

Architecture of Lower Oligocene source rocks in the Alpine Foreland Basin: a model for syn- and post-depositional source-rock features in the Paratethyan realm

R. F. Sachsenhofer¹ and H.-M. Schulz²

¹*Department of Applied Geosciences and Geophysics, Montanuniversität Leoben, Peter-Tunner-Str. 5, A-8700 Leoben, Austria (e-mail: Reinhard.Sachsenhofer@mu-leoben.at)*

²*Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hannover, Germany (e-mail: hm.schulz@bgr.de)*

ABSTRACT: Oligocene rocks are one of the most important sources of hydrocarbons within the Paratethyan realm. In the Alpine Foreland Basin (Central Paratethys) the main Oligocene source rock is the Schöneck Formation, but organic-rich rocks occur in the entire Lower Oligocene succession. Based on well-log calibration by core data, the spatial distribution and thickness variations of different Lower Oligocene source-rock facies are investigated. The deeper-water sediments are characterized by lateral continuity, but exhibit vertical variability. The latter reflects major palaeoceanographic changes in the Central Paratethys, such as the closure of seaways, basin-wide changes in salinity and in redox conditions. The upper shaly part of the Schöneck Formation has the highest source potential (>5% TOC, initial HI: 500–600 mgHC g⁻¹TOC) and reaches its maximum thickness (c. 5 m) in a narrow belt parallel to the palaeo-shoreline.

The present-day distribution of Lower Oligocene rocks is controlled by submarine erosion which affected the northern passive slope of the foreland basin. Erosion climaxed during the late Early Oligocene. The eroded material was re-deposited along the lower basin slope (Oberhofen facies). The source-rock potential of the re-deposited sediments is relatively low. The oil kitchen (4–7 km burial depth) is located beneath the Alpine nappes where the Lower Oligocene succession was removed locally by the advancing nappes. Both submarine erosion at the northern basin slope and tectonic erosion beneath the Alps have to be considered in the evaluation of the prospectivity of the basin.

Because deposition of the Lower Oligocene succession in the Alpine Foreland Basin is controlled by basin-wide processes, it may serve as a model for source-rock deposition in foreland basins of the Paratethyan realm (e.g. Carpathians, Terek–Caspian Foredeep).

KEYWORDS: *source rock, log facies, Paratethys, Oligocene, Molasse Basin*

INTRODUCTION

Oligocene organic-rich rocks were deposited during the initial separation of the Paratethys, a marginal sea which formed after the Eocene break-up of the Tethys (e.g. Popov *et al.* 2004). Proven and potential Oligocene source rocks in Central and Eastern Europe include, from west to east, the Schöneck Formation, the Menilite Formation (Carpathians), the Tard Clay (Pannonian Basin), the Ruslar Formation (western Black Sea) and the lower part the Maykop Suite (Black Sea, Caspian Sea; Fig. 1). These units have generated hydrocarbons in basins extending from the Alpine–Carpathian Foredeep in the west to the Terek–Caspian Foredeep in the east (e.g. Ziegler & Roure 1999, Ulmishek 2001). Although economically very significant, detailed data on depositional environments, lateral facies variations and resulting source-rock potential of these Oligocene sediments are largely missing.

In the present contribution, the architecture of source rocks in the eastern (Austrian) part of the Alpine Foreland Basin (Fig. 2a) is analysed for the impact of different geological processes. This regional study covers an area of approximately 7500 km², emphasizes vertical and lateral facies and thickness variations, and includes the northern marginal zone of the source rocks as well as their deeper, central parts. Within the boundaries of the study area, core-based investigations by Schulz *et al.* (2002, 2004) provided a detailed description on the vertical variability of lithology, palaeo-environment and source-rock potential of the Lower Oligocene Schöneck Formation and Dynow Marlstone. The present paper is based on this information, additional core studies, logs from more than 300 wells (Fig. 2b) and seismic data.

Based on the results of Schulz *et al.* (2002, 2004), well logs were calibrated with core data and used to study the regional

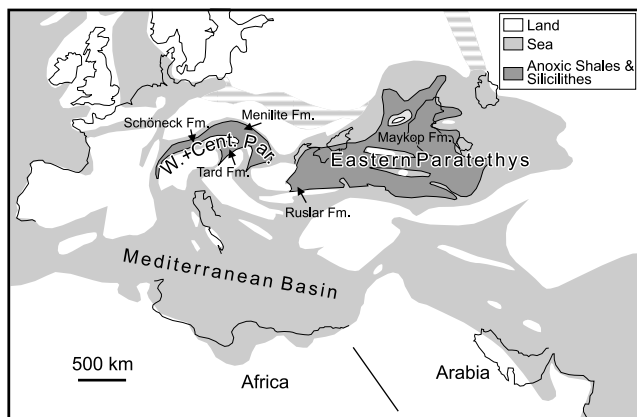


Fig. 1. Palaeogeography of the Paratethyan realm during early Oligocene (Pshiekian) time. The distribution of oxygen-depleted environments is shown after Popov *et al.* (2004). W.+Cent. Par., Western and Central Paratethys (=Alpine Carpathian Basin of Popov *et al.* 2004).

distribution and thickness variations of different source-rock facies. The Schöneck Formation is missing in nearly 20% of the wells (Fig. 2b). It has been speculated that this is due to erosion above basement highs (e.g. Kollmann 1966) or due to non-deposition (e.g. Gerhard 1988). Obviously, lack of source rocks in significant parts of a basin decreases its prospectivity. Therefore, the mechanisms that caused the absence of Lower Oligocene deposits are also studied. Finally, implications of the results for the hydrocarbon potential of the Alpine Foreland Basin are discussed.

GEOLOGICAL SETTING

The Alpine Foreland (Molasse) Basin extends along the northern margin of the Alps from Geneva to Vienna (Roeder & Bachmann 1996; Sissingh 1997; Wagner 1998; Fig. 2a). The southern part of the basin is overthrust by the Alpine nappes (Fig. 3). Within the Alpine foreland, the sedimentary history is characterized by three main stages separated by unconformities: Permo-Carboniferous graben sedimentation; Mesozoic mixed carbonate-siliciclastic shelf sedimentation; and Cenozoic molasse sedimentation (Wagner 1998).

The Molasse stage began in Late Eocene time with deposition of fluvial and shallow-marine sandstones, shales and carbonates (Fig. 4). Around the Eocene/Oligocene boundary, thrust loading by the advancing Alpine nappes caused flexural down-bending of the foreland (Fig. 5). This and a coeval sea-level rise resulted in drowning of the carbonate platform and a rapid deepening of the Molasse Basin (e.g. Zweigel 1998).

During Oligocene times, the tectonically active southern margin of the Molasse Basin was steep, whereas the northern basin slope was gently dipping (Fig. 5). Gravity flow deposits, up to 2 km thick (Deutenhausen, Rogatsboden, Puchkirchen formations; Fig. 4), accumulated near the active margin, whereas fine-grained pelagic and hemipelagic rocks were deposited on the northern basin slope. The pelitic rocks include from the base to the top (Fig. 4 Wagner 1998):

- the Schöneck Formation (formerly “Lattorf Fischechiefer”; nannoplankton zone NP19–20 to the lower part of NP23), a typically 10–20 m thick succession consisting of organic-rich marls and shales. Water depth during deposition of the Schöneck Formation increased from 400 m to 600 m (Dohmann 1991);

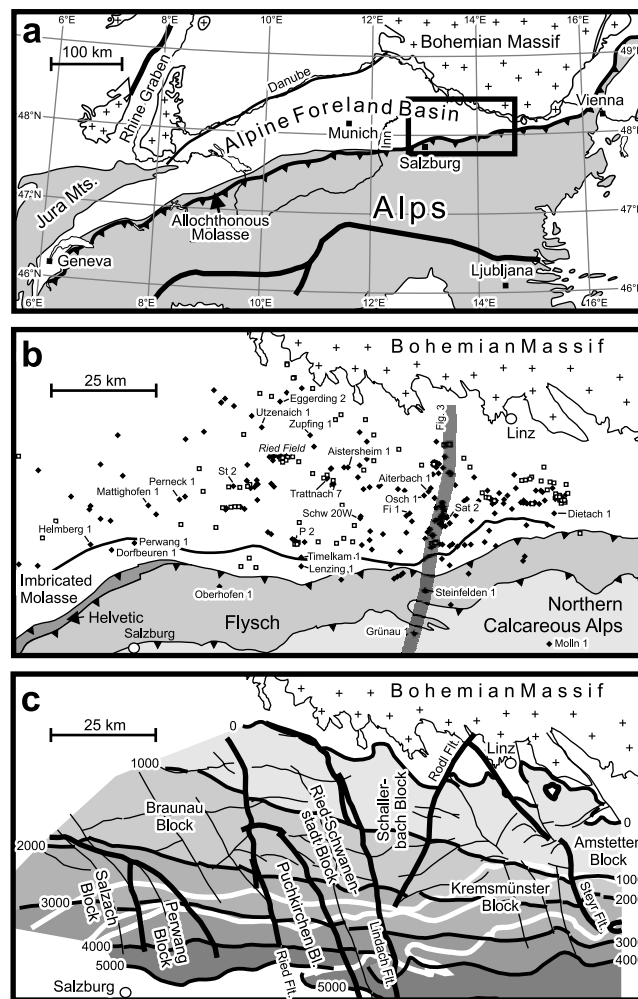


Fig. 2. (a) Geological situation of the study area. (b) Location map of wells used in the study. Some key wells are labelled. Full symbols indicate wells with Schöneck Formation; open symbols indicate wells without Schöneck Formation. Fi 1, Fischlham 1; Osch 1, Oberschauersberg 1; P 2, Puchkirchen 2; Sat 2, Sattledt 2; Schw 20W, Schwanenstadt 20W; St 2, Steindlberg 2. (c) Fault pattern and depth to base of Molasse sediments (after Wagner 1998; Kröll *et al.* 2005). White lines represent the position of the thrust front of the Imbricated Molasse, the Helvetic and Flysch zones and the Northern Calcareous Alps (see Fig. 2b).

- the Dynow Marlstone (formerly “Heller Mergelkalk”; NP23), about 5–15 m thick. It is composed of light-coloured marlstones partly dominated by coccolithophorides;
- the Eggerding Formation (formerly “Banded Marl”; NP23–24) composed of dark-grey laminated pelites with thin white layers of nannoplankton. The thickness of the Eggerding Formation is typically in the range of 35 m to 50 m;
- the Zupfing Formation (formerly “Rupelian Marl”), up to 450 m thick, consisting mainly of dark grey hemipelagites and distal turbidites from the south. They intercalate with slumps, slides and turbidites derived from the northern slope. Limestone layers with nannofossils occur in the lower part of the section.

According to sequence stratigraphic analysis (Jin *et al.* 1995; Zweigel 1998), shallow-marine Eocene sediments and deeper-marine Lower Oligocene deposits (Schöneck Formation, Dynow Marlstone, Eggerding Formation) form a transgressive systems tract. The Zupfing Formation represents very distal, basinal highstand deposits (Zweigel 1998). A major sea-level fall

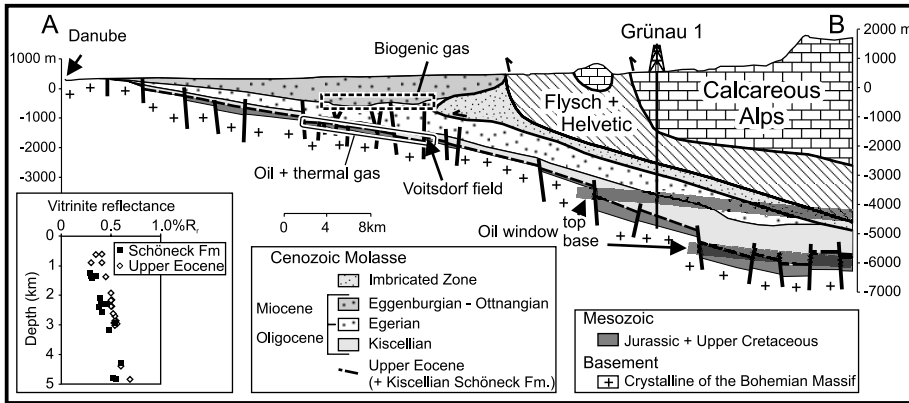


Fig. 3. Geological cross-section through the eastern part of the Alpine Foreland Basin, showing the position of reservoirs with thermogenic and bacterial hydrocarbons (modified after Wagner 1996). The depth of the oil window is indicated (after Schmidt & Erdogan 1996). Vitrinite reflectance data of Upper Eocene rocks and the Lower Oligocene Schöneck Formation are plotted versus drilling depth in the inset (Gier 2000; Colins *et al.* 1992; unpublished data). Note that all data are from the study area and that vitrinite reflectance of coaly Eocene rocks is slightly higher than that of the Schöneck Formation.

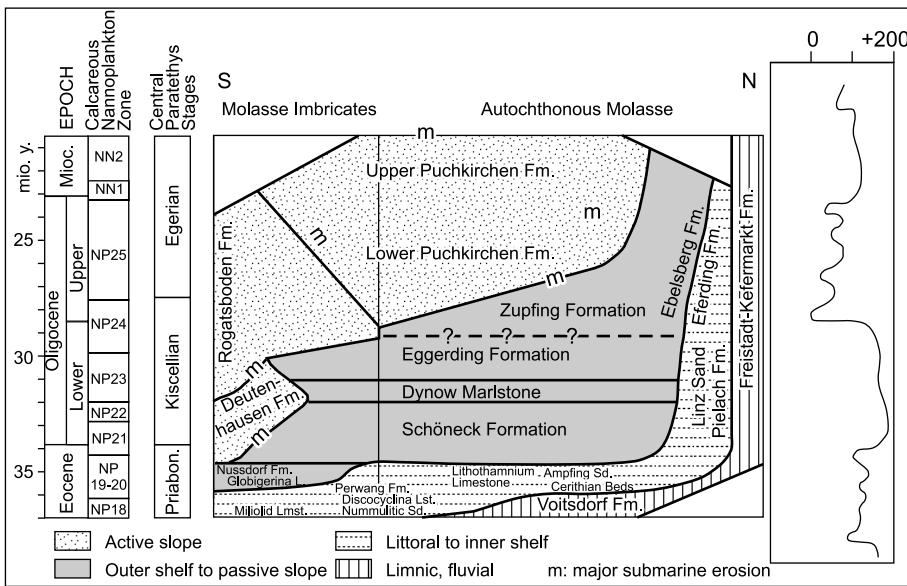


Fig. 4. Stratigraphic chart of Palaeogene sediments in the eastern part of the Molasse Basin (after Wagner 1998). The eustatic sea-level curve of Haq *et al.* (1987) is given for comparison.

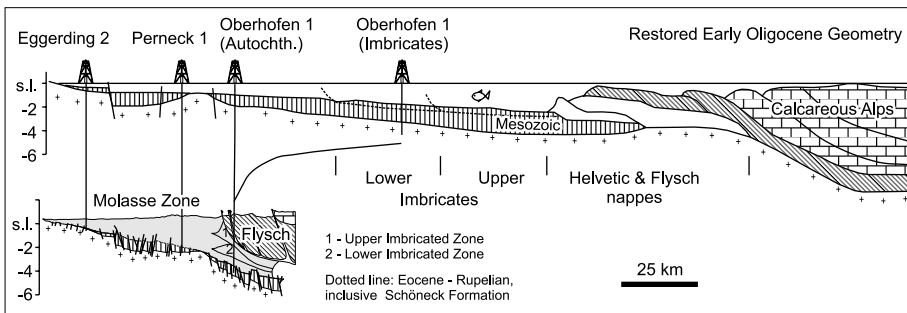


Fig. 5. Reconstruction of the early Oligocene geometry of the Molasse Basin (after Wagner 1996). The position of some key wells is shown. Inset shows the present-day situation.

(200 m) occurred at the boundary between Lower and Upper Oligocene (e.g. Haq *et al.* 1987). Its consequence for the development of the Molasse Basin is not fully understood (Zweigel 1998).

Whereas deep-marine conditions with water depths exceeding 1000 m persisted during Late Oligocene to Early Miocene times east of the river Inn, a prograding-retrograding deltaic complex filled the western part of the basin.

The Cenozoic sediments are divided structurally into the Autochthonous Molasse and the Allochthonous Molasse. The Autochthonous Molasse rests relatively undisturbed on the European basement. The Allochthonous Molasse, including the Imbricated Molasse, is composed of Molasse sediments,

which are included in the Alpine thrusts and which were moved tectonically into and above the southern Autochthonous Molasse.

Several fault systems occur in the Austrian part of the foreland basin (Fig. 2c). NW-SE- and NE-SW-trending faults existed already during Palaeozoic times and were reactivated in Mesozoic and Palaeogene times. Roughly W-E-trending extensional faults result from the down-bending of the foreland crust due to the subduction of the European Plate under the Periadriatic Plate and the weight of the advancing Alpine nappe system (Wagner 1998). Almost all Early Oligocene faults were reactivated during Miocene times.

Two petroleum systems occur in the Alpine Foreland Basin east of Munich: a Mesozoic to Lower Oligocene thermally

generated oil and gas system and an Oligo-Miocene biogenic gas system (Wagner 1996; Véron 2005; Fig. 3).

Most important reservoirs for oil and minor thermal gas are upper Eocene basal sandstones, typically on the upthrown side of W–E-trending antithetic normal faults. Some hydrocarbons are trapped in Eocene carbonates. Additional reservoirs occur in Mesozoic and Oligocene horizons. Correlations of the isotope and biomarker ratios of the oils with the rock extracts suggest that the thermogenic hydrocarbons are mainly sourced by the Lower Oligocene Schöneck Formation (e.g. Wehner & Kuckelkorn 1995; Sachsenhofer *et al.* 2006), but the Dynow Marlstone and the Eggerding Formation also have an oil potential. Vitrinite reflectance gradients in the Austrian part of the Alpine Foreland Basin are low (Fig. 3) and the source rock is immature in the vicinity of the oil fields. The kitchens are *c.* 4–7 km deep and lie only beneath the Alpine nappes, indicating long-distance migration (Schmidt & Erdogan 1996; Fig. 3). Generation started during thrusting in Miocene times.

Reservoirs for dry and isotopically light gas, considered biogenic in origin, are Oligocene (Egerian) and Miocene (Eggenburgian) sandstones and sandy conglomerates deposited within and in close vicinity of the “Puchkirchen” deep-sea channel belt (de Ruig 2003). Significant accumulations of gas are stratigraphically and structurally trapped in channel thalweg and slope-fan sandstones, with more modest amounts in overbank lobe and tributary-channel deposits (de Ruig & Hubbard 2006). Probably the biogenic gas was generated in Oligocene and Miocene shales.

DATABASE AND METHODOLOGY

The study area is situated in the eastern part of the Molasse Basin. It is bounded to the north by the pinchout of Lower Oligocene rocks at shallow depth (Fig. 2a) and to the south by the position of the southernmost wells (Molln 1, Grünau 1; for position of wells see Fig. 2b), which have drilled autochthonous Lower Oligocene sediments beneath the Alpine nappes. The base of the Oligocene in these wells is located at about 5 km depth (>4 km below sea-level). Information from even more southerly positions is provided by Lower Oligocene rocks incorporated into Allochthonous Molasse imbricates (e.g. Oberhofen 1, Fig. 5). The original position of these rocks was 30–60 km south of their present-day position.

The study is based on results from 320 wells including wireline logs from more than 200 of them. Conventional cores from the Schöneck Formation and the Dynow Marlstone were available for many wells, allowing a direct correlation between log facies, sedimentary facies and source-rock parameters (e.g. Fig. 6). In contrast, the Eggerding Formation is represented by only a few core fragments.

Each of the lithological units, described in the introduction chapter, is characterized by distinct vertical carbonate trends. In the case of the Molasse Basin, the sonic log, available for most wells, yields the best fit with carbonate content (see also Schulz *et al.* 2004) and, therefore, is used most often for correlation.

Wireline logs, together with core data, were used to determine thickness variations of different lithological units. Maps of the present-day thickness and the original thickness were constructed using the Kriging approach. W–E- and S–N-trending seismic sections were used to map erosional features.

RESULTS

Lithology and log facies

Sedimentology and organic geochemistry of the Schöneck Formation and the Dynow Marlstone have been described by

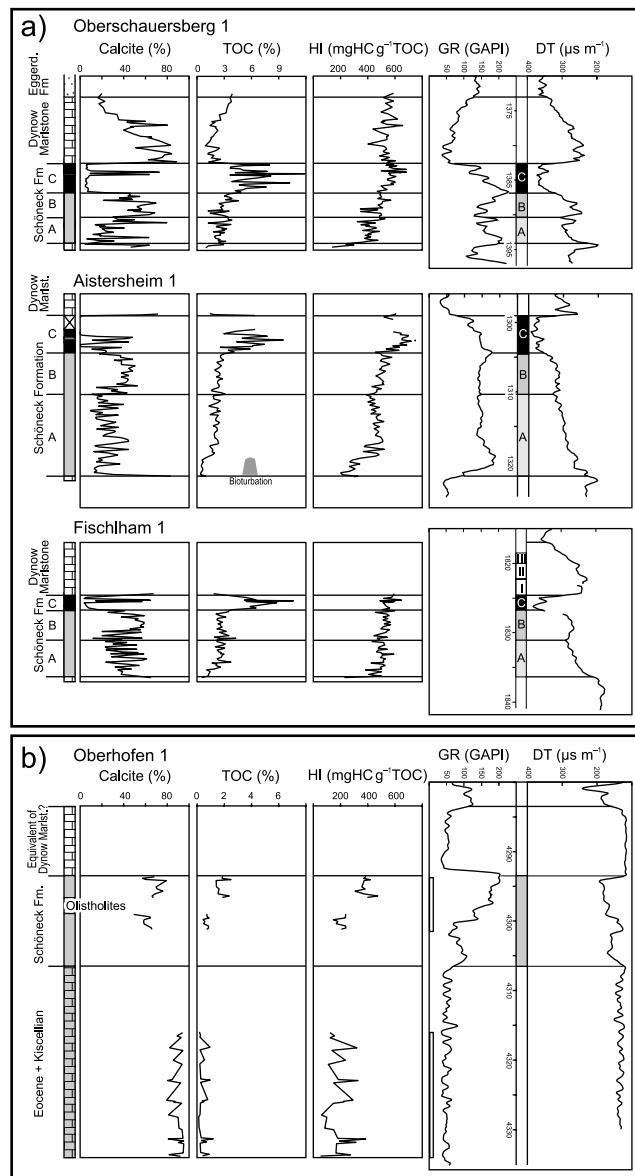


Fig. 6. Source-rock data from wells from the upper slope ((a) Oberschauersberg 1, Aistersheim 1, Fischlham 1) and from the lower slope ((b) Oberhofen 1) together with gamma ray (GR) and sonic logs (DT). Source-rock data from the Oberschauersberg 1 and Oberhofen 1 wells are from Schulz *et al.* (2002).

Schulz *et al.* (2002, 2004, 2005). Information on the Eggerding Formation is taken from Wagner (1998). Basic geochemical proxies for wells Oberschauersberg 1, Aistersheim 1, Fischlham 1 and Oberhofen 1 are shown together with log motifs in Figure 6. Sonic and gamma-ray log motifs of the organic-rich Lower Oligocene sequence using the examples of wells Eggerding 2, Perneck 1, and Oberhofen 1 are shown in Figure 7. These wells represent a transect from shallow water in proximal position to deep water in the distal basin (see also Fig. 5).

Although lateral facies variations exist, the Lower Oligocene succession is similar in most settings. Only the autochthonous part of the Oberhofen 1 well (lower slope) displays a significantly different facies. Therefore, this facies is discussed separately at the end of the present section.

Schöneck Formation The Schöneck Formation was deposited on the northern palaeoslope of the Molasse Basin. An expected narrow belt with shoreline sands along the northern coast is not

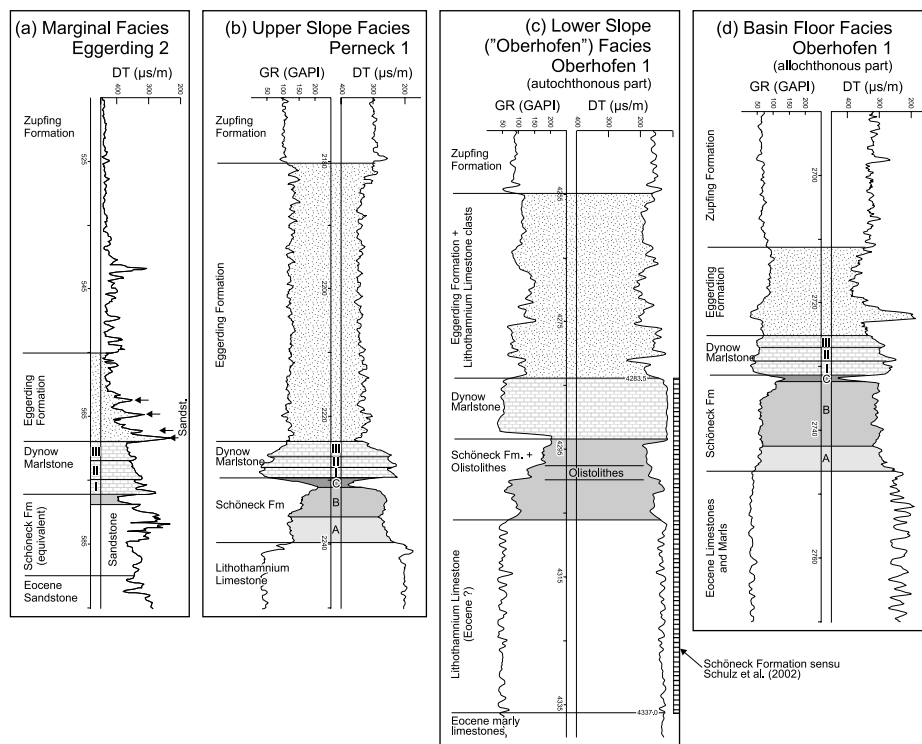


Fig. 7. Typical logs for wells from different bathymetric settings within the Molasse Basin (cf. Fig. 5): (a) proximal position (Eggerding 2); (b) upper slope (Perneck 1); (c) lower slope (Oberhofen 1); (d) basin floor (allochthonous part of Oberhofen 1). Only the lower part of the Zupfing Formation, several hundred metres thick, is shown.

preserved, but some northern, land-proximal wells show strong detrital influence (e.g. Eggerding 2; Fig. 7a).

Apart from the proximal wells, the Schöneck Formation from the upper slope is typically 10–20 m thick and can be divided into two marlstone units (A, B) and an upper shale unit (C) (Figs. 6a, 7b).

Unit A is characterized by strongly varying carbonate contents, a consequence of episodic globigerina blooms. Phosphorite and authigenic carbonate formed during deposition of unit A. In some wells, the base of unit A is bioturbated. Silty/sandy sediments, often with glauconite occur frequently in the lowermost few decimetres. Compared with unit A, unit B is characterized by more uniform carbonate contents and the lack of phosphorite nodules. With the exception of bioturbated intervals, total organic carbon (TOC) contents in units A and B are in the range of 2–2.5%. Hydrogen index (HI) values range from 400 mgHC g⁻¹TOC to 500 mgHC g⁻¹TOC (kerogen Type II). Unit C is dominated by black shales with TOC contents exceeding 5%. HI values reach 600 mgHC g⁻¹TOC (kerogen Type II–I). A few layers composed of micritic laminae with a nodular structure are intercalated. They are interpreted as zooplankton faecal pellets made up of coccolith debris from planktonic copepods (Haczewski 1989).

Typically, the interval transit time increases upward in unit A, displays a secondary minimum in unit B and is characterized by very high values in unit C (Figs. 6a, 7b). The interval transit time minimum in unit B is less significant in wells from the basin floor (Fig. 7d). For these wells, therefore the distinction between units A and B is often difficult. Subordinate transit time minima in the shaly unit C are related to thin marl layers (Fig. 6a).

The relation between gamma-ray values and lithological units A–C is more complicated. In many wells, gamma maxima occur near the base of unit A and at the transition between units B and C. Obviously the gamma lacks a clear response to lithology or TOC content. In contrast, the lower maximum reflects the occurrence of glauconite near the base of the Schöneck Formation. Crossplots of gamma-ray values versus

interval transit time show a decrease in the gamma-ray signal near the base of unit A with increasing distance from the palaeo-shoreline (Fig. 8). This decrease may be correlated with a decrease of glauconite content. At least in wells Oberschauersberg 1 and Aistersheim 1, local gamma-ray maxima at the base and within unit C can also be correlated to detrital glauconite.

Dynow Marlstone The Dynow Marlstone is c. 5–15 m thick and overlies the Schöneck Formation with a sharp boundary. It is composed of several sedimentary cycles, each starting with marlstone, including carbonate made up by coccolithophorides, and each ending with increasing shale and TOC contents. In contrast with the lower boundary, the transition of the Dynow Marlstone to the overlying marlstones of the Eggerding Formation is gradual (Fig. 6a). TOC contents range from 0.5% to 3.0% and are diluted by carbonate contents made up by calcareous nannoplankton. HI ranges generally between 500 mgHC g⁻¹TOC and 600 mgHC g⁻¹TOC (kerogen Type II–I).

With the exception of the autochthonous part of the Oberhofen 1 well, sonic and gamma-ray logs display a bell shape (Figs. 6, 7) and reflect the upward-decreasing carbonate contents (see also Schulz *et al.* 2004). Single peaks represent distinct limestone layers made up of coccolithophorides. Figure 8 displays a linear trend between gamma-ray and sonic values.

Eggerding Formation The Eggerding Formation is composed of dark grey laminated pelites with thin white layers of nannoplankton. The thickness of the Eggerding Formation is typically in the range of 35 m to 50 m. According to Schmidt & Erdogan (1996), the mean TOC is only 1.5% and the HI ranges from 100 mgHC g⁻¹TOC to 350 mgHC g⁻¹TOC. However, TOC and HI trends at the transition between the Dynow Marlstone and the Eggerding Formation (Fig. 6a) suggest that a significantly better source-rock quality has to be expected in the lower part of the Eggerding Formation. Nevertheless, the source-rock potential of the Eggerding Formation is considered to be less in

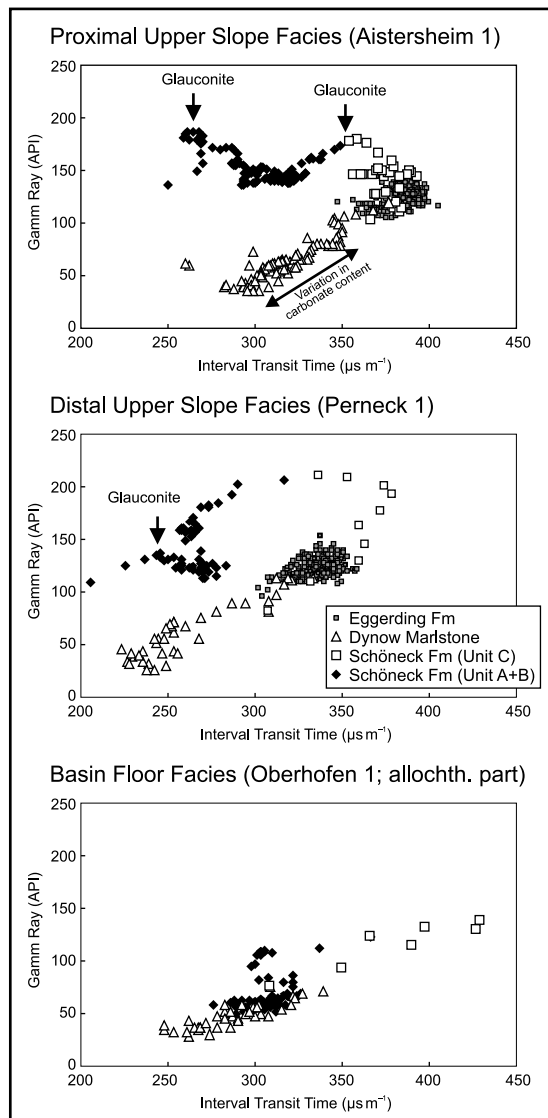


Fig. 8. Crossplots of gamma-ray values versus interval transit time for wells Aistersheim 1, Perneck 1 and Oberhofen 1 (allochthonous part). Note that the presence of glauconite – apart from mica and potassium feldspar – causes high gamma-ray values in the Schöneck Formation from the upper slope.

comparison with the lower formations. Thin, highly porous sandstone beds interfingering with marls were drilled in northern land-proximal position (e.g. Eggerding 2; Fig. 7a). Some of these sandstones carry viscous oil at shallow depth (<600 m), which is uneconomic because of heavy biodegradation (Brix & Schultz 1993).

The Eggerding Formation is characterized by high interval transit times and gamma-ray responses with little vertical variation (Fig. 7b Fig. 8). Single peaks represent either sandy or carbonaceous layers. A peak–peak correlation is locally possible, but usually fails for wells from different fields. The upper boundary of the Eggerding Formation is characterized by a decrease in interval transit time and gamma ray, a consequence of carbonate-rich layers within the lower part of the Zupfing Formation.

Oberhofen facies Following Wagner *et al.* (1986), Schulz *et al.* (2002) considered a 53.5 m thick succession in the Oberhofen 1 well (4283.5–4337.0 m depth; Fig. 7c) as a time-equivalent of the Schöneck Formation. These rocks were deposited on the

lower palaeoslope and consist of alternations of packstones and wackestones in the lower part, dark marls with olistholites of Eocene material in the middle part and limestones in the upper part. However, biostratigraphic age data are ambiguous. Carbonate contents, TOC contents, HI values and log signals of the respective depth interval are presented in Figures 6b and 7c. Based on new log correlations (see below), the upper limestone package, which was not cored, is considered to be an equivalent of the Dynow Marlstone, and the lower limestone package an equivalent of the Eocene Lithothamnium Limestone.

The log facies, which is termed the “Oberhofen facies”, differs significantly from that in other wells (Fig. 7c):

- the interval transit time in the Schöneck Formation is low, a result of the high carbonate content. A subdivision of Schöneck Formation into subunits A–C is impossible;
- the Dynow Marlstone is relatively thick and exhibits a blocky log motif without internal structure;
- the Eggerding Formation exhibits a highly structured log pattern and is characterized by relatively low interval transit times. Lithothamnium limestones found in cutting samples from this stratigraphic interval suggest that the structured log pattern is a result of re-deposited Eocene (and Lower Oligocene) material.

In addition to the Oberhofen 1 well, the Schöneck Formation and the Dynow Marlstone in “Oberhofen facies” were also encountered in two nearby wells (Lenzing 1, Timelkam 1).

Log correlations

Figure 9 presents a cross-section through the Ried, Trattnach and Aistersheim fields, an area where the Lower Oligocene rocks are partly missing. The cross-section is illustrated to aid in understanding whether the stratigraphic gap is due to non-deposition or to erosion. Note that most wells in this area are located at a considerable distance from faults. Reduction or lack of formations due to normal faulting, therefore, can be excluded largely.

A complete sequence from the Lithothamnium Limestone to the Zupfing Formation is present in the western Ried wells (Ried 2, 6, 1). The thickness of the Eggerding Formation in these wells is about 40 m. In wells Ried 5 and Ried 3 the thickness of the Eggerding Formation is significantly reduced (20–10 m). The eastern Ried wells (Ried 11, 8, Ost 1) are characterized by a few metres of Eggerding Formation directly overlying thin Lithothamnium Limestone. This geometry clearly shows that the organic-rich rocks in the eastern Ried Field are missing due to erosion rather than non-deposition. Erosion removed sediments *c.* 60 m thick and probably occurred during the final stages of the deposition of the Eggerding Formation.

Erosion was also active in the Trattnach area, but relatively thick Eggerding Formation overlying deeply eroded Lithothamnium Limestone (Trattnach 4 well; Fig. 9) suggests that erosion began earlier. Early erosion also removed the topmost part of the Dynow Marlstone and the lowermost part of the Eggerding Formation in the Aistersheim W1 well. On the other hand, in the Trattnach 11 well, Zupfing Formation directly overlies Schöneck Formation. This argues for a later erosional phase and suggests that erosion was a multi-stage process during and after deposition of the Eggerding Formation.

Three N–S-trending profiles are presented in Figure 10. Profiles a–b and c–d incorporate logs from the allochthonous, imbricated Molasse. According to Wagner *et al.* (1986) the allochthonous Lower Oligocene sediments from the

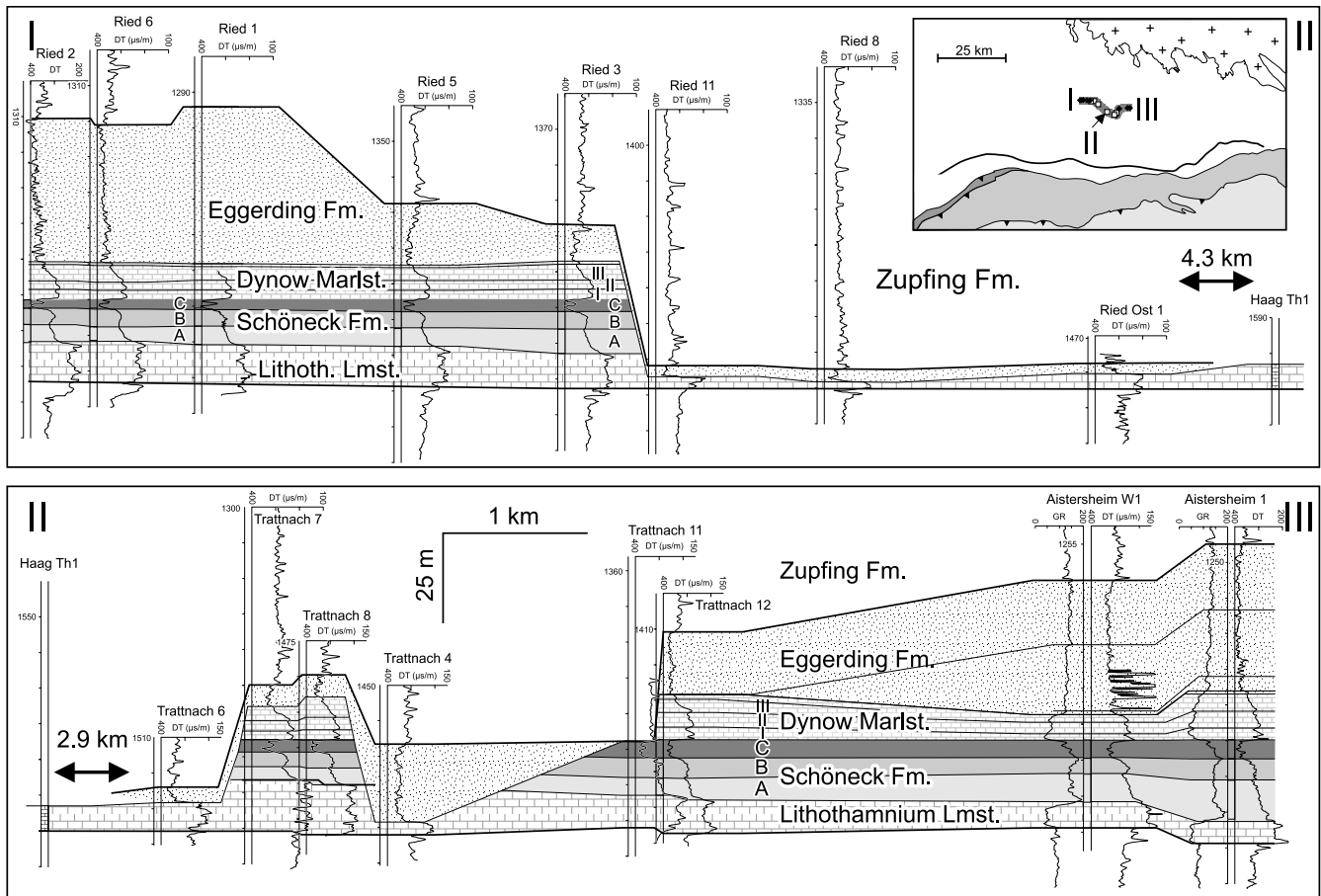


Fig. 9. Profile through the Ried, Trattnach and Aistersheim oil fields revealing significant erosion. Datum level is the base of the Lithothamnium Limestone. DT, sonic log; GR, gamma-ray log.

Oberhofen 1 well were transported 30–60 km northwards. The transport distance for the allochthonous sediments in the Dorfbeuren 1 and Perwang 1 wells (profile a–b) was probably in the same order of magnitude.

Despite the considerable transport distance, Schöneck Formation and Dynow Marlstone can be correlated easily along transect a–b. Unit A is thin in well Mattighofen 1. Unit B in well Helmberg 1 is *c.* 10 m thick and exhibits a rather flat sonic log pattern. This is a typical feature of wells from the southwestern part of the study area, which is also observed in the allochthonous Schöneck Formation in wells Dorfbeuren 1, Perwang 1 and Oberhofen 1.

Profile c–d crosses the autochthonous part of the Oberhofen 1 well in “Oberhofen facies”. The Eggerding Formation in this well shows a strongly structured log pattern. As discussed earlier, this is probably due to re-deposition of Eocene and Lower Oligocene material. All other sections, including that in the allochthonous part of the Oberhofen 1 well, exhibit normal log motifs. The uppermost part of the Dynow Marlstone in Steindlberg 2 is eroded, together with most of the Eggerding Formation.

The northern segment of profile e–f shows a southward decrease in thickness of the Dynow Marlstone and of unit C of the Schöneck Formation. In well Steinfeld 1 the upper part of unit B, the entire unit C and the Dynow Marlstone are missing due to erosion or normal faulting. At the southern end of the profile, the Schöneck Formation in the Grünau 1 well is characterized by a very thick unit B and a thin unit C. Similar to

the Oberhofen 1 well, the structured log motif of the succession overlying the Dynow Marlstone in Grünau 1 might indicate re-deposited sediments from the Schöneck Formation and the Dynow Marlstone.

NW–SE-trending profiles are shown in Figure 11. Profile 1–2 runs close to the northern margin of Molasse Basin between the land-proximal wells Eggerding 2 and Dietach 1. The thickness of the Schöneck Formation varies significantly. This is mainly a result of thickness variations of unit A. The thickness of the Dynow Marlstone is *c.* 10 m, but reaches maxima in well Zupfing 1 (17.2 m) and Aistersheim 1 (13.4 m).

Profiles 3–4 and 5–6 run in a more southern (distal) position. Dynow Marlstone and unit C of the Schöneck Formation are significantly thinner than along profile 1–2. Unit C is even missing in well Kirchdorf 1. Because Dynow Marlstone is present, this is probably because of non-deposition (or early erosion). Profile 3–4 shows a uniform facies distribution between Schwand 1 and Hörgersteig 2. Although well Puchkirchen 2 was cored, the situation is less clear along the southeastern end of this profile. Lower Oligocene rocks in well Timelkam 1 are present in “Oberhofen facies”. Sonic logs are unavailable from the old well Puchkirchen 2 (drilled in 1956) but Dynow Marlstone and unit C are clearly visible in the gamma-neutron log. However, units A and B cannot be distinguished. Similar to the Oberhofen 1 well, re-deposited Lithothamnium Limestone occurs within a 15 cm thick layer at 2585 m depth in unit A/B of the Schöneck Formation.

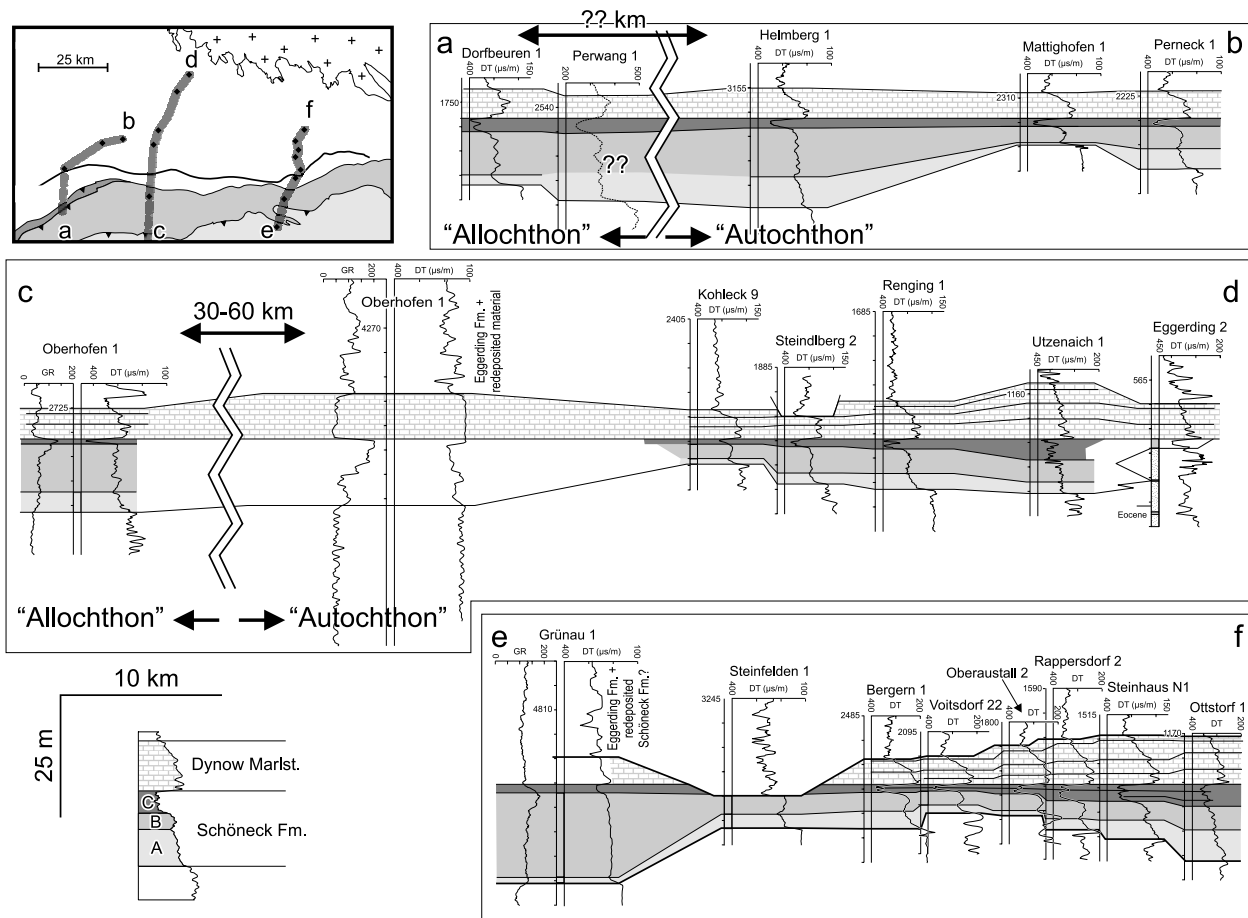


Fig. 10. S–N-trending profiles. The profiles show the wide lateral continuity of Lower Oligocene sediments in the Alpine Foreland Basin. Sediments in the autochthonous and allochthonous parts of the basin can be correlated easily. Only logs from the Autochthonous Molasse in the Oberhofen 1 well exhibit a different facies. Note also the highly structured logs of the Eggerding Formation in some wells (Oberhofen 1, Grünau 1, Steinfeld 1), which might be due to re-deposited material from the upper slope. Parts of the Lower Oligocene section in the Steindberg 2 and Steinfeld 1 wells are missing. DT, sonic log; GR, gamma-ray log.

Present-day thickness of Lower Oligocene source rocks

Isopach maps of the Schöneck Formation, the Dynow Marlstone and the Eggerding Formation are shown in Figure 12.

The Schöneck Formation is typically *c.* 10 m thick (Fig. 12a). Thickness maxima (>16 m) occur near the NE basin margin and in more distal southwestern positions. East of the Lindach Fault, the thickness distribution is rather uniform. Only in a few wells the Schöneck Formation is missing due to normal faulting. In contrast, the Schöneck Formation was not drilled in many wells located within the Ried-Schwanenstadt and Braunau blocks west of the Lindach Fault.

The Dynow Marlstone (Fig. 12b) extends slightly further northwards than the Schöneck Formation. A WNW–ESE-trending zone with up to 17 m thick Dynow Marlstone stretches along the northern basin margin. In a more southerly position the Dynow Marlstone is typically 4–8 m thick. Relatively thick Dynow Marlstone in the “Oberhofen facies” occurs in wells Lenzing 1, Timelkam 1 and Oberhofen 1. West of the Lindach Fault the Dynow Marlstone is missing in wells, which also did not drill Schöneck Formation.

The Eggerding Formation (Fig. 12c) is often 35–50 m thick. However, west of the Lindach Fault (Ried–Schwanenstadt and Braunau blocks) its thickness decreases strongly. In some wells located in these tectonic blocks the entire succession from the Schöneck Formation to the Eggerding Formation is missing due to erosion.

Maps of the original thickness of the Schöneck Formation and the Dynow Marlstone

In order to reveal depositional trends, isopach maps of units A, B and C and of the Dynow Marlstone, shown in Figure 13, include only information from wells unaffected by erosion or normal faulting.

The original thickness of unit A ranges from a few decimetres to more than 10 m. The lateral thickness distribution is quite irregular (Fig. 13a). Maxima occur near the northern basin margin in the Aistersheim area and in the autochthonous part of the distal well Perwang 1. The isopach map of unit B (Fig. 13b) is characterized by a strong southward increase in thickness. Within northern positions the thickness is uniformly in the order of 3–6 m, but increases to more than 10 m in distal wells (e.g. Grünau 1, Perwang 1). In contrast with older units, the WNW–ESE-trending thickness maxima of unit C (>5 m) are aligned along the northern basin margin (Fig. 13c). Very thin unit C was drilled in some distal wells. However, unit C, up to 3 m thick, occurs in some Molasse imbricates, suggesting that the thickness increases again in southern positions.

The Dynow Marlstone exhibits a thickness pattern similar to that in unit C, with maxima in proximal positions along the former basin margin (Fig. 13d). In well Zupfing 1 the Dynow Marlstone is 17 m thick. Another thickness maximum is related to the “Oberhofen facies” (wells Timelkam 1, Lenzing 1, Oberhofen 1) in a distal setting.

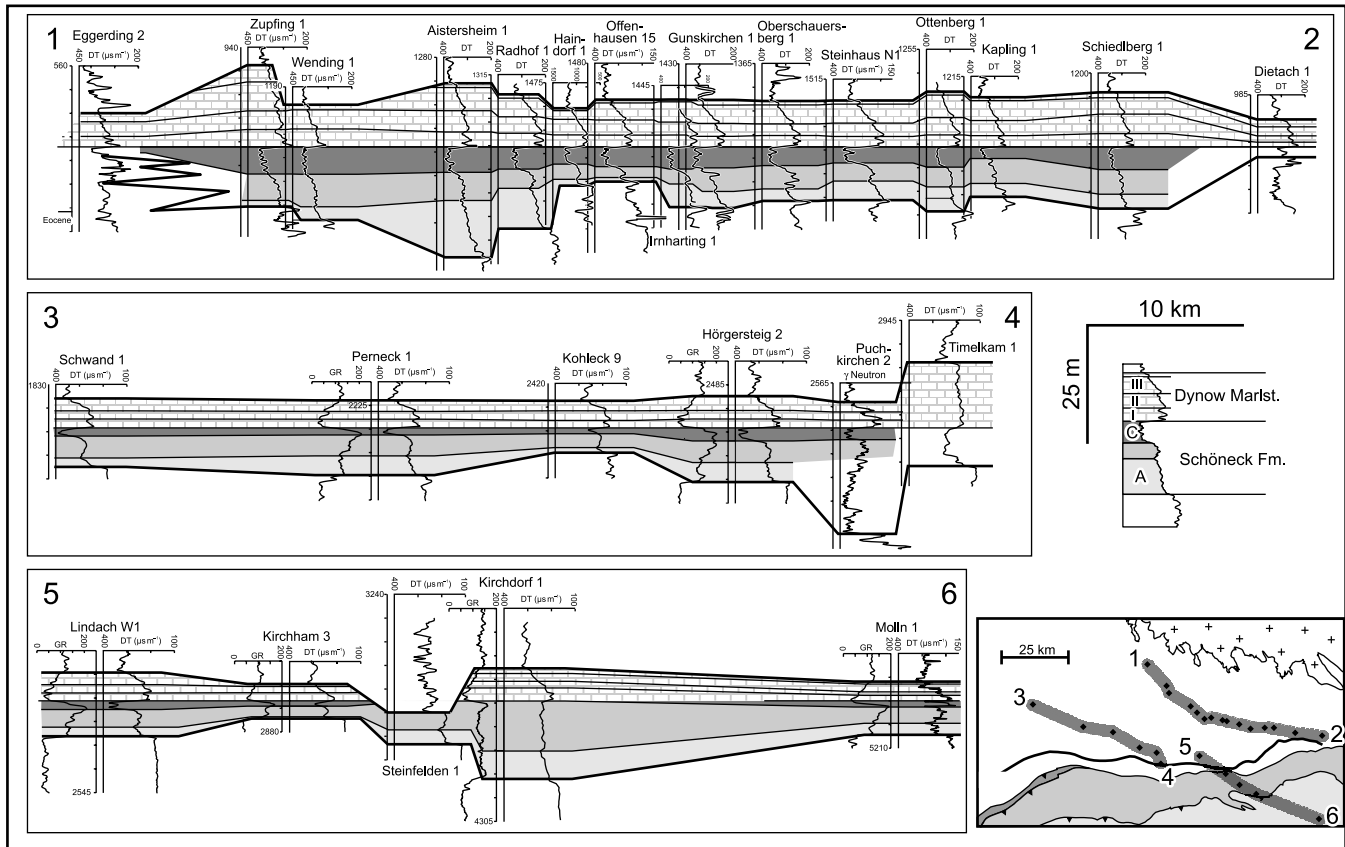


Fig. 11. NNW–SSE-trending profiles. The northern profile 1–2 is characterized by a very thick unit C, whereas this unit is thinner along the southern profiles 3–4 and 5–6. Note the significant thickness variation of unit A along profile 1–2. DT, sonic log; GR, gamma-ray log.

Seismic data

The top of the Lithothamnium Limestone and the top of the Schöneck Formation form prominent continuous high-amplitude reflectors (Fig. 14). In contrast, the top of the Dynow Marlstone and the top of the Eggerding Formation are characterized by reflectors with a low to medium amplitude. All reflectors are roughly parallel.

In some areas the parallel reflectors are cut by erosional surfaces. These are especially visible in shallow portions of the basins, for example in the northern part of the Ried–Schwanenstadt Block (e.g. Fig. 14). Here, an erosional channel, c. 60 m deep and up to 20 km wide, occupies nearly the entire area of the tectonic block. The channel margins follow the eastern (Lindach) and western boundary faults of the Ried–Schwanenstadt Block closely. Local relicts of Lower Oligocene strata are preserved near the northeastern end of the erosional channel and form island-like structures. The Trat 7 and 8 wells (Fig. 8) are located within one of these structures.

In some areas the internal reflection configuration of the Lower Oligocene succession is chaotic near erosive channels, suggesting that the rock sequence is loosened. The Eggerding Formation in the Kemating–Pattigham area shows complex reflection patterns (Fig. 14), reflecting different erosional phases.

The Eggerding Formation is overlain by the Zupfing Formation, characterized by parallel low-amplitude reflectors. The basal units of the Zupfing Formation onlap onto the margins of the erosive channels.

DISCUSSION

Depositional processes

Based on biomarker, isotope and pyrite data from key wells, Schulz *et al.* (2005) reconstructed palaeoceanographic changes in the Molasse Basin during deposition of the Schöneck Formation and the Dynow Marlstone (Fig. 15). The present study, using data from numerous wells, upscales their results to a basin-wide scale.

Schöneck Formation: Unit A A sharp break separates the Lithothamnium Limestone and unit A. Gradual transitions occur exclusively in land-proximal, northern positions, where the Schöneck Formation is partly underlain by Eocene and Lower Oligocene clastic rocks.

The base of unit A is often bioturbated and contains significant silt- and sand-sized detrital material. Abundant glauconite in the basal layer may cause a greenish colour. Glauconite is also a likely reason for the high gamma-ray response near the base of unit A. The observed general decrease in the gamma-ray peak from proximal to distal boreholes suggests that the amount of glauconite decreases with increasing palaeowater depth. Coaly debris occurs together with sand-sized detrital material in some proximal wells (e.g. Utzenaich 1; Sattledt 2). The bioturbated interval is typically 10–40 cm thick, but reaches 2.5 m in the proximal Aistersheim 1 well.

Biomarker data indicate that the lower part of the Schöneck Formation (unit A, B) was deposited in a stagnant basin with an oxygen-depleted (dysoxic to anoxic) bottom water (Fig. 15).

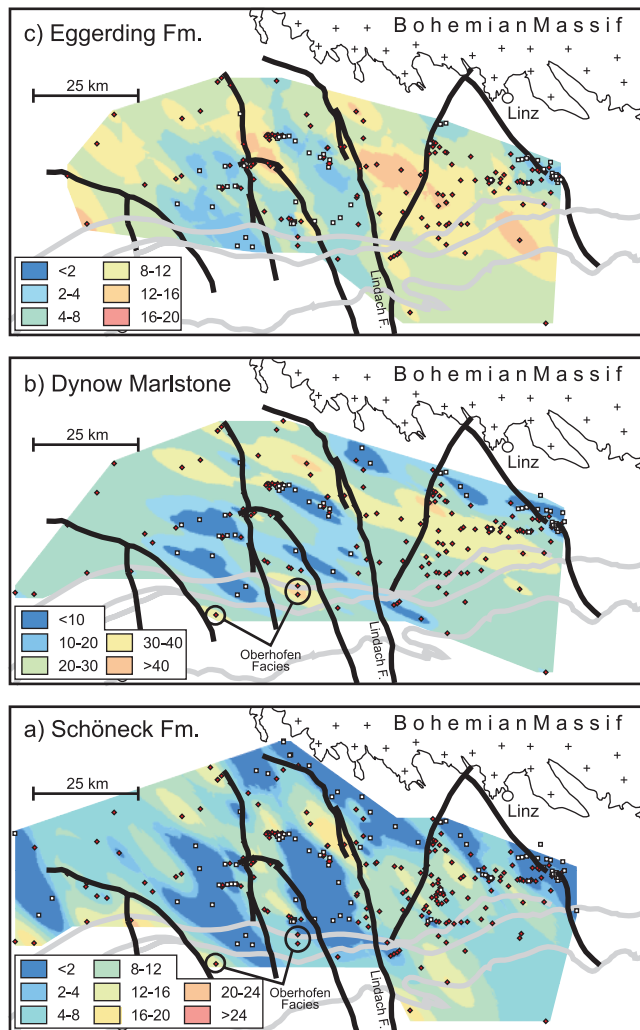


Fig. 12. Isopach maps of (a) Schöneck Formation, (b) Dynow Marlstone and (c) Eggerding Formation. Maps were constructed using a “simple Kriging” approach. The fault pattern is shown according to Wagner (1998).

Water stratification was caused by an estuarine circulation pattern and was accompanied by enhanced surface water productivity. Phosphorization and methanogenic dolomitization occurred during deposition of unit A and were especially effective in relatively shallow, proximal positions. Obvious variations in carbonate content are due to cyclic blooms of globigerinoides.

Primary lateral thickness variations are higher in unit A than in any other studied unit. Probably, this variability reflects the palaeorelief of the underlying Eocene rocks (Rasser & Piller 2004). The high thickness in the southwestern part of the study area may be related to increased subsidence rates. Slump structures in the topmost part of unit A were recognized in borehole Schwanenstadt 20W.

Schöneck Formation: Unit B Photic zone anoxia developed at the transition of units A and B. Clay-rich layers are less frequent in unit B than in unit A. Unit B, therefore, is characterized by a more uniform carbonate trend with a carbonate maximum in its central part. Carbonate contents are due to recrystallized nannoplankton. Because of the greater thickness of unit B in distal settings, the carbonate maximum in the middle part of unit B is less pronounced. Therefore – and because carbonate and phosphorite concretions are less frequent in distal settings

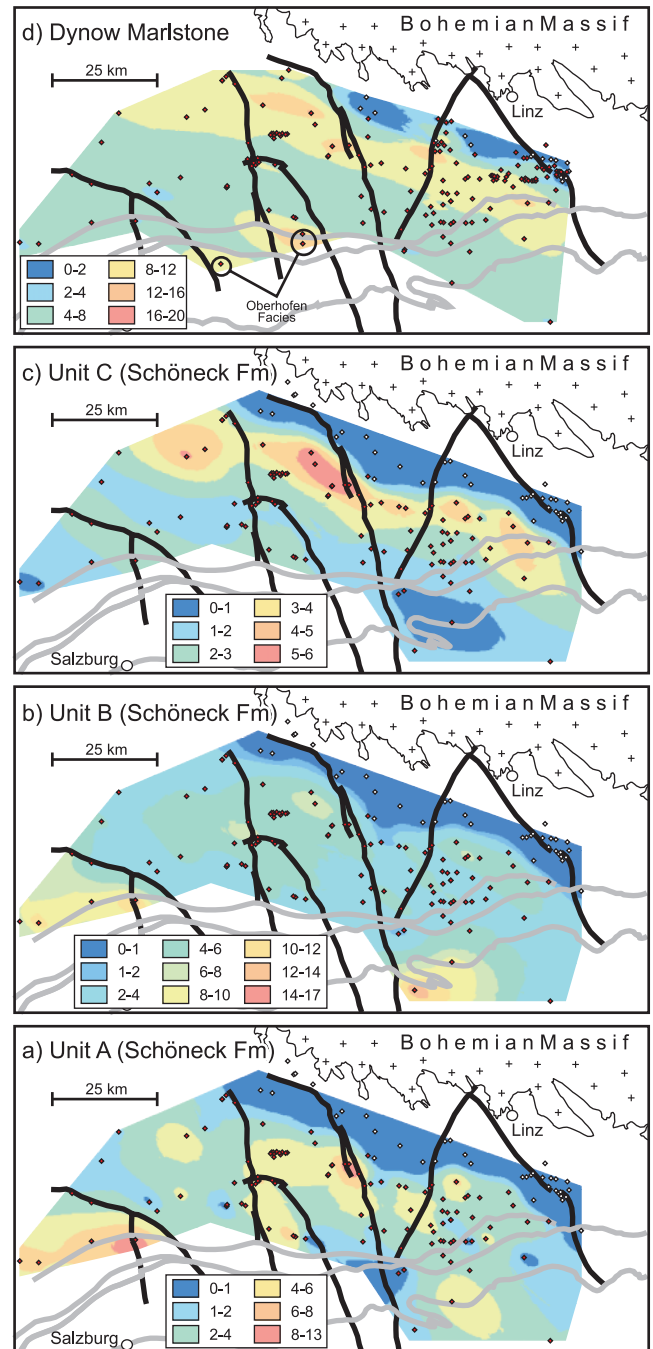


Fig. 13. Isopach maps of (a) unit A, (b) unit B, and (c) unit C of the Schöneck Formation, with (d) Dynow Marlstone. In order to show the original thickness distribution, only wells unaffected by normal faulting and erosion were considered. Maps were constructed using a “simple Kriging” approach.

– a subdivision of units A and B is difficult in cores from some distal wells. Turbidites occur in some northern, proximal wells (Aiterbach 1, Oberschauersberg 1). Thin tuff layers were also detected so far only in proximal setting.

Schöneck Formation: Unit C Biomarker and isotope data (Fig. 15) indicate that the environment during deposition of the lower part of unit C was characterized by low surface water productivity, high surface water salinity and CO_2 recycling within the water column. These features were supported by a rise in the chemocline into the photic zone. The environment changed significantly during deposition of the upper part of unit C:

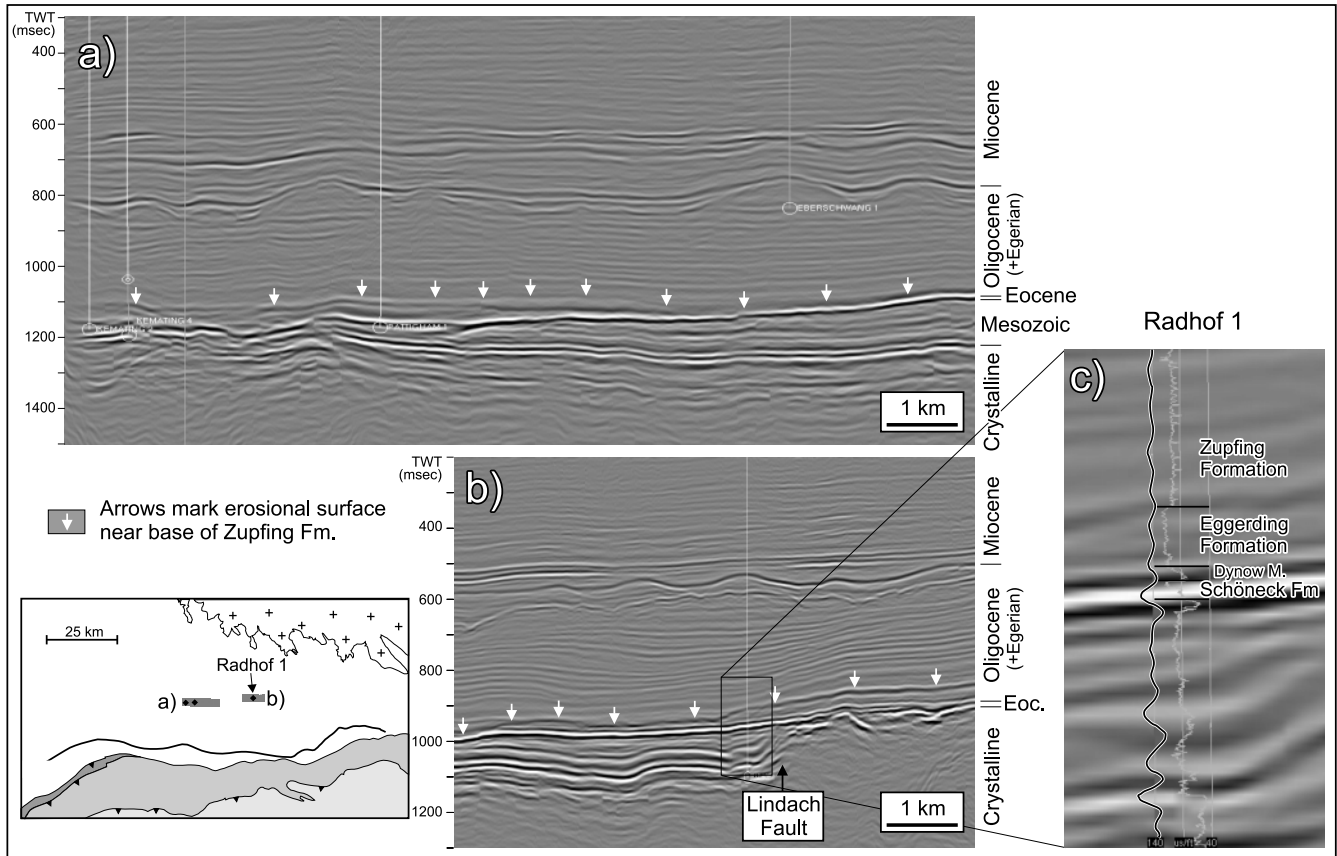


Fig. 14. W–E-trending seismic sections showing erosional features near the top of the Eggerding Formation (a), (b). Vertical axis is in two-way travel time (TWT). (c) Sonic log and synthetic seismogram of the Radhof 1 well provide a tie between log data and seismic data.

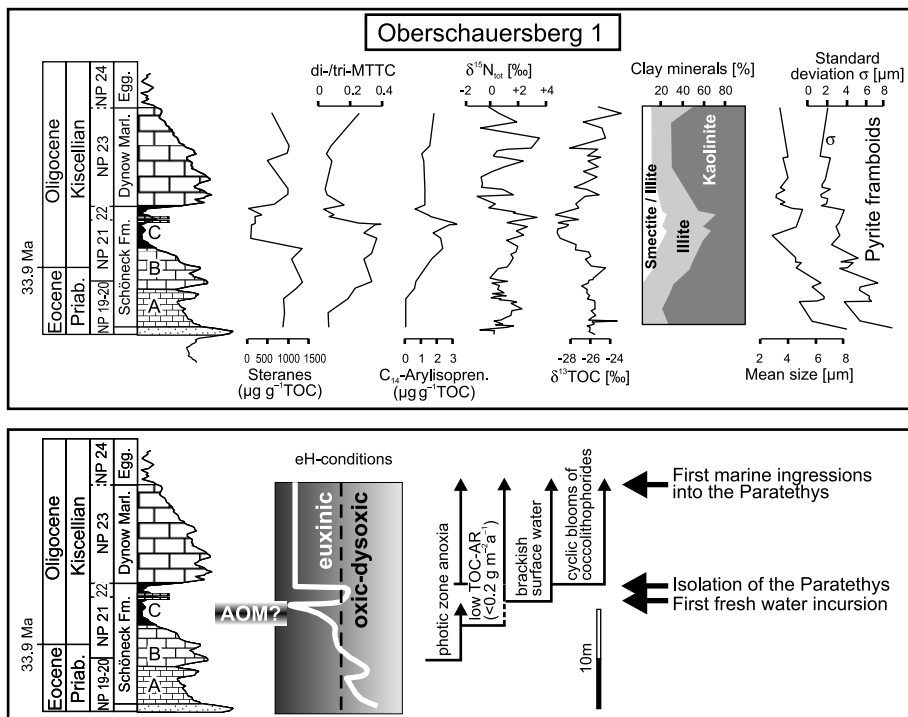


Fig. 15. Palaeogeographic proxy data (biomarkers, isotopes of nitrogen and organic carbon, clay mineralogy, size distribution of framboidal pyrite) in the Lower Oligocene succession (taking Oberschauersberg 1 well as an example). The lower part shows the inferred palaeoceanographic changes (after Schulz *et al.* 2005). AOM, anaerobic oxidation of methane; TOC-AR, accumulation rate of organic carbon.

water stratification, surface water salinity and bottom water anoxia decreased as a result of major fresh-water influx.

Unit C is characterized by dominant clay deposition. The detrital material has a northern provenance (Bohemian

Massif; Gier 2000). This may explain the observed significant northward increase in thickness. Occasional blooms of coccolithophorids resulted in marl layers. Number and thickness of the marl layers decrease southwards suggesting that the blooms

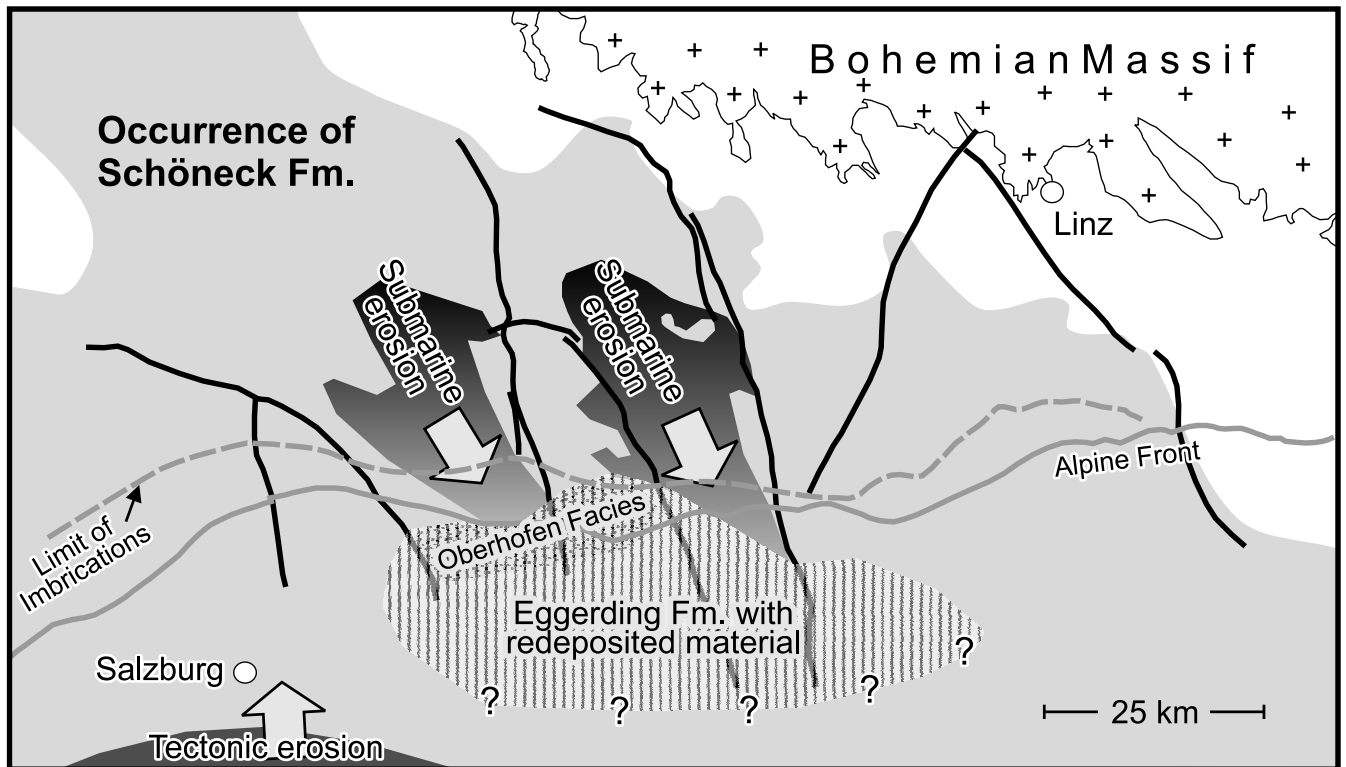


Fig. 16. Sketch summarizing the post-depositional evolution of the lower Oligocene succession in the Austrian part of the Molasse Basin. Note that the boundaries of erosional features are shown schematically.

of coccolithophorids were more intensive near the coast. However, these marl layers also occur in allochthonous Schöneck Formation deposited in southern basinal positions.

Dynow Marlstone The base of the Dynow Marlstone is characterized by an abrupt increase in productivity and photic zone anoxia persisted. During the late NP23 intensified photic zone anoxia and an increase in salinity worsened the ecological environment for calcareous nannoplankton and led to the deposition of marls of the Eggerding Formation.

The Dynow Marlstone has been formed by cyclic blooms of coccolithophorids. Its thickness decreases from proximal to distal settings. The decrease in thickness is mainly due to a basinward decrease in the thickness of individual cycles. Moreover, the lowermost cycle I splits in proximal settings. The northward increase in thickness, therefore, reflects both increased detrital input and increased productivity of coccolithophorides in nearshore environments.

“Oberhofen facies” An unusual log shape occurs in the Timelkam 1, Lenzing 1 and Oberhofen 1 wells. Unit C of the Schöneck Formation cannot be recognized. In Oberhofen 1 the Schöneck Formation includes olistolithes with Eocene Lithothamnium Limestone. Similarly, detrital Lithothamnium Limestone occurs in a thin layer within the Schöneck Formation in the Puchkirchen 2 well. Both phenomena are the result of gravity flows from topographic highs which disturbed marly/shaly background sedimentation. Moreover, it emphasizes that Eocene rocks were exposed north of the Oberhofen 1 and Puchkirchen 2 wells during deposition of the Schöneck Formation.

Because of the lack of core material from the Dynow Marlstone in the “Oberhofen facies”, the explanation for the unusual thickness and log shape remains speculative. It is proposed here that the enhanced thickness is due to re-deposition of unlithified ooze shortly after their original

accumulation, a phenomenon well known from the North Sea (e.g. Schatzinger *et al.* 1985; Hatton 1986). Whatever the reason, the “Oberhofen facies” seems to be a feature restricted to the lower slope, because log patterns from the Allochthonous Molasse show that sediments with “typical” Schöneck and Dynow facies were deposited in more southern, basinal positions. The distribution of the Oberhofen facies is shown schematically in Figure 16.

Post-depositional processes

Some important features of post-depositional processes are summarized in Figure 16. Pebbles and slides of Lithothamnium Limestone in the Schöneck Formation in wells Oberhofen 1 and Puchkirchen 2 show that erosion and re-deposition had commenced already during the earliest Oligocene (NP21/22). Perhaps the great thickness of the Dynow Marlstone in the “Oberhofen facies” is due to syn-sedimentary re-deposition of nannofossil ooze. Erosion during early stages of the deposition of the Eggerding Formation (NP23) is evident, e.g. in the Trattnach (Fig. 8) and Kemating–Pattigham areas (Fig. 14). However, major erosion, which created valleys up to 60 m deep and several kilometres wide, occurred only during late stages of the deposition of the Eggerding Formation (NP24).

All relevant formations were deposited in several hundred metres of water depth (Dohmann 1991; Wagner 1998). Therefore, even the major sea-level fall at the boundary between the early and the late Oligocene (NP24; see Fig. 4) could not establish subaerial conditions. Consequently, all erosional events are considered as submarine processes.

Submarine erosion occurred mainly west of the Lindach Fault in the Ried–Schwanenstadt and Braunau blocks (Fig. 6c; Fig. 16). These blocks experienced enhanced tectonic activity during Palaeogene times (Wagner 1998) suggesting that the gravity-induced movements were triggered by earthquakes. The

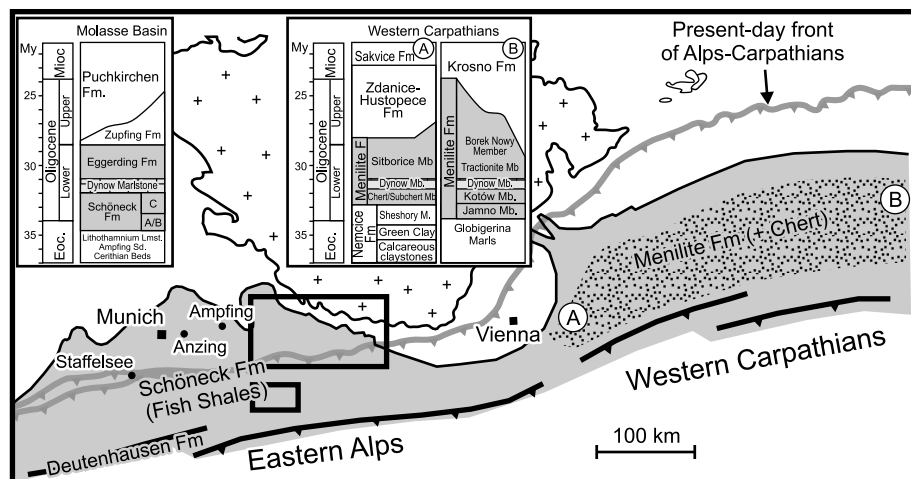


Fig. 17. Map showing the distribution of the Schöneck Formation and the Menilite Formation (after Picha & Stranik 1999). The position of the study area (large box) and the original position of sediments which are now found in Molasse imbricates (small box) are indicated. Staffelsee, Ampfing and Anzing are boreholes mentioned in the text. Insets show the stratigraphy of Oligocene successions in the Molasse Basin and the western Carpathians ((A) Slovakia, Krhovský *et al.* 2001; (B) Poland, Kotlarczyk 1988).

available stratigraphic dataset is insufficient for an exact dating of the uppermost part of the Eggerding Formation, but it is probably older than the sea-level fall during NP24. Thus, it remains unclear whether mobilization of sediments at the northern basin slope is related to sea-level fall. Southward transport directions were controlled by the deepening of the basin in front of the Alpine nappes (Fig. 5).

Deposition of slumps and pebbles of the eroded material probably occurred in basinal settings south of the study area. However, material overlying the Dynow Marlstone in the Grünau 1 and Oberhofen 1 wells (cf. Fig. 9) also may represent slides of Schöneck Formation and Dynow Marlstone. This is supported further by Eocene limestones in the Eggerding Formation in the Oberhofen 1 well (4255–4284 m depth; Wagner *et al.* 1986). Figure 16 gives an approximate idea on the regional distribution of re-deposited material.

Similar erosional features occurred in the western Carpathians during NP23 (“Sitborice Event”; Krhovský & Djurasinovic 1993). Correlations of such events highlight that slope instability may have occurred basin-wide rather than being a local phenomenon.

In contrast to more eastern areas, Molasse imbricates north of Salzburg (e.g. Oberhofen 1, Perwang 1, Dorfbeuren 1; see Fig. 2 for position of wells) contain Schöneck Formation, Dynow Marlstone and Eggerding Formation. For example, the Perwang 1 well penetrated Schöneck Formation in the Autochthonous Molasse and in three tectonic slices. This shows that lower Oligocene source rocks south of Salzburg were removed from their basement by the advancing thrusts. Tectonic erosion is highlighted schematically in Figure 16.

Implications for hydrocarbon exploration in the Alpine–Carpathian Foredeep

Molasse Basin in Austria The Schöneck Formation is the dominant source rock for oil and thermogenic gas in the Austrian part of the Alpine Foreland Basin (Wagner 1996; Schulz *et al.* 2002). The Dynow Marlstone and Eggerding Formation represent less effective source rocks. The Lower Oligocene succession is also the principal seal. East of Munich the oil kitchen is located at 4–7 km depth beneath the Alpine nappes. This indicates long-distance migration (Schmidt & Erdogan 1996). A continuous seal and a carrier bed are prerequisites for lateral migration.

The petroleum-generating potential of the Lower Oligocene sequence varies significantly in a vertical direction and reaches a maximum in unit C of the Schöneck Formation (Fig. 6a). The

thickness of unit C decreases southwards, implying that this unit is relatively thin where the source rock is mature. Nevertheless, this is a minor problem for the prospectivity of the basin as other units also possess an excellent potential. On the other hand the extrapolation of observed trends suggests mature Schöneck Formation with a very thick unit C east of borehole Molln 1. Therefore, additional exploration activities in the area of the Amstetten Block are recommended.

The Schöneck Formation in the “Oberhofen facies” has a source-rock potential (average TOC 1.3%; HI up to 400 mgHC g⁻¹TOC; Fig. 6b) that is significantly lower than that of the “normal” facies (see also Schulz *et al.* 2002). According to the available data, the extension of the “Oberhofen facies” is restricted. Nevertheless, further exploration activities should pay special attention to the distribution of the “Oberhofen facies”, which can be recognized easily in electric logs.

Submarine erosion removed substantial volumes of the Lower Oligocene sequence. This affects both the source-rock potential and the seal capacity of the sequence. Therefore, detailed knowledge of the geometry of the erosional features, both in the source area beneath the Alpine nappes, and along the migration pathways is necessary.

Tectonic transport of source rocks by the advancing nappes south of Salzburg also influences the hydrocarbon potential of the basin. This is because the source rocks were transported from the area of the present-day oil kitchen to the thrust front, where the rocks remained immature (Wagner *et al.* 1986).

Molasse Basin in Germany Only a few well logs from the German Molasse Basin are published in a scale useful for an investigation of the Lower Oligocene succession (e.g. Anzing 3, Köwing *et al.* 1968; Ampfing 15, Boigk 1981; Staffelsee 1; Müller 1970; see Figure 17 for position of wells). However, these few logs clearly reveal the subdivision of the Schöneck Formation into units A–C and the cyclic structure of the Dynow Marlstone. This emphasizes the lateral continuity of the organic-rich Lower Oligocene succession, which, for example, enables the correlation of specific decimetre-thick coccolith limestone layers between Staffelsee and Dietach over a distance of almost 250 km. In addition, data from Wehner *et al.* (1983) and Gerhard (1988) show that the source-rock potential also continues in an E–W direction.

On the other hand, well logs published by Zweigel (1998) suggest that the Schöneck Formation and the Dynow Marlstone are missing in some areas. By analogy with the situation in Austria, it is presumed that the stratigraphic gaps

are due to submarine erosion. Therefore, detailed investigations of the distribution and erosion features of the Lower Oligocene rocks are necessary for a thorough re-evaluation of the petroleum potential of the basin.

Western Carpathians The main source rock for oil in the Carpathians is the Menilite Formation. The Dynow Marlstone forms a marker horizon within the organic-rich sediments and facilitates correlations with the Molasse Basin (Picha & Stranik 1999; Krhovský *et al.* 2001; Fig. 17). The Sheshory (Globigerina) Marls (upper part of the Nemcice Formation), together with the Subchert and Chert Members of the Menilite Formation, are coeval with the Schöneck Formation, whereas the Sitborice Member correlates with the Eggerding Formation. Apart from the Dynow Marlstone, additional coccolith limestones occur in the Sitborice Member and can be correlated all along the Carpathians to Romania (Haczewski 1989). Slumps and pebble deposits in the basal part of the Sitborice Member indicate submarine erosion and were related to an Early Oligocene sea-level fall (e.g. Krhovský *et al.* 2001).

Picha & Stranik (1999) underlined the similarities between the Alpine Foreland and the Carpathians, which formed a continuous basin (Fig. 17). Obviously similar palaeoceanographic processes, including salinity variations triggering blooms of coccolithophorides (Haczewski 1989), photic zone anoxia and activity of methanotrophic bacteria (Köster *et al.* 1998b) were active in both realms. However, the distribution of diatomites and cherty (Menilitic) deposits shows that diatom blooms were restricted to the Carpathians.

A wealth of source-rock data from the Menilite Formation has been published (e.g. Bessereau *et al.* 1996; Köster *et al.* 1998a). According to these papers high TOC (up to 18%) and HI values (200–750 mgHC g⁻¹TOC) highlight substantial vertical and lateral variabilities. The highest TOC contents occur in the lower part of the Menilite Formation. Bessereau *et al.* (1996) emphasized that the observed lateral and vertical variations require high density data for a reliable evaluation of the petroleum potential.

Based on the results of this contribution, detailed sedimentological and geochemical investigations of key wells are recommended. These investigations may prove that a part of the “lateral” facies variability is actually due to sampling of different horizons. Similarly, because of a poor control on sampling locations, vertical facies variations between units A/B and C in the Molasse Basin were interpreted in terms of lateral facies variations (e.g. Gerhard 1988). Comparison of well-logs and the measurement of outcrop gamma-ray logs may help to correlate different profiles. Obviously, biostratigraphy is another important correlation tool. However, at least in the Molasse Basin, biostratigraphy alone is not precise enough to distinguish horizons with completely different source-rock potential.

Apart from this, a reliable evaluation of the petroleum potential should consider that significant volumes of the Menilite Formation might be missing due to erosion.

CONCLUSIONS

Like many other Paratethyan basins, the Molasse Basin contains organic-rich rocks with an Early Oligocene age, which were deposited in deeper water. The Schöneck Formation is the main source rock in the Molasse Basin. The Dynow Marlstone and Eggerding Formation represent secondary sources. The Lower Oligocene succession is characterized by lateral continuity, but very high vertical variability. The latter results from palaeoceanographic changes in the Paratethys (closing and opening of seaways, fresh-water incursions, etc.).

The Schöneck Formation is subdivided into three units. The marly unit A is characterized by cyclic blooms of globigerinoids. Its thickness distribution reflects the burial of an old relief. The thickness of the marly unit B increases towards the basin centre. Shaly unit C has the highest source potential. Thickness maxima occur in a narrow belt parallel to the palaeo-shoreline and are controlled mainly by detrital input.

The Dynow Marlstone shows a thickness distribution similar to unit C. As the carbonate content of the Dynow Marlstone is derived from coccolithes, nannoplankton blooms may have been concentrated along the basin margin. The Dynow Marlstone grades upward into the Eggerding Formation.

The present-day distribution of Lower Oligocene rocks is controlled by submarine erosion. Erosion commenced during deposition of the Schöneck Formation, but reached a maximum during deposition of the upper part of the Eggerding Formation. The eroded material became deposited along the lower basin slope where the series thickens (“Oberhofen facies”). Erosion was controlled by the inclination of the northern basin slope and the position of major basement faults.

Significant parts of the source potential were destroyed by submarine and tectonic erosion. Large parts of the Lower Oligocene succession south of Salzburg were tectonically removed by the advancing nappes.

The same processes, described from the study area, were probably also active in the German part of the Molasse Basin and in the western Carpathians. This suggests that the Lower Oligocene of the Alpine Foreland Basin can be considered a model for source-rock deposition in wide parts of the Western and Central Paratethys.

The authors thank Rohöl-Aufsuchungs AG (Vienna), OMV (Vienna) and GeoTeam (Gleisdorf) for providing core material, well logs and seismic data, as well as for permission to publish this paper. Special thanks go to H. Polesny, F. Rögl, A. Smuk, W. Tschelaut and L. Wagner, who helped greatly with their regional expertise. The help of G. Rantitsch (Leoben) and L. Stecken (Berlin) in the construction of thickness maps is highly appreciated. The paper benefited greatly from the critical remarks of J.-J. Biteau and A. le Merrec, and the editorial comments and suggestions of A. G. Doré.

REFERENCES

- Bessereau, G., Roure, F., Kotarba, M., Kusmierek, J. & Strzetelski, W. 1996. Structure and habitat of the Polish Carpathians. In: Ziegler, P.A. & Horvath, F. (eds) *Peri-Tethys Memoir 2, Structure and Prospects of Alpine Basins and Forelands*. Mémoire du Museum National d'Histoire naturelle, **170**, 343–373.
- Boigk, H. 1981. *Erdöl und Erdgas in der Bundesrepublik Deutschland*. Enke, Stuttgart.
- Brix, F. & Schultz, O. (eds) 1993. *Erdöl und Erdgas in Österreich*. Naturhistorisches Museum Wien, Vienna.
- Colins, E., Hamilton, W. & Schmidt, F. 1992. The hydrocarbon potential of the Alpine Subthrust and Overthrust, Austria. In: Spencer, A.M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons II*. European Association of Petroleum Geoscientists, Special Publication, **2**. Springer, Berlin, 193–199.
- de Ruig, M.J. 2003. Deep marine sedimentation and gas reservoir distribution in Upper Austria. *Oil & Gas European Magazine*, **29**, 64–73.
- de Ruig, M.J. & Hubbard, S.M. 2006. Seismic facies and reservoir characteristics of a deep-marine channel belt in the Molasse foreland basin, Puchkirchen Formation, Austria. *AAPG Bulletin*, **90**, 735–752.
- Dohmann, L. 1991. *Die unteroligozänen Fischeschiefer im Molassebecken*. PhD thesis. Ludwig-Maximilian-Universität, Munich.
- Gerhard, J. 1988. *Faziesdiagnose und Paläoenvironment des Sannois-Fischeschiefers (Alpines Molassebecken, Bayern, Süddeutschland)*. DG MK Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle e.V. Berichte, **406**.
- Gier, S. 2000. Clay mineral and organic diagenesis of the Lower Oligocene Schöneck Fishshale, western Austrian Molasse Basin. *Clay Minerals*, **35**, 709–717.
- Haczewski, G. 1989. Coccolith limestone horizons in the Menilite-Krosno Series (Oligocene, Carpathians) – Identification, correlation and origin.

- Annales Societatis Geologorum Poloniae*, **59**, 435–523 [in Polish with English abstract].
- Haq, B.U., Hardenbohl, J. & Vail, P.R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156–1167.
- Hatton, I.R. 1986. Geometry of allochthonous Chalk Group members, Central Trough, North Sea. *Marine and Petroleum Geology*, **3**, 79–98.
- Jin, J., Aigner, T., Luterbacher, H.P., Bachmann, G.H. & Müller, M. 1995. Sequence stratigraphy and depositional history in the south-eastern German Molasse Basin. *Marine and Petroleum Geology*, **12**, 929–940.
- Kollmann, K. 1966. Die Mächtigkeitsverhältnisse der Ablagerungen des Obereozäns und tiefen Rupels als Grundlage für eine Rekonstruktion der frühen Baugeschichte des Ölfeldes Ried (Molassezone Oberösterreich). *Erdoel-Erdgas-Zeitschrift*, **82**, 175–185.
- Kotlarczyk, J. 1988. Geologia Karpat Przemyskich – “Szkie do portretu”. *Przegląd Geologiczny*, **36**, 325–333.
- Krhovský, J. & Djurasinovic, M. 1993. The nannofossil chalk layers in the early Oligocene Sitborice Member in Velké Nemčice (the Menilitic formation, Zdanice Unit, South Moravia): Orbitally forced changes in paleoproductivity. In: Hamrsmid, B. (ed.) *Nové výsledky v teriéru Západních Karpat. Sborník referátů z 10. konference o mladším terciéru, Brno, 27.-28.4.1992*, **15**. Knihovnicka Zemni Plyn Nafta, Hodonin, 33–53.
- Krhovský, J., Rögl, F. & Hamrsmid, B. 2001. Stratigraphic correlation of the Late Eocene to Early Miocene of the Waschberg Unit (Lower Austria) with the Zdanice and Pouzdrany Units (South Moravia). In: Piller, W.E. & Rasser, M.W. (eds) *Paleogene of the Eastern Alps*. Österreichische Akademie der Wissenschaften. Schriftenreihe der Erdwissenschaftlichen Kommissionen, **14**, 225–254.
- Kröll, A., Wagner, L., Wessely, G. & Zych, D. 2005. *Molassezone Salzburg-Oberösterreich. Strukturkarte der Molassebasis 1:200 000*. Geologische Bundesanstalt, Vienna.
- Köster, J., Kotarba, M., Lafargue, E. & Kosakowski, P. 1998a. Source rock habitat and hydrocarbon potential of Oligocene Menilitic Formation (Flysch Carpathians, Southeast Poland): an organic geochemical and isotope approach. *Organic Geochemistry*, **29**, 543–558.
- Köster, J., Rospondek, M., Schouten, S., Kotarba, M., Zubrzycki, A. & Sinninghe Damsté, J.S. 1998b. Biomarker geochemistry of a foreland basin: the Oligocene Menilitic Formation in the Flysch Carpathians of Southeast Poland. *Organic Geochemistry*, **29**, 649–669.
- Köwing, K., Kraus, L. & Rückert, G. 1968. *Erläuterungen zur Geologischen Karte von Bayern 1:25 000, Blatt Nr 7837 Markt Schwaben*. Bayerisches Geologisches Landesamt, München.
- Müller, M. 1970. Die Ergebnisse der Bohrung Staffelsee 1 als Grundlage für neue Vorstellungen über Bau und Untergrund der gefalteten Molasse. *Geologica Bavarica*, **63**, 86–106.
- Picha, F.J. & Stranik, Z. 1999. Late Cretaceous to early Miocene deposits of the Carpathian foreland basin in southern Moravia. *International Journal of Earth Sciences*, **88**, 475–495.
- Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G. & Kovac, M. (eds) 2004. *Lithological-Paleogeographic maps of Paratethys. 10 maps Late Eocene to Pliocene*. Courier Forschungsinstitut Senckenberg, **250**, 1–46.
- Rasser, M.W. & Piller, W.E. 2004. Crustose algal frameworks from the Eocene Alpine Foreland. *Paleogeography, Paleoclimatology, Paleocology*, **206**, 21–39.
- Roeder, D. & Bachmann, G. 1996. Evolution, structure and petroleum geology of the German Molasse Basin. In: Ziegler, P. & Horvath, F. (eds) *Peri-Tethys Memoir 2, Structure and Prospects of Alpine Basins and Forelands*. Mémoire du Museum National d'Histoire naturelle, **170**, 263–284.
- Sachsenhofer, R.F., Gratzner, R., Tschelaut, W. & Bechtel, A. 2006. Characterisation of non-productive oil in Eocene reservoir sandstones (Bad Hall Nord field, Alpine Foreland Basin, Austria). *Marine and Petroleum Geology*, **23**, 1–15.
- Schatzinger, R.A., Feazel, C.T. & Henry, W.E. 1985. Evidence of re-sedimentation in Chalk from the Central Graben, North Sea. In: Crevello, P.D. & Harris, P.M. (eds) *SEPM Core workshop No.6*. Society of Economic Paleontologists and Mineralogists, New Orleans, 342–385.
- Schmidt, F. & Erdogan, L.T. 1996. Palaeohydrodynamics in exploration. In: Wessely, G. & Liebl, W. (eds) *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe*. European Association of Geoscientists and Engineers Special Publication, **5**. Alden Press, Oxford, 255–265.
- Schulz, H.-M., Sachsenhofer, R.F., Bechtel, A., Polesny, H. & Wagner, L. 2002. The origin of hydrocarbon source rocks in the Austrian Molasse Basin (Eocene–Oligocene transition). *Marine and Petroleum Geology*, **19**, 683–709.
- Schulz, H.-M., Bechtel, A., Rainer, T., Sachsenhofer, R.F. & Struck, U. 2004. Paleocyanography of the western Central Paratethys during nannoplankton zone NP 23: The Dynow Marlstone in the Austrian Molasse Basin. *Geologica Carpathica*, **55**, 311–323.
- Schulz, H.-M., Bechtel, A. & Sachsenhofer, R.F. 2005. The birth of the Paratethys during the early Oligocene: from Tethys to an ancient Black Sea analogue? *Global and Planetary Change*, **49**, 163–176.
- Sissingh, W. 1997. Tectonostratigraphy of the North Alpine Foreland Basin: correlation of Tertiary depositional cycles and orogenic phases. *Tectonophysics*, **282**, 223–256.
- Ulmshiek, G.F. 2001. *Petroleum Geology and resources of the middle Caspian Basin, former Soviet Union*. US Geological Survey Bulletin, **2201-A**.
- Véron, J. 2005. The Alpine Molasse Basin – Review of petroleum geology and remaining potential. *Bulletin angewandte Geologie*, **10**, 75–86.
- Wagner, L.R. 1996. Stratigraphy and hydrocarbons in Upper Austrian Molasse Foredeep (active margin). In: Wessely, G. & Liebl, W. (eds) *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe*. European Association of Geoscientists and Engineers Special Publication, **5**. Alden Press, Oxford, 217–235.
- Wagner, L.R. 1998. Tectono-stratigraphy and hydrocarbons in the Molasse Foredeep of Salzburg, Upper and Lower Austria. In: Mascle, A., Puigdefàbregas, C. & Luterbacher, H.P. (eds) *Cenozoic Foreland Basins of Western Europe*. Geological Society, London, Special Publications, **134**, 339–369.
- Wagner, L., Kuckelkorn, K. & Hiltmann, W. 1986. Neue Ergebnisse zur alpinen Gebirgsbildung Oberösterreichs aus der Bohrung Oberhofen 1 – Stratigraphie, Fazies, Maturität und Tektonik. *Erdöl, Erdgas, Kohle*, **102**, 12–19.
- Wehner, H. & Kuckelkorn, K. 1995. Zur Herkunft der Erdöle im nördlichen Alpen-/Karpätenvorland. *Erdöl, Erdgas, Kohle*, **111**, 508–514.
- Wehner, H., Hufnagel, H., Kuckelkorn, K., Schoell, M. & Teschner, M. 1983. *Zur Kohlenwasserstoffgenese im deutschen Alpenvorland*. Forschungsbericht T 83-103. Bundesamt für Geowissenschaften und Rohstoffe, Hannover.
- Ziegler, P.A. & Roure, F. 1999. Petroleum systems of Alpine–Mediterranean foldbelts and basins. In: Durand, B., Loivet, L., Horváth, F. & Séranne, M. (eds) *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen*. Geological Society, London, Special Publications, **156**, 517–540.
- Zweifel, J. 1998. Eustatic versus tectonic control on foreland basin fill. *Contributions to Sedimentary Geology*, **20**, 1–140.