

Depositional environment and petroleum potential of Oligocene rocks in the Waschberg Zone (Austria)

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Abstract: Oligocene successions in the North Alpine Foreland Basin (NAFB) and the Western Carpathians reflect Paratethys-wide paleogeographic changes, which also control their petroleum potential. Whereas these rocks have been studied in detail in both areas, the transition zone is still under-researched. In order to fill this gap, the Oligocene succession in the Waschberg Zone, comprising the Ottenthal Formation (NP21–23) and the overlying Thomasl Formation (NP23–24) has been studied using outcrop (Waldweg section) and borehole samples (Thomasl, Poysdorf) and a multi-disciplinary approach. The Ottenthal Formation is subdivided from base to top into marls and shales (Ottenthal Mbr.), diatomaceous shales (Galgenberg Mbr.) and marlstones (Dynow Mbr.). Biogenic silica contents, determined using atomic absorption spectroscopy, reach 30 wt. % in the carbonate-free Galgenberg Member, but also in the Dynow Members, which is characterized by upward decreasing productivity of calcareous nannoplankton. Close lithological relations exist with the Oligocene succession in the NAFB, but diatoms are largely missing in the latter. Organic matter contents are surprisingly low in the Ottenthal and Thomasl formations in the Waldweg section, which therefore are poor hydrocarbon source rocks. In contrast, the Thomasl Formation, encountered in the Thomasl and Poysdorf boreholes, holds a fair to good hydrocarbon potential (~2.2–2.5 wt. % TOC; type III and type II kerogen) and may generate 1.0 to 1.6 tons of hydrocarbons/m². Obviously TOC contents of borehole samples are significantly higher than in outcrop samples. Because of severe indications of weathering (e.g., presence of gypsum and jarosite), a detrimental effect of weathering on the samples from the Waldweg section cannot be excluded. Biomarker data suggest a nearshore depositional environment with changing oxygen-availability and salinity. Vitrinite reflectance measurements show that the investigated sections are thermally immature.

Keywords: Paratethys, Dynow marlstone, Ottenthal Formation, Thomasl Formation, source rocks, biomarkers.

Introduction

During Early Oligocene time, the Paratethys formed a large, isolated marginal sea with strong temporal salinity variations (e.g., Popov et al. 2004). These conditions favoured oxygen-depleted environments and deposition of fine-grained, often organic matter-rich rocks (Sachsenhofer et al. 2017 cum lit.). A paleogeographic sketch of Picha et al. (2006; Fig. 1) shows that the Lower Oligocene succession in the foreland of the Eastern Alps and in the Western Carpathians accumulated in a continuous depositional environment. Diatoms have only been found in the Carpathians and surrounding areas (e.g., Chert Mbr. in the Ždánice Unit; Galgenberg Mbr. in the Waschberg Zone; Fig. 2). In the rest of the basin, deposition of fine-grained pelitic rocks with abundant fish remains prevailed (e.g., Schöneck Fm., formerly termed “fish shale”; Schulz et al. 2002). Cherts and fish bearing shales are overlain in the North Alpine Foreland Basin and in the Western Carpathians, by bright-coloured marlstones dominated by coccoliths (Dynow Fm. and Dynow Mbr., respectively). They represent the low-salinity Solenovian event (nannoplankton zone NP23; e.g., Voronina & Popov 1984; Rusu 1999; Schulz et al. 2004; Popov & Studencka 2015).

A comparison of Oligocene stratigraphic units in the North Alpine Foreland Basin and the Western Carpathians is provided in Fig. 2. The Lower Oligocene succession contains the most important hydrocarbon source rocks in the North Alpine Foreland Basin (Schöneck Fm., Eggerding Fm.; e.g., Sachsenhofer et al. 2010; Gratzner et al. 2011) and in the Carpathian Foldbelt (Menilite Fm.; e.g., Picha et al. 2006). Lower Oligocene sediments may have also contributed to hydrocarbon accumulations in the Czech part of the Vienna Basin (Franců et al. 1996). Consequently, depositional environment and hydrocarbon potential of these rocks have been studied in detail in the North Alpine Foreland Basin (Schulz et al. 2002, 2004, 2005; Sachsenhofer & Schulz 2006; Sachsenhofer et al. 2010) and in the Western Carpathians (Kotarba & Koltun 2006; Franců & Feyzullaev 2010; Sachsenhofer et al. 2017). In contrast, no source rock data are available from the transition zone between the North Alpine Foreland Basin and the Carpathians in the Waschberg Zone north of Vienna (for location, see Figs. 1 and 3).

To fill this gap, the main aim of this study is to determine bulk mineralogical, geochemical and biomarker data from the Lower Oligocene sediments in the Waschberg Zone and to assess their depositional environment and petroleum potential.

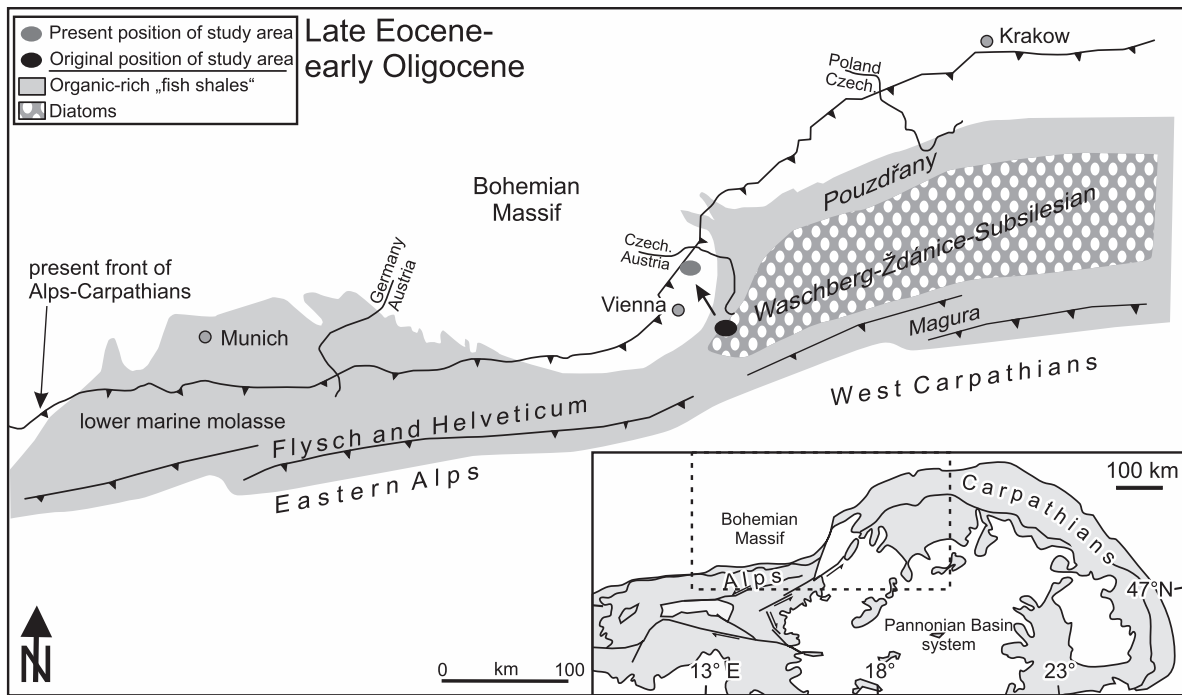


Fig. 1. Early Oligocene paleogeographic map of the North Alpine Foreland Basin and the Western Carpathians (modified after Picha et al. 2006).

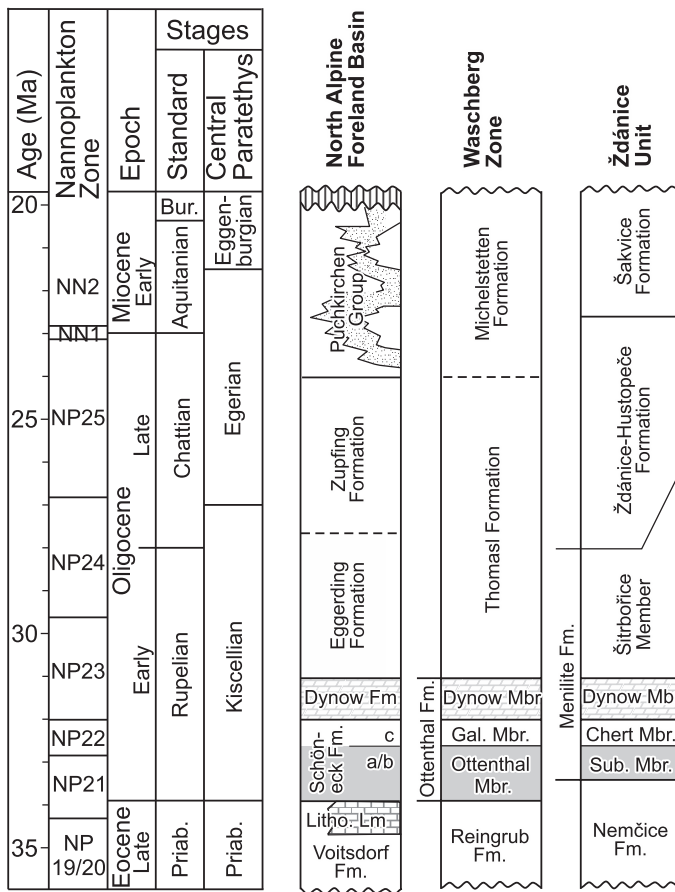


Fig. 2. Stratigraphy of the Oligocene succession in the North Alpine Foreland Basin, the Waschberg Zone and the Ždánice Unit of the Western Carpathians (after Fuchs et al. 2001 and Sachsenhofer et al. 2017).

The study is based on the investigations of surface samples (Waldweg section; Rögl et al. 2001) and core and cuttings samples from boreholes Thomasl 1 and Poysdorf 2 (Fuchs et al. 2001; see Figs. 1 and 3 for sample location).

Geological setting

Tectonic movements and a eustatic sea-level drop resulted in the disconnection of the Paratethys from the world oceans during Late Eocene/Early Oligocene time (e.g., Popov et al. 2004). Increased runoff and isolation of the basin resulted in thermohaline water stratification (Haczewski 1989; Schulz et al. 2005). These stagnant water conditions were favourable for the deposition of organic matter-rich shales and marls during the Early Oligocene (Sachsenhofer et al. 2017). Today the organic-matter rich Lower Oligocene rocks occur in autochthonous position near the base of the North Alpine Foreland Basin, but are incorporated in the Carpathian fold- and thrust belt.

In northeastern Austria (N of Vienna) the Lower Oligocene rocks occur in the Waschberg Zone, which includes Mesozoic and Paleogene rocks as well as very thick Lower Miocene sediments. The Waschberg Zone overthrusts autochthonous Lower Miocene (Eggenburgian to

Karpatian) sediments and is overthrust by Flysch units (Fuchs et al. 2001; Beidinger & Decker 2014; Fig. 3b). Rögl et al. (2001) and Fuchs et al. (2001) described the fine-grained Lower Oligocene succession in the Waschberg Zone micro-paleontologically in great detail and subdivided the succession into the lower Ottenthal Formation and the overlying Thomasl Formation (Fig. 2).

Ottenthal Formation

The Ottenthal Formation includes from base to top the Ottenthal Member (Seifert 1982), the Galgenberg Member and the Dynow Member (Rögl et al. 2001; Fig. 2). The lower part of the Ottenthal Member (NP21–22; Rögl et al. 2001) consists of *Globigerina*-marls and banded marls interbedded with bituminous clay. Sandy or silty layers of limonitic laminae are common. The Galgenberg Member (NP22 to lower NP23) includes diatomites and cherts. The Dynow Member (NP23) comprises light grey, partly silicified coccolithic marls. Diatom and calcareous nannoplankton assemblages suggest a strong decrease in salinity within the diatomites of the Galgenberg Member and that salinity remained low during deposition of the Dynow Member (Rögl et al. 2001). The Ottenthal Formation has been studied in the Waldweg section located east of the village Ottenthal. It is approximately 55 m long and heavily tectonized (Fig. 4). Rögl et al. (2001) distinguished twelve tectonic wedges (labelled by Roman numbers), which are separated by faults.

Thomasl Formation

The Thomasl Formation (upper NP23–NP25) overlies the Ottenthal Formation and consists of sandy shales and sandstones. Single layers of gypsum and jarosite are present in outcrop samples. Following deposition of the low-salinity Dynow

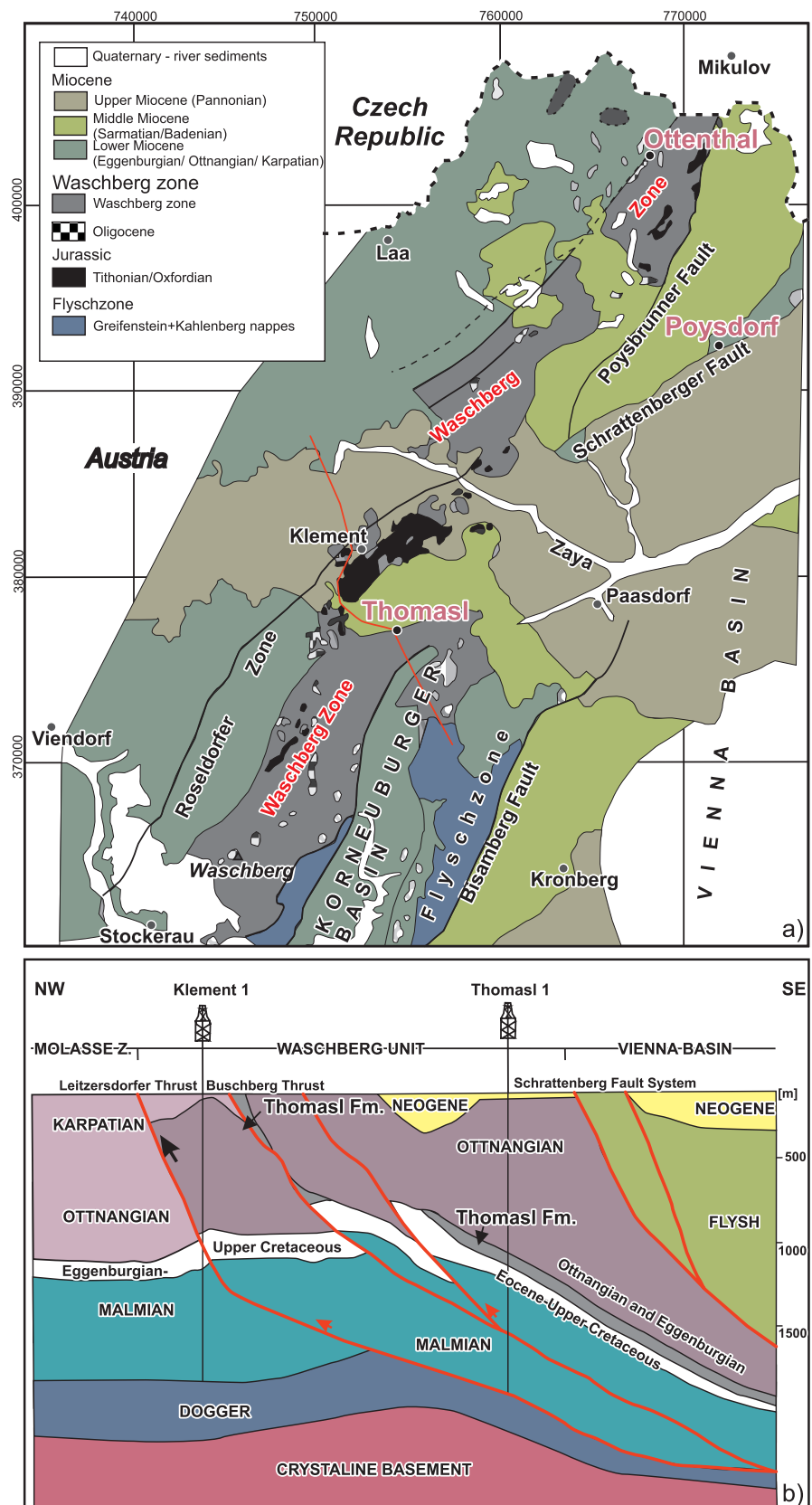


Fig. 3. a — Tectonic map of the Waschberg Zone (simplified from Wessely et al. 2006), showing location of the Ottenthal Waldweg section and the Thomasl 1 and Poysdorf 2 wells. **b** — Cross section through the Waschberg Zone after Fuchs et al. (2001).

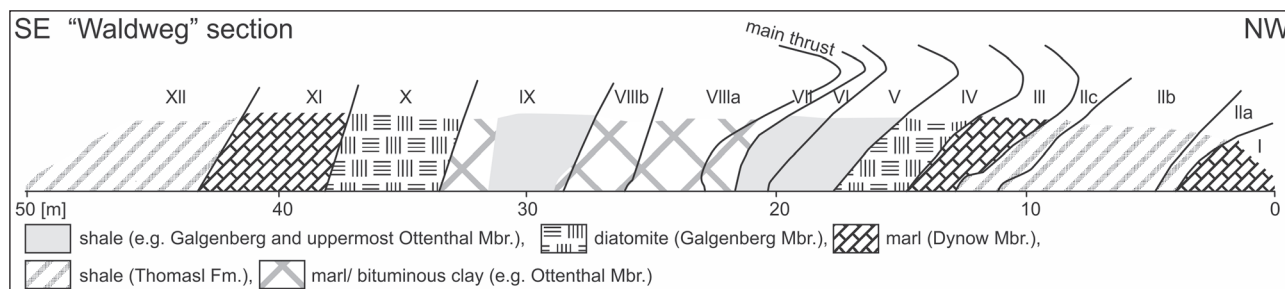


Fig. 4. Tectonic wedges (I–XII) of the Ottenthal Waldweg section (after Rögl et al. 2001).

Member, a gradual but fluctuating return to normal conditions is observed within the Thomasl Formation (Rögl et al. 2001). Slump bodies of shales, gravels and sands at the base of the formation represent the erosional “Šitbořice event” (Krhovský & Djurasinovic 1993).

In boreholes Thomasl 1 and Poysdorf 2 (for location see Fig. 3), the Thomasl Formation overlies Eocene and Upper Cretaceous sediments with a tectonic contact and is followed by Lower Miocene (Eggenburgian) sediments. The Thomasl Formation in well Thomasl 1 is 127 m thick. However, because of the basal tectonic contact, the true thickness may be higher. The autochthonous foraminifera argue toward an upper to middle bathyal environment (Fuchs et al. 2001).

Samples and methods

Samples

74 samples from the Waldweg section representing tectonic wedges Iia/b (Thomasl Fm.), IX (Ottenthal Mbr. and Galgenberg Mbr. “shale”), X (Galgenberg Mbr. “diatomite”), XI (Dynow Mbr.), and XII (Thomasl Fm.) were selected for this study. The samples were provided by NHM (Vienna) and have been previously studied by Rögl et al. (2001).

32 cuttings and 18 core samples from boreholes Thomasl 1 (48°32'1.21 N, 16°24'10.67 E) and Poysdorf 2 (48°41'7.56 N, 16°38'6.42 E) have been taken in the core shed of OMV (Gänserndorf). Cuttings samples were taken every 10 m (Thomasl 1: 1600–1800 m; Poysdorf 2: 2800–2910 m) and represent the Thomasl Formation as well as underlying Lower Eocene and overlying Eggenburgian sediments. Cuttings and cores have been (partly) described by Fuchs et al. (2001).

Methods

Total carbon (TC), total sulphur (S) and total organic carbon (TOC) contents were analysed using an ELTRA Elemental Analyser for all samples. Samples for TOC measurements were decarbonized with concentrated phosphoric acid. Total inorganic carbon (TIC) contents were determined ($TIC = TC - TOC$) and used to calculate calcite equivalent

percentages ($TIC \cdot 8.333$). Results are given in weight percent (wt. %). Pyrolysis measurements were performed using a Rock-Eval 6 instrument (Lafargue et al. 1998). The S_1 and S_2 peaks (mg HC/g rock) were used to calculate the petroleum potential ($S_1 + S_2$ [mg HC/g rock]) and the hydrogen index ($HI = S_2 / TOC \cdot 100$ [mg HC/g TOC]). T_{max} was measured as a maturity indicator.

Semi quantitative maceral analysis (ICCP 1998, 2001) was performed for 24 samples using reflected white light and fluorescence light in a single scan mode and a Leica MPV microscope equipped with 50× and 100× objectives. Vitrinite reflectance measurements followed established procedures (app. 50 measurements per sample, Taylor et al. 1998). Synthetic garnet standards (YAG: 0.89 % Rr; GGG: 1.69 % Rr) were applied.

48 samples were selected for biomarker analysis and extracted using dichloromethane in a Dionex ASE 200 accelerated solvent extractor at 75 °C and 50 bar. Afterwards, asphaltenes were precipitated with a hexane-dichloromethane solution (ratio 80:1 according to volume) and separated by centrifugation. Medium-pressure liquid chromatography (MPLC) using a Köhnen–Willsch instrument was used to separate the hexane-soluble fractions into NSO compounds, saturated hydrocarbons and aromatic hydrocarbons (Radke et al. 1980).

The saturated and aromatic hydrocarbon fractions were analysed by a gas chromatograph equipped with a 30 m DB-5MS fused silica column (i.d. 0.25 mm; 0.25 mm film thickness), coupled to a ThermoFischer ISQ quadrupole mass spectrometer. Using He as carrier gas, the oven temperature was programmed from 70 °C to 300 °C at 4 °C/min increase, followed by an isothermal period of 15 min. With the injector temperature at 275 °C, the samples were injected seamlessly. The spectrometer was operated in the EI (electron ionization) mode over a scan range from m/z 50 to 650 at 0.7 s total scan time. The procession of the data happened with an Xcalibur data system. Individual compounds were identified on the basis of retention time in the total ion current (TIC) chromatogram and the comparison of the mass spectra with published data. Percentages and absolute concentrations of various compound groups in the saturated and aromatic hydrocarbon fractions were calculated using peak areas in the gas chromatograms and their relations to the internal standards (deuterated

n-tetracosane and 1,1'-binaphthyl, respectively). Concentrations were normalized to TOC.

Stable carbon and oxygen isotope ratios of carbonate phases were measured. The powdered samples were treated with 100 % H_3PO_4 at 70 °C in an online system (Gasbench II) and the released CO_2 analyzed by a ThermoFisher DELTA-V ir-MS. The values were normalized to the V-PDB standard for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ and have a standard deviation of 0.8 ‰ for $\delta^{13}\text{C}$ and 0.1 ‰ for $\delta^{18}\text{O}$.

Atomic absorption spectroscopy (AAS) was performed to determine biogenic silica contents using a method described by Zolitschka (1988). Approximately 100 mg sample material and 50 ml of 0.5 mol/l KOH solution were boiled for 1 h to dissolve the opalitic shells. Afterwards 5 ml of the solution were diluted with distilled water (1:1). The light source of the Perkin Elmer 3030 AAS Spectrometer was a hollow-cathode lamp (reduced $\text{N}_2\text{O}-\text{C}_2\text{H}_2$ -flame) made from silicon and calibrated using Merck CertiPUR* Silicon-Standard solution (#1.1231.0500). The silica contents were used to calculate opal percentages (=biogenic silica*2.4).

For bulk mineralogy investigations, 75 X-ray diffractograms (XRD) analyses were recorded using a Panalytical (X'Pert³) diffractometer and sideward-filled powder (~10 μm) mounts with nearly random particle-orientation. XRD analysis was also used to distinguish different types of opal: Opal-A produces a prominent single diffuse band centred at ~4 Å, whereas opal-CT is characterised by three reflections with decreasing intensity (4.11, 4.32, 2.50 Å; Jones & Segnit 1971). Quantitative interpretation was done according to Schultz (1964). All mineral amounts are given as wt. %, with an relative estimated error at 5 %.

The texture and chemical composition of rock samples were investigated on freshly broken surfaces with a Zeiss Evo Ma 15 scanning electron microscope (SEM). In addition an Inca Dry Cool EDX (energy dispersive) spectrometer, a high vacuum system at 10 mm working distance, acceleration voltages of 15 to 20 kV and 10 nA beam current were used.

Results

The results are presented separately for the Waldweg section near Ottenthal (Ottenthal Fm. and Thomasl Fm.) and the Thomasl Formation drilled in boreholes Thomasl 1 and Poysdorf 2.

Waldweg section

Lithology and stratigraphy

Based on age data provided by Rögl et al. (2001), the samples of the Waldweg section (Fig. 4) are arranged into a continuous pseudo-section in Fig. 5. The studied rocks are about 32 m thick and include the Ottenthal Formation and the basal part of the Thomasl Formation. The Ottenthal Formation comprises the Ottenthal Member (33.0–29.6 m), the Galgenberg

Member (29.6–23.9 m), and the Dynow Member (23.9–20.3 m).

The Ottenthal Member consists of laminated brown marls and dark clays with pteropods (Rögl et al. 2001). Gypsum crusts are abundant. The average carbonate content is 21.4 wt. %, but the carbonate content decreases significantly in its upper part.

The Galgenberg Member is largely carbonate-free (average: 0.3 wt. %) and consists of silty shale, overlain by light grey banded and laminated diatomaceous claystone and clayey diatomite. Percentages of biogenic SiO_2 increase upwards (max. 30 wt. %), but are low at the boundary between the Galgenberg Member and the Dynow Member (Fig. 4). Some typical diatoms from the Galgenberg Member are shown in Fig. 6e–h.

The Dynow Member includes whitish to yellowish marl (nannofossil-chalk) with thin dark laminae. Carbonate contents are high (average: 44.6 wt. %) and decrease upwards. Interestingly, SiO_2 contents in the Dynow Member are as high as in the underlying diatomaceous sediments. Fig. 6a–d shows coccoliths and diatoms from a sample near the base of the Dynow Member.

The base of the Thomasl Formation is formed by variegated shales, sandy layers with clasts of glauconitic sand and clay pebbles representing the “Šitbořice Event” (Krhovský & Djurasinovic 1993). These rocks are overlain by dark, mostly carbonate-free shales (carbonate content: 0.9 wt. %), interbedded with marly layers (carbonate content: 22.0 wt. %). A layer with whitish chalk nodules occurs 2.13 m below the top of the profile (95 % calcite). The biogenic silica content is very low (<5 % SiO_2).

Mineralogy

X-ray diffractograms of 61 samples from the Waldweg section have been recorded. Selected X-ray diffractograms are shown in Fig. 7. Mineral percentages have been estimated and are listed in Table 1.

The mineralogical composition of the samples varies in vertical direction. Carbonate minerals are abundant in the marly Ottenthal and Dynow members. Carbonate minerals are dominated by calcite. Dolomite and siderite occur in significant amounts only in the Ottenthal and Galgenberg members. Under the SEM, zoned rhombohedral carbonate minerals can be observed in samples from the Galgenberg Member (23.81 m) and the Thomasl Formation (10.83 m).

According to XRD patterns, opal is abundant in the lower part of the section and present mainly as opal A. Opal A percentages could not be quantified using the XRD approach. However, as its occurrence correlates well with biogenic silica contents, the latter have been used as opal A percentages in the estimation of mineral percentages. Opal contents are most abundant in the Galgenberg and Dynow members (max. 30 %).

High amounts of quartz (max. 78 %) and feldspar (max. 21 %) occur in the Thomasl Formation. The percentages of

the detrital minerals are positively correlated ($r^2=0.67$). Clay mineral percentages vary strongly along the section and include variable amounts of smectite and other expandable clay minerals (ECMs), illite/muscovite and kaolinite.

Pyrite percentages are probably reduced by weathering. This is indicated by the occurrence of abundant jarosite and

gypsum. Clinoptilolite and heulandite, interpreted as alteration products of volcanic ash layers, occur in significant amounts in the Ottenthal Member (33.0–28.5 m) and the Thomasl Formation (13.5–11.5 m).

Stable isotope ratios of carbonate minerals have been determined in carbonate-bearing successions (Fig. 5). $\delta^{13}\text{C}$ values

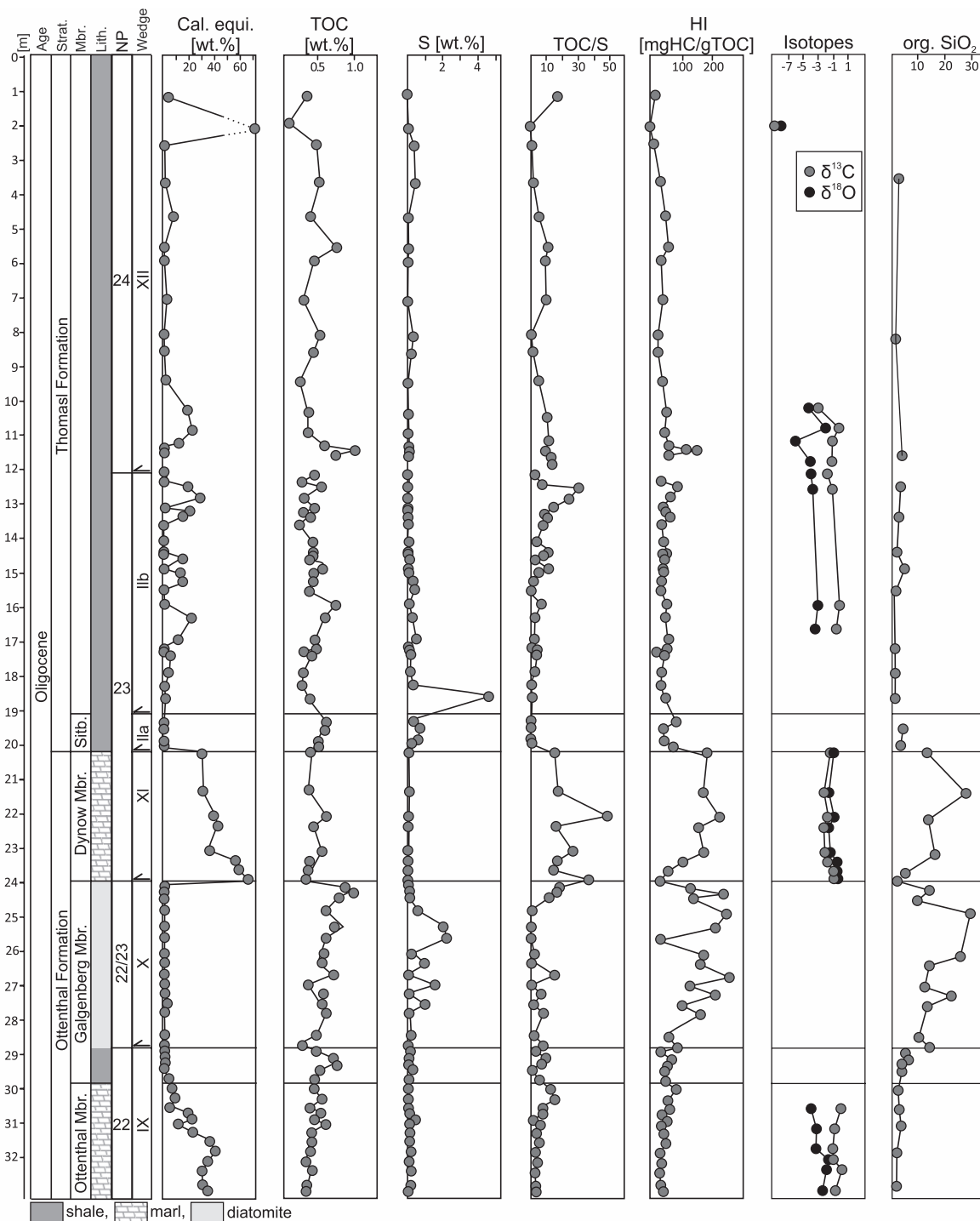
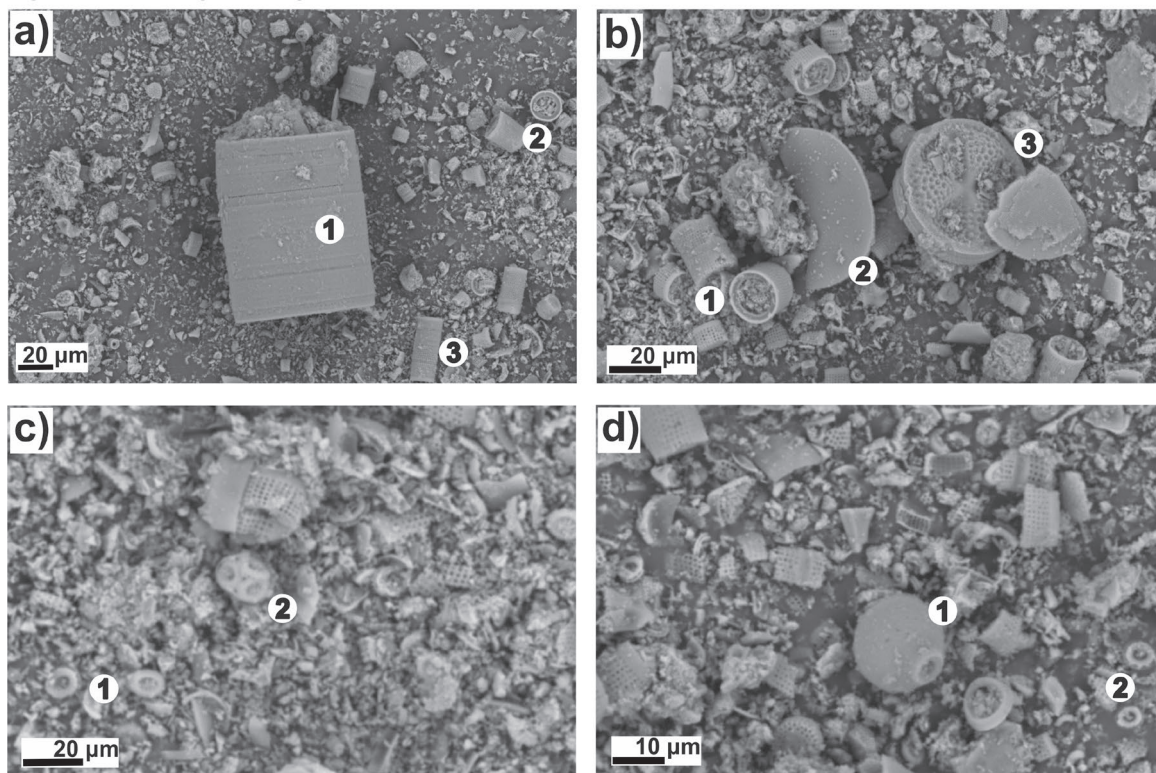


Fig. 5. Bulk geochemical parameters and isotopes of the Oligocene succession in the Waldweg section near Ottenthal. NP — nannoplankton zones; Cal. equi. — calcite equivalents; TOC — total organic carbon; S — total sulphur; HI — Hydrogen Index. Arrows mark boundaries between tectonic wedges.

Dynow Mbr. (~23 m)



Galgenberg Mbr.

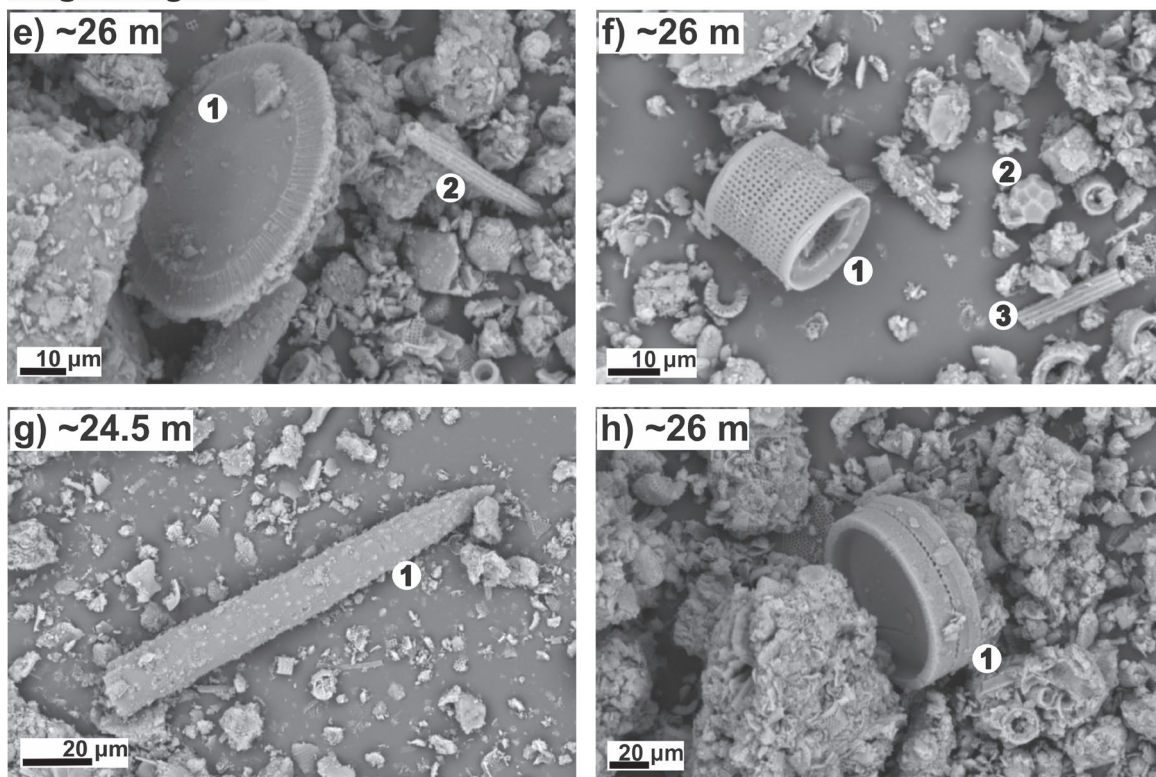


Fig. 6. Scanning electron microscopy (SEM) photographs of diatoms and coccoliths. **a:** 1 *Paralia* (?), 2–3 — *Aulacoseira*; **b:** 1 — *Aulacoseira*, 2 — *Coscinodiscus*, 3 — *Actinopterychus senarius*; **c:** 1 — *Coccolithites cribellum*, 2 *Reticulofenestra* sp.; **d:** 1 — unknown siliceous particle, 2 — *Coccolithites cribellum*; **e:** 1 — *Coscinodiscus*, 2 — sponge spiculae; **f:** 1 — *Aulacoseira*, 2 — Braarudosphaerales (?), 3 — sponge spiculae; **g:** 1 — sponge spiculae; **h:** 1 *Paralia* (?).

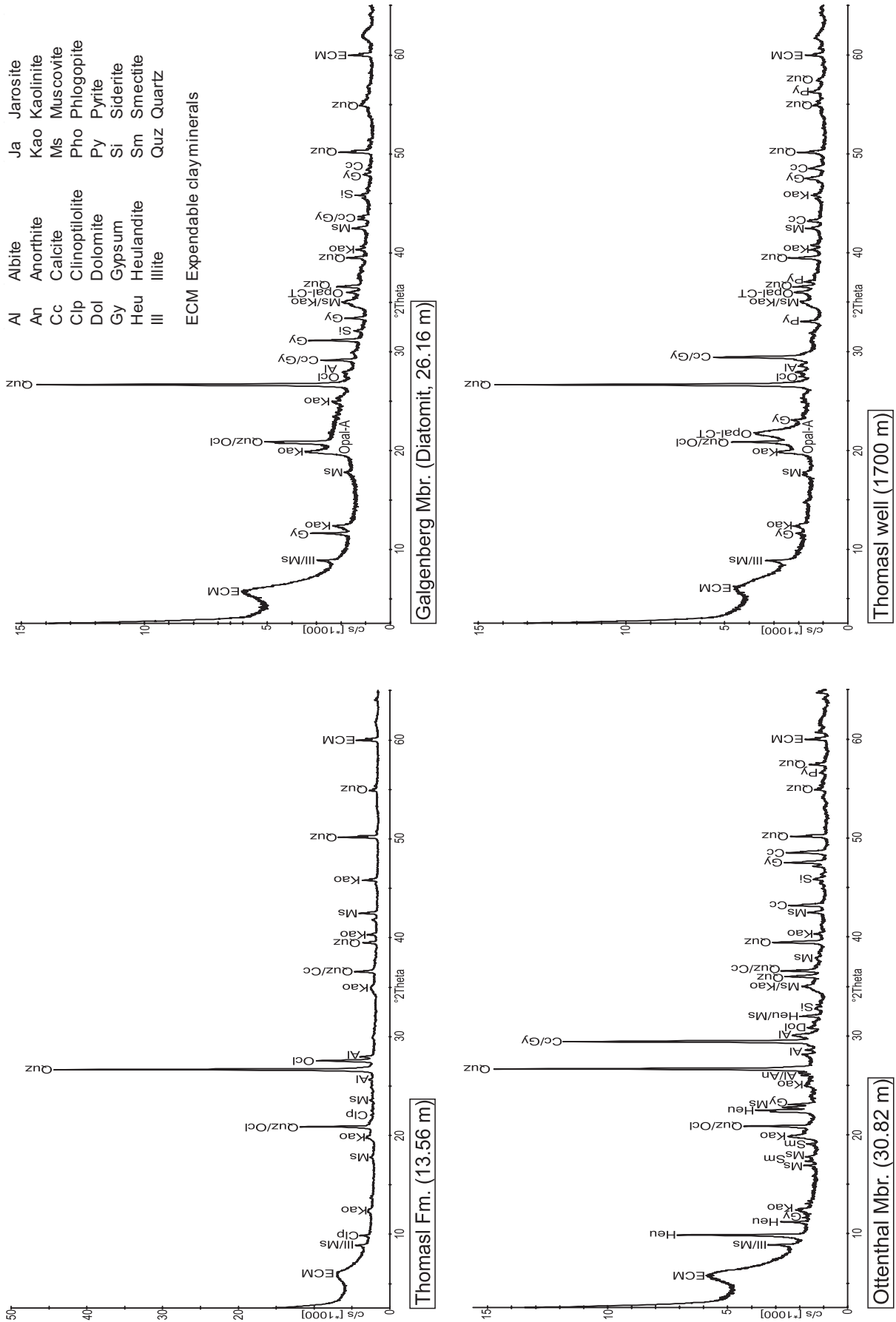


Fig. 7. XRD diagrams of three samples from the Waldweg section and one sample from the Thomasl well. Note the presence of opal-A in the outcrop section (26.16 m) and of opal-CT in the borehole sample (Thomasl, 1700 m). Heulandite is especially abundant in the Waldweg section (Thomasl Fm. and Ottenthal Mbr.).

Table 1: Semi-quantitative mineral percentages for the Ottenthal section.

XRD	Depth [m]	Quartz	Opal-CT	Opal-A	Plagioclase	K-Felspar	Calcite	Dolomite	Siderite	Pyrite	Jarosite	Heulandite*	Gypsum	Σ Clay
		[vol. %]												
Waldweg section														
Thomasl Fm.	1.22	26.7	0.0	0.0	3.0	1.7	0.0	2.7	0.0	0.0	0.0	0.0	0.0	65.9
	2.13	74.2	0.0	0.0	7.4	13.8	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.63	58.0	0.0	0.0	8.4	11.3	2.8	0.0	0.0	0.0	16.5	0.0	0.0	3.0
	3.72	50.9	0.0	2.5	0.0	5.4	5.3	0.0	0.0	0.0	13.6	0.0	0.0	22.4
	5.62	78.1	0.0	0.0	8.8	7.8	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6.01	25.3	0.0	0.0	3.3	3.1	1.4	0.0	0.0	0.0	0.0	0.0	0.0	66.9
	8.67	28.8	0.0	0.0	2.3	2.1	0.0	0.0	0.0	0.0	0.0	0.0	1.4	65.4
	9.52	71.2	0.0	0.0	6.3	6.1	0.0	0.0	0.0	0.0	0.0	0.0	4.4	11.9
	11.38	42.3	0.0	0.0	4.3	4.4	39.7	0.0	0.0	0.0	0.0	0.0	0.0	9.3
	11.52	37.9	0.0	3.8	4.1	3.0	0.0	0.0	0.0	0.0	0.0	41.6	0.0	9.7
	11.66	23.9	0.0	0.0	3.3	2.2	0.0	0.0	0.0	0.0	2.5	29.2	0.0	38.9
	12.45	14.0	0.0	3.5	1.7	1.2	25.8	0.0	0.0	0.0	0.0	25.7	0.0	28.1
	12.78	9.5	0.0	0.0	1.3	0.8	33.2	0.4	0.0	0.0	0.0	35.9	0.0	18.9
	13.07	57.3	0.0	0.0	4.7	4.1	0.0	0.0	0.0	0.0	1.8	32.1	0.0	0.0
	13.34	15.3	0.0	2.8	1.3	1.6	0.0	0.0	1.2	0.6	1.0	12.9	0.0	63.4
	13.56	44.4	0.0	0.0	0.0	16.3	0.0	0.0	0.0	0.0	0.0	3.8	0.0	37.5
	14.06	21.8	0.0	0.0	2.4	2.3	2.3	1.6	0.0	0.0	0.0	5.2	1.1	63.1
	14.45	28.8	0.0	0.0	2.2	1.8	0.0	0.0	0.0	0.0	0.0	9.2	0.0	57.8
	14.58	14.5	0.0	0.0	1.4	1.0	26.5	0.9	2.5	0.0	0.0	7.8	0.0	45.5
	14.97	13.6	0.0	0.0	1.6	1.1	25.9	0.0	0.0	0.0	4.4	7.1	0.0	46.2
15.21	17.8	0.0	0.0	1.2	1.4	25.2	0.0	0.0	0.0	2.1	8.2	3.7	40.5	
15.49	25.6	0.0	1.6	1.7	1.0	0.0	0.0	0.0	0.0	2.4	6.8	2.4	58.6	
16.28	14.5	0.0	0.0	1.3	1.0	31.1	1.4	0.0	0.0	2.2	10.2	2.8	36.2	
16.91	19.4	0.0	0.0	1.8	2.3	19.8	0.0	2.4	0.0	0.0	7.5	5.2	41.5	
17.28	36.4	0.0	0.0	1.6	3.8	0.0	0.0	0.0	0.0	0.6	1.0	1.0	55.7	
17.38	27.1	0.0	0.0	1.7	1.8	2.6	1.0	0.0	0.0	1.8	0.0	3.4	60.6	
17.87	69.6	9.1	1.4	4.8	4.9	0.0	4.0	0.0	0.0	0.0	0.0	6.1	0.0	
18.26	69.4	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	2.0	15.0	5.0	4.5	
18.63	8.9	0.0	1.3	0.9	0.7	0.0	0.0	0.0	0.0	11.8	0.5	56.1	19.9	
19.10	64.3	0.0	0.0	4.5	4.0	0.0	0.0	0.0	0.0	10.6	6.5	0.0	10.1	
19.29	30.3	0.0	4.5	4.3	2.4	0.0	0.0	0.0	0.0	18.1	22.1	0.0	18.3	
19.78	25.9	0.0	3.3	2.9	1.6	0.0	2.6	0.0	0.0	0.0	0.0	0.0	63.8	
20.00	19.9	1.7	13.3	0.0	0.0	46.9	0.0	0.0	0.0	0.0	0.0	0.0	18.2	
21.13	8.1	2.2	27.9	0.0	0.0	61.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	
22.15	9.5	0.0	20.0	0.0	0.0	58.4	0.0	0.0	0.0	0.0	0.0	0.0	12.1	
22.87	7.9	1.5	16.3	0.0	0.5	42.8	0.0	0.0	0.6	0.0	0.0	0.0	30.5	
23.42	5.0	1.2	5.2	0.0	0.6	88.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23.95	4.7	0.0	14.2	0.0	0.0	81.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
24.25	34.7	2.7	9.7	1.9	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.5	
24.63	16.0	0.0	29.5	0.0	0.0	5.3	0.0	0.0	0.0	6.9	0.0	2.9	39.4	
25.43	14.4	2.5	13.9	1.1	0.9	0.0	1.0	0.0	0.0	16.2	0.0	11.2	38.7	
26.16	19.9	0.0	14.2	1.5	1.1	0.0	6.8	0.0	0.0	0.0	3.3	3.5	49.7	
26.79	16.4	2.2	12.4	1.8	1.2	0.0	0.8	1.5	0.0	6.8	0.0	23.8	32.9	
27.05	4.9	0.0	22.4	0.0	0.0	0.0	1.4	0.0	0.0	0.0	5.0	1.1	65.1	
28.26	26.8	4.0	10.2	1.5	0.0	0.0	2.9	0.0	0.0	0.0	0.0	3.6	50.9	
28.83	39.4	16.3	5.2	6.8	4.6	0.0	5.6	7.5	0.0	0.0	14.6	0.0	0.0	
29.22	43.0	0.0	4.2	3.8	2.3	6.5	1.7	10.2	0.0	0.0	23.5	0.0	4.8	
29.65	29.7	0.0	0.0	2.7	0.0	3.1	0.0	4.5	0.0	0.0	19.2	0.0	40.8	
30.22	34.8	0.0	0.0	3.4	2.2	18.1	2.2	7.4	2.1	0.0	23.5	1.5	4.7	
30.82	16.1	0.0	0.0	1.4	0.0	26.6	1.3	3.6	0.0	0.0	16.7	0.6	33.8	
30.96	20.8	0.0	3.6	1.3	0.0	15.2	0.7	3.8	0.0	0.0	19.4	0.7	34.5	
31.20	16.1	0.0	0.0	1.2	0.8	27.9	1.3	1.4	1.1	0.0	24.7	0.8	24.7	
31.47	16.9	0.0	0.0	1.4	0.0	59.8	0.0	2.4	0.0	0.0	15.3	0.8	3.4	
31.75	12.9	0.0	2.0	0.8	0.8	42.5	1.5	2.1	1.1	0.0	17.5	0.5	18.4	
32.05	12.5	0.0	0.0	0.9	0.6	44.0	0.0	1.7	0.0	0.0	9.9	0.5	30.0	
32.73	22.6	0.0	1.9	0.0	1.8	52.3	1.5	2.3	0.0	0.0	9.4	1.1	7.2	
32.91	20.0	0.0	0	0.7	0.8	50.5	0.0	0.0	0.0	0.0	5.5	0.0	22.5	

*Heulandite and clinoptilolite

typically vary between +0.1 and -3.0 ‰. Only the chalk layer at 2.23 m depth is characterized by more negative values (-8.7 ‰; Fig. 5), indicating either reduced salinity or bacterial activity during carbonate diagenesis. $\delta^{18}\text{O}$ values are between -6.0 and -1.9 ‰ in the Ottenthal Member and the Thomasl Formation. The layer with chalk nodules has a $\delta^{18}\text{O}$ value of -7.9 ‰. Surprisingly, $\delta^{18}\text{O}$ values in the low-salinity Dynow Member are less negative (-1.8 to -0.7 ‰) than in the rest of the succession. A possible explanation would be lower water temperatures during deposition of the Dynow Member. However, any other supporting evidence for this explanation is missing.

Bulk geochemical parameters and organic petrography

TOC contents are low in Oligocene sediments of the Waldweg section (0.08–1.13 wt. %; average: 0.47 wt. %), but increase upwards in the Ottenthal and Galgenberg members (Fig. 5). Hence the maximum TOC content (1.13 wt. %), is observed near the top of the Galgenberg Member. TOC contents of the Dynow Member and the Thomas Formation are typically in the range of 0.3–0.9 wt. %. However, a sample at 11.52 m is characterized by a TOC content of 1.13 wt. % (Fig. 5).

HI values vary from 7 to 252 mg HC/g TOC, indicating the dominance of type III kerogen (Figs. 5 and 8). Values above 150 mg HC/g TOC are restricted to the diatomaceous section of the Galgenberg Member and the Dynow Member.

Sulphur contents are generally low (av.: 0.3 wt. %), except in the lower part of the Thomasl Formation (~18 m, max.: 4.6 wt. %). However, S contents are probably influenced by weathering. Consequently, the significance of TOC/S ratios (0.3–49.2) must not be overestimated. The highest values are

observed in the Dynow Member. Another upward increase in TOC/S ratios is observed within the Thomasl Formation (~12 m).

Two samples with TOC contents exceeding 1 wt. % were selected for maceral analysis (Table 2). The sample from the Galgenberg Member (23.81 m) comprises a high percentages of terrestrial macerals (vitrinite: 50 vol. %; inertinite: 8 vol. %; terrestrial liptinite (sporinite): 25 vol. %). In contrast, the sample from the Thomasl Formation (10.83 m) includes 72 vol. % aquatic liptinites (e.g., lam- and tel-alginite) and a relative low amount of terrestrial macerals. This difference is not reflected by HI values, which are low in both samples (Table 2). Foraminifera (<1.2 vol. %), dinoflagellate cysts and glauconite can be observed in small percentages. Vitrinite reflectance (~0.30 % R_o) and low T_{max} values (average: 420 °C) show that the organic matter is immature.

Molecular composition of hydrocarbons

The extractable organic matter (EOM) yields vary between 6.8 and 62.1 mg/g TOC and are dominated by polar compounds (NSO; 56–87 % of EOM). Due to the low extract yields, a separation of the saturated and aromatic compounds was impossible.

Ion traces of saturated and aromatic hydrocarbons as well as steranes and hopanes patterns of a sample from the Thomasl Formation (33 m) are shown in Fig. 9. Biomarker data of samples from the Waldweg section are listed in Table 3 and are plotted versus depth in Fig. 10.

n-alkanes and isoprenoids: The Waldweg section is dominated by long chain n-alkanes ($n\text{-C}_{26-32}$: av. 66 %), which are characteristic for higher land plants (mainly plant waxes; Eglinton & Hamilton 1967). Middle chain n-alkanes ($n\text{-C}_{21-25}$), typical for aquatic macrophytes (Ficken et al. 2000), occur in

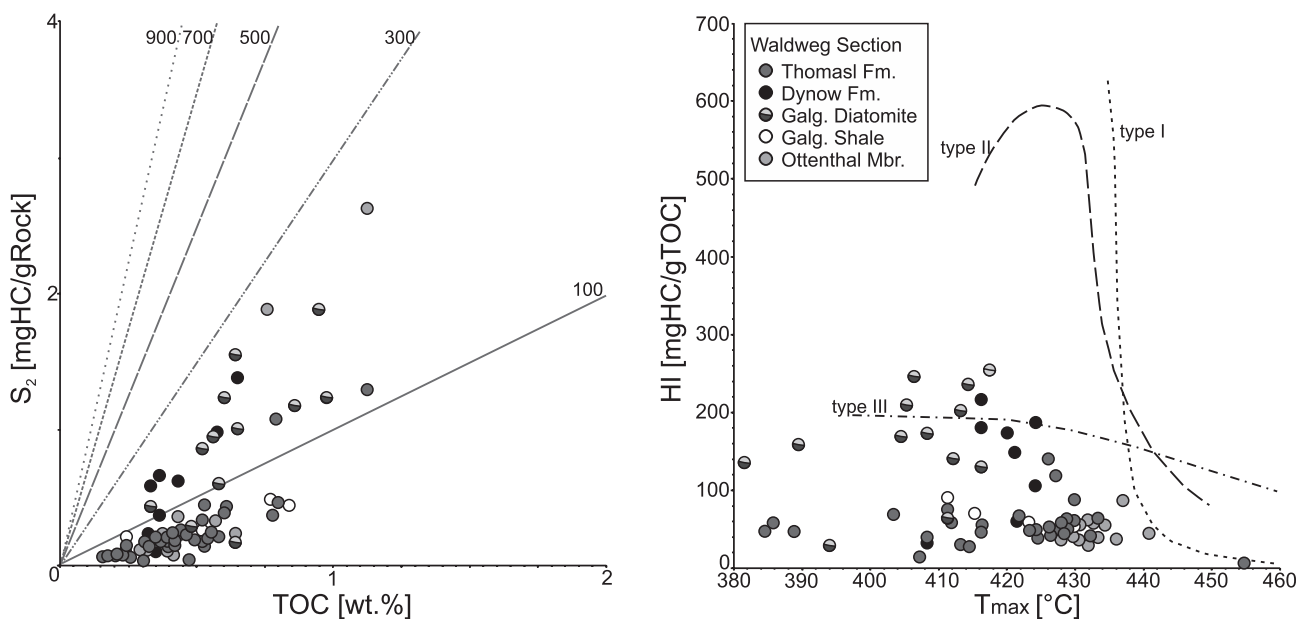


Fig. 8. Plots of S_2 vs. TOC and Hydrogen Index (HI) vs. T_{max} (according to Espitalie et al. 1984) for the Waldweg section.

Table 2: Organic petrography incl. maceral composition and vitrinite reflectance measurements of selected samples of the Waldweg section, Thomasl and Poysdorf wells.

Depth [m]	TOC [wt. %]	HI [mg HC/g TOC]	VR [% Rr]	Liptinite			Σ macerals [vol. %]	Foraminifera [vol. %]	Glauconite yes/no		
				Vitrinite	Inertinite	[% OM normalized]					
Waldweg Section											
10.83	1.13	115	0.25	17	0	11	31	41	2.83	0	y
23.81	1.13	139	0.33	50	8	25	17	<1	2.11	1.239	n
Thomasl 1 cuttings											
1610	1.88	29		41	47	12	0	0	2.1	0.0	y
1620	0.98	14		71	0	29	0	0	1.9	0.0	n
1630	1.13	37	0.37	56	6	11	6	22	2.8	0.6	y
1640	1.05	123	0.37	62	0	27	8	4	2.3	0.0	n
1650	1.88	165		57	0	25	14	4	3.9	0.0	y
1660	1.63	140	0.38	55	3	21	14	7	3.4	0.2	y
1670	2.32	208		50	0	18	21	11	4.5	0.0	y
1680	1.97	191		53	3	27	7	10	4.4	0.4	y
1690	2.39	161									y
1700	3.67	416	0.35	69	9	11	4	7	7.7	0.0	y
1710	3.26	307		66	9	17	9	0	6.6	0.9	n
1720	2.66	223		48	4	28	8	12	4.4	0.9	y
1730	2.57	168		64	18	13	3	3	5.3	0.1	y
1740	2.46	183	0.35	56	6	22	12	4	5.2	0.0	y
1750	3.18	135		76	0	12	7	5	6.4	0.3	y
1760	3.33	116	0.37	68	4	14	4	11	5.1	0.2	y
1770	2.54	101		61	0	21	7	11	4.2	0.0	y
1780	1.28	38		54	17	11	0	18	2.3	0.2	y
Thomasl 1 core											
1760.4	2.43	44		50	0	8	25	17	3.7	0.0	y
Poysdorf 2 core											
2814.8	6.23	32	0.38	70	8	15	6	2	8.9	6.2	y
2815.1	1.17	139	0.39	60	10	24	0	7	3.3	5.4	y
2817.0	1.5	122	0.35	52	3	24	7	14	3.0	0.3	y

Depth — measured depth, TOC — total organic carbon, HI — hydrogen index, VR — vitrinite reflectance. TOC and HI were determined using an ELTRA Elemental Analyser and a Rock-Eval 6 instrument, respectively.

very low amounts (av. 13 %). The short chain n-alkanes, in general related to algae and microorganisms, are by far less frequent than the long chains but more dominant than the medium-chain n-alkanes (n-C₁₅₋₂₀: av. 21 %).

The pristane/phytane (Pr/Ph) ratio is considered as a redox parameter by Didyk et al. (1978). The ratio varies between 0.46 and 1.27. It displays an upward decreasing trend in the interval comprising the diatomites of the Galgenberg Member and the Dynow Member. Pr/Ph ratios in the Thomasl Formation are typically below 1.0 and show a subtle upward decrease.

The C₂₅ HBI (highly branched isoprenoid) thiophenes are formed by the sulfurization of C₂₅ HBI alkanes and are indicative for diatoms. Their concentrations vary strongly along the profile. As expected, high concentrations of C₂₅ HBI thiophenes are observed in the diatomaceous Galgenberg Member (up to 9.9 µg/g TOC). Surprisingly, the maximum concentration (13.5 µg/g TOC) is detected in the Thomasl Formation at ca. 11 m depth.

Steroids: The steroid concentration varies from 1.2 to 8.1 µg/g TOC in the Ottenthal and Galgenberg members and reaches maxima in the Dynow Member (12.5 µg/g TOC) and in the lower part of the Thomasl Formation (12.9 µg/g TOC). C₂₇ and C₂₉

steranes dominate over C₂₈ steranes (Fig. 11). Algae are discussed as precursors for C₂₇, whereas land plant waxes are the likely origin of C₂₉ steranes (Volkman 1986). Steroids/hopanooids ratios range from 0.03 to 0.27, which indicates organic matter input with major contribution of bacterial biomass (Moldowan et al. 1986). The concentration of monoaromatic steroids ranges from 0.08–1.42 µg/g TOC.

Terpenoides: Hopanes are non-aromatic cyclic triterpenoides that originate from precursors in bacterial membranes (Ourisson et al. 1979). Their concentration varies between 4.5 and 122.4 mg/g TOC. The 22S/(22S+22R)C₃₁ hopane isomerization ratio is a maturity parameter and reaches its equilibrium (~0.6) before oil expulsion (Peters et al. 2005). Within the Waldweg section, the 22S/(22S+22R) ratio varies between 0.19 and 0.41. The ratio of Ts (C₂₈ 18 α -trisorhopane) and Tm (C₂₇ 17 α -trisorhopane) is a parameter both dependent on source and maturity (Moldowan et al. 1986). In the Waldweg section the Ts/Tm ratio varies between 0.06 and 0.24 (exception: sample 17.43 m with a Ts/Tm ratio of 1.0). The $\beta\beta$ -hopanes (1.4–43.38 µg/g TOC) are highly specific for immature to early oil generation source rocks (Seifert & Moldowan 1980). Hop-17(21)-ene is likely sourced from methanotrophic bacteria (Thiel et al. 1999) and often occurs in combination with

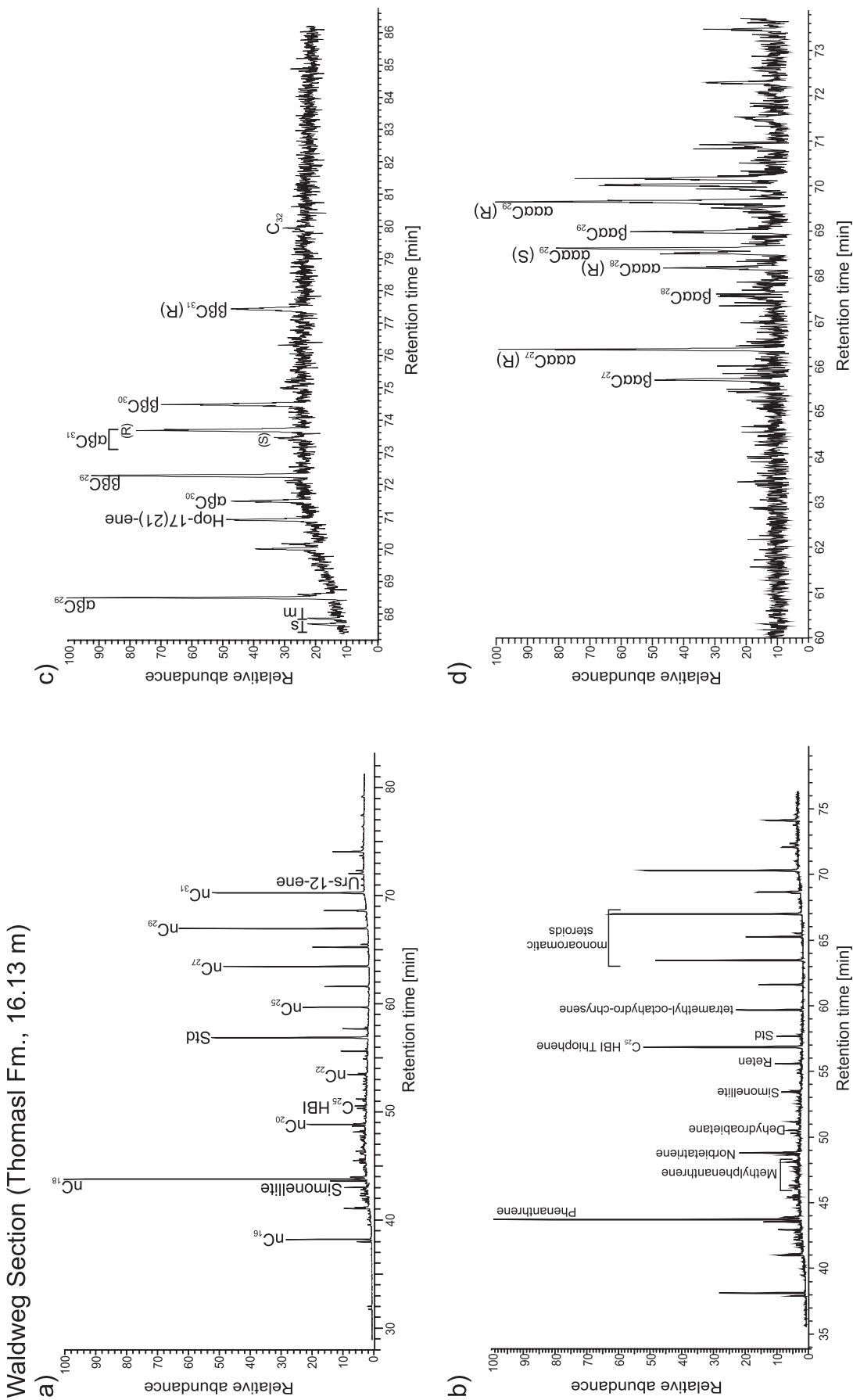


Fig. 9. Ion traces of the saturated (a; m/z 85) and aromatic (b) hydrocarbon fractions and hopanes (c; m/z 191) and steranes (d; m/z 217+218) patterns of the Waldweg section (Thomasl Formation, 16.13 m). n-alkanes are labelled according to their carbon number.

Table 3: Organic geochemical data of samples from the Waldweg section.

Waldweg section	Depth [m]	TOC	HI	EOM	HC	NSO	Asph.	n-C ₁₅₋₂₀	n-C ₂₁₋₂₅	n-C ₂₆₋₃	Pr/Ph	C25 HBI	Steroids	C ₂₇	C ₂₈	C ₂₉	
		[wt. %]	[mg HC/g TOC]	[µg/g TOC]				[wt. %]				[µg/g TOC]		Steranes/ Steranes/	Steranes/ Steranes/	Steranes/ Steranes/	
Thomasl Formation	1.44	2.58	2	6.81	5	72	23	24	14	62	0.61	2.40	5.6	0.50	0.13	0.36	
	3.03	0.52	33	35.02	5	71	24	5	16	79	0.86	0.02	2.9	0.39	0.22	0.40	
	4.93	0.80	58	27.88	7	56	37	12	12	76	0.55	5.90	4.3	0.36	0.16	0.48	
	7.48	0.53	27	17.07	2	75	23	3	10	88	0.47	0.89	4.0	0.40	0.16	0.44	
	10.83	1.13	115	22.94	4	65	31	8	16	77	0.93	1.50	2.8	0.54	0.10	0.36	
	10.97	0.79	138	40.14	2	74	25	7	18	77	0.80	13.53	3.9	0.56	0.10	0.34	
	12.70	0.53	85	25.11	10	87	4	16	17	65	0.70	1.66	4.0	0.41	0.23	0.36	
	13.32	0.42	39	31.41	13	74	13	29	17	55	0.98	2.91	2.4	0.49	0.14	0.38	
	15.10	0.54	37	37.14	7	73	20	35	12	53	0.71	2.92	2.0	0.40	0.17	0.43	
	16.13	0.78	47	30.46	8	66	27	28	12	60	1.27	0.83	1.1	0.48	0.14	0.38	
	17.43	0.46	49	38.94	4	73	23	7	13	81	0.04	1.78	4.5	0.45	0.17	0.38	
	Sitb.	18.88	0.58	36	33.58	12	69	19	33	17	50	1.08	2.09	12.9	0.44	0.26	0.30
		19.56	0.52	65	53.26	5	66	29	15	17	70	0.89	0.43	2.7	0.48	0.23	0.30
	Dynow Mbr.	21.58	0.65	214	34.92	3	62	35	13	10	78	0.50	0.68	5.8	0.34	0.18	0.49
22.60		0.57	172	40.96	5	60	36	14	9	77	0.46	1.70	12.3	0.22	0.26	0.52	
Galgenberg Mbr.	Diatomite	23.81	1.13	236	62.06	3	53	44	10	12	78	0.82	0.68	3.2	0.29	0.27	0.44
		24.80	0.94	202	55.93	2	66	32	24	11	66	1.06	0.89	5.5	0.29	0.21	0.50
		26.20	0.75	252	59.76	6	51	43	57	12	28	1.54	3.56	1.2	0.35	0.18	0.47
		27.32	0.67	156	62.61	16	59	25	74	9	13	1.57	9.93	3.1	0.46	0.17	0.36
		28.63	0.77	64	41.92	6	64	30	35	12	53	0.63	1.62	8.0	0.36	0.17	0.47
shale	29.82	0.57	58	26.80	4	77	19	6	12	82	0.52	0.70	1.5	0.42	0.12	0.46	
	30.59	0.64	34	45.76	3	57	40	16	14	70	0.68	1.66	2.2	0.36	0.16	0.49	

Waldweg section	Depth [m]	Steroids/ Hopanoids	Hopanes	22S/(22S+22R)	Ts/Tm	ββ-Hopanes	Hop-17(21)-ene	Benzohop.	Phenanthren	MPI	Di/(Di + Tri)	Di+Tri	
		[µg/g TOC]	[µg/g TOC]	C ₃₁ -Hopanes		[µg/g TOC]	[µg/g TOC]	[µg/g TOC]	[µg/g TOC]		terpeno.	terpeno.	
Thomasl Formation	1.44	0.13	14.42	0.19	0.17	5.76	0.78	1.87	0.8	0.12	0.71	0.80	
	3.03	0.05	24.18	0.21	0.19	8.13	1.92	5.33	1.8	0.23	0.63	0.75	
	4.93	0.06	122.37	0.14	0.16	43.38	7.56	2.99	17.4	0.30	0.58	11.83	
	7.48	0.05	59.32	0.22	0.16	22.12	3.34	1.01	1.3	0.14	0.20	1.30	
	10.83	0.05	22.38	0.20	0.13	10.20	0.90	2.37	5.6	0.27	0.68	2.11	
	10.97	0.06	69.40	0.21	0.13	27.26	3.03	20.55	8.2	0.71	0.72	5.92	
	12.70	0.11	17.93	0.34	0.24	6.95	2.51	8.16	1.8	0.32	0.54	2.36	
	13.32	0.12	87.10	0.25	0.20	26.32	8.73	11.19	5.6	0.57	0.44	8.51	
	15.1	0.15	31.94	0.30	0.19	9.95	2.11	5.27	16.1	0.26	0.48	4.01	
	16.13	0.08	25.63	0.30	0.11	8.00	1.50	4.58	6.4	0.27	0.51	2.17	
	17.43	0.11	96.74	0.18	1.00	38.02	7.93	8.20	2.8	0.35	0.15	5.92	
	Sitb.	18.88	0.27	16.04	0.21	0.28	4.81	1.27	0.12	2.5	0.34	0.15	3.38
		19.56	0.21	4.54	0.27	0.23	1.40	0.26	0.55	0.6	0.38	0.25	0.55
	Dynow Mbr.	21.58	0.04	38.89	0.34	0.07	16.83	1.62	7.10	2.4	0.28	0.47	1.68
22.60		0.04	53.68	0.41	0.12	24.94	2.79	5.68	3.0	0.23	0.32	1.46	
Galgenberg Mbr.	Diatomite	23.81	0.03	121.71	0.33	0.09	56.66	5.89	5.02	7.1	0.18	0.45	2.84
		24.80	0.04	77.40	0.31	0.06	36.01	3.81	22.59	4.3	0.45	0.70	2.96
		26.20	0.08	28.19	0.31	0.15	11.97	1.90	2.64	16.0	0.17	0.80	2.46
		27.32	0.14	24.77	0.43	0.19	9.62	1.79	2.41	13.6	0.31	0.67	4.55
		28.63	0.13	29.34	0.26	0.24	8.87	2.58	1.25	6.1	0.27	0.56	2.33
shale	29.82	0.09	21.65	0.30	0.24	7.15	2.11	10.08	1.7	0.48	0.38	2.89	
	30.59	0.09	49.93	0.19	0.18	15.75	3.62	11.60	15.3	0.42	0.53	5.92	

TOC - total organic carbon, HI - hydrogen index, EOM - extracted organic matter, HC - hydrocarbons, NSO - polar compounds, Asph. - asphaltenes, n-C₁₅₋₂₀ - short-chain alkanes, n-C₂₁₋₂₅ - medium-chain alkanes, n-C₂₆₋₃₂ - long-chain alkanes; Pr/Ph - Pristane/Phytane ratio; MAS - monoaromatic steroids; MPI - Methylphenanthrene Index; Di/(Di+Tri) terpeno. - Diterpenoids/triterpenoids ratio.

carbonate rocks. It is present in relatively low concentrations (<0.43 µg/g TOC). Benzohopanes (<22.59 µg/g TOC) are derived from unknown precursors and occur at an early or late mature range.

Phenantrenes, methylphenantrenes: Phenantrenes (Phen) and 3,2,9,1-methylphenantrenes derive from a variety of non-specific precursors (e.g., steroids and triterpenoids)

(Tissot & Welte 1984). The phenanthrene concentration varies between 0.6 and 16.1 µg/g TOC. The MPI-1 (Radke & Welte 1981) is typically below 0.5.

Land plant related biomarkers: Norbietetriene, simonelite, retene and dehydrobietetriene are gymnosperm-derived biomarkers and occur in low concentrations (<6.8 µg/g TOC), retene being the most abundant. Angiosperm derived

biomarkers (triterpenoids) like variations of crysene and picene vary between 0.23–5.02 µg/g TOC. The sum of di- and triterpenoids is often used as a proxy for landplant input, whereas the di-/((di+triterpenoids) ratio is an established proxy for the ratio of gymnosperms to angiosperms (e.g.,

Bechtel et al. 2008). The sum of di- and triterpenoid is relative constant in the lower part of the succession (<5.92) and reaches two peaks within the Thomasl Formation (<11.83 µg/g TOC). The di-/((di+triterpenoids) ratio is low (<0.80) indicating a predominance of angiosperms.

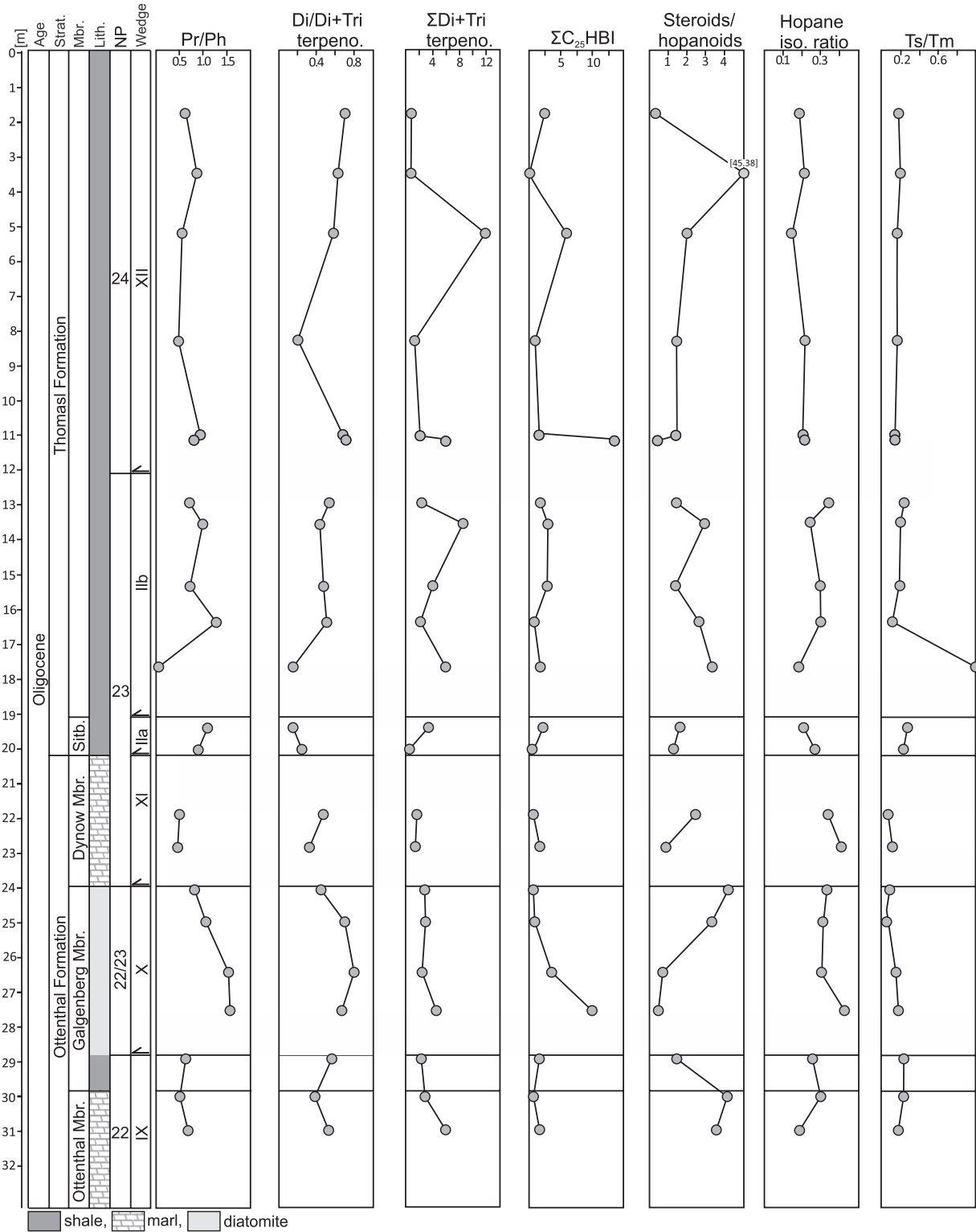


Fig. 10. Biomarker ratios and concentrations of Oligocene rocks from the Waldweg section.

Borehole Thomasl 1

Lithology and stratigraphy

The Thomasl Formation in borehole Thomasl 1 extends from 1763 to 1636 m depth. Its base is formed by a thrust plane separating the Thomasl Formation from Lower Eocene calcareous shale and clay. 12 core samples provide information on the lowermost 3 m of the Thomasl Formation

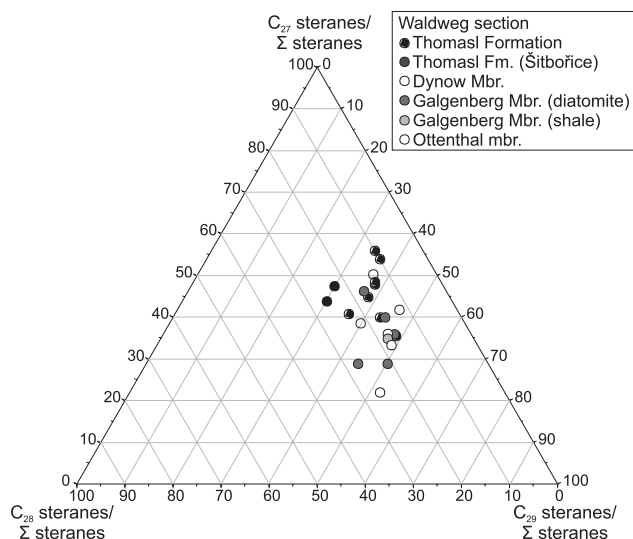


Fig. 11. Distribution of C_{27} , C_{28} and C_{29} steranes for samples from the Waldweg section.

(1763–1760 m) and indicate an upward increase in carbonate content in the dark brownish-grey sediments (Fig. 12).

Based on cuttings data, the Thomasl Formation consists mainly of marly shales with an average carbonate content of 17.1 wt. %. According to Fuchs et al. (2001), a prominent spike in the resistivity log at around 1695 m may indicate a layer with increased content of siliceous microfossils. This interpretation is supported by elevated organic SiO_2 percentages at 1700 m depth (Fig. 12). The Thomasl Formation is overlain by Lower Miocene (Eggenburgian) sediments (Fuchs et al. 2001).

Mineralogy

Based on bulk mineralogy of 19 samples (Table 4), the Lower Eocene and the Thomasl Formation are similar in composition. They contain high amounts of clay minerals (38–60 %) and moderate amounts of quartz (10–25 %) and feldspar (2–7 %). Calcite percentages vary between 2 and 26 %. In the sample at 1700 m depth, opal C–T is present in significant amounts (10 %). In comparison to the Thomasl Formation, Eggenburgian samples contain significantly higher percentages of quartz (38–48 %) and feldspar (10–22 %). Moreover, dolomite (9–27 %) is more abundant than calcite (9–17 %).

Most samples contain rhombohedral zoned dolomites with several carbonate phases that are distinguishable on the basis of their elemental composition measured with SEM. The phases are i) dolomite ($CaMg(CO_3)_2$) in the centre, surrounded by ii) kutnohorite ($CaMn^{2+}(CO_3)_2$) in the middle zone, and iii) ankerite ($Ca(Mg, Fe, Mn)(CO_3)_2$) in the outermost zone.

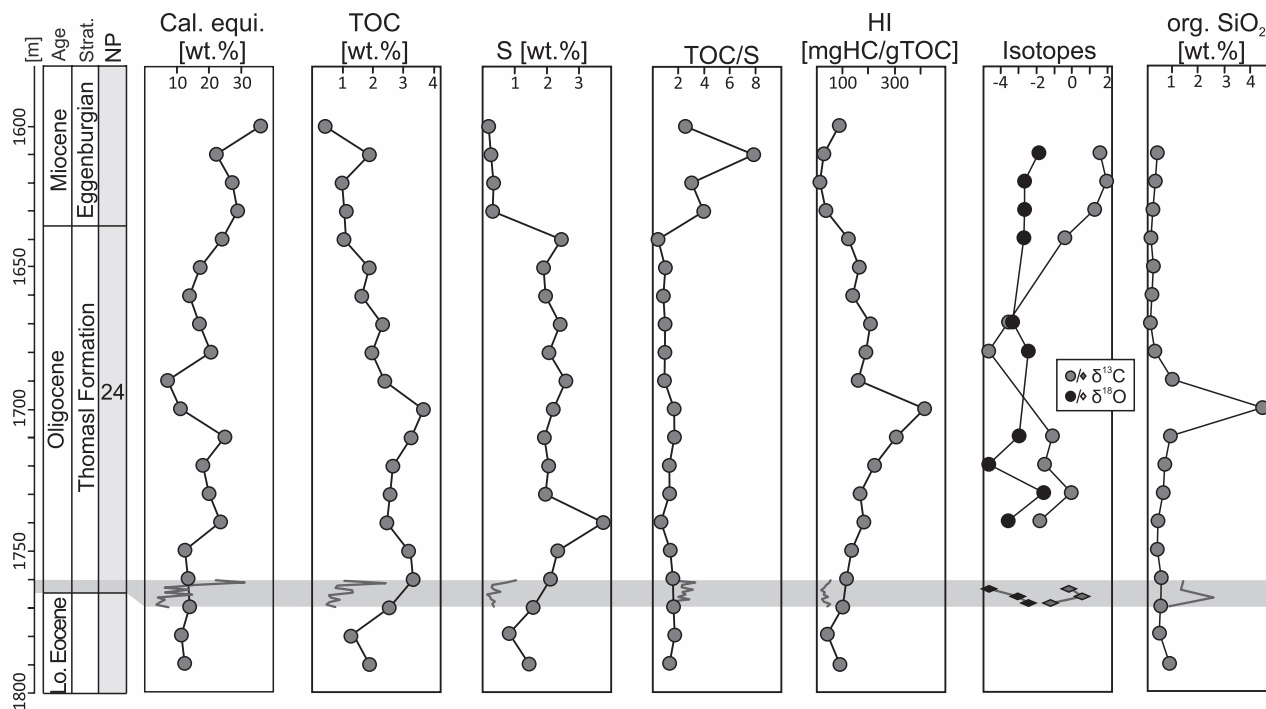


Fig. 12. Bulk geochemical parameters and isotopes of the Upper Oligocene Thomasl Formation in well Thomasl 1 with nannoplankton zones. Data from a core representing the lowermost 3 m of the Thomasl Formation are displayed (slightly enlarged; see grey bar) as lines.

Table 4: Semi-quantitative mineral percentages for the Thomasl well.

XRD	Depth [m]	Quartz	Opal-CT	Opal-A	Plagioclase	K-Felspar	Calcite	Dolomite	Siderite	Pyrite	Jarosite	Heul.*	Gypsum	Σ Clay [vol. %]
Thomasl I														
Eggenburgian	1610	47.9	0.0	0.4	4.5	12.1	9.3	22.2	0.0	0.0	0.0	0.0	0.0	4.0
	1620	40.2	0.0	0.3	4.3	9.1	10.8	24.3	0.0	0.0	0.0	0.0	0.0	11.3
	1630	37.7	0.0	0.2	4.8	4.5	10.4	27.3	0.0	0.0	0.0	0.0	0.0	15.3
	1640	46.3	0.0	0.1	12.0	10.1	17.4	8.7	0.0	0.0	0.0	0.0	0.0	5.5
Thomasl Formation	1650	25.0	0.0	0.2	3.0	2.4	1.6	3.6	0.0	3.7	0.0	0.0	0.8	59.9
	1660	22.6	0.0	0.2	1.2	2.4	14.6	1.8	0.0	3.5	0.0	0.0	0.0	53.9
	1670	11.3	0.0	0.1	3.8	1.8	19.4	2.5	0.0	5.2	0.0	0.0	0.0	56.0
	1680	18.8	0.0	0.3	1.9	1.9	22.7	1.8	0.0	3.7	0.0	0.0	0.0	49.7
	1690	21.6	0.0	1.0	2.1	1.8	9.7	1.0	0.0	0.0	3.2	0.0	1.2	59.3
	1700	20.0	10.5	4.5	2.0	1.5	13.1	0.9	0.0	1.5	0.0	0.0	0.0	49.7
	1710	18.3	2.7	0.9	1.9	2.1	32.7	0.7	0.0	3.5	0.0	0.0	0.0	37.9
	1720	24.5	2.8	0.7	1.4	1.4	24.6	0.8	0.0	3.8	0.0	1.9	0.0	38.6
	1730	22.8	2.1	0.6	3.7	1.4	23.0	0.7	0.0	3.2	0.0	0.0	0.0	43.1
	1740	25.1	2.9	0.4	1.4	2.7	17.9	0.0	0.0	3.9	0.0	0.0	0.0	46.1
	1750	23.1	0.0	0.4	2.1	1.8	20.6	0.8	0.0	4.0	0.0	0.0	0.0	47.6
Low. Eocene	1760	20.1	3.8	0.5	2.2	1.4	21.8	0.0	0.0	0.0	0.0	0.0	0.0	46.7
	1770	22.3	2.3	0.5	2.1	2.0	25.5	0.0	0.0	4.0	0.0	0.0	0.0	41.8
	1780	19.3	0.0	0.5	5.4	2.2	16.0	0.0	5.9	0.0	0.0	0.0	0.0	49.1
	1790	21.9	1.8	0.8	2.5	1.8	19.4	0.0	3.2	2.6	0.0	0.0	0.0	46.8

*Heulandite and clinoptilolite

The outer zones are in optical continuity with the host dolomite, but are easily distinguishable based on their luminescence behaviour.

$\delta^{13}\text{C}$ values of carbonate minerals in the lower part of the Thomasl Formation are around -1.5‰ and decrease upwards to a minimum value of -4.7‰ at 1680 m depth. The upper part of the Thomasl Formation is characterized by an upward increase $\delta^{13}\text{C}$ values. Positive values (max. $+1.9\text{‰}$) prevail in rocks with an Eggenburgian age. $\delta^{18}\text{O}$ values increase from -4.6‰ in lower part to -2.8‰ in the upper part of the Thomasl Formation and are between -2.7‰ and -1.9‰ in the Eggenburgian. In carbonate rich part the $\delta^{18}\text{O}_{\text{carb}}$ is again isotopically lighter than the $\delta^{13}\text{C}$.

Bulk geochemical parameters and organic petrography

Cuttings from the Lower Eocene succession contain 1.3 to 2.5 % TOC. HI values (38–101 mg HC/g TOC) indicate the presence of type III kerogen.

TOC contents from the basal 3 m of the Thomasl Formation (core samples) are low (0.4–2.4 wt. %; av. 0.91 wt. %). HI values (<50 mg HC/g TOC) show the presence of type III kerogen. The main part of the Thomasl Formation, represented by cuttings samples, contains high TOC contents (av. 2.5 wt. %). The maximum TOC is observed at 1700 m depth (3.7 wt. %). The HI of cuttings samples varies between 116 and 416 mg HC/g TOC, representing type III kerogen and type II kerogen (Figs. 12, 13). TOC contents of Eggenburgian sediments are moderately high (0.4–1.9 wt. %), but their HI is low (<90 mg HC/g TOC; type III kerogen).

The sulphur content of cuttings samples from the Thomasl Formation varies between 1.9 and 3.8 wt. % and is only slightly lower in Lower Eocene sediments (av.: 1.25 wt. %).

In contrast, Eggenburgian deposits are very low in sulphur (av. 0.3 wt. %). The average sulphur content of the core representing the lowermost 3 m of the Thomasl Formation is 0.5 wt. %. TOC/S ratios are low (<2) in Lower Eocene and Oligocene sediments. Elevated values occur in the Eggenburgian section (2.5–7.8).

The maceral composition (Table 2; Fig. 14 a–d) is dominated by terrestrial macerals (vitrinite: 41–76 vol. %; terrestrial liptinites, e.g. sporinite: 11–29 vol. %). Inertinite is hardly present (0–18 vol. %), including one exception (47 vol. %, 1610 m). Lam- (0–25 vol. %) and telalginite (including dinoflagellates; 0–22 vol. %) are less abundant. Foraminifera are present in low concentrations (<0.9 vol. %). Glauconite occurs in most samples. Vitrinite reflectance (<0.38 % Ro) in combination with T_{max} values ($\sim 412\text{ °C}$) show that the organic matter is immature.

Molecular composition of hydrocarbons

EOM yields of samples from the Thomasl well vary between 17 and 74 mg/g TOC and are dominated by NSO compounds (62–87 % of EOM). Saturated hydrocarbons (1–27 %) are more abundant than aromatic hydrocarbons (1–4 %). GC traces of the hydrocarbon fractions as well as steranes and hopanes patterns of a representative sample are shown in Fig. 15. Vertical variations of biomarker concentrations and ratios are displayed in Fig. 16 and Table 5.

n-alkanes and isoprenoids: The saturated hydrocarbon fractions of the Thomasl Formation are dominated by short chain (19–69 %) and medium chain (23–64 %) n-alkanes. Long chain n-alkanes (12–39 %) are less abundant. Whereas Lower Eocene sediments fall within the range of the Thomasl Formation, Eggenburgian sediments are dominated by

medium chain n-alkanes (55–71 %) with low amounts of short (6–15) and medium amounts of long chain (23–28 %) n-alkanes. Pr/Ph ratios vary between 0.2 and 1.25 and show a cyclic variation (Fig. 16). The concentrations of C_{25} HBI thiophenes and alkanes are elevated in the upper part of the Thomasl Formation (17.3–48.3 $\mu\text{g/g}$ TOC).

Steroids: The average sterane concentration is higher in the Thomasl Formation (17.1 $\mu\text{g/g}$ TOC) than in Eggenburgian (12.1 $\mu\text{g/g}$ TOC) and Lower Eocene units (10.6 $\mu\text{g/g}$ TOC). C_{27} Steranes dominate in the upper part of the section (1610–1660 m), whereas C_{28} and C_{29} steranes are most abundant in its lower part (Fig. 17). The sterane/hopane ratio shows a similar depth trend as the HBI thiophenes and alkanes and reaches maxima (2.6) in the upper part of the Thomasl Formation. The concentration of monoaromatic steroids

ranges from 1.5–52.3 $\mu\text{g/g}$ TOC, but reaches a maximum (445.3 $\mu\text{g/g}$ TOC) at a depth of 1700 m.

Terpenoids: Hopane concentrations vary between 3.4 and 68.2 $\mu\text{g/g}$ TOC. The $C_{31}22\text{S}/(22\text{S}+22\text{R})$ hopane isomerization ratio and the Ts/Tm ratio range from 0.28 to 0.52 and from 0.33 and 3.58, respectively. $\beta\beta$ -hopanes concentrations are about 8.6 $\mu\text{g/g}$ TOC, with the exception of the sample at 1770 m depth (33.5 $\mu\text{g/g}$ TOC). Hop-17(21)-ene is present in concentrations <3.72 $\mu\text{g/g}$ TOC (1700 m). Benzohopanes concentrations range from 0.9 to 25.9 $\mu\text{g/g}$ TOC, but reach a maximum concentration of 165.8 $\mu\text{g/g}$ TOC at a depth of 1700 m.

Phenantrenes, methylphenantrenes: The concentration of phenantrenes is elevated in the lower part of the Thomasl Formation (1700–1760 m; 29.3–289.6 $\mu\text{g/g}$ TOC) and significantly lower in its upper part (3.1–39.3 $\mu\text{g/g}$ TOC) and in

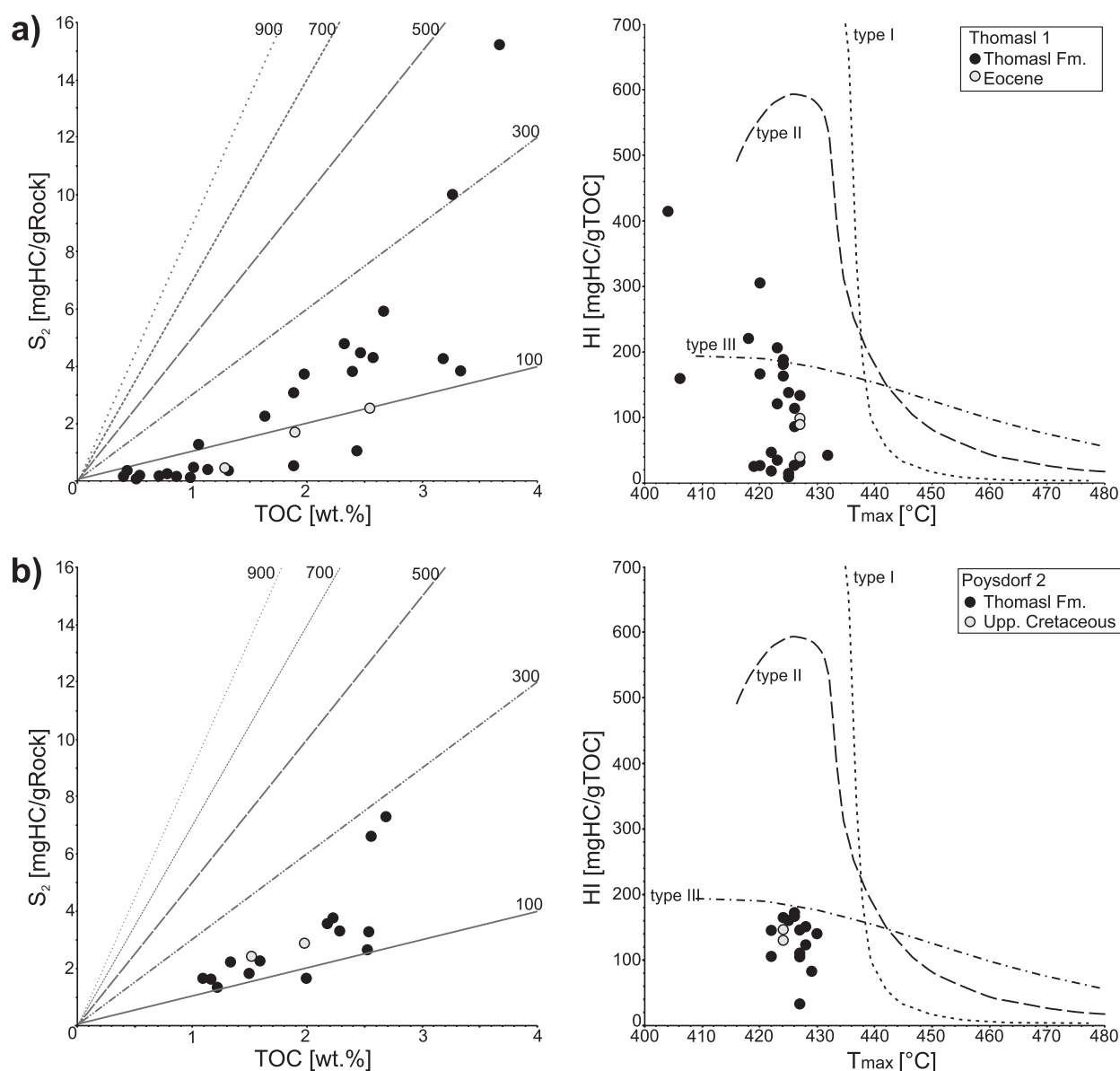


Fig. 13. Plots of S_2 vs. TOC and Hydrogen Index (HI) vs. T_{max} (according to Espitalie et al. 1984) for the Thomasl well (a) and the Poysdorf well (b).

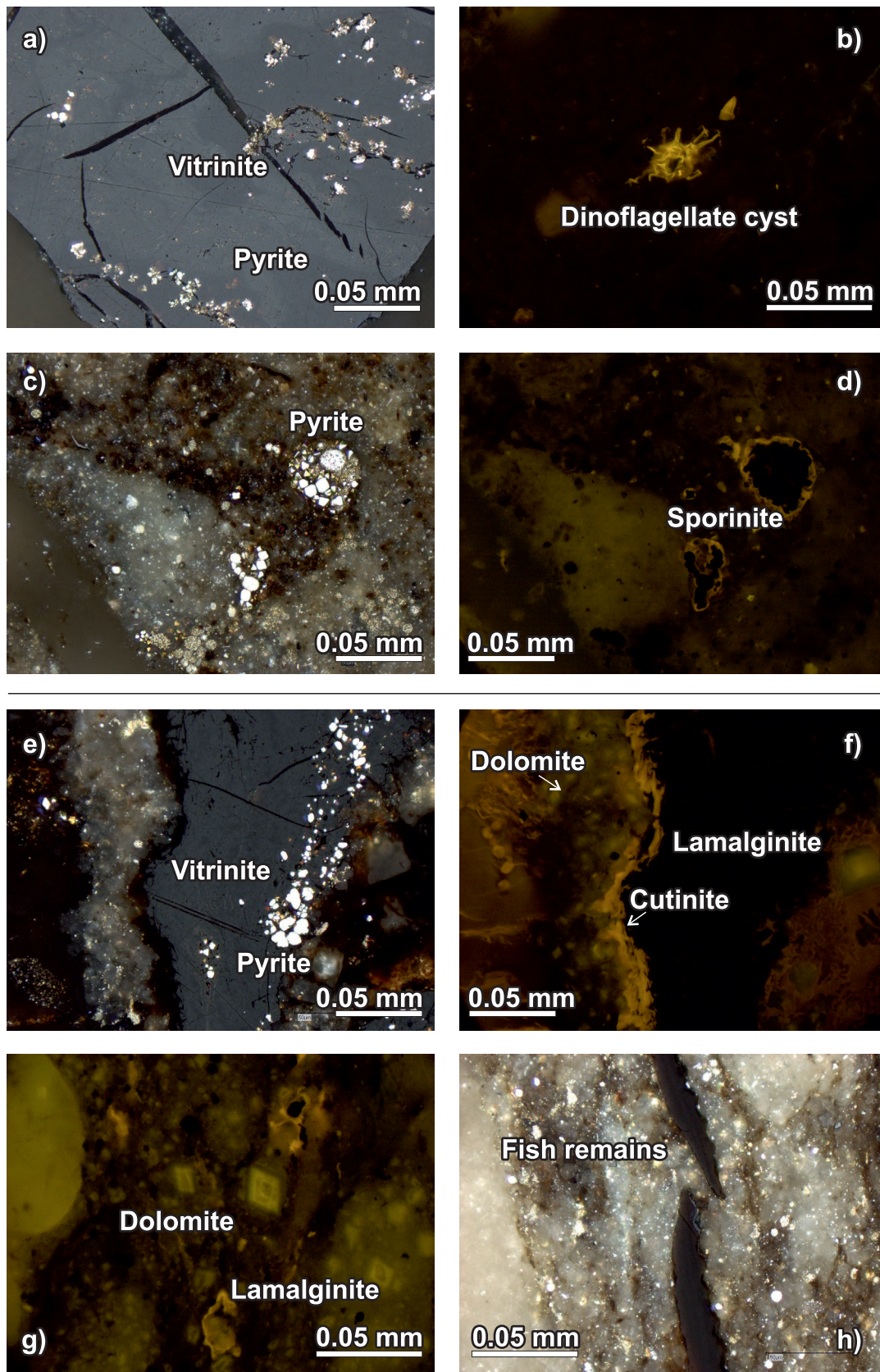


Fig. 14. Photomicrographs of the Thomasl Formation in the a-d) Thomasl (a–d) and Poysdorf wells (e–h): a — large vitrinite particle (1640 m); b — dinoflagellate cyst (1760 m; fluorescent mode); c, d — pyrite and sporinite in normal and fluorescent light (1660 m); e, f — vitrinite and cutinite in normal white light and in fluorescent light (2815.3 m); g — zoned dolomite crystals and lamalginite (2815.3 m; fluorescent mode); h — fish remains (2815.3 m).

Eggebürgian sediments ($\sim 0.4 \mu\text{g/g}$ TOC). 3,2,9,1-methylphenantrens concentrations display the same pattern than the phenentrenes with concentrations below $40.2 \mu\text{g/g}$ TOC.

Land-plant related biomarkers: Norbietetriene ($<24.4 \mu\text{g/g}$ TOC), dehydrobietetriene ($<27.5 \mu\text{g/g}$ TOC), simonellite ($<17.2 \mu\text{g/g}$ TOC) and retene ($<10.7 \mu\text{g/g}$ TOC) are most abundant at a depth of 1770 m. Crysene and picene vary from 0.3 to $15.9 \mu\text{g/g}$ TOC, with a maximum at 1770 m ($120.9 \mu\text{g/g}$ TOC). The sum of di- and triterpenoids is relative constant in the lower part of the succession (<70) and reaches a peak at 1770 m depth ($313.7 \mu\text{g/g}$ TOC). The di-/(di- + triterpenoids) ratio is low (<0.55).

Borehole Poysdorf 2

Lithology and stratigraphy

The Thomasl Formation in well Poysdorf 2 extends from 2801 to 2892 m depth (Fuchs et al. 2001). It overlies Upper Cretaceous sediments (Klement Fm.) with a tectonic contact and is overlain by Ottangian/Eggebürgian sediments. A core (core #21) was taken between 2813 and 2817.5 m depth, but only 2.6 m are left. The core is composed of mudstones with rare beds of thin silt- to sandstone. Fish remains are frequent. Fuchs et al. (2001) described prominent slump folds and the occurrence of frequent plant debris, including leaf fragments and partly large coalified wood fragments. Similar to the Thomasl Formation in the Thomasl well, diagenetic carbonate phase with distinct zonation occur in all core samples (Fig. 14g).

Bulk geochemical parameters and carbonate isotopes

The average TOC content of the Thomasl Formation in the Poysdorf well (2890–2800 m) is slightly lower (2.2 wt. %)

than that in the Thomasl well. Relatively low TOC contents (average: 1.3 wt. %) are observed in the core (2817–2813 m) and in cuttings from the same depth (Fig. 18). HI values in the lower part of the Thomasl Formation ($\sim 130 \text{ mg HC/g TOC}$) show the presence of type III kerogen HI values in the upper part (2840–2800 m) vary from 144 to 271 mg HC/g TOC indicating the presence of type III/II kerogen (Figs. 13, 18). The average sulphur content is 1.42 wt. %. TOC/S ratios <3.5 agree with the postulated marine depositional environment. T_{max} values ($\sim 425^\circ\text{C}$) show that the organic matter is immature.

$\delta^{13}\text{C}_{\text{carb}}$ values of cutting samples are rather uniform ($+0.6$ to -1.3 ‰). In contrast, core samples ($\sim 2815 \text{ m}$) have more negative values (min.: -6.4 ‰). $\delta^{18}\text{O}$ values range between -5.2 (core sample) to -2.8 ‰.

Organic petrography and molecular composition of hydrocarbons

Core samples from the upper part of the Thomasl Formation have been selected for organic petrographic and biomarker investigations. The maceral composition (Table 2, Fig. 14e–h) is dominated by terrestrial macerals like vitrinite (52–70 vol. %) and liptinite (e.g., sporinite, 15–24 vol. %). This fits nicely with the observation of frequent plant debris by Fuchs et al. (2001). Foraminifera and glauconite have been found as well.

The molecular compositions of core samples falls into the range of samples from the upper part of the Thomasl Formation in the Thomasl well (Table 2). However, phenantrens concentrations (max. $477 \mu\text{g/g}$ TOC) and the di-/(di- + triterpenoids) ratio (max. 0.78) are relatively high. The latter shows that the plant debris contains a high percentage of gymnosperms.

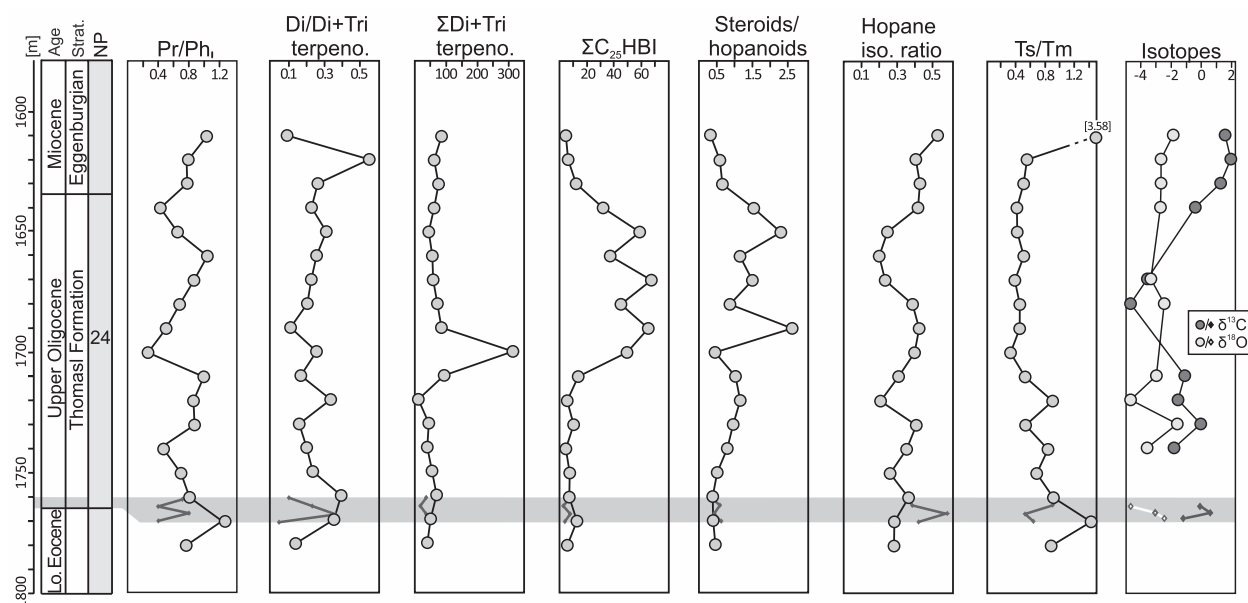


Fig. 16. Biomarker ratios and concentrations of Eocene/Upper Oligocene source rocks of the Thomasl well.

Table 5: Organic geochemical data of the Thomasl and Poysdorf wells.

	Depth [m]	TOC [wt. %]	HI [mg HC/g TOC]	EOM [µg/g TOC]	Sat. HC	Aro. HC	NSO	Asph.	n-C ₁₅₋₂₀	n-C ₂₁₋₂₅	n-C ₂₆₋₃₂	Pr/Ph	C25 HBI [µg/g TOC]	Steroids	C ₂₇	C ₂₈	C ₂₉
					[wt. %]	[wt. %]	[wt. %]	[wt. %]	[wt. %]	[wt. %]	[wt. %]				Steranes/ Steranes	Steranes/ Steranes	Steranes/ Steranes
Thomasl 1 Cuttings																	
Eggenburgian	1610	1.88	29	34.78	27	4	62	7	15	55	28	1.02	0.56	20.6	0.36	0.25	0.39
	1620	0.98	14	23.19	21	1	78	0	8	71	23	0.78	1.35	3.4	0.49	0.21	0.30
	1630	1.13	37	40.86	20	1	71	8	6	66	28	0.77	1.14	12.2	0.29	0.24	0.47
	1640	1.05	123	73.78	17	4	71	8	36	64	14	0.42	6.75	5.6	0.47	0.26	0.27
Thomasl Formation	1650	1.88	165	41.53	9	1	76	14	45	51	12	0.64	41.59	2.6	0.44	0.31	0.25
	1660	1.63	140	38.86	5	2	84	9	68	23	12	1.03	25.75	6.8	0.38	0.24	0.38
	1670	2.32	208	35.41	5	0	82	12	46	31	20	0.85	48.25	11.7	0.35	0.29	0.36
	1680	1.97	191	24.99	9	1	76	14	34	40	26	0.67	31.87	16.3	0.27	0.33	0.40
	1690	2.39	161	47.80	8	1	74	18	32	44	20	0.50	17.28	37.0	0.29	0.39	0.32
	1700	3.67	416	52.96	8	2	74	16	19	47	28	0.27	43.64	49.2	0.25	0.38	0.36
	1710	3.26	307	42.79	5	1	75	19	56	46	15	0.98	4.53	18.5	0.25	0.35	0.39
	1720	2.66	223	44.80	1	4	79	15	51	24	24	0.85	1.00	4.6	0.27	0.35	0.37
	1730	2.57	168	24.59	10	1	86	3	46	41	13	0.86	1.29	22.7	0.26	0.38	0.36
	1740	2.46	183	28.44	7	0	86	7	22	57	24	0.47	0.67	14.5	0.23	0.41	0.36
	1750	3.18	135	22.72	8	1	87	5	21	41	39	0.69	2.21	15.3	0.24	0.45	0.31
Eoc.	1760	3.33	116	22.53	9	2	86	3	29	45	27	0.80	3.27	12.4	0.21	0.48	0.31
	1770	2.54	101	22.80	7	1	91	1	58	26	15	1.25	6.17	9.5	0.25	0.38	0.37
1780	1.28	38	31.35	7	1	92	1	53	30	19	0.76	1.17	10.0	0.23	0.37	0.39	
Thomasl 1 Core																	
Thom. Fm.	1760.0	1.01	49	47.02	9	2	86	4	44	49	21	0.94	0.14	25.6	0.27	0.31	0.42
	1760.4	2.43	44	17.56	10	2	87	0	69	30	10	0.34	0.08	9.2	0.34	0.30	0.36
	1761.0	1.31	30	36.81	13	0	84	3	41	45	24	0.87	0.44	10.8	0.23	0.24	0.53
	1761.6	0.86	20	37.21	9	2	88	1	64	26	14	0.36	0.34	12.5	0.30	0.33	0.38
Poysdorf 2 Core																	
Thom. Fm.	2814.8	6.23	32	8.76	12	3	83	2	50	46	12	0.63	31.53	5.8	0.38	0.31	0.31
	2815.1	1.17	139	11.87	9	4	83	3	28	56	23	0.36	33.80	16.4	0.31	0.37	0.32
	2817.0	1.50	122	23.24	22	0	77	1	61	22	17	1.32	0.16	61.0	0.51	0.25	0.24
Thomasl 1 Cuttings																	
Eggenburgian	1610	0.4	50.00	0.52	3.58	9.68	1.20	14.23	0.3	5.24	0.09	84.71					
	1620	0.6	8.78	0.40	0.88	2.45	0.38	6.22	0.4	3.71	0.55	61.23					
	1630	0.7	31.06	0.42	1.43	7.32	1.14	3.08	0.5	4.77	0.26	75.34					
	1640	1.5	14.95	0.41	0.91	3.12	1.25	0.94	16.0	4.36	0.23	60.66					
	1650	2.2	8.73	0.24	0.69	3.41	0.14	2.42	39.9	3.17	0.31	43.68					
	1660	1.1	18.88	0.19	0.84	8.72	0.50	2.82	7.0	2.85	0.25	55.19					
	1670	1.5	19.13	0.23	0.53	9.28	0.48	2.87	3.1	2.82	0.22	57.64					
	1680	0.9	26.65	0.38	0.90	9.21	0.70	8.61	3.6	3.75	0.20	71.32					
	1690	2.6	27.72	0.41	0.53	8.89	1.59	5.67	28.8	3.83	0.11	84.40					
	1700	0.4	68.16	0.39	0.33	33.53	3.72	165.77	78.4	2.74	0.25	313.71					
	1710	1.0	29.47	0.30	0.45	12.48	1.18	13.65	151.3	3.16	0.17	93.10					
Thomasl Formation	1720	1.1	3.44	0.20	0.46	1.53	0.10	2.08	29.3	2.61	0.33	10.13					
	1730	0.9	28.83	0.40	0.39	11.50	2.02	3.19	43.7	3.15	0.15	43.88					
	1740	0.8	23.72	0.35	0.51	10.14	0.79	3.71	41.2	3.16	0.20	38.89					
	1750	0.5	27.98	0.25	0.42	11.37	0.64	25.89	84.0	3.41	0.23	54.16					
	1760	0.4	25.94	0.36	0.42	10.07	1.22	20.38	92.8	3.37	0.39	68.75					
	1770	0.4	20.78	0.28	0.51	8.82	0.86	12.70	54.2	3.10	0.35	49.87					
	1780	0.5	26.24	0.28	0.55	11.44	0.57	2.64	2.1	3.17	0.14	39.54					
Thomasl 1 Core																	
Thom. Fm.	1760.0	0.3	42.27	0.35	0.56	17.94	1.07	9.47	289.6	3.27	0.09	37.99					
	1760.4	0.6	17.49	0.38	0.55	7.13	1.11	3.22	260.9	3.05	0.23	17.39					
	1761.0	0.4	20.54	0.57	0.86	6.13	1.19	2.70	65.8	3.87	0.36	36.69					
	1761.6	0.6	44.71	0.42	1.02	15.65	0.68	1.75	1.5	3.90	0.04	55.48					
Poysdorf 2 Core																	
Thom. Fm.	2814.8	0.3	7.49	0.47	0.60	2.16	0.27	16.65	476.7	3.94	0.78	57.57					
	2815.1	0.5	108.79	0.27	0.62	35.12	8.22	0.71	17.9	3.72	0.28	53.01					
	2817.0	0.6	18.92	0.42	0.56	5.39	0.87	13.48	234.9	4.25	0.48	78.52					

TOC - total organic carbon, HI - hydrogen index, EOM - extracted organic matter, HC - hydrocarbons, NSO - polar compounds, Asph. - asphaltenes, n-C₁₅₋₂₀ - short-chain alkanes, n-C₂₁₋₂₅ - medium-chain alkanes, n-C₂₆₋₃₂ - long-chain alkanes; Pr/Ph - Pristane/Phytane ratio; MAS - monoaromatic steroids; MPI - Methylphenanthrene Index; Di/(Di+Tri) terpeno. - Diterpenoids/triterpenoids ratio.

Discussion

Maturity

Average vitrinite reflectance of the Waldweg section (0.29 %Ro), as well as the samples from the Poysdorf (0.37 %Ro) and Thomasl wells (0.37 %Ro) indicate that the organic matter is immature. This is supported by average T_{max} values (Waldweg section: 420 °C; Thomasl: 422 °C; Poysdorf: 425 °C) and the presence of C_{29-31} $\beta\beta$ -hopanes and C_{27-29} $\beta\alpha$ -steranes.

Hopane isomerisation varies between 0.19–0.43 (Waldweg section), 0.19–0.57 (Thomasl) and 0.27–0.47 (Poysdorf). Hopane isomerisation ratios reach their equilibrium at 0.6 (oil

window maturity, Seifert et al. 1980). Considering the low maturity indicated by measured vitrinite reflectance and T_{max} data, values >0.3 seem too high. These high values may reflect difficulties with the quantification of tiny peaks or the influence of facies on hopanoid maturity indices (e.g., ten Haven et al. 1986).

The observed slow increase in maturity with depth in the Waschberg Zone is an effect of low heat flow and has also been observed in autochthonous sediments beneath the Waschberg Zone and for the Miocene fill of the Vienna Basin (Ladwein 1988; Rupprecht et al. 2017). Consequently, Oligocene sediments of the Waschberg Zone will enter the oil window only at great depth (~4000 m according to Ladwein 1988).

Diagenesis

During diagenesis siliceous deposits undergo mineralogical changes from amorphous silica (opal-A) to microcrystalline opal (opal-CT/-C) to microcrystalline quartz (Williams et al. 1985; Lynne & Campbell 2004). Factors influencing the transformation are burial depth, temperature, time and host rock lithology (Jones & Segnit 1971). Williams et al. (1985) stated that opal-CT forms when temperatures reach ~50 °C. The higher thermal overprint of borehole samples, therefore, is reflected by the fact that opal-A is present in surface samples, but opal-CT in a sample from the Thomasl well (1700 m).

Diagenetic carbonate phases consisting of dolomite cores, surrounded by kutnohorite and ankerite rims, are commonly detected in calcareous sediments of the Thomasl Formations. A single sample from the Galgenberg Member has been investigated. This sample also includes zoned dolomite phases. Although the exact mechanisms and rates of dolomite formation in marine environments are still discussed controversially, it may be assumed that the activity of aerobic microbes and denitrifying bacteria caused changes in

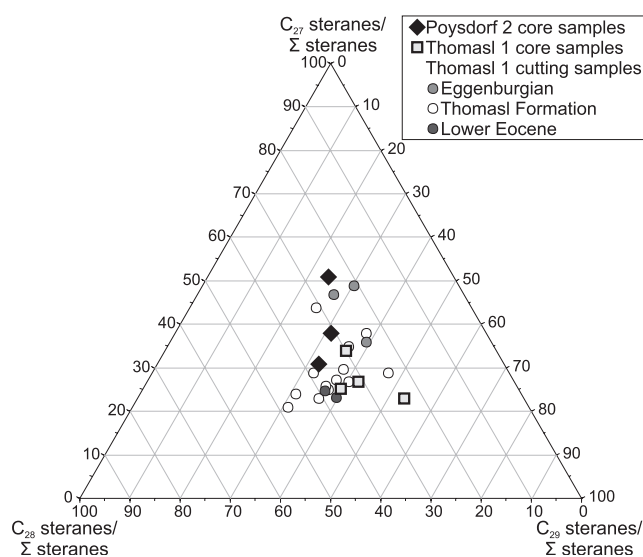


Fig. 17. Distribution of C_{27} , C_{28} and C_{29} steranes for samples from the Thomasl and Poysdorf wells.

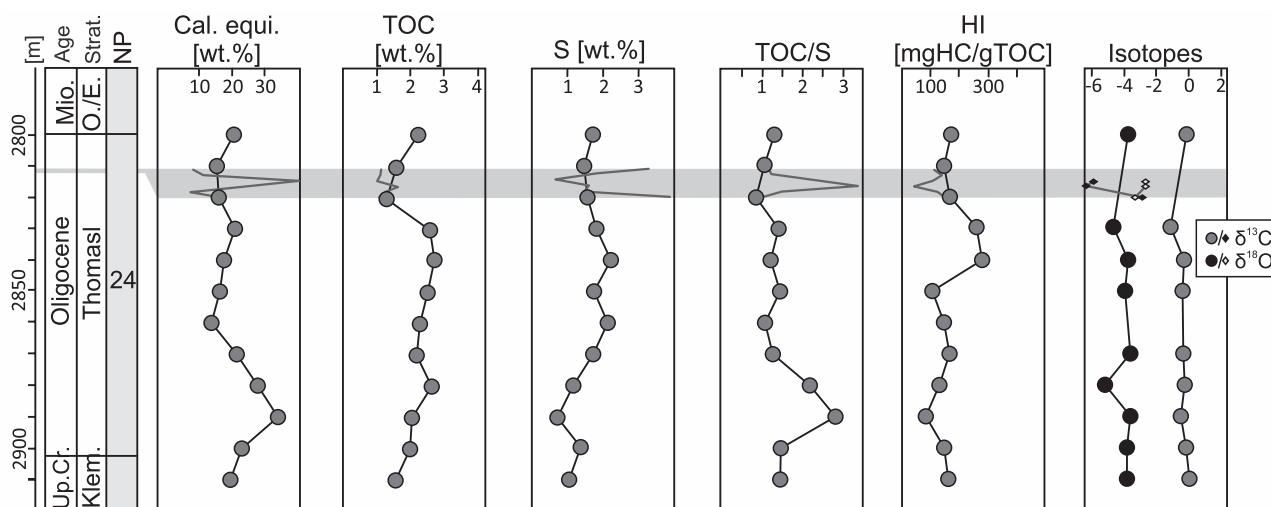


Fig. 18. Bulk geochemical parameters and isotopes with nannoplankton zones of the Upper Oligocene source rocks (Thomasl Formation) of the Poysdorf well. Core data are displayed (slightly enlarged; see grey bar) as lines.

alkalinity and pH values and favoured dolomite precipitation (Frölich et al. 1979). Mn-rich carbonate phases probably reflect strong Mn(IV) reduction in the sediment and Mn(II)-fixation at the chemocline (Algeo & Maynard 2004; Cruse & Lyons 2004). The formation of Fe-rich carbonate phases reflect Fe-reduction (and suppressed sulfate reduction) and postdates Mn-reduction. Omnipresent framboidal pyrite results from bacterial sulphate reduction (Canfield et al. 1993).

Depositional environment

Based on sedimentology and paleontological data, the depositional environment of the Oligocene successions in the Waschberg Zone has been described in detail by Rögl et al. (2001; Waldweg section) and Fuchs et al. (2001; Thomasl, Poysdorf wells). Some additional aspects are referred to in the following.

Waldweg section near Ottenthal

The vertical trend of Pr/Ph ratios (Fig. 10) indicates changing dysoxic to anoxic conditions. Relative high ratios indicate dysoxic conditions during deposition of the Galgenberg diatomites and the lower part of the Thomasl Formation.

Vertical variations in biogenic silica contents (Fig. 5) reflect the productivity of siliceous organisms, mainly diatoms. A general upward increase in siliceous bioproductivity is observed in the Ottenthal and Galgenberg members. Siliceous productivity decreased during deposition of the uppermost part of the Galgenberg Member. Biogenic silica contents in the Dynow Member are as high as in the Galgenberg diatomites and agree with diatom contents in the Dynow Member observed in this study (Fig. 6) and described by Rögl et al. (2001). Upward decreasing carbonate contents in the Dynow Member (Fig. 5) reflect a general decrease in the productivity of calcareous nannoplankton.

The TOC/S ratio is controlled by the availability of sulphate and often used to distinguished marine and freshwater environments, as well as anoxic deposits (Berner & Raiswell 1984). In the present case, because of weathering, the significance of TOC/S ratios as salinity proxy is reduced. Nevertheless, high TOC/S ratios in the Dynow Member match with the brackish depositional environment suggested by paleontological data (e.g., Rögl et al. 2001). The upward increase in the uppermost part of the Galgenberg Member indicates that brackish conditions commenced already before deposition of the Dynow Member. The presence of *Aulacoseira*, a brackish or freshwater diatom (Rögl 1998; Fig. 6), both in the upper part of the Galgenberg Member and in the Dynow Member supports this statement. Another upward decrease in salinity is suggested by TOC/S ratios in the Thomasl Formation at about 12 m depth.

C₂₅-HBI thiophenes and alkanes can indicate the contribution of diatoms to the biomass (Sinninghe Damste et al. 1989; Grossi et al. 2004). Maxima of the sum of C₂₅-HBI thiophenes and alkanes are observed in the diatomites (Galgenberg Mb.)

and the Thomasl Fm. (~11 m depth). However, concentrations are low in the Dynow Member, despite of high biogenic silica contents.

Steroids/hopanoids ratios reflect the input of eukaryotic (algae, higher landplants) versus prokaryotic (bacteria) organisms (Moldowan et al. 1986). Generally, the observed ratios (>1) indicate a minor input of bacterial biomass.

With the exception of the Galgenberg diatomites and the Dynow Member, HI values are very low in the entire Oligocene succession (<140 mg HC/g TOC) indicating a dominance of terrestrial plant material. HI values in the Galgenberg diatomites and the Dynow Member (<252 mg HC/g TOC) reflect a higher contribution of aquatic organic matter. The sum of di- and triterpenoids may be used as a proxy for the relative contribution of terrestrial plant material to the biomass. In agreement with HI values, the trend of di- and triterpenoid concentrations (Fig. 5) shows relative low landplant input to the biomass in the Galgenberg and Dynow members and a significantly higher input in the Thomasl Formation.

Ratios of di-(di+triterpenoids) show cyclic variations indicate that the relative amounts of gymnosperms and angiosperms varied significantly during deposition of the Oligocene succession. Gymnosperms dominated within the landplant fraction during deposition of the Galgenberg diatomites and during deposition of the lower and upper part of the Thomasl Formation. In contrast, angiosperms are prominent near the top of the Ottenthal Member, at the base and in the middle of the Thomasl Formation.

The presence of clinoptilolite and heulandite, which occur often in altered volcanic material, suggest volcanic activity during deposition of the Ottenthal Member and the Thomasl Formation. Clinoptilolite was also observed in a nearby section equivalent to the Ottenthal Formation by Rögl et al. (2001), but these authors found no evidence of clinoptilolite in the Thomasl Formation.

Thomasl Formation in the Thomasl and Poysdorf wells

The Thomasl Formation in both wells was deposited during NP 24. Its organic matter content is significantly higher than in the Thomasl Formation in the Waldweg section. Very low TOC/S ratios are typical for marine, oxygen-depleted conditions (Berner & Raiswell 1984). In contrast, high TOC/S in the Eggenburgian interval may indicate sulphate-limitation due to freshwater influx. HI values are typically low (<200 mg HC/g TOC), but some samples have significantly higher values (max: 416 mg HC/g TOC). This indicates the dominance of landplant derived type III kerogen, but the additional presence of type II kerogen, typical for marine organisms.

Biomarker and maceral data are available only for the Thomasl well and for the Poysdorf core. The following discussion, therefore, focusses on the Thomasl well. The Pr/Ph ratio in the Thomasl well ranges between 0.3 and 1.2 indicating anoxic to dysoxic conditions. Vitrinite and sporinite percentages are continuously high indicating a dominance of landplant derived macerals. Landplant related biomarkers

(di- and triterpenoids) are also high and reach a maximum at 1700 m depth. The di-(di+triterpenoids) ratios in the Thomasl Formation in the Thomasl well are typically low (av.: 0.24) compared to that in the Waldweg section (av. 0.51) indicating a higher contribution of angiosperms in the Thomasl well. In contrast, data from the Poysdorf core, representing the upper part of the Thomasl Formation, show a high percentage of gymnosperms.

C₂₅-HBI thiophenes and alkanes, attributed to diatoms (Sinninghe Damste et al. 1989; Grossi et al. 2004) occur in high concentrations in the upper part of the Thomasl Formation (1700–1640 m). However, only the sample at 1700 m depth is also rich in biogenic silica. This sample is also characterized by a very low Pr/Ph and steroids/hopanoids ratios and high TOC and HI values. High concentration of diatom-related biomarkers in the upper part of the Thomasl Formation are also supported by the Poysdorf core.

Comparison with the North Alpine Foreland Basin

The Ottenthal Formation is the time equivalent to the Schöneck and Dynow formations in the North Alpine Foreland Basin (Fig. 2). The carbonate-rich Ottenthal Member contains abundant abundant foraminiferas, similar to the marly units a/b of the Schöneck Formation (sensu Schulz et al. 2002). Carbonate contents decrease upwards in both succession. The overlying rocks (shale part of the Galgenberg Fm., shaly unit c of the Schöneck Fm.) are largely carbonate free. A strong decrease in salinity is recorded in both, the middle part of the Galgenberg Formation (Rögl et al. 2001) and in unit c of the Schöneck Formation (Schulz et al. 2005). Whereas diatomaceous rock accumulated after the decrease in salinity (diatomites in the Galgenberg Fm.), accumulation of shaly rocks continued in the North Alpine Foreland Basin.

The Dynow Member/Formation (NP23) forms an excellent marker horizon and reflects blooms of calcareous nannoplankton. Upward decreasing carbonate contents reflect decreasing productivity of calcareous nannoplankton in both areas (cf. Schulz et al. 2004, 2005). However in contrast to the Waschberg Zone, siliceous organisms are largely absent in the Dynow Formation in the North Alpine Foreland Basin (Schulz et al. 2004).

The base of the overlying Thomasl Formation is formed by slump deposits. Mass movements during deposition of the time-equivalent Eggerding Formation are also well known in the North Alpine Foreland Basin and locally

resulted in erosion of the underlying Dynow and Schöneck formations (Sachsenhofer & Schulz 2006; Sachsenhofer et al. 2010).

Whereas single lithological units can be easily correlated, there are significant differences in organic matter contents. These are several times higher in the North Alpine Foreland Basin (e.g., unit c of the Schöneck Fm. has an average TOC contents of 5.5 wt. %), but also in boreholes in the Western Carpathians (e.g., Francú & Feyzullayev 2010; Sachsenhofer et al. 2017). It is questionable if the low TOC contents can be explained by weathering alone. Hence, we assume that conditions for organic matter production and preservation (e.g., anoxia) were not as good in the studied Waldweg section than in other locations. The reasons for this are not yet well understood, but may be related to a relative shallow and/or marginal position of the studied section.

Source rock potential

TOC contents and the petroleum potential (S1+S2) are frequently used to classify the quality of potential source rocks (e.g., Peters 1986). The studied samples are characterized by varying, but often relative high TOC contents. In contrast, the petroleum potential is often low, which is therefore considered as the limiting factor (Fig. 19).

TOC contents (average: 0.5 wt. %) and HI values in the Oligocene succession exposed in the Waldweg section are surprisingly low. Therefore, the source rock potential of the outcrop section is poor (Fig. 19). Within this respect, it has to be emphasized that weathering may decrease the source potential of source rocks. The studied samples show severe indications of weathering (e.g., presence of gypsum and jarosite). Hence, it cannot be ruled out, that the “true” potential is higher.

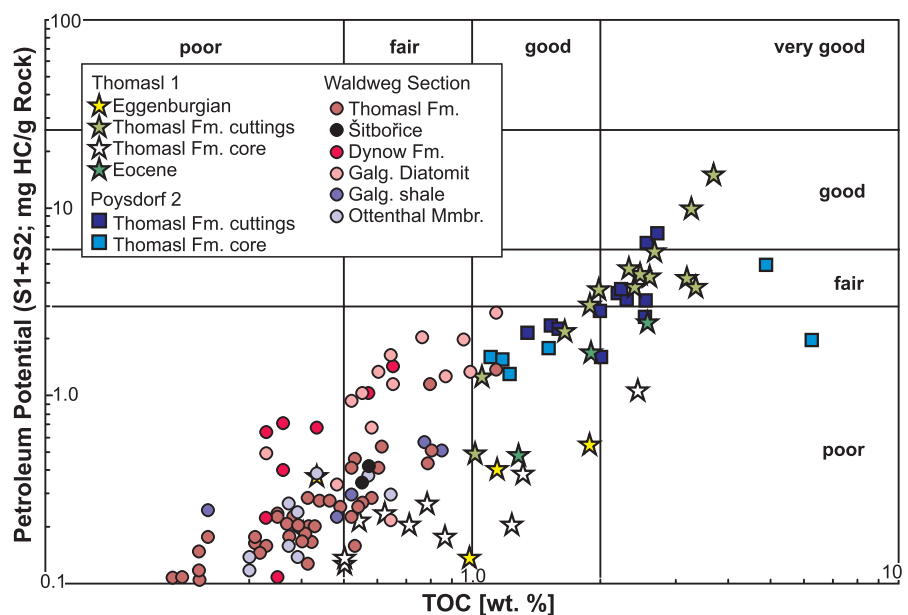


Fig. 19. Petroleum Potential versus total organic carbon (TOC) for the Waldweg section and the Thomasl Formation (Thomasl 1 and Poysdorf 2 well).

The core samples from the base of the Thomasl Formation in the Thomasl well do not hold any source rock potential. All other samples are characterized by a fair to good source rock potential (Fig. 19). The organic matter is dominantly of type III kerogen, but type II kerogen exists as well. Therefore it is likely that gas and minor oil would be generated in the oil window.

The amount of hydrocarbons, which can be generated below 1 m² of surface area can be calculated using the Source Potential Index (SPI=thickness*(S1+S2)*bulk density/1000) of Demaison & Huizinga (1994). Considering average S1+S2 values of cuttings samples, the total thickness of the Thomasl Formation and estimated density (Table 6), it can be expected that the Thomasl Formation can generate between 0.9 and 1.6 tons of hydrocarbons/m² if it is mature. Indeed, Franců et al. (1996) suggested that oil in the Czech part of the Vienna Basin could have been generated by an Oligocene source rock. The calculated SPI is similar to those determined for Lower Oligocene sediments in the North Alpine Foreland Basin and the Western Carpathians (Sachsenhofer et al. 2017). However, in these sections sediments equivalent to the Ottenthal Formation are typically more prolific than the time-equivalents of the Thomasl Formation.

Conclusions

The Oligocene succession in the Waschberg Zone has been studied using the Waldweg section near Ottenthal and two borehole profiles (Thomasl, Poysdorf). The Oligocene Ottenthal Formation and the lower part of the Thomasl Formation, exposed along the Waldweg section, hold negligible petroleum potential. This result is surprising, because equivalent Lower Oligocene rocks in the Western Carpathians (Menilite Fm.) and the North Alpine Foreland Basin (Schöneck Fm.) are prolific source rocks. Weathering of the outcrop section can explain the difference only partly. The Thomasl Formation in boreholes Thomasl and Poysdorf (~2.2–2.5 % TOC; type III and type II kerogen) holds a fair to good hydrocarbon potential and may generate 1.0 to 1.6 tons of hydrocarbons per m². Vitrinite reflectance measurements show that the investigated sections are thermally immature.

Bulk geochemical together with biomarker data contribute to the understanding of the depositional environment of the Ottenthal and Thomasl formations. Deposition commenced with calcareous sediments of the Ottenthal Member, which grade upwards into the largely carbonate-free, diatomaceous shales of the Galgenberg Member. Biogenic silica

Table 6: Calculation of the Source Potential Index (SPI) for the Thomasl Formation in boreholes Thomasl and Poysdorf.

Unit	S1+S2 [mg HC/g Rock]	total thickness [m]	estimated density [g/cm ³]	SPI [t HC/m ²]
Thomasl 1	5.33	127	2.3	1.55
Poysdorf 2	3.75	110	2.3	0.95

contents in the Galgenberg Member and the overlying marls of the Dynow Member reach 30 wt. %. The carbonate content of the Dynow Member decreases upwards, reflecting decreasing productivity of calcareous nannoplankton. A similar observation has been made in the North Alpine Foreland Basin. In contrast to the latter, siliceous organisms are present in high amounts in the Dynow Member and contributed significantly to the biomass in the Ottenthal, but not in the Thomasl Formation. Pr/Ph ratios indicate cyclic variations of oxygen availability, but oxygen-depleted conditions prevailed during deposition of the Ottenthal Formation. Pr/Ph ratios indicate the the Thomasl Formation was deposited in anoxic to dysoxic conditions. Maceral percentages and biomarkers data proof a high amount of terrestrial landplants and indicate a nearshore environment during deposition.

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