acted as local source areas. On the hangingwall, from the block crest towards the growth fault plane, accommodation space increased and was partly balanced by footwall-derived clastic material. The tilt of the blocks and the difference in elevation between footwall and hangingwall created subordinate depositional gradients, perpendicular to the graben axis.

(3) The third factor is the low-displacement segment of the western border fault, which controlled the sediment supplied to the basin (**Fig. 3.23**). This fault segment created a low-relief zone with a subordinate depositional gradient, which allowed drainage systems to enter the graben and to deliver sediment. Consequently, sediment supply was increased in the vicinity of this sediment entry point. The clastic material entering the basin was partly deflected toward the south, along the major axial gradient dipping into the southern sub-basin.

The activity of this sediment input point became significant mainly after the southern sub-basin started to act as one depozone (i.e. after the isolated depocentres coalesced and formed the two sub-basins). Thus, the low-relief zone principally delivered sediment during the deposition of the Middle and Upper Pechelbronn Beds. This interpretation is in accordance with the alluvial fans of the Upper Pechelbronn Beds which prograded from the western graben shoulder as mentioned by Plein (1992) and Gaupp & Nickel (2001).

In the following, several case studies will illustrate in more detail the accommodation space to sediment supply variation at various structural locations within the transfer zone and individual sub-basins (mainly southern sub-basin). Their characteristics are summarised in **Tables 3.2, 3.3 and 3.4**. The locations of the wells are marked in **Fig. 3.23**.

3.5.1 ACCOMMODATION SPACE AND SEDIMENT SUPPLY IN THE INTERBASIN TRANSFER ZONE

Two case studies will be discussed for the transfer zone. They represent the proximal and distal positions relative to the sediment entry point created by the low-displacement segment of the western border fault (**Fig. 3.24**, **Fig. 3.25**, location in **Fig. 3.23**).

<u>Interbasin transfer zone, proximal to the sediment entry point (W185, **Fig. 3.24**)</u>

Well W185 represents the succession of the interbasin transfer zone, proximal to sediment entry point (location in **Fig. 3.23**). The succession is characterised by low accommodation space, due to the elevated topography of the transfer zone. Thus, only a thin sediment pile could be accumulated and preserved (cycles C-I-1 and C-I-2 have a total thickness of about 90 metres). The proximity to the sediment entry point led to high sediment supply. Consequently, coarse-grained material (gravel and coarse sand) was deposited by high-energy fluvial systems and alluvial fans. As accommodation space was low, bypassing and amalgamation occurred, and the sediment was transported further towards the southern sub-basin.

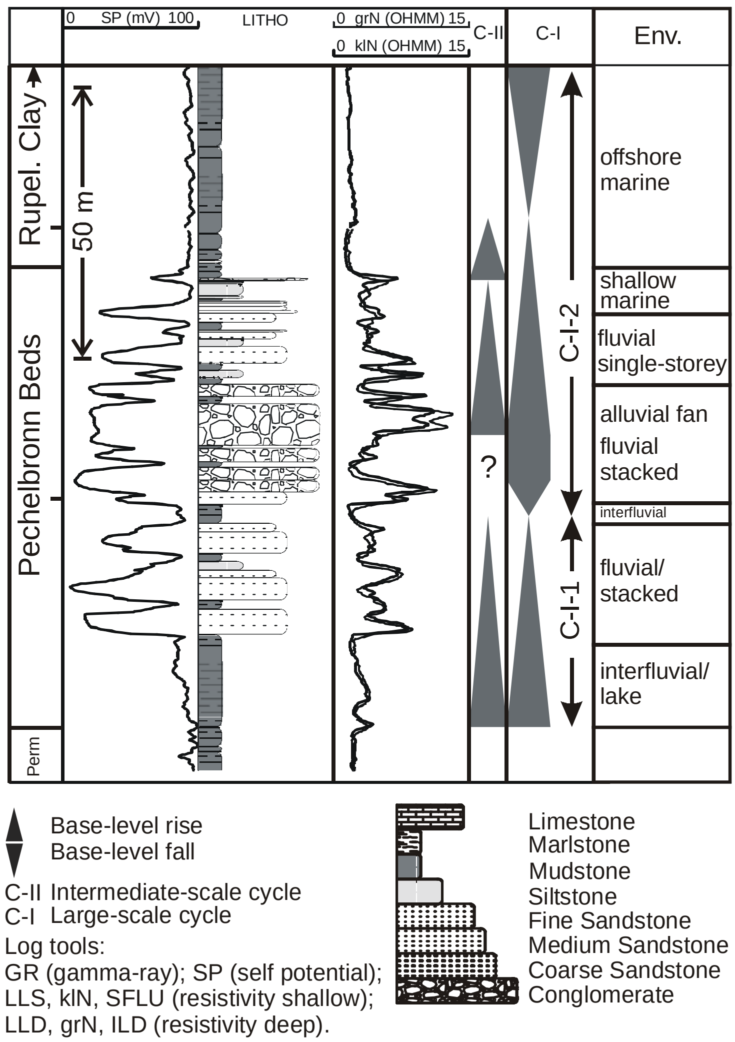


Fig. 3.24 Well W185, located within the transfer zone, proximal to the sediment entry point. Low accommodation space and high sediment supply through the low-relief zone. Location in **Fig. 3.23**. Legend for **figures 3.24** to **3.30**.

The low ratio of accommodation space to sediment supply of the C-I-1 cycle led to the deposition of stacked channel associations through high-energy fluvial systems. Due to subsidence and due to the northward migration of the brackish/marine conditions of the Middle Pechelbronn Beds, accommodation space increased with time.

The C-I-2 cycle is also rise-asymmetric, due to the unbalanced proportion between accommodation space and sediment supply. The fall-to-rise turnaround of cycle C-I-2 is represented by a zone, as an exact surface cannot be identified. The low-relief zone delivered high amounts of sediment, which outpaced the formation of accommodation space. As a consequence, stacked alluvial fans and fluvial channels developed. They were characterised by amalgamation and represented the proximal, terrestrial equivalents of the brackish/marine environments of the Middle Pechelbronn Beds developed in the southern sub-basin and the central transfer zone (compare to well W867 in the next section).

The accommodation space to sediment supply ratio remained low (alluvial fans and stacked channels dominated the sedimentation) till the late Rupelian transgression created sufficient accommodation space for single storey channels. These were topped by shallow marine and finally the offshore marine facies associations of the Rupelian Clay.

Interbasin transfer zone, distal to the sediment entry point (W867, **Fig. 3.25**)

Well W867 is located away from the direct influence of the sediment entry point of the western border fault (location in **Fig. 3.23**). At this location, the total accommodation space available for the early syn-rift succession was similar to the previous case (proximal to the sediment entry point, well W185). It was controlled, at a large scale, by the topographic high of the transfer zone. The base of cycle C-I-1 is composed of stacked fluvial channels, which towards the top are replaced by single-storey channels and interfluvial/lacustrine facies associations. They are drowned by the brackish/marine settings of the Middle Pechelbronn Beds.

The major difference from the location proximal to sediment entry point occurs at the turnaround between the C-I-1 and C-I-2 cycle and within the C-I-2 cycle. The location of well W867 is interpreted to be a facies zone positioned laterally relative to the sediment entry point. Gaupp & Nickel (2001) suggest that sediment delivered from the western border fault also might have reached this location. Anyhow, at this distal/lateral position the sediment supply was reduced. A small amount, and only the fine-grained fraction (clay, silt, fine-medium sand), reached this position. Thus, the creation of accommodation space outpaced sediment supply, and the brackish/marine environments of the Middle Pechelbronn Beds could develop. At the rise-to-fall turnaround, they were characterised by low energy offshore conditions. During the C-I-2 base-level fall they were gradually replaced by prograding delta/shoreface systems. These systems represented the coeval equivalents of the alluvial fans active in the vicinity of the sediment input point at the western border fault.

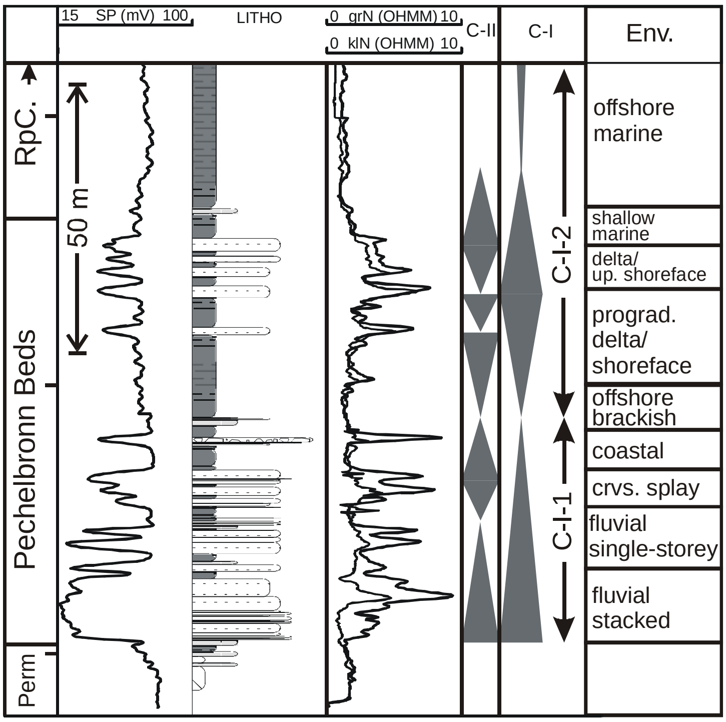


Fig. 3.25 Well W867, located within the transfer zone, distal relative to the sediment entry point. Low accommodation space, moderate sediment supply. Location in **Fig. 3.23**. Legend in **Fig. 3.24**.

3.5.2 ACCOMMODATION SPACE AND SEDIMENT SUPPLY WITHIN THE SUB-BASINS

<u>Southern sub-basin, transfer-zone-proximal position (W149, **Fig. 3.26**)</u>

Well W149 is on block C-D (i.e. the ramp) of the southern sub-basin, in a position proximal to the interbasin transfer zone (location in **Fig. 3.23**). In contrast to the transfer zone, the accommodation space in the southern sub-basin was much higher (i.e. at this position it allowed the creation and preservation of cycles C-I-1 and C-I-2, with a total thickness of ca. 200 metres). The sediment input was relatively high, via the interbasin transfer zone. In contrast to the transfer zone area, a higher diversity of depositional environments could develop.

Due to the high accommodation space, low-energy interfluvial/lacustrine systems formed at the base of the C-I-1 cycle. In the upper part of cycle C-I-1 and in the lower part of the C-I-2-cycle (C-I-2-fall hemicycle), the brackish/marine environments of the Middle Pechelbronn Beds developed (dashed line in **Fig. 3.26**). Here, prograding delta/shoreface systems suggest the proximity of a coastline. A part of the sediment entering the graben through the low-relief zone was deflected and transported axially toward the south, along the ramp-like block C-D (**Fig. 3.23**). This could also explain the fall-asymmetric C-II-4 cycle (**Fig. 3.26**). This delta/shoreface progradation occurred despite the coeval large-scale base-level rise (C-I-1). This means, that the A/S ratio was exclusively controlled by the high sediment supply. In contrast, the C-II-5 fall-hemicycle was controlled by both increasing sediment supply and decreasing accommodation space (C-II-fall hemicycle is coeval to the C-I-2 fall hemicycle).

At the fall-to-rise turnaround of cycle C-I-2, the top of the shoreface is capped by a subaerial exposure surface. This surface acted as bypassing area for an axial sediment flux towards the south. During the rise of the base-level in the C-I-2-cycle only thin fluvial/ interfluvial deposits accumulated. They were subsequently overlain by the shallow and offshore marine sediments of the Rupelian Clay.

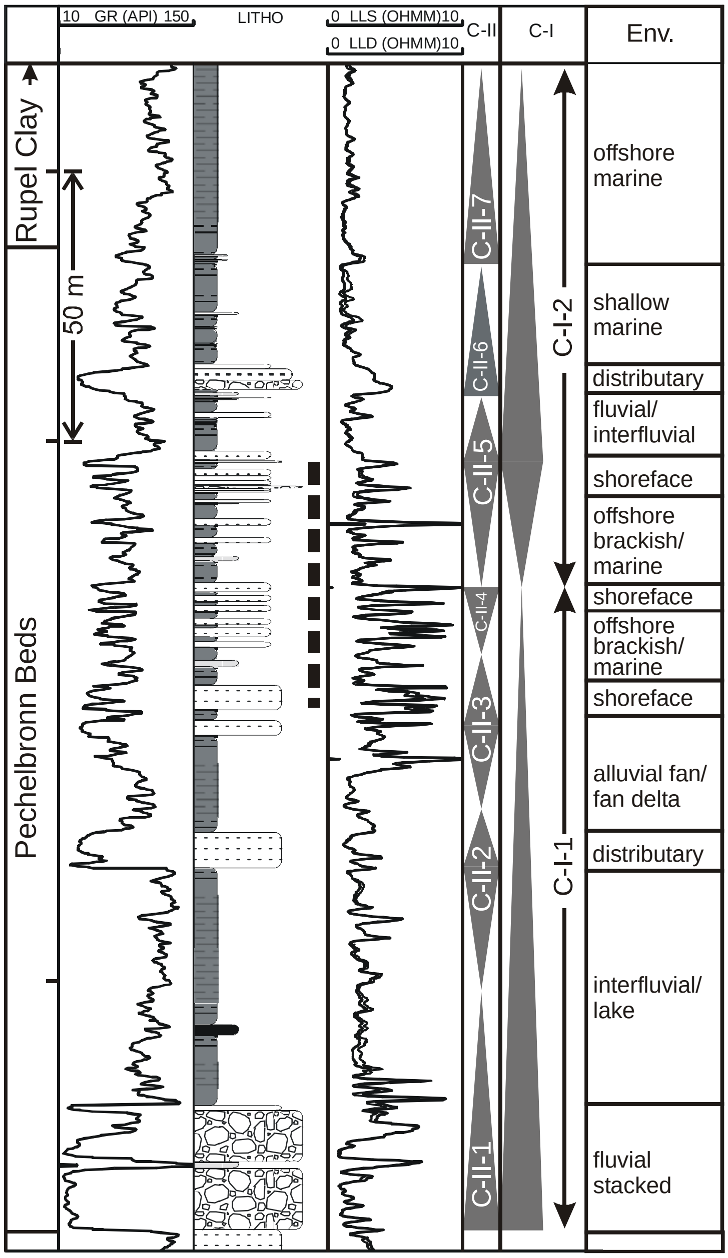


Fig. 3.26 Well W149, located in the transfer-zone-proximal southern sub-basin. Moderate accommodation space and moderate-high sediment supply from the low-relief zone, via the transfer zone. Dashed line marks prograding delta/shoreface systems of the brackish Middle Pechelbronn Beds. The C-II-4 cycle was controlled by high sediment supply only, as it is coeval to the C-I-1 rise. Location in **Fig. 3.23**. Legend in **Fig. 3.24**. Modified from Derer *et al*. (2003).

Southern sub-basin, transfer-zone-distal position (W640, **Fig. 3.27**)

Well W640 is located distally on the depositional gradient of block C-D (i.e. the ramp), created by the interbasin transfer zone in the southern sub-basin (location in **Fig. 3.23**). Here, the accommodation space increased relative to the proximal conditions, but the amount of clastic sediment reaching this site was subordinate. Consequently, at this location, the off-shore Middle Pechelbronn facies associations could develop (dashed line in **Fig. 3.27**). They were time-equivalent to the delta/shoreface systems in well W149 (dashed line in **Fig. 3.26**). Due to the higher accommodation space, the exposure at the fall-to-rise turnaround of cycle C-I-2 was not so significant. Therefore, also a thicker pile of single-storey channels and interfluvial/lacustrine facies associations could accumulate during the base-level rise of the C-I-2-cycle.

Northern sub-basin (W337, **Fig. 3.28**)

Well W337 is located within the northern sub-basin, in a position with similar A/S conditions as in well W640 of the southern sub-basin (high accommodation space and low sediment input, location in **Fig. 3.23**). This case is presented in order to show, that correlations of large-scale cycles between the two sub-basins are possible. In Well W337, also a thick succession of Eocene Clay occurs. However, only the Pechelbronn Beds will be discussed in detail, as information on the Eocene Clay are too scarce.

The C-I-1 cycle starts within the Pechelbronn Beds with a multi-storey channel association. Due to high rates of accommodation space creation and low sediment input, this association is followed in stratigraphic section by thick interfluvial/lacustrine deposits. These were drowned by the brackish/marine transgression of the Middle Pechelbronn Beds. The rise-to-fall turnaround is located within low-energy offshore brackish/marine deposits.

Due to low sediment input, the C-I-2 base-level fall is characterised by fine-grained, low-energy deposits. The following C-I-2 rise-hemicycle contains interfluvial/lacustrine environments, with thin single-storey channels. On top, a thin delta (fan delta?) developed, which was drowned and covered by offshore marine Rupelian Clay.

	proximal to sediment entry point	**distal to sediment entry point**
A/S ratio	very low	low
accommodation	low	low
sediment supply	high	moderate
facies diversity	low	moderate

Table 3.2 The variation of the accommodation space and sediment supply within the transfer zone, as a function of the position relative to the sediment entry point.

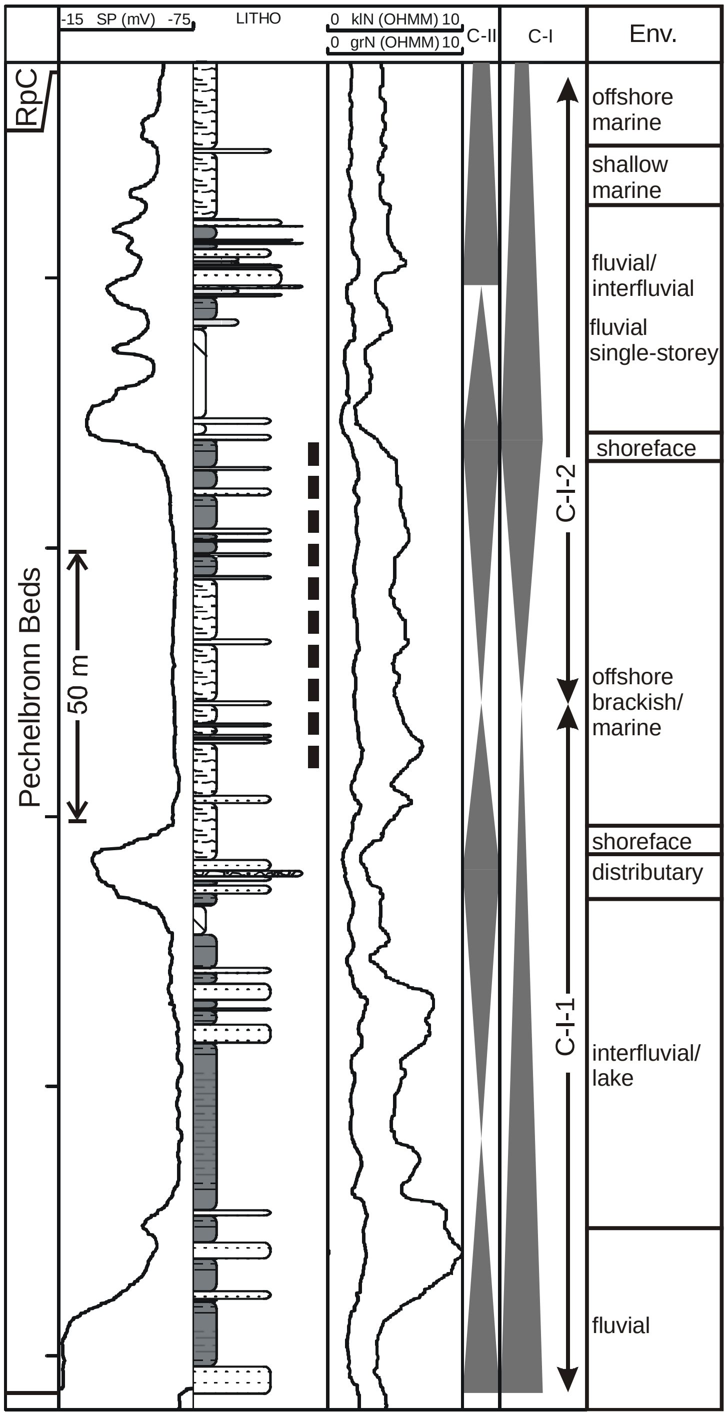


Fig. 3.27 Well W640, located in the transfer-zone-distal southern sub-basin. High accommodation space, moderate-low sediment supply. The offshore mudstones of the brackish/marine Middle Pechelbronn Beds (dashed line) are the distal equivalents of the delta/shoreface sands of the proximal sub-basin (W149, dashed line in **Fig. 3.26**). Location in **Fig. 3.23**. Legend in **Fig. 3.24**. Modified from Derer *et al*. (2003).

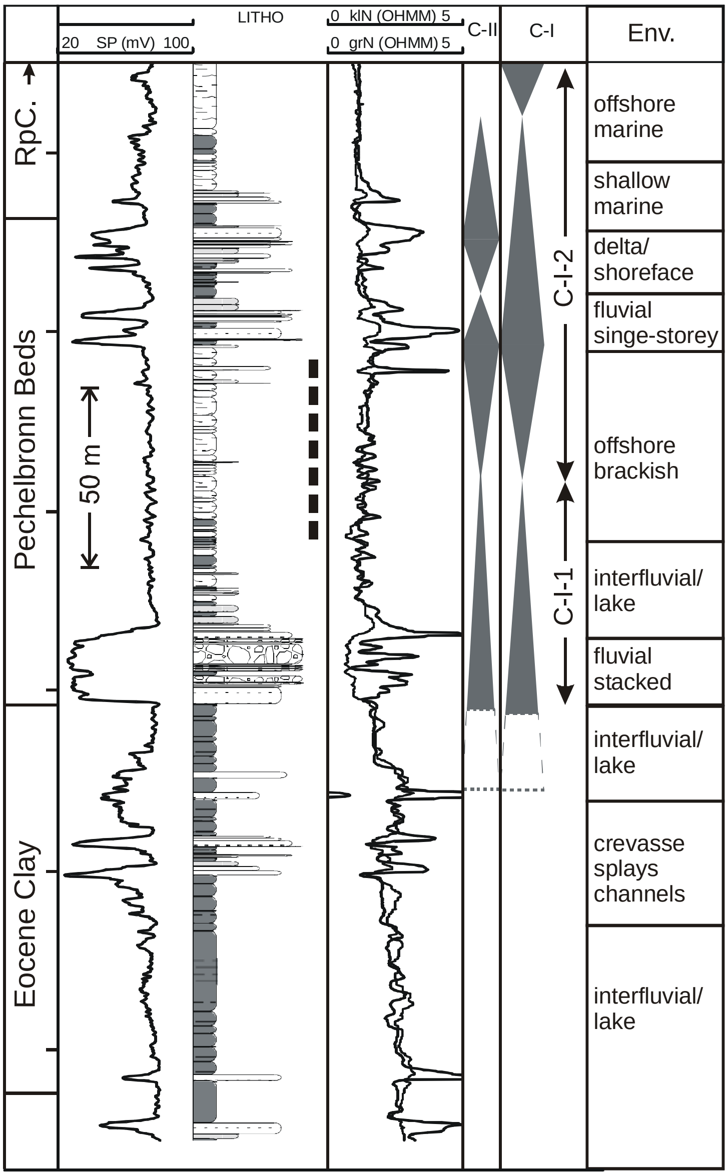


Fig. 3.28 Well W337, located within the northern sub-basin. High accommodation space, low sediment supply. Dashed line marks the offshore brackish/marine facies association of the Middle Pechelbronn Beds (coeval to the environments in the southern sub-basin, dashed line in **Fig. 3.26, 3.27**). The vertical scale is smaller than for the rest of the figures. Location in **Fig. 3.23**. Legend in **Fig. 3.24**.

	interbasin transfer zone	**transfer-zone-proximal southern sub-basin**	**transfer-zone-distal southern sub-basin**
A/S ratio	low	moderate	high
accommodation	low	moderate	high
sediment supply	high	moderate-high	moderate-low
facies diversity	low	high	moderate

Table 3.3 The variation of the accommodation space and sediment supply on the axial depositional gradient created by the transfer zone.

3.5.3 ACCOMMODATION SPACE AND SEDIMENT SUPPLY ON TILT-BLOCKS/HALFGRABENS

The following two case studies will discuss the palaeogeographic variation of the accommodation space to sediment supply in subordinate halfgrabens of the southern sub-basin.

Footwall, fault block crest (W971, **Fig. 3.29**)

The position of well W971 is on the crest of the subordinate tilted fault block B-C, in the western part of the southern sub-basin (location in **Fig. 3.23**). Here, accommodation space was moderate to low and sediment supply high. During falls in base-level, this elevated palaeotopographic position was probably exposed. Thus, incision, sediment bypassing, and sediment amalgamation occurred. Cycles C-I-1 and C-I-2 could not be differentiated. The diversity of environments was low: mainly coarse-grained, high-energy sediments of stacked river channels and alluvial fans were deposited and preserved during the rise of the base-level. Most of the time, at this position, sediment supply outpaced the formation of accommodation space. Only in the uppermost part of the cycle, the A/S ratio changed, and accommodation space creation outpaced sediment supply. Single-storey channels and interfluvial/lacustrine facies associations developed. They progressively drowned and were topped by the offshore marine Rupelian Clay.

Hangingwall, proximal to the growth fault (W706, **Fig. 3.30**)

Well W706 is located in the hangingwall C-D, close to the growth fault C, in the western part of the southern sub-basin (location in **Fig. 3.23**). The well probably intersects the plane of fault C, so parts of the Lower Pechelbronn Beds are missing. In this area, accommodation space was high due to significant syn-depositional subsidence. Sediment supply was moderate and both of the large-scale cycles were preserved. In the lower part of the C-I-1-cycle, stacked fluvial channels were formed, but the creation of accommodation space also allowed the development of thick interfluvial/lacustrine facies associations. A transition to brackish/marine environments followed. In the upper part of cycle C-I-1 (dashed line in **Fig. 3.30**), high footwall-derived sediment input kept pace with the creation of accommodation space and generated thick shallow-water sandstones. These were coeval with the offshore Middle Pechelbronn mudstones in the more central part of the southern sub-basin (dashed line in well W640 in **Fig. 3.27**). The shallow water deposits were topped by a thin succession of offshore sandstones and mudstones. The base-level fall of the C-I-2-cycle led to exposure and during the subsequent rise single-storey channels and interfluvial systems aggraded. These were gradually replaced by the marine conditions of the Rupelian Clay.

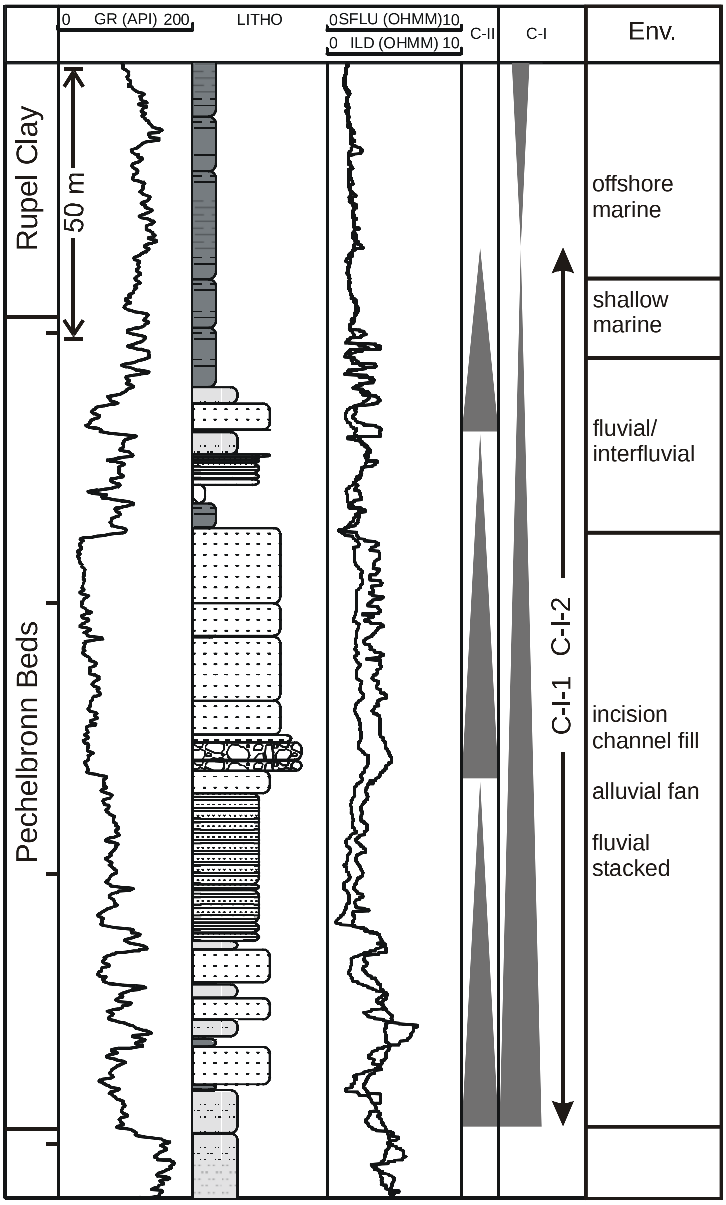


Fig. 3.29 Well W971, located on the crest of footwall B-C. Moderate to low accommodation space and high sediment supply. During base-level fall exposure and incision occurred. Cycles C-I-1 and C-I-2 cannot be differentiated. Location in **Fig. 3.23**. Legend in **Fig. 3.24**. Modified from Derer *et al*. (2003).

	footwall block crest	**hangingwall fault-proximal**
A/S ratio	moderate-low	high
accommodation	moderate-low	high
sediment supply	high	moderate
facies diversity	low	high

Table 3.4 The variation of the accommodation space and sediment supply on subordinate fault blocks (on the footwall crest and on the hangingwall, close to the fault plane).

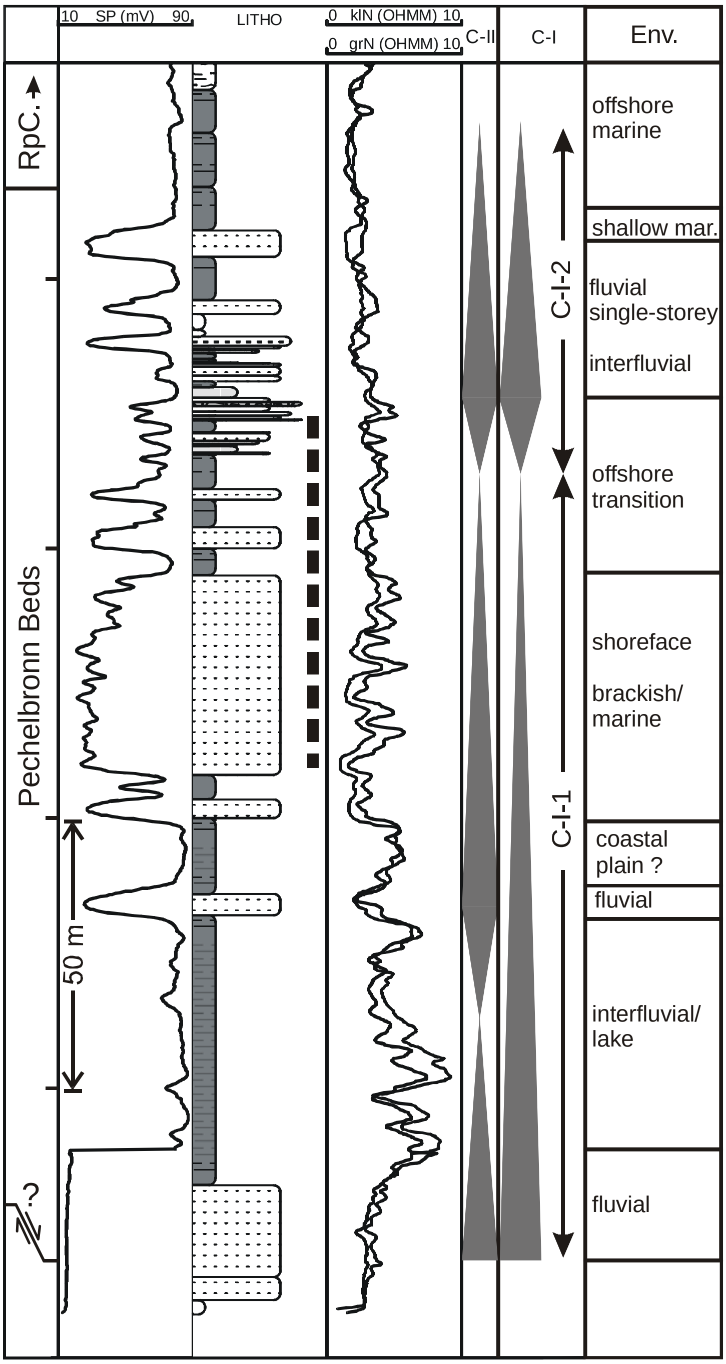


Fig. 3.30 Well W706, located on the hangingwall C-D, proximal to the active normal fault. High accommodation space due to syn-sedimentary subsidence and moderate sediment input. Thick shoreface deposits (with sediment supplied from the footwall, dashed line) are time equivalent with the Middle Pechelbronn offshore mudstones in well W640 (dashed line in **Fig. 3.27**). Location in **Fig. 3.23**. Legend in **Fig. 3.24**. Modified from Derer *et al*. (2003).

3.5.4 SUMMARY

The locations of the wells W185, W149 and W640 belonged to the major axial depositional gradient that was initiated by the interbasin transfer zone (**Fig. 3.23**). For the lower part of cycle C-I-1 the sediment was transported southward by fluvial systems (Gaupp & Nickel, 2001; Derer *et al*., 2003). For the upper part of C-I-1 and the whole C-I-2, sediment was mostly derived from the low-relief zone at the western border fault, and deflected towards the south by the axial gradient. On this proximal-distal profile, these three wells show an increase in the ratio of accommodation space to sediment supply. In well W149, the ratio of accommodation space and sediment supply was closest to equilibrium (creation of accommodation space approximately equal to sediment supply). In well W185 (proximal part of the gradient) the clastic input dominated (creation of accommodation space was outpaced by sediment supply, and sediment bypassing occurred). At a more distal location on the gradient (well W640), the formation of accommodation space was higher than sediment supply, leading to periods of sediment starvation.

During the time in which the low-relief zone of the western border fault functioned as sediment entry point (upper part of C-I-1 and entire C-I-2), the locations of wells W185 and W867 probably represented two coeval lateral facies zones. Their accommodation space conditions were similar. Only the sediment supply controlled the difference between the depositional conditions at the two locations.

High sediment input through the low-relief zone created in its vicinity stacked fluvial channels and alluvial fans (W185, **Fig. 3.24**). Here most of the sediment was transported down gradient, thus only a thin C-I-2 fall hemicycle was formed and preserved. Most of the succession was deposited during the C-I-2 rise hemicycle, when accommodation space increased.

Laterally, at the location of well W867 (**Fig. 3.25**) sediment supply was scarce, consequently offshore the brackish/marine environments of the Middle Pechelbronn Beds transgressed over the area. Enough accommodation space was available to develop a thicker C-I-2 fall hemicycle with fine-grained delta-shoreface systems prograding into the offshore settings.

Wells W971 and W706 belonged to different depositional gradients. However, it is obvious, that the accommodation to sediment supply ratio on the crest of the footwall B-C (W971) was lower than that on the immediate hangingwall C-D (W706). Thus, erosion and sediment bypassing was frequent on the block crest, whereas the creation of accommodation space within the downthrown area, adjacent to the footwall, kept pace or even outpaced the input of clastic material from the footwall.

The examples presented above, clearly show that due to the tectonic style, sedimentation pattern significantly changed within a relative small area. In the next section the base-level cycles are correlated between the sub-basins and along depositional gradients.

3.6 Correlation of base-level cycles

The early syn-rift successions of the northern and southern sub-basin are correlated across the interbasin transfer zone, by using large-scale base-level cycles. The base-level cycles are also correlated along the major axial depositional gradient, generated by the transfer zone in the southern sub-basin, and along a subordinate depositional gradient created by tilt block tectonics.

3.6.1 CORRELATION OF BASE-LEVEL CYCLES ACROSS THE INTERBASIN TRANSFER ZONE

The interbasin transfer zone represented a structural and palaeotopographic high, which separated the northern and southern sub-basin (**Fig. 3.31,** section 1 in **Fig. 3.32**). The depositional conditions in the two sub-basins were similar and characterised by high accommodation space and low sediment supply. Thus, both large-scale cycles (C-I-1 and C-I-2) were formed and preserved. In the northern sub-basin, even Eocene Clay was deposited. Sedimentation within the cycle C-I-1 of the two sub-basins started with fluvial and interfluvial/lacustrine systems, which were drowned and followed by the offshore brackish/marine settings of the Middle Pechelbronn Beds (rise-to-fall turnaround). These offshore conditions were probably created by the regional rise of relative sea level (Ru1 transgression of Hardenbol *et al*. (1998), **Fig. 3.22**), combined with the formation of the two depozones (northern and southern sub-basin), trough tectonic subsidence.

During the C-I-2 fall hemicycle, the offshore conditions were gradually replaced by more proximal environments and, at the fall-to-rise turnaround, were characterised by subaerial exposure. The C-I-2 base-level rise (Upper Pechelbronn Beds), created accommodation space for aggrading fluvial and interfluvial systems which were drowned by the second major transgression (Ru2 transgression of Hardenbol *et al*. (1998), **Fig. 3.22**), which then deposited the offshore marine Rupelian Clay.

The transfer zone was characterised by a low A/S ratio thus, a thin early syn-rift succession was deposited and preserved. In parts of the transfer zone, only one single base-level rise cycle formed (e.g. wells W333, W885 **Fig. 3.32**). Well W961 and W112 did not reach the top pre-rift. According to seismic profiles the top pre-rift at the location of well W112 is ca. 100 metres lower (as suggested in **Fig. 3.32**).

During the deposition of the lower C-I-1 cycle (Lower Pechelbronn Beds) and the C-I-2 rise hemicycle (Upper Pechelbronn Beds), the transfer zone represented a sediment barrier between the two sub-basins. Within the transfer zone, mainly sediment bypassing occurred.

During the brackish marine conditions of the Middle Pechelbronn Beds, an open communication between the sub-basins probably existed, across the central and eastern part of the transfer zone (cf. Gaupp & Nickel, 2001 and see next **chapter 3.7**). In the western transfer zone, during this time, the terrestrial equivalents of the offshore facies associations were formed (fluvial channels, alluvial fans). Thus, even though the rise in base-level was also triggered from outside the basin (i.e. regional transgression), the transfer zone controlled the distribution of depositional systems. The late Rupelian transgression (Ru2, **Fig. 3.22**) drowned in equal measure the transfer zone and the sub-basins, and the offshore marine Rupelian Clay was deposited.

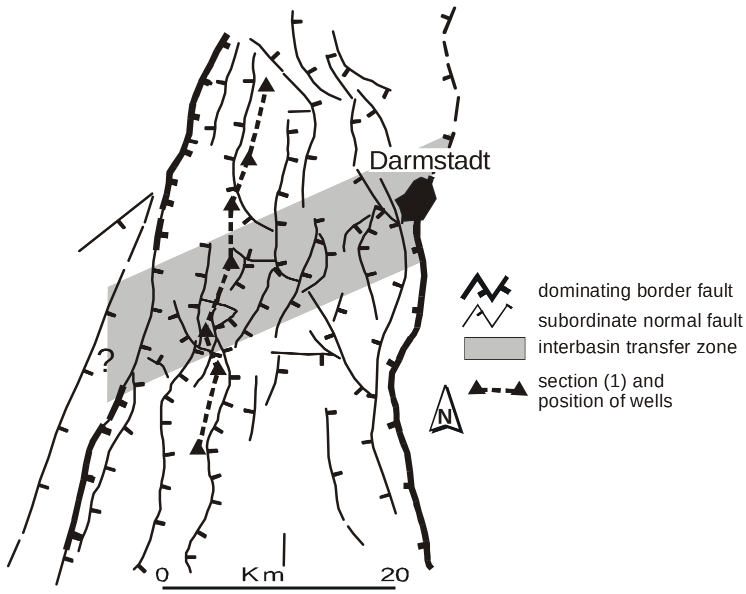


Fig. 3.31 Location of N-S section (1), correlating the northern and southern sub-basin across the interbasin transfer zone (section is shown in **Fig. 3.32**). Structure modified from Andres & Schad (1959); Straub (1962); Stapf (1988); Durst (1991); Plein (1992); Mauthe *et al.* (1993); Jantschik *et al.* (1996). The structural level of the fault pattern is top Rupelian Clay.

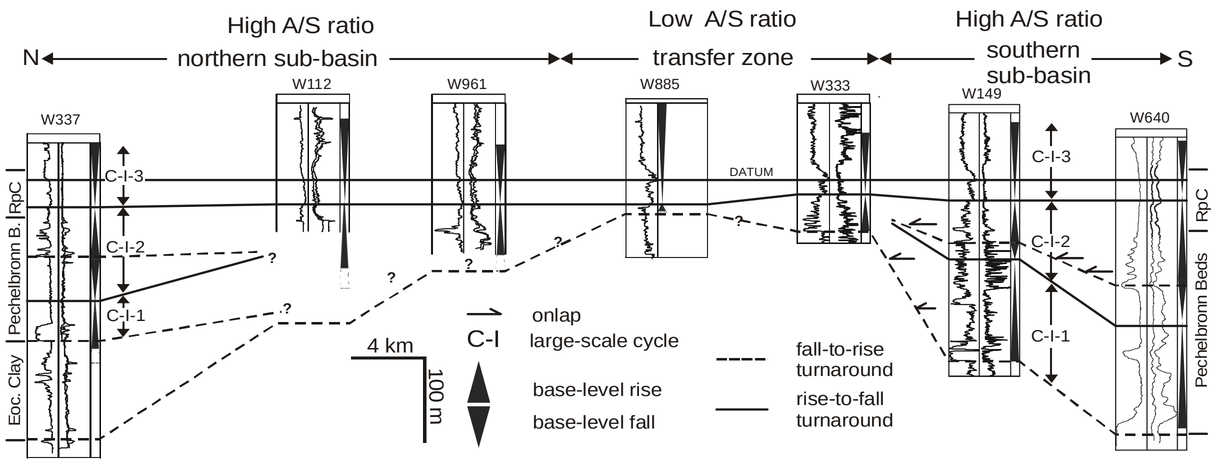


Fig. 3.32

Fig. 3.32 (bottom of previous page) Cross section (1) showing the correlation of large-scale cycles between the northern and southern sub-basin. High A/S ratio in the sub-basins. Thus, both cycles (C-I-1 and C-I-2) were deposited and preserved. Low A/S conditions in the interbasin transfer zone thus, locally only one rise-cycle could form. Wells W112 and W961 have not reached the top pre-rift. According to seismic interpretation at the location of well W112 the base syn-rift is ca. 100 metres deeper. The represented logs are gamma ray or self potential on the left, and resistivity on the right. Section datum is a GR and resistivity maximum in the offshore shales of the Rupelian Clay. Location of cross section in **Fig. 3.31**.

3.6.2 CORRELATION OF BASE-LEVEL CYCLES ALONG THE LARGE-SCALE AXIAL DEPOSITIONAL GRADIENT

The large-scale base-level cycles of the Pechelbronn Beds and Rupelian Clay (C-I-1 and C-I-2) are correlated along the major axial depositional gradient of the southern sub-basin, i.e. on the ramp setting of block C-D (**Fig. 3.34**, for location see profile 2 in **Fig. 3.33**). The cross-section illustrates the stratigraphic variation and the spatial linkage of depositional systems as a function of base-level fluctuations. The cross-section passes from the interbasin transfer zone (proximal part, up-gradient, i.e. the vicinity of the sediment input point of the western border fault) into the southern sub-basin (distal part, down-gradient).

<u>Cycle C-I-1 in the transfer zone</u>

The low A/S ratio within the transfer zone led to the deposition and preservation of a thin C-I-1 cycle (ca. 35 metres thick). It is mainly composed of stacked channels, generated by high-energy fluvial systems. Due to the increase of the A/S ratio in time, in the upper part of this cycle, interfluvial/lacustrine facies associations could be formed and preserved (but are relative thin). At the same time, down the depositional gradient, at the transition from the transfer zone to the southern sub-basin (well W143) thin shallow-water sediments were deposited. They represent the coastal equivalents of the brackish/marine Middle Pechelbronn Beds, developed in the southern sub-basin. The rise-to-fall turnaround between the C-I-1 and C-I-2 cycle is located within the interfluvial/lacustrine and shallow water sediments respectively.

<u>Cycle C-I-1 in the southern sub-basin</u>

After the formation of the northern Upper Rhine Graben, sedimentation was predominantly fluvial. The main drainage direction of the fluvial systems was from the transfer zone toward the south (Gaupp & Nickel, 2001; Derer *et al.*, 2003), along the axial gradient. In contrast to the transfer zone, relatively thick interfluvial/lacustrine facies associations were deposited over extended areas of the southern sub-basin.

During the base-level rise, the terrestrial systems passed through shallow-water conditions to the brackish/marine offshore environment of the Middle Pechelbronn Beds (rise-to-fall turnaround). In the transfer-zone-proximal southern sub-basin (wells W149, W138 in **Fig. 3.34**; dashed line in well W149 of **Fig. 3.26**), sediment was supplied via the transfer

zone by prograding delta/shoreface systems. At this position shoreface progradation occurred, despite the large-scale rise in base-level (see C-II-4 in well W149, **Fig. 3.26**). Thus, high sediment supply is assumed. It is possible, that already in the upper part of cycle C-I-1 the sediment entry point of the western border fault started to deliver clastic material.
The prograding wedges were replaced down-gradient, towards the south, by coeval offshore deposits characterised by starvation, marking the A/S maximum (wells W899 to W240 in **Fig. 3.34** and dashed line in well W640 of **Fig. 3.27**). In the upper part of the C-I-1-cycle, during the brackish/marine conditions, an axial, north-south sediment flux existed on the ramp-like block C-D. In the southern sub-basin the thickness of the C-I-1 cycle reaches 150 metres.

Cycle C-I-2 in the transfer zone

During the deposition of cycle C-I-2, the low-displacement segment of the western border fault functioned as sediment entry point (compare also Plein (1992) and Gaupp & Nickel (2001)). Thus, the increased sediment supply and the low accommodation space led to the formation of stacked alluvial fans and fluvial channels. These environments were characterised by sediment bypassing and amalgamation, and most clastic material was transported down-gradient, into the southern sub-basin.

Cycle C-I-2 within the transfer zone is rise asymmetric. Most of the sediments could be deposited only during the rise-hemicycle, which was induced by the late Rupelian regional transgression (Ru2 flooding, Hardenbol *et al*., 1998) and by the accelerated subsidence (**Fig. 3.22)**. The alluvial fans and stacked channels were replaced, up in stratigraphic section, by single-storey channels. These were overlain by the shallow marine and finally offshore marine facies of the Rupelian Clay. The thickness of the C-I-2 cycle in the transfer zone reaches ca. 55 metres.

Cycle C-I-2 in the southern sub-basin

The rise-asymmetry of the C-I-2-cycle in the transfer zone is replaced in the southern sub-basin by a symmetric pattern. The thickness of cycle C-I-2 here reaches ca. 130 metres. The development of the fall hemicycle was caused by the retreat of the brackish/marine environments towards the south. Sediments were delivered through the low-relief zone of the western border fault and deflected toward the southern sub-basin by the axial gradient. They formed prograding delta/shoreface wedges on the ramp. The fall-to-rise turnaround (minimum A/S) was marked by subaerial exposure and sediment bypassing. In the transfer-zone-proximal position the time of exposure and non-deposition was longer at the fall-to-rise turnaround than down-gradient, more to the south.

The following rise hemicycle within C-I-2 created new accommodation space for aggrading single-storey fluvial channels and interfluvial environments, which onlapped toward the north on the transfer zone. In the south, accommodation space was higher thus, thicker terrestrial deposits accumulated than in the vicinity of the transfer zone. Marginal marine environments, preceding the marine Rupelian Clay transgression, gradually replaced the fluvial and lacustrine systems. Due to low sediment input, shallow-water deltas, coastal bars or sandwaves developed only in the vicinity of the transfer zone (wells W138, W899 in **Fig. 3.34**). These were subsequently drowned and capped by offshore-marine deposits of the Rupelian Clay (rise-to-fall turnaround).

The southward increase of accommodation space to sediment supply ratio along the major axial depositional gradient (created by the transfer zone) induced an increase of cycle thickness and symmetry and the decrease of depositional energy downdip.

The drainage of the fluvial systems during the lower C-I-1-cycle was toward the south to southwest (Gaupp & Nickel, 2001; Derer *et al*., 2003). During the period of brackish/ marine conditions of the Middle Pechelbronn Beds (upper part of C-I-1-cycle and C-I-2 fall hemicycle), an axial north-south flux prevailed on the ramp of block C-D. The sediment was delivered through the low-relief zone at the western border fault. The footwall-derived sediment (i.e. supplied from the footwall B-C in the west) was confined to the neighbourhood of the fault plane (e.g. well W706, **Fig. 3.30**) and did not influence the axial sediment transport from the transfer zone. The transfer zone also influenced the coastline developed during fluctuations of the base-level.

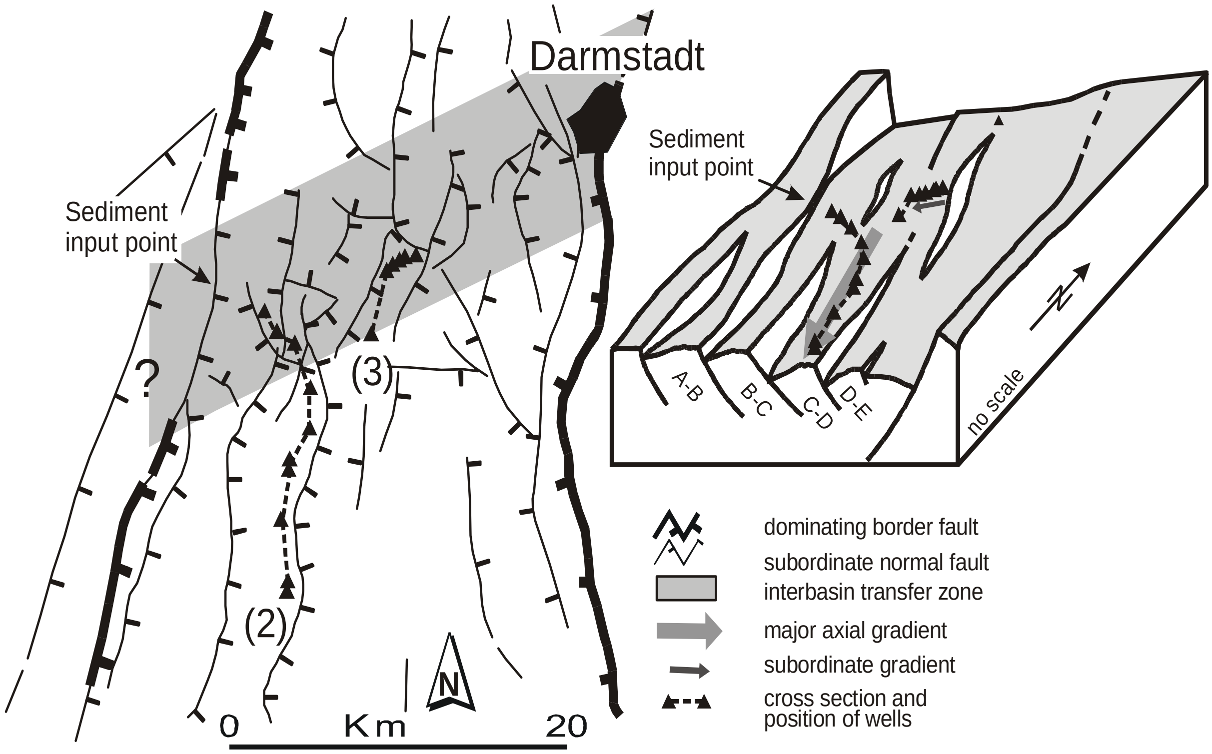


Fig. 3.33 Map and simplified block diagram showing the locations of cross sections (2) and (3). Cross section (2) is located on the ramp-block C-D, along the major axial depositional gradient dipping from the transfer zone into the southern sub-basin. Cross section (3) is located on a subordinate depositional gradient of a tilt-block/halfgraben within the transfer zone. Accommodation space increased in strike and dip direction of this block.

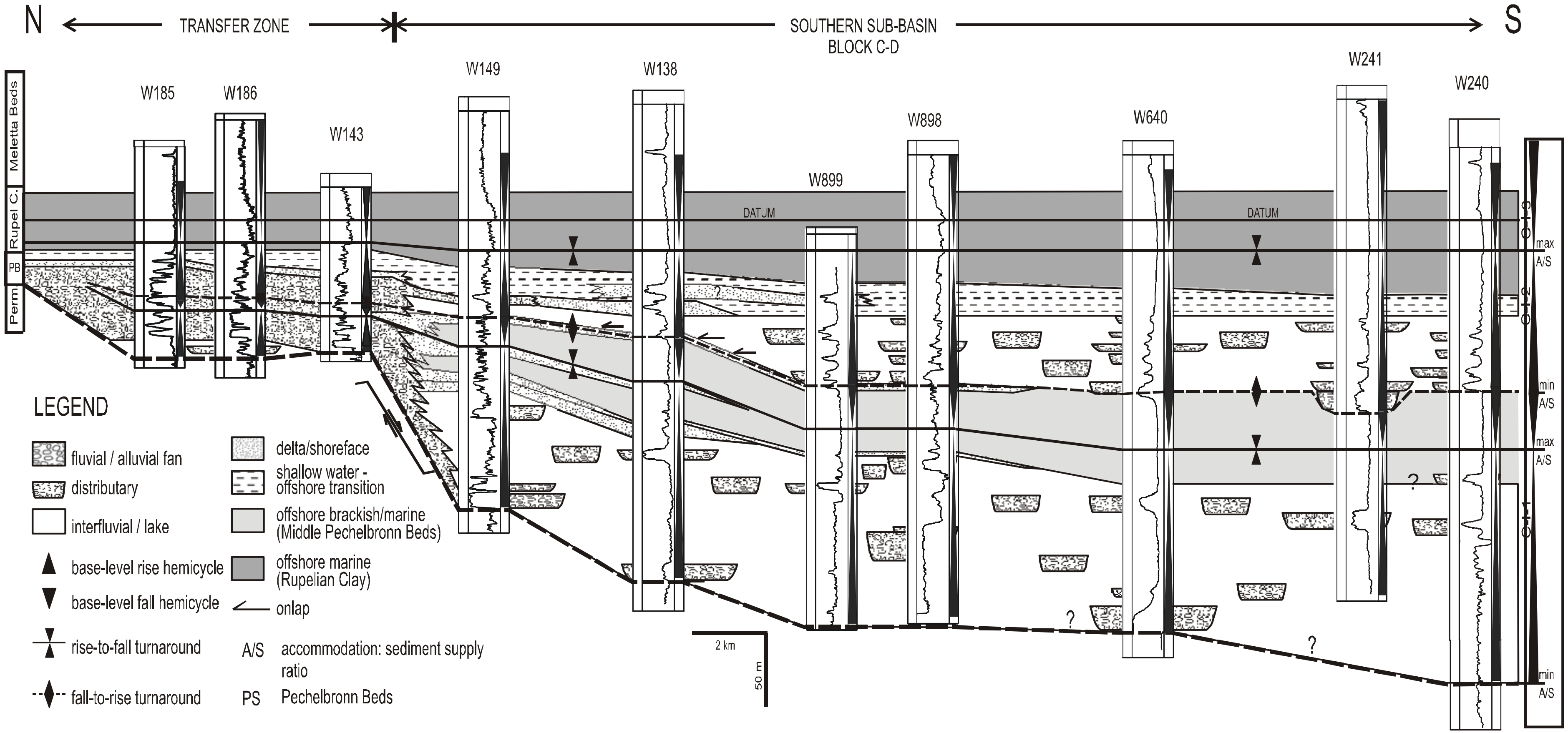


Fig. 3.34 Cross-section on the ramp setting of fault block C-D, from the transfer zone (in the vicinity of the sediment input point) into the southern sub-basin. The section shows the depositional environments and the correlation of the large-scale cycles (C-I-1, C-I-2) of the early syn-rift succession. Location in **Fig. 3.33**. The logs are gamma ray and self potential. Section datum is a GR and resistivity maximum in the offshore shales of the Rupelian Clay. Modified from Derer *et al*. (2003). Fig. 3.34 is presented as fold-out also in the appendix.

3.6.3 CORRELATION OF BASE-LEVEL CYCLES ALONG THE SUBORDINATE DEPOSITIONAL GRADIENT OF A TILT-BLOCK/HALFGRABEN

Section 3 is located on a block within the transfer zone (**Fig. 3.35**, location in **Fig. 3.33**). The fault block is tilted towards the W due to a graben-subparallel growth fault, and towards the south due to the existence of the transfer zone. Thus, accommodation space progressively increased from the block crest, in both dip and strike direction of this block. This fault block is located in a distal position relative to the sediment input point of the western border fault segment.

Cycle C-I-1

Due to a low A/S ratio, cycle C-I-1 starts with single-storey fluvial channels. The drainage was towards the south to south-west (Gaupp & Nickel, 2001; Derer *et al*., 2003). The accommodation space increased away from the block crest and controlled the lateral distribution of depositional systems. At the block crest, multi-storey channel facies associations occur, and the overbank/lacustrine units are subordinate (e.g. wells W778, W822). Laterally, down-gradient, the thickness of overbank/lacustrine units progressively increases, and also single-storey channels are preserved. Thus, the symmetry of the C-II cycles increases down-gradient, concomitant with the increase of the preservation potential of overbank/lacustrine deposits (e.g. wells W829 to W029).

Subsidence and the northward migration of brackish environments from the south increased the accommodation space to sediment supply ratio in time. Up in stratigraphic section, the fluvial and interfluvial systems passed, through to shallow water environments, to the offshore brackish settings of the Middle Pechelbronn Beds. Here, the rise-to-fall turnaround of the C-I cycle is located.

Cycle C-I-2

The thickness of the offshore brackish facies associations increases down-gradient, away from the block crest as a function of accommodation space. The C-I-2 fall hemicycle is characterised by fine-grained prograding delta/shoreface systems. The clastic material was probably delivered from northern or northwestern areas of the transfer zone (cf. Gaupp & Nickel, 2001). The studied fault block was distal relative to the sediment input point of the western border fault. Gaupp & Nickel (2001) suggests that reworked material from the western graben border might have reached this location. It is, however, certain that no important sediment source was active in the vicinity of this block.

Within the C-I-2 fall-hemicycle, the repeated shoreface progradations represent fall-asymmetric C-II cycles. The C-II-4 fall (**Fig. 3.35**) started with offshore shales, and gradually passed into fine-grained lower shoreface sands. These were drowned by a subordinate flooding. The following C-II-5 fall (**Fig. 3.35**) ended within upper shoreface sands, where also the large-scale turnaround was located. In most of the wells, these upper shoreface sands are sharp-based. This could imply that the C-II-5 base-level fall was mainly triggered by the decrease of accommodation space and not by the increase of the sediment supply. Thus, erosion occurred at the base of the shoreface.

The transfer zone was generally characterised by low accommodation space thus, only a thin pile of sediment could be deposited and preserved during the subsequent C-I-2 base-level rise. The rise was mainly triggered by the late Rupelian marine transgression (Ru2, Hardenbol *et al*., 1998, **Fig. 3.22**). During this base-level rise a delta/shoreface system developed, which was drowned (at its top a marine ravinement surface developed) and covered by the offshore marine shales of the Rupelian Clay.

Fig. 3.35 (next page) **a)** Cross section on a subordinate depositional gradient of a halfgraben within the transfer zone. The A/S ratio increases in dip (west) and strike (south) direction. The represented logs are self potential on the left, and resistivity on the right. Section datum is a GR and resistivity maximum in the offshore shales of the Rupelian Clay. The distance between W838 and W029 does not correspond to the scale. The location of the cross section in **Fig. 3.33**. **b)** Conceptual model showing changes in A/S ratio and in cycle symmetry as observed for cycle C-I-1. **c)** Projected locations of the wells on the palinspastically restored fault block (cut-out from profile T1 of **Fig. 3.6**). Well W029 is not plotted.

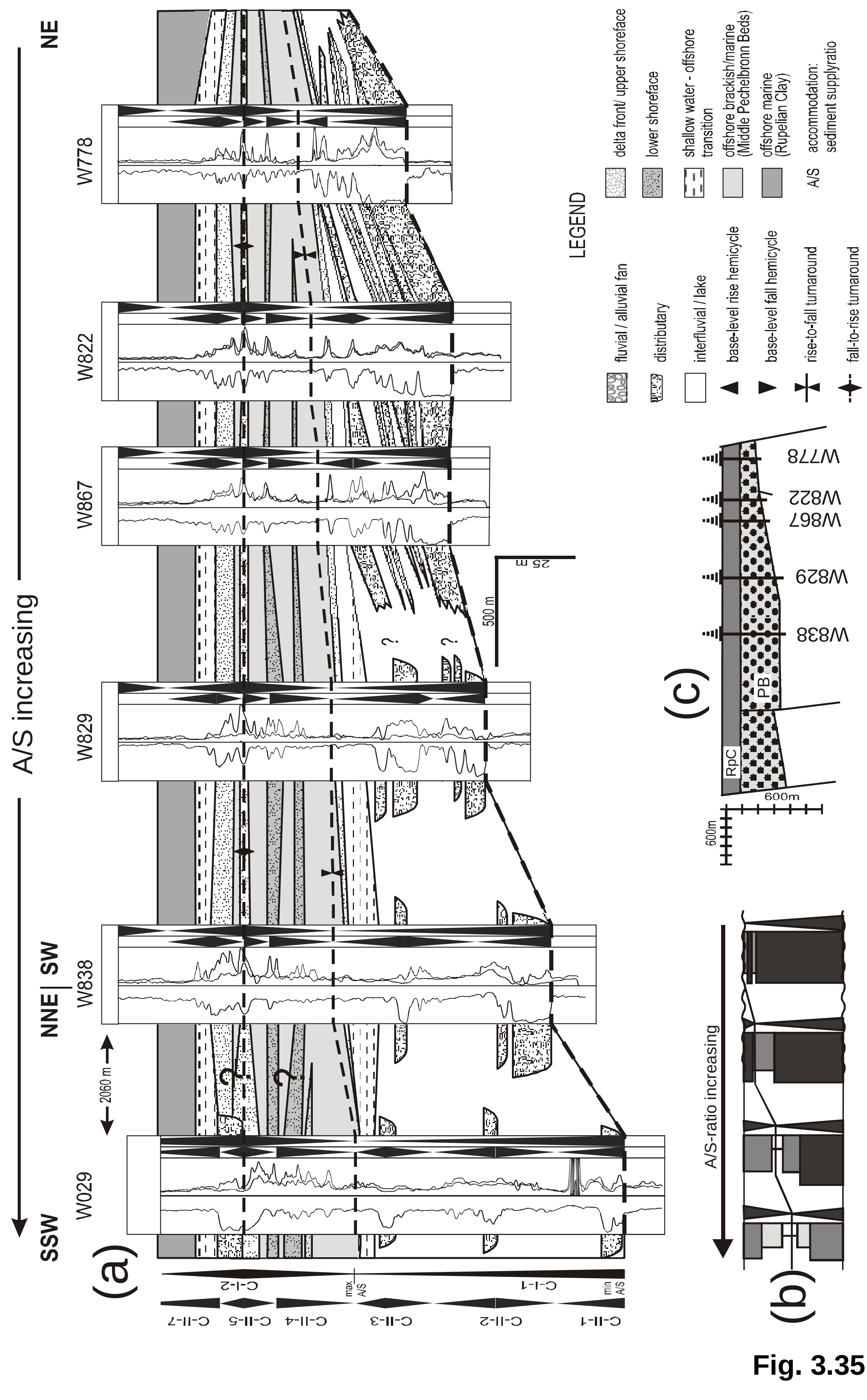

(a)
(b)
(c)
SSW
NE
NNE
SW
A/S increasing
A/S-ratio increasing
W029
W838
W829
W867
W822
W778
2060 m
500 m
25 m
600m
RpC
PB
C-II-1
C-II-2
C-II-3
C-II-4
C-II-5
C-II-7
C-I-1
C-I-2
max. A/S
min A/S
LEGEND
fluvial / alluvial fan
distributary
interfluvial / lake
base-level rise hemicycle
base-level fall hemicycle
rise-to-fall turnaround
fall-to-rise turnaround
delta front/ upper shoreface
lower shoreface
shallow water - offshore transition
offshore brackish/marine (Middle Pechelbronn Beds)
offshore marine (Rupelian Clay)
A/S accommodation: sediment supplyratio

Fig. 3.35

3.7 The early syn-rift stage: Summary and conclusions

Two large-scale base-level cycles (C-I-1 and C-I-2) are identified within the early syn-rift succession of the northern Upper Rhine Graben (cf. Derer *et al.*, 2003). These cycles were influenced by regional fluctuations of the relative sea-level, which have affected several European basins (Hardenbol *et al.*, 1998, **Fig. 3.22**) Yet, their evolution and the palaeogeographic distribution of their depositional systems was controlled by the syn-sedimentary tectonic structure of the graben.

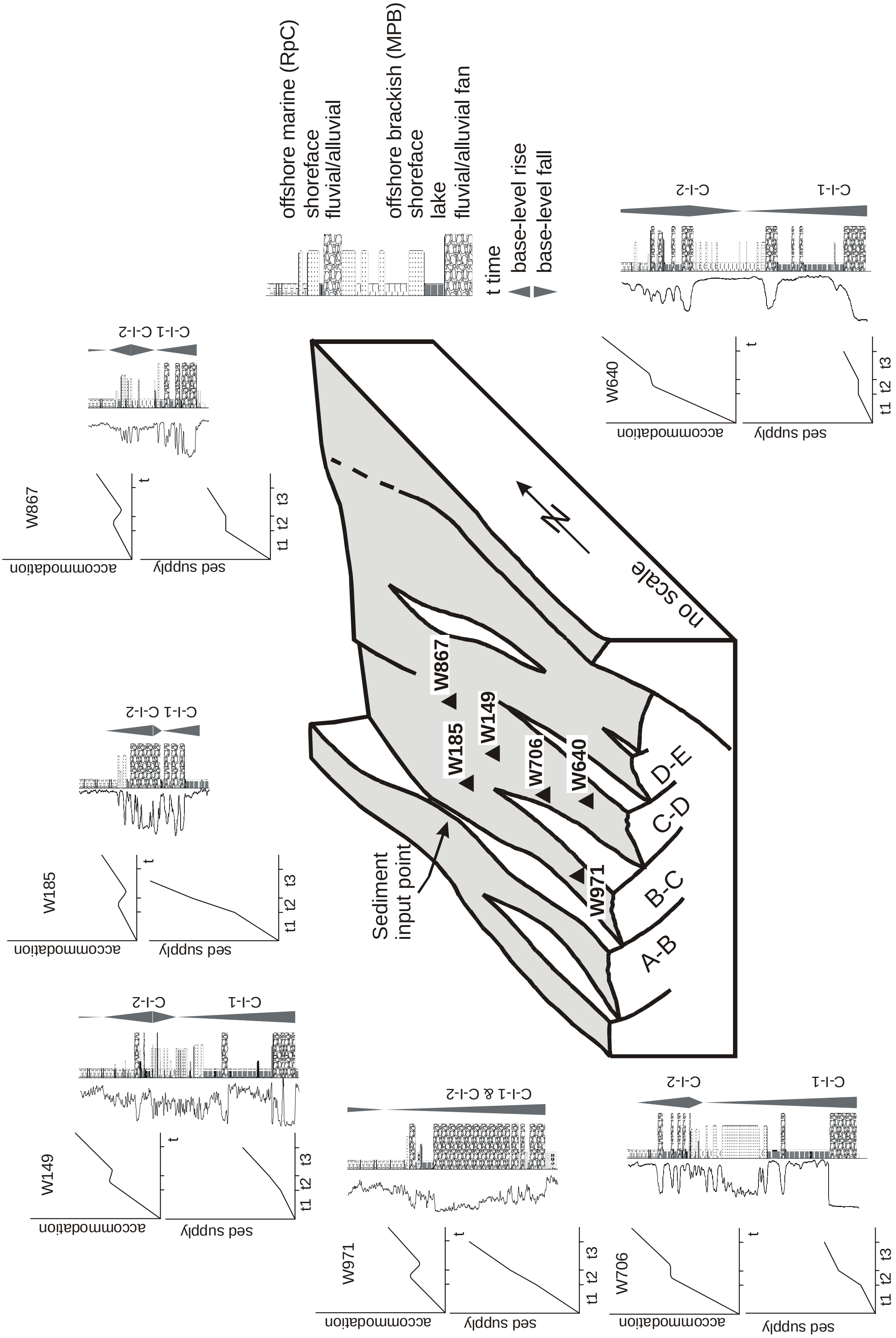
Figure 3.36 illustrates contemporaneous A/S conditions, and their related stratigraphic cycles, at different palaeogeographic and structural positions within the northern Upper Rhine Graben. The accommodation space and sediment supply curves have qualitative character for the time of deposition of the early syn-rift succession (latest Priabonian to early Rupelian). An antithetic interbasin transfer zone divided the study area into two asymmetric halfgrabens with opposing polarity. The transfer zone created two depozones (a northern and a southern sub-basin) and a major axial depositional gradient, dipping into the southern sub-basin. The accommodation space to sediment supply ratio within the transfer zone (W185, W867) was much lower than within the sub-basins (W149, W640, W706). The A/S ratio progressively increased towards the south, down the axial gradient (W185-W149-W640).

The fault segment, where the transfer zone intersects the western border fault, had a low displacement. It created a low-relief zone, which functioned, during the formation of the upper part of cycle C-I-1 and cycle C-I-2, as sediment input point. Consequently, in its vicinity (W185), sediment supply increased relative to lateral positions (W867).

The interbasin transfer zone and the southern sub-basin consist of a series of subordinate tilt-blocks/halfgrabens, bounded by growth faults striking subparallel to the graben margins. The tilted blocks created subordinate depocentres and depositional gradients, which were dipping from the block crest towards the fault plane, and across the fault scarp. The A/S ratio was low at the block crest (W971) and increased away from it. On the hangingwall, in the proximity of the fault plane accommodation space was created by fault activity and, at times, sediment was supplied from the block crest (W706).

Sedimentation of cycle C-I-1 started within isolated depocentres at the very beginning of the rifting. Due to continuous subsidence, which accelerated during the early Rupelian (**Fig. 3.22**), these minor depocentres coalesced. For the upper part of cycle C-I-1 and the C-I-2 fall hemicycle, the two sub-basins, showing high A/S ratios, functioned as depozones for

Fig. 3.36 (next page) Spatial variation of accommodation space and sediment supply in the northern Upper Rhine Graben. The pair of graphs for each location represents accommodation (top) and sediment supply (bottom) for the early syn-rift stage (t1-period of deposition of Lower Pechelbron Beds, t2- period of deposition of Middle Pechelbronn Beds, t3-period of deposition of Upper Pechelbronn Beds). Note the difference in cycle characteristics as a function of the location. All cycles and logs have the same vertical scale. RpC Rupelian Clay; MPS Middle Pechelbron Beds; C-I-1, C-I-2 large-scale base-level cycles.



offshore marine (RpC)
shoreface
fluvial/alluvial
offshore brackish (MPB)
shoreface
lake
fluvial/alluvial fan
t time
base-level rise
base-level fall
W867
W149
W185
W706
W640
W971
Sediment
input point
A-B
B-C
C-D
D-E
no scale
N
accommodation
sed supply
t
t1 t2 t3
C-I-1
C-I-2
C-I-1 & C-I-2

Fig. 3.36

the brackish/marine settings of the Middle Pechelbronn Beds. This transgression was probably linked to a regional rise of relative sea level in the early Rupelian (Ru1 **Fig. 3.22**).

The palaeogeographic settings during the upper C-I-1 and the C-I-2 cycle were controlled by the low accommodation space of the interbasin transfer zone and by the increased sediment supply through the low-displacement segment of the western border fault. These features created, during the upper C-I-1 cycle and C-I-2 fall hemicycle (during the deposition of the Middle Pechelbronn Beds), a palaeocoastline, which protruded from the western border into the graben (**Fig. 3.37, 3.38**). Delta/shoreface systems prograded from this coastline into the southern sub-basin. During this time, a communication between the northern and southern sub-basin was probably open through the central and eastern part of the transfer zone (cf. Gaupp & Nickel, 2001).

The interbasin transfer zone has acted as sediment barrier, placed between the northern and southern sub-basin, after the retreat of the brackish environments. Low A/S ratio within the transfer zone led to sediment bypassing during the subsequent C-I-2 rise hemicycle. At the same time, due to high A/S conditions, a thick sedimentary succession could accumulate within the southern sub-basin. The late Rupelian, marine transgression controlled the upper part of the C-I-2 rise hemicycle. This transgression was as well related to a regional rise of relative sea level (Ru2 and the maximum T4 transgressive halfcycle Hardenbol *et al.*, 1998; **Fig. 3.22**). During the late Rupelian also a second phase of increased subsidence affected the northern Upper Rhine Graben (**Fig. 3.22**). Thus, the northern Upper Rhine Graben acted as one depozone and deep marine conditions covered both sub-basins and the transfer zone, and led to the deposition of the offshore Rupelian Clay.

The subordinate fault blocks of the transfer zone and southern sub-basin led to variations of accommodation space and sediment supply, which influenced local sedimentation.

Fig. 3.37 (top of next page) Map view of the palaeogeographic settings during the upper C-I-1 cycle and C-I-2 fall hemicycle (time of deposition of the Middle Pechelbronn Beds) in the northern Upper Rhine Graben. Low accommodation space within the transfer zone and high sediment supply through the low-displacement fault segment built a coastline, which protruded from the western border into the basin. The northern and southern sub-basin had high A/S ratios. Here, offshore brackish settings developed. A communication between the two sub-basins was probably open in the central and eastern part of the transfer zone. A/S accommodation to sediment supply ratio.

Fig. 3.38 (bottom of next page) Palaeogeographic settings during the upper C-I-1 cycle and C-I-2 fall hemicycle (time of deposition of the MPS) in the northern Upper Rhine Graben (equivalent to **figure 3.37**). The low-displacement fault segment enabled drainage systems to enter the graben and to deliver sediment. The transfer zone partially separated the northern and southern sub-basins. Locations of four wells are shown.

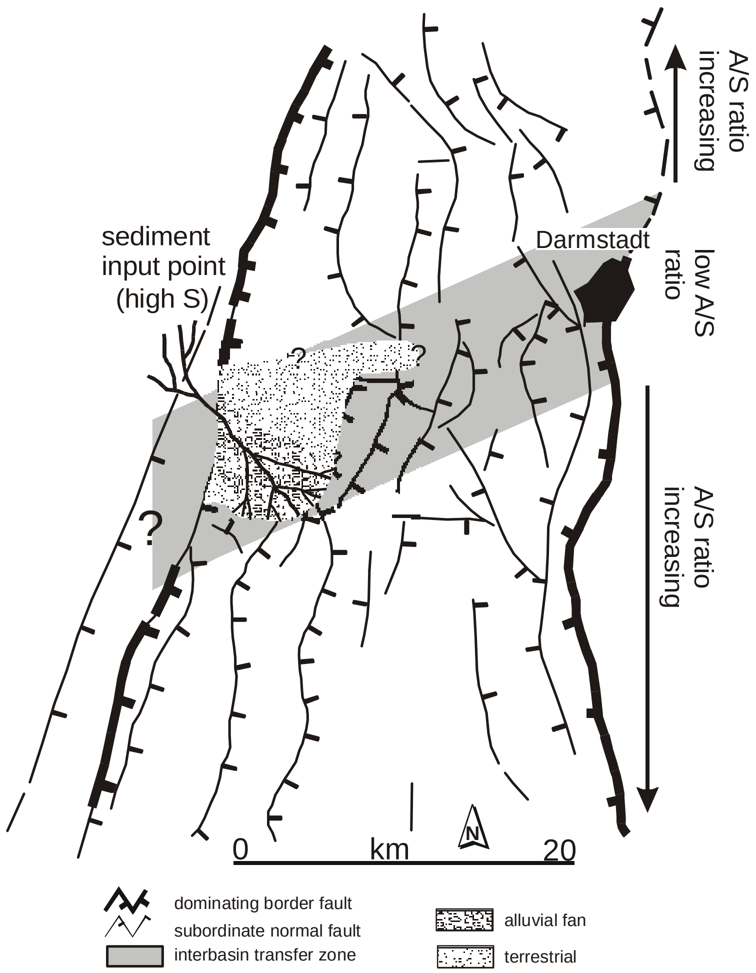


Fig. 3.37

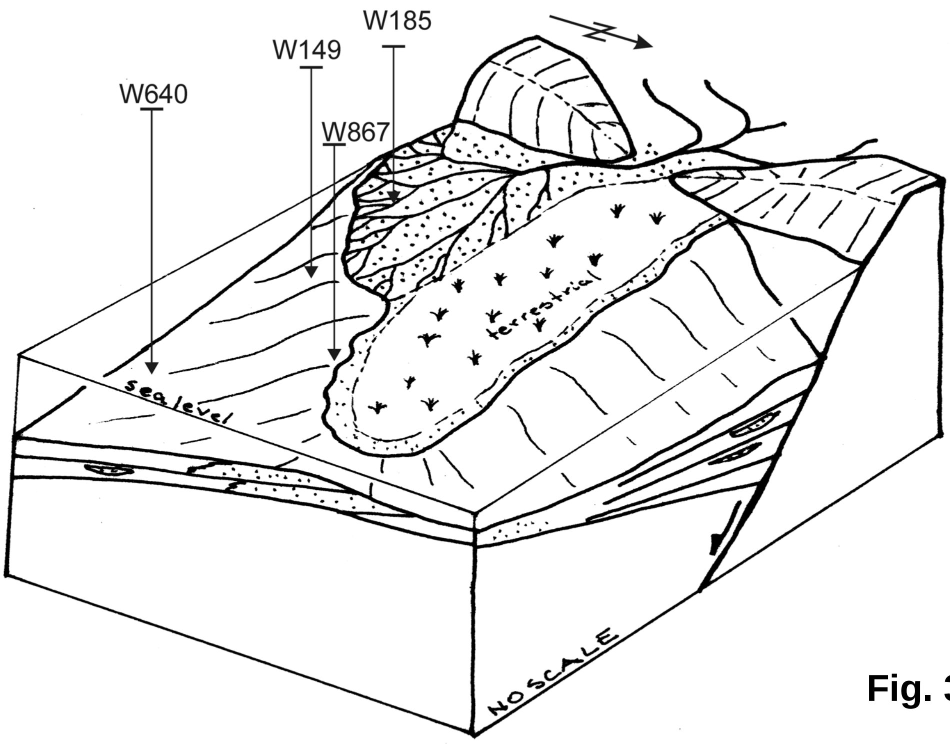


Fig. 3.38

4. SYNTHESIS: TECTONICS AND SEDIMENTATION

Several generations of previous workers analysed different facets of the Upper Rhine Graben (see **chapter 1.3**). The present study gives new insights in the evolution of the northern Upper Rhine Graben and confirms some of the existing interpretations. The new aspects especially consider the interaction between tectonics and sedimentation. Another new characteristic of this work is the use of sequence stratigraphy (base-level cyclicity, Cross & Lessenger, 1998), in order to interpret a part of the sedimentary graben fill of the northern Upper Rhine Graben. Meanwhile, the mechanisms of rifting and the sedimentary models for extensional basins are mostly understood from ancient and recent rifts (see below). Thus, the reinterpretation of the tectono-sedimentary evolution of the northern Upper Rhine Graben, with new approaches and concepts, is possible and reasonable.

The present study focuses on the northern Upper Rhine Graben. Consequently, the scale of the study area enables both a detailed interpretation of stratigraphic cycles on local structures, and cycle correlations of basin-wide extent. The latter also allows correlations with tectono-eustatic events from outside the basin. Previous attempts to classify the sedimentary graben fill in stratigraphic/genetic sequences were either at a very large scale (e.g. Durst, 1991; Sissingh, 1998), or at a small scale (e.g. Gaupp & Nickel, 2001; Jantschik *et al.*, 1996).

Overall Cenozoic evolution

The late Eocene to early Oligocene extensional stage of the northern Upper Rhine Graben was followed by late Oligocene to early Miocene and Pliocene to Quaternary strike-slip-controlled subsidence (Illies, 1978; Meier & Eisbacher, 1991; Schumacher, 2002).

This study (and Derer *et al.*, 2003) identified an antithetic interbasin transfer zone in the northern Upper Rhine Graben. It separates two asymmetric halfgrabens with opposite polarity of tilting. This transfer zone considerably influenced the basin geometry and sedimentation through Cenozoic times. Its location was probably influenced by pre-rift structures. Similar transfer zones were identified and understood in both recent and ancient rifts around the globe. The Tertiary to Quaternary East African rift system is composed by a series of halfgrabens with variable tilt directions, which are linked by transfer zones. The transfer zones form barriers for the recent depositional systems and control the drainage directions (Morley *et al.*, 1990; Gawthorpe & Hurst, 1993). The Suez rift is separated into three dip provinces by two transfer zones (Gawthorpe & Hurst, 1993; Moustafa, 1997). Pre-rift structures influenced the formation of the transfer zones during the late Oligocene rifting (Moustafa, 1997).

The performed subsidence analysis for the northern Upper Rhine Graben confirms for the study area the late Eocene to early Oligocene and latest Oligocene to early Miocene subsidence phases, known for the northern Upper Rhine Graben (e.g. Illies, 1978; Ziegler, 1992; Schumacher, 2002). The Pliocene to Quaternary subsidence episode cannot be interpreted, due to scarce dating.

The late Eocene to early Miocene sediment succession was classified into base-level cycles. These were compared with the subsidence curves and seismic profiles, and with coeval sequences of other European basins (Hardenbol *et al.*, 1998). The Cenozoic base-level cycles of the northern Upper Rhine Graben were generated by the interaction between the tectonic activity of the graben and major tectono-eustatic events, which affected several European Basins. A similar conclusion was also deduced by Sissingh (1998) for the correlative sequences. However, the base-level cycles identified in the present study have other boundaries and symmetries as have the correlative sequences of Sissingh (1998) or the marine cycles of Durst (1991).

Early syn-rift evolution

The detailed analysis of the early syn-rift stage of the northern Upper Rhine Graben revealed that, like in other extensional basins, sediment deposition was mainly controlled by syn-sedimentary tectonics. As a consequence, a structural analysis must precede any sedimentological and sequence-stratigraphical interpretation.

The early syn-rift subsidence phase was triggered by a WNW-ESE extension (e.g. Meier & Eisbacher, 1991; Schumacher, 2002). The interpretation of seismic sections and wells, and the palinspastically restoration of cross sections led to the reconstruction of the early syn-rift structural geometry of the northern Upper Rhine Graben. The major structural elements were tilt-blocks/halfgrabens of different proportions (the basic structural unit of the graben), the interbasin transfer zone, and a low-displacement segment of the western border fault (functioning as sediment entry point).

Similar structures were identified and described already in other rift systems. Halfgrabens, transfer zones and low-displacement segments, and their influence on sedimentation were interpreted for the Permian to early Triassic and middle Jurassic to early Cretaceous rift stages of the North Sea rift (e.g. Gibbs, 1984; Badley *et al*., 1984; Steel and Ryseth, 1990; Morley *et al*., 1990, Howell & Flint, 1996; Davies *et al*., 2000), for the Cenozoic to recent configuration of the East African rift (Morley *et al*., 1990; Gawthorpe & Hurst, 1993; Lambiase & Bosworth, 1995) and for the Pliocene-Quaternary basins in the Gulf of Corinth (e.g. Gawthorpe *et al*., 1994). An overall conclusion of all these studies is that tectonics controls the sediment supply and the creation of accommodation space. Often, tectonic subsidence played a more important role for the deposition than glacio-eustatic sea-level variations.

The early syn-rift fill of the northern Upper Rhine Graben was classified in base-level cycles. These base-level cycles were probably influenced by regional variations of the relative sea-level (which affected several European basins, Hardenbol *et al*., 1998). However, the distribution of the depositional systems and the palaeogeographic settings of the northern Upper Rhine Graben were controlled by the local syn-sedimentary tectonic structures.

The present study interpreted the key structural elements of the early syn-rift stage of the northern Upper Rhine Graben. These features were included in a basin-wide tectonic model, in accordance to the extensional settings of the area. In addition, the interactions between the tectonic framework and the sedimentation were established. For interpretation and correlation of strata, a combination of the sedimentary models for extensional basins (Gawthorpe *et al*., 1994; Howell & Flint, 1996) and the base-level sequence stratigraphy (Cross & Lessenger, 1998) was used. This method has proved to be a reliable tool for the structurally controlled settings of the northern Upper Rhine Graben. The method does not necessarily need stratigraphic bounding surfaces for correlations. Instead, boundary zones can be used. This is especially an advantage for the interpretation of well logs, where bounding surfaces often are difficult to interpret.

The understanding of the tectono-sedimentary interactions in the basin creates the premise to predict structures, the palaeogeography and the lateral distribution of depositional systems. These can be important to hydrocarbon exploration in terms of traps and reservoir bodies (e.g. Morley *et al*. (1990) exemplifies the importance of transfer zones in the distribution of oil fields).

Even though late Oligocene to early Miocene, and Pliocene to Quaternary strike-slip tectonics deformed the northern Upper Rhine Graben (e.g. Illies, 1978; Meier & Eisbacher, 1991; Schumacher, 2002), it represented a characteristic rift basin during the early syn-rift stage (late Eocene to early Oligocene).

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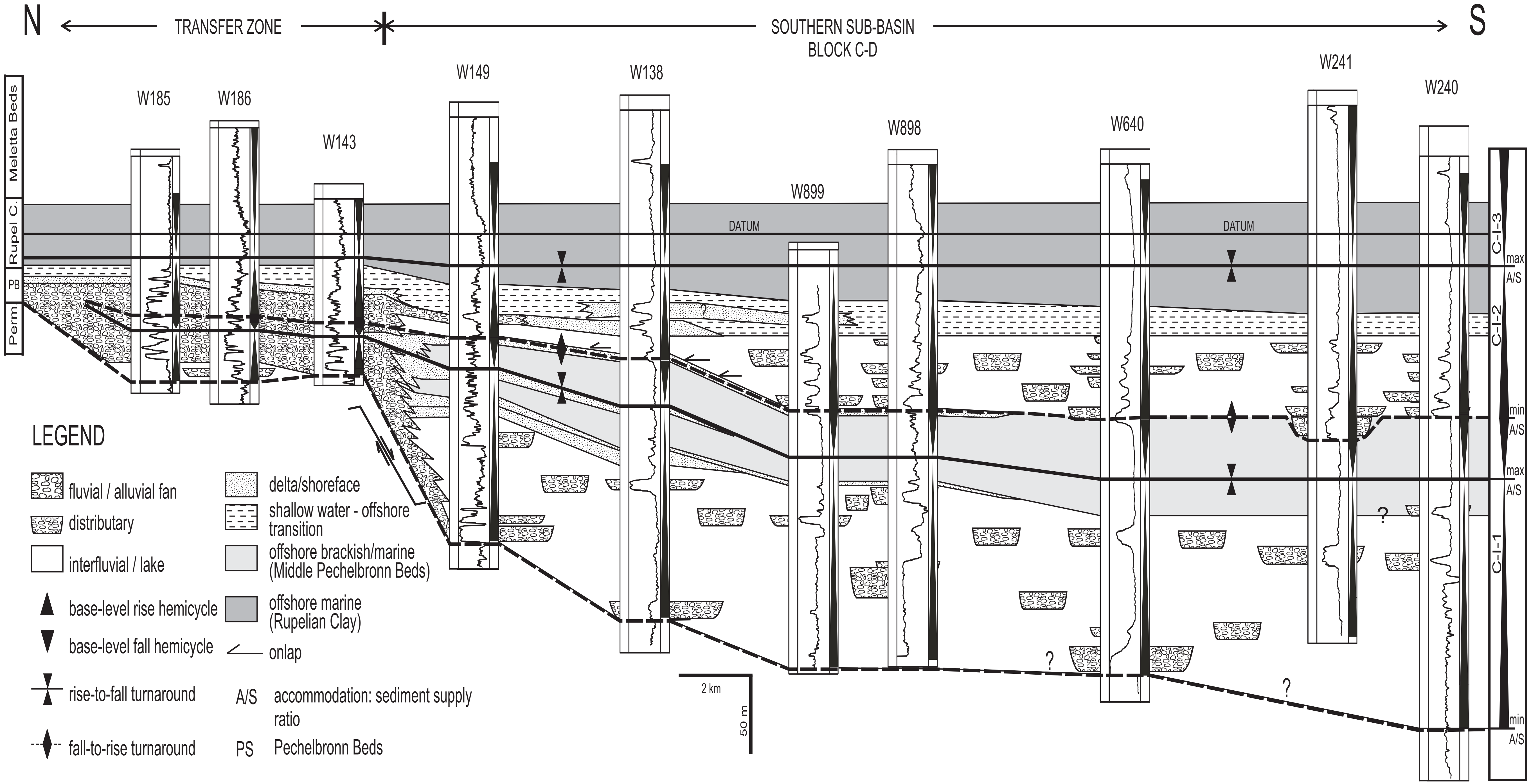

Fig. 3.34

APPENDIX

Figure caption on page 82