

The Germanic Triassic: correlations with the international chronostratigraphic scale, numerical ages and Milankovitch cyclicity

Die Germanische Trias: Korrelation mit der internationalen chronostratigraphischen Gliederung, numerische Altersdaten und Milankovitch-Zyklizität

with 13 Figures

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Abstract

The biostratigraphy of the Tethyan marine scale is discussed in some detail. Its correlation with the Germanic Triassic is partly rather well established, in part biostratigraphically impossible. Those marine deposits that do not contain an endemic fauna can be well assigned to the international scale, mainly with conodonts, ammonoids and echinoderms (Upper Buntsandstein, Lower Muschelkalk). The marine ammonoid- and conodont-rich Upper Muschelkalk faunas are endemic and very difficult to correlate with the Tethyan scale. Conchostracans and sporomorphs allow a good correlation of continental beds, but red hypersaline beds have neither sporomorphs nor conchostracans (e. g. Weser Formation). An important future correlation potential can be magnetostratigraphy, if bio- and chronostratigraphy are integrated in both the Germanic Basin and the Tethys. So far, it is particularly well established around the Permian-Triassic Boundary in Germany and in the middle Norian to Rhaetian of England. $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ isotopes and microsphaerules of cosmic, volcanic and biotic origin are significant correlation tools around the Permian-Triassic boundary, $\delta^{13}\text{C}_{\text{carb}}$ yields also good results for correlation up to the the lower Smithian.

Most important results are:

- (1) a revised conchostracan zonation of the Buntsandstein and its correlation with the short eccentricity cycles of the entire Lower Buntsandstein;
- (2) a detailed correlation of the Olenekian base by conchostracans and by a revised magnetostratigraphy;
- (3) the assignment of the Stammen Beds (and the time-equivalent Thüringer Chirotherien-sandstein) of the upper Solling Formation to the Anisian (Aegean);
- (4) the correlation of the Ladinian base (at the base of the *E. curionii* Zone) with a level above the Cycloidesbank γ of the Upper Muschelkalk; and
- (5) the assignment of the uppermost Löwenstein Formation (4th Stubensandstein), the time-equivalent uppermost Arnstadt Formation as well as the lower and middle Postera Beds to the Rhaetian.

The pronounced cyclicity of the Germanic Triassic is interpreted in terms of Milankovitch cycles of ~ 0.02 myrs, ~ 0.1 myrs and ~ 0.4 myrs, whereby the short eccentricity cycles of ~ 0.1 myrs seem to be best developed. There are 22 short eccentricity cycles in the Lower Buntsandstein. Regarding the Middle Buntsandstein, there seems to be between 9 and 14 short eccentricity cycles in the Volpriehausen Formation, at least 3 in the Detfurth Formation and probably 4 in the Solling Formation. Well developed short eccentricity cycles are known from the Upper Buntsandstein Röt Formation (9) as well as from the Lower Muschelkalk (20, and the lower part of a 21th cycle) and

Middle Muschelkalk (9). The approximately 40 cycles of the Upper Muschelkalk are most likely short eccentricity cycles. Well developed short eccentricity cycles are present in the Erfurt Formation (8), and in the Ladinian part of the Grabfeld Formation (9). Several shorter or longer well-known gaps have to be considered in the Lower and Middle Triassic. In the Germanic Upper Triassic the Milankovitch cycles are more difficult to establish, especially due to several long gaps, reduced sedimentation rates and condensation associated with pedogenic processes. It seems that in the Arnstadt Formation the ~0.4 myrs cycles are best developed as is the case in the Upper Triassic of the Newark Basin.

Zusammenfassung

Die biostratigraphische Gliederung der marinen Tethys wird ausführlich diskutiert. Ihre Korrelation mit der Germanischen Trias ist nur zum Teil belegt, zum Teil biostratigraphisch gar nicht möglich. Marine Abschnitte des Oberen Buntsandsteins und der Untere Muschelkalk enthalten nicht endemische Faunen von Conodonten, Ammonoideen und Echinodermaten und können dem internationalen Standard gut zugeordnet werden. Im Oberen Muschelkalk ist die Conodonten- und Ammoniten-reiche Fauna dagegen weitgehend endemisch und deshalb nur schwer korrelierbar. In kontinentalen Ablagerungen ermöglichen Conchostraken und Sporomorphen eine gute Korrelation. Diese Formen fehlen jedoch in roten hypersalinaren Ablagerungen, wie z. B. der Weser-Formation. Die Magnetostratigraphie kann in der Zukunft ein hohes Korrelationspotential haben, aber nur, wenn dabei bio- und chronostratigraphische Methoden berücksichtigt werden. Gut realisiert ist dies bisher an der Perm-Trias-Grenze in Deutschland und im Mittleren Nor bis Rhät von England. $\delta^{13}\text{C}_{\text{org}}$ - und $\delta^{13}\text{C}_{\text{carb}}$ -Isotopen sowie Mikrokügelchen (microsphaerules) kosmischer, vulkanischer und organischer Entstehung sind wichtige Korrelationsmethoden an der Perm-Trias-Grenze. $\delta^{13}\text{C}_{\text{carb}}$ gibt gute Resultate bis ins tiefere Smithium.

Die wichtigsten Ergebnisse der Arbeit sind:

- (1) eine revidierte Conchostraken-Gliederung des Buntsandsteins und deren Korrelation mit den kurzen Exzentrizitätszyklen des Unteren Buntsandsteins;
- (2) eine detaillierte Korrelation des tieferen Olenekiums mit Hilfe von Conchostraken und einer revidierten Magnetostratigraphie;
- (3) die Zuordnung der Stammen-Schichten und des zeitgleichen Thüringer Chirotheriensandsteins (obere Solling-Formation) zum Anis (Aegeum);
- (4) die Korrelation der Untergrenze Ladin (Basis *E. curionii*-Zone) mit einem Intervall über der Cycloidesbank γ (Oberer Muschelkalk);
- (5) die Zuordnung der obersten Löwenstein-Formation (4. Stubensandstein), der zeitgleichen obersten Arnstadt-Formation sowie der Unteren und Mittleren Postera-Schichten zum Rhät.

Die meisten der deutlich entwickelten Sedimentationszyklen in der Germanischen Trias werden als Milankovitch-Zyklen von ~20 kyrs, ~100 kyrs and ~400 kyrs interpretiert, wobei die kurzen Exzentrizitätszyklen von ~100 kyrs anscheinend am besten ausgeprägt sind. Im Unteren Buntsandstein gibt es 22 kurze Exzentrizitätszyklen, in der Volpriehausen-Formation zwischen 9 und 14, in der Detfurth-Formation mindestens 3 und in der Solling-Formation wahrscheinlich 4. Gut ausgebildete kurze Exzentrizitätszyklen treten im Oberen Buntsandstein auf (9), im Unteren Muschelkalk (20 Zyklen und der untere Teil eines 21.) und im Mittleren Muschelkalk (9). Die unfähr 40 Zyklen im Oberen Muschelkalk sind wahrscheinlich ebenfalls kurze Exzentrizitätszyklen. Gut ausgebildete kurze Exzentrizitätszyklen gibt es auch in der Erfurt-Formation (8) und der Grabfeld-Formation unterhalb der Estheriensschichten (9). Mehrere Schichtlücken treten in der Unteren und Mittleren Trias auf. In der Germanischen Obertrias sind die Milankovitch-Zyklen schwerer zu bestimmen, vor allem wegen großen Schichtlücken, verringerten Sedimentationsraten und Kondensation durch Bodenbildung. In der Arnstadt-Formation sind offenbar die ~400 kyrs-Zyklen am Besten entwickelt, wie es auch in der Obertrias des Newark-Beckens der Fall ist.

1 Introduction – Possibilities and problems with correlation of the Germanic Triassic

The Triassic was introduced by F. VON ALBERTI (1834) for the predominantly continental Buntsandstein, the marine and hypersaline Muschelkalk and the continental, brackish and hypersaline Keuper of southwestern Germany. Paleogeographically, it is in the southern part of the Central European Basin, which is also referred to as the Germanic Basin in Triassic times.

Early attempts to correlate these deposits with the open marine Tethyan Triassic failed, and today only the name “Triassic”, its three-fold subdivision, and names like Alpine Buntsandstein, Alpine Muschelkalk and Carpathian Keuper remain as reminders to those early attempts at correlation. The Rhaetian (GÜMBEL 1861), the first established Triassic Stage, was applied to both the Germanic and Alpine Triassic. The international scale for the pelagic Triassic (except the Rhaetian), established by MOJSISOVICS et al. (1895) was first not applied to the Germanic Triassic, or it was attributed to it without biostratigraphic correlation, e. g. the Scythian to the Buntsandstein, the Anisian and Ladinian to the Muschelkalk and the Upper Triassic to the Keuper. None of these correlations turned out to be precise.

The stages and substages of the modern international chronostratigraphic scale were correlated with the Germanic Triassic by KOZUR (1972a, 1974, 1975, 1984, 1993a, b, 1999, 2003b, c), DOCKTER et al. (1980), KOZUR & SEIDEL (1983a, b), and KOZUR & MOCK (1993), first the marine or partly marine Upper Buntsandstein, Muschelkalk and Lower Keuper, then the continental Lower and Middle Buntsandstein and the Middle Keuper. Later, new ammonoid, bivalve, crinoid and palynological data (e. g. URLICHS 1978, URLICHS & KURZWEIL 1997, BRACK et al. 1998, 1999, HAGDORN & GLUCHOWSKI 1993, VISSCHER et al. 1993, URLICHS & TICHY 1998, 2000) confirmed most of these correlations, but caused also some changes in correlation, especially concerning the Ladinian-Carnian boundary. There, the contradiction between the former Carnian bivalve age of the Bleiglanzbank and the much higher Ladinian-Carnian boundary (around the base of the “Estheriensichten” of the upper Grabfeld Formation), determined by sporomorphs and conchostracans, was solved by taxonomic revision of the *Myophoria kefersteini* group (URLICHS & TICHY 2000), which changed the allegedly Carnian bivalve age of the Bleiglanzbank to the late Ladinian.

In many parts of the Germanic Triassic miospores and megaspores yielded important data for correlation with the international scale (e. g. MARCINKIEWICZ 1971, KOZUR 1972c, MOSTLER & SCHEURING 1974, SCHEURING 1978, DOUBINGER & BÜHMANN 1981, KOZUR & SEIDEL 1983b, ORŁOWSKA-ZWOLIŃSKA 1984, BRUGMAN 1986, VISSCHER et al. 1993). However, there are two problems associated with palynological correlations. The Alpine sporomorph associations are derived from a distinctly more southern latitude with a rather different climate. This causes, in

part, different first appearances (FAD) of palynological guide forms. *Ovalipollis pseudoalatus* (THEIRGART) SCHUURMAN, for instance, begins at the base of the Tethyan Ladinian, but in the Germanic Basin as late as in the Longobardian Erfurt Formation (Lower Keuper), as was shown by VISSCHER et al. (1993). The different FAD of sporomorphs is the reason that palynologists (e. g. DOUBINGER & BÜHMANN 1981, BRUGMAN 1983, 1986, VISSCHER et al. 1993) place the base of the Pelsonian somewhat below the Myophorienschichten of the upper Röt Formation (Upper Buntsandstein). One evidence being used is the FAD of *Cristianisporites triangulatus* ANTONESCU in the upper Röt Formation and its occurrence in well dated Pelsonian strata of Romania and in uppermost Pelsonian and Illyrian strata of the Alps (BRUGMAN 1983). On the other hand, this example demonstrates that palynological correlations do not always consider other palaeontological correlations, as not only the upper Röt Formation, but also the overlying lower Jena Formation (Unterer Muschelkalk) up to the Oolithbank Member are Bithynian according to all stratigraphically important marine faunal groups (ammonoids, conodonts, holothurian sclerites, crinoids). The *Nicoraella germanica* conodont zone of the lower Jena Formation even has a world-wide distribution and is well dated by ammonoids. This discrepancy between palaeontological and palynological correlations can easily be solved if the FAD of *Dyupetalum vicentinense* BRUGMAN is taken to define the base of the Pelsonian in the Germanic Basin. This species (although rare in the Germanic Basin) begins at the base of the middle third of the Jena Formation, close to the level where the Pelsonian guide forms of ammonoids, conodonts and holothurian sclerites begin. In the Alps and Hungary this species begins at the base of the Pelsonian or somewhat below.

The second problem is that changes in sporomorph associations often occur before changes in faunas. This is the reason why palynologists assign the base of the palynological associations, dominated by *Lunatisporites obsoletus-Kraueselisporites* (trilete cavate spores) in the Alps, in Hungary, the Arctic and the Germanic Basin, to the basal Triassic, despite the fact that this association begins in undoubtedly Permian marine strata (e. g. in the Tesero Oolite with last occurrences of fusulinids and Permian brachiopods, common Permian conodonts and mass occurrences of *Tympanicysta stoschiana* BALME). On the other hand, palynological investigations in predominantly hypersaline sediments, with only few stratigraphically important faunas, have shown the correct age much earlier than palaeontological investigations did. MOSTLER & SCHEURING (1974) and SCHEURING (1978), for instance, have shown, on the base of former palynological investigations by SCHEURING (1970), that large parts of the Grabfeld Formation (Lower Gipskeuper) belong to the Longobardian, whereas palaeon-

tological correlations were blocked by the opinion that the Bleiglanzbank of the lower Grabfeld Formation is Carnian in age because of the assumed occurrence of the Carnian guideform *M. kefersteini*.

In the continental Lower and Middle Buntsandstein, detailed correlations are possible with conchostracans in reddish and grey fresh water to slightly brackish lake deposits. Greyish fresh water to hypersaline deposits can be also correlated with sporomorphs, especially around the PTB and in the Detfurth to Soling Formations. The Röt Formation (Upper Buntsandstein) can be well correlated by sporomorphs, bivalves, and, partly, by ammonoids and holothurian sclerites. Sporomorphs, conchostracans and partly vertebrates can be used in continental to slightly brackish deposits. The Jena Formation (Lower Muschelkalk) and the Trochitenkalk Formation (Upper Muschelkalk) can be correlated with conodonts and, in part, ammonoids, bivalves, brachiopods, echinoderms and sporomorphs. The Middle Muschelkalk can be mainly correlated with sporomorphs, in Upper Silesia also with dasycladacean algae. Brackish beds of the Diemel Formation (uppermost Middle Muschelkalk) also have stratigraphically important ostracods. The ammonoid and conodont-rich Meissner Formation of the Upper Muschelkalk cannot be correlated in detail with the international scale because of the endemic character of the fauna. Only in the upper *C. spinosus* Zone, very few Tethyan ammonoids allow an exact correlation

with the *Nevadites secedensis* Zone of the Southern Alps. Conchostracans, bivalves, ostracods and sporomorphs are useful in parts of the Grabfeld Formation (Bleiglanzbank, "Estheriensichten"), Stuttgart Formation (Schilfsandstein), marine intercalations of the Lehrberg Beds, Arnstadt Formation (Steinmergelkeuper), and Exter Formation. SWIFT (1989, 1995) found Rhaetian conodonts in equivalents of the Exter Formation in Great Britain.

Thus, in essence, the Germanic Triassic can be correlated, in part detailed, in part roughly, with the international scale on the basis of modern biostratigraphic methods, but a detailed correlation of the entire Germanic Triassic, including its fossil-free intervals, requires the stratigraphic evaluation of palaeomagnetic, stable isotope and other event stratigraphic data. A further, increasingly important, aspect is the cyclicity of the Germanic Triassic, which can be interpreted in terms of Milankovitch cycles.

This paper will discuss the international Triassic scale and its numerical ages. Correlation with the Germanic Triassic is suggested using different biostratigraphic and abiotic methods. Supposed Milankovitch cyclicity is proposed for estimating the duration of the individual units. We hope to stimulate discussion and further investigations of these aspects by the community of Triassic workers. A short version of this paper will be published in *Albertiana* **32** (KOZUR & BACHMANN 2005, in press).

2 International scale and numerical ages

The international scale was discussed by KOZUR (2003a, b) and only some further data are added here.

2.1 Permian-Triassic boundary (PTB)

The base of the Triassic is defined by the FAD of *Hindeodus parvus* (KOZUR & PJATAKOVA). For the correlation with continental Permian-Triassic boundary beds, auxiliary biostratigraphic and event stratigraphic data are important.

a) Biostratigraphy (Figs. 1, 4, 5)

H. parvus occurs in marine beds in all water depths and all faunal provinces. If conodonts are absent or very rare, other biostratigraphic important fossils are also lacking in most cases, and only ostracods may be common in such beds. Rich ostracod faunas can indicate the approximate position of the PTB. Under dysaerobic conditions *Hollinella tingi* (PATTE) is very common in the basal Triassic. However, this species seems to begin already in the *C. meishanensis*-*H. praeparvus* Zone of the uppermost Permian together with a few Permian forms like *Indivisia buekkensis* KOZUR and *Praepilatina* sp. In oxygen-rich facies, the basal Triassic ostracod fauna is dominated by *Praezabythocypris ottomanensis* (CRASQUIN-SOLEAU). It begins in the latest Permian *C. meishanensis*-*H. praeparvus* Zone, together with bairdiids and kirkbyids, and is already dominant in the *M.*

ultima-*S. ? mostleri* Zone immediately below the base of the Triassic, where it occurs together with *Indivisia*. For regional correlations some other forms can be used as well, e. g. *Praezabythocypris pustulosus* KOZUR & METTE, a disaster species, which can be observed around the PTB, e. g. in the Abadeh and Shahreza sections of Iran and a mass occurrence in a 10 cm interval at the very base of the Triassic in the Zal section (north-western Iran).

Claraia, which is often considered to be an exclusively Lower Triassic form, begins in fact already in the Changhsingian of China (YIN HONGFU 1985). In the Zal section, there are mass occurrences of *Claraia* some 25 cm below the FAD of *H. parvus*.

Conchostracans are the best guide fossils in continental beds. The upper Dorashamian is characterised by *Falsisca eotriassica* KOZUR & SEIDEL. It is followed, with short overlap, by *F. postera* KOZUR & SEIDEL, which defines the uppermost Permian conchostracan Zone. Some specimens of *F. postera* were found in brackish intercalations of the basal Werfen Beds of Hungary, which are well correlated with the lower Tesero Oolite of the Southern Alps containing *Hindeodus praeparvus* KOZUR and other conodonts of

the uppermost Permian *H. praeparvus* Zone (KOZUR & MOCK 1993). The Triassic begins with the *F. verchojanica* Zone, which in Siberia was correlated with the lowermost Triassic (KOZUR 1993b, 1998a, b, 1999). In the lowermost Triassic of the Germanic Basin *F. verchojanica* MOLIN and *F. cf. verchojanica* are often very rare and begin in most cases somewhat higher, following an interval without *Falsisca*. However, in the Holy Cross Mountains PTASZYŃSKI & NIEDŹWIEDZKI (2004a, b, 2005, in press) found the *F. postera* and *F. verchojanica* Zones in superposition with a short overlap of the index species, thus proving in Poland (as in Germany) the biostratigraphic position of the PTB to be in the lowermost Buntsandstein. The short interval with the co-occurrence of the two species belongs to the uppermost *F. postera* Zone of the uppermost Permian, as is the case in Dalongkou / Sinkiang, where *F. verchojanica* has its FAD somewhat below the LAD of *Dicynodon* at the base of the Triassic. Generally, in most of the Germanic Basin, the upper boundary of the *F. postera* Zone has to be used for the biostratigraphic definition of the PTB, as only *F. postera* is a common form. Fortunately, the so defined PTB could be confirmed by other events, like minima of $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{org}}$ (see below).

NAWROCKI (2004) and NAWROCKI et al. (2005, in press) doubted this biostratigraphic boundary, which can be traced from the Germanic Basin to China, and placed the PTB deeper, within a short reversed palaeomagnetic interval comprising the lower Fulda Formation and the lowermost part of the upper Fulda Formation (Bröckelschiefer), thus considering the assumed reversed interval around the PTB at Meishan to be more important than biostratigraphic data. As there is actually no reversed interval around the PTB at Meishan (see below), the palaeomagnetic succession in Poland fits the biostratigraphic boundary at the top of the *F. postera* Zone.

The uppermost Permian is characterised in both marine and continental beds by the *Lundbladispora obsoleta-Lunatisporites noviaulensis* miospore assemblage zone and by the lower subzone of *Otynisporites eotriassicus* megaspore assemblage zone. Permian occurrences are, for instance, in the marine Tesero Oolite of the Southern Alps with *H. praeparvus* and *S. dobruskinae* KOZUR & PJATAKOVA (KOZUR, 1994, 1998a, b). In the continental Nedubrovo Formation of the Russian Platform (LOZOVSKY et al. 2001a, b), the lower *O. eotriassica* megaspore assemblage occurs together with the typical Permian *Tatarina* megaflora assemblage and contains, among others, common *Tatarina conspicua* MEYEN, *Quadrocladus dvinensis* MEYEN and *Ullmannia cf. bronni* GOEPPERT.

The index species *Lundbladispora obsoleta* BALME, *Lunatisporites noviaulensis* (LESCHIK) SCHEURING and lower subzone of the *Otynisporites eotriassicus* FUGLEWICZ, as well as other species of these assemblage zones, ranges far into the Early Triassic (see range chart KOZUR 1994: Fig. 3). For this reason, NAWROCKI (2004) and NAWROCKI et al. (2005, in press) doubted the Permian age of these assemblage zones. However, these species occur in the Lower

Triassic together with other species, which start close to the base of the Triassic, such as *Lundbladispora willmotti* BALME, *Lunatisporites heyxagonalis* (JANSONIUS) KOZUR, *L. pellucidus* (GOUBIN) HENELLY (*Lundbladispora willmotti-Lunatisporites hexagonalis* Assemblage Zone, KOZUR 1998a).

In vertebrate stratigraphy, the PTB is close to the LAD of the Permian genus *Dicynodon*. In Dalongkou (Sinkiang) there is an interval with *Lystrosaurus* and *Dicynodon* occurring together. In this level KOZUR (1998a, b) found the conchostracan faunas of the Permian *F. postera* Zone and the *Lundbladispora obsoleta-Lunatisporites noviaulensis* miospore and *Otynisporites eotriassicus* megaspore assemblage zones.

b) Palaeomagnetism (Figs. 1, 4, 5)

According to LI HUAMEI & WANG JUNDA (1989) the PTB of Meishan is situated in the lower third of a relatively long normal interval straddling the PTB. A similar position of the PTB was found all over the world by different authors (see discussion in KOZUR, 2003a, b, 2004a, b, SZURLIES & KOZUR, 2004). LIU YUYAN et al. (1999) and ZHU YANMING & LIU YUGAN (1999), however, found an allegedly reversed horizon around the PTB in Bed 27 at Meishan, and these data were adopted by YIN HONGFU et al. (2001). This reversed horizon could not be verified in any other well-dated section of the world and, therefore, KOZUR (2003a, b, 2004 a) concluded that these data are not reliable. SZURLIES & KOZUR (2004) checked the uppermost Permian *M. ultima-S. ? mostleri* Zone and the lowermost Triassic *H. parvus* Zone and *I. isarcica* Zone of Abadeh, Shahreza and Jolfa (Iran) and found that all samples had a normal polarity with the PTB in the lower third of a relatively long normal interval straddling the PTB.

Obviously, these problems and contradictions have been solved now by Chinese and Japanese colleagues themselves. Prof. YIN HONGFU, Wuhan, authorised H. KOZUR in a written communication to publish the following statement: "Dr. LIU YUYAN made an initial research and published the result in 1999 (LIU YUYAN et al. 1999). He did the palaeomagnetic study in Wuhan and in Kobe, Japan. In their paper LIU YUYAN et al. (1999) found 3 samples (43–45) of Bed 27 at Meishan section bearing reversed polarity. Samples around equivalent layers at Meishan, section A, gave similar results. These results were quoted by YIN HONGFU et al. (2001). Later Dr. LIU YUYAN made a second sampling at sections D and A (sampling whole rock column of P-T boundary strata without interruption). The samples were measured by Dr. NAROMOTO at the Kyoto University. He found that there was no such reversal around Bed 27. After discussion between LIU YUYAN and NAROMOTO they decided that the first result by LIU YUYAN et al. (1999) was probably due to secondary magnetisation which had not been eliminated during processing, and that there should not be a reversal around the PT boundary."

The data by LIU YUYAN et al. (1999) concerning the allegedly reversed interval caused considerable confusion in PTB correlation. PENG YUANQIAO et al.

(2001) used these data for a high-resolution correlation between the Meishan and Shangsi sections in South China. They correlated the reversed Bed 26 of Shangsi with the allegedly reversed Bed 27 of Meishan. As can clearly be seen from fauna and carbon isotopes, however, this palaeomagnetic correlation cannot be right. Bed 26 of Shangsi, below the event boundary, has a rich conodont fauna, which belongs to the *C. changxingensis*-*C. deflecta* Zone. On the other hand, Bed 27 of Meishan, above the event boundary, has a very poor conodont fauna belonging to the *C. zhejiangensis* Zone (equivalent of the *M. ultima*-*S. ? mostleri* Zone of Iran) and the entire *H. parvus* Zone, i. e. 4 to 5 conodont zones higher. Whereas in these conodont-bearing sections it becomes immediately obvious that the correlation cannot be correct, it is much more difficult to recognise incorrect correlations in continental PTB sections. NAWROCKI (2004) and NAWROCKI et al. (2005, in press) used the data of ZHU YANMING & LIU YUGAN (1999) to place the PTB in Poland within a short reversed interval in the uppermost Zechstein Fulda Formation (Bröckelschiefer). This reversed horizon, however, can be well correlated with the upper *C. changxingensis*-*C. deflecta* Zone and the largest part of the *C. zhangi* Zone, i. e. 4 to 5 conodont zones lower than the assumed reversed interval around the PTB at Meishan. As stated above, there is no reversed horizon around the PTB, thus the correlation by NAWROCKI (2004) and NAWROCKI et al. (2005, in press) can be rejected, as has already been done by PTASZYŃSKI & NIEDŹWIEDZKI (2005, in press).

The following succession of palaeomagnetic events (from below) is found around the PTB (Figs. 1, 4, 5):

- Interval 0r: Short reversed interval within the upper Dorashamian. As shown by KOZUR (2004a) and SZURLIES & KOZUR (2004), the interval begins in the upper *C. changxingensis*-*C. deflecta* Zone of the upper Dorashamian of Iran and comprises also the largest part of the *C. zhangi* Zone. According to ZAKHAROV & SOKAREV (1991), this reversed horizon ends in the Dorashamian II, 0.5 m below the top of the *Paratiro-lites* Limestone. In the similar section Zal (NW Iran) this corresponds to the uppermost *C. zhangi* Zone.
- Interval 1n: The uppermost Permian to lowermost Triassic is characterised by a long normal interval straddling the PTB. Its Permian part ranges from the uppermost *C. zhangi* Zone up to the *M. ultima*-*S. ? mostleri* Zone (4 short conodont zones; see Fig. 1), and its Lower Triassic part comprises the *C. parvus* and *I. isarcica* Zones. A correlation of the top of N1 within the upper Mazzin Member of the Pufels (Bulla) section, Southern Alps (SCHOLGER et al. 2000), with conodont data from this section (FARABEGOLI & PERRI 1998), indicates that the top of 1n coincides approximately with the top of the *I. isarcica* Zone. This is also shown by data of SZURLIES & KOZUR (2004) from Jolfa (Iran), where the corresponding normal interval ranges up to the upper *I. isarcica* Zone.

The curve of magnetic susceptibility across the PTB may also be used for correlation according to HANSEN et al. 2000 (and pers. comm; Fig. 8).

c) Carbon isotopes

Numerous papers show a strong negative excursion of carbon isotopes around the PTB (HOLSER & MARGARITZ 1987, BAUD et al. 1989, HOLSER et al. 1989, XU & YAN 1993, WANG et al. 1994, BOWRING et al. 1998, CAO & SHANG 1998, KORTE 1999, WIGNALL et al. 1998, JIN et al. 2000, HEYDARI et al. 2001, PENG et al. 2001, KORTE et al. 2004a, b, c, NEWTON et al. 2004, KORTE & KOZUR, in press a, b). Very detailed investigations on unweathered and very well-dated material from Iran, Southern Alps and Hungary by KORTE et al. (2004a, b, c) and KORTE & KOZUR (in press a) have shown a continuous drop towards more negative values from the upper Dorashamian *C. nodosa* Zone to the basal Lower Triassic, with a first minimum close to the PTB and, often, a second minimum in the lower *I. isarcica* Zone. In Meishan, a strong minimum in the *C. meishanensis*-*H. praeparvus* Zone of the Boundary Clay (BOWRING et al. 1998, JIN et al. 2000) was proven to be a secondary signal caused by the strongly weathered clay of very low carbonate content (KORTE et al. 2004b, c, KORTE & KOZUR, in press a).

A similar negative excursion was also found within the Boundary Clay of Abadeh and Jolfa, if weathered claystones and siltstones with low carbonate content were analysed. If unweathered limestones and marls were used for determining $\delta^{13}\text{C}_{\text{carb}}$ (e. g. Zal and Shahreza sections of Iran, Gerennavár section in Bükk Mts, Hungary and all South Alpine sections investigated) there was no minimum found in the level of the Boundary Clay. The first minimum of the primary signal is always situated above the Boundary Clay and corresponds to the PTB (KORTE et al. 2004b, c, KOZUR & KORTE, in press a).

Based on unpublished measurements of $\delta^{13}\text{C}_{\text{org}}$ by Prof. H. J. HANSEN, Copenhagen (pers. comm.) and $\delta^{13}\text{C}_{\text{carb}}$ by Dr. C. KORTE, Oxford (pers. comm.), BACHMANN & KOZUR (2002, 2003), have shown that the minima at the PTB are also found in continental deposits, thus providing a very good tool for the correlation of the marine PTB with the continental PTB (Fig. 8). This was confirmed by HIETE (2003, 2004) and HIETE et al. (2004).

d) Abrupt facies change caused by a strong climatic change somewhat below the PTB

The predominant carbonate sediments of all continuous low latitude pelagic deposits are suddenly interrupted, somewhat below the PTB, by a clayey-silty horizon, the Boundary Clay (South China; Abadeh and Shahreza in Central Iran; Jolfa and Zal in NW Iran; e. g. Dorasham II, Sovetoshen, Achura in Transcaucasia; Gerennavár, Bükk Mts in Hungary). The Boundary Clay begins at the base of the *C. meishanensis*-*H. praeparvus* Zone, about 120,000 years below the PTB according to astronomic calibration (KOZUR 2003a, b). The main extinction event of tropical warm water faunas was at the base of this horizon, independently if it coincides with the beginning of dysaerobic or anoxic sediments, or if it is situated

Ma		Stage/Substage	Ammonoid Zone		Conodont Zone		M
247	MIDDLE TRIASSIC	ANISIAN	Bithynian	Aghardandites ismidicus	Paragondolella bulgarica	Nicoraella germanica	■
				Nicomedites osmani			
				Lenotropites caurus			
		Aegean	Pseudokeyserlingites guexi	Neogondolella ? regalis		■	
Japonites welteri	Chiosella timorensis						
249	LOWER TRIASSIC = SCYTHIAN	OLENEKIAN	Late Olenekian (Spathian)	Neopopanoceras haugi	Chiosella gondolelloides		■
				Prohungarites-Subcolumbites	Triassospathodus sosioensis		
				Procolumbites	Triassospathodus triangularis		
				Columbites parisianus	Triassospathodus homeri		
				Tirolites cassianus	Triassospathodus hungaricus		
		Early Olenekian (Smithian)	Anasibirites kingianus	Neospathodus waageni-Scythogondolella milleri		4n	
			Meekoceras gracilitatis	Scythogondolella milleri		3r	
251	BRAHMANIAN (INDUAN)	Gandarian (Dienerian)	Flemingites flemingianus	N. waageni-Scythogond. meeki		3n	
			Rohillites rohilla	Chengyuania nepalensis		2r	
251.6	BRAHMANIAN (INDUAN)	Gangetian	Gyronites frequens	Neospathodus cristagalli		■	
			"Pleurogyronites" planidorsatus	Neospathodus dieneri			
			Discophiceras	Sweetospathodus kummeli			
			Ophiceras tibeticum	Clarkina krystyni			
252.5	BRAHMANIAN (INDUAN)	Gangetian	Otoceras woodwardi	H. postparvus-H. sosioensis		1r	
			Otoceras fissisellatum	Isarcicella isarcica			
			T. pascoei	Hindeodus parvus			
252.6	LOPINGIAN	DORASHAMIAN	Upper Dorasham.	Merrillina ultima-Stepanovites ? mostleri		■	
Hypoph. changxingense				Otoceras boreale	Clarkina meishanensis -H. praeparvus		
Pleuronodoc. occidentale				Clarkina hauschkei			
Paratirolites kittli, pars				Clarkina iranica			
Clarkina zhangi				Clarkina changxingensis-C. deflecta s.s.			
252.7						1n	
						0r	

■ Normal polarity □ Reversed polarity ▣ No reliable data

Fig. 1:

Lower Triassic stages, substages and numerical ages. Low latitude biostratigraphic zonations from KOZUR (2003a, b). Magnetostratigraphy (M) of low latitude marine sediments after SCHOLGER et al. (2000), TONG JIN-NAN (2005) and MUTTONI et al. (1996). Chronostratigraphic correlations of magnetozones of SCHOLGER et al. and MUTTONI et al. modified according to text. Compiled radiometric ages in normal text, extrapolated numerical ages in italics.

within red sediments deposited in an environment without oxygen deficiency. In most shallow water deposits the Boundary Clay is either not present, or it cannot readily be recognised, because high-resolution correlation with pelagic deposits is difficult, and thus it is impossible to decide which of the numerous clayey-silty beds might be the corresponding one. However, at Gerennavár section, Bükk Mountains of Hungary, the Boundary Clay is well preserved in the shallow water deposits between the highly fossiliferous Nagyvisnyó Formation (Badiota facies of Belleophon Limestone) and the lower part of the dark-grey, commonly laminated platy limestones of the Gerennavár Formation, which contains only a few fossils, all of Permian character (KOZUR 1988). As all stenotherm warm-water fossils disappear at this level, a rather dramatic climatic change is indicated, i. e. a short-lasting rapid cooling.

Very different, but also abrupt, facies changes can be observed in pelagic PTB sections of medium sou-

thern latitudes along the Perigondwana margin of the Tethys. A particular good example is known from Spiti (India), where the lithostratigraphy and ammonoid biostratigraphy of the uppermost Permian and the Triassic of Spiti was revised and well described by BHARGAVA et al. (2004) and KRYSSTYN et al. (2004). According to these authors, the black shales of the Gungri Formation are separated from the overlying *Otoceras* Beds of the basal Mikin Formation by a rather long hiatus. The Gungri Shale was assigned to the Wuchiapingian, the *Otoceras* Beds to the Triassic *H. parvus* and lower *I. isarcica* Zones, but with a strange range of *C. meishanensis* into the *H. parvus* and *I. isarcica* Zones. This association is certainly caused by both extremely strong condensation and reworking. At the base of the *Otoceras* Beds there is a yellowish-brownish ferruginous layer that was often regarded as an indication of subaerial weathering, but Prof. O. N. BHARGAVA, Haryana, did not assume a subaerial gap (pers. comm.). In a roadcut at the nor-

Ma	Stage/Substage	Ammonoid Zone/Subzone	Conodont Zone	Radiolarian Zone/Subzone			
237	LATE TRIASSIC CARNIAN	Julian	Trachyceras aonoides	Gladigondolella tethydis- Paragondolella polygnathiformis I.Z.	Tetraporobrachia haeckeli unnamed radiolarian zone		
		Cordevolian	Trachyceras aon	Budurovignathus diebeli- Paragondolella polygnathiformis	Tritortis kretaensis		
	Daxatina canadiensis- Frankites sutherlandi						
	238 237.9	LADINIAN	Longobardian	Frankites regoledanus	Budurovignathus supralongobardica	M. kretaensis dispiralis Spongoserrula fluegeli Spongoserrula rarauana Pterospongos priscus	
Protrachyceras archelaus			Budurovignathus mungoensis	M. cochleata			
238.8		Protrachyceras grederi	Budurovignathus hungaricus	Muelleritortis firma			
240.5	FASSANIAN	Eoprotrachyceras curionii	E. recubariense	Budurovignathus truempyi	unnamed radiolarian fauna		
			E. curionii				
241.5 241.2 242.6 240.4 240.5 242.9 241.1	MIDDLE TRIASSIC ANISIAN	Illyrian	Nevadites secedensis	Paragondolella ? trammeri- Neogondolella aequidentata	Ladinocampe multiperforata		
			Reitziites reitzi	Aplococeras avisianum	Paragondolella ? trammeri trammeri- Paragondolella alpina	Ladinocampe annulooperforata	
				Reitziites reitzi	Paragondolella alpina Paragondolella trammeri praetrammeri	Spongosilic. italicus Oertlispongos primitivus	
			Kellnerites felsocersensis	K. felsocersensis L. pseudohungaricum	Neogondolella mesotriassica	Spongosilic. transitus Yeharaia annulata Tiborella florida	
		Paraceratites trinodosus	Asseretoc. camunum	Neogondolella constricta	Tetraspincocytis laevis		
			Semionites aviticus Schreyerites abichi				
		Pelsonian	Schreyerites binodosus	S. binodosus Bulogites zoldianus	Paragondolella bifurcata	Nicoraella germanica- Nicoraella kockeli	Parasepsagon robustus
			Balatonites balatonicus	Beyrichites cadoricus B. balatonicus	N. shoshonensis	Baratuna cristianensis	
		Bithynian	Agdharbandites ismidicus	Paragondolella bulgarica	Nicoraella germanica	Paroertlispongos diacanthus	
			Nicomedites osmani				
Lenotropites caurus Silberlingites muelleri							
247	Aegean	Pseudokeyserlingites guexi	Neogondolella ? regalis	Hozmadia gifuensis			
		Japonites welteri	Chiosella timorensis				

Fig. 2:

Middle Triassic stages and substages; low latitude ammonoid, conodont and radiolarian zonations and numerical ages after KOZUR (2003a, b). Further details see Fig. 1.

thern entrance of Guling village (Pin River), the soft ferruginous layer grades laterally into strongly weathered ferruginous limestone, both of which are rich in conodonts including *C. hauschkei* KOZUR, *C. meishanensis* ZHANG, LAI, LING & LIU, Permian *Clarkina* of *C. carinata* group, *Hindeodus praeparvus* KOZUR and *H. typicalis* (SWEET). All *Clarkina* of *C. carinata* group are without a platform brim, thus indicating an age older than the *C. meishanensis*-*H. praeparvus* Zone, where they have, as in younger beds, a distinct platform brim. The fauna belongs to the *C. hauschkei* Zone. Ammonoids are common, but poorly preserved. *Otoceras* is absent and all ammonoids seems to be xenodiscids. The overlying main part of the *Otoceras* Beds contains a mixture of Triassic forms of the *H. parvus* and *I. isarcica* Zones with Permian forms, such as *C. meishanensis* (see ORCHARD & KRISTYN 1998, KRISTYN et al. 2004). Because of extreme condensation and reworking there is no Boundary Clay preserved. The upper Gungri Shale contains *H. typicalis* and primitive *Clarkina* of the *C. carinata* group without posterior platform brim, similar or identical with the forms in the basal 3 cm of the *Otoceras* Beds. This fauna certainly belongs to the Dorashamian, thus excluding a longer hiatus between the pelagic Gungri Shale and the overlying pelagic *Otoceras* Beds.

The reasons for the sudden change from the Gungri Shale to the limestones of the *Otoceras* Beds are

unknown. Both contain cool water faunas. One possibility could be an abrupt shallowing, but the fauna does neither indicate nor exclude it. Another possibility could be a sudden warming, but the cool water fauna below and above the facies change do not favour this explanation. A third possibility, a strong increase in productivity, is in contrast to Tethyan faunal development around the PTB.

In continental beds of the low latitude arid girdle a very pronounced facies change can be observed. Depending on the position in the individual basins, sediments of arid environments, like fanglomerates or hypersaline sabkha deposits, are abruptly overlain by conglomerates or sandstones, transported by large amounts of running water, or by fresh water lake deposits (claystones, siltstones and fine-grained sandstones with conchostracans, *Darwinula* and charophytes). This sudden shift can be seen both in the Permian-Scythian of the European Tethys and in the Germanic Basin. In the basal parts of the Germanic Basin there are widespread hypersaline and sabkha sediments of the Zechstein overlain by fresh water lake and fluvial deposits of the Lower Buntsandstein indicating a dramatic climatic change from arid to humid conditions at the Zechstein-Buntsandstein boundary. For about 0.2 myrs there was an "evaporite gap" without any hypersaline deposits in the Germanic Basin and worldwide. In the Germanic Basin it comprises the

Ma	Stage/Substage	Ammonoid Zone/Subzone Standard		Conodont Zone/Subzone				
				Tethys/Western Pacific		North America		
199.6	Upper Rhaetian	Chor. marshi	Choristoceras marshi	Misikella ultima		Norigondolella sp.		
			Chor. ammonitiforme	Misikella koessenensis		Misikella posthernsteini		
206	Lower Rhaetian	"Ch." haueri	Vandaites stuerzenbaumi			Misikella posthernsteini	Misikella hernsteini-Misikella posthernsteini	Orchardella mosheri
			"Choristoceras" haueri					
			Cochloceras suessi					
211	Sevatian		Sagenites reticulatus	M. hernsteini-P. andrusovi		Mockina bidentata		
			Sagenites quinquepunctatus	Mockina bidentata	Subzone 2			
			Halorites macer		Subzone 1			
216	Alaunian		Mesohimavatites columbianus	Mockina postera		Mockina ? serrulata		
					Mockina postera			
					Orchardella elongata			
					Mockina ? spiculata		Mockina ? spiculata	
225	Early Norian ("Lacian")		Juvavites magnus	Epigondolella triangularis-Norigondolella hallstattensis		Epigondolella triangularis		
			Malayites paulcke	Epigondolella quadrata		Epigondolella quadrata		
			Stikinoceras kerri	E. orchardi-N. navicula	M. prim.	M. primitius	M. comm.	
231	Tuvalian		Klamathites macrolobatus	Carnepigondolella pseudodiebeli		Orchardella ? n. sp. "Metapolyg. communisti"		
				Carnepigondolella zoeae		Carnepigondolella zoeae		
			Tropites welleri	Paragondolella carpathica		Carnepigondolella lindae		
				P. postinclinata-P. noah		Paragondolella polygnathiformis		
			Tropites dilleri	Gladigondolella tethydis-Paragondolella polygnathiformis				
				Budurovignathus diebeli-Paragondolella polygnathiformis				
226	Julian		Austrotrachyceras austriacum					
			Trachyceras aonoides					
226	Cordevolian		Trachyceras aon					
			D. canadensis-F. sutherlandi					

Fig. 3:

Upper Triassic stages and substages; ammonoid zonations, Tethyan and North American conodont zonations and numerical ages after KOZUR (2003a, b). Further details see Fig. 1.

two lower short eccentricity cycles of the Calvörde Formation. Higher up, semihumid, semiarid and arid conditions prevailed in the Germanic Basin. Strong climatic changes can also be observed in other continental basins with continuous sedimentation across the PTB, such as in Gondwanan Australia, India and South Africa. There, the humid Late Permian climate with coal-bearing deposit changed into a more arid conditions with predominantly red beds deposition. However, a short humid interval occurred as well in these areas around the PTB, as indicated by a spore-dominated palynoflora. As the abrupt climatic change, and hence the sedimentological change within the uppermost Permian, is a little below the PTB, it can be used to find the PTB in continental successions.

As a whole, almost everywhere there are indications for strong climatic changes in the uppermost Permian close to the PTB, except in the high southern latitudes. These changes are rather abrupt and accompanied by a strong extinction event in the low latitudes.

e) Microsphaerules

From the uppermost *C. changxingensis*-*C. deflecta* Zone to the lower *H. parvus* Zone there is an approximately 0.3 myrs long interval with a relatively high amount of cosmic and volcanic microsphaerules (Fig. 4) consisting of iron oxide or molten silicates, even molten spinels (BACHMANN & KOZUR 2003, BACHMANN et al. 2004). The highest concentration of cosmic microsphaerules with a high Ni and often a high Cr content can be found in the lower Boundary Clay, except its very base. In the *C. zhangi* Zone there occur many microsphaerules as well, mainly of volcanic origin, as indicated by a high Ti content. Most of the microsphaerules have been found in marine sediments (HE 1985, GAO ZHENGANG et al. 1987, HANSEN et al. 1987, TIAN SHUGANG 1991, YIN HONGFU et al. 1992, YIN & ZHANG 1996, DETRE et al. 1998, 2000, MIONO & ZHENG 1998, SOLT et al., 2002), but they occur in continental deposits too (WANG SHANGYAN & YIN HONGFU 2001, BACHMANN & KOZUR 2002, 2003,

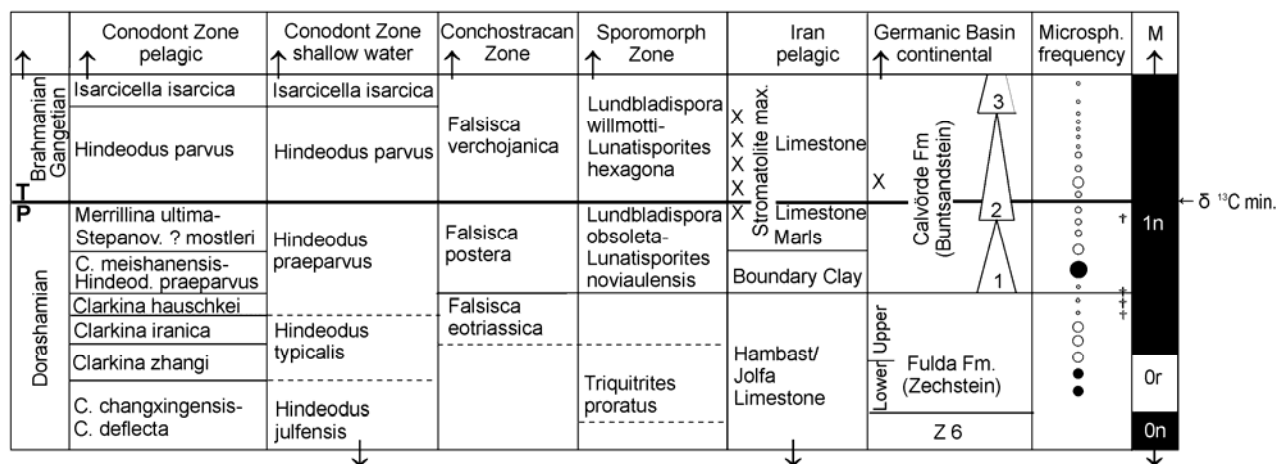


Fig. 4: Conodont, conchostracan, sporomorph zonation, microspore frequency around Permian-Triassic Boundary (PTB) in Iran and Germany. Not to scale.

P – Permian, T – Triassic

M – Magnetostratigraphy after SZURLIES (2004a)

X – Stromatolites

Arrows 1, 2, 3 – short eccentricity cycles

Frequency of microspores:

● – very common, • – common, ○ – moderately common, ◦ – rare, ◌ – very rare (sporadic)

† – levels of mass extinction

max. – maximum

BACHMANN et al. 2003, 2004, PENG YUANQIAO et al., 2002, 2005, in press). In combination with other events they can be used for global stratigraphic correlation, as first proposed by DETRE & DON (1996). Some of the iron oxide microsphaerules are of biotic origin, fills of prasinophyte algae, which occur in both marine and fresh water environments (HANSEN et al. 1987, 2000, YIN HONGFU et al. 1992). Those microsphaerules must not be eliminated for correlation, as Prasinophytes are typical disaster biota, which occur in times of strong ecological stress, as was the case around the PTB. Abundant prasinophyte occurrences around the PTB are not present below and above the mass occurrences of volcanic and cosmic microsphaerules, instead their occurrence is rather more restricted to the interval Boundary Clay to lower *H. parvus* Zone.

f) Microbialites (stromatolites, thrombolites)

Microbialites including stromatolites and thrombolites have a distinct maximum in the *H. parvus* Zone (Fig. 4). They begin either in this zone or in the underlying *M. ultima-S. ? mostleri* Zone. The PTB lies either at the base or, more commonly, within this short interval. Broken stromatolite crusts may occur in continental beds as well, in equivalents of the lower *H. parvus* Zone (BACHMANN & KOZUR 2002, 2003).

In summary, the evaluation of all biota and events around the PTB allows a very detailed correlation around the PTB and the immediately under- and overlying beds, not only within different marine facies, but also with continental beds (see chapter 4).

2.2 Lower Triassic

For a long time only one stage, the Scythian, was used for the Lower Triassic, despite the fact that the Scythian was introduced originally as a Lower Triassic Series. New results have shown that the Lower Triassic is rather short and could fit well into one stage. MENNING (1995) assumed 10 myrs for the Lower Triassic, whereas MENNING (Stratigraphic Table of Germany 2002) reduced it to 7 myrs. LEHRMANN et al. (2002) calculated 4 myrs for the Lower Triassic based on their own radiometric data (247 Ma for the base of the Anisian) and 251 Ma for the base of the Triassic (BOWRING et al. 1998). KOZUR (2003a, b) calculated 5.6 myrs for the Lower Triassic on the base of radiometric data and astronomic calibration with

Milankovitch cycles. Our own investigations have confirmed the latter value.

The stage and substage names and their historical development were discussed in some detail by KOZUR (2003a, b). He stated that the Induan has the worst original definition of all Triassic stages, originally comprising the largest part of the lower Olenekian (Smithian) and the uppermost Permian (KIPARISOVA & POPOV 1956), too. In its present range it corresponds exactly to the Brahmanian of MOJSISOVICS et al. (1895), originally the most precisely defined stage. Thus, for reasons of priority and with regard for the great pioneers of Triassic stratigraphy and palaeontology, the term Brahmanian should be used rather

than the term Induan, which was introduced 60 years later and re-defined differently several times. This is also true for the substage Gangetian, which can be used unchanged (e. g. KRYSYTN et al. 2004). The lower half of Griesbachian, on the other hand, is Permian. The Dienerian is well defined but is a junior synonym to the Gandarian of MOJSISOVICS et al. (1895), which was established earlier for more than half a century. In this paper the priority names Brahmanian Stage, Gangetian Substage and Gandarian Substage are used.

The base of the Gandarian is generally defined with the base of the *Sweetospathodus kummeli* Zone (KOZUR 2003a, b). Only KRYSYTN et al. (2004) used the base of the overlying *Neospathodus dieneri* Zone. From a biostratigraphic standpoint there is no preference for the one or the other zone because *S. kummeli* is neither a *Neospathodus* nor the forerunner of *Neospathodus*. However, the Gandarian Substage would become extremely short if defined with the base of the *N. dieneri* Zone. It would be shorter than the palaeomagnetic 2n interval (see Fig. 1), which comprises only 0.4 myrs according to astronomic calibration (Bernburg cycles 4 to 7, see Fig. 13). The duration of the Gangetian, on the other hand, would be more than 1.3 myrs. If the *S. kummeli* Zone is assigned to the Gandarian, as generally accepted, the duration of the Gandarian is between 0.6 and 0.7 myrs according to astronomic calibration (uppermost part of Calvörde cycle 10 and Bernburg cycles 1 to middle of 7), and that of the Gangetian is somewhat less than 0.9 myrs.

The base of the Olenekian is at the base of the *Flemingites flemingianus* Zone, which coincides with the FAD of *Neospathodus waageni* Sweet. A candidate for the GSSP is Chaohu in China (TONG JIN-NAN et al. 2004), which has ammonoids, conodonts and is thermally not altered, allowing palaeomagnetic investigations. Important new data were published in TONG JIN-NAN et al. (2005, in press). The base of the Olenekian

is immediately below the top of 2n (Fig. 1). This base was checked in the shallow marine section Pufels (Bulla), where SCHOLGER et al. (2000) published very precise palaeomagnetic data with, however, poor chronostratigraphic correlation. They correlated the top of 2n with the middle Dienerian. The top of 2n, however, is situated about 2.6 m below sample Bu 45 of FARABEGOLI & PERRI (1998) with *Pachycladina obliqua* STAESCHE, an undoubtedly Lower Olenekian (Smithian) conodont species. Own re-sampling of a thin limestone bed around the top of 2n yielded *P. obliqua* as well, whereas the deeper samples belong to the *Hadrodontina anceps* zone of the upper Gandarian. Thus, the correlation of the Olenekian base a little below the top of 2n could be confirmed, a very good palaeomagnetic marker for correlation with continental beds in the Germanic Basin.

PAYNE et al. (2004) indicated a strong positive excursion in $\delta^{13}\text{C}_{\text{carb}}$ around the base of the Smithian. Their correlation with the conodont zonation in this level is not very precise because there is a conodont-free interval in their conodont ranges between the top of the *N. dieneri*-*N. cristagalli* fauna of the upper Gandarian and the "*Platyvillosus*" (= *Eurygnathodus*) - *N. waageni* conodont fauna of the Smithian. In the Pufels (Bulla) section, the distinct positive excursion has a maximum at sample Bu 48 of FARABEGOLI & PERRI (1998), according to astronomic calibration about 0.35 myrs above the base of the Smithian, but clearly within the lower Smithian (KORTE et al., in press). The same positive excursion can be found in the Germanic Basin within cycle 11 of the Bernburg Formation, at exactly the same time above the continental Olenekian base.

The base of the Upper Olenekian (Spathian) lies at the base of the *Tirolites* fauna and the base of the *Triassospathodus hungaricus* conodont zone (KOZUR 2003a, b), i. e. within the palaeomagnetic interval 4n.

2.3 Middle Triassic

There is general agreement between the ammonoid and conodont workers to define the base of the Anisian with the FAD of the conodont *Chiosella timorensis* (NOGAMI). The precise distinction of this species from *C. gondolelloides* (BENDER) is important. The platform of *C. timorensis* reaches at least on one side to the posteriormost denticle or surrounds it as a very narrow posterior brim. The platform of *C. gondolelloides*, on the other hand, ends on both sides before the posteriormost denticle. The length of the forms is not decisive because very long *C. gondolelloides* occur already in the lower *C. gondolelloides* Zone. During the Val Gardena Meeting 2003, Prof. E. GRADINARU, Bucharest, and H. KOZUR compared the ammonoid boundary of Gradinaru (at the base of ammonoid horizon GR 7 and DC 3 of the Anisian base GSSP candidate Desli Caira, Romania; GRADINARU et al. 2002, GRADINARU 2003) and confirmed the coincidence of the ammonoid boundary with the conodont

boundary at the FAD of *C. timorensis* according to the above mentioned taxonomic definition.

There is a pronounced positive excursion of $\delta^{13}\text{C}_{\text{carb}}$ around the base of the Anisian (e. g. ATUDOREI 1999, PAYNE et al. 2004, KORTE et al., in press), which can be used for correlating the lower boundary of the Anisian. Important for the correlation with the continental Olenekian-Anisian boundary is the specific palaeomagnetic pattern around this boundary that was first recognised by MUTTONI et al. (1996) in the Kçira section, Albania. As in that time *C. gondolelloides* was considered to be a juvenile form of *C. timorensis*, the boundary was drawn too deep, within the uppermost Spathian. GRADINARU (2003) presented the exact correlation of this palaeomagnetic succession with his ammonoid boundary, which corresponds to the FAD of *C. timorensis* (see above) for the base of the Anisian. The palaeomagnetic pattern around the Olenekian-Anisian boundary

and its correlation is shown in Fig. 1. The base of the Anisian lies within a very short reversed interval between two likewise very short normal intervals.

The base of the Bithynian is defined by ammonoids and conodonts (see Fig. 2; MUTTONI et al., 1996, KOZUR 2003a, b). Auxiliary markers are the FAD of *Costatoria costata* (ZENKER) s. s. with 16–17 extra-areal ribs (in the Aegean *C. costata* has 10–13, rarely 14–15 extra-areal ribs), the FAD of *Myophoria vulgaris* (von SCHLOTHEIM), and, in continental beds, the FAD of *Euestheria albertii albertii* (VOLTZ), the Bithynian index species of Eurasia, North and South America.

The magnetisation of the Lower Anisian (Aegean and Bithynian) is predominantly normal. The lowermost Aegean comprises two short reversed horizons, separated by a short normal interval (Fig. 1), in the lower of which the base of the Anisian is situated (see above). A somewhat longer reversed interval, which can be recognised easily, occurs in the uppermost Aegean to lowermost Bithynian between two long lower Anisian normal intervals. It is important for the correlation of the marine Lower Anisian with continental beds. However, one should not use palaeomagnetic data without careful consideration of biostratigraphy, as this may lead to serious miscorrelations.

The base of the Pelsonian is defined with the base of the *Balatonites balatonicus* Zone, overlying the *B. ottonis* Zone, in the GSSP Aszófő, Balaton Highland (VÖRÖS 2003). In the Germanic Basin the *Balatonites*

ottonis-Acrochordiceras-Noetlingites fauna below the Oolithbank Member of the Jena Formation (Lower Muschelkalk) can be assigned to the Bithynian by ammonoids, e. g. *Acrochordiceras damesi* (NOETLING) and *Balatonites ottonis* (VON BUCH), which are both present in the upper Bithynian strata of the Pelsonian GSSP. These beds were already considered to represent the upper part of the Lower Anisian (upper Bithynian) by KOZUR (1974, 1999), mainly on the base of microfaunas.

The base of the Illyrian is generally placed at the base of the *Paraceratites trinodosus* Zone (Fig. 2).

In 2004, the International Subcommission on Triassic Stratigraphy accepted the base of the *Eoprotrachyceras curionii* Zone as the Ladinian base at the Bagolino GSSP, Southern Alps, Italy (BRACK et al. 2003). The base of the Longobardian, however, is not yet well established, as the *Protrachyceras margaritosum-P. gredleri* Zone is poorly defined by ammonoids. The conodont and radiolarian fauna is equidistant from those of the underlying Fassanian *E. curionii* Zone and the overlying Longobardian *P. archelaus* Zone. The Fassanian would be very short (one ammonoid Zone only), if the agreed base of the *E. curionii* Zone is used as the base of the Ladinian and the base of the *Protrachyceras margaritosum-P. gredleri* Zone as the base of the Longobardian. For this reason we prefer the base of the *P. archelaus* Zone as the base of the Longobardian, but have shown both alternatives in Fig. 2.

2.4 Upper Triassic

BROGLIO LORIGA et al. (1998) proposed the Stuares Wiesen (Prati di Stuares) section in the Dolomites, Italy, with the base of the *Daxatina canadiensis* Zone at bed SW 4 as GSSP for the base of the Carnian. The correlation of this boundary was already discussed by MIETTO & MANFRIN (1995). With this correlation, the base of the *Frankites sutherlandi-D. canadiensis* Zone of British Columbia was included into the Carnian, as already proposed by KOZUR (1976a) based on the faunal character of this zone. The conodont zonation around the Carnian base is not yet well established. *Paragondolella polygnathiformis* (BUDUROV & STEFANOV) s. s. already occurs in the upper Ladinian of Spiti, but *P. noah* (HAYASHI), which was mostly regarded as a junior synonym of *P. polygnathiformis*, may appear at this boundary. This cannot be checked at the GSSP candidate because there is no gondolellid facies.

Close to the base of the *D. canadiensis* Zone there is a distinct change in sporomorphs. About 3.7 m above the base of the zone (total thickness almost 150 m) in the proposed GSSP *Patinasporites densus* LESCHIK, *Vallasporites ignacii* LESCHIK and several other species begin, which are important for the correlation with the Germanic Triassic. The conchostracan species *Laxitextella multireticulata* (REIBLE) begins close to this Carnian base, too. The suggested base of the Carnian at the base of the *D. canadiensis* Zone has a

high correlation potential and is therefore supported by us.

As pointed out by KOZUR (2003a, b), the priority subdivision of the Carnian into the Cordevolian, Julian and Tuvolian substages (MOJSOSIVICS et al. 1895) should be preserved and is used in this paper (Fig. 2, 3). Lumping the original Cordevolian and Julian into a new extended Julian substage (KRYSZYN 1974) violates the priority without convincing faunistic reason. Very characteristic for the Cordevolian is the co-occurrence of Ladinian and Carnian elements in all fossil groups, whereas the Ladinian elements disappear around the base of the Julian (see KOZUR 2003b). The high percentage of Ladinian elements, in addition to the first occurrence of many Carnian forms, is the reason why the Cordevolian was for a long time considered to represent the youngest substage of the Ladinian. Finally, the strong faunistic differences between the Cordevolian and Julian lead to a new two-fold subdivision of the Julian sensu KRYSZYN (1974), i. e. a Julian 1 and a Julian 2 (KRYSZYN 1978). However, the Julian 1 does not correspond to the Cordevolian, because it begins later (at the base of the *Trachyceras aon* Zone) and ranges higher (until the top of the *T. aonoides* Zone s. s., which is part of the original Julian).

The Julian begins with the *Trachyceras aonoides* Zone, which is characterised by both the disappearance of the last Ladinian holdovers and by the appea-

rance of numerous new Carnian or Carnian-Norian types in all stratigraphically important fossil groups, especially well recognisable in radiolarian faunas.

The base of the Tuvalian at the base of the *Tropites dilleri* Zone is, regarding the conodonts, a kind of extinction event characterised by the disappearance of *Gladigondolella* (which, however, occurs only in Tethys). Regarding radiolarians there appear numerous new species, but only a few new genera, partly ranging up to the Jurassic. A correlation of the Julian-Tuvalian boundary with continental deposits is very difficult, because neither changes of the sporomorphs and conchostracans, nor abiotic events (i. e. $\delta^{13}\text{C}$, palaeomagnetism) are well known and dated across this boundary.

Several biostratigraphic boundaries can be used for the base of the Norian. We have chosen the base of the *Stikinoceras kerri* Zone (see Fig. 3), following TOZER (e. g. 1974, 1994), which is close to the FAD of the conodonts *E. orchardi* KOZUR (Neotethys, northern Tethys, ?North America) and the FAD of *M. primitius* (MOSHER) s. s. (North America, Neotethys, but not northern Tethys). This boundary does not show a distinct change in radiolarians, which occurs higher close to the base of the *Epigondolella quadrata* Zone. This latter level would also be suitable as the base of the Norian. MUTTONI et al. (2004) proposed the Pizzo Mondello section as GSSP of the Norian base. We agree with this proposal, because in this section both *E. orchardi* (allowing a correlation with the northern Tethys), and *M. primitius* s. s. (allowing a correlation with North America) are present. Moreover, the rocks in this section are unaltered (CAI = 1), which provides a good palaeomagnetic control (MUTTONI et al. 2004) and hence a good correlation potential with the continental facies. However, further palaeontological studies (e. g. radiolarians) around the Carnian-Norian boundary and detailed investigation of carbon isotopes are needed from the proposed section.

Regarding the conchostracans of continental lake deposits, there is a distinct change from upper Carnian faunas with many strongly sculptured *Laxitextella* (e. g. fauna of the Coburg Sandstone, and contemporaneous faunas in Texas), to weakly sculptured lower Norian fauna of *Howellisaura* and *Euestheria* (e. g. fauna of the Locketong Formation in the Newark Basin). Magnetostratigraphically, this Norian base is in the uppermost E 7n magnetozone (sensu KENT & OLSON 1999, 2000, OLSEN & KENT 1996, 1999) of the Newark Basin, in the uppermost SB 3n.3n magnetozone of Silická Brezová, Slovakia (CHANNELL et al. 1999, 2002, 2003), and in the uppermost PM 4n magnetozone of Pizzo Mondello (Sicily). In all cases mentioned, as well as in the correlations by KRYSZYN et al. (2002) and GALLET et al. (2003), the Tuvalian is characterised by frequent reversals, whereby the normal parts are much longer than the reversed ones. The lower Norian, on the other hand, shows palaeomagnetic zones with relatively short normal and long reversed parts. Close to the Norian base sensu CHANNELL et al. (2003), there is positive shift of $\delta^{13}\text{C}$ from 1.4 to 2.6 ‰ (MUTTONI et al. 2004).

In North America, the base of the Alaunian can well be separated from the lower Norian with both ammonoids and conodonts. In the Tethys there is a clear separation only according to ammonoids, whereas most of the early Norian conodonts continue into the Alaunian. The Alaunian conchostracan fauna in Eurasia and North America is characterised by *Shipingia*, which ranges up into the lower Sevatian.

The base of the Sevatian is well defined in marine beds by ammonoids, conodonts (Fig. 3) and radiolarians. Continental Sevatian biota are not well correlated with marine beds with respect to their lower and upper boundaries. The Sevatian, however, shows a normal magnetisation, except in its lowermost and upper part.

There are many problems regarding the Norian-Rhaetian boundary, mainly because of different definitions of the base of the marine Rhaetian. This can be shown best if the correlation of the different bases of the marine Rhaetian are compared with the astronomically well calibrated Late Triassic of the Newark Basin. CHANNELL et al. (2003) and MUTTONI et al. (2004) calculated 19–20 myrs for the Norian and 6–7 myrs for the Rhaetian. GALLET et al. (2003), on the other hand, came up with 25 myrs for the Norian and 2 myrs for the Rhaetian and, by this, rather with a Norian Subsystem, comprising nearly half of the entire Triassic System, than a Norian Stage. Therefore, an important argument for the position of the Norian-Rhaetian boundary is that the time span of Rhaetian should not be so much reduced that the Norian is of the time-span of a subsystem.

The priority for the base of Rhaetian is quite clear as it was the first of all Triassic stages that was already established by GÜMBEL (1861). Therefore, only the lower boundary of those units, which were assigned to the Rhaetian by GÜMBEL, have to be considered. Later assignments of certain beds to the Norian are irrelevant for priority reasons. GÜMBEL (1861) defined the Rhaetian with the Kössen Beds of the Alps, and in areas outside the Alps with the FAD of *Rhaetavicula contorta*, which is, however, very dependent on facies. Most of the Kössen Beds begin close to the base of the *M. posthernsteini* Zone (GAŹDZICKI et al. 1979), a boundary that was used by CHANNELL et al. (2003) and MUTTONI et al. (2004) for correlating the base of the marine Rhaetian with the continental Newark Basin. However, as shown by GOLEBIEWSKI (1986, 1990) and KRYSZYN (1990), in some places the Kössen Beds begin already within the underlying *M. hernsteini* Zone. Thus, according to priority, the base of the Rhaetian should be either at the base of the *M. posthernsteini* Zone or at the base of the *M. hernsteini* Zone. Any younger boundary would violate the priority. For a long time the Rhaetian was defined with the FAD of *Rhaetavicula contorta*. According to GOLEBIEWSKI (1990) this species begins within Unit 2 of the Hochalm Member of the Kössen Formation, which is its oldest known occurrence. In Unit 2 there is also the FAD of *M. posthernsteini*. The Rhaetian sensu KRYSZYN (in Gallet et al. 2003) would comprise only part of the original upper Rhaetian and, more-

over, this boundary cannot be well correlated on a global scale, not even in marine beds.

An applicable Rhaetian base was proposed by CARTER (1993), who placed it above the top of the *Monotis* beds at the base of the *Paracochloceras amoenum* Zone of North America, which corresponds to the *Cochloceras suessi* Zone and the *Choristoceras ? haueri* Zone of the Tethys. CARTER defined the base with radiolarians at the base of the *Proparvicingula moniliformis* Zone. Most radiolarians of this zone are also present in Panthalassa and Tethys, but the zonal index species occurs only in medium (? and high) latitudes, but not in low latitude Tethys. In Baja California, the conodont fauna of the lower *M. posthernsteini* Zone, with *M. hernsteini* (MOSTLER) and *M. posthernsteini* KOZUR & MOCK, occurs together with radiolarians from the lower *P. moniliformis* Zone (WHALEN et al. 2003, and lecture at Interrad 2003 in Lausanne). The *P. moniliformis* radiolarian zone has to be subdivided into 2 zones, corresponding to Subassemblages 1 and 2 of CARTER (1993). As zonal index forms such species should be chosen, which occurs both in low latitude Tethys, low latitude Panthalassa and in medium latitude deposits of western North America.

The base of the *P. amoenum* Zone can be correlated with the base of the *C. suessi* Zone in the Tethys and would be an ideal marker for the base of the Rhaetian as it can be correlated with the base of the *Orchardella mosheri* Zone in western North America and the base of the *M. posthernsteini* Zone in the Tethys and Panthalassa.

Currently, the base of *M. posthernsteini* (= base of the *C. suessi* ammonoid zone = base of the *Paracochloceras amoenum* Zone = base of the *Orchardella mosheri* conodont zone) is used as the base of Rhaetian. It can easily be correlated, and is in agreement with CHANNELL et al. (2003) and MUTTONI et al. (2004) in

the Tethyan Triassic and with CARTER (1993) and ORCHARD & TOZER (1997) in North America. However, the base of the *M. hernsteini* Zone is left as an alternative base of the Rhaetian. Any base of the Rhaetian younger than the base of the *M. posthernsteini* Zone is rejected because (a) it violates the priority (GÜMBEL 1861), (b) has a low global correlation potential, and (c) would result in too long Norian of subsystem character instead of stage character.

Especially misleading is the term Sevatian 2. Originally introduced for the *Sagenites reticulatus* Zone, it was later used for ammonoid-free deposits, too. GALLET et al. (1996: p. 116) considered *Cochloceras* to be the "Sevatian 2 zonal guide genus". In this case, the entire Sevatian 2 would belong to the Rhaetian *M. posthernsteini* Zone (as used in the paper, CHANNELL et al. 2003, MUTTONI et al. 2004) because the base of the *Cochloceras suessi* Zone coincides roughly with the base of the *M. posthernsteini* Zone (KOZUR 1996). However, GALLET et al. (1996: Fig. 2) show that ammonoids occur only in the upper Sevatian 2 of the Scheiblkogel section, where no conodonts are present, whereas *Misikella hernsteini* is present in the lower Sevatian 2. In contrast to the definition by GALLET et al. (1996), the Sevatian 2 is really defined with the FAD of *M. hernsteini*. Thus, using our Rhaetian base, the Sevatian 2 belongs either entirely to the Rhaetian (ammonoid definition with *Cochloceras*), or the Rhaetian begins within the Sevatian 2 (conodont definition with FAD of *M. posthernsteini*). When the FAD of *M. hernsteini* is used as the base of the Rhaetian, Sevatian 2 would belong to the Rhaetian, but in its original definition it contains also upper Sevatian beds below the FAD of *M. hernsteini*. In summary, the problem of the Sevatian 2 is very important for the correlation of the Germanic Rhaetian with the marine scale because by using Sevatian 2 some Rhaetian faunas would be changed into Sevatian faunas.

3 Germanic Triassic

3.1 Lithostratigraphy and facies

Nowadays, the Germanic Triassic has the rank of a supergroup, consisting of the three groups Buntsandstein, Muschelkalk and Keuper. Each of them is subdivided into three subgroups (e. g. Lower, Middle and Upper Buntsandstein) which consist, in turn, of several formations and members (BACHMANN 1998, BACHMANN et al. 1999, MENNING in STD 2002; Figs. 5–7). Units of formation rank were earlier referred to as "Folge", a term that is sometimes used until today, with a new definition as synchronous or quasi-synchronous units (e. g. MENNING in STD 2002).

The Germanic Triassic may attain a thickness of more than 3000 m in the basin centre. In the more marginal parts it is, on average, some 500–1000 m thick.

3.1.1 Buntsandstein

The first modern lithostratigraphic subdivision of a unit of the Germanic Triassic was established by

BOIGK (1951, 1957, 1959, 1961a, b) for the Buntsandstein based on a combination of geological mapping and well logs in Niedersachsen (Lower Saxony). An updated description of the Buntsandstein is given by LEPPER & RÖHLING (1998).

The base of the Lower Buntsandstein is characterised in large parts of the basin by the sudden change of uppermost Zechstein redbeds of hypersaline sabkha character (Fulda Formation/Bröckelschiefer) into the fluvial and fresh water lake deposits (Calvörde Formation) consisting of sandstones, shales and oolites, so-called "Rogensteine" (roestones). This change was caused by a rather dramatic climatic shift of an arid climate to a short interval of humid climate corresponding to the short eccentricity cycles 1 and 2 of the Calvörde Formation. The base of the Calvörde Formation is drawn at the base of the first distinct sandstone interval. Whereas the lower part of the Cal-

vörde Formation is relatively rich in conchostracans, *Darwinula* and partly charophytes, all indicating dominantly fresh water, its upper part is rather poor in fauna suggesting hypersaline conditions of the playa deposits in an again semiarid to arid climate. A certain brackish influence might have been temporarily present in the lower part of the Calvörde Formation as indicated by the brackish-water ostracod *Callicythere mazurensis* (STYK). However, it occurs there together with *Darwinula* and common conchostracans, indicating fresh water to mesohaline deposits, and, therefore, the brackish influence was obviously very weak. Charophytes, which occur in the central parts of the basin as well, indicate continental lakes and non-marine sedimentation. A marine transgression at the base of the Lower Buntsandstein Baltic Formation in Poland, as assumed by NAWROCKI (2004), can be excluded because of the occurrence of conchostracans, *Darwinula* and charophytes.

The Bernburg Formation begins commonly with a thick oolitic limestone (oolite ζ 1), in the more marginal parts of the Basin with a thick sandstone. Characteristic for the basinal environments is a facies shift from predominantly hypersaline sabkha deposits in the upper Calvörde Formation to conchostracan-rich fresh water playa deposits in the Bernburg Formation.

The Volpriehausen, Detfurth, Hardegsen and Solling Formations of the Middle Buntsandstein are characterised by predominantly fluvial sandstones interfingering with fresh water lake deposits. The individual formations have commonly a thick, often coarse-grained basal sandstone overlying a longer or shorter hiatus, with the exception of the Hardegsen Formation, which follows on the Detfurth Formation without a gap (Fig. 5).

In addition to the traditional formations of the Middle Buntsandstein, RÖHLING (1999) introduced the Quickborn Sandstone, a relatively thick unit occurring between the Bernburg and Volpriehausen Formations in the centre of the basin. If compared with the other formations it can be regarded as a member of the Volpriehausen Formation.

Parts of the predominantly continental Middle Buntsandstein indicate a certain marine or brackish influence, which is strongest in the upper part of the Volpriehausen Formation, the so-called *Avicula* Beds, where it extends from the central parts of the basin into Thuringia. Indicators are acritarchs (SCHÖN 1967) and small brackish-water forms of the otherwise marine bivalve *Bakevella* ("*Avicula*") *murchisoni* (GEINITZ). However, large conchostracans are sometimes mistaken for bivalves, like up to 12 mm long *Magnietheria mangaliensis* (JONES), which is also common in mesohaline brackish intercalations in marine Werfen Beds of Hungary (KOZUR & MOCK 1993). In the Solling area there occur relatively large specimens of *B. murchisoni*, the large *B. ? geinitzi* (FRITSCH) as well as *Unionites* sp., which all indicate a relatively strong marine influence (LEPPER & UCHMANN 1995, KOZUR & LEPPER, in prep.). These beds are probably brachyhaline marine because they

do not contain any conchostracans. Hypersaline playa lake deposits occur in the Solling Formation.

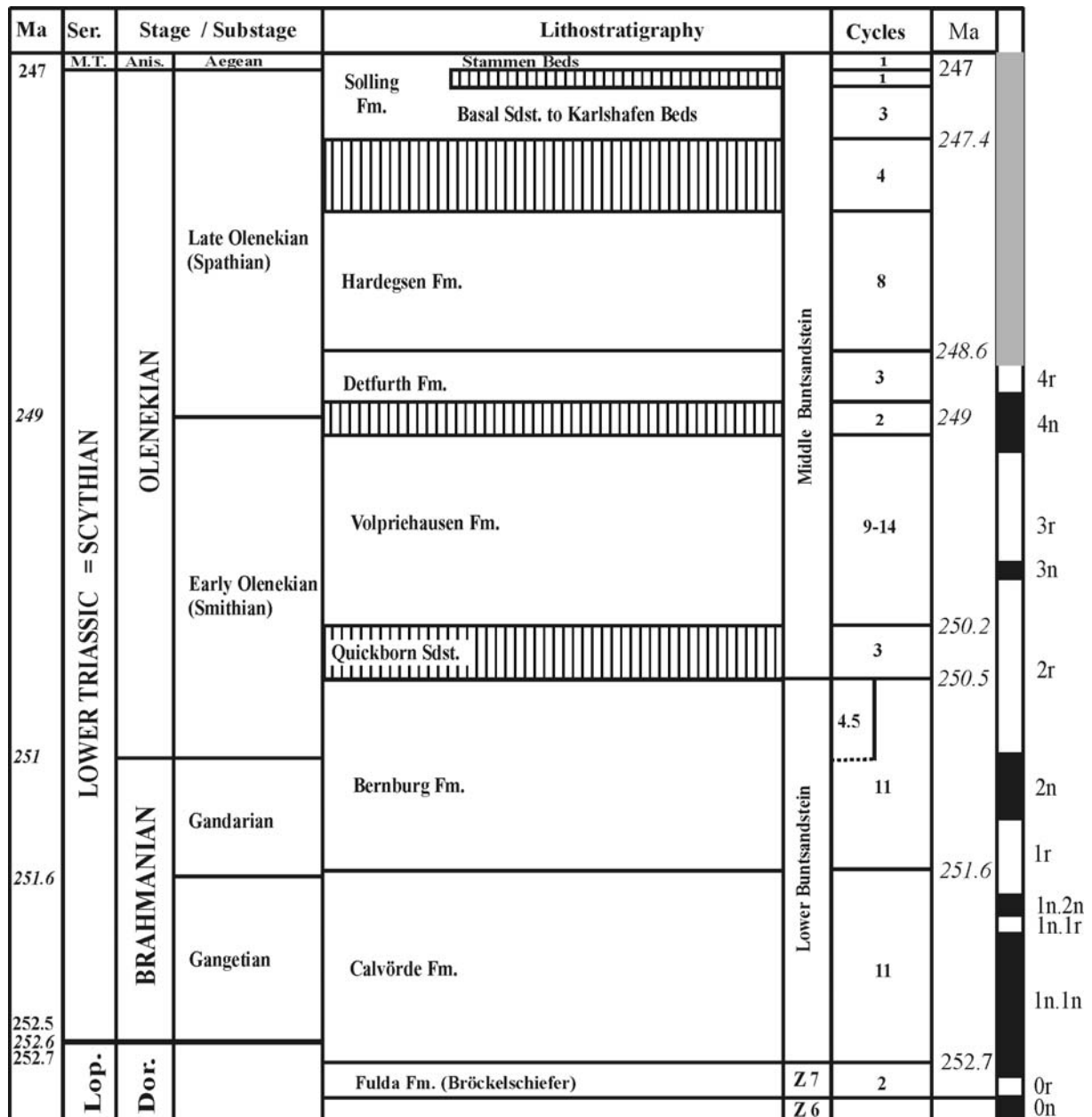
The Upper Buntsandstein (Röt Formation) consists of marine, hypersaline, and brackish deposits. Hypersaline marine beds with gypsum and halite occur at its base. Continental beds (with soil horizons) containing conchostracans, vertebrates and vertebrate footprints are present in the marginal parts of the basin. The conchostracans allow a good correlation within the Röt between marine and continental beds, as they may occur in brackish intercalations of marine beds.

3.1.2 Muschelkalk

The Muschelkalk is the most marine part of the Germanic Triassic and one of the oldest lithostratigraphic terms worldwide (FÜCHSEL 1761). It is subdivided into the fully marine Lower Muschelkalk, the predominantly hypersaline Middle Muschelkalk and the again fully marine Upper Muschelkalk. Traditionally, many units, mostly named after common fossils or typical lithology, have been in use. Several marker beds can be traced in large parts of the basin, like the Terebratelbank in the Lower Muschelkalk or the Cycloidesbank in the Upper Muschelkalk allowing a high-resolution lithostratigraphy. A modern lithostratigraphic subdivision of the Muschelkalk into formations and members has been suggested by HAGDORN et al. (1998). Fig. 6 shows only the major formations in the basinal parts of the Germanic Basin.

The base of the Muschelkalk is in large parts of the central and western Germanic Basin, a quasi-isochronous dolomitic limestone bed, the so-called "Grenzgelbkalk". In Upper Silesia and southeastern Poland, close to the connecting gates to the Tethys realm, the fully marine Muschelkalk facies begins earlier than in the central and western Germanic Basin, in the so-called Lower Gogolin Beds, corresponding to the Myophorienschichten of the upper Röt Formation in the central and western parts of the basin. At the western basin margin, on the other hand, the onset of Muschelkalk facies is later, e. g. the Upper *Voltzia* Sandstone of Lorraine (in Buntsandstein facies) is time-equivalent to the lowermost Jena Formation (Lower Muschelkalk) in the central parts of the basin (KOZUR 1974).

The Middle Muschelkalk begins with the slightly hypersaline dolomites of the Karlstadt Formation overlying the fully marine Schaumkalkbank Member of the Lower Muschelkalk. The Heilbronn Formation is hypersaline and contains anhydrite, gypsum, halite as well as dolomites and shales. An especially interesting facies change occurs in the Diemel Formation of the upper part of Middle Muschelkalk. In the northern parts of the basin a strong fresh water input from northerly to northeasterly directions caused the hypersaline facies to change into oligo- to miohaline brackish grey to reddish marls with many charophytes, *Darwinula* and brackish water ostracods (KOZUR 1971). Further to the south the influence of fresh water caused mesohaline environments and, in Thuringia,



■ Normal polarity □ Reversed polarity ▒ No reliable data

Fig. 5:

Correlation of the Germanic uppermost Zechstein, Lower and Middle Buntsandstein with the biostratigraphic scale, short eccentricity cycles and numerical ages. Compiled radiometric ages from Tethys in normal text, extrapolated numerical ages in italics. Chronostratigraphic correlation of magnetozones of SZURLIES (2001, 2004a, b), modified except around the PTB. Magnetozones sn1, sr1 and sn2 of SZURLIES (2004a, b) are united into one magnetozone termed 1n (sn1 = 1n.1n, sr1 = 1n.1r; sn2 = 1n.2n), as the duration of sr1 is very short (< 80 000 years) and therefore it was not found in Tethys or in South China sections, with sedimentation rates 10 to 100 times less than in the Germanic Basin. Numbers in column "Cycles" = inferred numbers of ~100 kyrs short eccentricity cycles in lithostratigraphic units and calculated duration of gaps in 100 kyrs.

meso- to pliohaline brackish environments. In south-western Germany, the same interval shows a pliohaline brackish to brachyhaline marine environment.

Following this fresh water influx there was an ingress of seawater into the basin, first in its deepest parts. The transgression is indicated by brachyhaline marine limestones with chert nodules that mark the

base of the fully marine limestones and marls of the Upper Muschelkalk. The Upper Muschelkalk of the basin centre is subdivided into the Trochitenkalk Formation and the Meissner Formation (Fig. 6).

The upper boundary of the Upper Muschelkalk is the most diachronous lithological boundary of the Germanic Basin. Following the Cycloidesbank γ , in

Ma	Stage / Substage		Lithostratigraphy		Cycles	
237.0	LADINIAN	Longobardian	Grabfeld Fm (Unterer Gipskeuper) without "Estherienschichten"	Middle Keuper	9	
238 237.9			Erfurt Fm (Lettenkeuper)	Lower Keuper	8	
238.8 239.0		Fassanian			2	
240.5	ANISIAN	Illyrian	Meissner Fm	Upper Muschelkalk	28	
241.5 241.2			CB			Spinosus Zone
			Trochitenkalk Fm			12
		Diemel Fm	1			
		Heilbronn Fm	M. M.	7		
		Karlstadt Fm	1			
		Pelsonian	Schaumkalk Member	3		
			TB	9		
		Bithynian	Jena Fm	Lower Muschelkalk	9	
			OB			
	Aegean	DGB	Upper Buntsandst	7		
		Röt Fm			2	
247			Stammen Beds of Solling Fm		9	
					2	

Fig. 6: Correlation of the Germanic Middle Triassic with the international chronostratigraphic scale, short eccentricity cycles and radiometric numerical ages. Further details see Fig. 5.

the entire northeastern part of the basin, the marine facies of the Ceratitenschichten is replaced by brachyhaline marine to brackish grey shales, siltstones and sandstones with common plants debris, similar to the Lettenkeuper facies. Further to the northeast this facies grades into reddish shales, siltstones and a few

sandstones containing an oligohaline to mesohaline ostracod fauna and charophytes (KOZUR 1971, 1972b, c, 1976b). These facies belts shifted with time in a southwesterly direction until, finally, the Muschelkalk facies was replaced by the Lettenkeuper facies in the entire Germanic Basin (KOZUR 1971, 1976b).

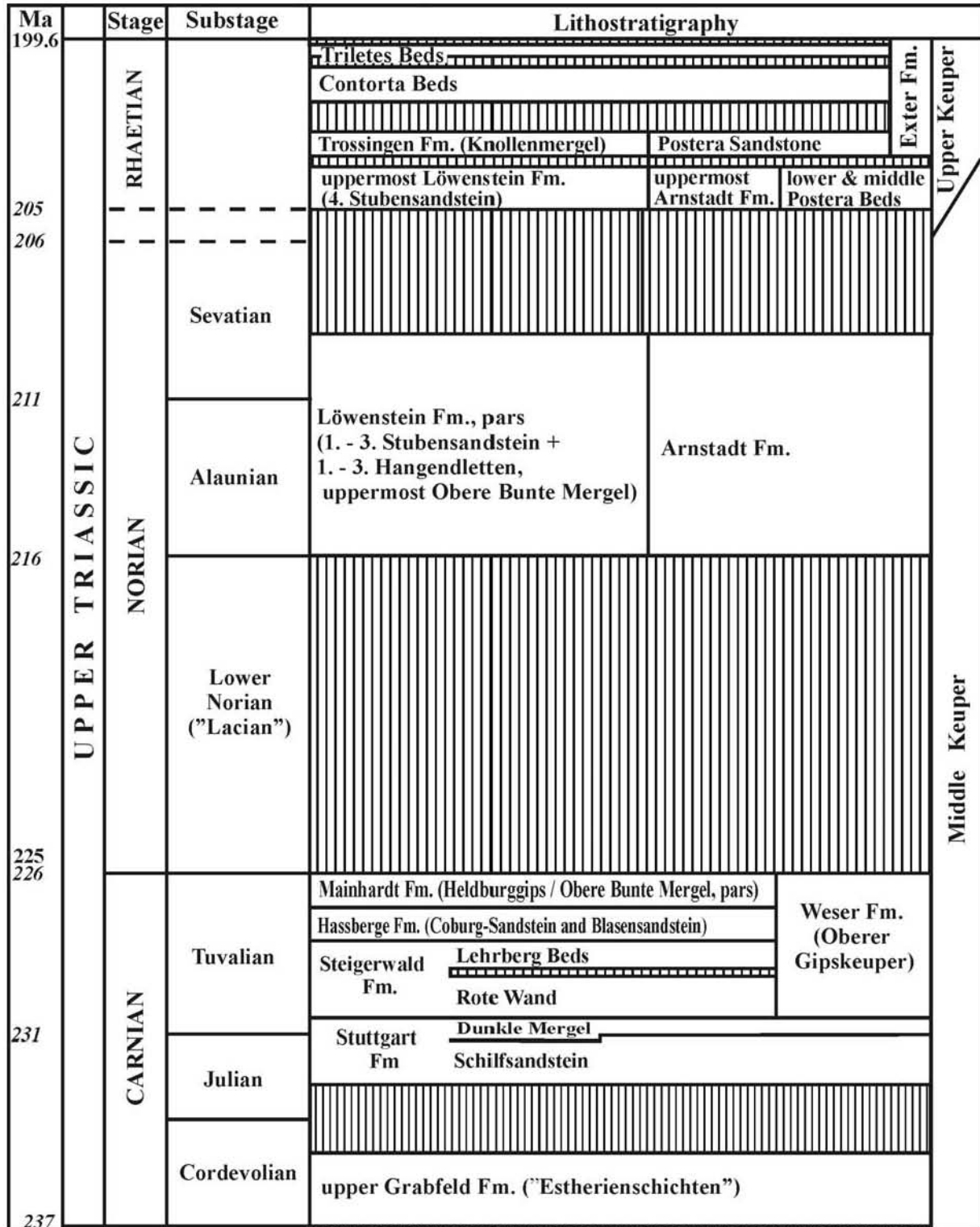


Fig. 7: Correlation of the Germanic Upper Triassic with the international scale and numerical ages. Rhaetian base not yet decided upon (probably at 206 to 205 Ma). Further details see Fig. 5.

3.1.3 Keuper

The term Keuper in a stratigraphic sense was first used by KEFERSTEIN (1824) and HOFFMANN (1825) as a "formation" between the Muschelkalk and Liassic. Like the Buntsandstein and Muschelkalk, it is subdivided into three parts, the Lower, Middle and Upper

Keuper. Following GÜMBEL (1861) the Upper Keuper has frequently been named as the Rhaetian.

BEUTLER (1998) introduced a modern subdivision of the Keuper with 6 formations for the basal facies (Fig. 7). The Lower Keuper (Lettenkeuper, Letten-

kohlenkeuper) was called the Erfurt Formation. The Middle Keuper was subdivided into the Grabfeld Formation (Lower Gipskeuper), Stuttgart Formation (Schilfsandstein and Dunkle Mergel), Weser Formation (Upper Gipskeuper) and Arnstadt Formation (Steinmergelkeuper).

Some problems exist with the uppermost Arnstadt Formation, which is an equivalent to the lower and middle Postera-Schichten. It is separated from the main body of the Arnstadt Formation by a relatively long hiatus (Fig. 7).

The Upper Keuper was called the Exter Formation comprising the marine Contorta-Schichten and, after a short hiatus, the continental Triletes-Schichten and

can be considered, from a genetic standpoint, to represent two formations.

Several large gaps are present within the Keuper (Fig. 7). Many of them have been known for a long time, but were not shown in most lithostratigraphic tables. Their significance was especially shown by WOLBURG (1969), BEUTLER & SCHÜLER (1978), BEUTLER (1979, 1995), DUCHROW (1984a, b), DITTRICH (1989), FRISCH & KOCKEL (1999), NITSCH (2002), NITSCH et al. (2002) and KOZUR & BACHMANN (2003). The time associated with the different hiatuses can be estimated only if there are well-dated beds above or below the hiatus.

3.2 Cyclicity and possibility of astronomic calibration of the Germanic Triassic

3.2.1 Milankovitch cyclicity in the Triassic

In the Quaternary the following Milankovitch cycles can be observed, which can be explained in terms of orbital motion (MILANKOVITCH 1941): precession cycles (19 and 23 kyrs), obliquity cycles (41 kyrs) and eccentricity cycles (95, 123, 413 kyrs). Although the predictability of the earth orbit is lost within a few tens of million years (LASKAR 1989), the duration of the Milankovitch cycles can be also estimated for earlier geological times. Most important is the study of the stacking patterns of the cycles, as was done in the Newark Basin by KENT & OLSON (1999, 2000) and OLSON & KENT (1996, 1999). They found basic so-called Van Houten cycles, short modulating cycles, intermediate McLaughlin cycles, and long modulating cycles. On average, the short modulating cycles contain 5 Van Houten cycles (between 4 and 6, mostly 5), whereas the McLaughlin cycles contain 4 short modulating cycles. OLSON & KENT (1996) assigned the Van Houten cycles to the ~20,000 years precession cycle, the short modulating cycle to the ~100,000 year short eccentricity cycle, the McLaughlin cycle to the ~400,000 year long eccentricity cycle and the long modulating cycle to a ~2 myrs eccentricity cycle. This would mean that the Milankovitch cyclicity of the Triassic is caused by orbital movements similar to the recent ones, with the exception of the ~2 myrs cycle. In the Newark Basin the McLaughlin cycles are best recognised, whereas the ~2 myrs eccentricity cycles are the least distinct. Based on these data, and using 202 Ma for the Triassic-Jurassic boundary, OLSON & KENT (1996) calculated the base of the astrochronologically dated deposits of the Newark Basin at 233 Ma. CHANNELL et al. (1999, 2002, 2003), KRYSZYN et al. (2002), GALLET et al. (2003) and MUTTONI et al. (2004) presented a new correlation of the Newark continental Upper Triassic with the international scale by comparison of magnetostratigraphic data in the Newark Basin (e. g. KENT et al. 1995, KENT & OLSON 2000) with marine magnetostratigraphy in Silická Brezová (Western Carpathians, Slovakia), Turkey, the Alps and Pizzo Mondello (western Sicily). They recognised that the base of the astrochronological dated beds in the Newark Basin (lower Stockton Formation) corresponds

to the lower Tuvallian, which is in agreement with vertebrate correlation (HUBER et al. 1993). Using ~200 Ma for the Triassic-Jurassic boundary (199.6 Ma according to radiometric data from well-dated marine beds by PÁLFY et al. 2000), the base of the astrochronological dated beds of the Newark Basin is at 231 Ma. As discussed by CHANNELL et al. (2003), this fits very well with the base of the Carnian at 237 Ma (5 myrs for the Tuvallian, 6 myrs for the Cordevolian and Julian), and the 238 Ma radiometric age for the *Protrachyceras archelaus* Zone (MUNDIL et al. 1996, PÁLFY et al. 2003). This convincingly confirms the results of KENT and OLSON, and also confirms their assumption that the length of the Milankovitch cycles has not been significantly changed since the Triassic. The only radiometric dating in the entire Late Triassic, the 225 ± 3 Ma for a level close to the base of the Norian (GEHRELS et al. 1986, 1987), coincides with the magnetostratigraphically correlated and astrochronologically dated base of the Norian in the Newark Basin by CHANNELL et al. (2003) at 226 Ma.

Whereas there seem to be few problems with Milankovitch cyclicity in continental playa lake deposits, the evaluation of Milankovitch cyclicity in open-sea marine deposits is often more difficult, as is best demonstrated on the Middle Triassic Latemar carbonate platform. According to HINNOV & GOLDHAMMER (1991) and GOLDHAMMER et al. (1990), a minimum time span of 11 myrs can be estimated for the Latemar platform according to supposed Milankovitch cyclicity when extrapolated to the recorded sequence. According to radiometric dating, however, the sedimentation of the Latemar carbonate platform was much shorter (BRACK et al. 1996, MUNDIL et al. 2003, ZÜHLKE 2003, ZÜHLKE et al. 2003). This suggests clearly the presence of Triassic sub-Milankovitch cycles in marine beds, which seem not to be present in continental playa lake deposits. The basic sub-Milankovitch microcycle on Latemar carbonate platform is 4.2 kyrs. Therefore 4–5 of those microcycles are within one precession cycle of ~20 kyrs. This was the reason why, without knowing the radiometric data, the precession cycles were regarded as ~100 kyrs short eccentricity cycles and the basic sub-Milankovitch microcycles as precession cycles.

Therefore we support the opinion of ZÜHLKE et al. (2003) that “cyclostratigraphic models require an integrated approach including bio- and chronostratigraphic data”, similar to magnetostratigraphy.

Similar sub-Milankovitch cycles, which may, in part, be caused by oceanic tidal cycles, are well known from the Quaternary, too (e. g. 1800 years cycles; KEELING & WHORF 2000).

In open sea marine environments, the orbitally induced insolation changes translate into sea-level cycles by the waxing and waning of ice caps, volume changes of alpine glaciers, thermal expansion and retraction of oceans' surface waters, volume changes in deep-water circulation, and water retention and release in lakes and aquifers (STRASSER & SAMANKASSOU 2003). Under icehouse conditions this may lead to very distinct, but often highly asymmetrical, cycles with high amplitude, above all the 100 kyrs eccentricity cycles. During greenhouse conditions, as was the case in the Triassic, the volumes of ice were not sufficient to induce significant glacio-eustatic fluctuations of the sea-level. At that time only the other processes mentioned above may cause cyclic sea-level fluctuations, but with low amplitude and more symmetrical cycles (STRASSER & SAMANKASSOU 2003). These orbitally induced low amplitude cyclic sea-level fluctuations are difficult to distinguish from other low amplitude cyclic sea-level fluctuations. Moreover, sedimentary cyclicity may become overprinted by non-cyclic tectonic events, current-transported sediments and by local factors, like pre-existing morphology of the sea floor that may have influence on carbonate-producing organisms, fluctuations in productivity by climatic changes, different nutrient supply etc.

In Triassic continental playa lakes, the cyclic climatic changes had a direct influence on sedimentation, mainly by cyclic changes in humidity and aridity, thus causing considerable fluctuations of water influx into the lakes. This resulted in different amounts and grain-sizes of transported sediments, pronounced fluctuations of water depth and size of the lakes, cyclic changes of fresh water and hypersaline conditions, and hence the deposition of evaporites. Tidal-forced cyclic changes and other sub-Milankovitch cyclicity do not exist in the continental realm, and the sedimentation rates are not substantially influenced by bioproduction. Vegetation may have some influence on the rates of sedimentation, but not on its cyclicity. The shortest distinct cycles, as it seems, can be attributed to the ~20 kyrs precession cycle. If cross-correlation with marine beds is possible, a very high time resolution can be expected, e. g. for the Newark Upper Triassic, Lower Buntsandstein and other units of the Germanic Triassic.

3.2.2 Milankovitch cyclicity in the Germanic Triassic

Many sediments of the Germanic Lower and Middle Triassic show a well developed cyclicity. The cycles occur in continental, mixed continental-marine, marine and hypersaline deposits and are best recog-

nised in the basinal facies of terrestrial playa lake systems. Most of the cycles are between 1–2 m and 10–25 m thick and have often been used, by purpose or unconsciously, for stratigraphic subdivision and correlation (“lithostratigraphic cycles”). At the first glance they are mostly asymmetrical “fining-upward”, “coarsening-upward” or “shallowing-upward” cycles, similar to the “parasequences” of sequence stratigraphic concepts. Alternatively, they can sometimes be interpreted as more or less symmetrical “transgressive-regressive cycles”, “baselevel cycles” or “high-frequency sequences”. Although important for sedimentological studies, the type of interpretation seems to be of minor significance for the recognition of Milankovitch signals. This paper postulates that most small-scale cycles of the Germanic Triassic are Milankovitch cycles and uses them for calculating the time span of the individual formations and members as well as for the improvement of the numerical ages of cross-correlated stage boundaries. We are well aware of the possible pitfalls of our approach and consider it as a step to further, more thorough, evaluations including time-series analyses (WEEDON 2003).

Not all cycles present are Milankovitch cycles, but from the Buntsandstein to the Middle Muschelkalk most seem to represent well pronounced ~100,000 year eccentricity cycles. To identify the cycle stacking pattern as a Milankovitch cyclicity, an average of five precession cycles (mostly 5, sometimes 4, rarely 6; as in the Newark Basin, see above) should be present in each short eccentricity cycle throughout a continuous succession consisting of several short eccentricity cycles. Even more convincing is Milankovitch cyclicity, if ~400,000 year eccentricity cycles can be recognised as well.

In general, the short eccentricity ~100,000 year cycles are best developed in the Lower and Middle Triassic of the Germanic Basin and have, therefore, been used as the base of lithological cycles. Precession cycles (~20,000 years) are more or less well developed, too. However, ~400,000 year eccentricity cycles are not well developed in most formations, much in contrast to the Newark Basin, where ~400,000 year (McLaughlin) cycles are developed best. The different manifestation of Milankovitch cyclicity in the Germanic Basin (situated north of the Triassic Tropic of Cancer) and the Newark Basin (situated around the palaeoequator) is, perhaps, caused by the different palaeolatitudes. However, there is another possible explanation. If the data of TOUGIANNIDES (2004) can be confirmed that the best recognisable cycles in the middle to upper Norian Arnstadt Formation (Steinmergelkeuper) are indeed ~400,000 year cycles, this would suggest a remarkable coincidence to the Upper Triassic of the Newark basin. Thus, possibly, for reasons still unknown, the ~100,000 year short eccentricity cycles would be best developed in the Lower and Middle Triassic, as is the case in the Germanic Basin, and the ~400,000 year cycles in the Upper Triassic (at least the Norian), as in the Germanic Basin and the Newark Basin.

Obliquity cycles of ~40,000 years are not, or not

well, recognisable, neither in the Upper Triassic of the Newark Basin nor in the Germanic Lower and Middle Triassic. However, for the marine Middle Triassic Latemar carbonate platform, the ~40,000 year obliquity cycles are readily recognised, the ~20,000 year precession cycles and the ~100,000 year short eccentricity cycles as well, but not the ~400,000 year cycles (MUNDIL et al. 2003, ZÜHLKE et al. 2003). The latter is understandable because even in continental lake deposits, with very well developed precession and short eccentricity cycles, the ~400,000 year cycles are mostly not well recognisable in the Lower and Middle Triassic. To date it is not possible to decide if cycles of 2 myrs are present in the Germanic Triassic because of the many gaps.

Lower Buntsandstein cycles

Best investigated is the cyclicity of the Lower Buntsandstein as shown for the Calvörde Formation in Figs. 8–10 after SZURLIES (2001). Most obvious in the basinal facies are 10–20 m thick fining upward-cycles with sandstones and oolites at their bases and shales in their upper parts (e. g. BEST 1989, BRÜNING 1986, PAUL & KLARR 1987, RÖHLING 1991, 1993, SZURLIES 2001, 2004a, b). They can well be recognised in outcrops and gamma-ray logs of boreholes and can be correlated in large parts of the basin and have been interpreted as ~100,000 year eccentricity cycles, e. g. by PAUL (1993), Szurlies (2001) and GELUK & RÖHLING (1999). This is supported by their subdivision into 5, sometimes 4, smaller cycles, which we interpret to represent ~20,000 year precession cycles (Figs. 8, 9).

According to GELUK & RÖHLING (1999) and SZURLIES (2001) the Calvörde Formation consists of 10 short eccentricity cycles. We interpret 11 Milankovitch cycles by subdividing cycle 4 sensu SZURLIES into two subcycles 4 a and 4 b, each of which represents one ~100,000 year short eccentricity cycle and consists, in turn, of 5 or 4 ~20,000 year precession cycles (Figs. 5, 8, 9). The ~400,000 year eccentricity cyclicity can be only recognised if lithocycle 4 is subdivided into two short eccentricity cycles resulting in two complete and 3/4 of a third long eccentricity cycle to be present in the Calvörde Formation (Fig. 10). The sandy intervals at the bases of the individual ~100,000 year cycles are much thicker than in the underlying Fulda Formation of the Zechstein (Figs. 8, 10). This is the expression of strong climatic change, from a long lasting arid climate in the Zechstein to a more humid climate in the Lower Buntsandstein, causing a relatively high fluvial input of coarser clastic material (see chapter 2.1).

SZURLIES (e. g. 2001) defined 10 lithostratigraphic cycles in the Bernburg Formation of similar character as in the Calvörde Formation. The uppermost cycle 10 contains the conchostracan fauna of the *M. subcircularis* Zone. Conchostracan studies suggest one more cycle exists in the Halle area and in the Solling Mountains, which contains the *M. truempyi* Zone and the lower *M. rybinskensis*-*L. radzinskii* Zone, resulting in a total of 11 cycles (Fig. 5, 13; KOZUR & SEIDEL 1983a, b, KOZUR & LEPPER, in prep.). The underlying cycle

10 in these areas also belongs to the *M. subcircularis* Zone. The presence of an 11th Bernburg cycle in the Solling Mountains with its very characteristic conchostracan faunas is important, as RÖHLING (1991, 1993) and GELUK & RÖHLING (1999) defined 14 cycles in the more central parts of the basin including the Solling Mountains. Thus, it seems that not all cycles of GELUK and RÖHLING are short eccentricity cycles.

Middle Buntsandstein cycles

The several 100 m thick Middle Buntsandstein consist of numerous fining-upward cycles similar to those of the Lower Buntsandstein, but with many more sandstones. In the Volpriehausen Formation, 17 lithostratigraphical cycles were defined by GELUK & RÖHLING (1999), but only 9 cycles by SZURLIES (2004b). Similar to the Bernburg Formation, the area investigated by SZURLIES is not in the basin centre, where the number of cycles should be higher than 9. The 17 cycles of GELUK & RÖHLING (1999), on the other hand, are most likely not all short eccentricity cycles. Currently, our best estimate is that the Volpriehausen Formation has between 9 and 14 short eccentricity cycles, and we have used 11 cycles for calculating its duration (Fig. 5). ROMAN (2003) determined 4 lithostratigraphic cycles in the Volpriehausen Formation, which can be correlated from Germany to Poland, but do not represent Milankovitch cycles.

The cyclicity of the Detfurth, Hardegsen and Solling formations is established only in part (BINDIG 1991, RÖHLING 1991, GELUK & RÖHLING 1999). Therefore, the respective 3, 8 and 5 Milankovitch cycles of these formations are only preliminary estimations (Fig. 5). Additionally, the biostratigraphic and time intervals of the gaps in the Middle Buntsandstein have to be estimated and taken into account for numerical calculations (Fig. 5). The first, however, is only possible if the under- and overlying beds have different sporomorph associations or faunas and the missing biostratigraphic unit is known outside of the Germanic Basin. For instance, the upper Hardegsen Formation is characterised in the basinal facies of Germany by a *Densoisporites nejburgii* association with few *Cyclo-verntriltes presselensis* Schulz. Overlying the Hardegsen Formation and the so-called “H-Unconformity” there occurs in the lower Solling Formation an association dominated by *Voltziaceasporites heteromorphus* Klaus, which contains only a few *D. nejburgii* (SCHULZ) Balme. In the upper, but not uppermost, Csopak Marl Formation of Hungary there is a further association between two sporomorph associations, which are very similar to those of the Germanic Basin below and above the “H-Unconformity”. It is dominated by *D. nejburgii* but also containing 11–25 % *V. heteromorphus*. In its lower part rare *C. presselensis* is present. This interval corresponds to the *T. homeri*-*T. triangularis* Zone of middle Spathian age. In this case the biostratigraphic interval, which is absent in Germany (but in its lower part present in central Poland; KOZUR 1999) due to the “H-Unconformity”, can be recognised rather well. This helps to estimate the duration of the gaps, but, as no radiometric ages or

Milankovitch cycles were investigated in the Olenekian of Tethys, the duration of the gaps within the Olenekian of the Germanic Basin can only be estimated approximately (Fig. 5).

Upper Buntsandstein cycles

9 cycles are recognised in the 150–300 m Upper Buntsandstein Röt Formation (EXNER 1999). As most of them can be subdivided into 5 smaller cycles, we consider them as short eccentricity cycles.

Muschelkalk cycles

The Lower Muschelkalk (Jena Formation) is about 100 m thick and consists mostly of marine marlstones, thin-bedded micrites and intercalated bioclastic or oolitic limestones that show a pronounced cyclicity, first recognised by FIEGE (1938). Detailed work by several authors (e. g. GÖTZ 2002, 2004, GÖTZ & FEIST-BURKHARDT 2000, GÖTZ & WERTEL 2002, KEDZIERSKI 2002) identified some 20 small-scale cycles that are mostly a few metres thick and were interpreted as either asymmetrical shallowing-upward parasequences or more or less symmetrical baselevel cycles or high-frequency sequences. We agree with GÖTZ (2004) that the 20 cycles of the Jena Formation and the beginning of a 21st cycle are short eccentricity cycles (Fig. 6). We assign the same numbers of cycles as GÖTZ (2004) did to the individual members of the Jena Formation, i. e. the three Wellenkalk Members, which are subdivided by the Oolithbank Member (OB) and the Terebratelbank Member (TB). However, for the Schaumkalkbank Member, which has two cycles and the beginning of a third cycle (GÖTZ 2004), we assign 3 cycles, as BRÜCKNER-RÖHLING & HEUNISCH (2004) did, to avoid decimals in the cycle numbers of the Schaumkalkbank Member (and by this in the Jena Formation) and the overlying Karlstadt Formation of the Middle Muschelkalk. Altogether, there are 4 short eccentricity cycles in the Schaumkalkbank Member and the Karlstadt Formation, whereby one of them straddles the formation boundary.

The nine shallowing-upward evaporite cycles of the, on average, 100 m thick Middle Muschelkalk (e. g. RÖHLING 2002, BRÜCKNER-RÖHLING & HEUNISCH 2004) can all be interpreted as short eccentricity cycles (Fig. 6). Each of the cycles is normally about 10 m thick and can be correlated in large parts of the basin. In areas of high subsidence, however, the Middle Muschelkalk may attain thicknesses of several 100 m. This is mainly due to thicker-than-normal salt deposits in some of the cycles.

The Upper Muschelkalk, which is on average 100 m thick, consists in most parts of the basin of an alternation of well-bedded marlstones, micritic and bioclastic limestones. Its pronounced cyclicity was first established by AIGNER (1985) and RÖHL (1988). AIGNER determined up to 13 shallowing-upward cycles between the base of the Upper Muschelkalk and the Spiriferinabank, and up to 19 cycles between the Spiriferinabank and the base of the Hauptterebratelbank. Four further cycles are present from the Hauptterebratelbank to the top of the Upper Muschelkalk.

At least three of AIGNER's cycles can be further subdivided into two or three cycles (e. g. AIGNER 1985: Fig. 76, section 27, from below: cycle 8 twofold subdivision, cycle 12 threefold subdivision, cycle 13 twofold subdivision). Thus, as a whole, some 40 cycles can be recognised. As the Upper Muschelkalk comprises about 4 myrs (according to dense radiometric dating of the biostratigraphically correlated beds in the Southern Alps and Hungary) they most likely represent short eccentricity cycles (Fig. 6). However, only few of these cycles show precession cycles. GAERTNER (1993) determined only 10 cycles in the Upper Muschelkalk, but they cannot be compared with those by AIGNER (1985), as they are exclusively based on gamma ray and sonic logs. The time relation of Lower, Middle and Upper Muschelkalk is 20:9:40, whereas GAERTNER's (1993) cycle relation is 13:13:10, thus obviously not related to Milankovitch cyclicity.

Keuper cycles

NITSCH (2005, in press) gives a detailed review of Keuper cyclicity.

The Lower Keuper (Erfurt Formation), from which an average thickness of 30–50 m has been recorded, consists of an alternation of shales and dolomitic carbonates with some fine-grained channelised sandstones of variable thicknesses. The formation exhibits a pronounced cyclicity across the basin. Based on earlier work of SEIDEL (1965) and KÄSTNER (1972), BEUTLER & SCHUBERT (1987) and BEUTLER et al. (1999) determined 6 cycles across the entire Germanic Basin. PÖPPELREITER (1998) determined 10 symmetrical baselevel cycles and AIGNER et al. (1990) 12 shallowing-upward cycles. Our tentative best estimate are 8 short eccentricity cycles (Fig. 6), each which contain 5 or 4 cycles, which may be precession cycles. The duration of the gap between the Muschelkalk and Keuper is unknown, the supposed 0.2 myrs are certainly a maximum value.

The lower Grabfeld Formation (below Estherien-schichten) is on average 100–150 m thick and consists in large parts of the basin of shaly redbeds with dolomite beds and gypsum layers (BEUTLER et al. 1999). Thick halite deposits occur in some parts of the basin centre and the South German subbasin. VON FREYBERG (1954, 1965) was among the first who described the pronounced cyclicity of the Grabfeld Formation. He determined 4 large prograding fining-upward cycles in the marginal Benk facies of northeastern Bavaria. HAUSCHKE (1985) and HAUSCHKE & RÖHL (1988) described some 26 small-scale cycles in the lacustrine basinal facies of northwestern Germany between the base of the Grabfeld Formation and the Bleiglanzbank equivalent. In southwestern Germany, AIGNER & BACHMANN (1992a, b) defined 17 (–19) small-scale cycles between the base of the Grabfeld Formation and the Bleiglanzbank. Most of these shallowing-upward cycles are only 1–2 m thick. These contain abundant gypsum that can be deposited rapidly. It is thought that they represent precession cycles. This would correspond to 4 short eccentricity cycles. NITSCH (1997) described similar small-scale cycles stacked

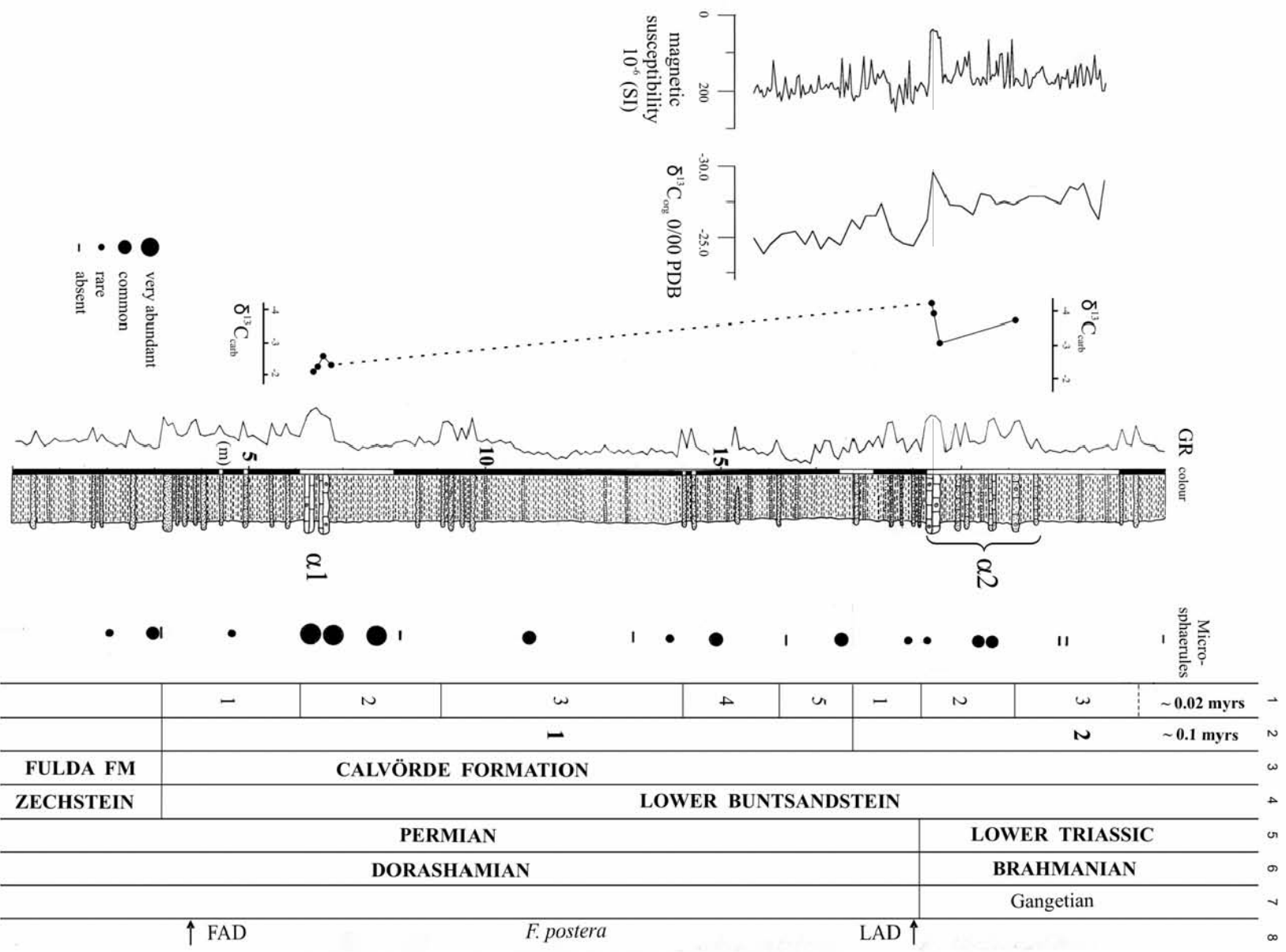


Fig. 8:

Uppermost Zechstein (Fulda Formation) and lowermost Buntsandstein (lower Calvörde Formation) at Nelben section near Könnern, 25 km NW of Halle (SZURLIES 2001).

GR = Gamma Ray Log; colour bar: black = red to reddish brown lithology, white = grey to green lithology;

α 1, α 2 = Oolite horizons α 1, α 2; short eccentricity cycles (column 2) after SZURLIES (2001);

magnetic susceptibility and δ¹³C_{carb} after H. J. HANSEN, Copenhagen (pers. comm.);

δ¹³C_{carb} after KORTE & KOZUR (in press); chronostratigraphy after KOZUR (1999).

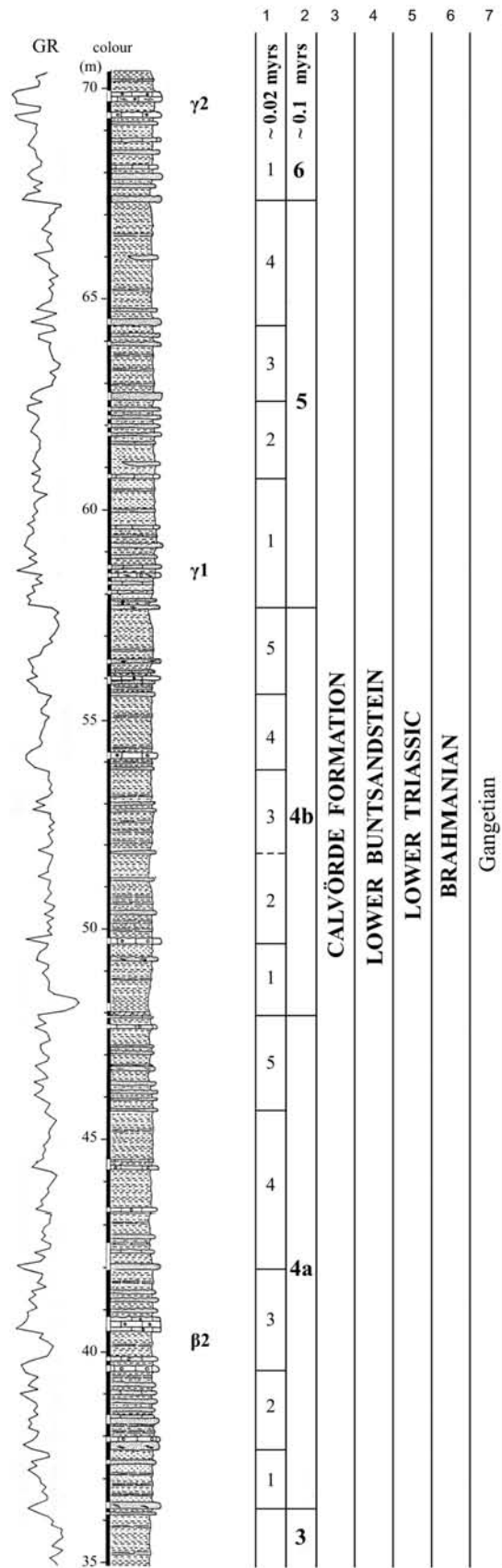


Fig. 9:

Lower Buntsandstein (Calvörde Fm) in part (cycles 4 and 5) of the Thale section, 55 km SW of Magdeburg. Gamma Ray Log (GR) after SZURLIES (2001); cycle 4 subdivided into two short eccentricity cycles (4a, 4b) with precession cycles added. Precession cycles 2 and 3 of eccentricity cycle 4b may be one precession cycle. Further details see Fig. 8.

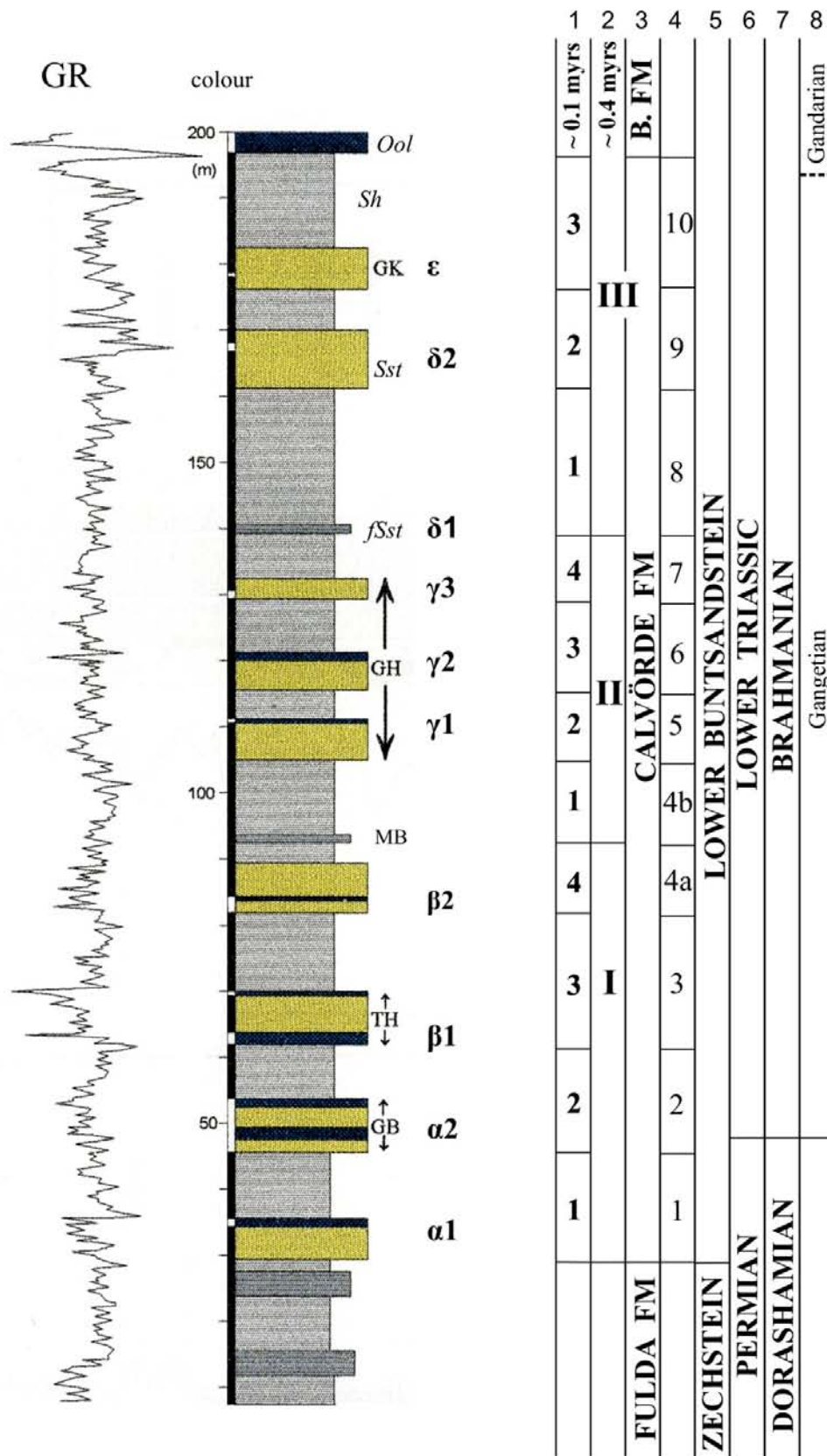


Fig. 10: Schematic of uppermost Zechstein (Fulda Formation) and Lower Buntsandstein (Calvörde Formation) in Remlingen 5 well, 20 km SSE Braunschweig. Gamma Ray Log (GR) and lithocycles (column 4) after SZURLIES (2001). Cycle 4 subdivided into two short eccentricity cycles (4a, 4b); short eccentricity cycles (column 1) and long eccentricity cycles (column 2). Lithology: *Ool* = oolitic carbonates, *Sh* = shale, siltstone, *Sst* = sandstone, *fSst* = fine sandstone. Marker horizons: *GK* = Grobbank, *GH* = Gamma Horizont, *Mb* = Malachitbank, *TH* = Thale Horizont, *GB* = Graubankbereich; colour bar: see Fig. 8.

into 2 mesocycles between the base of the Grabfeld Formation to the base of the Bleiglanzbank, which are over long distances recognisable, but cannot be assigned to any Milankovitch cyclicity.

The interval between the Bleiglanzbank and base of the Engelhofen Horizont (Acrodus-Corbula Horizont) consists of an alternation of shaly redbeds with dolomite beds and gypsum layers. Brunner (1988) determined 4 units (based on different rock colours) that contain up to 25 small-scale cycles, which we consider to be precession cycles. NITSCH (1997) described 3 mesocycles that consist of numerous small-scale cycles. We have tentatively assigned 5 short eccentricity cycles for that interval, resulting in a total of 9 short eccentricity cycles for the Grabfeld Formation below the Estheriensichten (Fig. 6). A supposed hiatus at the base of the Engelhofen Horizont (upper Grabfeld Formation; Carnian) is probably very short and we have assigned only 0.1 myrs to this.

In summary, Erfurt Formation and lower Grabfeld Formation (Longobardian) together exhibit approximately 17 short eccentricity cycles. This results, including gaps, in some 2 myrs, which fits well with the time span of the Langobardian (Fig. 6).

The Upper Triassic is several 100 m thick and consists mostly of shaly redbeds, fluvial sandstones and some gypsum deposits (BEUTLER et al. 1999). Halite deposits occur in some parts of the basin centre. Cyclicity is, to date, not yet well established and needs further work. Several long gaps in the stratigraphic record have impeded the calculation of numerical ages (Fig. 7). The predominantly fluvial sandstones and shales of the 20–60 m thick Stuttgart Formation (Schilfsandstein) may comprise three cycles (BACHMANN & BEUTLER 1996). Milankovitch cyclicity is not attributed because

of a basal hiatus and additional internal gaps of unknown duration as well as the lateral shift of the river systems.

In the Weser Formation and its equivalents (Fig. 7) there is a distinct cyclicity of different scales in the basinal shaly redbeds as well as in the more fluvial deposits of the basin margin (e. g. FREYBERG 1965, BRENNER & VILLINGER 1981, SEEGIS 1996, BACHMANN et al. 1998: p. 189, HORNING & AIGNER 2004). Strong pedogenic overprint may, however, obliterate bedding and cycles in some parts (BEUTLER et al. 1999).

Promising attempts have been made to establish Milankovitch cyclicity in the marlstones and dolomites of the Arnstadt Formation (KELLNER 1997, REINHARDT & RICKEN 2000, TOUGIANNIDES 2004). TOUGIANNIDES (2004) established in the main part of the Arnstadt Formation numerous precession, obliquity and short eccentricity cycles that bundle to 17 long eccentricity (~400,000 years) cycles, which would correspond to 6.8 myrs. If it can be confirmed that ~400,000 years cycles are best developed in the Norian Arnstadt Formation, much in contrast to the Lower and Middle Triassic formations of the Germanic Triassic, this would be a remarkable coincidence to the Norian of the Newark Basin. An open question is the relation to large prograding fining-upward cycles of the marginal facies in southwestern Germany (e. g. Löwenstein Formation; FREYBERG 1965, BRENNER & VILLINGER 1981).

No cycles were determined so far in the Exter Formation, but it seems to be possible, especially in the central and western part of the Germanic Basin (SEELING 2000, SEELING & KELLNER 2002).

4 Correlation of the Germanic Triassic with the international scale

4.1 Buntsandstein

The correlation of the Lower and Middle Buntsandstein is mainly based on conchostracans (Figs. 11–13), which are well correlated with marine faunas (e. g. KOZUR 1993b, 1998a, b, 1999, KOZUR & MOCK 1993). KOZUR et al. (in press) revised some conchostracan zones of Lower Buntsandstein, and correlated them with the cycles and magnetozones (Fig. 13) as established by SZURLIES (2001) and modified in this paper.

The PTB (base of the Gangetian Substage of Brahmanian Stage) was placed by KOZUR (e. g. 1993a, b, 1998a, b, 1999) at the boundary between the *Falsisca postera* and *F. verchojanica* conchostracan zones. This boundary is found in the entire central part of the Germanic Basin, but can also be recognised in more marginal parts (PTASZYŃSKI & NIEDŹWIEDZKI 2004b, 2005, in press, for the Holy Cross Mts). This boundary can be confirmed by sporomorph and abiotic events, e. g. by a distinct minimum in $\delta^{13}\text{C}_{\text{org}}$ (Fig. 8; H. J. HANSEN, Copenhagen, pers. comm., HIETE 2003, 2004,

HIETE et al. 2004) and $\delta^{13}\text{C}_{\text{carb}}$ (Figs. 4, 8; KORTE & KOZUR, in prep.). Furthermore it is supported by a set of events at and below the PTB that can also be recognised in pelagic PTB sections of China and Iran (Fig. 4; see section 2.1). The PTB is in the lower part of the so-called Oolith α 2, one precession cycle above the base of the second short eccentricity cycle of the Calvörde Formation, i. e. ~120,000 years above the base of the Buntsandstein (Figs. 4, 8).

NAWROCKI (2004) and NAWROCKI et al. (2005, in press) correlated the PTB with a short reversed magnetozone within the uppermost Zechstein, named “Or” in Fig. 5. The reason for this correlation was an assumed short reversed interval around the PTB of Meishan, which was already rejected by KOZUR (2004) and SZURLIES & KOZUR (2004), and is now shown not to be present by new measurements of Chinese and Japanese specialists (pers. comm. Prof. YIN HONGFU, see section 2.1).

The base of the Gandarian is correlated with the

base of the *M. seideli* Zone in the upper part of cycle 10 of the Calvörde Formation. Outside of the Germanic Basin, the strongly spined Vertexiidae of this zone are only known from the Gandarian. TONG JIN-NAN et al. (2005, in press) have shown that the base of the *S. kummeli* Zone, corresponding to the base of the pelagic marine Gandarian, lies in Chaohu (China) in the middle part of a reversed magnetozone. If this position is real (and not only caused by graphic presentation), the base of the Gandarian would be one ~100,000 years cycle higher, within the upper part of cycle 1 of the Bernburg Formation. SZURLIES (2001) found this reversed horizon (1r in Figs. 1, 5 and 13) in the Germanic Basin, where it ranges from the middle part of cycle 9 of the Calvörde Formation up to the top of cycle 3 of the Bernburg Formation. Currently, the Gandarian base is placed at the biostratigraphic boundary (base of *M. seideli* Zone).

KOZUR & SEIDEL (1993a, b) have shown the base of the Olenekian (base of Smithian, in that time named as Jakutian) to be within the upper Bernburg Formation, and KOZUR (1993a, b, 1999), KOZUR & MOCK (1993) and KOZUR & LEPPER (in prep.) gave additional evidences. Most of the Smithian index species are known from sections with interfingering of marine and brackish to fresh water beds in the Tethys and in Siberia (KOZUR & MOCK 1993). SHEN YANBIN et al. (2002) found *Magnietheria truempyi* KOZUR & SEIDEL, the index species of the second highest conchostracan zone of the Bernburg Formation, even in Madagascar close to marine beds with *Flemingites*, the ammonoid index genus of the lower Smithian.

MENNING (2000) adopted that correlation, which is also shown in MENNING & GSC (2002). SZURLIES (2004a, b) and NAWROCKI et al. (2005, in press), however, correlated even the lower Volpriehausen Formation with the Gandarian (Dienerian). The reason for this miscorrelation seems to be in part an erroneous correlation of the respective magnetozone by SCHOLGER et al. (2000), who extended the Gandarian (Dienerian) to at least the middle of the Campil Member (upper Smithian). The correlation of the magnetozone by SCHOLGER et al. (2000) around the Olenekian base is discussed in section 2.2. As pointed out there, it is only somewhat below the top of magnetozone 2n, as was also shown by TONG et al. (2005).

BEUTLER & SZULC (1999) placed the base of the Olenekian within the lower Polczyn Formation of Poland corresponding to a level within the Detfurth Formation. *Densoisporites nejbürgii* (Schulz) Balme is strongly dominant in this level, as it is typical for lower Spathian. Thus, the correlation by BEUTLER & SZULC (1999) is an entire substage too high.

According to SZURLIES (2001, 2004a, b), the only normal magnetozone of the Bernburg Formation ends around the base of cycle 8. Thus, the Olenekian base should be somewhat lower, within cycle 7. Here it is placed between the *E. nodosocostata* Zone s. s. and the *C. germari-M. subcircularis* A. Z.

The biostratigraphically and magnetostratigraphically correlated base of the Olenekian in the continental beds of the Germanic Basin can be also confirmed

with carbon isotopes by comparison with the Pufels (Bulla) section. There occurs a distinct positive $\delta^{13}\text{C}$ excursion somewhat more than 3 short eccentricity cycles above the Olenekian base (KORTE et al., in press). In the Germanic Basin, a distinct positive $\delta^{13}\text{C}$ excursion is present in the lower *M. truempyi* Zone, likewise somewhat more than 3 short eccentricity cycles above the base of the Olenekian (KORTE & KOZUR, in press).

As shown in Figs. 5 and 12, the Detfurth, Hardeggen and the largest part of the Solling Formation belong to the Spathian. This is indicated by both conchostracans and sporomorphs (KOZUR & SEIDEL 1983a, b, KOZUR 1993, 1999). BRUGMAN (1986) assigned the Hardeggen Formation and the largest parts of the Solling Formation to the Spathian. However, the strong dominance of *D. nejbürgii* and of the *Pleuromeia sternbergi* megaspore (= *Talchirella daciae* ANTONESCU & TAUGOURDEAU-LANTZ), which characterise the base of the Spathian, begins already in the lower Detfurth Formation. Moreover, the transition from the Smithian *Magnietheria mangaliensis* to the Spathian *M. deverta* (NOVOZHILOV) occurs in the uppermost Volpriehausen Formation indicating that the base of the Spathian is not far from this level.

Conchostracan studies of KOZUR & LEPPER (in prep.) have shown that the Anisian begins with the Stammen Beds of the upper Solling Formation, which have the same Aegean conchostracan fauna as the lower to middle Röt Formation below the Dolomitische Grenzbank. This Aegean conchostracan association is characterised by *Euestheria albertii mahlerselli* KOZUR & LEPPER n. subsp. and *Palaeolimnadia alsatica alsatica* (REIBLE). All typical Spathian conchostracans, such as *Euestheria exsecta* (NOVOZHILOV) and *Palaeolimnadia nodosa* (NOVOZHILOV), are absent in the Stammen Beds, but still present below this level. By the assignment of the Stammen Beds and its equivalents to the Solling Formation we confirm BRUGMAN (1986), who had already shown this correlation based on palynological studies. The significance of palynological studies in beds, which had not yielded any fauna in that time, is therefore demonstrated. Unfortunately, this dating was later not taken into consideration. The assignment of the Stammen Beds to the Anisian means that the contemporaneous Thuringian Chirotherien-Sandstein belongs to the Aegean too. Until now, the tetrapod footprints of this level were regarded as a typical Lower Triassic footprint association.

The base of the Bithynian lies at the base of the Dolomitische Grenzbank (DGB) within the upper Röt Formation (Fig 6). Its equivalents in Franken (Franconia) contain typical Bithynian euryhaline marine bivalves and the first *Euestheria albertii albertii* (VOLTZ) (KOZUR et al. 1993), thus showing an interfingering of mesohaline brackish conchostracan-bearing beds with pliohaline brackish to brachyhaline marine bivalve-bearing beds. *E. albertii albertii* can be found in continental lake deposits throughout Eurasia, but also in North and South America. Therefore this correlation of the marine and continental Bithynian base in the Germanic Basin, is of outstanding importance

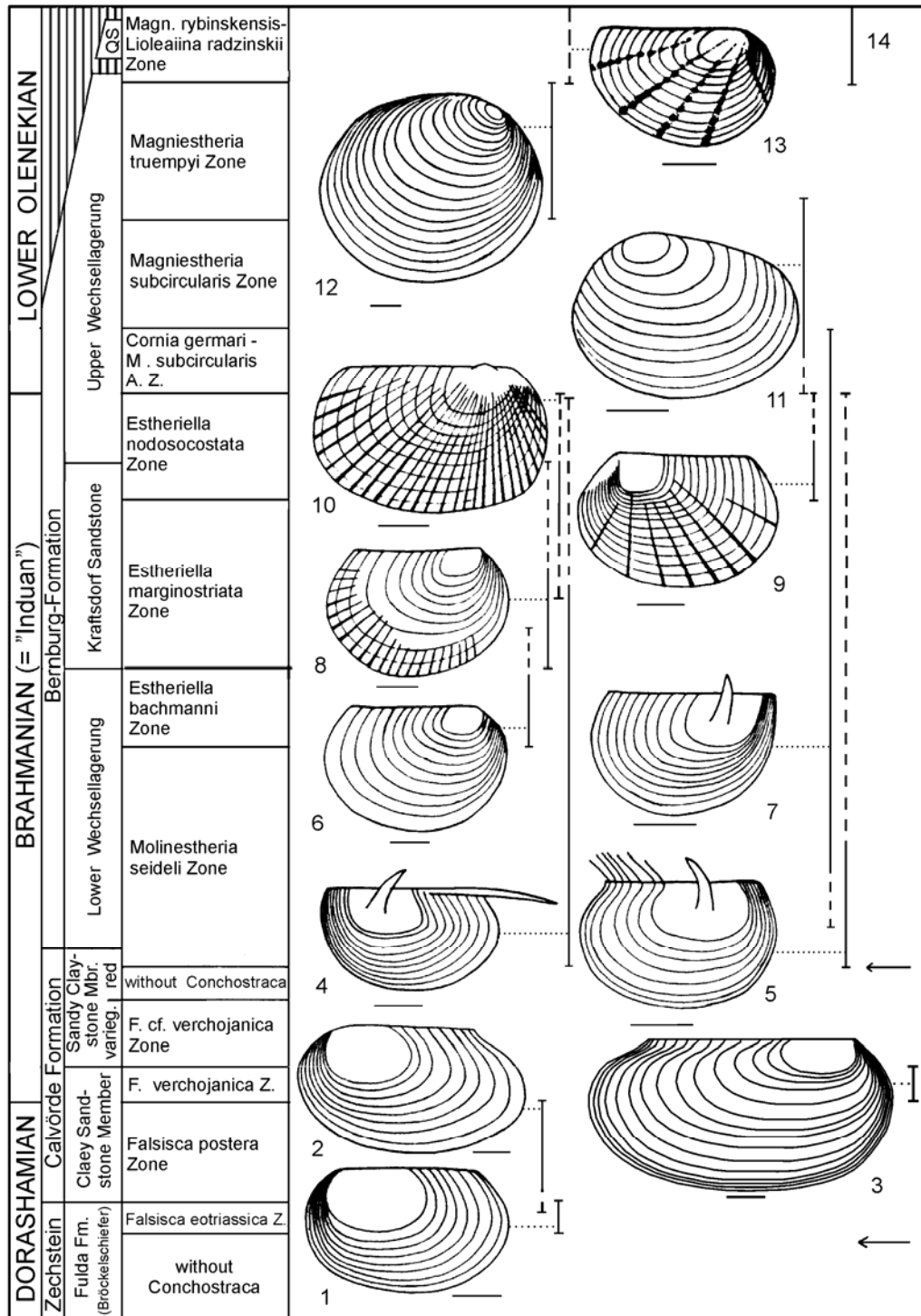


Fig. 11: Conchostracan zonation in the uppermost Zechstein (upper Fulda Formation/upper Bröckelschiefer) and Lower Buntsandstein (Calvörde Formation and Bernburg Formation). Not to scale. Ranges of the index species and some selected other species are also shown. Scale for conchostracans = 1 mm. The lithostratigraphic Members of the Calvörde and Bernburg Formations in the Thuringian Basin are shown in the 3rd column. Arrows indicate the time of conchostracan migration into the Germanic Basin after facies-controlled conchostracan free intervals. QS = Quickborn Sandstone. 1 = *Falsisca eotriassica* KOZUR & SEIDEL; 2 = *Falsisca postera* KOZUR & SEIDEL; 3 = *Falsisca verchojanica* (NOVOZHILOV); 4 = *Molinessia seideli* KOZUR; 5 = *Vertexia tauricornis* LJUTKEVICH; 6 = *Estheriella bachmanni* KOZUR & HAUSCHKE; 7 = *Cornia germari* (BEYRICH); 8 = *Estheriella marginostriata* KOZUR; 9 = *Estheriella nodosocostata* (GIEBEL); 10 = *Estheriella costata* WEISS; 11 = *Magniestheria ? subcircularis* (CHERNYSHEV); 12 = *Magniestheria truempyi* KOZUR & SEIDEL; 13 = *Lioleaiina radzinskii* KOZUR & SEIDEL; 14 = *Magniestheria rybinskensis* (NOVOZHILOV), range below the Volpriehausen Formation is shown (for upper range and illustration see Fig. 12).

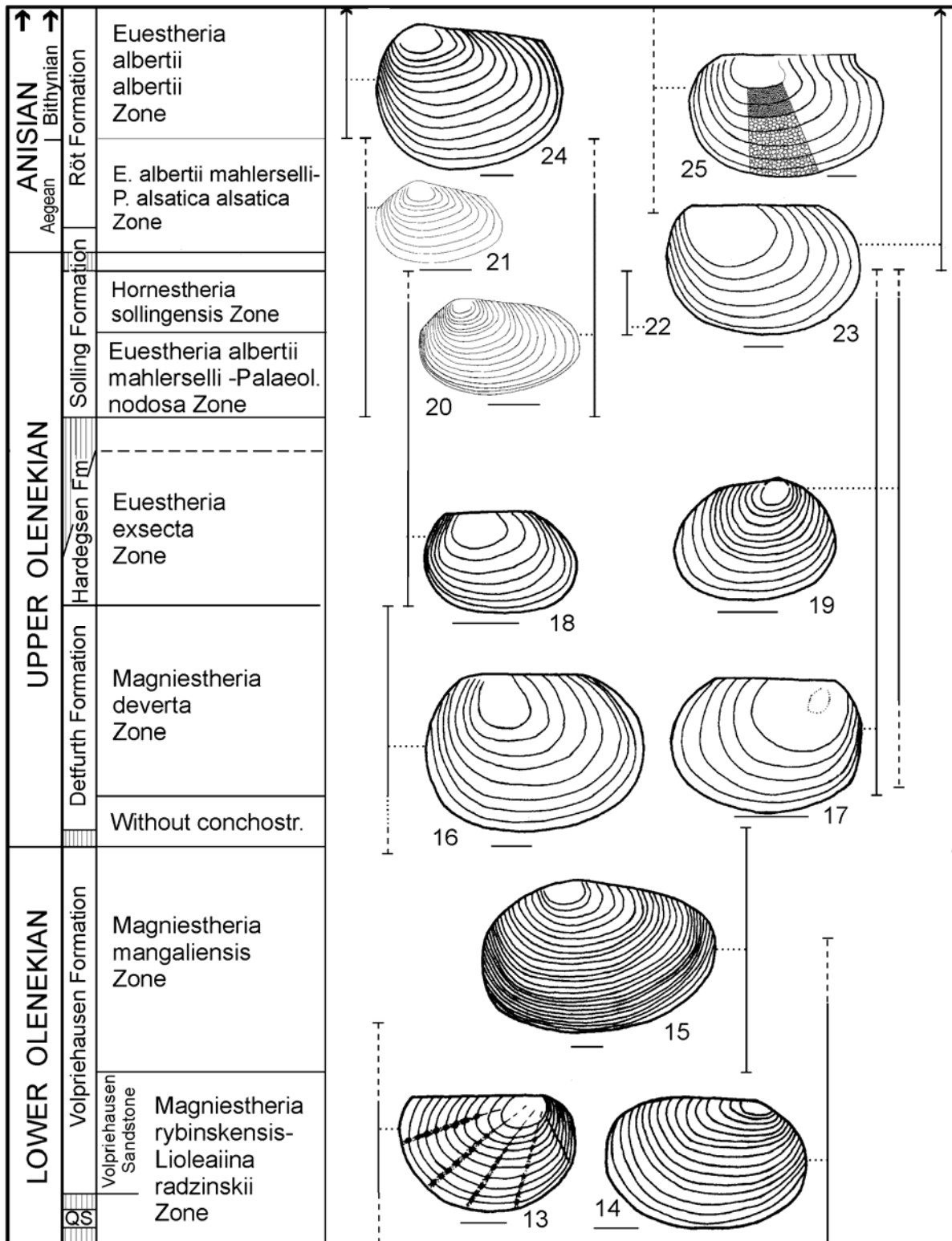


Fig. 12:

Conchostracan zonation in the Middle and Upper Buntsandstein. Not to scale.

The ranges and illustrations (except *Hornestheria sollingensis* KOZUR & LEPPER n. gen. n. sp.) of the index species and of some selected species are shown. Scale for conchostracans = 1 mm. QS = Quickborn Sandstone.

13 = *Lioleaiina radzinskii* KOZUR & SEIDEL; 14 = *Magnietheria rybinskensis* (NOVOZHILOV); 15 = *Magnietheria mangaliensis* (JONES); 16 = *Magnietheria deverta* (NOVOZHILOV); 17 = *Palaeolimnadia alsatica defurthensis* KOZUR & SEIDEL; 18 = *Palaeolimnadia nodosa* (NOVOZHILOV); 19 = *Euestheria exsecta* (NOVOZHILOV); 20 = *Euestheria albertii mahlerselli* KOZUR & LEPPER n. subsp., slender morphotyp; 21 = *Euestheria albertii mahlerselli* KOZUR & LEPPER n. subsp., stout morphotyp; 22 = *Hornestheria sollingensis* KOZUR & LEPPER n. sp., due to space only the range is shown; 23 = *Palaeolimnadia alsatica alsatica* REIBLE; 24 = *Euestheria albertii albertii* (VOLTZ); 25 = *Dictyonatella dictyonata* (REIBLE).

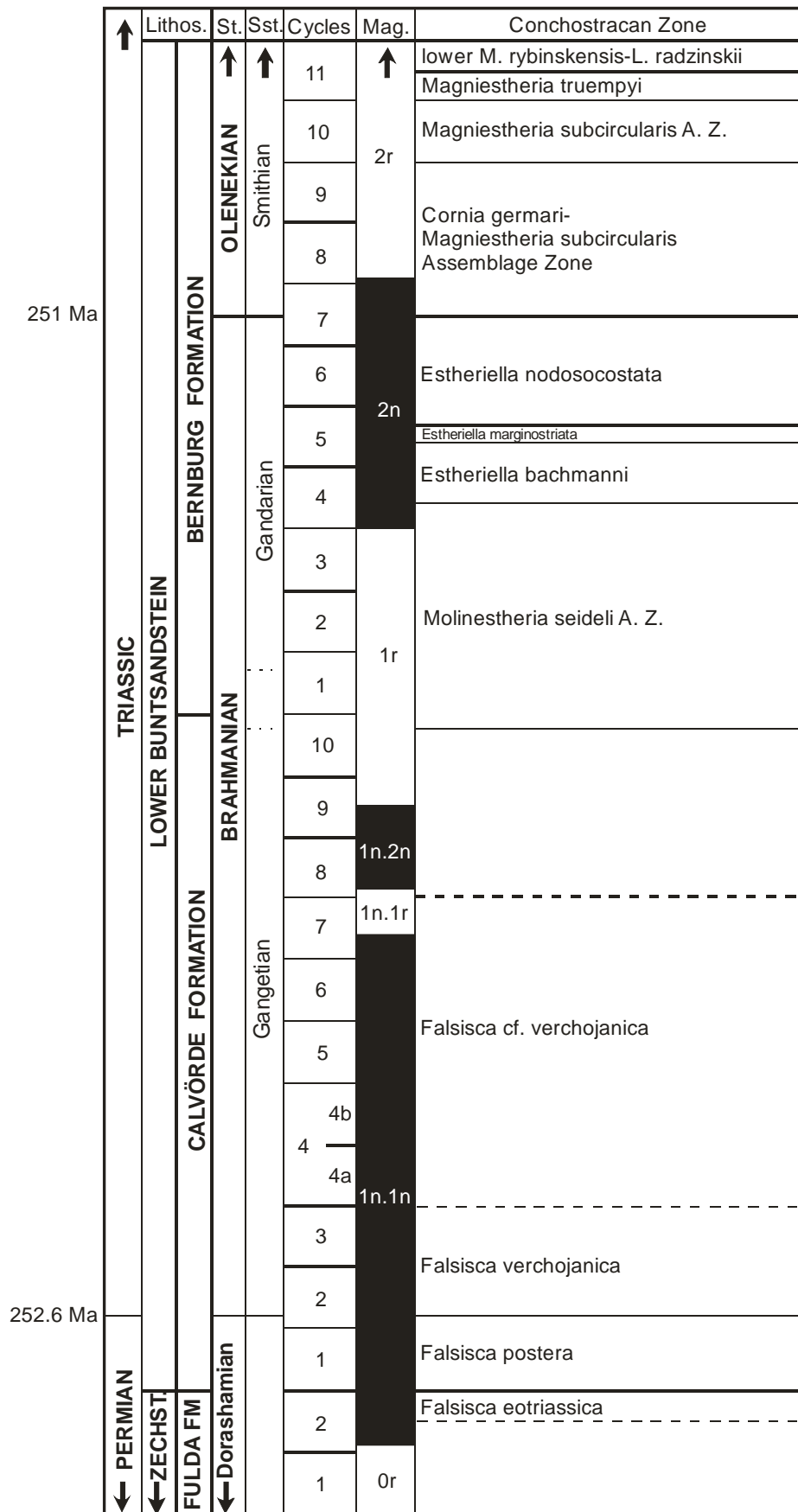


Fig. 13: Conchostracan zones (KOZUR et al., in press) of the Lower Buntsandstein and their correlation with the litho-cycles and magnetostratigraphic zones, sensu SZURLIES (2001). Cycle 4 of the Calvörde Formation subdivided into two short eccentricity cycles 4a and 4b. All other cycles of SZURLIES (2001) are in their original scope short eccentricity cycles (~100 000 years). Magnetostratigraphic zones of SZURLIES (2001, 2004a, b) are renamed, see Fig. 5.

for the international correlation of continental beds.

There are numerous palynological and palaeontological data, which prove an Aegean to lower Bithynian age of the Röt Formation. The *Theelia mostleri* holothurian fauna of the Röt Dolomite above the hypersaline basal Röt Formation is well dated in Tethys. From Nepal to the Küre Basin in northern Turkey, this fauna occurs in the Aegean *C. timorensis* Zone (e. g. KOZUR 1999, KOZUR et al. 2000). After the Permian-Triassic biotic crisis, holothurian sclerites did not exist in the Lower Triassic of the Tethys, not even in Hallstatt Limestones, the facies most favoured by holothurians (KOZUR 1998a, b). During the Aegean *C. timorensis* Zone, holothurians re-settled Tethys, and invaded from the Küre Basin through the Dobrogea and East Carpathian Gate the Germanic Basin as well. All other marine faunas of the Röt show Anisian age, too. The Anisian ammonoid genus *Beneckeia* already begins in the dolomites of the lower Röt Formation with *B. tenuis* (VON SEEBACH), and the Bithynian species *B. buchi* (VON ALBERTI) has its FAD in the upper Röt Formation. The lower Röt bivalves consists of long-ranging forms and species, which begin within the Aegean. The upper Röt bivalves contain species, which begin in the Tethyan Bithynian (see chapter 2.3). The continental flora and fauna of the Röt Formation shows Aegean to lower Bithynian age, too. As clearly shown by BRUGMAN (1986), the sporomorph association of the entire Röt is Anisian, with the Anisian index species *Hexasaccites thiergartii* (MÄDLER) KOZUR and numerous other Anisian sporomorphs. The *Eocyclosaurus* vertebrate fauna of the Röt Formation (e. g. ORTLAM 1970) indicates also an Anisian age (HUNT & LUCAS 1993: p. 49). *E. albertii albertii*, which has its FAD in brackish equivalents of the Dolomitische Grenzbank, is the Bithynian conchostracan guide form of Eurasia, North and South America.

NAWROCKI & SZULC (2000) and NAWROCKI (2005) found these biostratigraphic data not convincing, especially not the holothurian sclerites, and correlated by comparison of palaeomagnetic reversals the entire Röt with the Olenekian. The Anisian base was

placed within the lowermost Muschelkalk of Poland, which corresponds to the Myophorienschichten of the uppermost Röt Formation in Germany (e. g. KOZUR 1974, KEDZIERSKI 1999). BEUTLER & SZULC (1999) used this erroneous correlation of the Anisian base as well.

The assignment of the Röt Formation to the Olenekian is based on the correlation of the reversed magnetozone in the upper Röt Formation with the interval Kç1r (MUTTONI et al. 1996) of the uppermost Olenekian. However, the reversed interval in the upper Röt Formation actually corresponds to the reversed interval Kç2r of the Kçira section that straddles the Aegean-Bithynian boundary (MUTTONI et al. 1996), as clearly shown by fauna and palynology.

If the palaeomagnetic data of NAWROCKI & SZULC (2000) are correlated correctly, under consideration of biostratigraphy, they are indeed of great significance for correlation at global scale. Below the reversed interval in the upper Röt Formation of Poland, there is a relatively long normal magnetozone beginning in the dolomites of the lower Röt Formation after a long gap (NAWROCKI et al. 2005). Compared with the marine palaeomagnetic succession (Fig. 1), even the lower Röt dolomites are, therefore, not older than the upper part of lower Aegean. As the lowermost hypersaline Röt, underlying the lower Röt dolomites, has a very short duration (probably not longer than a short eccentricity cycle), there is not enough time for the entire lower *C. timorensis* Zone of the lower Aegean (with 3 reversals, see Fig. 1) in the basal hypersaline Röt Formation. Therefore, the proper correlation of palaeomagnetic data by NAWROCKI & SZULC (2000) indicates that the base of the Anisian must be below the base of the Röt (if a gap between Solling and Röt Formation can be ruled out), thus confirming the palynological data of BRUGMAN (1986) and the above mentioned Aegean age of the conchostracan fauna of the Stammen Beds. Even the very short reversed horizon within the Aegean Kç2n at Kçira section, which is only indicated by a single measurement, seems to be present in the lower Röt (NAWROCKI & SZULC 2000).

4.2 Muschelkalk

VÖRÖS (2003) defined the base of the Pelsonian at the GSSP in the Balaton Highland (Hungary) with the base of the *Balatonites balatonicus* Zone s. s., and assigned the *B. ottonis* fauna of the Germanic Basin (Lower Wellenkalk Member and Oolithbank Member) to the upper Bithynian. This confirms the conodont correlation by KOZUR (e. g. 1974, 1999). It indicates that the correlation of the upper half of the Röt with the Pelsonian by palynologists (e. g. BRUGMAN 1986, VISCHER et al. 1993) must be caused by different FAD of important guide forms in the Alps and the Germanic Basin.

The Pelsonian base lies above the Oolithbank Member and is characterised by the FAD of *Nicoraella kockeli* (TATGE), an important Pelsonian guideform in the Tethys, too. Pelsonian macrofaunas (ammonoids, brachiopods; see KOZUR 1974) are as well present in

the middle and upper Wellenkalk.

The Tethyan ammonoid *Judicarites* appears in the Schaumkalkbank Member. In the Southern Alps, it begins within the uppermost Pelsonian, in the youngest *Balatonites* fauna close to the Pelsonian-Illyrian boundary, and ranges into the lower Illyrian (BRACK et al. 1999). In the Schaumkalkbank Member, it occurs together with last Pelsonian forms, such as *Schreyerites binodosus* (HAUER), an ammonoid fauna indicating uppermost Pelsonian. Somewhat higher up, above equivalents of the Karlstadt Formation, a rich dasycladacean association begins in Upper Silesia, which consists almost exclusively of *Diplopora annulatissima* PIA, a typical Illyrian association.

The base of the Ladinian was confirmed at the base of the *E. curionii* Zone by the STS in 2004. Following this decision, most of the Upper Muschelkalk is Ani-

sian in age. The base of the newly defined Ladinian lies somewhat above the Cycloidesbank γ , within the upper *enodis-laevigatus* Zone (or within the lower *sublaevigatus* Zone sensu URLICHS 1991). This is in agreement with the sequence stratigraphic interpretation of AIGNER & BACHMANN (1992) and VISSCHER et

al. (1993) who identified the Cycloidesbank γ level (or immediately above it) as a maximum flooding surface. In the Southern Alps, the maximum water depth was within the *Nevadites* interval or slightly above (*chie-sense* groove), as pointed out by BRACK et al. (1999).

4.3 Keuper

The base of the Longobardian can be determined by sporomorphs at the base of the Erfurt Formation (VISSCHER et al. 1993). It is important to note, that according to URLICHS & TICHY (2000), *Myophoria kefersteini* MÜNSTER occurring in the Bleiglanzbank (Grabfeld Formation, Unterer Gipskeuper) is in fact not the Carnian guideform *M. kefersteini kefersteini* MÜNSTER, but the upper Ladinian guideform *M. kefersteini okeni* (EICHWALD), thus solving the problem that the Bleiglanzbank seemed to have a (middle) Carnian guideform, whereas in the much younger basal part of the Estherienschichten (upper Grabfeld Formation) there occurs a conchostracan fauna that is characteristic of the Ladinian-Carnian boundary (KOZUR 1999). Likewise, sporomorphs indicate an early Carnian (Cordevolian) age of the Estherienschichten (MOSTLER & SCHEURING 1974, SCHEURING 1970, 1978), if the base of Carnian is defined with the base of *D. canadiensis* Zone (BROGLIO LORIGA et al. 1998).

The correlation of the Germanic Upper Triassic with the international chronostratigraphic scale is shown in Fig. 7. The base of the Carnian coincides with the base of the Estherienschichten of the upper Grabfeld Formation, as indicated by the FAD of *Laxitextella multireticulata* (REIBLE). It is also known from the uppermost Meride Limestone of the Southern Alps in the basal Carnian, if the base of the Carnian is defined by the base of the *D. canadiensis* Zone. *L. multireticulata* is also present in the lower Dunscombe Mudstone Formation on the south Devon coast, England.

The basal Schilfsandstein belongs, according to miospores, megaspores and ostracods to the Julian. The best correlation is possible for the basal parts of the Schilfsandstein, where a distinct marine ingression can be observed. In northern Germany, there are even some limestones and marly interbeds with a brachyhaline marine fauna containing mass occurrences of the ostracods *Simeonella alpina* BUNZA & KOZUR and a few *Lutkevichinella oblonga* KOZUR, which indicate, as in the Alps and Hungary, brachyhaline marine deposits of Julian age (BUNZA & KOZUR 1971, KOZUR 1975, WIENHOLZ & KOZUR 1970). As *S. alpina* begins in the Alps and Hungary above the base of the Julian, its base in the Germanic Basin is probably in the gap between the Grabfeld and Stuttgart Formations (Fig. 7).

More common in the lowermost Schilfsandstein are brackish shales with *Karnocythere germanica* WIENHOLZ & KOZUR and *Limnocythere ? triassica* KOZUR and, partly, *S. alpina*. Therefore these beds can be well correlated with the Julian. If *Darwinula* is absent, this fauna indicates pliohaline brackish environments, with additionally a few *Darwinula*, mesohaline brackish environments are proven. Immediately above the bra-

chyhaline marine beds, there are brackish beds, which grade from mesohaline via mio- and oligohaline to fresh water deposits. This is indicated by increasing percentage of *Darwinula* and decreasing percentage of *K. germanica* and *L. ? triassica*. The fresh water deposits contain only *Darwinula* and sometimes conchostracans. Brachyhaline marine to pliohaline deposits with *Simeonella alpina*, *L. ? triassica* and a few *Lutkevichinella oblonga* occur also in areas without limestones in the southern part of northern Germany and in the Thuringian Basin. No investigations of the ostracod faunas were made in southern Germany, but LINCK (1968, 1971) and WARTH (1988, 1990) described poorly preserved euryhaline marine bivalves. Similar forms are known from the brachyhaline marine Lunz Beds in the Alps. Bivalves are also present in the basal Schilfsandstein of northern Germany and the Thuringian Basin (KANNEGIESER & KOZUR 1972, WIENHOLZ & KOZUR 1970). Within the upper Schilfsandstein, there is only one horizon with oligo-/miohaline brackish ostracod faunas containing *Darwinula* and some *Karnocythere germanica* (KANNEGIESER & KOZUR 1972). In the same level, KANNEGIESER & KOZUR (1972) found *Ompaloptycha lunschensis* YEN, an euryhaline marine gastropod, which indicates in association with the oligo-/miohaline brackish ostracod fauna, brackish conditions, too. A Julian age of these deposits is probable. The "Gaildorfer Bank" of the upper Stuttgart Formation (Dunkle Mergel) in southwestern Germany contains bivalves and shark teeth (SEILACHER 1943) of unknown stratigraphic importance.

The base of the Tuvallian cannot be determined yet, because the assumed Julian-Tuvallian boundary interval contains no biostratigraphically important fossils in the Germanic Basin. A distinct marine ingression occurred in the Lehrbergschichten. The strongest marine influence is in the Gansinger Dolomit of Switzerland, where *Costatoria vestita* (VON ALBERTI) indicate (brachyhaline) marine conditions. The euryhaline marine gastropod *Promathilda theodorii* BERGER is common in southern Germany and the Thuringian Basin, but has no stratigraphic value. The dolomitic beds of the Lehrbergschichten in Thuringia yielded numerous ostracods, mainly *Reubenella* sp., which cannot be distinguished from marine *Reubenella* of the Tuvallian in Hungary. Some *Albacythere* sp. are also present, but these ostracods cannot be determined in species level because they are preserved as internal moulds. Stenohaline marine taxa, like bairdiids, are absent. Thus, slightly hypersaline marine environments are indicated, in which *Reubenella* and *Albacythere* are also common in the Alps (e. g. Hauptdolomit facies). Shales and dolomitic marls between the dolomite beds

contain an ostracod fauna consisting of strongly euryhaline genera that occur in both brackish and slightly hypersaline environments. North of the Harz Mountains, only brackish ostracods are known in the equivalents of the Lehrbergschichten including *Darwinula*, indicating mesohaline to oligohaline brackish environments.

The base of the Tuvallian is situated between the Julian upper Schilfsandstein and the Tuvallian Lehrbergschichten. For palaeoclimatological reasons (hypersaline beds are known from the Alpine Tuvallian, but not from the Julian, where a rather wet climate is indicated), we prefer a Tuvallian age of the entire Weser Formation and equivalents and, possibly, also for the Dunkle Mergel. The youngest Carnian (late Tuvallian) conchostracan fauna was found by KELBER in the Coburg Sandstone (KELBER & KOZUR, in prep.). It is characterised by *Laxitextella* of the *L. laxitexta* group, which is absent in the lower Norian. This species occurs also in the late Tuvallian of Texas and has, therefore, a good correlation potential for the uppermost Carnian.

The oldest conchostracan fauna from the Arnstadt Formation and equivalents contains the genus *Shipingia*, which begins in the lowermost Passaic Formation of the Newark Basin, thus providing a good correlation marker. The FAD of *Shipingia* is in the Alaunian. As the Heldburggips Member (Mainhardt Formation) was most likely deposited rather rapidly or represents, in part, a gypcrete long hiatus is supposed to be present between the Mainhardt Formation and the Arnstadt Formation comprising the lower Norian (so-called "Altkimmerische Hauptdiskordanz", BEUTLER 1979). It could be related to the closure of the Palaeotethys around the Carnian-Norian boundary. The Löwenstein Formation (Stubensandstein/Burgsandstein), the marginal equivalent of the Arnstadt Formation (except its uppermost part), contains *Shipingia* in its lower part (Lower Stubensandstein). Tetrapods of the Löwenstein Formation are characterised by *Aetosaurus* and *Mystriosuchus*, which occur in the *Mesohimavatites columbianus* Zone of late Alaunian age in the Lombardian Alps (northern Italy). Thus, both conchostracans and vertebrates indicate an Alaunian age for the main body of the Arnstadt Formation and equivalents.

However, according to Milankovitch cyclicity it seems that the main body of the Arnstadt Formation may comprise some 7 myrs (TOUGIANNIDES 2004), i. e. about 2 myrs more than the Alaunian (5 myrs; CHANNELL et al. 2003). Therefore, the Arnstadt Formation should comprise, in addition to the Alaunian, 2 myrs of the late Lacinian or 2 myrs of the early Sevatian. As neither *Shipingia* nor Alaunian vertebrates have been found in well dated lower Norian, but are at least present in the lower Sevatian, it is assumed that the main body Arnstadt Formation/Löwenstein Formation begins in the middle Norian and ranges up to the lower Sevatian.

The base of the Sevatian can so far not be defined in the Germanic Basin as the conchostracan and vertebrate fauna of the upper Alaunian and the Sevatian are very similar.

Very important magnetostratigraphic and biostratigraphic data were presented by HOUNSLOW et al. (2004) from the well known Triassic/Jurassic boundary sections at St. Audrie's Bay, UK. They allow for the first time a good magnetostratigraphic correlation of the Alaunian to basal Jurassic interval of the UK part of the western Germanic Basin with the Newark Basin and of the upper Bull Canyon and Redonda Formations of New Mexico. The Westbury Formation (which can be correlated with the Contorta Beds in Germany) and the Williton Member of the Blue Anchor Formation, correspond to the predominantly normally magnetised upper Rhaetian (E 22–E 23), in the Newark Basin comprising a maximum of ~2 myrs. The almost completely reversed lower Rhaetian of the Newark Basin (E 19–E 20) corresponds to the Blue Anchor Formation (HOUNSLOW et al. 2004).

According to LUCAS (1999), *Coburgosuchus* from the uppermost Löwenstein Formation (4th Stubensandstein), is very similar to, if not the same, taxon as the Apachean index fossil *Redondasaurus* of the Redonda Formation of New Mexico. Using the traditional assignment of the entire Stubensandstein to the Norian, LUCAS (1999) changed his former view on the Rhaetian age of the Apachean land-vertebrate faunachron (LVF) to late Norian to Rhaetian. But, as it seems, the opposite conclusion might be much more likely that the uppermost Löwenstein Formation belongs in fact to the Rhaetian because the entire Redonda Formation (Apachean LVF) has a Rhaetian conchostracan fauna (collection KOZUR). According to this correlation, the upper two thirds of the Rydon Member of the Blue Anchor Formation would be of Rhaetian age and hence an equivalent to the uppermost Löwenstein Formation/ uppermost Arnstadt Formation/ lower and middle Postera Beds (Fig. 7). The Trossingen Formation (Knollenmergel) and the Postera Sandstone are either equivalents of the Williton Member of the uppermost Blue Anchor Formation or of the uppermost Rydon Member of the Blue Anchor Formation.

CHANNELL et al. (2003) and MUTTONI et al. (2004) correlated the marine Norian-Rhaetian boundary at the FAD of *Misikella posthernsteini* KOZUR & MOCK with the astrochronological calibrated continental Newark Basin, calculating 6 to 7 myrs for the Rhaetian. In this case, the base of the Rhaetian cannot be younger than base of E 19 in the Newark Basin. This would place the entire Blue Anchor Formation into the Rhaetian. On the other hand, GALLET et al. (2003) used a very high Rhaetian base, expanded the Norian to 25 myrs, almost half of the entire Triassic, and reduced the Rhaetian to 2 myrs. The Rhaetian of these authors begins much above the FAD of *M. posthernsteini* and *Cochloceras* within the Rhaetian radiolarian faunas. Therefore, it cannot be correlated with North America and Panthalassa, and even not with radiolarite successions within Tethys. As pointed out in section 2.3, this boundary does not fit with the priority of the Rhaetian at the base of the Kössen Beds. According to this boundary, the base of the Rhaetian would be inside the Contorta Beds.

5 Conclusions

(1) There are several biostratigraphic and abiotic events around the PTB, which allow a very detailed correlation in the marine realm as well as between marine and continental beds. By cross correlation of marine and continental beds, using biostratigraphic correlation and all events mentioned in section 2.1, the well recognisable Milankovitch cycles of continental lake deposits can be applied for detailed numerical dating of all major events around the PTB. An estimation of the duration of the conodont zones around the PTB may be made as well. The following duration of uppermost Permian-earliest Triassic conodont zones can be calculated as follows:

C. zhangi Zone: 70,000 years,

C. iranica Zone: 60,000 years,

C. hauschkei Zone: 15,000 years (the extreme short duration of this zone is caused by the main extinction event at the base of the Boundary Clay terminating this zone),

C. meishanensis-*H. praeparvus* Zone and *M. ultima*-*S. mostleri* Zone together: 120,000 years,

H. parvus Zone: 100,000 years,

I. isarcica Zone: >0.5 myrs.

(2) Milankovitch cycles can well be recognised in continental lake deposits and shallow marine or hypersaline deposits of the Germanic Triassic. They are best investigated in the Lower Buntsandstein, but good results are also known from parts of the Middle Buntsandstein, especially the Volpriehausen Formation, from the Upper Buntsandstein (Röt Formation), the Muschelkalk, and the Erfurt Formation, Grabfeld Formation and Arnstadt Formation of the Keuper. Models of Milankovitch cyclicity require an integrated approach including bio- and chronostratigraphic data, to make sure that the basic cycles are precession cycles.

(3) The following correlations between the international chronostratigraphic scale and the Germanic Triassic were established or confirmed:

- The base of the Triassic is at the top of the *Falsisca postera* Zone, at the base of precession cycle 2 (base of Oolite α_2), within the second short eccentricity cycle of the lower Calvörde Formation.

- The base of the Gandarian is at the base of the *M. seideli* Zone, in the uppermost part of cycle 10 of the Calvörde Formation. An alternative position is ~100,000 years younger, in the uppermost cycle 1 of the Bernburg Formation, which lies in the middle of the reversed horizon straddling the Gangetian-Gandarian boundary.

- The base of the Olenekian (at the base of the *Flemingites flemingianus* Ammonoid Zone and *Neospathodus waageni* Conodont Zone) is in the Germanic Basin at the top of the *E. nodosocostata* Zone s. s. in the middle of cycle 7 of the Bernburg Formation. Magnetostratigraphically this is somewhat below the top of the only normal interval in the Bernburg Formation. This coincides with the magnetostratigraphic

position of the base of the Olenekian in the GSSP candidate, Chaohu, China (TONG JIN-NAN et al. 2005, in press). It may also be correlated with the palaeomagnetic data of SCHOLGER et al. (2000), if their magnetozones have been biostratigraphically correctly dated.

- The base of the Anisian is at the base of the Stammen Beds of the upper Solling Formation as indicated by the base of the Aegean *E. albertii mahlerselli*-*P. alsatica alsatica* Zone (KOZUR & LEPPER, in prep.) and by sporomorphs (BRUGMAN 1986). This means that the time-equivalent Thuringian Chirotherien-Sandstein with its rich vertebrate footprint association is Anisian (Aegean) as well.

- The base of the Bithynian is at the base of the Dolomitische Grenzbank in the upper Röt Formation as indicated by marine bivalves (FAD of *Myophoria vulgaris* and *Costatoria costata* s. s. with 16–17 extra-areal ribs), and in fresh-water to slightly brackish deposits by the FAD of *E. albertii albertii*. This latter event can be traced to western North America and South America.

- The base of the Pelsonian is immediately above the Oolithbank Member of the Lower Muschelkalk as indicated by the FAD of the conodont *Nicoraella kockeli* and of Pelsonian ammonoids, brachiopods and holothurian sclerites (KOZUR 1974).

- The base of the Illyrian is close to the Lower/Middle Muschelkalk boundary. It is placed at the base of the dasycladacean flora with mass occurrences of *Diplopora anulatisima* above the Karlstadt Formation.

- The base of the Ladinian at the base of the *Eoprotracyceras curionii* Zone is above the Cycloidesbank γ , somewhat above a maximum flooding surface.

- The base of the Longobardian is at the base of the Erfurt Formation (Lettenkeuper) as demonstrated by VISSCHER et al. (1993) with sporomorphs.

- The base of the Carnian is placed at the base of the Estheriensichten in the upper Grabfeld Formation as indicated by the FAD of *L. multireticulata*, which occurs at the Ladinian-Carnian boundary in brackish intercalations of the western Southern Alps. *L. multireticulata* is also present in the lower Dunscombe Mudstone Formation of England.

- The base of the Schilfsandstein (Stuttgart Formation) contains a brackish to brachyhaline marine Julian fauna and flora (miospores, megaspores and an euryhaline marine ostracod fauna with *Simeonella alpina*). The base of the Julian, however, seems to be within the gap between the Grabfeld Formation and the Stuttgart Formation.

- The base of the Tuvallian can be not defined with palaeontological methods. The first Tuvallian fossils above the Julian Schilfsandstein are marine ostracods in the Lehrbergschichten, demonstrating that the dolomites of the Lehrbergschichten are slightly hypersaline marine deposits. The youngest Tuvallian fossils are known from the Coburg Sandstone: *Laxitextella* of the *L. laxitexta* group that do not range up to the Norian.

- The main body of the Arnstadt Formation has an Alaunian to early Sevatian fauna with the conchostracan *Shipingia*, which has its FAD in the lower Passaic Formation of the Newark Basin. The vertebrates *Aetosaurus* and *Mysrtriosuchus* indicate Alaunian to early Sevatian age as well.
- Currently, the base of the Sevatian cannot be defined in the Germanic Basin because both *Shipingia* and *Aetosaurus* and *Mysrtriosuchus* range from the Alaunian to, at least, the lower Sevatian.
- The base of the Rhaetian is disputed in the marine realm, but most authors prefer the FAD of the ammonoid *Cochlocears* and the conodont *Misikella posthernsteini*, a boundary that can be recognised easily in different marine facies including radiolarite successions of Panthalassa, Tethys and North America. The

Rhaetian Apachean LVF of the Redonda Formation in New Mexico can be correlated by the very similar, or even identical, *Coburgosuchus* and *Redondasaurus* with the uppermost Löwenstein Formation (4th Stubensandstein). This boundary occurs in the lower third of the Blue Anchor Formation of UK and at the base of E 20 in the Newark Basin, 5 myrs below the base of the Liassic. According to CHANNELL et al. (2003) and MUTTONI et al. (2004), the Rhaetian comprises a time span of 6–7 myrs. In that case the Rhaetian base would be situated in a hiatus within the upper Löwenstein and Arnstadt Formations below the 4th Stubensandstein / uppermost Arnstadt Formation / lower Postera Sandstone. In England, this boundary is at the base of the Blue Anchor Formation.

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