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The Anisian carbonate ramp system of Central Europe (Peri-Tethys Basin): sequences and reservoir characteristics

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ABSTRACT:

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During Middle Triassic times, the Peri-Tethys Basin bordered the north-western Tethys shelf and was connected to the open Tethys Ocean via three seaways. Today, Lower Muschelkalk carbonates of this epeiric sea cover large parts of Central Europe, documenting the evolution of a low-relief, homoclinal, mud-dominated ramp system during the Anisian. In view of their geotectonic/climatic setting, depositional processes, facies architecture, and distribution, the rocks are considered as an outcrop analogue for layer-cake reservoirs of world-wide importance, e.g. the Permo-Triassic Khuff or Jurassic Arab carbonates in the Middle East.

In general, two different reservoir types and their interplay might be considered: The proximal stacks of muddy dolostones (NW part of the basin) and the more distally developed grainy limestones (central and SE part of the basin). The rather uncommon depositional setting with minor relief and minimal accommodation contributed to both, the stratal and lateral facies development, and to unusual and possibly even "inverted" facies patterns with thick, grainy facies found in the more distal environments.

Based on litho- and microfacies analyses, six main facies types are distinguished, building characteristic cyclic facies successions of different hierarchies. The stratal architecture of small-scale depositional sequences systematically changes in relation to their relative proximal-distal position on the Muschelkalk ramp system. Here, we present porosity and permeability data of the different facies types and within the basin-wide sequence stratigraphic framework. Dolo-wacke-/packstones and peloid grainstones attain the highest porosities of up to 24%, whereas bioclastic grainstones show porosities of up to 8%. The platy and nodular mud-/wackestone and most of the bioclastic wacke-/packstones typically show porosities below 2%. Even in the most porous strata, permeabilities do not exceed 10 mD, and only a few carbonates show higher permeabilities up to 90 mD. Within large-scale, third-order depositional sequences late highstand deposits represent the most permeable sediments.

Key words: Depositional sequences; Reservoir characteristics; Carbonate ramp deposits; Middle Triassic, Anisian; Central Europe.

INTRODUCTION

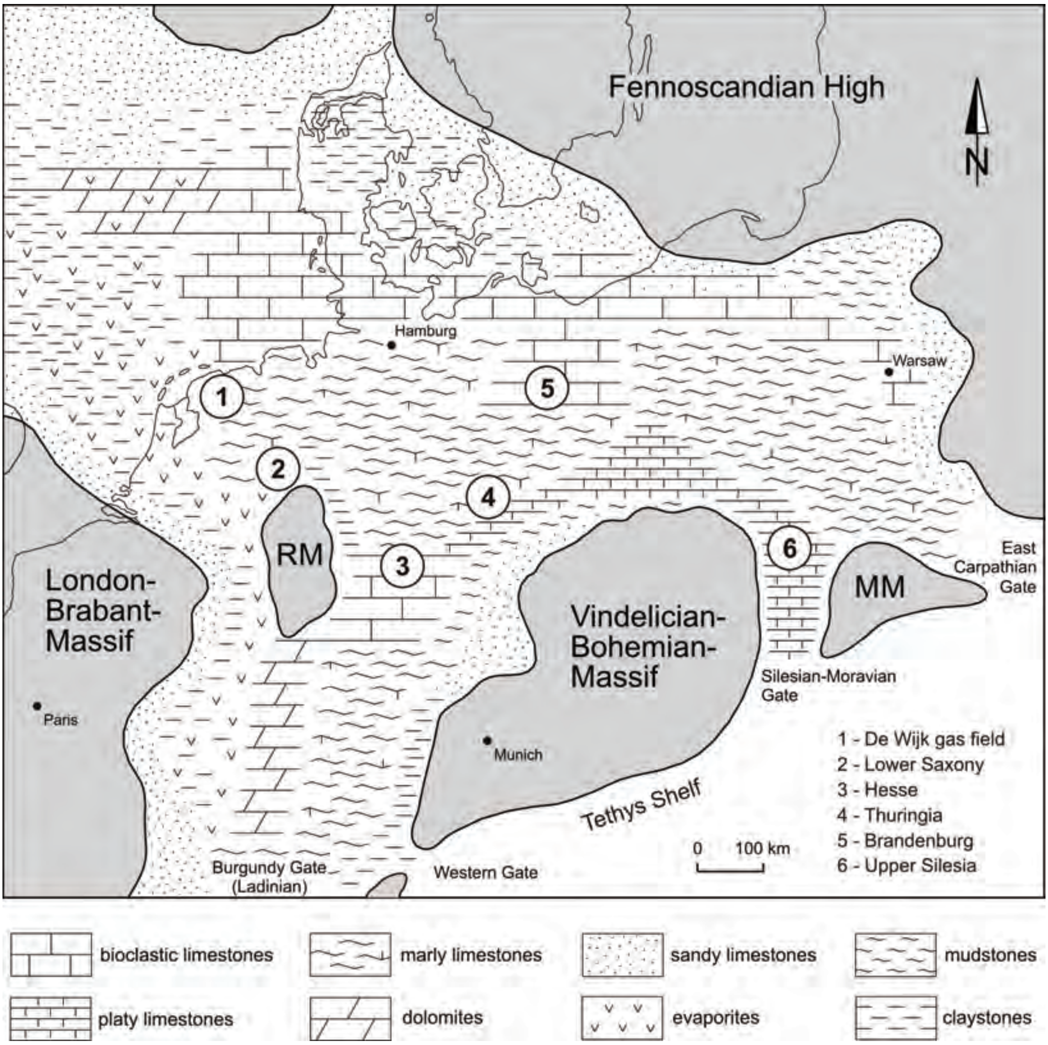
The Lower Muschelkalk carbonates of the Triassic Germanic (Peri-Tethys) Basin cover large parts of Central Europe, documenting the evolution of a homoclinal, mud-dominated ramp system during Anisian (Middle Triassic) times. This epeiric sea bordered the north-western Tethyan shelf and was connected to the open Tethys Ocean via three seaways. Inner, mid, and outer ramp deposits of the Muschelkalk Basin are analyzed along a palaeogeographic transect from peritidal environments in the north-western part of the basin (NW Germany) to subtidal sediments in the south-east (E Germany and S Poland) with respect to reservoir characteristics. Peritidal sediments of the inner ramp are documented in abandoned quarries at Osnabrück (Lower Saxony). Large-scale outcrops (active quarries) in the Fulda area (E Hesse), near Jena (E Thuringia), and in Upper Silesia (S Poland) document mid to outer ramp deposits, including the type section of the German Lower Muschelkalk (Jena Formation). In the north-western part of the Germanic Basin (E Netherlands) the Lower Muschelkalk carbonates are exploited as a gas reservoir (Pipping *et al.* 2001). In view of their geotectonic/palaeoclimatic setting, depositional processes, reservoir facies, architecture, and distribution, the ramp deposits studied are considered as an outcrop analogue for layer-cake reservoirs of world-wide importance, e.g. the Permo-Triassic Khuff or Jurassic Arab carbonates in the Middle East. Khuff carbonates were deposited on a broad, poorly circulated, very low-relief epeiric platform and consist in large part of interbedded mudstones and grainstones having fine grain size with finely crystalline dolomite fabrics. Arab reservoir rocks were deposited under better circulated conditions near platform margins facing deep, intracratonic basins and, thus, have coarser, more grain-dominated fabrics (e.g., peloidal grainstones, grain-dominated packstones) and lesser overall content of chemically precipitated grains, calcium sulfate, and dolomite. Khuff deposits were likely composed of less stable mineralogy than Arab carbonates since the Late Permian was a time of aragonite seas, whereas the Late Jurassic was a time of calcite seas (Sandberg 1983). In summary, Arab reservoirs are characterized by greater preservation of primary depositional pore types, more coarsely crystalline dolomite fabrics, and lesser plugging by anhydrite (Ehrenberg *et al.* 2007).

GEOLOGICAL SETTING

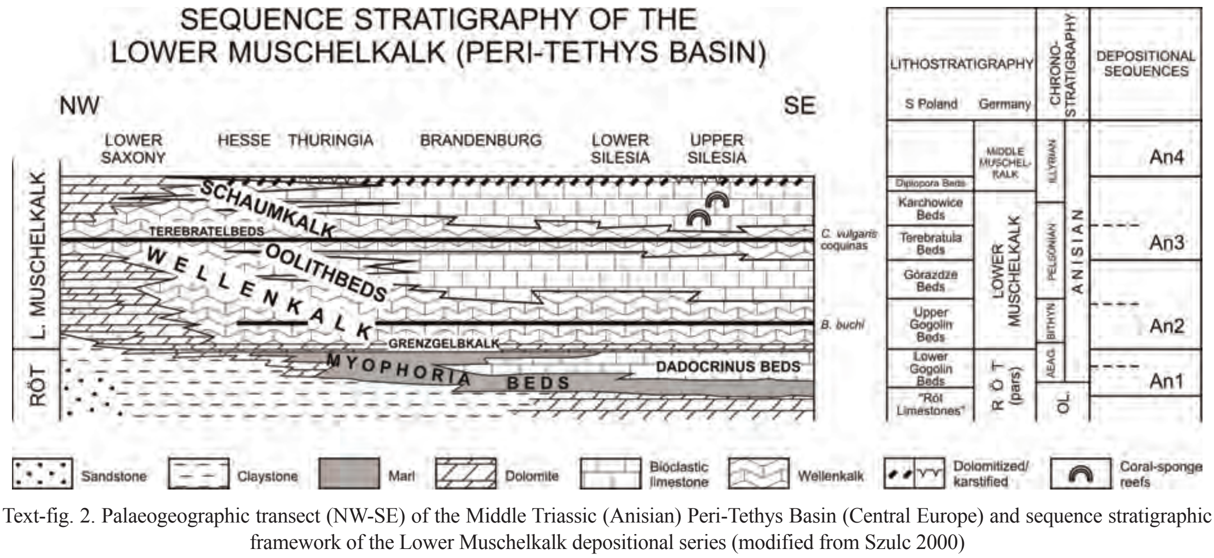
During Triassic times, the Germanic Basin was a peripheral basin of the western Tethys Ocean, the so-called northern Peri-Tethys (Szulc 2000). The basin was bordered by landmasses and open to the Tethyan shelf by three tectonically controlled gates in the south and south-east (Text-fig. 1), known as the East Carpathian, Silesian-Moravian, and Western Gates. The East Carpathian Gate was already active in the Late Induan, the Silesian Gate opened in the Olenekian (Szulc 2000) and the westernmost communication to the Tethys developed during the Anisian (Feist-Burkhardt *et al.* 2008a; Götz and Gast 2010). The semi-closed situation of the basin and the diachronous communication with the Tethys Ocean resulted in a distinctive facies differentiation between the western and eastern parts of the basin (Text-fig. 2). While in the Silesian and Carpathian domains the Early Anisian is already represented by carbonates, the central and western areas were still dominated by siliciclastic red beds (Röt facies). In the eastern subbasin, open marine sedimentation continued during almost the entire Anisian, while the western part experienced restricted circulation during the Early and Late Anisian.

The biostratigraphic framework of the Germanic Middle Triassic is based mainly on conodonts (Kozur 1974) and palynomorphs (cf. Heunisch 1999). The well-established lithostratigraphic framework of the Anisian carbonate ramp system uses characteristic marker beds for basin-wide correlation (e.g., Hagdorn *et al.* 1987). Facies diachroneity and the scarcity of age-diagnostic index fossils (conodonts, ammonoids), however, make unequivocal basin-wide correlations difficult (for detailed discussion see Feist-Burkhardt *et al.* 2008b). Sequence stratigraphy has been employed to approach the problem of regional lithofacies variations and provided a framework of principal stages in basin evolution during Middle Triassic times (Aigner and Bachmann 1992; Szulc 2000; Text-fig. 2). Recently, studies of conodont assemblages and their migration and distribution patterns served to interpret eustatic signatures of basin evolution on high time resolution (Narkiewicz and Szulc 2004; Götz and Gast 2010).

In addition to the presence of marker beds, the vertical facies succession of the Lower Muschelkalk deposits is characterized by a hierarchically organized cyclic sedimentation pattern. Stacked small-scale depositional sequences build characteristic sets of 3 to 4 sequences that are characteristic features of the large-scale composite sequences (Rameil *et al.* 2000). Geochemical and palynofacies signatures also show stacked cyclic patterns that confirm the high-resolution sequence stratigraphic interpretation (Rameil *et al.* 2000; Conradi *et al.* 2007). The stratal architecture of small-scale depositional sequences systematically changes in relation to their relative proximal-distal position on the Muschelkalk ramp system (Text-fig. 3). Deposits of the proximal ramp in the western part of the Peri-Tethys Basin show asymmetric sequences. Bioclastic beds with reworked hardground pebbles



Text-fig. 1. Palaeogeography of the Germanic Basin during Pelsonian times and location of outcrops in Germany, Poland and the Netherlands; based on Szulc (1999) and modified from Götz *et al.* (2005) and Götz and Gast (2010). RM – Rhenish Massif, MM – Małopolska Massif. 1 – De Wijk, NE Netherlands; 2 – Osnabrück, 3 – Großenlüder, 4 – Steudnitz, 5 – Rüdersdorf, Germany; 6 – Strzelce Opolskie, Poland



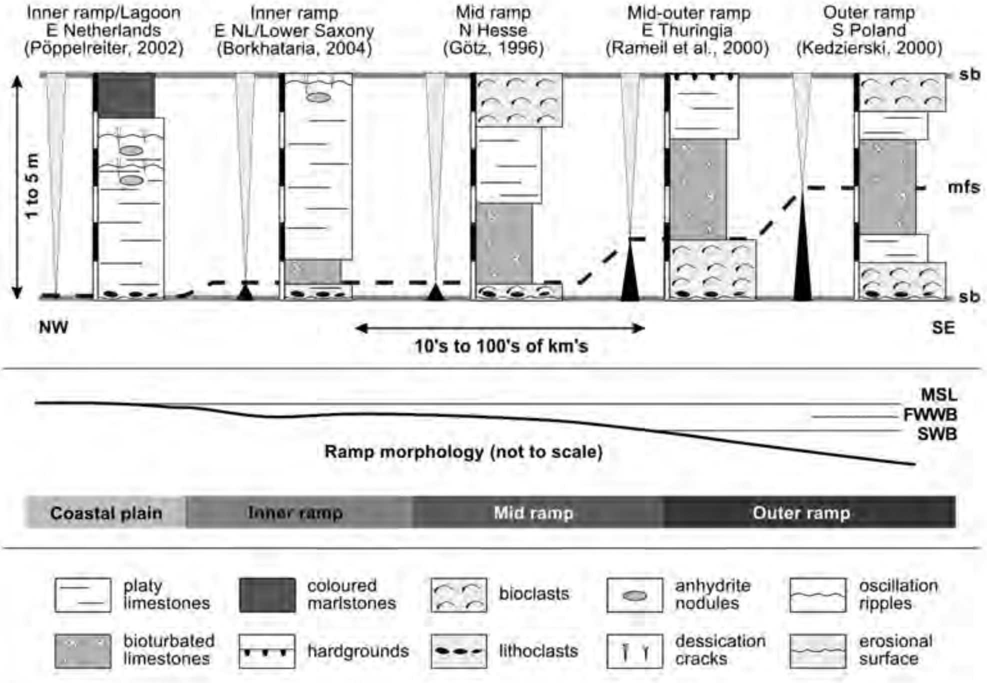
Text-fig. 2. Palaeogeographic transect (NW-SE) of the Middle Triassic (Anisian) Peri-Tethys Basin (Central Europe) and sequence stratigraphic framework of the Lower Muschelkalk depositional series (modified from Szulc 2000) represent the transgressive phase. Since pebbles were reworked during transgression, the hardground may correspond to the sequence boundary. Bioturbated and laminated mudstones are interpreted as highstand deposits. Maximum flooding is recognized by thin condensed marly layers at the top of bioclastic beds. Lowstand deposits are not recorded so that the transgressive surfaces at the base of bioclastic beds directly overlie the sequence boundaries or even erode it away. Reworked lithoclasts at the base of bioclastic beds derive from mudstones or hardgrounds below these beds; they may be completely reworked or are partially eroded. These erosional surfaces are developed within the entire basin and are used for basin-wide high-resolution correlation (Text-fig. 3). Deposits of the outer ramp are represented by nodular and platy mudstones and crinoidal wacke-/packstones, showing symmetric cycle patterns. Highly proximal sedimentary series are characterized by small-scale sequences built of dolomitic mudstones and red marlstones of the lagoonal and inner ramp setting. These sediments represent highstand deposits. Due to permanent reworking, transgressive deposits are recorded by a pebble lag (Text-fig. 3).

Conceptual correlation of small-scale depositional sequences within a cyclo- and sequence stratigraphic framework improved time resolution and the understanding of basin evolution (Götz 1996; Kedzierski 2000; Pöppelreiter 2002). Furthermore, the application of palynofacies analysis to high-resolution sequence stratigraphy of carbonate series of the Peri-Tethys Basin and the northern Tethys shelf area proved to be a powerful correlation tool (Götz and Feist-Burkhardt 1999; Rameil *et al.* 2000; Götz *et al.* 2003; Götz *et al.* 2005; Feist-Burkhardt *et al.* 2008a; Götz and Török 2008). On a regional scale, debris-flow deposits, seismites, and tsunamites are used to define time-lines from short-term events (Föhlisch and Voigt 2001).

MATERIALS AND METHODS

We analyzed a total of 98 outcrop samples from Lower Saxony, Hesse, Thuringia (Germany), and Upper Silesia (Poland), and used published data from Brandenburg (Germany) and the Netherlands (De Wijk gas field) to analyze porosities and permeabilities with respect to the reservoir potential of the main facies types. The selected type sections cover the entire Germanic (Peri-Tethys) Basin, documenting a NW – SE palaeogeographic transect (Text-fig. 2).

Oven dried plug samples (35 mm length and diameter) drilled from rock samples collected from all four outcrop sections were investigated to document the relation between lithology, porosity types, and permeability. Additionally, microfacies analysis was car-



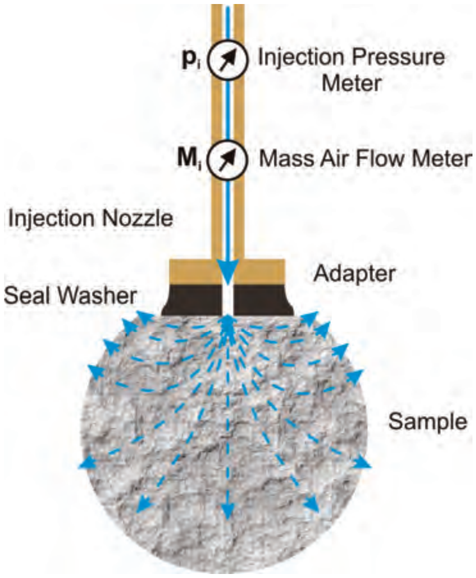
Text-fig. 3. Conceptual correlation of small-scale sequences of the Lower Muschelkalk ramp system, modified after Pöppelreiter (2002) and Götz and Török (2008). Abbreviations: sb – sequence boundary, mfs – maximum flooding surface, MSL – mean sea-level, FWWB – fair-weather wave base, SWB - storm wave base ried out on polished slabs and thin sections to classify the main facies types (MFT). Separate measurements of skeletal density (helium pycnometer AccuPyc 1330) and envelope density (DryFlo pycnometer GeoPyc 1360) enabled the calculation of porosity. Permeability measurements were carried out using a gas mini-permeameter constructed at the TU Darmstadt, Institute of Applied Geosciences. As known from reservoir engineering (Vosteen *et al.* 2003), the correlation between porosity and permeability is in many cases poor to very poor. The problem of conventional permeability measurements is that the well known standard methods allow only to determine the bulk sample permeability of a drill core specimen etc., resulting in a wide range of permeability data.

In this study, a gas mini-permeameter is used which utilizes pressured differential air flow through a plug sample. Permeability is calculated by incorporating the injection pressure p_i, the mass flow rate M_i and the ambient atmospheric pressure p_a (Text-fig. 4).

RESULTS

Main Facies Types (MFT)

The analyzed outcrop samples from four key sections of Lower Saxony, Hesse, Thuringia, and Upper Silesia are subdivided into six main facies types.



Text-fig. 4. Scheme of the gas pressure permeability measurement. The permeameter utilizes pressured differential air flow through a plug sample. Permeability is calculated by incorporating the injection pressure p_i, the mass flow rate M_i and the ambient atmospheric pressure p_a (Goggin *et al.* 1988)

MFT1: Peloid Grainstone

(e.g., Schaumkalkbank Member, Lower Schaumkalk Bed)

The main components of these sediments are peloids with minor marginally or totally micritized shell fragments and echinoderm debris. Peloids are interpreted to originate mainly from micritization of shell fragments and may have dolomitized later during the diagenesis. All stages in size and degree of rounding can be observed, from angular shell fragments to ellipsoidal peloids of 10 to 500 µm in diameter ("bahamites" sensu Beales, 1958). Solution seams and dolomitization are common. These sediments are interpreted as shallow peloid shoals, permanently exposed to waves and currents (Götz 2004). Recent peloid sands of the Persian Gulf are deposited in very shallow water and with elevated salinity (Wagoner and van der Togt 1973; Knaust 1997).

MFT2: Dolo-Wackestone

(e.g., uppermost Röt, Grenzgelbkalk)

These sediments are thin-bedded (cm-scale) and locally laminated, because of varying clay content (Zwenger 1988), possibly as a result of tidal influence. Thin-bedded mud- and wackestones may contain foraminifera and holothurian sclerites but lack shells of bivalves and gastropods (Götz 1996). Predominance of muddy deposits and the lack of resediments point to calm depositional conditions, e.g. to lagoons protected from the open sea (Lukas 1991; Knaust 1997).

Some of these mudstones (*Gelbkalke*, yellow limestones) were dolomitized during early diagenesis. The typical yellow colour originates from weathering processes (dedolomitization and oxidation of Fe^{2+} to Fe^{3+}). Horizontal laminae may occur due to thin clay seams. Laterally, in the proximal ramp area and stratigraphically, in the uppermost part of the Lower Muschelkalk succession, calcified gypsum nodules are common. Macro-, micro- and ichnofossils are absent. These sediments are interpreted as intertidal to supratidal, hypersaline carbonates (cf., Tucker and Wright 1990; Lukas 1991). In the proximal ramp area they show desiccation cracks and tepee structures (Borkhataria *et al.* 2006).

MFT3: Bioclastic Grainstone

(e.g., Terebratelbank Member, Lower Terebratel Bed)

Main components are marginally or totally micritized shell fragments (bivalves, gastropods, brachiopods) and echinoderm debris. The average grain diameter is small (< 1mm) and points to multiple reworking. Bioclastic grainstones are commonly associated with bioclastic packstones. They are inferred to have been deposited in a proximal setting where wave action and bottom currents led to permanent winnowing (Rameil *et al.* 2000).

MFT4: Bioclastic Packstone

(e.g., Wellenkalk-1-Member, Konglomerat Bed f4)

These sediments mainly contain shell fragments of all stages of preservation, and bored intraclasts. Shells may be micritized or display an inversion of fabric. Other components are echinoderm fragments and vertebrate remains (Götz 1996). The bored lithoclasts show borings of two different diameters pointing to *Trypanites* sp. (1 mm) and *Balanoglossites* sp. (up to 5 mm). According to Knaust (1998) this ichnospecies association is typical for proximal ramp areas.

MFT5: Bioclastic Wackestone

(e.g., Wellenkalk-3-Member, Spiriferina Bed)

Main components are shells of bivalves, brachiopods, gastropods and echinoderm fragments. Wackestones commonly display a rich microfauna: foraminifera, holothurian sclerites, conodonts, and vertebrate remains are found (Götz and Gast 2010). Bioclastic wackestones commonly appear in close association with laminated mudstones. This fact and their high matrix content imply a calm, shallow subtidal depositional environment (Rameil *et al.* 2000).

MFT6: Nodular Mudstone

(e.g., Wellenkalk-2-Member, Lower Wellenkalk)

Commonly heavily bioturbated, these mudstones usually lack any primary texture because it was completely homogenized by burrowing and subsequently overprinted by diagenesis. Within the Wellenkalk mudstones, rare beds of detrital carbonates are found, which often pinch out laterally. According to Aigner (1982, 1985) they are interpreted as distal tempestites. Thus, a quiet, subtidal environment is assumed, at a depth just below storm wave base. Knaust (2000) interprets the Wellenkalk mudstones as a result of “low energy background sedimentation”.

Pore Types and Origin

Lower Muschelkalk porosity (Pl. 1) includes primary (interparticle, intraparticle) and secondary (moldic, vuggy, stylolitic) porosities (cf. Choquette and Pray 1970; Lucia 1995, 2007). *Moldic porosity* (Pl. 1, Figs 1-2) is a secondary porosity created through the dissolution of a preexisting constituent of a rock, such as a shell, rock fragment or grain. The pore preserves the shape, or mold, of the dissolved material. *Vuggy porosity* (Pl. 1, Fig. 3) is also a secondary porosity generated by the dissolution of large features (such as macrofossils) in carbonate rocks leaving large holes up to the size of a cave. *Interparticle porosity* (Pl. 1, Fig. 4) is characterized by the pores between the grains and other particles whereas *intraparticle porosity* (Pl. 1, Fig. 5) is characterized by the space within the skeletal material which was not filled by cement. *Stylolitic porosity* (Pl. 1, Fig. 6) is a secondary porosity which is formed by pressure solution, a dissolution process which reduces pore space under pressure during diagenesis. The stylolites mostly contain concentrated insoluble residue such as clay minerals and iron oxides.

Porosity and Permeability

Here, we present the porosity and permeability data of the six main facies types of mid/outer Muschelkalk ramp deposits, defined by litho- and microfacies analyses, in comparison to published data of inner ramp deposits and those of carbonates of Middle East Arab and Khuff formations (Text-fig. 5). The dolo-wacke-/packstones and bioclastic grainstones attain the highest porosities of 24 % (e.g., *Gelbkalke*), and 12 % (*Terebratel Beds)*, respectively. Peloid grainstones reach porosities of up to 8 % (Schaumkalkbank Member, *Schaumkalk Beds*). The mud-/wackestones of the Wellenkalk members typically show porosities below 2 %. Even in the most porous strata (Grenzgelbkalk, Oolithbank and Schaumkalkbank members; Text-fig. 6), permeabilities do not exceed 10 mD, and only a few carbonates (peloid shoals of the Schaumkalkbank Member, Brandenburg; grainstones of the distal ramp, Gorazdze and Karchowice beds, Upper Silesia) show higher permeabilities up to 90 mD. Average porosities are 4.7 %, however most of the sediments are platy and nodular mud-/wackestones and bioclastic wacke-/packstones (Wellenkalk members; Text-fig. 6) with an average porosity of 0.6 %. The average permeability is 7.2 mD.

In general, Muschelkalk rocks with permeabilities lower than 1 mD are considered tight; higher values indicate reservoir rocks (cf. Borkhataria *et al.* 2006). Figure 5 shows that grain-supported carbonates of the mid and outer ramp setting group together in the reservoir field, indicating high reservoir potential compared to values from other carbonate reservoirs (Ehrenberg and Nadeau 2005, Lucia 2007). Most of the dolo-wacke-/packstones are tight despite their generally high porosities.

According to the measured permeabilities, Muschelkalk deposits of the Anisian Peri-Tethys ramp system are grouped into three classes: low permeability rocks (k < 2 mD), medium permeability rocks (k < 7 mD), and high permeability rocks (k < 20 mD; max. 90 mD).

Besides facies related porosity and permeability of distinct rock types, one has to consider karstification

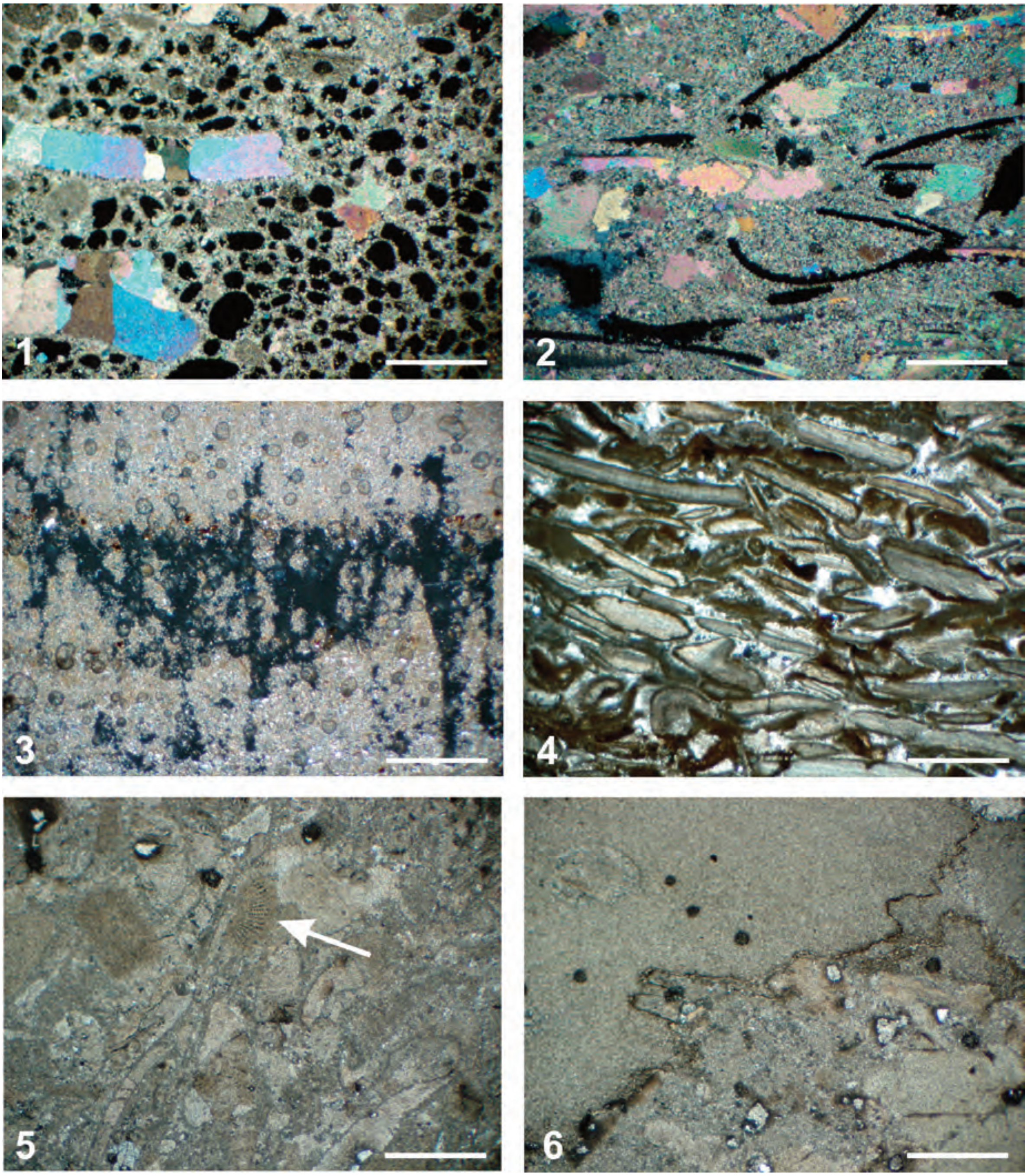
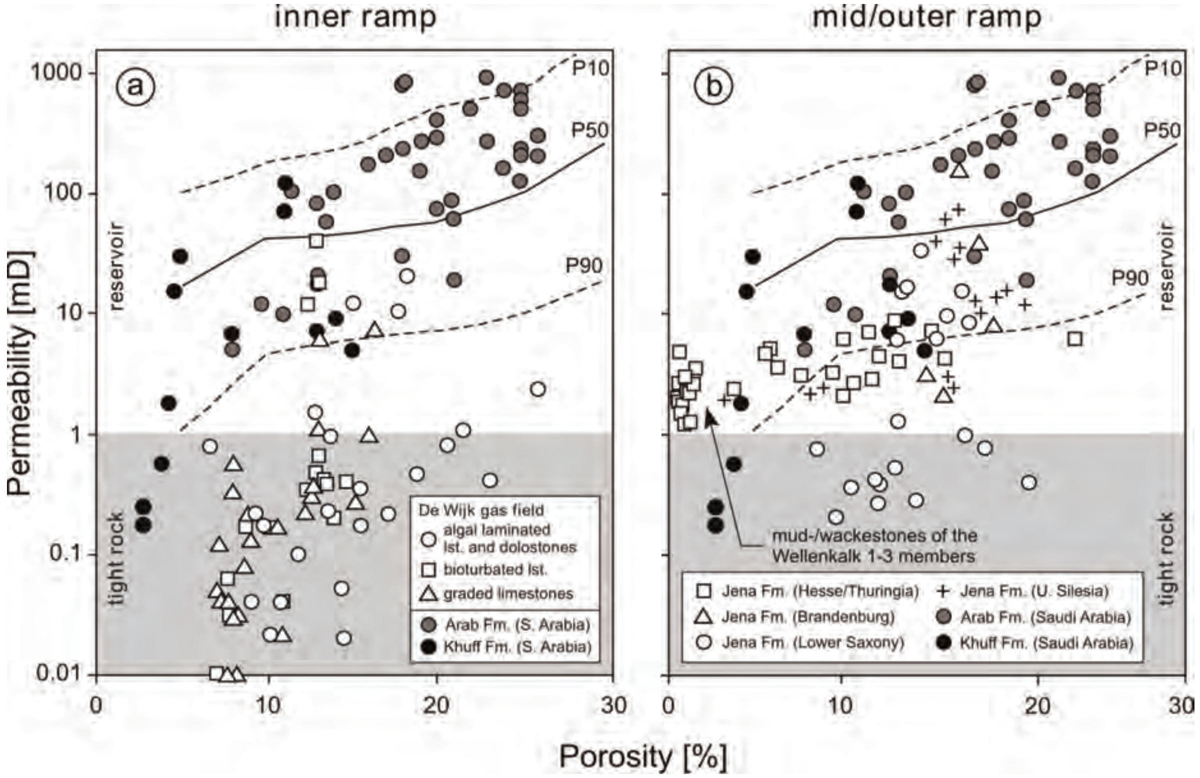


Plate 1. Photomicrographs showing the different types of porosity within the analyzed samples. 1-2 – moldic porosity; 3 – vuggy porosity; 4 – interparticle porosity; 5 – intraparticle porosity; 6 – stylolitic porosity. Scale bar is 1 mm.

as major process forming porous strata. The oomoldic porosity of the Schaumkalk and Gorazdze Beds as well as the growth porosity of the reefal Karchowice Beds represent primary or early diagenetic porosity. Whereas karstification leads to much higher porosities within these rock units and thus plays a crucial role in the formation of a reservoir.

DISCUSSION

The described main facies types show a characteristic hierarchical stacking pattern within the stratigraphic succession (Text-fig. 6). Mud-/wackstones are overlain by bioclastic grain-/packstones, followed by mud-/wackestones and peloid grainstones and/or dolo-

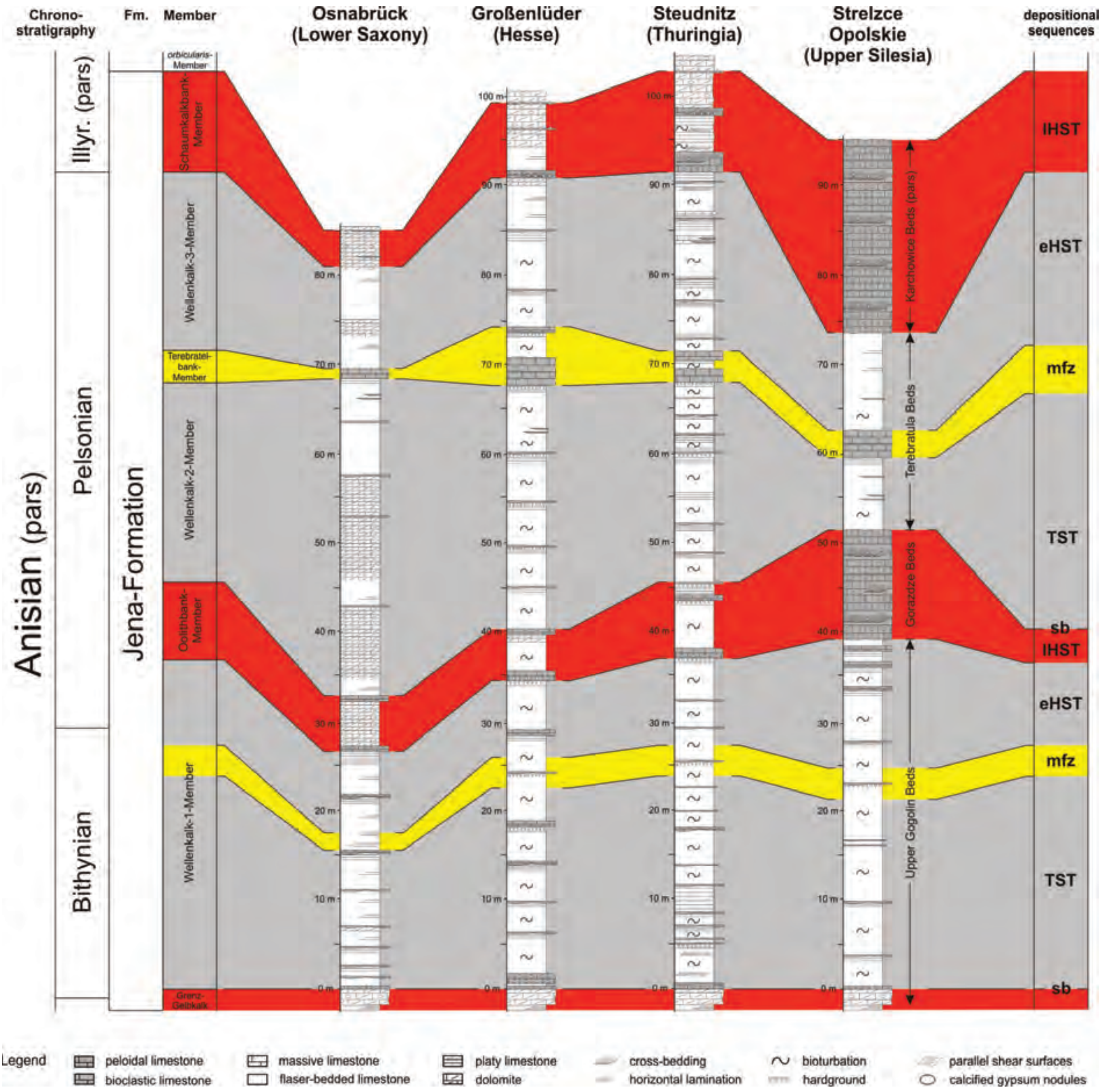


Text-fig. 5. Porosity/permeability cross plots comparing Lower Muschelkalk values from Central Europe (this study) to average values from Middle East Arab and Khuff reservoirs (Bahrain, Qatar, Iran, Oman, Saudi Arabia, United Arab Emirates; Ehrenberg *et al.* 2007): a) Inner-ramp facies from the De Wjik gas field, NE Netherlands (data from Borkhataria *et al.* 2006); b) Mid- and outer-ramp facies from the Osnabrück, Großenlüder, Steudnitz and Rüdersdorf quarries, Germany (Rüdersdorf data from Noack and Schroeder, 2003), and the Strzelce Opolskie quarry, Poland. P10 = 10 %, P50 = 50 %, and P90 = 90 % of international carbonate reservoirs

wackestones. Laterally, these sediments are correlatable in a NW-SE transect, representing inner (Osnabrück), mid (Großenlüder, Steudnitz) and outer (Strzelce Opolskie) ramp settings. Tight rocks are represented by most of the laminated dolostones and bioturbated mudstones (De Wjik gas field, NE Netherlands; Borkhataria *et al.* 2006; Osnabrück, Lower Saxony). High porosities are characteristic of bioclastic peloid grainstones (Großenlüder, Steudnitz, Strzelce Opolskie). Compared to international carbonate reservoirs, permeabilities of the most porous Muschelkalk strata are low (Text-fig. 5). However, we can identify low, medium, and high permeability stratal zones, that can be correlated basin-wide (Text-fig. 6).

In a sequence stratigraphic context, the facies architecture consists of layer-shaped depositional sequences of tens of metres subdivided in small-scale, metre-thick cycles (Text-fig. 3). Transgressive and early highstand deposits, build up by nodular mudstones and bioclastic wackestones, have low permeability; bioclastic carbonates of maximum flooding phases, grainstones and packstones, have medium permeability. Late highstand deposits, peloid grainstones and dolo-wackestones, represent the most permeable sediments, thus characterizing the potential reservoir zones (Text-fig. 6). In terms of reservoir geometry, the area studied represents a layer-cake structure with laterally continuous fluid-flow units.

In comparison to much higher permeabilities of well-known carbonate successions building layer-cake reservoirs such as the Permian-Triassic Khuff and Jurassic Arab formations from Saudi Arabia (Alsharhan 1993, 2006; Alsharhan and Magara 1994, 1995, Ehrenberg *et al.* 2007), the Middle Triassic Muschelkalk carbonates display muddy epeiric sediments deposited under similar climatic conditions (semiarid, greenhouse climate with low-amplitude, high-frequency variations in relative sea level). The best reservoir facies is recognized in dolo-mudstones of the inner ramp area (Lower Saxony) and peloid grainstones deposited in the mid and outer ramp areas (Hesse, Thuringia, Upper Silesia). Besides thick intervals of almost tight rocks (Wellenkalk members), two thick intervals of high permeability



Text-fig. 6. Lower Muschelkalk stratal units characterized by low (grey), medium (yellow) and high (red) permeabilities, building basin-wide layer-cake reservoir zones. Within large-scale, third-order depositional sequences late highstand deposits (red) represent the most permeable sediments

carbonates (Oolithbank Member, Schaumkalkbank Member) are identified basin-wide. To estimate the reservoir quality one has to consider palaeogeographic factors, such as distance to oceanic gates, wind direction, the proximity to basin-bounding landmasses, fine-grained siliciclastic input, low-energy conditions and poor water quality (Szulc 2000, Götz and Török 2008; Feist-Burkhardt *et al.* 2008b), promoting the deposition of muddy epeiric carbonates and pore-plugging early cements, thus resulting in generally low-permeability carbonate reservoirs (Borkhataria *et al.* 2006). On the other hand, the low-relief, homoclinal ramp morphology and minimal accommodation cause the deposition of thick, grainy carbonate successions in the outer ramp setting. This "inverted" facies pattern results in high permeability sediments in the distal part of the Muschelkalk basin, exposed in Upper Silesia.

Recently, grainy shoal bodies of the Ladinian Muschelkalk ramp system have been addressed in terms of reservoir architecture of epeiric shallow-water carbonates (Kostic and Aigner 2004, Ruf and Aigner 2004, Palermo *et al.* 2010) interpreting volume and dimension of distinct shoal bodies and resulting facies distribution along the ramp as mainly controlled by the combination of stratigraphic cycles and palaeorelief. Our studies from the Anisian support the cyclic (eustatic) and palaeotectonic (ramp morphology) control of facies successions and thus stacked reservoir units of different quality.

CONCLUSIONS

Lower Muschelkalk carbonates were deposited on a poorly circulated, low-relief, homoclinal ramp, consisting mostly of mudstones and intercalated grainstones with relatively fine grain sizes (mud-dominated carbonate ramp system). Similar ramp carbonates are well-known from Saudi Arabia (Permian-Triassic Khuff Formation and Jurassic Arab Formation), building layer-cake reservoirs (Ehrenberg *et al.* 2007).

In the Middle Triassic Peri-Tethys Basin, two different reservoir types might be considered: The proximal stacks of muddy dolostones (examples De Wijk, NE Netherlands and Osnabrück, Germany) and the more distally developed grainy limestones (examples Großenlüder, Steudnitz and Rüdersdorf, Germany; Strzelce Opolskie, Poland). The depositional setting with low-relief and minimal accommodation contributed to both, the development of the distinct facies types and to unusual and possibly even "inverted" facies patterns with thick, grainy facies found in the distal part of the basin (Poland).

The knowledge of lateral and stratal facies successions and sequence architecture is crucial for interpretation of reservoir characteristics and contributes to a reliable reservoir prognosis. Within large-scale, third-order depositional sequences transgressive and early highstand mud-dominated deposits with very minor pore space are low permeable, whereas bioclastic carbonates of maximum flooding phases are medium permeable. Late highstand deposits represent the most permeable sediments, thus characterizing stratigraphic units with the best reservoir qualities. The thickness of these units increases from proximal to distal ramp parts. However, generally the thicknesses of low, medium, and high permeability intervals within the Anisian ramp system are unchanging, resulting in lateral continuity of reservoir quality. Thus, the vertical and lateral succession of petrophysical rock properties can be used to predict reservoir qualities of Muschelkalk carbonates. The here detected high degree of lateral facies and poroperm continuity is seen to contribute to subsurface reservoir characterization, where often only limited well and seismic data are available.

Acknowledgements

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REFERENCES

Aigner, T. 1982. Calcareous tempestites: storm dominated stratification in Upper Muschelkalk limestones (Middel Triassic, SW-Germany). In: Einsele, G., Seilacher, A. (Eds), Cyclic and event stratification, pp. 180–198. Springer; Berlin.

Aigner, T. 1985. Storm depositional systems. Dynamic stratigraphy in modern and ancient shallow marine sequences. *Lecture Notes in Earth Sciences*, **3**, 1–174.

Aigner, T. and Bachmann, G.H. 1992. Sequence-stratigraphic framework of the German Triassic. *Sedimentary Geology*, **80**, 115–135.

Alsharhan, A.S. 1993. Facies and sedimentary environment of the Permian carbonates (Khuff Formation) in the United Arab Emirates. *Sedimentary Geology*, **84**, 89–99.

Alsharhan, A.S. 2006. Sedimentological character and hydrocarbon parameters of the middle Permian to Early Triassic Khuff Formation, United Arab Emirates. *GeoArabia*, **11**, 121–158.

Alsharhan, A.S. and Magara, K. 1994. The Jurassic of the Arabian Basin: Facies, depositional setting and hydrocarbon habitat. In: Embry, A.F. (Ed.), Pangea: Global environments and resources. *Canadian Society of Petroleum Geologists Memoir*, **17**, 397–412.

Alsharhan, A.S. and Magara, K. 1995. Nature and distribution of porosity and permeability in Jurassic carbonate reservoirs of the Arabian Gulf Basin. *Facies*, **32**, 237–254.

Beales, F.W. 1958. Ancient sediments of Bahaman type. *AAPG Bulletin*, **42**, 1852–1880.

Borkhataria, R. 2004. Integrated exploration- and production-scale reservoir prediction in "grainy" and "muddy" epeiric carbonate ramp deposits: The Muschelkalk (Triassic), The Netherlands. PhD Thesis, University of Tübingen, 163 p., Tübingen.

Borkhataria, R., Aigner, T. and Pipping, K.J.P. 2006. An unusual, muddy, epeiric carbonate reservoir: the Lower Muschelkalk (Middle Triassic) of the Netherlands. *AAPG Bulletin*, **90**, 61–89.

Choquette, P.W. and Pray, L.C. 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. *AAPG Bulletin*, **54**, 207–250.

Conradi, F.A., Götz, A.E., Rameil, N. and McCabe, R. 2007. Integrating chemostratigraphy and palynofacies into sequence stratigraphic models: A case study of the Lower Muschelkalk (Anisian) from the Germanic Basin. Geophysical Research Abstracts 9, 01763, 2007, SRef-ID: 1607–7962/gra/EGU2007-A-01763.

Ehrenberg, S.N. and Nadeau, P.H. 2005. Sandstone *vs.* Carbonate petroleum reservoirs: A global perspective on porosity-depth and porosity-permeability relationships. *AAPG Bulletin*, **89**, 435–445.

Ehrenberg, S.N., Nadeau, P.H. and Aqrawi, A.A.M. 2007. A comparison of Khuff and Arab reservoir potential throughout the Middle East. *AAPG Bulletin*, **91**, 275–286.

Feist-Burkhardt, S., Götz, A.E., Ruckwied, K. and Russell, J.W. 2008a. Palynofacies patterns, acritarch diversity and stable isotope signatures in the Lower Muschelkalk (Middle Triassic) of N Switzerland: evidence of third-order cyclicity. *Swiss Journal of Geosciences*, **101**, 1–15.

Feist-Burkhardt, S., Götz, A.E. and Szulc, J. (coord.), Borkhataria, R., Geluk, M., Haas, J., Hornung, J., Jordan, P., Kempf, O., Michalík, J., Nawrocki, J., Reinhardt, L., Ricken, W., Röhling, G.-H., Rüffer, T., Török, Á. and Zühlke, R. 2008b. Triassic. In: McCann, T. (Ed.), The Geology of Central Europe, pp. 749–821. Geological Society London.

Föhlisch, K. and Voigt, T. 2001. Synsedimentary deformation in the Lower Muschelkalk of the Germanic Basin. *IAS Special Publications*, **31**, 279–297.

Goggin, D.J., Thrasher, R.L. and Lake, L.W. 1988. A theoretical and experimental analysis of minipermeameter response including gas slippage and high velocity flow effects. *In Situ*, **12**, 79–116.

Götz, A.E. 1996. Fazies und Sequenzanalyse der Oolithbänke (Unterer Muschelkalk, Trias) Mitteldeutschlands und angrenzender Gebiete. *Geologisches Jahrbuch Hessen*, **124**, 67–86.

Götz, A.E. 2004. Zyklen und Sequenzen im Unteren Muschelkalk des Germanischen Beckens. *Hallesches Jahrbuch für Geowissenschaften*, **B 18**, 91–98.

Götz, A.E. and Feist-Burkhardt, S. 1999. Sequenzstratigraphische Interpretation der Kleinzyklen im Unteren Muschelkalk (Mitteltrias, Germanisches Becken). *Zentralblatt für Geologie und Paläontologie*, Teil I (1997) **7/9**, 1205–1219.

Götz, A.E. and Gast, S. 2010. Basin evolution of the Anisian Peri-Tethys: implications from conodont assemblages of Lower Muschelkalk key sections (Central Europe). *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **161**, 39–49.

Götz, A.E. and Török, Á. 2008. Correlation of Tethyan and Peri-Tethyan long-term and high-frequency eustatic signals (Anisian, Middle Triassic). *Geologica Carpathica*, **59**, 307–317.

Götz, A.E., Török, Á., Feist-Burkhardt, S. and Konrád, Gy. 2003. Palynofacies patterns of Middle Triassic ramp deposits (Mecsek Mts., S Hungary): A powerful tool for high-resolution sequence stratigraphy. *Geoaustria*, **46**, 77–90.

Götz, A.E., Szulc, J. and Feist-Burkhardt, S. 2005. Distribution of sedimentary organic matter in Anisian carbonate series of S Poland: evidence of third-order sea-level fluctuations. *International Journal of Earth Sciences*, **94**, 264–274.

Hagdorn, H., Hickethier, H., Horn, M. and Simon, T. 1987. Profile durch den hessischen, unterfränkischen und baden-württembergischen Muschelkalk. *Geologisches Jahrbuch Hessen*, **115**, 131–160.

Heunisch, C. 1999. Die Bedeutung der Palynologie für Biostratigraphie und Fazies in der Germanischen Trias. In: Hauschke, N., Wilde, V. (Eds), Trias, eine ganz andere Welt: Mitteleuropa im frühen Erdmittelalter, pp. 207–220. Verlag Dr. Friedrich Pfeil; München.

Kedżierski, J. 2000. Sequenzstratigraphie des Muschelkalks im östlichen Teil des Germanischen Beckens (Deutschland, Polen). PhD Thesis, Martin Luther University Halle-Wittenberg, 210 p. Halle (Saale).

Knaust, D. 1997. Die Karbonatrampe am SE-Rand des Persischen Golfes (Vereinigte Arabische Emirate) – rezentes Analogon für den Unteren Muschelkalk der Germanischen Trias? *Greifswalder Geowissenschaftliche Beiträge*, **5**, 101–123.

Knaust, D. 1998. Trace fossils and ichnofabrics on the Lower Muschelkalk carbonate ramp (Triassic) of Germany: tool for high-resolution sequence stratigraphy. *Geologische Rundschau*, **87**, 21–31.

Knaust, D. 2000. Signatures of tectonically controlled sedimentation in Lower Muschelkalk carbonates (Middle Triassic) of the Germanic Basin, in: Bachmann, G.H., Lerche, I. (Eds), Epicontinental Triassic. *Zentralblatt für Geologie und Paläontologie*, Teil I (1998), **9/10**, 893–924.

Kostic, B. and Aigner, T. 2004. Sedimentary and poroperm anatomy of shoal-water carbonates (Muschelkalk, South-German Basin): an outcrop-analogue study of inter-well spacing scale. *Facies*, **50**, 113–131.

Kozur, H. 1974. Biostratigraphie der germanischen Mitteltrias. *Freiberger Forschungshefte*, **C 280**, 1–71.

Lucia, F.J. 1995. Rock fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG Bulletin*, **79**, 1275–1300.

Lucia, F.J. 2007. Carbonate Reservoir Characterization. 2nd ed., pp. 1–336. Springer; Berlin.

Lukas, V. 1991. Die Terebratelbänke (Unterer Muschelkalk, Trias) in Hessen – ein Abbild kurzzeitiger Faziesänderungen im westlichen Germanischen Becken. *Geologisches Jahrbuch Hessen*, **119**, 119–175.

Narkiewicz, K. and Szulc, J. 2004. Controls of migration of conodont fauna in peripheral oceanic areas. An example from the Middle Triassic of the Northern Peri-Tethys. *Géobios*, **37**, 425–436.

Palermo, D., Aigner, T., Nardon, S. and Blendinger, W. 2010. Three-dimensional facies modeling of carbonate sand bodies: Outcrop analog study in an epicontinental basin (Triassic, southwest Germany). *AAPG Bulletin*, **94**, 475–512.

Pipping, J.C.P., Carlson, T., Frikken, H.W. and Vallinga, P.M. 2001. Sedimentary cycles – key to improved reservoir performance in carbonates (Triassic, Lower Muschelkalk); De Wijk gas field, The Netherlands. Abstract EAGE 63rd Conference and Technical exhibition, p. 54.

Pöppelreiter, M. 2002. Facies, cyclicity and reservoir properties of the Lower Muschelkalk (Middle Triassic) in the NE Netherlands. *Facies*, **46**, 119–132.

Rameil, N., Götz, A.E. and Feist-Burkhardt, S. 2000. High-resolution sequence interpretation of epeiric shelf carbonates by means of palynofacies analysis: an example from the Germanic Triassic (Lower Muschelkalk, Anisian) of East Thuringia, Germany. *Facies*, **43**, 123–144.

Ruf, M. and Aigner, T. 2004. Facies and poroperm characteristics of a carbonate shoal (Muschelkalk, South German Basin): a reservoir analogue investigation. *Journal of Petroleum Geology*, **27**, 215–239.

Sandberg, P.A. 1983. An oscillating trend in Phanerozoic nonskeletal carbonate mineralogy. *Nature*, **305**, 19–22.

Szulc, J. 1999. Anisian-Carnian evolution of the Germanic Basin and its eustatic, tectonic and climatic controls. In: Bachmann, G.H., Lerche, I. (Eds), Epicontinental Triassic. *Zentralblatt für Geologie und Paläontologie*, Vol. 1, 813–853.

Szulc, J. 2000. Middle Triassic evolution of the northern Peri-Tethys area as influenced by early opening of the Tethys Ocean. *Annales Societatis Geologorum Poloniae*, **70**, 1–48.

Tucker, M.E. and Wright, V.P. 1990. Carbonate Sedimentology, pp. 1–215. Blackwell; Oxford.

Vosteen, H.-D., Rath, V., Clauser, C. and Lammerer, B. 2003. The thermal regime of the Eastern Alps from inversion analyses along the TRANSALP profile. *Physics and Chemistry of the Earth*, **28**, 393–405.

Wagoner, C.W. and van der Togt, C. 1973. Holocene sediment types and their distribution in the southern Persian Gulf. In: Purser, B.H. (Ed.), The Persian Gulf, pp. 123–155. Springer; Berlin.

Zwenger, W. 1988. Mikrofazies und Milieuanalyse des Unteren Muschelkalkes von Rüdersdorf. *Freiburger Forschungshefte*, **C 427**, 113–129.

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