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Palynofacies patterns, acritarch diversity and stable isotope signatures in the Lower Muschelkalk (Middle Triassic) of N Switzerland: Evidence of third-order cyclicity

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Key words: palynofacies, acritarchs, stable isotopes, sea-level changes, Middle Triassic, Northern Switzerland

ABSTRACT

The Lower Muschelkalk of N Switzerland is characterised by a relatively monotonous succession of marly and dolomitic limestones with siltstone layers and thin sandstone beds. The studied Leuggern, Weiach and Benken wells comprise completely cored sections of the Lower Muschelkalk (Anisian). Due to the lack of characteristic marker beds and vertical facies changes, cyclic interpretation based on sedimentary features proves to be difficult. Therefore, palynofacies patterns, acritarch diversity and stable isotope signatures are used to detect eustatic signals related to relative sea-level changes. The major flooding phase is recognised in the Middle Wellenmergel (Pelsonian). It is characterised by maximum abundance of marine plankton and the highest amount of refractory opaque phytoclasts. Transgressive deposits are identified by a significant increase of marine constituents and a relatively high number of translucent woody fragments of the phytoclast group. Highstand deposits show a high terrigenous input of blade-shaped, opaque plant debris. Palynofacies of late highstand deposits is dominated by bisaccate pollen grains. This sequence stratigraphic break down allows correlation of the Swiss wells and their correlation with Anisian deposits of other parts of the Germanic Basin.

Acritarch diversity is analysed by a morphometric study on vesicle size, process length, process bifurcations, and the number of processes. These parameters correlate with the eustatic evolution during Anisian times as interpreted from palynofacies data. Vesicle size, process length and the percentage of specimens with bifurcated processes are seen to increase during transgression and intervals of maximum flooding. They are decreasing within highstand phases. The number of processes shows the opposite trend and is high during the late highstand. Stable isotope curves both of $\delta^{13}C$ and $\delta^{18}O$ point out two intervals of maximum flooding. These geochemical signatures correlate with the palynological data.

The example from the Middle Triassic of N Switzerland highlights the value of using organic facies and plankton associations in an integrated approach for reconstructing the eustatic history of an epeiric sea characterised by monotonous depositional series lacking significant sedimentary features.

ZUSAMMENFASSUNG

Der Untere Muschelkalk der Nordschweiz ist als relativ monotone Abfolge von Dolomiten und Mergeln mit siltigen Lagen und dünnen Sandsteinbänkchen ausgebildet. Die untersuchten Bohrungen Leuggern, Weiach und Benken haben vollständig gekernte Profile des Unteren Muschelkalk (Anis) geliefert. Eine zyklische Interpretation dieser Sedimente ist aufgrund fehlender Leitbänke und markanter Faziesvariationen schwierig. Daher wurden stratigraphische Veränderungen der Palynofazies und der Acritarchendiversität sowie geochemische Signaturen zum Erkennen eustatischer Signale herangezogen. Die maximale Überflutungsphase wurde im Mittleren Wellenmergel (Pelson) festgestellt. In diesem stratigraphischen Intervall sind die maximalen Häufigkeiten des marinen Planktons und der höchste Anteil an opaken Phytoklasten zu finden. Transgressive Ablagerungen lassen sich an einer deutlichen Zunahme mariner Komponenten sowie an einem relativ hohen Anteil durchscheinender Pflanzenreste aus der Gruppe der Phytoklasten erkennen. Hochstand-Ablagerungen zeigen einen erhöhten terrigenen Eintrag an opaken, meist länglichen Phytoklasten. Ablagerungen des späten Hochstand zeichnen sich durch einen hohen Anteil an bisaccaten Pollenkörnern aus. Die mit Hilfe der Palynofazies gewonnene sequenzstratigraphische Interpretation ermöglicht die Korrelation der Schweizer Bohrungen miteinander und ihre Korrelation zu anisischen Ablagerungen in anderen Teilen des Germanischen Beckens.

Die Acritarchendiversität wurde anhand der Vesikelgröße, der unterschiedlichen Fortsatzlängen und -verzweigungen und der Fortsatzanzahl untersucht. Diese Parameter scheinen mit der eustatischen Entwicklung während des Anis wie sie anhand der Palynofaziesdaten interpretiert wurde zu korrelieren. Vesikelgröße sowie Fortsatzlänge und -verzweigung zeigen eine deutliche Zunahme während transgressiver Phasen und im Bereich maximaler Überflutung. Eine Abnahme ist während der Hochstandphasen zu beobachten. Die Anzahl der Fortsätze lässt einen gegenläufigen Trend erkennen und ist während des späten Hochstands am höchsten. Sauerstoff- und Kohlenstoffisotopendaten der untersuchten Muschelkalkkarbonate dokumentieren ebenfalls eine zyklische Entwicklung des Ablagerungssystems. Anhand der $\delta^{18}O$ und $\delta^{13}C$ Kurven lassen sich zwei Intervalle maximaler Überflutung ableiten. Diese geochemischen Signale korrelieren mit den palynologischen Daten.

Am Beispiel des Unteren Muschelkalks der Nordschweiz wird deutlich, dass die integrierte Analyse von organischer Fazies und Planktonassoziationen ein aussagekräftiges Werkzeug zur Interpretation der eustatischen Entwicklung eines epikontinentalen Randmeeres mit sedimentologisch monotonen Ablagerungsserien darstellt.

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1. Introduction

The Lower Muschelkalk (Anisian) of N Switzerland is little known due to the lack of well-exposed outcrop sections. The studies of Schwarz (1970, 1975) focused on Muschelkalk series of SW Germany. He described outcrop sections from Francony, Swabia, and the southern part of the Black Forest and presented a facies model for these deposits. Paul (1971) gave an overview of the Muschelkalk succession exposed in the Wutach region. Becker et al. (1997) described a completely cored Lower Muschelkalk succession from the SE margin of the Black Forest. Up to now, the knowledge of the Anisian of the southwestern part of the Germanic Basin is mainly based on these works.

The drilling programme of the NAGRA (National Cooperative for the Disposal of Radioactive Waste) provided numerous cores in the northern part of Switzerland including sediments of Anisian age. These Muschelkalk series represent key sections for the interpretation of the palaeogeographical evolution of the northern Peri-Tethyan realm during Middle Triassic times. In the present study, palynofacies, acritarch diversity and stable isotope signatures of the Lower Muschelkalk of the Leuggern, Weiach and Benken wells (Fig. 1) were studied with respect to relative sea-level changes. The data presented below are used for palaeoenvironmental and sequence stratigraphic interpretation of the Muschelkalk series of N Switzerland.

2. Materials and methods

The studied wells from Leuggern, Weiach and Benken provide completely cored sections of the Lower Muschelkalk. The sections are characterised by a relatively monotonous succession of marly, dolomitic limestones with intercalated thin sandstone beds. A detailed description of these wells, the lithology and facies of the Middle Triassic sediments is found in Matter et al. (1988), Peters et al. (1989) and NAGRA (2001). Palynofacies analysis was carried out on a total of 69 samples from the three wells. All samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for dissolution of carbonates and silicates, and saturated $ZnCl_2$ solution ($D \approx 2,2$ g/ml) for density separation. Residues were sieved at 15 µm mesh size. Slides have been mounted in Eukitt, a commercial, resin-based mounting medium. The relative percentages of sedimentary organic constituents are based on counting at least 400 particles per slide.

Acritarch diversity was analysed by a morphometric study on vesicle size, process length, process bifurcations, and number of processes. 11 samples from the Benken well were studied, where acritarch abundance allowed for a statistically significant analysis of at least around 50 specimens. A total of 904 specimens was measured, between 48 and 110 per slide.

Carbon and oxygen stable isotope data from 20 bulk samples of the Benken well were determined by measurements with a mass spectrometer SUMY. Stable isotope ratios refer to the V-PDB standard. We measured pure calcite samples except the dolomitized carbonates of the upper Orbicularis-Mergel and lowermost Middle Muschelkalk.

3. Geological setting

During Triassic times, the Germanic Basin was a peripheral basin of the western Tethys Ocean, the so-called Northern Peri-Tethys (Szulc 2000). The basin was bordered by landmasses and open to the Tethyan shelf by tectonically controlled gates in

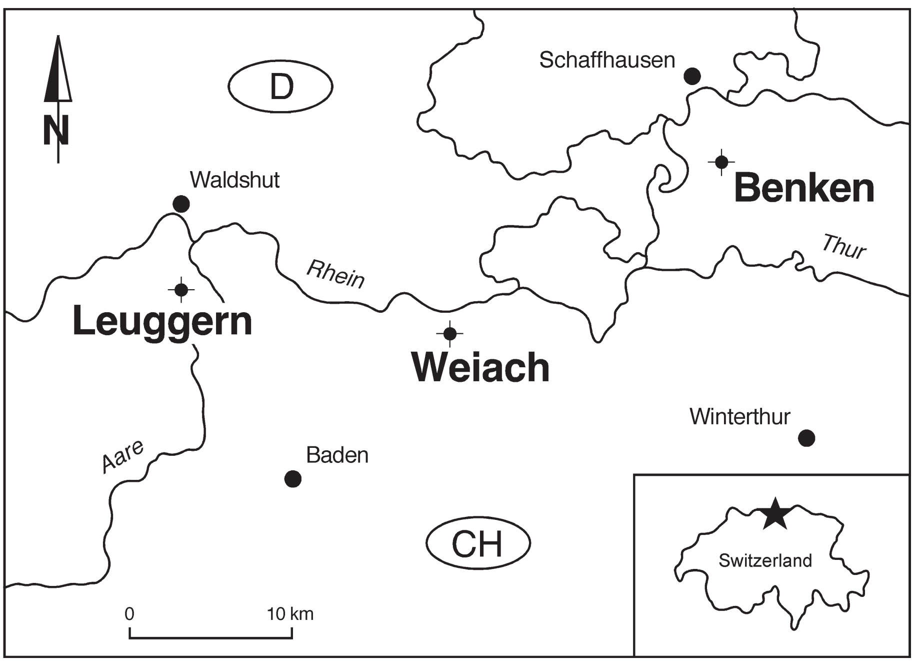

Fig. 1. Location of the study area in northern Switzerland.

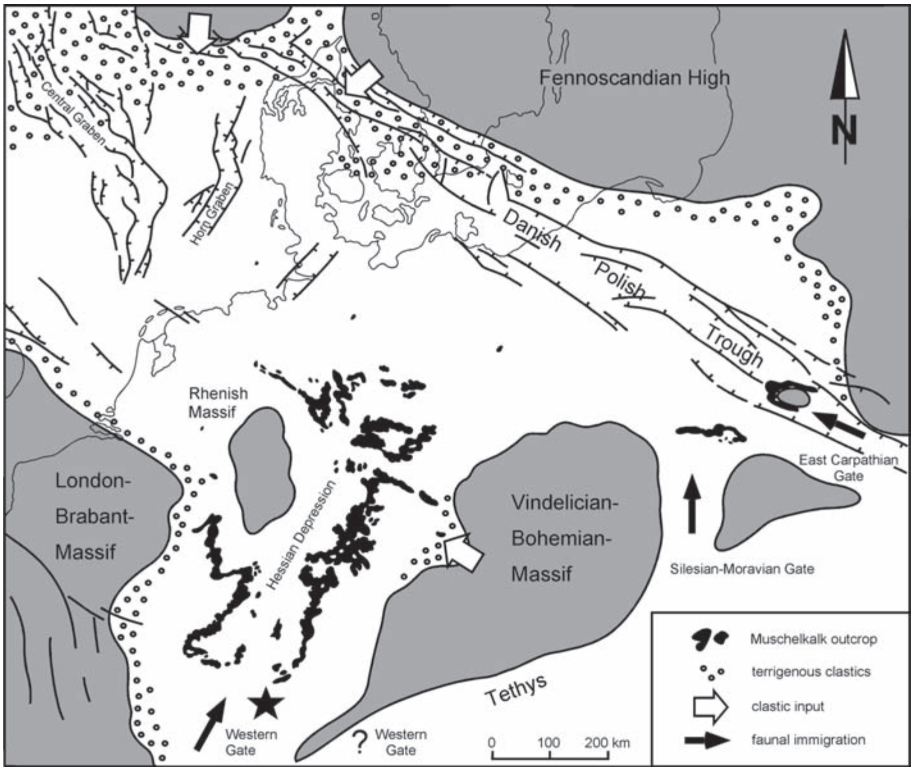

Fig. 2. Palaeogeography of the Germanic Basin during Anisian times (modified from Ziegler 1990 and Szulc 1999) and position of a western gate under discussion. Star indicates location of the study area.

the south (Fig. 2). The East Carpathian Gate was already active in the late Induan, the Silesian Gate opened in the Olenekian (Szulc 2000) and the western communication to the Tethys developed during the Anisian. The semi-closed situation of the basin and the diachronous communication with the Tethys Ocean resulted in a distinctive facies differentiation between the western and eastern parts of the basin. While in the Silesian and Carpathian domains the early Anisian is already represented by carbonates, the central and western areas were still dominated by Röt facies. In the eastern subbasin open marine sedimentation continued during almost the entire Anisian, while the western part experienced restricted circulation. This is documented in dolomitic series with evaporitic units in SW Germany and N Switzerland.

The Lower Muschelkalk of N Switzerland represents Anisian shallow-water deposits of the SW part of the Germanic Basin. The relatively monotonous succession of marly and dolomitic limestones reaches a thickness of up to 50 m and is subdivided into three lithostratigraphic units: Wellendolomit, Wellenmergel and Orbicularis-Mergel (Fig. 3). Dolomitic limestones of the lower Wellendolomit are overlain by silty marlstones and siltstones with intercalated bioclastic beds of the upper Wellendolomit and Wellenmergel. An erosional surface in the middle part of the Wellendolomit unit is most prominently developed in the Leuggern well (201.5 m). Crinoidal limestone beds were recognized in the lower and middle Wellenmergel only in the Leuggern (192–194 m, 177–180 m) and Weiach (971 m, 958–960 m) wells. Also the *Spiriferina* Bed, a marker bed in the Anisian of SW Germany, was only identified in these two wells (Leuggern 177.32–177.74 m; Weiach 957.69–958.39 m). Bläsi (in NAGRA 2001) points out the problem of identifying the *Spiriferina* Bed in the Benken well. A bioclastic siltstone bed in the uppermost Wellenmergel of the Leuggern (168 m) and Weiach (951.5 m) wells is characterised by an erosional base. Upsection a ca. 2 m thick evaporitic interval marks the lower part of the Orbicularis-Mergel, overlain by marlstones. The next dolomitic limestones represent the basal part of the Middle Muschelkalk (Matter et al. 1988; Peters et al. 1989; NAGRA 2001).

The biostratigraphical framework of the Anisian in N Switzerland is still very poorly constrained. During the course of the present study, we found conodonts (e.g. *Neohindeodella* spp., *Neogondolella bulgarica, Nicoraella kockeli)* in the Benken and Leuggern wells (Götz & Gast 2007). These are the first findings of conodonts in the Lower Muschelkalk of N Switzerland. The first appearance of *Nicoraella kockeli* allows identification of the Bithynian/Pelsonian boundary in the upper part of the Wellendolomit.

4. Palynofacies analysis

Palynofacies describes the total acid-resistant organic matter content of sedimentary rocks within a specific depositional environment (Combaz 1964). The study of sedimentary organic matter involves the identification of palynomorphs, plant debris, and amorphous organic particles, their absolute and relative proportions, size spectra, and preservation states (Combaz

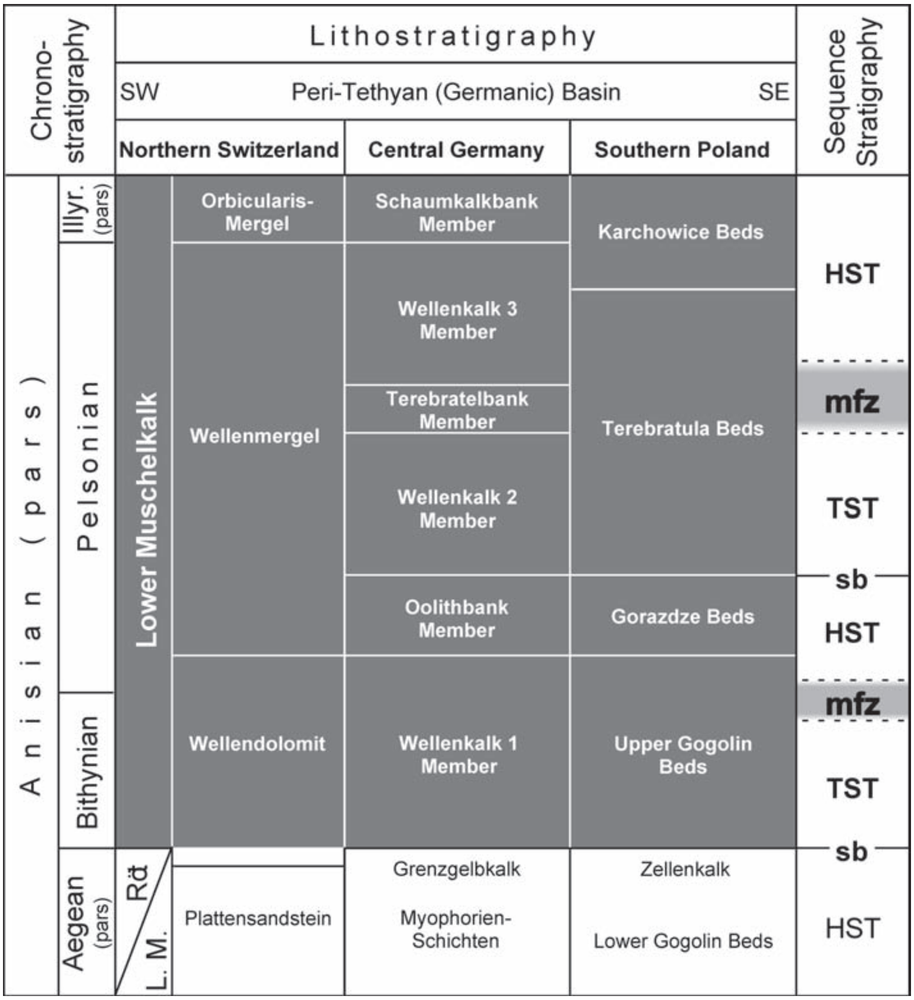

Fig. 3. Lithostratigraphy of the Swiss Lower Muschelkalk and its correlation based on the present study with the central (Germany) and eastern part (Southern Poland, Silesia) of the Germanic Basin. Correlation between Germany and Poland from Götz et al. (2005). L.M. Lower Muschelkalk, TST transgressive systems tract, mfz maximum flooding zone, HST highstand systems tract, sb sequence boundary.

1980). Distribution patterns of organic particles in stratigraphic series and their interpretation in a sequence stratigraphic context were outlined by Tyson (1995). In the present study, stratigraphic variations in the distribution of sedimentary organic matter are 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 foraminiferal test linings (Fig. 4). Since foraminiferal test linings are extremely rare in the studied sections and barely enter the counts, the marine fraction corresponds almost entirely to marine plankton. The relative percentages of these components are based on counting at least 400 particles per slide.

Three palynofacies parameters were calculated to characterise 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 the distance to the coastline, water depth, temperature, salinity, and nutrient availability. (2) *The ratio of continental to marine particles (CONT/MAR ratio).* Composition and relative abundance of the continental fraction display the hinterland vegetation and the source distance. Stratigraphic variations of 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 & Gorin 1998). For the sake of clarity, this parameter is plotted as the log (CONT/MAR). (3) *The ratio of opaque to translucent phytoclasts (OP/TR ratio).* Opaque phytoclasts partly consist of charcoal originating from forest fires, but mainly form 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 & Gorin 1997; Bombardiere & 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 & Riddick 1986; Bustin 1988; Tyson 1993), enhanced by the high porosity and permeability

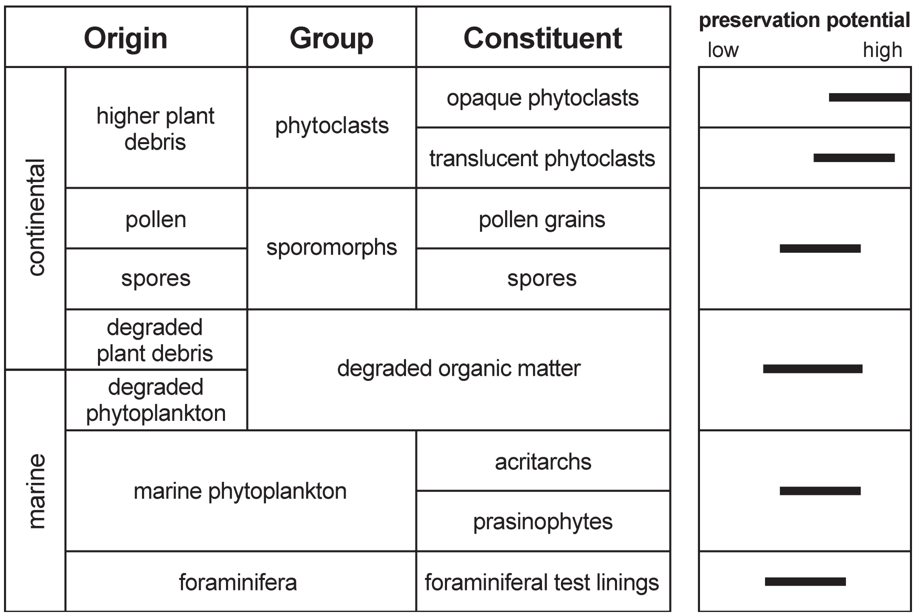

Fig. 4. Classification and preservation potential of sedimentary organic matter (modified from Steffen & Gorin 1993 and Pittet & Gorin 1997) applied to Muschelkalk carbonates of northern Switzerland.

of coarse-grained sediments (Tyson 1993; Rameil et al. 2000). 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 & Gorin 1993). In addition, proximal assemblages show a greater variety of particle sizes (Tyson 1993; Tyson & Follows 2000).

4.1. Palynofacies patterns of the Lower Muschelkalk in the Leuggern, Weiach and Benken wells

Palynofacies of the Wellendolomit is characterised by a high amount of terrigenous particles. Phytoclasts of higher land plants are the most common constituents. The group of land-derived sporomorphs is dominated by bisaccate pollen grains (Fig. 5). The marine fraction is composed almost entirely of marine plankton (acritarchs and prasinophytes), with foraminiferal test linings being rare and barely entering the counts. The values for the parameters relative abundance of plankton and log (CONT/MAR) are therefore approximately inversely proportional. In the Wellendolomit the marine plankton reaches relative percentages of up to 5%. Acritarchs of the genus *Micrhystridium* are predominant. A first significant plankton peak occurs within the lower Wellenmergel, which appears most clearly in the Leuggern well (Fig. 6, samples 8, 9). The palynofacies of this part of the succession is also characterised by a dominance of small, equidimensional opaque fragments in all studied sections. The marine fraction decreases again within a short interval of the Wellenmergel unit. The major eustatic signal is documented in the middle part of the Wellenmergel by maximum abundance of marine plankton (24%), representing the most prominent palynofacies signature within the entire Anisian succession. This stratigraphic interval is also characterised by a high amount of opaque, equidimensional phytoclasts, as documented by the high values of the OP/TR ratio. Samples from the uppermost part of the Wellenmergel show a clear decrease of the marine plankton, whereas the ratio of opaque to translucent phytoclasts is still high. Palynofacies of the overlying Orbicularis-Mergel is dominated by continental particles. Translucent plant debris is quite abundant within the phytoclast group. Marine constituents are nearly absent.

The described stratigraphical changes in the composition of sedimentary organic matter clearly display long-term sea-level fluctuations within the Anisian of northern Switzerland. Transgressive deposits of the upper Wellendolomit and middle Wellenmergel were identified by an increase of marine plankton and opaque, equidimensional woody fragments. Maximum abundance of these organic components indicates intervals of maximum flooding that occurred in the lower and middle part of the Wellenmergel. Early highstand deposits, which are represented by the upper Wellenmergel, show a significant decrease of marine particles, whereas the amount of small, opaque plant debris is still high. The Orbicularis-Mergel document restricted conditions with deposition of evaporites. Marine plankton is nearly absent. Furthermore, the dominance of large, blade-shaped phytoclasts documents a regressive trend within the stratigraphic series. Therefore, these sediments are here interpreted as late highstand deposits.

In the epeiric setting studied, we expect sequence boundaries to be only weakly expressed by sedimentary structures, or not documented at all. Lowstand deposits are not documented in this setting at all. Sedimentary signatures that can be indicators for sequence boundaries, such as erosional surfaces and/or reworked lithoclasts, were found in the middle part of the Wellendolomit and in the uppermost part of the Wellenmergel.

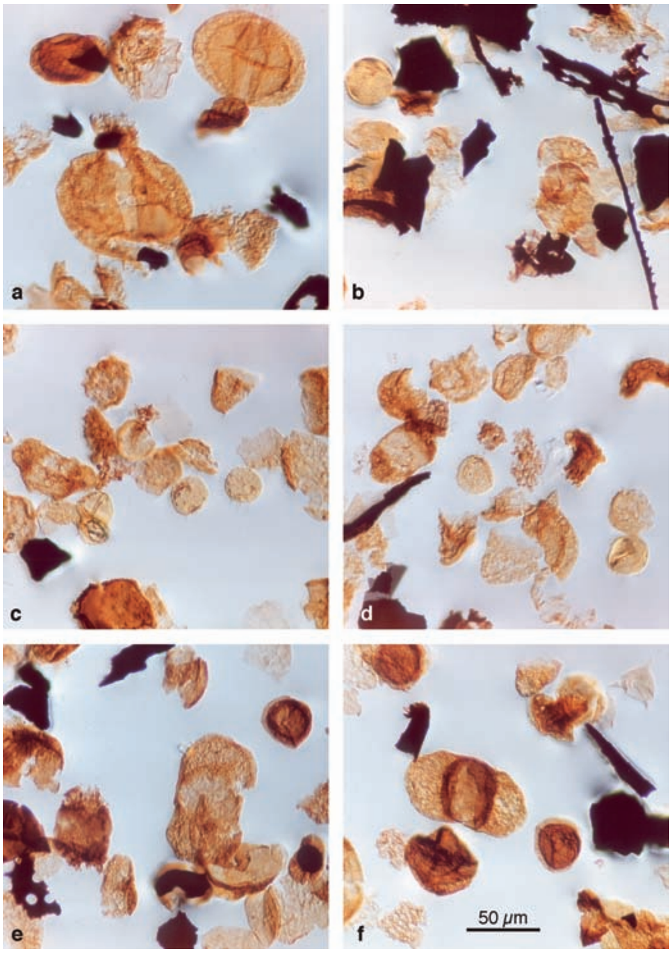

Fig. 5. Palynofacies and sequence stratigraphical interpretation of Anisian Muschelkalk deposits of N Switzerland; examples from the Benken well. a) Orbicularis-Mergel, late highstand systems tract (lHST), sample 19. Highest amount of pollen grains. b) Upper Wellenmergel, early highstand systems tract (eHST), sample 14. Strong terrestrial influx of wood and plant remains. c) Middle Wellenmergel, maximum flooding zone (mfz), sample 10. Maximum abundance of marine plankton (*Micrhystridium* spp.). d) Middle Wellenmergel, maximum flooding zone (mfz), sample 9. e) Lower Wellenmergel, transgressive systems tract (TST), sample 5. High amount of pollen grains, spores are rare. f) Wellendolomit, transgressive systems tract (TST), sample 3.

From this sedimentological evidence alone, the interval could be interpreted as one third-order depositional sequence, but integration of palynofacies data into the sequence interpretation enables us to discriminate two depositional sequences, with the following sequence boundary situated higher up in the succession of the Middle Muschelkalk. Using the sedimentological features alone, position of this sequence boundary could arguably be placed near the base of the Orbicularis-Mergel at one of the beds with erosional structures. This interpretation is rejected as the evaporites and marlstones of the Orbicularis-Mergel and the basal Middle Muschelkalk clearly show no transgressive, but a regressive palynofacies signature. Interpretation of these sediments as late highstand deposits seems therefore the most appropriate.

Identification of two depositional sequences in the Swiss Lower Muschelkalk by means of palynofacies analysis compares well with other Anisian series of the Peri-Tethyan realm (Central Germany, Southern Poland), where there is evidence for also two Anisian depositional sequences (An2, An3) in this interval (Szulc 2000). The most prominent marine signature is documented by maximum abundance of marine plankton in the middle Wellenmergel corresponding to the deposition of crinoidal limestones and the *Spiriferina* Bed (Leuggern, Weiach). Even though this marker bed was not identified in the Benken well (NAGRA 2001), the plankton peak within this stratigraphical interval (963–956 m) enables a precise correlation of this maximum flooding zone.

The major eustatic signal recognized within the middle part of the Wellenmergel is also documented in Anisian Muschelkalk deposits of the central Germanic Basin (Götz & Feist-Burkhardt 1999, 2000; Rameil et al. 2000), the eastern gate area (Götz et al. 2005) and the adjacent shelf area of the Tethys Ocean (Götz et al. 2003). In all those areas, maximum flooding is marked by brachiopod shell beds. This supports the hypothesis of a connection between the Peri-Tethyan realm and the Tethys Ocean during Pelsonian times as interpreted from sedimentary and facies signatures (Szulc 2000). 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 central basin (upper Wellenkalk 1 Member) and the western gate area (uppermost Wellendolomit/lower Wellenmergel) studied in Germany and Switzerland the marine fraction reaches a first significant maximum.

The low abundances of acritarchs in the lowermost and the upper part of the studied section with values of <5% must be interpreted very carefully from the statistical point of view. As discussed by Traverse (1988, p. 490) at a counting rate of 500 particles per slide, the standard deviation for a component of 5% (i.e. 25 counts) is 20% if two-thirds of all runs are supposed to be within the interval of doubled standard deviation. Thus, accuracy of the 5%-component is 5 ± 1% (i.e. 25 ± 5 counts). If only 200 particles are counted in a slide, standard deviation of the 5%-component increases to 32% and accuracy decreases to 5 ± 1.6% (i.e. 10 ± 3 counts). In this case, for fluctuations in relative abundance of components that are below the 5%-limit, only a small statistical evidence is left (Tyson 1995, p. 433). It is therefore that rather than interpreting discrete values, we used the stratigraphical trends of change in palynofacies composition for the analysis and correlation of the studied sections.

5. Acritarch diversity

Middle Triassic acritarchs, as compared to the Palaeozoic, are not very diverse and mainly consist of species of the two genera *Veryhachium* and *Micrhystridium* (Strother 1996; Götz & Feist-Burkhardt 1999, 2000). The acritarch assemblages of the Muschelkalk deposits from N Switzerland are dominated by mor-

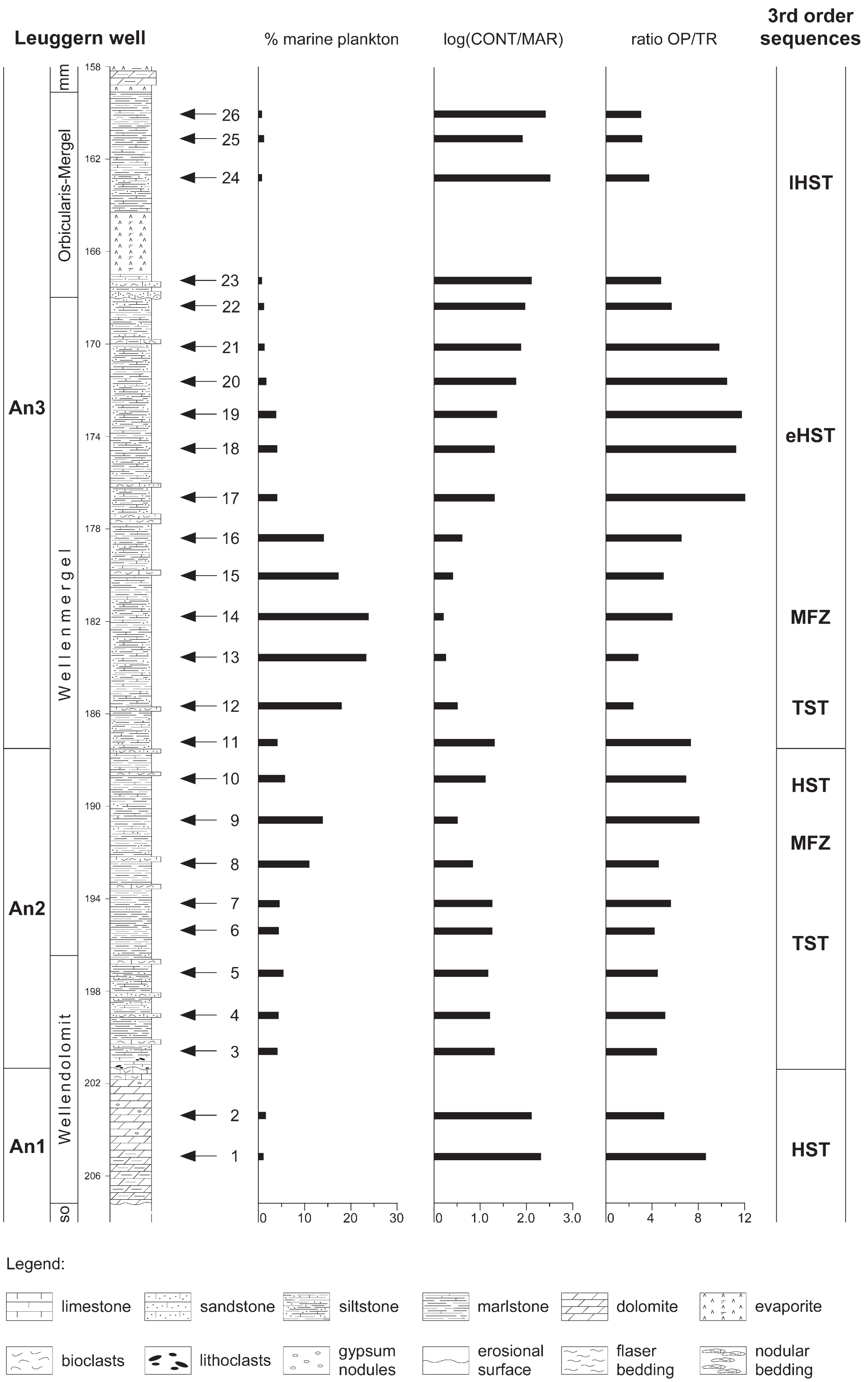

Fig. 6. Stratigraphy, palynofacies patterns, and third-order depositional sequences of the Lower Muschelkalk (Anisian, An2-An3) of the Leuggern well. Lithological legend for Figures 6, 7, 8, and 10. TST transgressive systems tract, mfz maximum flooding zone, HST highstand systems tract, eHST early highstand systems tract, lHST late highstand systems tract.

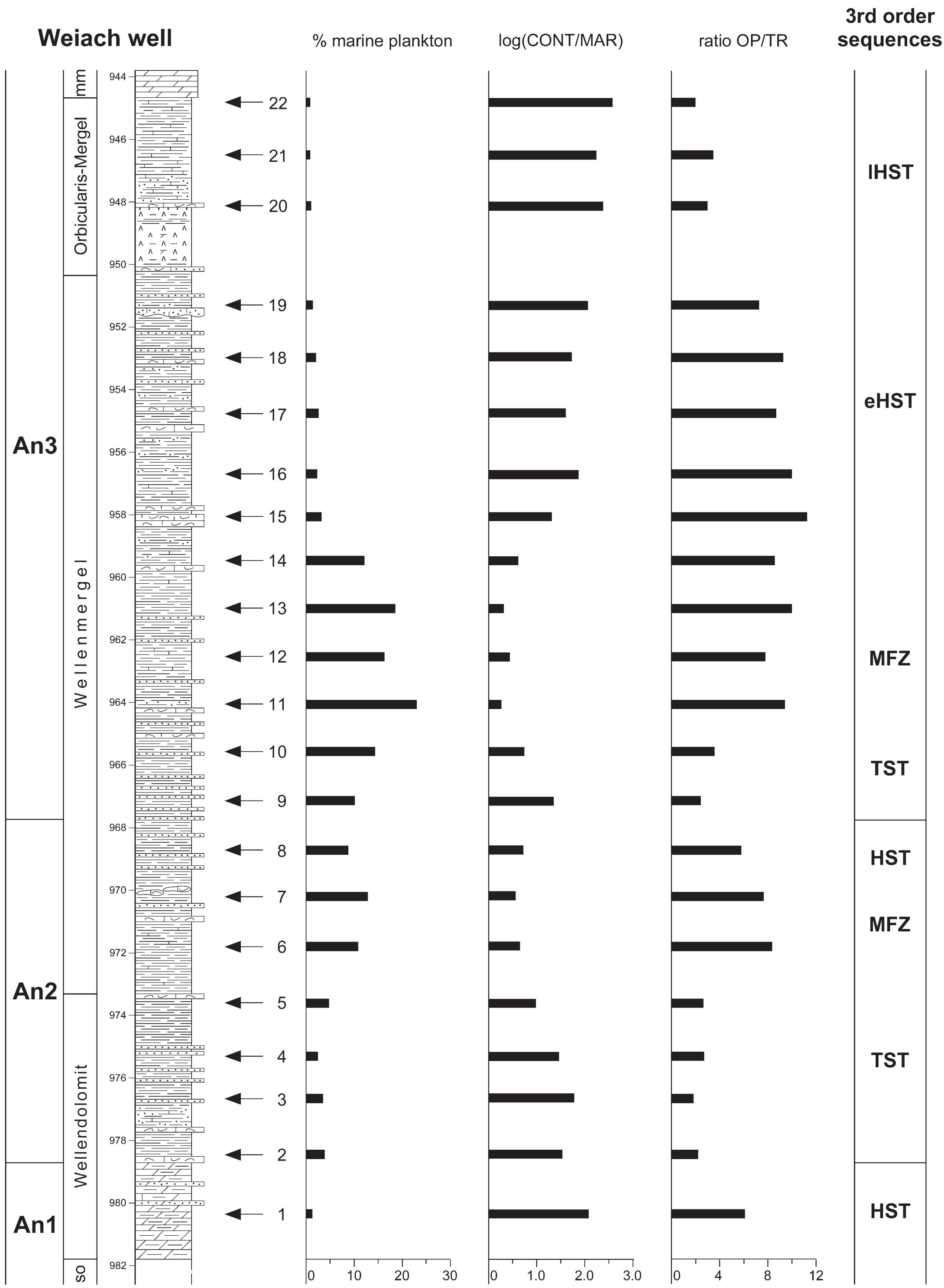

Fig. 7. Stratigraphy, palynofacies patterns, and third-order depositional sequences of the Lower Muschelkalk (Anisian, An2-An3) of the Weiach well. For legend see Figure 6.

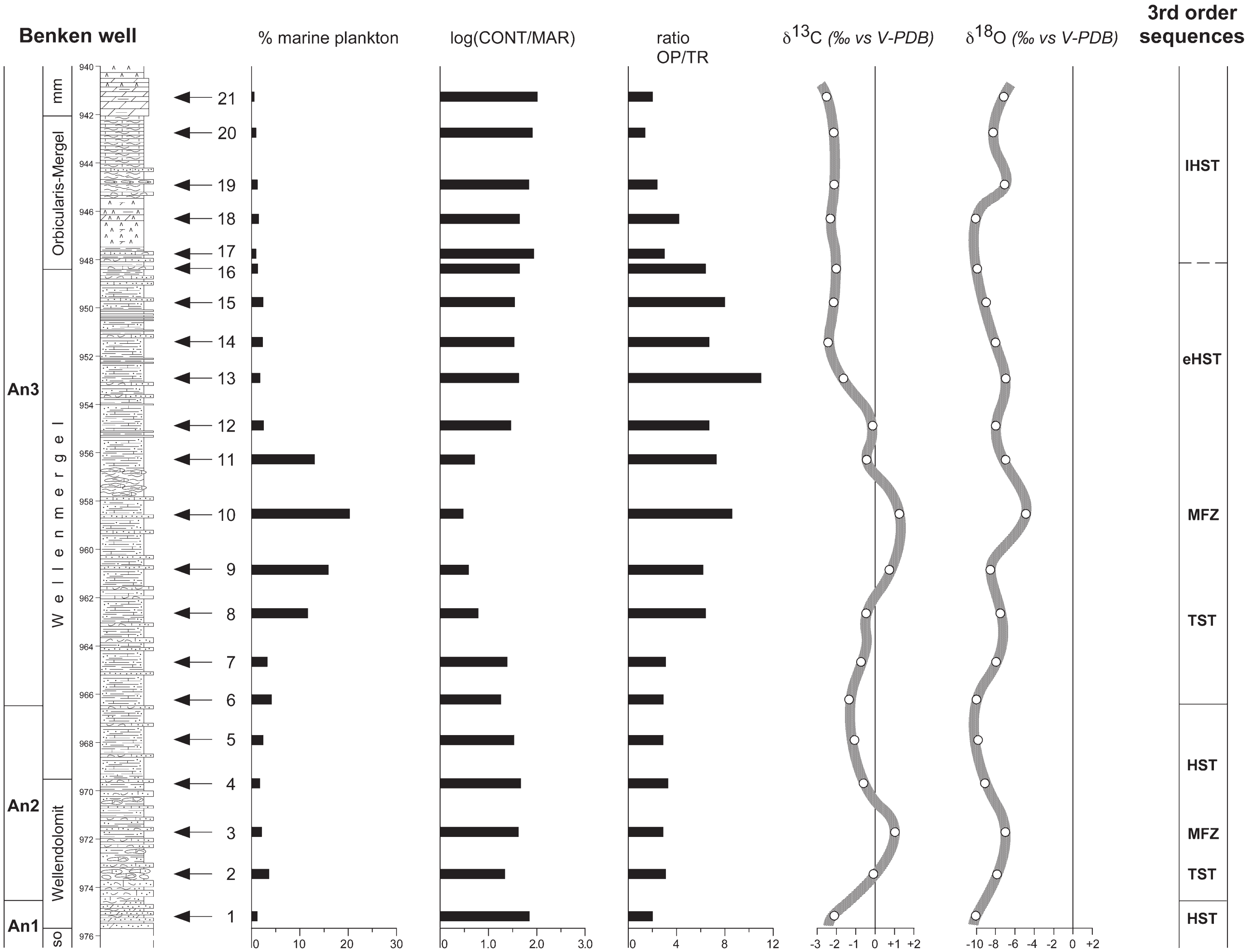

Fig. 8. Stratigraphy, palynofacies patterns, stable isotope signatures, and third-order depositional sequences of the Lower Muschelkalk (Anisian, An2-An3) of the Benken well. For legend see Figure 6.

photypes that can be attributed to the genus *Micrhystridium* (Fig. 9). This genus circumscribes relatively simple forms, characterised generally by a single-walled, small, spherical vesicle with numerous hollow or solid processes. Processes are usually simple, distally closed and may flare proximally. Within this definition, a wide variety of forms is encountered. Combination of the characters vesicle size, number, size and shape of processes, has therefore led to the definition of a high number of species (e.g. Wall 1964; Fensome et al. 1990) that are in practice difficult to identify and probably to quite some extent arbitrary.

The palynofacies analysis of the Muschelkalk sediments from the Swiss wells revealed a high amount of acritarchs, and their abundance pattern show a relationship to the sequence stratigraphic interpretation of the sections. As the encountered micrhystrid acritarchs show a wide variety of morphologies, we initiated a morphometric study on these morphotypes for testing if their morphological variety is related to the palaeoenvironmental changes represented by the sequence stratigraphic trends (Russell 2003). The acritarch assemblages of the Middle Triassic are indeed an ideal object for such a study. As explained above, unlike Palaeozoic assemblages where the number of acritarch groups present in any one assemblage is much higher, study of the Middle Triassic acritarchs is limited to just one group, the micrhystrid acritarchs. The Middle Triassic Lower Muschelkalk is also an ideal succession because of the almost continuous sediment record, the relatively uniform lithology, and the relatively short time interval it corresponds to. The Lower Muschelkalk has been deposited in only about 3 mio years (Gradstein et al. 2004; Menning et al. 2005) during which we would not expect phylogenetical changes to have influenced the acritarch floras to a significant extent. Details of that study including discussion of the population dynamics

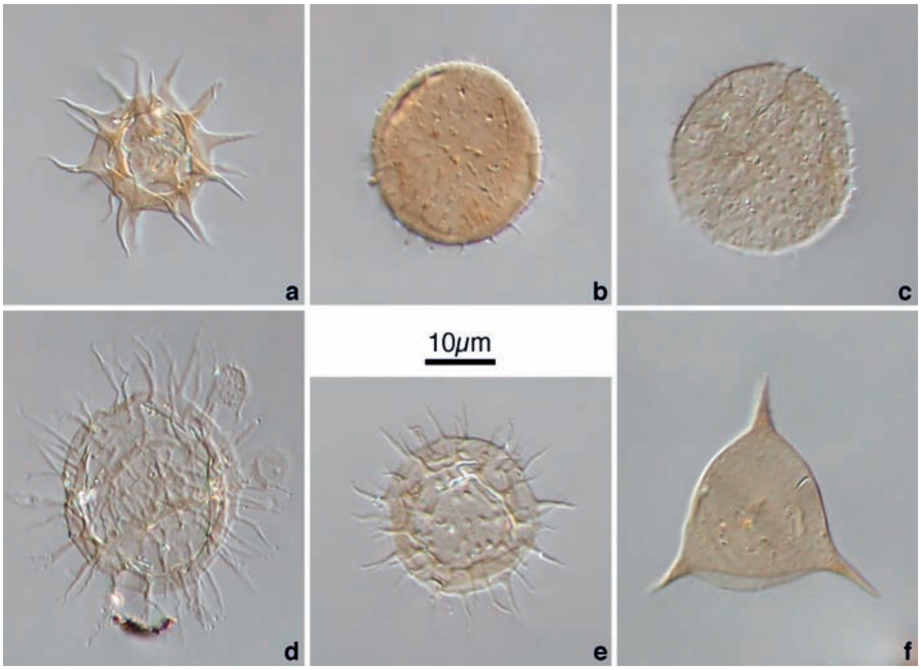

Fig. 9. Selection of acritarchs from the Lower Muschelkalk of the Benken well, N Switzerland, showing the variety of morphotypes encountered. a) *Micrhystridium stellatum* Deflandre 1945. Species with hollow processes that flare at the base and communicate freely with the vesicle cavity. Sample 12, slide Ben12-o-2, ref. 14.2*79.6. b) *Micrhystridium* sp. Specimen with numerous short processes that are thickened or plugged at the base. Sample 6, slide Ben 6-o-1, 18.0*92.1. c) *Micrhystridium* sp. Specimen with numerous, very short, conical processes. Sample 9, slide Ben 9-o-1, 18.4*97.3. d) *Micrhystridium* spp. One large specimen with numerous long, hollow processes, some of them having bifurcations, and two very small specimens (at 2 o'clock). Sample 3, slide Ben 3-o-1, 16.3*85.1. e) *Micrhystridium* sp. Specimen with numerous hollow processes. Sample 13, slide Ben 13-o-1, 8.3*80.2. f) *Veryhachium reductum* (Deunff 1959) Downie & Sarjeant 1965. Sample 5, slide Ben 5-o-2, 6.9*85.1.

and palaeobiological implications shall be published elsewhere (Feist-Burkhardt et al., in prep.).

For the morphometric analysis, all those samples from the Benken well were studied that yielded enough specimens (about 50) to warrant statistical significance. From all the different parameters measured, those that show significant trends are (1) the average vesicle size, (2) the average process length, (3) the percentage of specimens with bifurcated processes, and (4) the density of the process cover expressed as the number of processes per 25 μm^2. The values for these parameters are plotted next to the log and the sequence stratigraphic interpretation of the section in Figure 10.

5.1. Morphological changes of micrhystrid acritarchs in the Benken well

The average vesicle size, process length and the percentages of specimens with bifurcated processes change through the succession in the same direction. Their values are higher in those samples interpreted to belong to the mfz, and generally lower in-between. The average number of processes generally shows an opposite trend (Fig. 10).

The highest values for average vesicle size are between 25.8 µm and 26.5 µm found in the samples 3, 9 and 11 that are interpreted to correspond to the mfz. The smallest vesicle size is noted in sample 17 (lHST) with an average of only 17.2 µm.

Average process length is biggest in sample 3 (mfz) with 5.15 µm, decreases to 2.7 µm and 2.32 µm in samples 5 and 6, and increases again in samples 8 to 12 with a maximum of 4.85 µm in sample 10 (mfz). Sample 17 (lHST) shows the lowest value for average process length of 2.28 µm. Also when plotting process length as a percentage of the vesicle diameter, we note the same trend. A peak in sample 3 (20.1%, mfz) is followed by a decrease in samples 5 and 6 (12.9%, 11.9%). Then we observe a steady increase from sample 8 to 12 with values of 14.1% to 24.2%, and finally a decrease to 15% in sample 17 (lHST).

The percentage of those acritarchs with bifurcated processes is generally low in the lower samples of the succession, reaching just 5% in sample 3 (mfz). In samples 8 to 11 of the mfz the percentage is high and increasing, with values between 10% and 20% and a maximum of 21% in sample 11. Percentage then sharply drops to 0% in sample 12, stays low in sample 13 (6.1%) and drops to 0% again in sample 17.

Whereas the previous parameters show maxima or an increase in the samples of the mfz, the process density on the acritarch vesicle, expressed as the number of processes per 25 μm^2, shows generally an opposite trend. Values are relatively high in the lower samples of the succession (samples 2 to 6) with average numbers of 6.2 to 8.1. They decrease in the samples of the mfz (samples 8 to 11) to 4.8 to 5.5, are still low in samples 12 and 13 (eHST) and increase strongly to 9.7 in sample 17 that is interpreted as the lHST.

5.2. Palaeoenvironmental interpretation

The observed change of morphological diversity of micrhystrid acritarchs through the succession correlates well with the sequence stratigraphic interpretation and strongly suggests to be related to the change of depositional environment. Changes of morphological diversity can either be the reflection of a change in species composition of the assemblage, meaning proper species diversity changing in response to palaeoenvironment, or

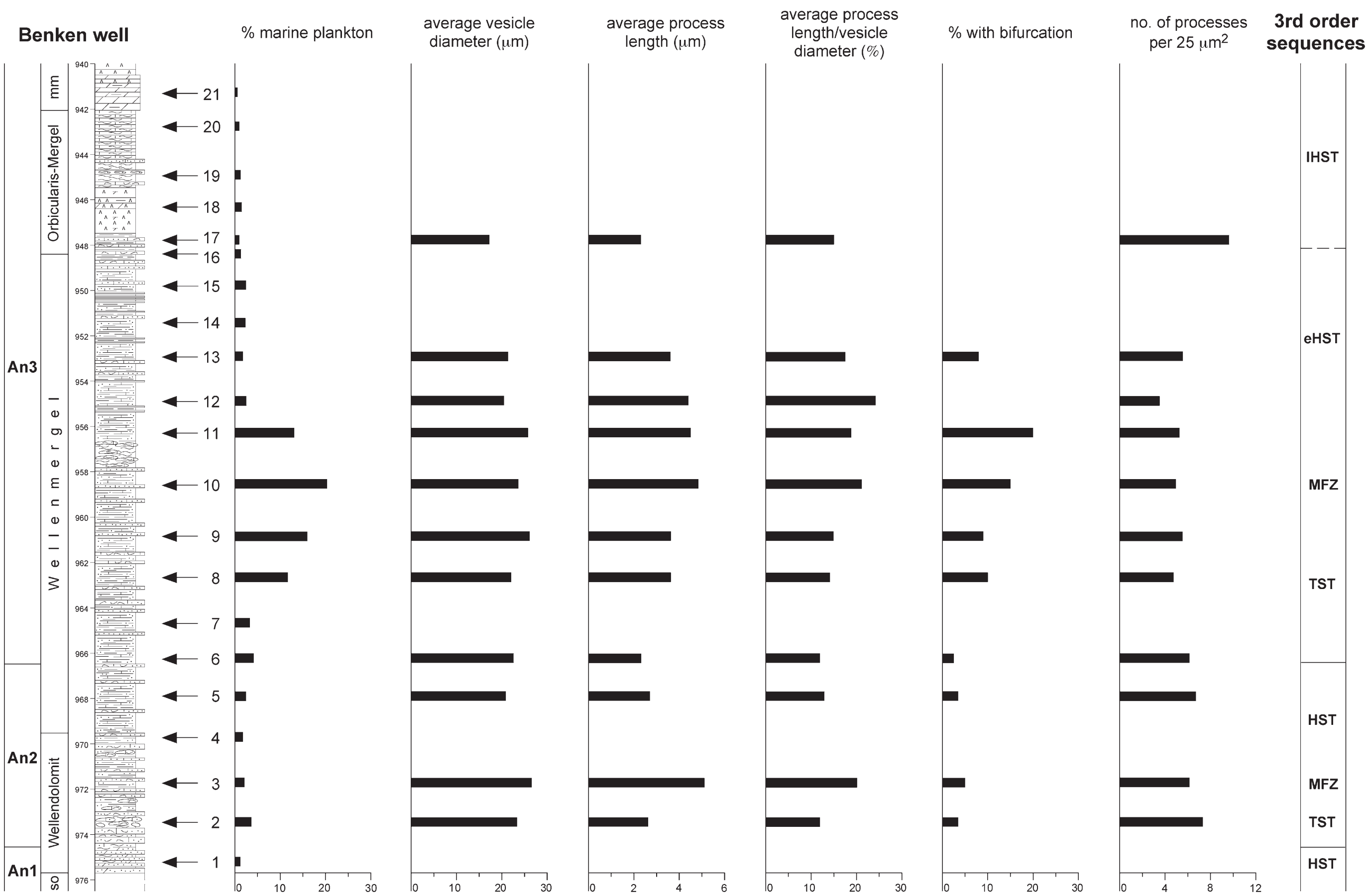

Fig. 10. Relative abundance of marine plankton and acritarch morphometric data (average vesicle diameter, average process length, average process length/vesicle diameter, percentage of specimens with bifurcated processes, and number of processes per 25 μm^2) in relation to the third-order depositional sequences of the Lower Muschelkalk of the Benken well. For legend see Figure 6.

it can be caused by ecophenotypy, the environmentally controlled morphological plasticity of a biological species.

Among the earliest, pioneering studies dealing with acritarchs and palaeoenvironment are those of Staplin (1961) and Wall (1965). Staplin (1961) described Late Devonian acritarchs from sediments associated to a reef complex in Canada and observed different acritarch associations depending on the distance from the reef complex. The study of Wall (1965) is one of the most-cited references in this context. He studied organic-walled microplankton from the Lower Jurassic of Britain and concluded that the stratigraphic distribution of acritarchs in these sediments is environmentally controlled. He observed acanthomorph acritarchs (*Micrhystridium* sensu lato) to prefer relatively inshore, but basinal environments, whereas polygonomorph (*Veryhachium*) and netromorph acritarchs (i.e. *Leiofusa*) favoured an open-sea environment. He also observed that proximal assemblages are dominated by one species, whereas offshore assemblages are more heterogeneous and species rich. In those and similar later studies (for a recent example see e.g. Stricanne et al. 2004, and references therein), the encountered variety of microplankton morphological types was interpreted to represent species diversity. There is, however, more and more evidence from recent studies that this kind of morphological diversity may be due to morphological plasticity.

Current research on the formation of organic-walled cysts in modern dinoflagellates (e.g. Hallett & Lewis 1996; Lewis et al. 1999; Hallett 2000) has shown that considerable morphological variation can be produced by a single biological species, depending on culture conditions such as salinity and temperature. These results from culture experiments are most relevant to the interpretation of fossil organic-walled microplankton assemblages and have been discussed with regard to acritarchs for the first time by Servais et al. (2004). These authors analysed the acritarchs of six samples from a 35 m thick marine section across the Cambrian/Ordovician boundary from a borehole in Algeria and found very similar results to those observed in the present study of the Middle Triassic of the Benken well. They observed an increase in process length and process complexity through the succession of coarse-grained sandstones to siltstones. Although their available sedimentological data are very limited, the succession is interpreted representing a gradual deepening of the basin. They interpret the observed fluctuations of acritarch morphometric parameters (increase in process length, increase of specimens with more complex and elaborate processes) to be possibly related, in analogy with modern dinoflagellates, to increasing salinity, i.e. with more open marine conditions, and therefore due to ecophenotypy rather than species diversity.

The results from the morphometric analysis of acritarchs in the present study of the Middle Triassic of the Benken well provide strong evidence for the environmental control of acritarch morphological diversity. The morphological diversity of micrhystrid acritarchs is here interpreted as morphological plasticity in response to different environmental conditions, causing the formation of different ecophenotypes. Thanks to the well-known sedimentary and sequence stratigraphical framework of the Middle Triassic in the Germanic Basin, the observed fluctuations of morphological characters may be interpreted with quite some confidence. Acritarch vesicle size, process length, and process bifurcations are seen to increase during transgression and the intervals of maximum flooding, when open-marine, probably close to normally saline conditions prevail. In environments of restricted circulation with elevated salinity and probably also elevated temperature, as recorded in the Anisian highstand deposits, vesicle size, process length, and the percentage of specimens with bifurcated processes are decreasing. The number of processes shows the opposite trend and is high during the late highstand.

6. Stable isotope signatures

C and O isotope signatures yield information on the sedimentary history of distinct depositional environments (Veizer 1992; Kump & Arthur 1999). Main processes determining the isotopic signatures in shallow marine epeiric settings are (1) ingression of cooler waters from the open ocean, (2) evaporation, (3) meteoric influence, (4) dissolved and solid matter fluvial inputs including nutrients, influencing (5) net primary production, (6) reworking of organic matter, and (7) diagenetic alteration.

The relation between geochemical changes in the sedimentary record and sea-level fluctuations has in particular been investigated for Cretaceous carbonate systems, also containing economically important hydrocarbon source rocks (e.g. Ginsburg & Beaudoin 1990; Joachimski 1994; Patterson & Walter 1994; Grötsch et al. 1998; Keller et al. 2004; Bjerrum et al. 2006).

Isotopic studies on Middle Triassic shelf deposits of the NW Tethys are limited to the Male Karpaty Mountains (Lintnerova & Hladikova 1992) and the Karavanke Mountains (Dolenec et al. 2003). Recently, stable isotope data from Middle Triassic series of the Peri-Tethyan realm were published by Szulc (1999, 2000) and Götz et al. (2005). These works focus on the eastern gate areas (Silesian and Carpathian domains) in southern Poland. The stratigraphic evolution of $\delta^{13}C$ and $\delta^{18}O$ values in these carbonate series shows two intervals characterised by distinctive positive shifts of $\delta^{13}C$, accompanied by heavier $\delta^{18}O$ values. These signatures are interpreted as a result of rapid transgressive influx of normal marine waters, which, in terms of sequence stratigraphy, represents maximum flooding.

The stable isotope curves obtained from the $\delta^{13}C$ and $\delta^{18}O$ data of the Benken well show a similar trend to those of the Polish record (Szulc 2000) with ranges from –2.5 to 1.5 and –10 to –6 (‰ vs V-PDB), respectively. The two strongest local maxima in $\delta^{13}C$ and $\delta^{18}O$ occur in the uppermost Wellendolomit and middle part of the Wellenmergel (Fig. 8) and coincide with acritarch maxima. Therefore, we assume that the course of the stable isotopes displays the eustatic evolution of the depositional system. The heavier $\delta^{18}O$ values give evidence for ingression of normal marine waters from the Tethys Ocean into the Peri-Tethys Basin as shown for the Polish gate area (Szulc 2000). Maximum abundance and highest diversity of marine plankton in the Benken well section supports this interpretation. Bivalves are preserved as steinkerns exclusively and brachiopods only occur in distinct beds in the Pelsonian interval, representing the most open marine deposits. Potentially, the oxygen isotopic composition of conodonts could provide a palaeotemperature proxy. However, this is not available yet. It is assumed that the water of the Peri-Tethyan epeiric sea was probably relatively warm (cf. Korte 1999) and ingressions from the open Tethys Ocean during major flooding phases would bring cooler waters into the Muschelkalk Basin.

Restricted conditions are indicated by the presence of evaporites and dolomites in the upper part of the section (Orbicularis-Mergel and basal Middle Muschelkalk). This interval is characterised by generally light $\delta^{13}C$ values. A clear increase of $\delta^{18}O$ values is observed in sample 19 and upsection, representing a characteristic isotopic signature of evaporitic settings (cf. Joachimski 1994).

Meteoric influence on the $\delta^{18}O$ signature is regarded to be low, since the climate during Anisian times was arid (cf. Szulc 2007) and no high runoff from continental sources should be expected. Therefore, no high loads of dissolved and particulate carbon should be discharged by river systems into the Peri-Tethys Basin. Numerous silt layers and sporadically intercalated thin sandstone beds present in the Benken well point to aeolian transport. Thus, the dilution effect due to fluvial inputs or meteoric water sources can be neglected.

Increasing net primary production generally leads to increased $\delta^{13}C$ in the water column due to fractionation processes. Our data show that intervals of maximum abundance of marine plankton correlate with local $\delta^{13}C$ maxima. This can be attributed to the incorporation of heavier $\delta^{13}C$ into the limestones studied.

Another process affecting the isotopic signatures is the reworking of organic matter in the sediments or in the water column close to the seafloor. This process may either occur under highly oxidising or anaerobic conditions (for the latter see Kempe 1990; Kempe & Kazmierczak 1994). During anaerobic respiration of sinking organic carbon, sulphate is reduced and its negative charge is substituted by bicarbonate ions, increasing the alkalinity in proportion to the lost sulphate and making the dissolved inorganic carbon isotopically lighter (Kempe 1990). In the studied Benken section lighter $\delta^{13}C$ values may therefore indicate phases of increased sulphate reduction under anaerobic conditions, whereas the peaks in the $\delta^{13}C$ curve point to normal marine conditions during maximum flooding.

Finally, a diagenetic alteration of the sediments studied must be considered. The $\delta^{18}O$ range from –6 to –10 (‰ vs V-PDB) could, at first thought, be taken as such a diagenetic overprint since either early diagenetic (meteoric) influence or high amounts of late diagenetic cements during burial both usually bear a low $\delta^{18}O$ signature (James & Choquette 1984; Choquette & James 1990). However, sulphate reduction also results in lighter $\delta^{18}O$ in bicarbonate (cf. Blake et al. 2006), which in turn is precipitated with dissolved Ca as $CaCO_3$.

Generally, the isotope signature of lithified mudstones differs from the isotopic composition of the originally precipitated carbonate. The Anisian micrites studied do not show any significant cementation in thin sections. Therefore, it is assumed that the primary isotope signature most probably is preserved.

Furthermore, reliability of the isotopic data is supported by the striking correlation of the observed trends in palynofacies and acritarch diversity and the isotopic courses. This suggests that alteration of the isotopic signals by diagenesis does not play a major role.

As the isotopic signatures of the Benken well predominantly reflect processes induced by relative sea-level changes, their use for sequence interpretation of monotonous carbonate series within an epeiric setting seems to be suitable. However, to establish a chemostratigraphy for the Middle Triassic Peri-Tethyan realm further sections have to be studied and correlated (cf. Conradi et al. 2007).

7. Conclusions

The studied Anisian carbonate series of northern Switzerland 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 at a third-order scale. Two major flooding phases are recognized.

Acritarch diversity correlates with the eustatic evolution during Anisian times as interpreted from palynofacies data. Vesicle size, process length, and the percentage of specimens with process bifurcations are seen to increase during transgression and intervals of maximum flooding. They are decreasing within highstand phases. The number of processes shows the opposite trend and is high during the late highstand.

The results from the morphometric analysis of acritarchs in the present study of the Middle Triassic of the Benken well provide strong evidence for the environmental control of acritarch morphological diversity. The morphological diversity of micrhystrid acritarchs is here interpreted as morphological plasticity in response to different environmental conditions, causing the formation of different ecophenotypes.

Stable isotope signatures confirm the cyclic interpretation of the Muschelkalk series based on palynological data. The Anisian sequences An2 and An3 described from the eastern and central part of the Peri-Tethys Basin are also recognized in the depositional series of northern Switzerland. Furthermore, the two strongest local maxima in $\delta^{18}O$ give strong evidence for ingression of cooler, normal marine waters from the Tethys Ocean into the Peri-Tethys Basin via a western gate.

All compared indicators point to a connection between the Peri-Tethyan realm and the northwestern Tethys shelf area during Bithynian and Pelsonian times. The position of an Anisian gate area in the southwestern part of the Germanic Basin is still under discussion. Here, we assume that the connection did exist more to the East of the postulated later (Ladinian) Burgundy Gate (Fig. 2) with marine ingression into the western part of the Germanic Basin from the South via a central alpine gate (Western Gate of Szulc 2000; Alpenrhein-Depression of Einsele & Schönenberg 1964) and continuing northwards into the Hessian Depression (Götz & Gast 2007). This hypothesis is corroborated by Gisler et al. (2007) who investigated early Triassic deposits from the central part of Switzerland. However, further studies are necessary to clarify the position and temporal influence of a western gate area during the Anisian.

The results of the present study provide a more precise stratigraphical framework for the Germanic Middle Triassic and basin wide correlation (Fig. 3). The marly limestones and *Spiriferina* Bed of the middle Wellenmergel in northern Switzerland are interpreted to represent a stratigraphical equivalent of the Pelsonian brachiopod shell beds known from Muschelkalk deposits of Germany (Terebratelbank Member) and Poland (Hauptcrinoidenbank of the Terebratula Beds) and to document the most open marine interval within the Anisian. Furthermore, first conodont findings in the Benken and Leuggern wells (Götz & Gast 2007) enabled us to determine the Bithynian/Pelsonian boundary in the upper part of the Wellendolomit. A flooding phase around this boundary interval was first detected in Upper Silesia (Upper Gogolin Beds, cf. Szulc 2000; Götz et al. 2005) and Central Germany (upper Wellenkalk 1 Member, cf. Götz & Feist-Burkhardt 2000; Rameil et al. 2000), and based on conodont data from these parts of the Germanic Basin (Götz 1995; Narkiewicz & Szulc 2004), the correlation with the upper Wellendolomit of N Switzerland is evident.

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