PARATETHYAN PETROLEUM SOURCE ROCKS: AN OVERVIEW

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The Paratethys area extends from Central Europe to the borders of the Caspian Sea in Central Asia and hosts a significant number of petroleum provinces, many of which have been charged by Eocene to Miocene source rocks of supra-regional significance. These include highly oil-prone Middle Eocene marls and limestones in the Eastern Paratethys (Kuma Formation and equivalents) which are several tens of metres thick. Estimates of the source potential index (SPI) indicate that the Kuma Formation in the northern Caucasus and the Rioni Basin (Georgia) may generate 1 to 2 tons of hydrocarbons per square metre (tHC/m²). This implies that the Kuma Formation may also be an important and additional source rock in the eastern Black Sea.

Oligocene and Lower Miocene pelitic rocks (Maikop Group and equivalents) are considered to be the most important source rocks in the Paratethys. Vertical variations in source potential record different stages of basin isolation that reached a maximum during the Early Oligocene (NP23) Solenovian Event. However major variations exist between different sub-basins in the Central and the Eastern Paratethys. In the Central Paratethys, the highest quality source rocks occur in the Carpathian Basin where the Menilite Formation, several hundreds of metres thick, can generate up to 10 tHC/m². Locally the Menilite Formation is about 1500 m thick and continues into the Lower Miocene. In these settings, the Menilite Formation can generate approximately 70 tHC/m². In the Alpine Foreland Basin (Schöneck and Eggerding Formations) and the Pannonian Basin (Tard Clay Formation), oil-prone source rocks are restricted to the Lower Oligocene. In the Eastern Paratethys, the best source rock intervals of the Maikop Group are typically associated with the Early Oligocene Solenovian Event. By contrast, with the exception of the Kura Basin in Azerbaijan, the potential of Upper Oligocene and Lower Miocene rocks is often limited. In total, the Maikop Group may generate up to 2 tHC/m² in the North Caucasus area and 4 tHC/m² in the Rioni Basin.

A particular source rock facies is found in the Western Black Sea where diatomaceous rocks with good oil potential accumulated in the Kaliakra Canyon during Early Miocene.

Key words: Source rock, Paratethys, source potential index, organic matter, Eocene, Oligocene, Maikop Group, Menilite Formation, Kuma Formation, Solenovian Event.
time. This facies may generate up to 8 tHC/m², but is probably limited to shelf-break canyons.

Middle and Upper Miocene rocks are the main source for oil and thermogenic gas in the Pannonian Basin System, and also contributed to thermogenic hydrocarbons in the Moesian Platform and the South Caspian Basin. In addition, Upper Oligocene and Miocene rocks are the source for microbial gas in several basins including the Alpine and Carpathian foredeeps.

INTRODUCTION

The Paratethys Sea covered large parts of Eurasia during Cenozoic time and the present-day Black Sea and Caspian Sea are considered to be its final remnants. Formation of the Paratethys is usually dated to around the Eocene/Oligocene boundary, when a sea-level fall in combination with the effects of the Alpine orogeny caused the separation of the Paratethys from the Mediterranean (Rögl, 1999; Allen and Armstrong, 2008). Subsequent basin isolation resulted in the development of an endemic fauna in the Paratethys, together with varying salinity and redox conditions which favoured the accumulation of organic matter-rich rocks (Popov and Stolyarov, 1996; Rögl, 1999; Popov et al., 2004a; Sachsenhofer et al., 2017b). However, major changes in the seaways which connected Paratethys to the open oceans resulted in oxygen-depleted conditions as early as the Middle Eocene (e.g. Beniamovski et al., 2003). Thus deposition of organic matter-rich successions, which serve as hydrocarbon source rocks in different parts of the Paratethys, took place at least from the Middle Eocene to the Late Miocene.

Based on differences in environmental histories, the Paratethys is divided into the relatively small-scale Western Paratethys, comprising the Rhône Basin and the Alpine Foreland Basin west of Munich; the Central Paratethys, including the remaining part of the Alpine Foreland Basin, the Carpathian Basin and the Pannonian Basin; and the larger Eastern Paratethys (Fig. 1). An overview of the correlation of standard and Paratethys biostratigraphic stages and of the sedimentary successions in different parts of the Central and Western Paratethys is presented in Fig. 2.

The aim of this contribution is to present an overview of the most important Paratethyan source rock intervals. The paper focusses on the Middle Eocene (Kuma-type) and Oligocene - Lower Miocene (Maikopian) source rocks, but Middle and Upper Miocene rocks charging hydrocarbon fields in the Paratethys area are also considered. However, organic matter-rich rocks which did not reach oil-window maturities (e.g. Pliocene and Pleistocene high-TOC intervals in the South Caspian Basin; Katz et al., 2000) are not included in this paper, although they may...
Fig. 2. Stratigraphy and average petroleum potential (S1+S2) mg HC/g rock of the sections discussed in the present paper (supplemented after Sachsenhofer et al., 2015). J. Jaba Limestone. Numbers in round and square brackets refer to papers on stratigraphy and hydrocarbon potential, respectively: 1 – Grunert present paper (supplemented after Sachsenhofer 45); 2 – Zaporozhets (1999); 3 – Morton et al. (2012); 4 – Tabara and Popescu (2012); 5 – Francu and Zeugma (2015); 6 – Mayer et al. (2017); 7 – Kotarba et al. (1986); 8 – Radulski and Sachsenhofer (2010); 9 – Sarkissian et al. (2015); 10 – Bechtel et al. (2013); 11 – Amadori et al. (2010); 12 – Tabora and Popescu (2012); 13 – Saint Germès (1998); 14 – Peshkov et al. (2017); 15 – Morozkina et al. (2010); 16 – Bechtel et al. (2013b); 17 – Kaspar and Kalmar (2017); 18 – Peshkov et al. (2017); 19 – Bechtel et al. (2013b); 20 – Krotov et al. (2013); 21 – Morton et al. (2012); 22 – Sachsenhofer et al. (2015); 23 – van der Boon et al. (2017); 24 – Bechtel et al. (2013); 25 – Bechtel et al. (2013); 26 – Bechtel et al. (2013); 27 – van der Boon et al. (2017); 28 – Bechtel et al. (2013); 29 – Mirshahani et al. (2017).
serve as source rocks for microbial gas. Likewise, pre-Middle Eocene source rocks such as the Upper Jurassic Mikulov Marl in the Vienna Basin (e.g., Gerslova et al., 2015; Rupprecht et al., 2017), which charged Mesozoic and/or Cenozoic reservoir rocks, are not considered either.

In order to quantify the hydrocarbon potential of Middle Eocene to Lower Miocene units, the amount of hydrocarbons which can be generated below a surface area of 1 m² was calculated using the Source Potential Index, 

$$SPI = \text{thickness} \times (S_1 + S_2) \times \text{bulk density} / 1000$$

(cf. Demaison and Huizinga, 1994). Demaison and Huizinga (1994) classified SPIs in vertically drained petroleum systems as low (<5 t/m²), moderate (5-15 t/m²) or high (>15 t/m²). In laterally drained petroleum systems, the threshold values are lower (<2; 2 – 7; >7 t/m²) because of the larger drainage areas.

OUTLINE OF THE EVOLUTION OF THE PARATETHYS (AND THE EOCENE NORTHERN PERI-TETHYS)

The Paratethys evolved from the northern part of the Peri-Tethyan platform which was characterized by a series of east-west trending basins separated by structural highs (Gaetani et al., 2003). Patterns of sedimentation during Eocene time were controlled by sea-level variations and by changes in the seaways which connected these basins with the Boreal and Tethyan oceans (e.g., Akhmetiev and Beniamovskiy, 2004; Akhmetiev et al., 2012).

By the Middle Eocene, a large epicontinental dysoxic basin, which at times became anoxic, was established on the southern margin of the Eastern European Platform between the NW rim of the Black Sea and the Aral Sea (Beniamovskiy et al., 2003) known as the Kuma Basin (Fig. 3). According to Beniamovskiy et al. (2003), oxygen-depleted conditions in this basin resulted from tectonic activity in the Caucasus fold belts, which narrowed the straits connecting the basin to the western Siberian and northern European basins. Organic-rich sediments of the Kuma Formation, 20 to 50 m thick, were deposited in this basin, mostly during a relative cool period (Beniamovskiy et al., 2003). These authors suggested that carbon storage in the Kuma Formation was one of several factors contributing to global cooling which led to the establishment of the East Antarctic ice sheet by the end of the Eocene, which in turn contributed to the isolation of the Paratethys.

In the Late Eocene, most of Europe consisted of an archipelago of island areas surrounded by an oxygenated, semi-open, subtropical sea. The subsequent evolution of this area is briefly described below following Rögl (1999) and Popov et al. (2004a,b). Around the Eocene/Oligocene boundary, intense tectonic activity and a sea-level fall resulted in the separation of Paratethys from the evolving Mediterranean (Fig. 4a). Thereafter, water depths in the Paratethys increased locally to more than 1000 m. Basin isolation resulted in oxygen-depleted conditions during Early Oligocene time (nanoplankton zones NP21-22) and caused deposition of organic matter-rich
rocks in deep-water settings which extended from the Western Alps to the North Usturt Depression (Fig. 1). Palaeobotanical data show a gradual change from a xerophytic subtropical to a temperate mesophilic climate around the NP21/22 boundary (Popov et al., 1993a). These climatic changes led to salinity and thermal stratification of the water column and stagnation in the deepest zones of the Paratethys at the beginning of NP22 (Fig. 4a).

At the onset of nannoplankton zone NP23, the connection between Paratethys and the world ocean was lost (Solenovian Event; Voronina and Popov, 1984; Rusu, 1999). Light-coloured, oligospecific nannomarls (Dynow and Polbian marls) with ostracods and molluscs, which form a widespread synchronous marker horizon in the Paratethys, accumulated in a basin with strongly reduced salinity (12-14‰; Popov et al., 1993b). During the later Rupelian (upper NP23, NP24), communication with the open ocean was partly restored and outboard of the shelf zone, dark-coloured, largely carbonate-free clays without benthic fauna were deposited. Salinity was probably in the range 13-15‰ and occasionally reached 20‰ (Popov et al., 1993b).

In the Late Oligocene (NP24-25), the entire Paratethys was inhabited by a fully marine fauna although a marine regression occurred in the western part of the Alpine Foreland Basin. The restoration of marine environments caused alternating aerobic-anaerobic conditions. Later, the basin again became anoxic and dark, carbonate-free clays without benthic fauna were deposited. Salinity was probably in the range 13-15‰ and occasionally reached 20‰ (Popov et al., 1993b).

At the beginning of the Early Miocene (Karadžhalganian; NN1-2), the pattern of sedimentation in the Eastern Paratethys (“fish facies”) was similar to that in the early Late Oligocene. Despite a regressiv trend, the seaways connecting the Paratethys with the Mediterranean had widened during the early Burdigalian (Sakaraulian). The Lesser Caucasus seaway connected the Eastern Paratethys with the eastern Turkey and Iranian parts of the Burdigalian Sea (Fig. 2c; Popov et al., 2004b). Oxygenation improved and benthic fauna inhabited new areas. Fossil data suggest that there was a pronounced warming, especially in the Transcaucasian part of the basin (Popov et al., 1993a).

A major palaeogeographic rearrangement in the late Burdigalian (Kozakhurian) isolated the Eastern Paratethys, forming the Kozakhurian Sea with strongly reduced salinity and endemic brackish-water faunas which appear simultaneously in the (late Ottangian) Central Paratethys (Popov et al., 1993b). A Middle Miocene (early Badenian) transgression flooded the entire Central Paratethys, except the Alpine Foreland Basin, and for a short time a seaway reopened connecting the Eastern Paratethys with the Indian Ocean. Aerobic conditions enabled benthic fauna to inhabit most parts of the Eastern Paratethys during Tarkhanian time. Deposition of diatomaceous sediments (Diatom Suite) in the South Caspian Basin commenced during Karaganian time and continued into the Late Miocene (Alizadeh et al., 2016). In the Late Miocene, the Eastern Paratethys was a water mass with strongly varying salinity, whereas a brackish to freshwater lake system (Lake Pannon), which was progressively filled by prograding deltaic sediments, dominated the Central Paratethys.

**EOCENE SOURCE ROCKS**

This section focuses on the Middle Eocene Kuma Formation in the Eastern Paratethys. Plots of bulk parameters versus depth for some key sections and of petroleum potential ($S_1 + S_2$) versus TOC are shown in Figs 5 and 6, respectively.

**Late Middle Eocene Kuma Formation (and its analogues)**

The organic matter-rich Kuma Formation (and its analogues) was deposited in late Middle Eocene time in a dysoxic to anoxic basin extending from Crimea in the west to the Aral Sea in the east (Beniamovski et al., 2003; Fig. 3). The formation overlies light-coloured marls and limestones of the Keresta Formation and analogues, and is overlain by intensely bioturbated, Upper Eocene white marls (Belaya Glina Formation; Fig. 2). The average thickness of the Kuma Formation is 80 m, but varies from 20 m (in the northern and western North Caucasus) to 800 m in the western Kuban Depression SE of the Azov Sea (Fig. 3) (Distanova, 2007). The Kuma Formation consists of coffee- to dark-brown marls and may include frequent bentonite beds in its lower part (Beniamovski et al., 2003). Indeed, the presence of volcanic material in the depositional environment may have contributed to increased organic productivity (e.g. Vincent and Kaye, 2017). In the following paragraphs, the stratigraphic variability of the amount and type of organic matter in the Kuma Formation is briefly reviewed. Locations are shown in Fig. 3.

**Bakhchisaray section, Crimea:** The Kuma Formation in the Bakhchisaray section is 57 m thick and consists mainly of grey and black laminated marls with bentonite layers in its lower part (Beniamovski et al., 2003). Rhythmic alternation (~0.5 m) between
Paratethyan petroleum source rocks: an overview

(a) Early Oligocene
(Early Rupelian, Early Kiscellian, Psekhian)

(b) Late Oligocene
(Chattian, Egerian, Kalmykian)

(c) Early Miocene
(Burdigalian, Eggenburgian, Sakaramulian)

Fig. 4. Palaeogeographic sketches of the Paratethys for (a) Early Oligocene, (b) Late Oligocene and (c) Early Miocene time after Popov et al. (2004a). Deep-water zones with permanent anoxia (dark red) and zones with temporary anoxia (light red) are shown for the Eastern Paratethys (Popov and Stoljarov, 1996). SPI values and the expected petroleum type are shown after Sachsenhofer et al. (2017b) and Raubal and Sachsenhofer (2017). Note that the age assignment of some units is ambiguous resulting in some uncertainties.
relatively light marls and 3 to 5 cm thick beds of darker marls is typical, as is the occurrence of abundant fish remains. Plant debris and grey-green intercalations become abundant in the upper part of the formation. Only a few bivalves (*Lucina* sp.) were found by Beniamovski et al. (2003). TOC contents in the Bakhchisaray section vary and reach 8 wt.% in the lowermost part of the formation (Fig. 5a). Peshkov et al. (2016) reported Rock-Eval data which indicate that organic matter is immature ($T_{\text{max}}$: 413-430°C). HI values are in the range of 237 to 498 mgHC/gTOC, and the petroleum potential is good (Fig. 6).

**Belaya River, western North Caucasus:** The age and depositional environment of the Eocene succession in the Belaya River section has been studied by van der Boon (2017) and Popov et al. (2017). Here we present new bulk geochemical data (Morton et al., 2017).
The Kuma Formation in the Belaya River section is 43 m thick and is composed of laminated calcareous marls with abundant fish remains. The presence of prasinophytes and acritarchs suggests an anoxic depositional environment with indications of reduced salinity. Reduced salinity is also supported by TOC/S ratios, which are higher than expected for marine rocks (>2.8; Berner, 1984) (Fig. 5b). TOC contents gradually increase upwards within the lowermost 6 m of the Kuma Formation (Fig. 5b) and are fairly constant (3-4 wt.%) in the main part of the formation, but show a subtle minimum at about 30 m above datum. Above, TOC contents decrease rapidly, coinciding with the presence of small oysters and benthic foraminifera in the bioturbated uppermost 3 m of the Kuma Formation (Popov et al., 2017). The organic matter is thermally immature (average $T_{\text{max}}$: 416°C). The HI (400-600 mgHC/gTOC; Fig. 5b) and the petroleum potential (average: 15.6 mgHC/grock; Fig. 6) classify the Kuma Formation as a good to very good oil-prone source rock at this location. Similar values have been determined in outcrops along the adjacent Pshish and Kuban Rivers by Distanova (2007) and Distanova and Bazhenova (2007). Assuming a density of 2.4 g/m³ for this carbonate-rich unit, the Kuma Formation at the Belaya River can generate about 1.6 tHC/m².

Kheu River, central North Caucasus: The Kuma Formation exposed along the banks of the Kheu River (Fig. 3) has been studied by Gavrilov et al. (2000). Twenty bentonite layers, up to 10 cm thick, occur in the lower part of the formation, which is about 50 m thick at this location (Fig. 5c). TOC contents are more variable than in the Belaya River section, and the average TOC is lower. According to Distanova (2007), the HI of two samples is about 350 and 600 mgHC/gTOC, respectively.

Kuma Uplift and eastern North Caucasus: Saint-Germes (1998) reported TOC and Rock-Eval data from three borehole samples from the Kuma Uplift (Fig. 3) where the Kuma Formation is about 20 to 30 m thick (e.g. Ulmishek, 2001). TOC (1.8-10.9 wt.%), HI (76-366 mgHC/gTOC) and $T_{\text{max}}$ data (424-441°C) indicate the presence of immature to mature source rocks with partly very good source potential (Fig. 6). The Kuma Formation in the eastern North Caucasus at Chirkey (in Dagestan) is mature ($T_{\text{max}}$: ~440°C). Consequently HI is reduced (50-350 mgHC/gTOC; Distanova and Bazhenova, 2007).

Keresta section, Volga-Don: The northernmost facies of the Kuma Formation were recovered in a borehole at Keresta in 1995 (Beniamovski et al., 2003) (location in Fig. 3). Here the Kuma Formation unconformably overlies the Keresta Formation and consists of 6 m of brown-grey calcareous clays in the lower part and green-grey clays in the topmost 4 m. There are no bentonites in this section. Although geochemical data are missing, the lithological description suggests limited source potential.

Rioni Basin, western Georgia: Pupp et al. (2018, this issue) studied two sections of the Kuma Formation in the Rioni Basin on the SW flank of the Greater Caucasus in Georgia (Khobi and Martvili: Fig. 3) using bulk geochemical data and biomarker proxies. The vertical variation of bulk parameters in the Khobi section, where the Kuma Formation is immature and at least 35 m thick, is shown in Fig. 5d. TOC contents in the Khobi section are typically in the order of 3 wt.%. HI values vary between 300 and 600 mgHC/gTOC. The position of the Khobi and Martvili samples in the cross-plot in Fig. 6 indicates that both sections contain oil-prone source rocks with a good to very good
source potential. The SPI has been calculated as 1.0 and 2.4 tHC/m² for the Khobi and Martvili sections, respectively. However, because the uppermost part of the Kuma Formation is missing in the Khobi section and because the thickness of the Kuma Formation in the Martvili section is increased due to tectonic processes, the “true” value is probably somewhere in-between (Pupp et al., 2018 this issue).

Sochi, Tuapse Basin: Selected samples of the Kuma Formation from the Sochi area (location in Fig. 3) have been studied by Distanova (2007) and Vincent and Kaye (2017; Fig. 6). These authors reported very high TOC contents (up to 10 wt.%), HI values up to 790 mgHC/gTOC, and petroleum potential values exceeding 40 mgHC/g rock. However, as these data are from cm-thick intervals, a final assessment of the source potential of the Kuma Formation in the Sochi area is not yet possible.

The Middle Eocene in the SE margin of the Kura Basin (Moghan Basin, NW Iran): Source rock data have been collected from the Salm Aghaji and Lower Ojagheshlagh Formations in the Moghan Basin, NW Iran (the extension of the Talysk Basin of Azerbaijan) by Mirshahani et al. (2018, this issue). Conventionally both formations are considered to be of Late Eocene age. However, radiometric age data from the overlying Peshtasar volcanics (Vincent et al., 2005) and new bio- and magnetostratigraphic data from the top of the Arkevan Formation, which is equivalent to the Lower Ojagheshlagh Formation (van der Boon et al., 2017), suggest that the formations are in fact Middle Eocene in age and they are therefore discussed briefly in this section.

The Salm Aghaji Formation, composed of clayey sandstones and marls with thin limestone intercalations, is on average 600 m thick and is overlain by the Peshtasar volcanics. The Lower Ojagheshlagh Formation contains marls and bituminous shales, varying in thickness from 140 m in the south to 650 m in the central part of the Moghan Basin (Mirshahani et al., 2018, this issue). Average TOC and HI values for the Salm Aghaji (0.7 wt.%; 131 mgHC/gTOC) and Lower Ojagheshlagh Formations (1.0 wt.%, 178 mgHC/gTOC) are low, indicating a dominance by terrigenous organic matter. However samples with a good hydrocarbon potential (2-4 wt.% TOC; HI: up to 400 mgHC/gTOC; Fig. 6) occur in the NE part of the Moghan Basin. This trend may indicate that the source potential of Middle Eocene rocks may increase eastwards into the South Caspian Basin.

Middle Eocene in the Carpathians: Middle Eocene (Bartonian) rocks rich in organic matter occur in the Carpathians where they consist of dark shaly intervals, 20 m thick, within the green-grey shales of the turbiditic Hieroglyphic Beds (Waskowska, 2015; Waskowska et al., 2016) (Fig. 2). Maximum TOC contents (1.1-2.8 wt.%) occur in the lower 10 m and decrease upwards. According to Waskowska et al. (2016), the (immature) organic matter is classified as Type III kerogen.

Upper Eocene organic matter-rich intervals in Paratethys

The prevailing oxic conditions prevented the deposition of extensive organic matter-rich rocks in Paratethyan basins during the Late Eocene. However, Upper Eocene source rock intervals may be of local importance. For example, some intervals within the Upper Eocene Avren Formation in the western Black Sea have fair generative potential for oil and gas (Sachsenhofer et al., 2009). More important are Eocene mudstones in the western Kura Basin which have been drilled to the east of Tbilisi in several deep wells (Samsu, 2014). In the Norio well, Eocene mudstones, nearly 400 m thick, contain on average 3.3 %TOC with HI values ranging from 122 to 402 mgHC/g TOC. Tₚₚ values of about 430°C suggest that the organic matter is immature. However, contamination of the cuttings analysed by oil-based mud cannot completely be excluded. Upper Eocene rocks with high TOC contents and Type III(-II) kerogen have also been drilled in the nearby Manavi well (average TOC: 4.0%; HI: 120-279 mgHC/g TOC) (Samsu, 2014).

Saint-Germès (1998) and Saint Germès et al. (2002) described a unique Upper Eocene facies in the eastern part of the Kura Basin in Azerbaijan (the Perkeckkul-2 profile). They observed thin (<1 cm) layers with very high TOC contents (up to 18.5 wt.%), HI values (up to 675 mgHC/gTOC) and with very good source potential (83 mgHC/g rock) intercalated with 10 to 60 cm thick intervals with low potential (1.4 mgHC/gTOC). Hence, the average petroleum potential was only 5.3 mgHC/g rock.

OLIGOCENE EARLY MIocene MAIKOPIAN SOURCE ROCKS

Oligocene to Early Miocene (Maikopian) source rocks are widely distributed within the Paratethys, and comprise the main source for oil in a number of basins including the Alpine Foreland Basin (Gratzer et al., 2011), the Carpathian Basin (Kotarba et al., 2007), the Caucasus Foredeep basin (Ulmishek, 2001; Yandarbiev et al., 2017), the Kura Basin and the South Caspian Basin (e.g. Inan et al., 1997; Katz et al., 2000; Guliyev et al., 2003). Sachsenhofer et al. (2017b) presented an overview of the source potential of Maikopian successions in the different sub-basins
Central Paratethys

Alpine Foreland Basin: The Lower Oligocene succession in the Alpine Foreland Basin overlies shallow-marine Upper Eocene sandstones or limestones. Data from two boreholes are combined in Fig. 7 to show the marked vertical variations of source rock parameters, which contrast with the high lateral continuity (Sachsenhofer and Schulz, 2006). The deposition of pelitic rocks in the Alpine Foreland Basin began at about the Eocene/Oligocene boundary (NP21 or NP19/20; see Schulz et al., 2002) with the Schöneck Formation (Fig. 7). The Schöneck Formation, 10 to 25 m thick, is composed of a marly lower part with an average TOC content of about 2.5 wt.%; and an upper black shale interval with TOC of about 5.5 wt.% (up to 12 %; Schulz et al., 2002). Hydrogen index (HI) values indicate the presence of Type II kerogen and display a general upward increasing trend from 400 to 600 mgHC/gTOC. Very high TOC and HI values in the black shales result from photic zone anoxia during deposition.

Salinity was reduced significantly during deposition of the black shales and remained low during the deposition of the overlying light-coloured Dynow Formation, which represents the Solenovian Event (Schulz et al., 2004). Limestones with low TOC contents were deposited during coccolithophorid blooms, whereas organic-rich marls (max. 2.0 wt.%) accumulated during periods of low productivity by calcareous nannoplankton. HI values in the order of 500 to 600 mgHC/gTOC reflect excellent preservation conditions due to the prevailing anoxia (Schulz et al., 2004, 2005).

Subsequently, the reconnection of Paratethys to the open oceans caused an increase in salinity, but oxygen-deficient conditions continued during deposition of the Eggerding Formation (NP23-24) which is typically about 45 m thick. Its lower part consists of dark grey, laminated shaly marlstones with high TOC contents (1.9-6.0 wt.%) and HI values (up to 600 mgHC/gTOC). The upper part consists of homogenous mudstones with a low carbonate content (~10 wt.%) and a moderate amount of organic matter (~1.5 wt.% TOC) dominated by Type II/III kerogen (HI: 200-400 mg HC/g TOC) (Sachsenhofer et al., 2010). Slope instabilities are indicated by the occurrence of slumps and extensive submarine slides which culminated at the transition from the Eggerding to the Zupfing Formations; at this time, stratigraphic successions up to 70 m thick were remobilized and redeposited on the northern slope of the basin (Sachsenhofer and Schulz, 2006; Sachsenhofer et al., 2010).
The Zupfing Formation (NP24-25) consists of calcareous mudstones up to 450 m thick, but only the lowermost few metres contain high amounts of Type II/III kerogen (1.5 wt.% TOC; HI 200-400 mg HC/g TOC; Fig. 7). The main part of the Zupfing Formation contains moderate amounts of Type III kerogen (1.1 wt.% TOC; HI 100-250 mg HC/gTOC) (Sachsenhofer et al., 2010).

The black shale “unit C” of the Schöneck Formation has the highest petroleum potential in the Alpine Foreland Basin. Results from pyrolysis-gas chromatography (Py-GC) indicate that the Lower Oligocene units will generate paraffinic-naphthenic-aromatic (P-N-A) mixed oils, typically with high wax contents (Sachsenhofer et al., 2010). The SPI has been estimated to be 1.1 tHC/m² (Sachsenhofer et al., 2010; Fig. 4).
Carpathian Basin: Oligocene to Lower Miocene organic matter-rich rocks in the Carpathian orogenic belt are referred to as the Menilite Formation (e.g., Picha et al., 2006; Kotarba and Koltun, 2006). The formation is generally up to 550 m thick (Oszczypko, 2006), but locally reaches significantly greater thickness (~1500 m) in the Eastern Carpathians of Ukraine (Andreyeva-Grigorovich et al., 1997). The Menilite Formation overlies the Upper Eocene Green Clays and pelagic Globigerina Marls (Fig. 2). The upper boundary of the Menilite Formation is diachronous (NP24-NP3) and is marked by a change to flysch- (“Krosno-type”) or molasse-type deposits. Locally “Transitional Beds” occur below the Krosno Beds.

The Menilite Formation includes calcareous and non-calcaceous black shales and siliceous sediments. Chert, interpreted as diagenetically altered diatomite (e.g., Krhovský et al., 1992), is a prominent lithological component. According to Picha and Stranik (1999), cherty rocks were deposited due to upwelling and resulting high siliceous bioproducitivity. Based on fish and trace fossil assemblages, Kotlarczyk and Uchman (2012) proposed that chert deposited during NP23 accumulated in a silled, anoxic basin with a stratified water column. Thin beds of coccolith limestones are used as stratigraphic markers (Haczewski, 1989). The Jasło Limestone (middle part of NP24) is used here to separate Lower and Upper Oligocene units. Deep marine turbiditic sequences (e.g., Kliwa sandstones) occur within the Menilite Formation.

Western Carpathians (Czech Republic): The Menilite Formation in the Western Carpathians is divided from base to top into the Subchert, Chert, Dynow and Siborice members. It is discussed below with reference to the succession at borehole Kre-5, where the Menilite Formation has an apparent thickness of about 90 m (Fig. 7).

The Subchert Member (NP22) consists of laminated marls and shales. In the Kre-5 well succession, the Subchert Member is only a few meters thick but contains abundant organic matter (2.5-5.9 wt.% TOC) with moderately high HI values (250-345 mgHC/gTOC). The Chert Member is up to 4 m thick. Its upper part was deposited in an environment with a strongly reduced salinity (Krhovský et al., 1992). Thus in both the Carpathian Basin and the Alpine Foreland Basin, the major fall in salinity characteristic of the Solenovian Event occurred shortly before deposition of the Dynow Marlstone (NP23). Both the Chert Member (3.8-5.3 wt.% TOC; HI: 580-680 mgHC/gTOC) and the Dynow Marlstone (5.1-5.9 wt.% TOC; HI: 460-560 mgHC/gTOC) contain abundant Type II kerogen with good to very good petroleum potential (Fig. 8a) (Francu and Feyzullaev, 2010; Sachsenhofer et al., 2017b).

The Siborice Member is composed of carbonate-free shales with thin layers of nanno-chalk. According to palaeontological evidence, oxygen contents were depleted and salinity was low but variable during deposition (Krhovský et al., 1992). Debris flow deposits in the lower part of the Siborice Member (e.g., Picha et al., 2006) may represent the same phase of slumping and submarine erosion as that described by Sachsenhofer and Schulz (2006) in the Alpine Foreland Basin. In the Kre-5 well, the Siborice Member includes moderate amounts of organic matter (~1.5 wt.% TOC), but with low HI (~70 mgHC/gTOC). Consequently its petroleum potential is very low in comparison with the underlying members (Fig. 8a). The Menilite Formation is overlain by light grey mudstones which locally may contain elevated amounts of organic matter, and turbiditic Krosno-type sandstones (Zdanice-Hustopece Formation). In the Kre-5 succession, the boundary is located within NP23 (Svabenicka et al., 2007). The SPI of the Menilite Formation in Kre-5 is 1.5 tHC/m².

Eastern Carpathians (Poland, Ukraine, Romania): Reviews of the hydrocarbon potential and maturity of the Menilite Formation in the Outer (Flysch) Carpathians in Poland and Ukraine include Kotarba and

Table 1. Rock-Eval data, thickness of source rock complex and SPI for the Menilite Formation in different nappes of the Polish Outer Carpathians. Data for the Transitional Beds are given in brackets (after M. Kotarba in Sachsenhofer et al., 2017b).

| Sector | Skole Nappe | | | Silesian Nappe | | | Dukla Nappe | |
|--------|---------|-------|------|----------------|-------|-------|----------------|------|
|        | A       | B     | C    | Lower Oligocene |       |       | Lr Oligocene    | B    |
| Stratigraphy | Lr+ U. Oligocene |       |       |                  |       |       |                  | B    |
| TOC (wt.%) | 5.0    | 4.7   |      |                  |       |       |                  |      |
| HI (mgHC/gTOC) | 104   | 289   |      |                  |       |       |                  |      |
| T_max (°C) | 415    | 418   |      |                  |       |       |                  |      |
| S1+S2 (mgHC/gRock) | 18.5  | 14.5  |      |                  |       |       |                  |      |
| Net thickness (m) | 90   | 110   |      |                  |       |       |                  |      |
| SPI (tHC/m²) | 3.3   | 3.2   |      |                  |       |       |                  | 2.1  |

Sectors A to C are aligned from W to E, SPI - Source Potential Index.
Koltun (2006) and Kosakowski et al. (2018, this issue). Based on a large data set, these authors show that rocks with a high petroleum potential occur in different tectonic units including the Boryslav-Pokuttya, Skole/Skyba and Silesian/Krosno nappes (Fig. 8b) (see also Köster et al., 1998; Kotarba et al., 2007, 2013, 2014).

The Menilite Formation in Poland contains varying mixtures of Type II, Type IIIS and subordinate Type III kerogen (Lewan et al., 2006). Sachsenhofer et al. (2017b) summarized the work of M. Kotarba and listed average Rock-Eval data and net thicknesses for the Menilite Formation and the Transition Beds (excluding sandy intervals) in different sectors of the Skole, Silesian and Dukla nappes in the Polish Carpathians and calculated their SPI (Table 1). According to these data, the SPI of the Menilite Formation ranges from 2.1 to 5.5 tHC/m². The SPI of the Lower Oligocene Transitional Beds in sector B of the Silesian Nappe is 4.3 tHC/m². Consequently, the total SPI of the Lower Oligocene succession in the Silesian Nappe may reach 9.7 tHC/m². The Menilite Formation in the Polish part of the Skole Nappe extends into the Upper Oligocene. It is difficult to quantify the SPI for the Upper Oligocene succession alone, but a value of about 1.5 tHC/m² appears to be reasonable.

In the Ukrainian part of the Skole/Skaiba Nappe, the Menilite Formation is exposed along the Chechva River with an extraordinary thickness of ~1500 m. According to Andreyeva-Grigorovich et al. (1986; 1997), the Menilite Formation includes lower (Lower Oligocene; NP22-24), middle (Upper Oligocene) and upper Menilite subformations (Lower Miocene; NN1-2).

The source potential of the Lower and Upper Menilite has been studied by Rauball and Sachsenhofer (2017; Fig. 9). In contrast, source rock data are not available for the poorly-exposed, 100 to 200 m thick, Middle Menilite which contains only isolated organic-rich layers. The Lower Menilite subformation is about 300 m thick. It contains a chert layer near its base, a high number of turbiditic sandstone beds in its lower part, and a coccolith limestone (Jaslo Limestone) in its upper part. The average TOC content of shaly intervals is 9.8 wt.% (max. TOC: 24 wt.%). HI values reach 800 mgHC/gTOC near the base and decrease upwards to 400 mgHC/gTOC (average HI: 448 mgHC/gTOC; Fig. 9). Considering a net source rock thickness of 190 m and a rock density of 2.0, the SPI is 15.8 tHC/m².

The Upper Menilite subformation is more than 1000 m thick and includes the basal Upper Chert interval and a tuff layer, 75 m thick (Andreyeva-Grigorovich et al., 1986; Fig. 9). Sandstone beds are rare. The average TOC (4.9 wt.%) and HI values (364 mgHC/gTOC) indicate a high oil potential. Nearly half of the Upper Menilite subformation is not exposed (Fig. 9). Assuming that it contains a similar oil potential to that in the exposed section, the SPI of the entire Upper Menilite subformation is calculated as 55.2 tHC/m². Apart from excellent source rock quality, this high value, which significantly exceeds the SPI of any other source rock unit in the entire Paratethys area, is a consequence of the high net shale thickness (1225 m).

The southern continuation of the Boryslav-Pokuttya Nappe in Romania is termed the Vrancea Nappe. The evolution of depositional environments and the vertical variation of the source rock potential of the Menilite Formation in the Vrancea Nappe has been studied in the Tazlau section by Sachsenhofer et al. (2015; Fig. 10). At Tazlau, the Menilite Formation is about 430 m thick and comprises from bottom to top the Lower Menilites, the Bituminous Marls, the Lower Dysodilic Shales, and the Upper Dysodilic Shales (e.g. Miclăus et al., 2009). Unfortunately the precise age of the Menilite Formation is still a matter of debate (see Melinte, 2005; Melinte-Dobrinescu and Bustur, 2008; Amadori et al., 2012; Guerrera et al., 2012; Sachsenhofer et al., 2015).

The Menilite Formation overlies Eocene mudstones with low TOC contents (Bisericanii Formation; Fig. 9). Deposition of the Lower Menilite Member marks a change towards strongly oxygen-deficient conditions, which together with high siliceous bioproductivity caused accumulation of organic matter-rich rocks including cherts. TOC contents (2.1-8.6 wt.%; av. 3.8 wt.%) and HI values (250-580 mgHC/gTOC; av. 426 mgHC/gTOC) of 17 samples from a location in the Nechit valley (about 4 km north of Tazlau) indicate good to very good source potential (Fig. 10; Wendorff et al., 2017). Calcareous nanoplankton date the overlying Bituminous Marl Member to zones NP21-22, making it older than the Dynow Marlstone, although they are often correlated (e.g. Wendorff et al., 2017). According to Miclăus and Schieber (2014), the marls accumulated in a deep-marine environment with strong bottom currents. The organic matter is mainly derived from marine organisms including bacterial biomass. TOC contents are moderate (average 1.7 wt.%; HI: 400-650 mgHC/gTOC) because of dilution by carbonate minerals. Salinity and redox conditions varied from reducing to slightly enhanced and from strictly anoxic to dysoxic, respectively (Sachsenhofer et al., 2015).

The lower part of the Lower Dysodilic Shale Member contains black shales and a large number of sandstone beds deposited in a deep-marine lobe setting (Fig. 10). The anoxic environment resulted in the accumulation of abundant organic matter (average TOC: 2.6 wt.%). Although land plants form a significant part of the organic matter, HI values are high (500-650 mgHC/gTOC) (Sachsenhofer et al., 2015). As with the Bituminous Marl Member, salinity varied significantly during the deposition of the Lower
Dysodilic Shale Member. Channel fill sediments (the Kliwa Sandstone) are present in the top of the member.

The Upper Dysodilic Shale Member shows a fining upward trend and represents a transition from a deep-water depositional lobe to a basin plain setting (Fig. 10). Both autochthonous marine biomass and land plants contributed to the organic matter (average TOC in the lower part: 2.2 wt.%; upper part: 3.2 wt.%) which is classified as Type II kerogen, but which has a lower HI (300-400 mgHC/gTOC) than that in the Lower Dysodilic Shale Member. Deposition of the Burdigalian Gura Soimului Formation (NN2-NN3;
Tabara and Popescu, 2012) in an oxic environment terminated the accumulation of OM-rich rocks.

The SPI of the Menilite Formation is about 6 t HC/m². Whereas its main part is attributed to the Lower Oligocene succession, a significant proportion is present in the Upper Oligocene and Lower Miocene. However, because of the uncertain age dates, the precise separation of the different chronostratigraphic intervals is not clear.

Pannonian Basin: The Lower Oligocene succession in the Pannonian Basin accumulated in a retroarc foreland setting (Tari et al., 1993), and includes the bathyal Buda Marl Formation and the organic matter-rich Tard Clay Formation (e.g. Vető and Hertelendi, 1996; Fig. 2). Bechtel et al. (2012) and Badics and Vető (2012) studied the source rock potential of the Tard Clay and investigated its shale gas/shale oil potential.

In Fig. 7, data from borehole Ad-3 are used to characterize the Lower Oligocene succession in the Pannonian Basin. TOC contents of the Buda Marl Formation (NP20-22; Danisik et al., 2015) are typically below 1.0 wt.% (max. 2.3 wt.%) and HI values (<150 mgHC/gTOC) indicate the presence of Type III or inert Type IV kerogen (Bechtel et al., 2012). The Tard Clay Formation is on average 68 m thick (up to 200 m).
m; Badics and Vető, 2012), and in well Ad-3 reaches a thickness of 86 m. Its non- to weakly laminated lower part (698-679 m; uppermost NP22) was deposited in a semi-marine environment and displays TOC contents of up to 5.0 wt.% but with low HI values (<185 mgHC/gTOC) (Bechtel et al., 2012). Higher HI values (210-440 mgHC/gTOC) occur between 679 and 640 m depth (lower NP23) in the strongly laminated, low-salinity middle part of the formation, which corresponds to deposition during the Solenovian Event (Vető and Hetény, 1991; Vető and Hertelendi, 1996). Brukner-Wein et al. (1990) assumed that the presence of volcanic tuff induced high bioproductivity due to an increased supply of nutrients in this interval. Biomarker proxies suggest photic zone anoxia (Bechtel et al., 2012). Interestingly, in contrast to many other basin locations, the Solenovian Event in well Ad-3 is represented by rocks with a low carbonate content. The upper part of the Tard Clay (640-610 m; upper part of NP23) is characterized by an increase in salinity and a gradual decrease in TOC and HI to values of about 0.5 wt.% TOC and 75 mgHC/gTOC, respectively (Bechtel et al., 2012). Fig. 8c shows that the middle and upper part of the Tard Clay has a good source potential (Bechtel et al., 2012), although it is lower than in most other basins in the Central Paratethys. The SPI of the Lower Oligocene succession in borehole Ad-3 is 0.9 tHC/m².

At a depth of 612 m in well Ad-3, the Tard Clay Formation is truncated by the terrestrial Csatka Formation (NP23/24) which is overlain by marine clays of the Kiscell Formation (NP24) (Danisik et al., 2015). Data from Milota et al. (1995) show that the source potential of the Kiscell Formation is low (<1.0 wt.% TOC; HI < 200 mgHC/gTOC).

**Eastern Paratethys**

Pelitic Oligocene to Lower Miocene rocks in the Eastern Paratethys have been given different regional names, but they are referred to here as the Maikop Group. Plots of petroleum potential versus TOC for Maikopian sediments in the Eastern Paratethys are shown in Fig. 11.

**Western Black Sea:** The architecture of the Maikop Group offshore Bulgaria is controlled by a regional erosional unconformity ("top-Eocene") and the incision of the west-east trending Kaliakra Canyon during late Solenovian time (Mayer et al., 2017; Fig. 12a). Oligocene rocks outside this shelf-break canyon and the Solenovian to Middle Miocene fill of the canyon itself are discussed separately below on the basis of boreholes Samotino More (Sachsenhofer et al., 2009; Fig. 12b) and Samotino Melrose 1 (Mayer et al., 2017; Fig. 12c).

**Oligocene rocks outside the Kaliakra Canyon:** Pshekhian (Lower Oligocene) rocks are characterized by an upward decrease in carbonate content (Fig. 12b), and have an average TOC of 1.7 wt.%. The average HI in well Samotino More is only 130 mgHC/gTOC but is significantly higher (~300 mgHC/gTOC) in other wells, suggesting the presence of Type III to II kerogen with gas and minor oil potential. Overlying marls represent deposition during the low salinity Solenovian Event (early NP23) and contain moderate amounts of Type II/III kerogen (1.4 wt.% TOC; HI: 290 mgHC/gTOC). The upper part of the Solenovian succession is dominated by largely carbonate-free shales with similar TOC contents (~1.5 wt.%) but significantly lower HI (70 mgHC/gTOC), suggesting low quality Type III/IV kerogen. Sediments with upward increasing carbonate contents are attributed to the Upper Oligocene. The lower part of the succession has up to 2.0 wt.% TOC; however HI values remain below 200 mgHC/gTOC.

**Canyon fill:** The fill of the Kaliakra Canyon in well Samotino Melrose is more than 1000 m thick (Fig. 12a) and comprises upper Solenovian to Middle Miocene rocks (Mayer et al., 2017). With the exception of the Middle Miocene, the succession is largely carbonate-free (Fig. 12c). Oligocene deposits include a high percentage of sandstone intervals.

Pelitic intervals within the Solenovian to Sakaraulian succession contain moderate amounts of Type III kerogen (~1.5 wt.% TOC; HI: ~240 mgHC/gTOC). However good quality source rocks (~2.5 wt.%; HI: up to 530 mgHC/gTOC), more than 200 m thick, were deposited during Kozakhurian time (Figs. 11a; 12c). High TOC/S ratios confirm a low salinity environment which fits well with a second isolation event in the Eastern Paratethys (Sachsenhofer et al., 2017b). The content of biogenic opal reaches 50 wt.% suggesting a high contribution of diatoms to the biomass. Similar sediments, but with significantly lower thickness, also occur south of the Kaliakra Canyon (Mayer et al., 2017). Based on the relationship with the shelf-break canyon, a model implying locally enhanced upwelling of subsurface waters onto the continental shelf (e.g. Kaempf, 2007) seems reasonable. The overlying Middle Miocene (NN5-6) sediments have poor source rock potential (~0.8 wt.% TOC; HI: ~130 mgHC/gTOC).

**North Caucasus:** The type section of the Maikop Group is located along the Belaya River at the southern rim of the Indol-Kuban Depression in the western North Caucasus (Russia), to the south of the city of Maikop. Its depositional environment and hydrocarbon potential has been studied by Sachsenhofer et al. (2017a). Bulk geochemical parameters (Fig. 13a) are discussed in the following paragraphs.
The Pshekha Formation (604.0-543.3 m; upper NP20 to NP22) overlies Eocene marls (Belaya Glina Formation), and is dominated by calcareous shales although the uppermost part is carbonate-free. The average TOC content is 1.7 wt.%, but the HI is relatively low (~180 mgHC/gTOC). An HI of 365 mgHC/gTOC is reached only in the uppermost part of the Pshekha Formation.

The overlying Polbian “Ostracoda” Bed, a 30 cm thick white shaly limestone, represents deposition during the low-salinity Solenovian Event (base NP23). Salinity remained low during deposition of the Lower Morozkina Balka Formation (543-508 m; upper NP23), but increased gradually. High productivity by aquatic organisms resulted in deposition of organic matter-rich rocks (with up to 3.5 wt.% TOC) with high HI values (up to 404 mgHC/gTOC) in the lower part of the formation.

The Upper Morozkina Balka Formation (508-460 m; NP23-24; Akhmetev et al., 1995) contains significant amounts of carbonate. TOC (1.5-2.6 wt.%), but low HI values (40-240 mgHC/gTOC) are also characteristic of the largely carbonate-free pelitic sediments of the Batalpashinsk (460-370 m) and Septarian Formations (370-267 m; NP25-NN1). Thin intervals of sand shed from the uplifting and eroding Greater Caucasus mountains (Vincent et al., 2007; 2013) are present in the upper part of the Septarian Formation.
Uplift and erosion of the Greater Caucasus caused a sharp increase in detrital input to the lowermost part of the Lower Miocene succession. TOC contents (average: 1.3 wt.%) and HI values (~95 mgHC/gTOC) are typically low. Relatively high TOC contents (max. 3.0 wt.%) in the Olginskaya Formation are due to the presence of large amounts of terrigenous organic matter. The Maikop Group is conformably overlain by fossiliferous Tarkhanian marls.

A large number of TOC and Rock-Eval data from borehole and outcrop samples analyzed by Saint-Germès (1998), Saint Germès et al. (2000) and Gavrilov et al. (2017) show that the above values are representative for the entire North Caucasus ranging from the Indol-Kuban depression in the west to the Terek-Caspian depression in the east. Hence, Maikopian sediments contain moderately high organic matter contents, but the presence of Type II kerogen (HI >100 mgHC/gTOC) is restricted to intervals overlying the Solenovian Polbian “Ostracoda” Bed. Consequently the SPI of the Lower Oligocene succession is higher (1.3 t HC/m²) than that of the Upper Oligocene (0.5 t HC/m²) and Lower Miocene successions (0.2 t HC/m²; Fig. 4).

Partly higher TOC contents, but similar HI values, have been reported (Saint-Germès, 1998) from Lower Oligocene sediments in boreholes in the Kuma Uplift in the eastern North Caucasus area (Table 2; Fig. 11). In contrast, the source potential of the Maikop Group in the Crimea and Volga-Don areas is low (Saint-Germès, 1998; Sachsenhofer et al., 2017b; Fig. 11).

Tuapse Basin: The Tuapse Basin (for location see Fig. 4a) is a foredeep which was formed at the SW margin of the Greater Caucasus. The thickness of the Maikop Group reaches 5 km thick in the basin centre and decreases in the onshore area (Mityukov et al., 2012). Vincent and Kaye (2017) studied the source rock quality of the Maikop Group along the Mzimta section, where it is about 1900 m thick. Olistostrome packages are developed near the base of the Maikop Group and numerous turbiditic sandstone beds occur in the upper part of the Lower Oligocene and the Lower Miocene section (Vincent and Kaye, ibid.). The source potential of olistostromal sediments and of the Upper Oligocene and Lower Miocene rocks is typically low. In contrast, excellent source rocks with TOC contents up to 5.0 wt.% and Type II kerogen (HI <497 mgHC/gTOC) are found in pelitic samples of early and mid Rupelian age.

Rioni Basin: Source rock data from the Rioni Basin, western Georgia, located between the Greater and Lesser Caucasus (Fig. 4), are available from the Martvili (Pupp et al., 2018 this issue) and Chanis River sections (Vincent and Kaye, 2017).

The Oligocene section at Martvili is about 500 m thick (Fig. 13b). The most prospective samples occur in the 60 m thick Pshekhian unit (up to 5.2 wt.%TOC; HI: 460 mgHC/gTOC; Figs. 11d, 13b). At the Chanis River, the Oligocene section is about 700 m thick and maximum TOC contents (4.8 wt.%) and HI values (381 mgHC/gTOC) occur in the upper Solenovian interval (Vincent and Kaye, 2017). In contrast, the source potential of the Upper Oligocene rocks is typically lower. Abundant sandstone layers and pelitic rocks with low source rock potential (<1.0 wt.%TOC; HI: <100 mgHC/gTOC) occur in the Lower Miocene section at the Chanis River location, which is about 700 m thick (Vincent and Kaye, 2017).

The overall source potential of the Maikop Group in the Rioni Basin is higher than in the North Caucasus area. The Lower Oligocene succession alone can generate ~1.9 t/m² (Chanis River; Sachsenhofer et al., 2017b) or 2.5 t/m² (Martvili; Pupp et al., 2018, this issue). The Upper Oligocene succession at Martvili may contribute another 1.5 t/m².

Kura Basin: The Kura Basin, located mainly in Georgia and Azerbaijan, forms the eastern continuation of the Rioni Basin and extends eastwards to the South Caspian Basin (Fig. 1). The source potential of the western Kura Basin has been studied in the Tbilisi area (central Georgia), where the Maikop Group contains a large number of sand intervals and is more than 3500 m thick (Pupp et al., 2018 this issue). Because of its thickness and because of deep burial beneath a Miocene succession that is about 3000 m thick, the Lower Oligocene part of the Maikop Group is thermally mature (~0.75 %R, T_max: ~450°C). Hence,
HI values may be reduced. However, even if this effect is taken into account, HI values for the entire succession are low (average: 67 mgHC/gTOC; max: 230 mgHC/gTOC). This indicates the dominance of Type III (and IV) kerogen, which is corroborated by the presence of large amounts of detrital land plants. TOC contents are low (<1.0 wt.%) in Eocene, Pshekhian and Kozakhurian units, but moderately high in Solenovian to Sakaraulian rocks (up to 2.1 wt.%). Overall, the low to moderate TOC contents and the dominance of Type III kerogen indicate a low hydrocarbon potential.

A wealth of data has been gathered on the Maikop Group in the eastern part of the Kura Basin in Azerbaijan (Saint Germès, 1998; Katz et al., 2000; Hudson et al., 2008; Johnson et al., 2010; Bechtel et al., 2013, 2014). However, the results do not yield a consistent pattern. Bechtel et al. (2013, 2014) observed the best source rock interval (~3 wt.% TOC; HI ~300 mgHC/gTOC) in Lower Oligocene units at Angeharan and Lahich, whereas Saint-Germès (1998) observed source rock intervals with elevated TOC contents and HI values also occurring in the Upper Oligocene (TOC...
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up to 3.5 wt.%; HI up to 350 mgHC/gTOC) and Lower Miocene units (TOC up to 5.8 wt.%; HI up to 400 mgHC/gTOC) (Fig. 11). Data published by Johnson et al. (2010) suggested that maximum TOC contents occur in Upper Oligocene rocks. These differences either indicate major lateral variability in source rock parameters, or – more likely – may reflect problems with age dating.

Fig. 13. Bulk parameters for the Maikop Group along the Belaya River (after Sachsenhofer et al., 2017) and in the Martvili section (after Pupp et al., 2018, this issue). TOC and HI data from the Oligocene part of the Chanis River section (Vincent and Kaye, 2017) are projected into the Martvili section.
Moghan – Talysh Basin: The Pirembel Formation in the Talysh Basin (Azerbaijan) and the Lower Ziveh Member in the Moghan Basin (NW Iran) are considered to be time-equivalents of the Oligocene part of the Maikop Group, whereas the Upper Ziveh Member has been considered to be equivalent to the Early Miocene part. New bio- and magnetostratigraphic data indicate that the entire Pirembel Formation is probably Late Eocene in age (van der Boon et al., 2017). Hence, the same age has to be assumed for the Lower Ziveh Member. In contrast, the Upper Ziveh Member may be Oligocene (or Early Miocene) in age. Source rock data from the Ziveh Formation have been presented by Mirshahani et al. (2018, this issue). As these authors did not distinguish between the Lower and the Upper Ziveh members, all data are discussed here, despite the fact that the lower member is Late Eocene in age. The Lower Ziveh Member is about 2100 m thick and is composed of grey shales with thin marl intercalations. The Upper Ziveh Member, up to 1500 m thick, is lithologically similar and rests on the coarse-grained Middle Ziveh Member.

Mirshahani et al. (2018, this issue) emphasize that the Ziveh Formation in surface sections from the westernmost part of the Moghan Basin (NW Iran) exhibits negligible potential (TOC <0.5 wt.%); but that in boreholes located in the NE of the basin, the Ziveh Formation has good source potential for oil and gas (TOC: 0.3-3.7 wt.%; S2: 0.2-8.9 mg HC/g rock; Type II/III kerogen).

MIOCENE SOURCE ROCKS

Isotopically light gas is produced from uppermost Oligocene and Lower Miocene sediments in the eastern part of the Alpine Foreland Basin (Schulz and van Berk, 2009; Pytlak et al., 2017) and from Middle Miocene sediments in the Carpathian Foredeep, the Vienna Basin (Ladwein, 1988; Rupprecht et al., 2018) and the Transylvanian Basin (e.g. Kotarba and Koltun, 2006; Ciulavu et al., 2000). This gas is predominantly microbial in origin and has been sourced from uppermost Oligocene and Miocene rocks which are often low in organic matter (Sachsenhofer et al., 2017b; Kotarba and Koltun, 2006). These rocks are not discussed further here. However Miocene sediments are important source rocks for thermogenic hydrocarbons in the Pannonian Basin System and may also contribute to hydrocarbons in the Moesian Platform (Dacic Basin) and the South Caspian Basin.

Pannonian Basin System

Lower to Middle Miocene syn-rift and Upper Miocene post-rift sediments have sourced the majority of hydrocarbons in the Pannonian Basin System (Alajbeg et al., 1990; 1996; Badics and Vétő, 2012; Baric et al., 1998; 2000; Hasenhüttl et al., 2001; Sarkovic et al., 1992). Badics and Vétő (2012) presented an overview of the distribution and quality of source rocks in the Hungarian part of the basin. The following description is based on their data.

The marine Karpatic and Badenian syn-rift sediments (e.g. Budafá, Kiskunhalas, Tekeres and Szilágy Formations) were deposited in narrow graben structures (Fig. 14) resulting in variable facies and the alternation of deep-marine marls with coarse-grained clastic deposits. Hence, it is difficult to determine the net thickness of the source rock intervals. In Hungary, syn-rift sediments contain up to 3.3 % TOC and Type II to III kerogen (HI up to 347 mgHC/gTOC). Badics and Vétő (2012) considered them as fair quality, mixed oil- and gas-prone source rocks with major vertical and lateral heterogeneities.

Upper Miocene (Pannonian) sediments were deposited in Lake Pannon which was filled from the NW with turbiditic siliciclastic rocks (Szolnok Formation, Algyő Formation), deltaic deposits (Ujfalú Sandstone) and alluvial sediments (Zagyva and Nagylöföld Formations). The deep basin sediments (Endröd Marl) are up to 800 m thick. Because of their high maturity, it is difficult to determine the original source rock characteristics, but data available from immature rocks (with TOC up to 3.1 % and HI up to 322 mgHC/gTOC) suggest that they may be considered as fair quality, gas-prone source rocks, with minor amount of oil-prone kerogen. Turbiditic, deltaic and alluvial sediments either cannot be considered as source rocks or are thermally immature.

The above data may be considered to be representative of the Pannonian Basin System, although HI values are higher in the Sava and Drava depressions (generally 300-600 and up to 790 mgHC/gTOC; Troskot-Čorbić et al., 2009; Cvetković et al., 2018) and the southern Pannonian Basin System (Mrkic et al., 2011).

Moesian Platform

In addition to older source rocks, Middle Miocene (Badenian, Sarmatian) bituminous shales have generated thermogenic hydrocarbons in the northern (Romanian) part of the Moesian Platform. According to Stefanescu (2006), TOC contents vary from 1.3 to 2.5 wt.% (average 2.0 wt%) and HI values indicate a variation from prevailing Type I-II kerogen in the west to Type II-III kerogen in the east. The thickness of the source rocks (200-800 m) increases in the same direction. Middle Miocene source rocks also continue into the southern part of the Carpathian Foredeep.

South Caspian Basin

The lower Middle Miocene Spiralisian Formation and the Middle to Upper Miocene (Karaganian to Meotian)
Diatom Suite in the Kura Basin and the South Caspian Basin (Fig. 2) have been considered as important source rocks. They consist of shales, marls, sandstones, and limestones with interbeds of volcanic ash and coquina (Smith-Rouch, 2006). According to Alizadeh et al. (2017 and references therein), TOC contents are typically low (average 0.6 wt.%), but TOC contents up to 7.8 wt.% (average 1.0 wt.%) and HI values ranging from 107 to 807 mgHC/gTOC (average 308 mgHC/gTOC) occur in rocks ejected from mud volcanoes and in on- and offshore boreholes to the south of Baku. Low TOC contents in onshore samples have been confirmed by Katz et al. (2000), Feyzullayev et al. (2001) and Johnson et al. (2010). The Diatom Suite has reached oil maturity only in the deepest basinal parts of the Caspian Sea. Here, the basal facies is kilometres thick, but the net thickness of the source rock is still unknown (Baganz et al., 2012).

DISCUSSION AND SUMMARY

The Paratethys area contains a significant number of petroleum provinces (Boote et al., 2018, this issue). Many provinces contain reservoir rocks deposited in the Oligocene to Pliocene Paratethys, but older reservoir rocks are present as well. Reservoirs have been charged by Palaeozoic, Mesozoic and Cenozoic source rocks. The present paper focuses on source rocks deposited during the final (Eocene) stages of the Peri-Tethys and within the Oligocene to Miocene Paratethys.

Two source rock horizons with supra-regional significance are present: the Middle Eocene Kuma Formation (and its equivalents) in the Eastern Paratethys; and the Oligocene to Lower Miocene (“Maikopian”) source rocks in both the Central and Eastern Paratethys.
The highly oil-prone Kuma Formation, typically several tens of metres thick, has good to very good petroleum potential, and its significance as a source rock has probably been underestimated hitherto. Estimates of the SPI for different localities in the North Caucasus area and the Rioni Basin suggest that its petroleum potential is similar to that of the Maikop Group, despite its significantly smaller thickness. Although significant lateral variations of the source potential of this interval exist, the available data suggest that in addition to the Maikop Group, another possibly prolific source rock horizon may be present in the eastern Black Sea.

Important source rocks were deposited throughout the entire Paratethys during Early Oligocene time. The most prolific source rocks accumulated in the eastern Carpathians of Poland, Ukraine and Romania. There, the Lower Oligocene part of the Menilite Formation alone can generate up to 15 tHC/m². The outstanding quality of the Menilite Formation is a consequence of the interplay of several factors, including the very high bioproductivity of siliceous organisms and the excellent preservation, which is mainly due to water column stratification in a very deep, silled basin (Sachsenhofer et al., 2017b). In contrast, the source potential of the Lower Oligocene succession in the Eastern Paratethys is significantly lower and exceeds 1.0 tHC/m² only in the North Caucasus area, the eastern Kura Basin and the Rioni Basin. Vincent and Kaye (2017) suggested that it is tempting to extrapolate the promising results from the Rioni Basin to the Maikop Group in the eastern Black Sea. However, they also pointed out that the Shtatsky Ridge (location in Fig. 4c) formed a bathymetric high during deposition of the Maikop Group, and there is therefore some uncertainty as to whether the results apply only to the area to the NE of the ridge or to the entire Eastern Black Sea Basin.

The petroleum potential of Upper Oligocene rocks is typically low, although there are exceptions in the Carpathian Basin and the eastern part of the Kura Basin. The latter area also includes important Lower Miocene source rocks. Excellent Lower Miocene source rocks, although probably with restricted lateral extent, occur in the Western Black Sea where deposition of diatomaceous rocks with high TOC contents and a prevailing Type II kerogen was probably related to upwelling along a shelf-break canyon (Sachsenhofer et al., 2017b).

The most outstanding source rock succession, however, accumulated during Early Miocene times in the Eastern Carpathians (Chechva River section). Its very high SPI (~50 tHC/m²), from which the Early Miocene section can be characterised as a world-class source rock (c.f. Demaison and Huizinga, 1994), results from the interplay of a very high net shale thickness (>1000 m) with high TOC contents (4.9 wt.%) and a high petroleum potential (22.5 mgHC/g rock).

Middle and Upper Miocene source rocks charged oil and gas fields in the Pannonian Basin System. The Diatom Suite is probably an important source rock in the South Caspian Basin. However in onshore areas, the Diatom Suite typically contains low amounts of organic matter.

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