Int J Earth Sci (Geol Rundsch) (2005) 94: 267–274
DOI 10.1007/s00531-005-0469-0

ORIGINAL PAPER

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Distribution of sedimentary organic matter in Anisian carbonate series of S Poland: evidence of third-order sea-level fluctuations

Received: 26 April 2004 / Accepted: 11 December 2004 / Published online: 16 February 2005

Abstract The stratigraphic distribution of sedimentary organic matter in Anisian carbonate series of southern Poland is studied with respect to relative sea-level fluctuations. Palynofacies patterns clearly reflect transgressive–regressive trends that are interpreted in terms of third-order cyclicity. Major flooding phases are detected by maximum abundance of marine plankton in the upper Bithynian and Pelsonian. Transgressive and highstand deposits are recognized by changes in the terrestrial input of organic particles and the relative percentages and diversity of the plankton group. The palynological data support the sequence stratigraphic interpretation based on sedimentological features and geochemical signatures. The corresponding eustatic signals of sedimentary and organic facies are discussed. The study highlights the potential of palynofacies analysis for sequence stratigraphical interpretation.

Keywords Palynofacies · Sequence stratigraphy · Middle Triassic · Anisian · Southern Poland

Introduction

The present study focuses on reconstruction of the eustatic history of the Western Tethys marginal basin (northern Peri-Tethyan realm) by means of palynofacies analysis. Based on the well established litho-, bio- and chronostratigraphic framework of Anisian Muschelkalk deposits of Upper Silesia (Assmann 1944; Zawidzka 1975; Hagdorn and Gluchowski 1993; Nawrocki and Szulc 2000), the stratigraphic distribution of sedimentary organic matter is analysed with respect to relative sea-level fluctuations.

Major eustatic signals at a third-order scale detected from sedimentological and geochemical data were first interpreted in terms of sequence stratigraphy by Szulc (1999). Subsequently, an integrated sedimentological, palaeobiological and geochemical study analysed the evolution of the northern Peri-Tethyan basin, in terms of palaeooceanographical circulation between it and the open ocean (Szulc 2000).

Here, palynological study of the organic facies is used to test the earlier inferred sedimentological and palaeoenvironmental conclusions. On the other hand, a positive result of the cross-checking of the palynological analysis with the other methods (including sedimentological, palaeobiological and geochemical) would testify the value of palynofacies analysis as a powerful tool for sequence stratigraphical interpretation. Silesia is a particularly well-suited area for this research strategy since in Middle Triassic times, it was situated just between the Tethys Ocean and its northern marginal Germanic Sea.

Materials and methods

In Upper Silesia, the studied Strzelce Opolskie and Plaza sections west of Kraków (Fig. 1) expose a nearly 100 m thick carbonate series of the Anisian. A description of these outcrops and the sedimentology and sequence stratigraphic interpretation of the Middle Triassic are found in Szulc (1991, 1999, 2000). Palynofacies analysis was carried out on 28 samples. All samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for dissolution of carbonates and siliciclastics, and saturated $ZnCl_2$ solution ($D \approx 2.2$ g/ml) for density

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Fig. 1 Location of the study area in southern Poland (Upper Silesia). Today's Muschelkalk outcrop west of Kraków is indicated in *black*. The quarries Strzelce Opolskie (50°31′N; 18°18′E) and Plaza (50°6′N; 19°28′ E) provide continuous sections of the Anisian

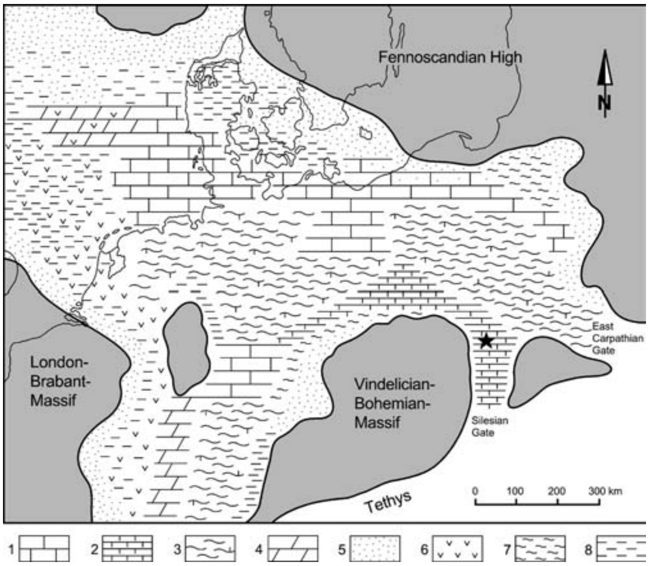


Fig. 2 Palaeogeography of the Germanic Basin during Pelsonian times (modified from Szulc 1999). *1* bioclastic limestones, *2* basinal fine-grained limestones, *3* marls, *4* dolomites, *5* sandstones, *6* evaporites, *7* mudstones and *8* claystones. *Star* marks the study area

separation. Slides have been mounted in Eukitt, a commercial, resin based, mounting medium. The relative percentage of sedimentary organic constituents is based on counting at least 400 particles per slide.

Carbon and oxygen stable isotope data from bulk carbonate samples of the Middle Triassic series of Upper Silesia were first published and discussed in detail by Szulc (1999, 2000). For the purpose of the present study, only the δ^{13}C data of the Anisian interval have been used for discussion.

Palaeogeography and stratigraphy

During the Triassic, the Germanic Basin was a peripheral basin of the western Tethys Ocean, the so-called Northern Peri-Tethys (Szulc 2000). The basin was closed toward the north and open to the south by tectonically controlled depressions (gates) adjacent to the Vindelician-Bohemian Massif, separating the Tethys from its northern periphery sea (Fig. 2).

The communication pathways (gates) opened diachronously. The eastern seaway (East Carpathian Gate) was active already in late Induan times, the Silesian Gate opened in the Olenekian, while the western communication to the Tethys developed only during the Pelsonian. The diachroneity is explained as a result of the westward relocation of the connection tracts following a shift of the Tethyan spreading centre (Szulc 2000).

The semi-closed setting of the basin resulted in it showing distinctive environmental differentiation. Open marine environments dominated the southeastern part of the basin, near the Tethys. Northward and westward from the Silesian and Carpathian domains the environments became more restricted. This resulted in a significant facies diachroneity between the western and eastern parts of the basin. Faunal diversity, facies variability and geochemical properties of the sediments all indicate that open marine sedimentation dominated during almost the entire Anisian in the eastern subbasin, while the western part displayed restricted circulation, typical of a semi-closed, evaporitic basin. The circulation reversed in Ladinian times when the westward shift of the Tethyan spreading centre gave rise to the opening of the western gate. Meanwhile, the eastern and northern parts of the basin were uplifted and exposed by the end of the Ladinian. Since the northern Peri-Tethys was situated within the subtropical zone (Nawrocki and Szulc 2000), its climate was generally hot and semi-arid. The chronostratigraphical subdivision of the Middle Triassic of the Polish basin and in particular its Silesian part is well established (Fig. 3), based on conodont biostratigraphy (Zawidzka 1975; Narkiewicz and Szulc 2004) and magnetostratigraphy (Nawrocki and Szulc 2000). However, the facies diachroneity, the scarcity of index fossils and lack of magnetostratigraphical data in the German part of the basin, make unequivocal basin-wide correlation difficult. Recently, sequence stratigraphy has been employed to approach the problem of the regional lithofacies variation and correlation of the main stages of basin evolution during Middle Triassic times (Szulc 2000).

Sedimentary facies and depositional sequences

The Anisian succession in southern Poland is composed of several lithological units reflecting transgressive pulses, which culminated in Pelsonian times when the most

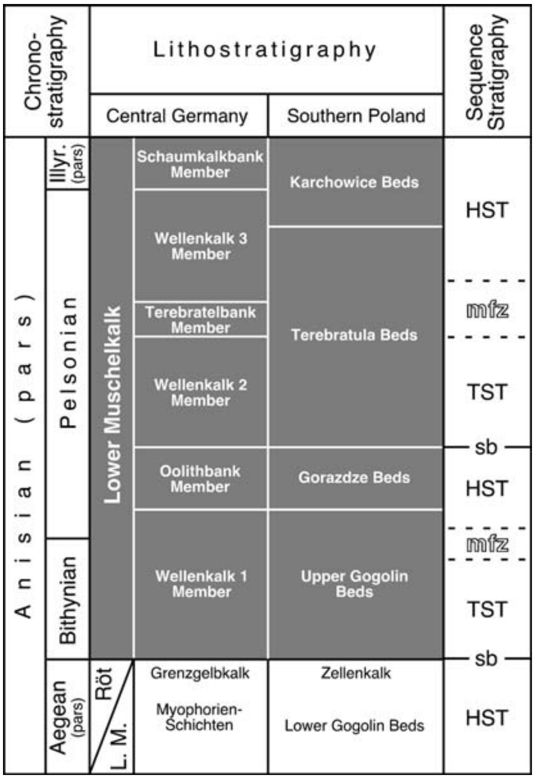


Fig. 3 Chronostratigraphy, lithostratigraphy and sequence stratigraphy of the Anisian in Central Germany and Southern Poland (Silesia). Chronostratigraphy after Nawrocki and Szulc (2000). Lithostratigraphic units of the German Muschelkalk series after Hagdorn et al. (1993), lithostratigraphic units of the Silesian Muschelkalk deposits after Szulc (1999), sequence stratigraphic interpretation after Szulc (2000). *L.M.* Lower Muschelkalk, *TST* transgressive systems tract, *mfz* maximum flooding zone, *HST* highstand systems tract, *sb* sequence boundary

pronounced transgression encompassed the entire area of the Northern Peri-Tethys Basin. In Upper Silesia, open marine carbonate sedimentation started at the beginning of the Anisian and is recorded by bioclastic limestones (which include stenohaline crinoids such as *Dadocrinus gracilis*) of the Lower Gogolin Beds. The open marine sedimentation was terminated by basin-wide shallowing and emersion, producing post-evaporitic vuggy limestones and dolomites (Zellenkalk horizon). The next marine incursion resulted in a gradual deepening and the sedimentation of fine-grained, slightly dysoxic limestones and marls of the Upper Gogolin Beds (Fig. 4). These sediments contain numerous Tethyan faunal elements (conodonts and crinoids) indicating established free communication between the Tethys and the Peri-Tethys Basins. Subsequent deposition of coarser grained limestones of the Gorazdze Beds (Fig. 4) reflect gradual shallowing of the basin up to emersion.

Fig. 4 Transition between the micritic limestones of the Upper Gogolin Beds (*below*) and shoal bar calcarenites of the Gorazdze Beds (*above*). Hammer for scale and indicating the boundary between the two units. Strzelce Opolskie quarry

The next transgression progressed very quickly and the exposed shoals were directly covered by partly dysoxic fine-grained limestones, the Terebratula Beds, that represent the most pronounced Anisian transgressive event recognized over the whole Peri-Tethys Basin (Szulc 1999). After this drowning, the basin underwent progradational filling and shallowing that led to the onset of bioclastic shoals and sponge–coral reefs of the Karchowice Beds. As the shallowing progressed, the reefs were replaced by oncolites and oolitic bars of the Diplopora Beds at the top of the Lower Muschelkalk succession in the Upper Silesian area.

The outlined facies succession can be explained in terms of third-order depositional sequences and systems tracts driven by eustatic sea-level fluctuations (Fig. 3). The only definite indication of tectonic control is the drastic drowning during the early transgressive phase of the sequence An3 (Szulc 2000).

Depositional sequences and faunal records

Changes in faunal composition and diversity of the Anisian sequences in Upper Silesia, analysed in terms of the Tethyan versus local species proportion, indicate a close relationship between the structure of the community and the type of systems tracts (Szulc 2000; Narkiewicz and Szulc 2004). The Tethyan species always dominate in transgressive systems tracts and decrease substantially in abundance in highstand systems tracts. In contrast, the faunal diversity is always much higher during highstand phases than in transgressive intervals.

These patterns appear to reflect the biota's response to ecological constraints. The basic environmental parameters (energy, water depth, light, oxygen and nutrient supply) may have changed too rapidly during transgressions for the biota to adjust in time. As a consequence, the population became dominated by

Tethyan elements and generally impoverished in species number. During the highstand phase, the environmental conditions stabilized and the fauna became more diverse. The main mechanism of this enrichment was speciation of endemic taxa (Szulc 2000).

Stable isotope signals

Since the Germanic Basin was a partly enclosed shallow sea in a subtropical setting, the composition of C- and O-isotopes of its water would have been primarily controlled by interplay between marine and continental water influx and by evaporitic fractionation. Generally, the two isotopes are covariant (Szulc 2000). Since the C-isotope fractionation is less sensitive to evaporation effects, we assume here that variations in δ^{13}C act as a proxy for the net balance of seawater and meteoric water. So, an increase of meteoric water input results in ^{13}C depletion in seawaters, while the transgressive events should increase the water exchange with the oceanic reservoir and hence, give more positive, "normal" marine signals within the epicontinental sea.

The isotopic data published so far from the Middle Triassic sediments of the western Tethyan realm are very sporadic and incomplete (Lintnerova and Hladikova 1992; Dolenec et al. 2003). Therefore, the obtained δ^{13}C curve could not be applied for chemostratigraphy as has been done in the case of Cretaceous platform carbonates (Jenkyns et al. 1994; Grötsch et al. 1998). Nonetheless, the Muschelkalk deposits show δ^{13}C values comparable to the δ^{13}C contents from the Tethys basins. This concerns in particular the maximum signals reaching 3.5‰ in Silesia, e.g. close to Anisian signals from the Karavanke Mountains (Dolenec et al. 2003) and Male Karpaty Mountains (Lintnerova and Hladikova 1992). However, in contrast to the alpine basins negative shifts around 0‰ (and below) are more common in the studied succession than in the Tethyan ones.

It is also worth noting that the Scythian (Röt) carbonates, that precede the Anisian succession, show distinct negative isotopic signals with a δ^{13}C range from −6 to −5‰ (Szulc 2000), although the sediments formed under evaporitic conditions, that should result in just the opposite trend, i.e. the sediments should be isotopically heavier.

This all supports the assumption of a substantial influence of meteoric waters on C-isotope fractionation in the semi-closed Muschelkalk basin.

^{13}C evolution

Within the studied section of the Lower Muschelkalk carbonates some fluctuations of the ^{13}C content are obvious (Fig. 5). The δ^{13}C curve starts with a positive shift (from −2‰ to 0.5‰ PDB) reflecting an increasing influence of normal marine waters. The subsequent negative shift at the top of the Lower Gogolin Beds coincides with the An1 sequence boundary (Zellenkalk horizon) and provides evidence for meteoric dilution of the marine waters.

The next positive trend matches the transgressive phase of sequence An2 (Upper Gogolin Beds). The maximum δ^{13}C values (3.5‰) coincide with the maximum flooding event of the sequence and with the appearance of Tethyan cephalopods and gondolellid conodonts in Silesia. The subsequent negative trend (to −0.5‰) in the uppermost part of the Gogolin Beds is characteristic of the early highstand phase and may reflect increasing contribution of isotopically lighter meteoric water. The subsequent positive trend in the middle part of the Gorazdze Beds during the late highstand phase reflects the effect of fast cementation of the shoal bar under slightly evaporitic, very shallow water conditions (Szulc 2000).

The next transgressive pulse (sequence An3) again brought normal marine waters into the Silesian basin as indicated by the positive trend of the δ^{13}C curve. The heaviest values of δ^{13}C (3‰) fall around the maximum flooding interval of the Terebratula Beds.

From the highstand interval onward (upper Terebratula Beds and Karchowice Beds) the δ^{13}C curve clearly displays a negative trend indicating a gradual decrease of the open marine influence.

As shown above, the geochemical signals obtained from the δ^{13}C curve run parallel to the evolution of the recognized shallowing/deepening trends and the defined systems tracts (Szulc 2000).

The already mentioned scarce isotopic data from the Middle Triassic hinder more general conclusions about stratigraphic variance of carbon isotopes interpreted in terms of global palaeooceanographical evolution or climatically driven changes in the hydrosphere during Anisian–Ladinian times.

Nonetheless, we believe that continuation and extension of such studies would give an insight on these overall processes during a global sea-level lowstand of the Triassic Aragonitic Ocean. Similar studies carried out so far mostly dealt with periods of a global sea-level highstand (Cretaceous and Devonian). Therefore, they cannot serve as an adequate reference for the Triassic.

Palynofacies patterns

Palynofacies analysis involves the identification of palynomorphs, plant debris and amorphous particles, their absolute and relative proportions, size spectra and preservation states (Combaz 1964, 1980). Its application in a sequence stratigraphic context was outlined by Tyson (1995). In the present study, stratigraphic variation in the distribution of sedimentary organic matter, is used to detect major eustatic signals at the scale of third-order cyclicity. Two groups of organic particles are distinguished: a continental fraction including terrigenous phytoclasts, pollen grains and spores and a marine fraction composed of acritarchs, prasinophytes and

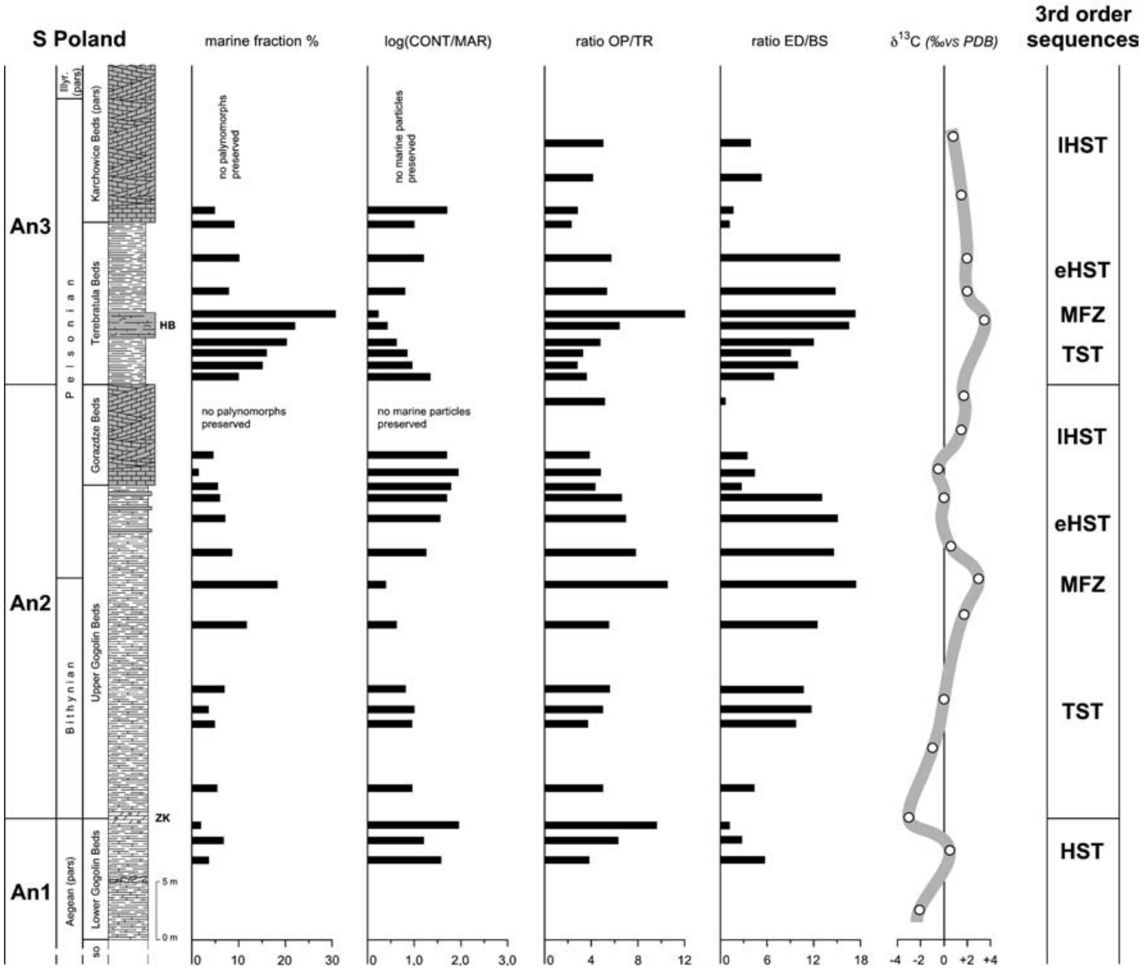


Fig. 5 Stratigraphy, palynofacies patterns, stable isotope signatures and third-order depositional sequences of the Anisian (An1–An3) of southern Poland (Upper Silesia). Isotope data and sequence stratigraphic interpretation after Szulc (1999, 2000). *TST* transgressive systems tract, *MFZ* maximum flooding zone, *eHST* early highstand systems tract, *lHST* late highstand systems tract, *HB* Hauptcrinoidenbank, *ZK* Zellenkalk, *CONT/MAR* ratio of continental to marine organic particles, *OP* opaque phytoclasts, *TR* translucent phytoclasts, *ED* equidimensional, opaque phytoclasts, *BS* blade-shaped, opaque phytoclasts. *PDB* Pee-Dee Belemnite Standard (Craig 1957)

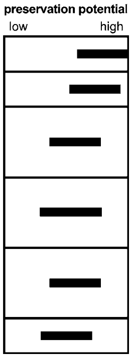
foraminiferal test linings (Table 1). The relative percentage of these components is based on counting at least 400 particles per slide.

Three palynofacies parameters were calculated to enable the recognition of transgressive and highstand deposits as well as maximum flooding zones and sequence boundaries. (1) The relative abundance of marine plankton. This parameter quantifies the percentage of acritarchs and prasinophytes in the entire sedimentary organic matter. It is linked to the marine conditions of the water column, depending on distance to coastline, water depth, temperature, salinity and nutrient availability. (2) The ratio of continental to marine particles (CONT/MAR ratio). The composition and relative abundance of the continental fraction reflects the hinterland vegetation and the source distance. Stratigraphic variations in the CONT/MAR ratio document prograding and retrograding coastlines. This ratio decreases basin-ward and increases stratigraphically in a shallowing-upward succession (Tyson 1995;Wood and Gorin 1998). (3) The ratio of opaque to translucent phytoclasts (OP/TR ratio). Opaque phytoclasts partly consist of charcoal originating from forest fires, but mainly develop by oxidation of translucent phytoclasts. Generally, the ratio of opaque to translucent phytoclasts increases basin-ward due to fractionation processes and the higher preservation potential of opaque particles (Summerhayes 1987; Tyson 1993; Pittet and Gorin 1997; Bombardière and Gorin 1998). Most of the oxidation is of subaerial, continental origin (Tyson 1995). However, in proximal high-energy shelf areas, this trend may be reversed by in-situ (bio)oxidation at the seafloor (Batten 1982; Boulter and Riddick 1986; Bustin 1988; Tyson 1993), enhanced by the high porosity and permeability of coarse-grained sediments (Tyson 1993). Therefore, the size and shape of opaque plant debris are additionally used to decipher proximal-distal and transgressive–regressive trends. Small, equidimensional woody fragments are characteristic of distal deposits, whereas in proximal settings large, blade-shaped particles are quite abundant (Steffen and Gorin 1993). In addition, proximal assemblages reveal a greater variety of particle sizes (Tyson 1993; Tyson and Follows 2000).

Palynofacies of the Lower Gogolin Beds are characterized by a high amount of terrigenous phytoclasts (Fig. 6a). An increase of opaque, mainly blade-shaped particles of varying sizes is documented within the uppermost part of this stratigraphic unit. The group of land-derived sporomorphs is dominated by bisaccate pollen grains. The marine fraction reaches relative percentages of up to 7%. Prasinophytes of the genus *Cymatiosphaera* are predominant. The first significant plankton peak (18%) of acritarchs (*Micrhystridium* spp.) occurs within the Upper Gogolin Beds (Fig. 5). The palynofacies of this part of the succession is also characterized by a clear dominance of small,

Table 1 Classification and preservation potential of sedimentary organic matter (modified from Steffen and Gorin 1993 and Pittet and Gorin 1997) applied to Muschelkalk carbonates of southern Poland

Origin		Group	Constituent
continental	higher plant debris	phytoclasts	opaque phytoclasts
			translucent phytoclasts
	pollen	sporomorphs	pollen grains
	spores		spores
	degraded plant debris	degraded organic matter	
marine	degraded phytoplankton		
	marine phytoplankton		acritarchs
			prasinophytes
	foraminifera		foraminiferal test linings



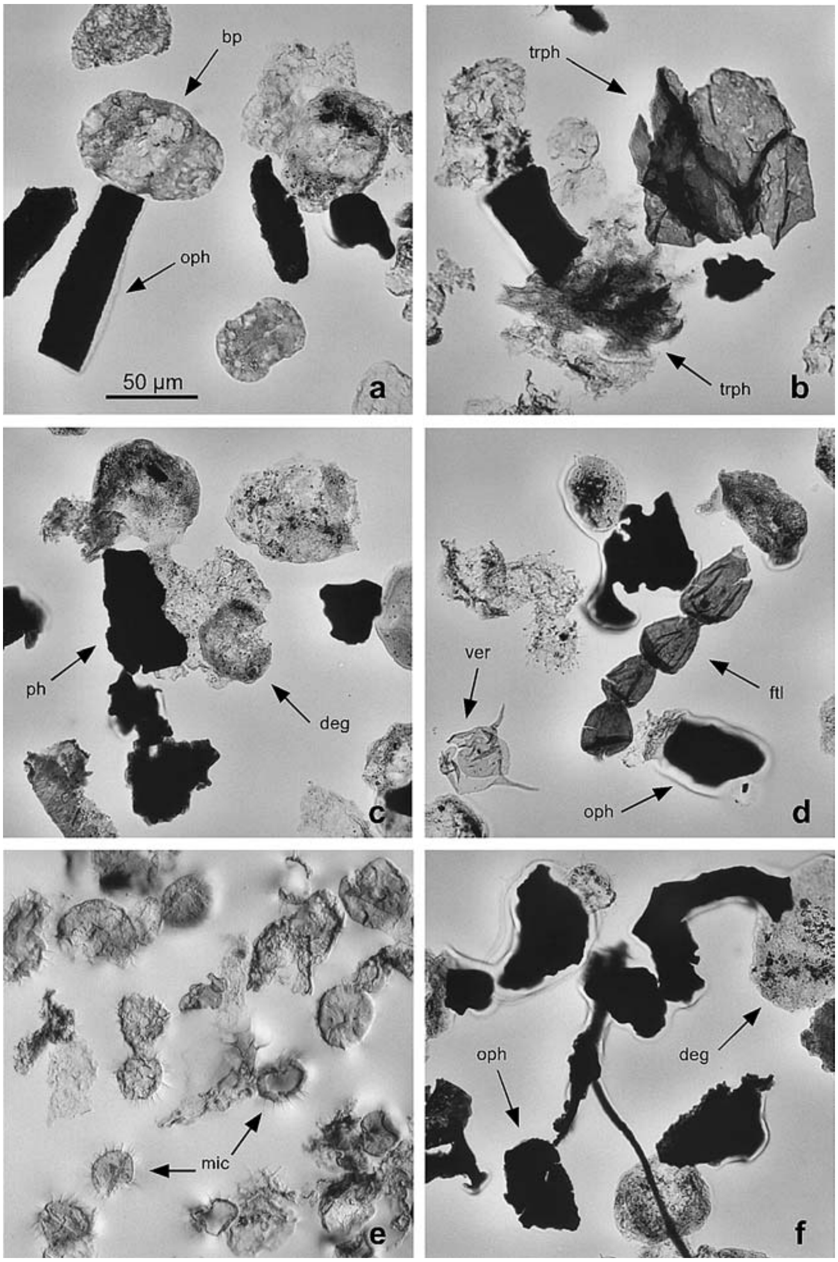


Fig. 6 Palynofacies and sequence stratigraphical interpretation of Anisian Muschelkalk deposits of southern Poland (Upper Silesia) **a** Uppermost part of the Lower Gogolin Beds (highstand deposits): highest amount of opaque, mainly blade-shaped phytoclasts (*oph*) and bisaccate pollen grains (*bp*). **b** Basal part of the Upper Gogolin Beds (transgressive deposits): high amount of translucent plant remains (*trph*) within the phytoclast group. **c** Gorazdze Beds (late highstand deposits): high amount of phytoclasts (*ph*) and degraded particles (*deg*). **d** and **e** Terebratula Beds (maximum flooding zone): maximum abundance of marine plankton (*ver Veryhachium* sp.; *mic Micrhystridium* sp.) and foraminiferal test linings (*ftl*), high amount of opaque, equidimensional woody fragments (*oph*). **f** Lower part of the Karchowice Beds (highstand deposits): high amount of opaque phytoclasts (*oph*) and degraded organic matter (*deg*)

equidimensional opaque fragments within the phytoclast group (67%). The marine fraction decreases again from the uppermost part of the Upper Gogolin Beds to the base of the Gorazdze Beds. Further upwards no palynomorphs are preserved; phytoclasts and degraded particles are the only organic components (Fig. 6c).

The Terebratula Beds represent the most marine interval of the studied succession. Maximum abundances of marine plankton (25%) and foraminiferal test linings (6%) occur within the Hauptcrinoidenbank (HB in Fig. 5), representing the most prominent palynofacies signature within the entire Anisian series (Fig. 6d, e). This bed is also characterized by a high amount of opaque, equidimensional phytoclasts, as documented by the high values of the OP/TR ratio (Fig. 5). Samples from the uppermost part of the Terebratula Beds show a clear decrease of the marine fraction.

The palynofacies of the overlying Karchowice Beds is dominated by opaque phytoclasts and degraded organic matter (Fig. 6f). Palynomorphs are preserved only in the basal part of this stratigraphic unit.

The described palynofacies patterns clearly reflect long-term sea-level fluctuations within the Anisian of southern Poland. Transgressive deposits of the lower Upper Gogolin Beds and lower Terebratula Beds were identified by an increase of marine particles and opaque, equidimensional woody fragments. Maximum abundance of these organic components indicates intervals of maximum flooding, which occurred in the upper part of the Upper Gogolin Beds and during the deposition of the Hauptcrinoidenbank (Fig. 5). Early highstand deposits, which are represented by the uppermost Gogolin Beds and the upper marly part of the Terebratula Beds, show a significant decrease of the marine fraction, whereas the amount of small, opaque plant debris is still high.

Sedimentary organic matter of the Gorazdze Beds and Karchowice Beds is poorly preserved due to reworking of coarse-grained carbonates in a highly oxidizing, proximal setting. Furthermore, the dominance of large, blade-shaped phytoclasts documents a regressive trend within the stratigraphic series. Therefore, these sediments may be interpreted as late highstand deposits (Fig. 5).

The palynofacies patterns of the investigated Anisian series thus support the sequence stratigraphic interpretation based on sedimentological investigations and stable isotope data of Szulc (1999, 2000). The major eustatic signal recognized within the Pelsonian Terebratula Beds is also documented in the Muschelkalk deposits of the central Germanic Basin (Götz and Feist-Burkhardt 2000a; Rameil et al. 2000), the western gate area (Götz and Feist-Burkhardt 2000b) and the adjacent shelf area of the Tethys Ocean (Götz et al. 2003). The phase of maximum flooding during the Bithynian is best indicated by pronounced plankton peaks in the eastern gate area of Upper Silesia (Upper Gogolin Beds) and the proximal shelf deposits of southern Hungary (Lapis Limestone). However, also within the Wellenkalk series of the intracratonic basin and the western gate area studied in Germany and Switzerland the marine fraction reaches a first significant maximum.

Conclusions

The Anisian carbonate series of southern Poland display stratigraphic variations of sedimentary organic matter related to relative sea-level changes. The relative abundance of marine plankton, the ratio of continental to marine particles and the ratio of opaque to translucent phytoclasts clearly reflect transgressive–regressive trends of a third-order scale. Major flooding phases are recognized in the upper Bithynian and Pelsonian.

Palynofacies data are in agreement with the isotopic signatures, displaying the eustatic history of the Silesian gate area. The maxima of the marine fraction coincide with the most positive intervals of the δ^{13}C curve that in turn fall within the maximum flooding zone of each of the defined third-order depositional sequences. Studying several indicators in parallel provides a cross-check of the dependability of them. In this case, the covariant trends seen in all compared indicators strongly support the basic correctness of the palaeooceanographical interpretation.

The presented example may serve as a model for an integrated sequence stratigraphical analysis carried out in a peripheral zone of an ocean domain.

Acknowledgements This study is part of a project on Lower Muschelkalk sequence stratigraphy supported by the Deutsche Forschungsgemeinschaft (project Fe 435/3–1). Joachim Szulc is grateful to the Alexander von Humboldt Foundation, Bonn for financial support. The constructive reviews by Gordon Forbes and Volker Vahrenkamp (Petroleum Development Oman, Muscat) are gratefully acknowledged. We thank Jeremy Young (The Natural History Museum, London) for many useful remarks on the manuscript and for adjusting the English text.

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