Asymmetry of an epicontinental basin—facies, cycles, tectonics and hydrodynamics: The Triassic Upper Muschelkalk, South Germanic Basin

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Abstract
The Middle Triassic–Upper Muschelkalk deposits of central Europe form an excellent, “laboratory-scale” outcrop analogue for subsurface hydrocarbon reservoirs in epeiric basins. This study provides a detailed sedimentological analysis at microfacies to basin-wide scales within a well-constrained biostratigraphic and sequence stratigraphic framework. The database comprises 31 outcrops and 27 drill cores in the southern part of the Triassic Germanic Basin, from Luxembourg, eastern France, northern Switzerland and southwestern Germany. The Upper Muschelkalk comprises 21 lithofacies types which are grouped into eight distinct lithofacies associations encompassing coastal sabkha, peritidal, backshoal, shoal, shoal fringe, foreshoal to offshoal environments. A 1D sequence stratigraphic framework was established on different cyclic scales ranging from depositional sequences, cycle sets, cycles to mini-cycles. Regional 2D correlations based on 1D cycle analysis and biostratigraphic conodont/ceratite zonation reveal the temporal and spatial distribution of reservoir bodies and the morphological variance of 1D cycles across the carbonate ramp. A basin-wide W–E ‘coast to coast’ cross-section shows an asymmetric basin architecture with significant differences in facies distribution, cycle morphology, and consequently sizes of potential reservoir bodies. This distinct asymmetry is controlled by the palaeo-tectonic setting (quiet versus more active) and the hydrodynamics (windward versus leeward, inflow of freshwater versus marine waters) which differs from coast to coast. Such asymmetric patterns will have to be considered in exploration scenarios of subsurface hydrocarbon-bearing epeiric basins in the Middle East and elsewhere.

KEYWORDS
carbonate ramp, correlations, facies analysis, Middle Triassic, sequence stratigraphy

1 | INTRODUCTION

Some of the world’s biggest oil and gas reservoirs are located in epeiric carbonate basins (Ghawar Field or North Field). Crucial for exploring and exploiting such reservoirs is a sound knowledge of facies distribution, geometries and factors controlling their spatial and temporal development which are in part still poorly understood. The low latitude
mid-Triassic Germanic Muschelkalk Basin of Central Europe provides an excellent, albeit smaller, outcrop analogue for vast petroleum basins deposited under similar climate and palaeo-oceanographic conditions such as the low latitude Middle Eastern Permo-Triassic Khuff or Jurassic Arab Formations. The “laboratory-scale” Muschelkalk Basin allows for detailed microfacies to basin-scale analysis within a robust sequence stratigraphic framework. There is no direct modern analogue for vast carbonate ramps such as the Khuff and Arab systems; however, the coast of the Persian Gulf may serve as an analogue, albeit on a smaller scale (Purser, 1973).

This study draws on a detailed stratigraphic framework stemming from nearly 200 years of scientific research within the German Muschelkalk Basin (von Alberti, 1834; Aust, 1969; Paul, 1936; Vollrath, 1955a,b,c; Wagner, 1913), three decades of modern sedimentology and sequence stratigraphic studies (Adams & Diamond, 2017; Aigner, 1985; Aigner & Bachmann, 1992; Aigner, Hornung, Junghans, & Pöppelreiter, 1999; Franz, Henniger, & Barnasch, 2013; Franz et al., 2015; Köhrer, Heymann, Prousa, & Aigner, 2010; Kostic & Aigner, 2004; Palermo, Aigner, Nardon, & Blendinger, 2010; Palermo, Aigner, Seyfang, & Nardon, 2012; Petrovic & Aigner, 2017; Petrovic, Aigner, & Pontiggia, 2018; Ruf & Aigner, 2004; Vecsei & Duringer, 2003) and includes new and/or revised outcrop and borehole data (this study). While these previous modern studies provide an extensive and unique database for the Upper Muschelkalk, they only do so for selected palaeogeographic locations and stratigraphic intervals.

This study presents the first complete basin-wide analysis of the southern Germanic Upper Muschelkalk Basin establishing a universal facies atlas and stratigraphic framework for the whole of the basin thereby merging and re-evaluating previous studies from the eastern German part of the basin with newly described sections from the western margin in France and Luxembourg. This leads to regional 2D correlations highlighting lateral thickness and facies variations and a regional 2D basin transect. Thereby, it is possible to distill general patterns of reservoir body distribution, quality and partitioning during the overall transgressive/regressive facies trend. The correlation indicates a basin asymmetry between the eastern and western margin on different scales—facies (small), cycles (medium) and tectonics (large). With the help of palaeo-current measurements and by integrating the facies and sequence stratigraphic analysis a synoptic hydrodynamic model of the Germanic Basin was established which may explain many of the observed the asymmetric patterns in the Upper Muschelkalk Basin.

2 GEOLOGICAL SETTING

The study area (Figure 1) covers the southern part of the Germanic Basin. Its Upper Muschelkalk (Middle Triassic)
deposits can nowadays be found in natural outcrops, road cuttings, quarries and in the subsurface of Southwestern Germany, Eastern France, Northern Switzerland and Luxembourg. In some areas such as the Vosges Mountains, Black Forest, Pfälzischer Wald and Odenwald, the Upper Muschelkalk strata are missing due to Palaeocene and Neogene uplift and erosion.

The Germanic Basin originated in Late Permian to Early Triassic times and persisted until the end of the Jurassic. It was confined by the Vindelician/Bohemian Massif in the South, the London/Brabant Massif in the West and the Fennoscandian Massif in the North (Figure 1). Between these major landmasses several smaller islands and structural highs such as the Rheinisch Massif and the Malopolska Massif existed (Ziegler, 1990). The basin was temporarily connected to the Tethys-Ocean by three gateways, the Burgundy, Silesian/Moravian and the East-Carpathian Gate, through which marine transgressions occurred (Dercourt, Ricou, & Vrielynck, 1993; Ziegler, 1990). The depositional centre of the southern subbasin was in the area around Heidelberg, Germany (Feist-Burkhardt et al., 2008). The cyclic opening and closure of these seaways, controlled by 2nd-order and 3rd-order sea-level changes, lead to evaporative and terrestrial deposits during Buntsandstein and Keuper times while during Muschelkalk times mainly carbonate deposits dominated (von Alberti, 1834; Kostic & Aigner, 2004; Wagner, 1913). The basin margins were characterized by clastic deposits (Hagdorn & Simon, 2005; Lucius, 1941; Vecsei, 1998; Wagner, 1989).

At the beginning of the Upper Muschelkalk in the Upper Anisian the gateways were reopened by a marine transgression leading to fully marine conditions in the Germanic Basin (Kozur, 1974). Gently inclined carbonate ramps developed along the coastal margins of the Vindelician Massif and the London/Brabant Massif directed towards the basin centre. Particle-rich shallow water carbonates were deposited in zones parallel to the coastline (Aigner, 1985; Demonfaucon, 1982) forming shoals often located on top of local palaeohighs like the Siercker High or the Gammesfelder High akin to modern shoals in the Persian Gulf (Braun, 2003; Dittrich, 2011; Düringer & Vecsei, 1998; Gittinger, 1969; Hohage, 1996; Lucius, 1941; Palermo et al., 2010, 2012; Petrovic & Aigner, 2017; Purser, 1973; Rössle, Himmerkus, & Dittrich, 1999; Vecsei, 1998; Wagner, 1989). During the 3rd-order transgression, they retrograde towards the coast. Maximum flooding is indicated by low-energy fully marine deposits and marly lithologies in the basin. The shoal areas moved basinward during the overall regression (Alesi, 1984). A subsequent dolomitization of the deposits located in the constricted area between the shoals and the coastline can be observed. In accordance with the basinward movement of the facies belts, the dolomitic belt also shifted basinwards with the onset of the 3rd-order regression towards the end of the Upper Muschelkalk (Early Ladinian). With the Early Ladinian, fluvial systems prograde from the north (Fennoscandinavian Massif) into the basin but freshwater input throughout the Upper Muschelkalk is postulated by Korte, Kozur, and Veizer (2005) and Franz et al. (2015). During the Middle Ladinian, coastal to lacustrine deposits (lower Keuper) dominate the study area (Geyer, Gwinner, & Geyer, 2011). The Muschelkalk/Keuper boundary is considered to be a sequence boundary (Aigner et al., 1999) and represents the end of fully marine conditions.

The Middle Triassic was generally characterized by a greenhouse climate (Preto, Kustatscher, & Wignall, 2010) and the presence of temporary polar ice-caps was discussed by Veevers (1989) and Franz et al. (2015). The huge landmass of Pangaea caused enormous seasonal high-pressure areas above Eurasia and India, which influenced the trade winds at that time. Dry continental air masses transported by the northeast trade wind dominated the climate during winter, while during summer air masses from the inner regions of Pangaea, transported by a very strong south east monsoon prevailed (Feist-Burkhardt et al., 2008; Kutzbach & Gallimore, 1989; Mutti & Weissert, 1995). This led to arid to semiarid subtropical conditions in the Germanic Basin (Marsaglia & Klein, 1983; Vischer & van der Zwan, 1981) with water temperatures between 25 and 35°C (Korte et al., 2005). Marsaglia and Klein (1983), Aigner (1985) and Parrish (1993) suggested that huge seasonal tropical cyclones were generated over the Tethys and directed towards the northeast.

Numerous previous studies have generated a well-constrained and high-resolution biostratigraphic subdivision of the German Muschelkalk (Figure 2). The succession of ceratites provided the basis for the well-established ceratite zonations (Hagdorn & Simon, 1993, 2005; Kozur, 1974; Urlichs & Mundlos, 1990). However, the occurrence of ceratites is restricted to the southern and central parts of the basin and therefore application of the zonation is limited. Conodont zonations established by Kozur (1974) in Central and North Germany were also confirmed in the western margin of the basin (Demonfaucon, 1982; Dittrich in press a,b; Vecsei, Heunisch, & Luppold, 2000). Rare findings of both ceratites and conodonts within one lithostratigraphic interval of investigated location of the western basin margin lead to comparable stratigraphic zonations useful for basin-wide correlations (Dittrich in press a,b).

The Upper Muschelkalk, and the entire Mesozoic overburden was deposited above a mosaic of three differentially subsiding major Variscan blocks (Aigner, 1985; Behr & Heinrichs, 1987; Mostler, 1993): Moldanubian Zone, Saxothuringian Zone and Rhenohercynian Zone (Figure 3).
3 | MATERIALS AND METHODS

This research is part of a synoptical study (unpublished PhD-thesis; Warnecke, 2018) which integrated data from several previous projects (see below) from the research group Sedimentary Geology at the University Tübingen with new field data (see Appendices).

3.1 | Field work and sedimentological logging

A total of 13 quarries and 12 borehole cores were logged sedimentologically by the authors (texture after Dunham, 1962), lithology, particle size after Wentworth (1922), sedimentary structures, sorting, components and porosity at a scale of 1:50 and where necessary in greater detail.

Additionally, 18 logged quarries and 15 logged borehole cores generated by previous studies (Braun, 2003; Köhrer et al., 2010; Kostic & Aigner, 2004; Palermo et al., 2010, 2012; Petrovic & Aigner, 2017; Petrovic et al., 2018; Ruf & Aigner, 2004) were reevaluated by visiting outcrops and proof-checking existing logs to incorporate them into this study. Field logs were digitized and visualized in WellCad 5.0.

3.2 | Thin section analysis

A total of 526 thin sections were generated out of samples taken in the field and from cores and described after Dunham (1962). They were further classified focusing on lithologies, components and sedimentary features (diagenesis, sorting and structures) and lithofacies types. Additionally, 1170 thin sections from unpublished PhD-projects and MSc-thesis’ from the research group Sedimentary Geology at the University Tübingen (161 from Petrovic (2016), 23 from Allgöwer (2006), 49 from Braun (2003), 33 from Dimitrieva (2006), 88 from Heymann (2007), 27 from Adler (2015), 26 from Tauer (2015), 26 from Looser (2005), 125 from Tilg (2015), 302 from Palermo (2007),...
62 from Prous (2003) and 53 from Warneck (2014) were re-analysed and quality checked by this study using the criteria described above.

3.3 | Gamma-ray measurements

Since gamma-ray trends are sufficient for 2D correlations, spectral gamma-ray measurements were taken in every logged quarry. Clean outcrop walls were tested with a portable GR-spectrometer Georadis GT-30/32(Rs- 125/230) SUPER SPEC and/or a portable gamma-ray device by G.B.-H. Elektronik and Geofyzika Co. The devices record counts per second (cps) after measuring the spectral counts (Th, K, U) within a distinct time window. The time interval chosen was 30 seconds, the vertical sampling rate 25 cm. Gamma-ray logs of cored sections or from exploration wells within the study area were provided by Nagra (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle), LGRB (Geological Survey of Baden-Württemberg), GeoThermal GmbH, ENGIE E-P Deutschland GmbH, Geo Explorers LTD and SGL (Geological Survey of Luxembourg).

3.4 | Biostratigraphy

Biostratigraphic data were taken from the literature as most of the outcrops and cores were already described in terms of ceratites or conodont zonations. (Demonfaucon, 1982; Dittrich, 1989; Dittrich in press a,b; Duringer & Hagdorn, 1987, 1988; Duringer & Vecsei, 1998; Franz et al., 2015; Geyer et al., 2011; Gwinner, 1970, 1977; Gwinner & Hinkelbein, 1972a,b, 1974a,b; Hagdorn & Simon, 1993, 2000, 2005; Kozur, 1974; Urlichs & Mundlos, 1990; Vecsei, 1998; Vecsei et al., 2000; Vecsei, Rauscher, & Hohage, 2003).
Furthermore, a well-established correlation between eco-stratigraphic marker beds and biostratigraphic zonation (Figure 2) is given.

3.5 | Facies analysis

For facies and sequence stratigraphic analysis, the workflow described by Schauer and Aigner (1997) was used. Based on components (biogenic/abiotic), lithology, Dunham (1962) texture and sedimentary structures, the lithofacies types of the Upper Muschelkalk were established in this study. They were grouped into lithofacies associations (LFA), representing unique depositional environments resulting mainly from differing depositional energy regimes along the gently inclined carbonate ramp.

3.6 | Sequence stratigraphic cycles

Cycles were delineated by detailed vertical facies analysis and are based on Walters’ facies law (Walter, 1894), but in order to confidently define cycles and in particular cycle boundaries, the identification of stratal surfaces such as maximum regression surfaces, transgressive surfaces and maximum flooding surfaces was critical. Several types of stratal surfaces or significant beds were determined in the Upper Muschelkalk Basin:

3.7 | Cycle indicators

3.7.1 | Hard-/Firmgrounds

Hardgrounds are characteristically dark grey in colour which may be caused by iron mineralization according to Christ et al. (2012). Generally, hardgrounds suggest very low sedimentation rates and syn-sedimentary lithification indicated by distinct traces of boring organisms and colonization by sessile benthos. Hagdorn and Simon (2000) described biostromal growth induced by the right valves of Placunopsis ostracina, left valves are removed postmortem. These Placunopsis reefs exist as elongated growthforms on the basinward shoulders of palaeohighs with low sediment supply and wave action. In general, they are relatively slow growing biohermal structures favoured by phases of minor sediment supply and fully marine conditions indicating rising sea-level (transgressive) or maximum flooding (Hagdorn, 1982; Petrovic, 2016). Occasionally, ceratite pavements are observed indicating very low accommodation rates and low sediment supply.

3.7.2 | Terebratula beds

Massive brachiopod colonization on hard-/firmgrounds form eco-stratigraphical marker beds (Figure 2) throughout the Upper Muschelkalk and thus mark a clear change in depositional facies (Hagdorn & Simon, 1993). Some of the brachiopods commonly found are Coenothyris vulgaris, e.g. in the “Obere Terebratelbank,” “Haupterebratelbank” or Coenothyris cycloides, in the “Cycloidesbank” (Wagner, 1913). These brachiopods require clean, fully marine seawater, their appearance is therefore interpreted as a transgressive impulse.

3.7.3 | Bonebeds

The appearance of the bonebed lithofacies type (LFT 20) varies throughout the study area (Figure 2) although they are mostly located in the upper part of the depositional sequence. Reif (1982) described them as condensation horizons induced by reduced sedimentation rates and/or as transgressive surfaces with heavy concentrations of vertebrate remains from both terrestrial and marine organisms (the transgressive lags of Klein & Hagdorn, 2014). The prominent “Grenzbonebed” is interpreted as having been generated by a depositional sequence boundary and a subsequent transgressive flooding. During low stands and at depositional cycle boundaries, accommodation space on a carbonate ramp is limited leading to generally low and/or absent sedimentation and potential erosion. The following transgression led to the deposition of a “transgressive conglomerate.” The “Grenzbonebed” (LFT 20) cuts erosively into the Upper Muschelkalk and increases in thickness from a few millimetres up to 10 cm. Minor bonebeds normally occur as very thin layers on top of grainstone packages and are interpreted as transgressive surfaces on a smaller scale.

3.7.4 | Chicken wire fabric

Chicken wire fabrics (LFT 1) occasionally occur in the southern outcrops and cores of the basal Upper Muschelkalk (Switzerland/NAGRA cores) but are widespread features within the dolomitic facies in the south-central part of the Muschelkalk Basin (Rottweil-Formation). Large vugs suggest leaching of anhydrite or gypsum initially precipitated via evaporation of pore-waters although at times these vugs may be secondarily filled with calcite or barite crystals. These fabrics were formed by intrasedimentary growth and indicate a coastal sabkha environment (Schauer & Aigner, 1997; Warren, 2006). Chicken wire fabrics represent the shallowest facies observed in the study and highlight peak regression.

3.7.5 | Tonhorizonte—clay horizons

The origin of the Tonhorizonte (clay horizons within the Upper Muschelkalk, Figure 2) is uncertain with Röhl
(1993) suggesting either an eustatic or a tectonic signal. Aigner (1985) described the Tonhorizonte as the basal part of coarsening, thickening and shallowing-upwards cycles and therefore representative of possible maximum flooding intervals of minor cyclicity in the Upper Muschelkalk. Based on biostratigraphic arguments, Franz et al. (2015) correlated the Tonhorizonte with progradational phases of deltaic sandstones in the Northern Germanic Basin. Altogether, the Tonhorizonte exhibit different stages of sequence stratigraphic cycles. There is an ambiguity of facies reflecting a proximal (clastic input) signal on the one hand versus the shaley deep water facies of a distal environment on the other. Siliciclastic input to carbonate ramps usually happens preferentially during sea-level lowstand (LST) and/or during periods of fluctuating climate. However, lowstands are rarely preserved on carbonate ramps within epeiric basins because of their very flat topography. Evidence for a rather brackish environment during the initial deposition of the Tonhorizonte are provided by Ostrakodentone (*Bairdia pirus*; Aust, 1969). However, the clastic facies may subsequently be re-suspended and dispersed via bottom currents and storms during sea-level rise. The high abundance of ceratites (considered endemic fauna) found within the Tonhorizonte indicates fully marine conditions and thus potentially represent intervals of maximum flooding. Therefore, the Tonhorizonte are interpreted as maximum flooding surfaces in this study.

### 3.7.6 | Mechanical stratigraphy

Dolomitization often destroyed the primary rock fabric, therefore describing Dunham texture and lithofacies types can be challenging in dolomites. However, under tectonic strain, different lithologies show distinctive behaviours. The calcareous deposits of the Upper Muschelkalk display significant fractured grainstones while in the thinly bedded mud and marlstones no fractures are observed. The same is apparent for the dolomites of the Rottweil-formation (formerly Trigonodus-Dolomit), even though dolomitization destroys original textures (Figure 4). Mechanical stratigraphy can thus be utilized as a trend for Dunham description, facies interpretation and thus cycle recognition in dolomitized strata (Al Kharusi, 2009; Laubach, Olson, & Gross, 2009), as it is apparent that coarse-grained dolomites (former grainstones) show brittle behaviour by fracturing and the finer-grained dolomites (former mudstones) exhibit ductile stress behaviour. This may have a major impact on permeability and fluid flow in the subsurface as well.

### 4 | FACIES ANALYSIS

A comprehensive facies atlas applicable for both outcrop and borehole data for the whole of the southern Muschelkalk Basin including its French, Swiss and Luxembourg sections is presented here. It integrates new observations and expands on previously established lithofacies schemes (Figure 5) for the eastern part of the Muschelkalk Basin in Baden-Württemberg and Bavaria (Braun, 2003; Köhrer et al., 2010; Kostic & Aigner, 2004; Palermo et al., 2010; Petrovic & Aigner, 2017; Ruf & Aigner, 2004; Schauer & Aigner, 1997a, 1997b). These schemes were made for specific ramp sub-environments (such as shoals) but did not cover the entire Upper Muschelkalk facies in the Southern Germanic Basin. For the sake of consistency, already existing lithofacies types (LFT) from previous
studies are not renamed. New LFT described mainly at the western basin margin confined by this study are marked with (*).

4.1 Lithofacies types

LFT 1* is a fine to coarse-grained dolomite containing large cavernous vugs. Gypsum is occasionally seen displacing the substrate lithology or is present as vug infill (Figure 6A). LFT 1 forms thin intervals, 0.5–10 cm thick. LFT 1* is interpreted to represent the diagenetic overprint of pre-existing sediments with intrasedimentary growth—leached/crystal shaped barite/dolomite/gypsum-filled vugs probably related to gypsum/anhydrite precipitation in a coastal sabkha environment during arid conditions. Large unfilled vugs probably stem from dissolved gypsum nodules.

LFT 2* is a thin-bedded, fine-grained dolomite partially mottled and/or brecciated. It is often associated with dark deformed layers (Figure 6B) and interpreted as the supratidal diagenetic overprint of pre-existing facies developed in a coastal marsh environment. Mottling and brecciation result from organic activity (plant roots), while palaeosoils and intense plant rooting indicate a humid climate.

LFT 3* is a brecciated laminated dolo-mudstone with, at times, a poorly sorted, subrounded conglomerate with filled vugs probably related to gypsum/anhydrite precipitation in a coastal sabkha environment during arid conditions. Large unfilled vugs probably stem from dissolved gypsum nodules.

LFT 4* is a thin-bedded, fine-grained dolomite partially mottled and/or brecciated. It is often associated with dark deformed layers (Figure 6B) and interpreted as the supratidal diagenetic overprint of pre-existing facies developed in a coastal marsh environment. Mottling and brecciation result from organic activity (plant roots), while palaeosoils and intense plant rooting indicate a humid climate.

FIGURE 5 Integration of existing Upper Muschelkalk lithofacies type databases into this study. Existing studies and facies atlas' solely cover local areas. For lithostratigraphic levels see Figure 2.

FIGURE 6 Chart of lithofacies types (LFTs) of the Upper Muschelkalk with used colour code in each header. a) LFT 1: Dolomite with vugs—chicken wire gypsum on top of a fining upwards sequence. Gypsum concretions limited on thin horizontal intervals. Thin section shows gypsum nodules displacing substrate lithology. Image on the right displays large empty vugs, interpreted as dissolved evaporites. b) LFT 2: Rooted Dolomite above dark deformed layer interpreted as hardground on the left, right: dark rootlet structures in a fine-grained dolomite. c) LFT 3: Conglomerate/Breccia—left: subrounded conglomerate and corresponding thin section with dolomitic components and black pebbles. Right: desiccation cracks and reworking lead to brecciation of layers. d) LFT 4: Laminated dolo-mudstone with cm-thick chert concretions concentrated in several horizons with large lateral (100s of km) extent. Thin section shows silicate chert layer with ooids within a laminated dolo-mudstone.
black pebbles (Figure 6C). This reworked material is believed to have been deposited within a high-energy supratidal surf zone near the shoreline or as intertidal channel fill representing algal breccia resulting from a combination of desiccation, bioturbation and/or wave reworking.

LFT 4 is a centimetre-thick to metre-thick, very fine-grained laminated dolomudstone, displaying thin (cm thick), laterally extensive (100s km) horizons with siliceous concretions.

LFT 4 is believed to have formed in an overall low-energy to moderate-energy intertidal environment, with algal and cyanobacterial growth in very shallow water producing very fine-grained and laminated mudstones. Occasionally, diagenetically overprinted oolitic intervals (LFT 5) indicate higher energy events.

LFT 5* is a moderately to poorly sorted, low-angle, trough to planar cross-beded intraclastic packstone to grainstone made up of arenitic to ruditic sized grains. Red algal debris, ooids, coated grains and shell hash composed of bivalves and brachiopods are common (Figure 7A; slabbed core). LFT 5* is interpreted as a high-energy to moderate-energy supratidal deposit occupying tidal channel fills, washover lobes or beach ridges, the latter revealed by low-angle bedding.

LFT 6* is a partially trough to planar cross-beded, silt to arenitic sandstone displaying a dolomitic matrix (Figure 7B). While subrounded quartz grains dominate (Figure 7B), minor constituents are shell and echinoderm debris, bone and plant fragments. Cross-beded sets are stacked to channel-like fills. LFT 6 indicates high sedimentation rates in a peritidal setting. The subrounded quartz grains point to a proximal clastic input, possibly deposited in tidal channel fills (Gilsdorfer Sandstein; Vecsei, 1998).

LFT 7* is a bioturbated, poorly sorted dolomitic mudstone with occasional layers of glauconitic pebbles (Figure 7C) and minor, scattered silt-sized quartz grains. The fine quartz content suggests a distal tidal fill environment (LFA 2–LFA 3). Glauconite tends to form under low oxygen/reducing conditions, often in association with phosphatic pellets (Triplehorn, 1966). The presence of glauconite pellets is therefore interpreted as diagenetic overprint of faecal pellets.

LFT 8 consists of metre-scale packages of nodular, strongly bioturbated, poorly sorted peloidal dolomitic wackestone to packstone layers. Pellets, often extensively micritized, are concentrated in bioturbation traces (Figure 7D), while bivalves and brachiopod shell fragments occur sporadically. LFT 8 is considered to have formed following the intense feeding activity of infauna occupying shallow, low-energy lagoonal (LFA 3) or foreshoal (LFA 7) settings. The nodular appearance is due to bioturbation.

LFT 9 is a poorly sorted, ruditic oncolite wackestone to packstone where the minor components are ooids, shell hash and peloids. Fine crystalline oncolitic dolomite structures appear to have different nuclei including bivalve, brachiopod or gastropod hash or intraclasts and display abundant intercrystalline porosity (Figure 8A). Occasionally these oncoids may be flattened by compaction. The oncoids and micritic envelopes are produced by algal growth indicating deposition within the wave-dominated photic zone of a moderate-energy backshoal (LFA 4) to high-energy shallow water environment (LFA 5) (Flügel & Munnecke, 2010).

LFT 10 consists of (trough) cross-beded packstone to grainstone either dominated by 1) arenitic oolites, 2) shell hash or 3) crinoids (Figure 8B). All subtypes display coated grains and/or micritic envelopes. The shelly and crinoidal dominated LFT 10 display interparticle porosity, separate and touching vugs (blue; Figure 8B). These well-sorted particles and trough cross-beding indicate high-energy conditions in a shallow water shoal environment (LFA 5). Coated grains and micritic envelopes indicate shallow marine conditions, while the crinoid debris indicates fully marine waters.

LFT 11 is a moderately to well-sorted arenitic to ruditic packstone to grainstone. Decimetre-thick layers of massive oolithic or shelly (dolo)-grainstones form metre-scale bedded packages (Figure 9A) in which crinoidal fragments are occasionally present. The oolites and shell hash are indicative of a high energy, shallow water shoal environment (LFA 5). Their massive bedding suggests event deposition such as intra-shoal spill-over or storm deposition.

LFT 12 represents poorly sorted, mostly massive intraclastic and ruditic packstones (Figure 9B) in which faint layering is occasionally visible. Three subtypes are differentiated: shelly, crinoidal and intraclastic (Figure 9B). The shelly dominated packstones often contain large bivalves, which underwent leaching followed by calcite recrystallization during diageneis. All subtypes can contain black

**FIGURE 7** Chart of LFTs of the Upper Muschelkalk with used colour code in each header. a) LFT 5: low-angle cross-beded intraclastic packstone to grainstone with red algal debris at the base of the sequence. Detailed image of thin sections shows typical structures of a red algal. b) LFT 6: Siltstone to Sandstone with through cross-bedding, microscopic view displays subrounded sorted sandstone with dolomitic matrix and good porosity (blue stain). c) LFT 7: (glauconitic) dolomite—Images show a bioturbated dolomudstone with selective enrichments of glauconitic pebbles. Microscopic view also displays scattered occurrence of siltitic quartz grains. d) LFT 8: nodular m-scale packages of strongly bioturbated peloidal dolo-wackestone to packstone layers. Pellets concentrated in bioturbation traces and are often hardly visible due to extensive micritization.
FIGURE 8 Chart of LFT 9–10 of the Upper Muschelkalk with used colour code in each header. a) LFT 9: Oncolithic wackestone to packstone. Thin section shows fine crystalline dolomite with oncolithic ghost structures and high amount of intercrystalline porosity. Right: oncoloids flattened by diagenesis exposed in a slabbed core. Note different nuclei of oncoloids. b) LFT 10: cross-bedded packstone to grainstone—subtype oolitic: packages of very well-sorted oolitic dolo grainstones showing internal through cross-bedding. Subtype shelly: m-scale poorly sorted shelly grainstones showing through cross-bedding, note separate vug porosity in microscopic view. Subtype crinoidal—left: through cross-bedded crinoidal grainstone, right: poorly sorted crinoidal grainstone showing oo-moldic porosity and mechanical destroyed crinoidal fragments.
pebbles. The occasional black pebbles, indicative of exposure horizons or forest fires (Strasser, 1984), suggest a more coastal depositional environment. Abundant shell debris indicates high-energy deposition of rather short duration (= (sub-)rounded mudclasts) probably to result from intense storm-induced reworking.

LFT 13 consists of a poorly sorted massive arenitic packstone forming metre-thick amalgamated packages with the individual packstone sheets characterized by strong basal erosion. The main components are shell hash, bivalves, brachiopods, gastropods and crinoids. These allochems often underwent leaching followed by calcite recrystallization during diagenesis (Figure 9C). LFT 13 represents proximal tempestites in which successive storm events in shoal to shoal fringe environments lead to erosion and reworking of underlying deposits resulting in thick amalgamated packstone packages.

LFT 14 consists of poorly sorted arenitic packstone beds, forming metre-thick packages (Figure 10A). The beds are massive or graded with frequent bioturbation from their tops. Bioclastic components such as shell hash, crinoids, gastropods, echinoderm fragments and peloids often display micritic envelopes. The massive texture, grading, poor sorting and the muddy matrix indicate rapid sedimentation with high suspension loads from proximal tempestites.

LFT 15 represents very poorly sorted arenitic wackestones to packstones displaying abundant, selectively dolomitized bioturbation. The main components of LFT 15 are shell hash, bivalves, brachiopods, gastropods and peloids. Feeding borrows (Figure 10B, arrow) within the peloids and shell debris-rich packstone and *Thalassinoides* traces at bed bottoms are commonly present. The intense activity of sediment-feeding organisms in moderate-energy lagoonal (LFA 4) or foreshore settings (LFA 7) suggests bottom waters were oxic. The wackestones to packstones are interpreted as intensely bioturbated, distal tempestites.

LFT 16 is composed of poorly sorted arenitic wackestones to packstones alternating with mudstones (Figure 10C). Beds are graded, and hummocky cross-bedding is commonly observed. Graded bivalve debris displays leaching and subsequent blocky calcite recrystallization. The dolostone variety displays intercrystalline porosity at its base and graded dolomite crystals. Rapid suspension load deposition associated with storm activity in an otherwise well-oxygenated, moderate-energy lagoonal (LFA 4) or foreshore setting (LFA 7) leads to distal tempestite facies with intense postdepositional bioturbation.

LFT 17 is a thinly bedded nodular mudstone which forms metre-scale packages in the field. On the micro-scale, finely laminated mudstones alternate with intensely bioturbated ones, occasionally with vertical features (Figure 10D). Bioturbation points to oxygenated, low-energy environments with sediment-feeding organisms in unconsolidated sediment. An absence of bioturbation indicates hostile living conditions and thus preservation of the original sedimentary layering. Therefore, LFT 17 was probably deposited in an environment prone to changes in oxygen supply such as offshore (LFA 8) or sheltered lagoonal deposits (LFA 3).

LFT 18 denotes laminated calcisiltites and fine-grained arenites often overlying LFT 16 distal tempestites. In thin section, swales with basal erosive contacts (arrows) and fine micritic particles are revealed (Figure 11A); interpreted as swaley cross-stratification formed during storm-induced deposition in shallow marine environments (LFA 7). LFT 18 is therefore interpreted as a distal tempestite.

LFT 19 is a marl and claystone, alternating with limestone or dolomite layers with sharp bottom/top contacts (Figure 11B). It is characterized by very high gamma-ray values due to the high clay mineral content. This facies type is encountered either within intertidal mud flats (LFA 3) as distal river inputs, in low-energy outer ramp environments (LFA 8), located below the storm wave base or in deeper nearshore lagoonal environments (LFA 4) often associated with plant debris.

LFT 20 is an often faintly laminated arenitic to ruditic bonebed containing a mix of subrounded quartz grains, a high concentration of vertebrate bone fragments, shell hash, intraclasts and diagenetic pyrite within a dolomitic or calcitic matrix. Coarser bonebeds could contain centimetre-scale bone fragments (Figure 11C). Some beds may display wave ripples on top. The terrigenous quartz input, marine components and wave ripples point to a high-energy environment forming distinct bone concentration horizons. Within the sequence stratigraphic framework, these bonebeds are associated with transgressive flooding surfaces but are not related to specific environments. They are interpreted as tempestitic condensation horizons (Reif, 1982).

LFT 21 encompasses a crinoidal encrinite or shelly boundstone which forms decimetre-scale to metre-scale biostromes or bioherms. Figure 11D shows an intact crinoid crown in a crinoidal grainstone (LFT 10) and biostromal, nodular growth of the bivalve *Placunopsis ostracina*. The Placunopsis bioherms are mound-like biostromes growing on hardgrounds in eutrophic water conditions (Hagdorn & Simon, 2000), whereas crinoid boundstones are interpreted as small reef-like bioherms growing on deeper seaward flanks of the carbonate ramp under fully marine conditions.

4.2 | Lithofacies associations

A LFA is a group of LFTs which are genetically related to one another and which typically occur together in specific depositional environments (Walker & James, 1992). Based on components (biogenic/abiotic), lithology, Dunham...
LFT 11: Bedded Pack- to Grainstone

LFT 12: Poorly Sorted Interclastic Packstone

A Subtype shelly

B Subtype clasts

C Subtype crinoidal

LFT 13: Massiv Amalgamated Packstone
textured and sedimentary structures, 21 LFTs were established for the Upper Muschelkalk in this study (Figs 5 through 11). They were grouped into eight lithofacies associations, representing unique depositional environments resulting mainly from differing depositional energy regimes along the gently inclined carbonate ramp. They range from coastal sabkha through high-energy shoal environments to low-energy outer ramp deposits (Figure 12).

4.2.1 | LFA 1 supratidal sabkha

Overall, the encountered sabkha sediments are marked by very low gamma-ray signals indicating dolomitic and sometimes sandy lithologies. Thin section analysis confirms the presence of evaporite mineral displacement structures indicative of intrasedimentary growth. Leaching of evaporite crystals and/or “chicken wire” fabrics leaves vugs either filled with secondary barite or calcite minerals (LFT 1), or produces large vuggy porosity. Palaeosoils with intense plant rooting (LFT 2) indicate periods of humid climate in a coastal marsh environment.

4.2.2 | LFA 2 peritidal

The peritidal facies association ranges from tidal flats to shallow subtidal lagoons (Wright, 1984) including a complex of sub-environments such as tidal mudflats, ponds, tidal channels and beach ridges, which are often barely distinguishable in the Upper Muschelkalk succession. Peritidal areas are mainly characterized by microbial boundstones/laminated mudstones (LFT 4), brecciated boundstones and conglomerates (LFT 3). Silt, clay and marine detritus are found in the tidal mud flats of estuarine systems (LFT 19) characteristic of protected, brackish landward areas indicated by common plant debris or ostracod shells. Tidal channels (LFT 6) cut erosively into surrounding strata, depositing cross-bedded ooids and/or mixed carbonate-siliciclastic silt/sandstones. Low-angle cross-bedded intraclastic grainstones (LFT 5) are interpreted as peritidal beach ridges forming along the tidal flat belt during more intense high-energy conditions. Overall gamma-ray signals of the peritidal lithofacies association are very low and clear due to the dolomitic fabric, but claystones (LFT 19) have prominent gamma-ray peaks.

4.2.3 | LFA 3 low-energy backshoal

Mud supported wackestones to packstones and nodular mudstones are typical deposits of the low-energy backshoal environment, representing the protected lagoonal setting between shoal and coastline. Deposition occurs above the storm wave base (SWB) but below the fair-weather wave base (FWWB). Common components are pellets and peloids, gastropods, shell hash and black pebbles. Organisms living in the sediment, like bivalves or gastropods can be found in situ. Low-energy backshoal deposits are often strongly bioturbated due to the high activity of sediment-feeding organisms. Trace fossils like Thalassinoides and Rhizocorallium (Seilacher, 1969, 2007), with some preserved spreiten structures, are very common (LFT 8, LFT 15, LFT 17). Claystones (LFT 19) are occasionally deposited in this low-energy environment presenting times of intense clastic input from the hinterland probably due to lowstand conditions or extreme climate changes. Sporadically interbedded storm deposits (LFT 16) hint of storms affecting the backshoal environment.

4.2.4 | LFA 4 moderate-energy backshoal

This lithofacies association represents the leeward shoal-margin environment. Higher energy facies indicate deposition above the FWWB. Graded wackestone to packstone sheets (LFT 16) display proximal storm deposits, while thin packstones to grainstones sheets (LFT 14, LFT 11) are interpreted as being generated by spill-overs from the nearby shoals. While components of these spill-overs normally consist of ooids and shell hash, crinoid fragments in the succession indicate transgression-induced more open marine conditions. Spill-over deposits often display postdepositional bioturbation in the upper parts of the layers due to the activity of postdepositional organisms indicating times of quiescence. Oncoids (LFT 9) and micritic envelopes are products of algal growth and indicate relatively warm and shallow water conditions within the photic zone (Flügel & Munnecke, 2010).

4.2.5 | LFA 5 shoal

The shoal facies association represents the highest energy environment encountered in the Upper Muschelkalk
succession above FWWB. Shoal lithofacies are grain dominated (LFT 5, 10, 11, 12) and typically display trough cross-bedding, often present over a thickness of several metres. Individual beds are marked by sharp or erosive bases. Components are both biogenic (shells, crinoids) and abiogenic (ooids). Strong variations in grain size are frequent and result from differences in depositional energy. The LFA shoal encompasses several typically high-energy geobodies such as shoals, channels and beach ridges.

4.2.6 | LFA 6 shoal fringe

The area surrounding the shoal—the shoal fringe—is marked by considerably lower water-energy and particle movement. However, LFA 6 is strongly influenced by storm-generated spill-overs on the leeward flank of the shoal. Amalgamated packstone sheets (LFT 13) interpreted as proximal tempestites are common. Facies are often poorly sorted with intraclasts (LFT 12) indicating reworking of underlying sediments and subsequent rapid deposition. During the overall transgressive Upper Muschelkalk hemicycle, and hence during times of open marine conditions, crinoid mounds develop on the seaward shoal flanks. Placunopsis reefs (Hagdorn & Simon, 2000) appear (LFT 21) commonly in this moderate-energy zone.

4.2.7 | LFA 7 foreshoal

Further basinwards, moderate to low-energy environments of the foreshoal prevail around SWB. Characteristic deposits are graded wackestone to packstone (LFT 16) commonly with hummocky cross-stratification (Cheel & Leckie, 2009; Dumas & Arnott, 2006) and medium to strongly bioturbated wackestones to packstones (LFT 15) where both are interpreted as storm-induced tempestites (Aigner, 1985; Pérez-López & Pérez-Valera, 2012).

4.2.8 | LFA 8 offshoal

The offshoal environment is characterized by low-energy mud-dominated deposits in a distal setting below SWB. Alternating mudstones (LFT 18), marlstones and claystones (LFT 19) dominate, intercalated only by scarce distal storm-sheets showing hummocky cross-stratification (LFT 18).

5 | SEQUENCE STRATIGRAPHY

The vertical succession of lithofacies types shows a cyclic pattern which is also evident in related outcrop gamma-ray measurements. Commonly, lithofacies types are regularly stacked to form cycles which can be correlated over a lateral distance of several kilometres. The 1D sequence stratigraphic analysis of this study is embedded in a well-constrained lithostratigraphic and biostratigraphic framework (Figure 2) of ceratite zones after Hagdorn and Simon (2005), conodont zones after Kozur (1974) and eco-stratigraphic marker beds after Hagdorn and Simon (1993). Overall, the Upper Muschelkalk represents a transgressive–regressive depositional sequence (Aigner & Bachmann, 1992) which can be further subdivided into cycle sets and cycles.

5.1 | Upper Muschelkalk cycles

Menning (2018) suggested the time span of the Upper Muschelkalk to be approximately 3.8 Myr. This study proposes that a hierarchical 4-tier sequence stratigraphic cycle subdivision is possible (Table 1).

The lowest tier cycles observed in the Upper Muschelkalk, the mini-cycles, are only apparent in selected localities. They are on average 0.3 cm thick, but 1.5 m thick mini-cycles are occasionally observed. Köhrer et al. (2010) and Petrovic and Aigner (2017) used mini-cycles for local-scale correlations. The identification of mini-cycles may be challenging as they are often poorly preserved, particularly in a foreshoal to offshoal setting, and/or contained in surfaces. Alternatively, mini-cycles may be generated by autocyclic processes and here caution is necessary to avoid misinterpreting these as allocyclic. Mini-cycles often prove difficult to correlate on a local scale and even more so on a regional one; because of this they are not treated further in this study. The sedimentological study of Aigner (1985) interpreted the Upper Muschelkalk as an almost symmetrically shaped transgressive–regressive cycle which Aigner

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**FIGURE 10** Chart of LFT 14–17 of the Upper Muschelkalk with colour code in each header. a) LFT 14: bedded packstone—m-thick packages of bedded packstones. Each bed with erosive bases. Thin section displays fine poorly sorted bivalve and brachiopod debris. b) LFT 15: strongly bioturbated wackestone to packstone of a slabbed core. Thin section shows poorly sorted shell debris and feeding borrows (arrows). Right: bottom side of a bioturbated wackestone to packstone sheet with traces of Thalassinoides (arrows). c) LFT 16: left side shows packages of graded wackestones to packstones alternating with mudstones (LFT 17), right: graded wackestone to packstone sheet with hummocky cross-stratification. Thin section shows graded bivalve debris, leached and recrystallized with blocky calcite. d) LFT 17: m-scale packages of thinly bedded nodular mudstones. Thin section displays a clean mudstone without any bioturbation whereas image on the right shows large vertical bioturbation within a slabbed core.
and Bachmann (1992) classify as a Transgressive Systems Tract with retrogradational stratal pattern and a Highstand Systems Tract with a progradational stratal pattern. However, localizing the exact position of the maximum flooding surface is rather difficult. Aigner and Bachmann (1992) did not commit to an exact position within the shaly intervals around the marker bed “Cycloidesbank” (Figure 2) which indicates basin-wide starvation and the formation of firmgrounds, which were colonized by brachiopods for a short period of time. Hagdorn and Simon (1993) and Palermo et al. (2010) favour the Tonhorizonte beta for maximum flooding as it records the most widespread occurrence of ceratites. Franz et al. (2015) proposed the depositional sequence maximum flooding deeper in the section around conodont-zone II and the pulcher/robustus ceratite zone (corresponding to mfz of Cs3 in this study). In terms of lithology, maximum flooding corresponds to the maximum extension of the typical mixed carbonate-siliciclastic lithologies of the basinal “Tonplatten” facies (valid for the area around Tonhorizont beta). Vecsei and Duringer (2003) proposed the depositional sequence maximum flooding around the compressus/evolutus ceratite zone boundary, conodont-zone II–III after Kozur (1974). Based on gamma-ray log patterns, facies distributions, highest amount of basinal cycles and due to its most prominent development among the regionally traceable clay horizons,
Tonhorizonte beta (corresponding to mfz of Cs4) has been chosen for practical reasons as the best candidate for the maximum flooding zone within this study. The term “zone” is chosen as the authors do not believe in the preservation of a distinct maximum flooding “surface” within a carbonate ramp setting, but more in an interval where the maximum flooding is hidden.

In total, 23 cycle sequences were identified throughout the complete Upper Muschelkalk section and can generally be traced on a regional scale. Cycle thickness ranges from a metre to several metres (average 2–5 m) but particularly in the uppermost and lowermost section of the Upper Muschelkalk, cycles are very thin and/or may even be absent. Cycle thickness, their architecture as well as their lateral and vertical development are strongly linked to their palaeogeographic position (Figure 13). Based on lithofacies-type stacking patterns, six basic types of cycles can be distinguished in the Upper Muschelkalk of the Southern Germanic Basin.

### 5.2 | Offshoal to foreshoal cycle

This cycle type (Figure 14) is found in distal sections (basin centre) and around the overall maximum flooding zone. Cycle thickness varies between 2 to 10 m. The lithologies are limestone, marl and some prominent clay horizons, the latter producing easily recognizable high gamma-ray signals, whereby gamma-ray patterns generally reveal cleaning-upward cycles. The lowermost part of the succession is characterized by thin-bedded, intensively bioturbated mudstones (LFT 17), interrupted by thin bioclastic beds (LFT 12, 13, 14, 15, 16). They often show internal fining upward tempestite sequences often with hummocky cross-stratification on top (LFT 18). The middle part is characterized by an abundance of clay and marl-rich horizons including the Tonhorizonte marker beds (LFT 19). The upper part shows an overall coarsening upward trend and starts with thinly bedded bioturbated mudstones (LFT 17), overlain by centimetre to decimetre (increasingly thicker towards the top of the cycle) thick bioclastic wackestones to packstones showing fining upward patterns, and strong postdepositional bioturbation.
This cycle type represents an offshoal (LFA 8) to foreshoal (LFA 7) shift of palaeoenvironments. Offshoal sedimentation is depicted by thin mudstone layers resulting from suspension settling. Wave action and tempestite events become increasingly more common during sea-level fall (Einsele, Chough, & Shiki, 1996; Einsele & Seilacher, 1982) and are marked in this cycle type by bioclastic, often hummocky cross-stratified beds indicating slightly more proximal environments. Cycle boundaries are delineated by bioclastic beds, often eco-stratigraphic marker beds such as the Spiriferinabank or the Trochitenbänke. Maximum floodings are sometimes expressed as hardgrounds indicating times with very low sedimentation rates.

5.3 | Offshoal to shoal/shoal fringe cycle

This cycle type (Figure 15) is the most common cycle style in the Upper Muschelkalk, present in every studied section. Its thickness varies between 2 and 8 m. It consists mainly of centimetre-thick to decimetre-thick limestone beds interbedded with thin marl intervals, occasionally single dolomitic beds may be interspersed. Limestones are light grey in colour while dolomites appear beige. The lowermost part of the section commences with thinly bedded, strongly bioturbated mudstones (LFT 17) interlayered by thin marl layers passing upward into more clay-rich layers with high gamma-ray values (LFT 19). They are overlain by bioturbated mudstones to packstones (LFT 15) that show characteristic burrow selective dolomitization (Gingras, Pemberton, Muelenbachs, & Machel, 2004; Rameil, 2008). Seams between these layers are also strongly dolomitized. The upper part is characterized by a distinct gamma-ray cleaning-upward trend composed of smaller cleaning-ups. It typically starts with a 1 to 2 m thick package of thinly bedded and strongly bioturbated mudstones (LFT 17) overlain by bioturbated wackestones to packstones with peloids (LFT 8). The wackestones to packstones display thinner cleaning-upward trends corresponding to fining upward patterns and hummocky cross-stratification at the top (LFT 18). Massive amalgamated and poorly sorted packstones (LFT 12 and 13) make the transition to cross-bedded packstones to grainstones (LFT 10 and 11) which cut erosively into them. A packstone to grainstone composition is dominated by ooids and brachiopod and bivalve shell hash. Crinoids occur exclusively in cycles of the lower part of the Upper Muschelkalk (Trochitenkalk-Formation).

This cycle style is interpreted as an asymmetrical offshoal (LFA 8) to shoal (LFA 5) shallowing-upward cycle. Cross-bedded grainstones and erosive channels deposited in shallow water environments suggest a proximal environment. Ooids and shell hash display lots of micritic envelopes and micritization indicating deposition within the photic zone. In many sections, the cycles are composed of distinct mini-cycles. The regressive part is usually thicker, whereas the transgressive part is less developed or even absent. The cycle boundaries are marked by prominent,
massive cross-bedded bioclastic grainstone beds with erosive bases. Marl and clay-rich layers indicate the zone of maximum flooding.

5.4 Shoal fringe to shoal cycle

This cycle type (Figure 16) occurs only in the lower part of the Upper Muschelkalk depositional sequence. Its thickness varies between 4 and 6 m. The gamma-ray signal is overall low in light coloured grainstones with slightly higher values in packstones. The lower part of the section starts with massive amalgamated mostly poorly sorted and slightly bioturbated packstones (LFT 12, 13, 14, 15) with abundant crinoid debris. Bioclastic components show micritic envelopes and black pebbles are common. They transition into faintly darker packstones with slightly higher mud content resulting in higher gamma-ray values. The upper part is dominated by cross-bedded grainstones (LFT 10 and 11) with a high number of crinoids. Crinoids are sometimes rock-forming (LFT 21), often with individual crinoids still bound together and fossilized crinoid cups.

This cycle is interpreted as symmetrical shoal fringe (LFA 6) to shoal (LFA 5) cycle. Amalgamated crinoid-rich packstone (LFT 13) layers represent storm-reworked debris derived from a nearby shoal which hosted massive, reef-like crinoid colonization yielding high amounts of crinoidal debris. As crinoids prefer open marine conditions, it is assumed that they colonized the offshore directed side of the shoal. The maximum flooding zone is indicated by faintly darker packstones with slightly higher mud content resulting in higher gamma-ray values. Cycle boundaries are characterized by poorly sorted, strongly reworked grainstone horizons (LFT 12 and 15). Abundant amalgamation and reworking of packstone and grainstone sheets resulted in very limited identification of mini-cycles.
Shoal to backshoal cycle

This cycle type (Figure 17) is only present in marginal sections of the Upper Muschelkalk Basin. Its total thickness varies between 2 and 4 m. The shoal to backshoal cycle lithology is solely characterized by dolomites and thin marlstone layers. Gamma-ray signals are generally low in dolomites with little peaks in marly intervals. The lowermost part of the cycle begins with cross-bedded dolo-packstone to grainstone (LFT 10) with erosive bases which cut into the underlying mudstones (LFT 17). The packstones to grainstones display vertical fractures indicating later mechanical stress and are sometimes overlain by dislocated Placunopsis reefs (LFT 21) within poorly sorted intraclastic packstones (LFT 12). These are succeeded by strongly bioturbated and thinly bedded dolo-mudstone (LFT 17) dominating the sections to the end of the section.

This cycle type is interpreted as an asymmetrical shoal (LFA 5) to backshoal (LFA 3 and 4) cycle. Placunopsis debris indicates reworking and transport probably as roll reefs via ocean currents, whereas they normally grow during transgressive phases with slightly rising sea-level. Cycle boundaries are marked by grainstones erosively cutting into underlying strata, often displaying lateral accretion features suggesting channels. The regressive hemicycles are not preserved and hidden in erosive surfaces. Note the different response to mechanical stress in grainstone packages (vertical fractures) versus the mudstone layers (no fractures).

Backshoal to intertidal cycle

This cycle type (Figure 18) is only present in the most proximal sections of the uppermost part of the Upper Muschelkalk and the Trierer Bucht. Its thickness varies between 1 and 3 m. Thick dolomite layers interbedded with marlstones and claystones dominate the section. Gamma-ray signals are generally low in dolomites with peaks in clay and marl horizons. The lowermost part of the succession starts with thinly bedded and laminated claystones (LFT 19) containing terrestrial plant debris and bone fragments overlain by bioclastic peloidal dolo-wacke stone to packstones (LFT 8) across a sharp contact. An overall upward increase in bioturbation can be observed. The upper part of the cycle is dominated by peloidal wackestones to packstones (LFT 8). Selective horizons are characterized by a concentration of centimetre-thick vugs (LFT 1).

This cycle is interpreted as an asymmetrical intertidal (LFT 2) to backshoal (LFT 3 and 4) shallowing cycle. The claystones mark the distal fluvial-terrigenous input representing cycle boundaries. The cycle is rise-dominated, the
regressive hemicycles either absent or hidden in surfaces. The occurrence of large vugs implies the subsequent leaching of evaporite minerals, probably chicken wire fabrics. Occasionally, these vugs display secondary calcite or barite crystal growth. These horizons might represent regressive pulses on a mini-cycle scale.

5.7 | Peritidal cycle

This cycle type (Figure 19) only occurs in the uppermost and lowermost part of the Upper Muschelkalk. Its thickness varies between 1 and 2 m and it is characterized by alternating dolomites, thin silicielastic bonebeds (LFT 20) and marlstone intervals. Gamma-ray signals overall are very low with peaks identifying marly intervals. This cycle has a strong variance in internal structure. The lowermost part typically commences with strongly bioturbated dolo-wackestones to packstones with peloids and oncoids (LFT 8 and 9) or with laminated dolo-mudstones (LFT 4) interpreted as algal laminae. Sometimes the lowermost part starts with erosive cross-bedded dolograinstones (LFT 5). Each style of this cycle shows a distinct fining upwards sequence topped by bioturbated mudstones.

The thickly aggrading laminated dolo-mudstones produced by algal mats can only be generated by increasing accommodation space during rising sea-level. They are therefore interpreted as transgressive pulses. Large vugs indicate leaching of evaporite minerals (chicken wire fabrics) originally produced by inerasemental growth. Occasionally, these vugs display secondary filling with calcite or barite. The distinct accumulation of chicken wire fabrics in an individual horizon points to a sea-level lowstand. They probably represent regressive pulses on a mini-cycle scale.

5.8 | Cycle sets

Seven well-defined cycle set sequences (Cs1–Cs7) of tens of metres in thickness were identified in the Upper Muschelkalk Basin, formed by stacking cycles with distinct gamma-ray and facies distribution patterns (Figure 20). The depositional style of these cycle sets varies markedly according to their position within the basin (central basin, shoal or marginal). Cycle sets Cs1 and Cs7 display a transgressive hemicycle and are solely developed in the central basin, while Cs2–Cs6 display full transgressive–regressive hemicycles and are found throughout the basin. Cycle set duration is approximately 540 kyr, possibly corresponding to the 400,000-year Milankovic signal reflecting the eccentricity of earth’s orbit (Upper Muschelkalk time span divided by number of cycles sets: 3.8 Ma/7 cycle sets = 542,857 yr/Cs; the top of the Upper Muschelkalk is affected by the erosive Grenzbonebed thus cycles are probably to be missing). Cycle set boundaries are often denoted.
6 | 2D CORRELATIONS

Basin-wide correlations (Figure 21) were carried out using facies analysis, biostratigraphy, gamma-ray data and 1D-sequence stratigraphic analysis. All sections were correlated in 7 dip and 5 strike sections by Warnecke (2018). Gamma-ray signatures prove to be significant as Borkhataria, Aigner, Pöppelreiter, and Pipping (2005) were able to trace larger scale cyclicities (depositional sequence, cycle sets) with major variations in signature. Cycles are the smallest scale of cyclicity correlatable on a regional scale. The smaller mini-cycles, found especially within the shoal facies of Braun (2003), Palermo et al. (2010) and Petrovic and Aigner (2017), are easily identified at outcrop scale; however, correlation between outcrops is not always possible and therefore, they are not represented in the basin-wide correlations.

Lithostratigraphic correlations of the eastern part of the southern Germanic Basin, both on a regional Geyer et al. (2011) and a local scale, have been widely reported, e.g. by Paul (1936); Vollrath (1938, 1952, 1955a,b,c). Merki (1961a,b), Aust (1969), Brüderlin (1969, 1970, 1971), Skupin (1969, 1970), Gwinner (1970); Gwinner and Hinkelbein (1972a,b, 1974a,b). Brunner and Simon (1985) and Stier (1985) provided an excellent basis for sequence-based correlations, while Franz et al. (2015) provided a general comparison of the Upper Muschelkalk deposits constrained by $\delta^{18}$O values, $^{87}$Sr/$^{86}$Sr-ratios, palynofacies, as well as inorganic and organic geochemistry in a basin-wide N–S section (Denmark to Switzerland). Initial detailed sequence stratigraphic correlations were carried out for the eastern part of the Swabian and Franconian Upper Muschelkalk Basin but are limited to selected study areas (Aigner, 1985; Braun, 2003; Palermo et al., 2010; Petrovic & Aigner, 2017).

An in-depth high-resolution sequence stratigraphic correlation has so far not been attempted for the western part of the southern Germanic Basin. Demonfaucon (1982) provided an excellent sedimentological study of carbonate facies of the Upper Muschelkalk in Luxembourg. Meanwhile, Vecsei et al., 2000 did a first attempt on the overall sequence stratigraphic framework in this area. Good lithostratigraphic descriptions are also provided by Lucius (1941), Gittinger (1969), Bock and Wagner (1986), Wagner (1989) and Dittrich (in press a,b). Cross-sections across the western part of the southern Germanic Basin provide the first sequence stratigraphic correlations.

FIGURE 18  Peritidal to backshoal cycle in quarry Meckel, Germany. Left: outcrop data and sedimentary analysis showing asymmetrical cycles with distinct dirtying upward transgressive hemicycles. Right: a) chicken wire vugs in within a wackestone to packstone, b) m-thick claystone horizon.
With the help of biostratigraphic data such as ceratite and conodont zonation (Kozur, 1974; Düringer & Hagdorn, 1987; Urlichs & Mundlos, 1990; Hagdorn & Simon, 2005; Dittrich in press a,b) as well as basin-wide eco-stratigraphic marker beds (Hagdorn & Simon, 1993, 2000), a first basin-wide coast to coast correlation was established.

For this study, the maximum flooding zone (mfz) of Cs4 was chosen as the correlation datum for Line A and Line B as it also represents the candidate maximum flooding zone of the entire Upper Muschelkalk depositional sequence. The mfz of Cs4 is accompanied by prominent basin-wide eco-stratigraphic marker beds such as Cycloidesbank and Tonhorizont beta. Its selection as correlation datum, is further supported by the following facts: (1) the mfz of Cs4 is present in most sections; (2) the mfz of Cs4 is easy to detect in well-logs due to its significant gamma-ray peak; (3) the mfz of Cs4 elucidated the symmetrical architecture of the Upper Muschelkalk carbonate ramp. Line C is flattened on the Grenzbonebed to visualize downlapping clinoforms.

6.1 | Description

Line A: The north–south cross-section is 68.3 km long (Figure 22) revealing a southward increase in thickness of the Upper Muschelkalk from less than 40 m in Sülm (N) to ca. 55 m in core Si 08 (S). The cross-section is dominated by dolomite intercalated by thin, but prominent, marl intervals. The Muschelkalk-Keuper boundary represented by bonebeds (Dittrich, in press b; Gittinger, 1969; Löffler & Prinz-Grimm, 2013) cuts erosively into the sections with increasing influence towards the south, where it completely erodes Cs7 and partly erodes Cs6. The section is wholly located on the Rhenohercynian (Behr & Heinrichs, 1987).
The transgressive depositional hemisequence is dominated by asymmetrical shoal to backshoal cycles and a heterogeneous shoal complex (Schengen Formation) dominates the complete section with a maximum thickness in core Si04 and Si06 (Figure 23). During the regressive depositional hemisequence, shoal accumulations occur only in the northern part (Meckel) and southern part (cores Si 04–08). The hemisequence is dominated by peritidal and backshoal to intertidal cycles.

Line B: The southwest–northeast regional strike cross-section is 290 km long (Figure 24). The thickness of the Upper Muschelkalk increases from ca. 70 m in well Riniken (S) to 90 m in well Würzburg (N). The overall lithology pattern shows limestone–marl alternations in the transgressive depositional hemisequence but increasing dolomitic facies (Rottweil-Formation) within the regressive depositional hemisequence towards the south-west. The Grenzbonebed (dotted red line) cuts erosively into the Upper Muschelkalk with increasing influence towards the south-west, where it completely erodes Cs7 and partly erodes Cs6. The boundary between deep Variscan palaeotectonic elements Saxothuringian and Moldanubian is located between the cores 7020/713 and 7020/B1 (Behr & Heinrichs, 1987). The Moldanubian block is subdivided by the alpine deformation front in Moldanubian I and Moldanubian II.

In the transgressive depositional hemisequence, individual cycles of Cs1 and Cs2 display onlaps onto the lower depositional cycle boundary. Thin grainstone beds are deposited in the lowermost part of Cs1 while in the uppermost part of Cs2 oolitic grainstones (LFT 3) are found in the area between Wutach and Dauchingen (Marbacher Oolith; Paul, 1936), showing fragments of red algae and a northward progradation of oolitic grainstones (Figure 25).

In the regressive depositional hemisequence, asymmetrical shoal to backshoal cycles and intertidal to backshoal
cycles dominate the section. There is a northward progradation of shoals (within Cs5 and Cs6), particularly in the south (Dauchingen, Wutach) (Figure 25). Chicken wire fabrics are concentrated in horizons (LFT 1) within the dolomitic facies (Southern part of Cs5 and Cs6).

A number of eco-stratigraphic marker beds were identified. The Haßmersheimer Schichten (gamma-ray peak, mfz Cs2) displays a progressive decrease in thickness, eventually pinching out towards the south (last occurrence in core 7617/94). The Tonhorizonte (gamma-ray peaks within Cs4 and Cs5) also displays a progressive decrease in thickness and eventually pinches out towards the south, while the Tonhorizonte beta, is last seen in core Dauchingen. Ostrakodentone (Cs7) progressively decreases in thickness and pinches out towards the south, while the Trochitenbänke (bio-clastic packstones within Cs2 and Cs3) are present over the complete section with little variation in thickness. Spiriferinabank (top of Cs3) and Cycloidesbank (top of Cs4) could be traced up to the area around Wutach. A gradual transition from lithostratigraphic formations Tonplatten to Plattenkalk, both marl–mudstone alternations within Cs3 and Cs4 is visible.

Line C: The regional dip cross-section covers 345 km from west to east (Figure 26). The thickness of the Upper Muschelkalk is 30 m in well Garnich (W), obtains a maximum thickness of 94 m in well SB 2 (centre) and gradually decreases to 50 m in core Dinkelsbühl (E). The Upper Muschelkalk thickness decreases towards the palaeo-coastlines and on both margins clastic deposits dominate in the very proximal sections. Both margins show predominantly asymmetrical backshoal, intertidal and peritidal cycle morphologies. Shoals accumulated on gently inclined carbonate ramps on both sides of the basin; however, shoals are significantly thicker on the western side. Furthermore, shoals on the western side solely consist of ooids, whereas mixed shelly/oooidal shoals exists on the eastern side. The basin centre (well SB 2) is dominated by distal/basinal facies only interrupted by bioclastic tempestite sheets. Crinoids are common during the transgressive depositional hemisequence and disappear at the same time on both basin margins (mfz Cs4). Eco-stratigraphic marker beds could not be correlated throughout the basin (last occurrence of all relevant marker beds in well SB 2) and are absent in the western part. Placunopsis reefs seem to be deposited at similar times in the Germanic Basin (Hagdorn & Simon, 1993, 2000).

6.2 | Interpretation

Line A: The thickest shoal accumulation in core Si04 and Si06 is related to a prominent palaeohigh structure (Siercker High). Massive shoal accumulation above the Siercker High builds up a barrier at the gateway of the Trierer Bucht towards the southern Germanic Basin. Small-scale
Variscan horst and graben structures seem to control shoal accumulation during the regressive depositional hemisequence. *Placunopsis* reefs found by Dittrich (in press a) in the uppermost part of quarry Meckel (uppermost Cs6) may be correlated with the eco-stratigraphic marker bed Obere Terebratelbank in southwestern Germany (Hagdorn & Simon, 2000).

Line B: The oolithic grainstones (Liegendoolith, LFT 5) in Cs1 and Cs2 in the northern part of the section are interpreted as beach ridges deposited during the initial transgression. Chicken wire fabrics concentrated in horizons (LFT 1) within the dolomitic facies (Southern part of Cs5 and Cs6) point to episodic sabkha conditions.

Massive shoal accumulation within Cs5 and Cs6 in sections Bettenfeld and Gammesfeld are related to the subtle palaeohigh structure Gammesfelder High (Wagner, 1913). Similar gamma-ray log patterns indicate a ‘pseudo layer cake’ system for the Upper Muschelkalk. Oolitic cross-bedded grainstones within the uppermost part of Cs6 in Dip section 6 are interpreted as peritidal channel deposits, due to their internal fining upwards structure and their erosive base. Large-scale geometries such as onlapping are commonly observed in peritidal sequences. Retrograding oolitic grainstones (LFT 5) in Cs1 and Cs2 are interpreted as beach ridges deposited during the initial transgression. Shoal accumulation in the southern part of the eastern margin (Dögginger Oolith) within Cs6 is interpreted as a rise-dominated shoal consisting exclusively of ooids. Strongly restricted conditions during the uppermost regressive hemisequence lead to similar deposits at the western and the southeastern margin.

Line C: A basin-wide E–W correlation connecting the eastern and western basin margins provides insight into the overall basin configuration, revealing a marked asymmetry on different levels.

Detailed analysis of 1D sequence stratigraphic cycles revealed different depositional styles. At the western margin, peritidal to backshoal cycles and rise-dominated shoals indicate restricted environments. At the basin centre, symmetrical offshoal to foreshoal cycles are common. At the eastern margin, all cycle styles can be found but shoals are fall dominated.

2D sequence stratigraphic cross-sections revealed heterogeneous facies distributions across the southern
FIGURE 24 About 290 km long sequence stratigraphic strike section, Line B, from core Würzburg (Ger) to core Böttstein (Ch). For exact location, see Figure 20. Variscan block segments are indicated below.

FIGURE 25 Sedimentological features on Line B. Cycles and logged Dunham texture on the right of each figure. a) Channelling, quarry Frommenhausen, Germany. b) Trough cross-bedded grainstone, quarry Herrenberg, Germany. c) m-scale channel, Dögginger Oolith, Wutach-Gorge.
Germanic Basin: The western margin is dominated by proximal facies; shoals are solely ooid-dominated indicating restricted palaeo-conditions. The eastern margin is dominated by distal to proximal facies; shoals appear to consist of shells or mixed shells and ooids.

The segmentation of larger Variscan elements and their activity during deposition of the Upper Muschelkalk appears to be significantly different: The western margin was tectonically active leading to a high number of smaller scale segments within the Saxothuringian block, whereas the eastern margin was tectonically quiet with a homogeneous Moldanubian block.

7 | HYDRODYNAMICS

Previous studies in the Upper Muschelkalk include palaeo-current measurements from wave ripples, channel directions, gutter casts and from cross-bedding but these cover only selected areas (Aigner, 1985; Braun, 2003; Demonfaucon, 1982; Diedrich, 2008; Duringer & Vecsei, 1998; Heymann, 2007; Looser, 2005; Palermo et al., 2010; Petrovic & Aigner, 2004). This paper provides a synopsis of all published measurements covering the southern Germanic Basin as well as 15 additional locations investigated in this study.

The analysis of palaeo-current measurements leads to the following conclusions (Figure 27). Wave ripple crests are oriented in a general north-eastern–south-western direction in distal parts of the basin, but slightly deviate to northwest–southeast in marginal parts. This might indicate longshore winds in the distal areas, and wave crests moving perpendicular to the coastline. Cross-bedding indicates a predominant NE transport direction in the eastern part of the basin but a southward directed transport in the Trierer
FIGURE 27  Top: Orientations of gutter casts in the Upper Muschelkalk: blue arrows from Aigner (1985), black arrows this study. Middle: Orientations of cross-beddings in the Upper Muschelkalk: blue arrows Aigner (1985), Grey arrows Braun (2003), red Petrovic (2016) and black arrows (this study). Bottom: Orientation of oscillating currents taken from wave ripple crests, Upper Muschelkalk. Blue arrows Aigner (1985), black arrows (this study)
Bucht. Heterogeneities within shoal complexes are common and caused by the complex hydrodynamics within such landscapes. Gutter casts are generally orientated in a north-eastern–south-western direction.

8 | DISCUSSION

Facies: 2D sequence stratigraphic cross-sections revealed major differences in the distribution of 21 LFT’s across the southern Germanic Basin. The western margin is characterized by restricted palaeo-environmental conditions (shallow marine with probably high salinity). Lithofacies with limited fauna and fossil content (LFT 1, 2, 3, 6 and 7) predominate in this area. The eastern margin displays more “open” marine palaeo-environmental conditions leading to a diverse fauna. Brachiopod eco-stratigraphic marker beds occur exclusively within the eastern part of the basin. The internal facies-composition of shoals (LFT 10, 11) shows that the western margin is dominated by purely oolitic facies (subtype oolitic, LFT 10) whereas the eastern margin shoals are marked by a greater variety of components. Hagdorn and Simon (1993); Szulc (2000); Narkiewicz & Szulc (2004) and Feist-Burkhardt et al. (2008) indicate ocean water input from the Tethys via all three gateways - East Carpathian Gate, Silesia-Moravian Gate, West Burgundian Gate - during Anisian / Ladinian times. 2D sequence stratigraphic analysis points to a very shallow peritidal western Burgundian gateway with limited ocean-water input and a probably partly exposed gateway in the regressive depositional hemisequence. The following evidence supports this: shoals of the regressive depositional hemisequence are purely oolitic in the most southern part and of shell hash in the northern part. This is interpreted as a result of significant differences in ocean water chemistry and ecologic conditions (restricted environments in the south, fully marine environments in the north). Dolomite thickness, backshoal (LFA 3-4) and peritidal facies (LFA 2) in combination with chicken-wire fabrics (LFT 1) increases towards the south. Adams and Diamond (2017) described cements precipitated from meteoric groundwaters prior to early dolomitization in the uppermost part of the Swiss Upper Muschelkalk (Nagra1 cores) which favours a very shallow peritidal gateway.

Cycles and shoals: The observed complex oceanographic current system (Figure 26) overprinted by fluctuating eustatic sea-level probably controlled water chemistry within the basin, i.e. subtle changes, either favouring calcite or aragonite precipitation. The accumulation of shoals
and their subsequent movement reveals markedly different developmental influences depending on their location within the basin (Figures 22 and 27):

- Western margin: in the leeward dominated wind-system aggradation of shoals dominates. The western basin is dominated by exclusively rise-dominated cycles forming massive, stacked shoals (up to 10 m, Figure 26).
- Eastern margin: a windward dominated wind-system caused shoals to prograde towards the NE (longshore to dominant winds) or towards the west (backflowing gradient currents), in addition to a variety of cycle patterns (Figure 13).

These observations differ from the windward aggradation and leeward progradation documented by Bergman, Westphal, Janson, Poiriez, and Eberli (2010) and Westphal, Riegli, and Eberli (2010) on isolated carbonate platforms such as the Bahamas.

Palaeo-tectonics (Subsidence patterns): The southern Germanic Basin is located on three large Variscan palaeo-tectonic units—the Rhenohercynian Block forming the northwest margin, the Saxothuringian in the centre and the Moldanubian forming the southeast margin (Figure 2). Different degrees of tectonic/subsidence activity (Vollrath, 1955a,b) characterize these blocks particularly affecting the marginal basin areas leading to distinct basin asymmetry (Figure 28). The Rhenohercynian block (northwest margin) is internally made up of complex horst and graben structures, which appear to have been partially tectonically active during deposition of the Upper Muschelkalk (Dittrich, 1989). In contrast, the Moldanubian block (southeast margin), probably to have been tectonically quiet, displays a relatively homogeneous internal structure. Both marginal blocks have slightly less subsidence than the intervening Saxothuringian block (Vollrath, 1955a,b). Seismites, e.g. in the Würzburg area (Warnecke, 2014), breccias and slumps in Héming (Duringer & Vecsei, 1998; Vecsei & Duringer, 2003) point to some seismic activity during the time of deposition and possibly indicate tsunami occurrences in the basin. The underlying irregular basin configuration apparently initiated distinctly asymmetrical depositional patterns across the basin. A similar asymmetry is also visible in the inherited tectonic configuration of the Arabian platform (Murriss, 1980; Ziegler, 2001) and could be assumed for many other epicontinental basins (e.g. Paris Basin, Rub’al Khali Basin).

Hydrodynamics: All palaeo-current measurements on the eastern basin margin indicate a strongly wind-driven hydrodynamic system with dominantly longshore winds and storm tracks reaching from the Tethys in the south-west towards the north-eastern part of the basin. Aigner (1985) confirmed the hydrodynamic model of Marsaglia and Klein (1983) with alongshore palaeo-currents in offshore areas and on-offshore flows in nearshore zones. In contrast, the western margin of the basin is dominated by a south-facing current system. Lithofacies analysis shows the Trierer Bucht to be very shallow thus probably focusing southern backflow around the Rhenish Massif in a circular current system. Southern palaeo-currents in Luxembourg and western Germany (Figure 27) support this. Therefore, an asymmetric palaeo-oceanographic flow system is assumed for the Upper Muschelkalk Sea (Figure 28).

- Freshwater influence: The northern part of the Germanic Basin is dominated by the Fennoscandian deltaic system, responsible for fresh water input into the basin (Franz et al., 2015). Feist-Burkhardt et al. (2008) concluded that an overall change towards a more humid climate occurred in the Fassanian. A humid climate in the Northern Germanic Basin versus a more arid climate in the Southern Germanic Basin as proposed by Franz et al. (2015) probably lead to an estuarine circulation pattern (Franz et al., 2015; Seibold, 1970) forming an outflow of surface water with reduced salinity towards the south. Chemical weathering is much higher under humid climates and probably resulted in large suspension loads carried from the Fennoscandian delta via the estuarine circulation into southern, carbonate dominated areas of the Germanic Basin. These suspension clouds may be an important contributor to the basin-wide deposition of the clay/marl marker beds (Tonhorizonte) of the Upper Muschelkalk.

- Marine influence: The main open marine water input into the southern Germanic Basin happened via the eastern East-Carpathian and Silesian-Moravian gates (Hagdorn & Simon, 1993). The southern Burgundian gateway, a possible conduit for marine waters from the south, is shown to be almost closed at the end of the Upper Muschelkalk (dominated by peritidal and sabkha facies). As a possible analogue, Röhl, Schmid-Röhl, Oschmann, Frimmel, and Schwark (2001) found that humid summers and a southwest–directed monsoon established an estuarine circulation pattern at the East-Carpathian and Silesian-Moravian gates during Lower Jurassic times. Here the outflow of lower salinity surface water towards the Tethys was countered by an inflow of high salinity marine water from the Tethys resulting in a stratified water column. Seasonal climate variations caused by dry, arid winters possibly led to an anti-estuarine circulation pattern during those times. High evaporation lead to increasingly saline and higher density surface waters which sank to the bottom, destroying the stratified water column. Similar processes may have occurred in the Upper Muschelkalk.

- Wind influence: The suggested hydraulic flow system caused by freshwater input from the north and marine water inputs from the south is seasonally interrupted by strong hurricanes (Marsaglia & Klein, 1983). These
storms most probably derived from the south-west generating a northward directed longshore current system along the Vindelician-Bohemian Massif. Aigner (1985) documented that these hurricanes had a main impact on sediment dispersal patterns of shoals in an overall storm dominated Germanic Basin.

The Persian Gulf, as a modern analogue is characterized by different shallow marine geostrophic (thermohaline) currents resulting in a water circulation system further influenced by seasonally prevailing wind systems, all leading to a complex and not quite fully understood flow system; however, the dominantly northerly “Shamal” winds exert a major influence on sediment dispersal and depositional patterns (Elhakeem, Elshorbagy, & Bleninger, 2015; Elshorbagy, Azzam, & Karim, 2002; Peng & Bradon, 2016; Pous, Carton, & Lazure, 2013).

9 | CONCLUSIONS

This study is based on the detailed sedimentological analysis of 86 gamma-ray logs, 27 cores and 31 outcrop sections in the Upper Muschelkalk in the southern Germanic Basin. The facies analysis reveals 21 distinct LFT which can be grouped into eight LFA covering a gently inclined carbonate ramp from coastal sabkha environments to offshoal environments. The well-established lithostratigraphic and biostratigraphic framework together with the established facies, the resulting 1D and 2D sequence stratigraphic analyses and a first simplified hydrodynamic model provide evidence of asymmetric patterns on different scales within the Southern Germanic Basin:

The segmentation of larger Variscan elements and their activity/differential subsidence patterns during Upper Muschelkalk deposition appears to be significantly different in the more active western margin when compared to the quieter eastern margin. Carbonate ramps developed on both the western and eastern margin of the Germanic Basin, but differ fundamentally in internal facies distribution, lateral extent and thus potential reservoir bodies. The 2D sequence stratigraphic cross-sections support this and reveal major differences in facies distribution and composition. The western margin is dominated by purely oolitic shoals, whereas the eastern margin is marked by a greater variety of facies and mixed component shoals. Furthermore, detailed sequence stratigraphic analysis revealed different depositional cycle styles. The western margin is dominated by exclusively rise-dominated cycles, whereas the eastern margin shows a variety of cycle patterns.

All palaeo-current measurements on the eastern basin margin indicate a strong wind-driven current system with dominantly longshore winds and storm tracks reaching from Tethys in the south-west towards the northeastern part of the basin. In contrast to that the western basin margin displays southerly directed currents. Palaeo-current indicators along with the established basin-wide hydrodynamic model indicate aggradational shoal development in the western windward basin margin and progradational shoal movements in the eastern leeward basin margin.

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