GEOLOGICA CARPATHICA, APRIL 2009, 60, 2, 139–149 doi: 10.2478/v10096-009-0009-0

Climate change at the Triassic/Jurassic boundary: palynological evidence from the Furkaska section (Tatra Mountains, Slovakia)

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(Manuscript received January 14, 2008; accepted in revised form October 23, 2008)

Abstract: The palynology of the Triassic/Jurassic boundary interval of the Furkaska section (Tatra Mts, Slovakia) was studied with respect to a major climatic change during that period. The palynofacies is dominated by terrestrial particles, indicating a shallow marine depositional environment. The palynomorphs are fairly well-preserved and the assemblage shows characteristic changes within the Triassic/Jurassic boundary interval: the lower part of the section is characterized by high abundance of *Ricciisporites tuberculatus*. The sudden increase in abundance of trilete spores, the decrease in the abundance of *Ovalipollis* spp., the last appearance of *Alisporites minimus* and *Corollina* spp., and the first appearance of *Concavisporites rhaetoliassicus*, *Cyatidites australis*, *Callialasporites dampieri*, *Pinuspollenites minimus*, *Platysaccus* spp. and *Zebrasporites fibmriatus* are striking features for a subdivision of two palynomorph assemblages. The detected spore shift is interpreted to display a sudden increase in humidity most probably caused by the volcanic activity of the Central Atlantic Magmatic Province (CAMP) associated with the onset of rifting of Pangaea during early Mesozoic times.

Key words: Triassic/Jurassic boundary, Tatra Mountains, Slovakia, climate change, palynology, palynofacies.

Introduction

The end-Triassic extinction event represents one of the five biggest mass extinctions during the Phanerozoic (Sepkoski 1996; Hallam & Wignall 1997a). The causes of this ecosystem collapse are still under discussion. Climatic changes, sea-level changes, oceanic anoxia (Hallam 1997; Hallam & Wignall 1997b), as well as flood basalt volcanism (Marzoli et al. 1999; Hesselbo et al. 2002; Pálfy 2003) and extraterrestrial impacts (Olsen et al. 2002) are frequently cited agents that could be responsible for this sudden decrease of biodiversity.

For dating and correlation of significant environmental changes around the Triassic/Jurassic boundary in different paleogeographic settings, detailed biostratigraphic investigations in terrestrial and marine depositional series are needed. Palynology provides an excellent tool for correlation of continental and marine environments, since sedimentary organic matter of marine sediments comprises two fractions: a terrestrial allochthonous fraction, made up of phytoclasts, pollen grains and spores and a marine relatively autochthonous fraction composed of marine plankton. Palynological studies of the Triassic/Jurassic boundary with special focus on the extinction event are still rare. Fowell & Olsen (1993) describe a sudden floral turnover and a strong decrease in pollen and spore diversity coevally with an Iridium anomaly in terrestrial sediments of the Newark Supergroup (Newark Basin, USA). In other paleogeographical settings, indicators for a microfloral mass extinction are absent. In marine sections of the NW Tethyan realm a bloom of prasinophytes, known as "disaster species" (Tappan 1980), was reported by Kuerschner et al. (2007), Van de Schootbrugge et al. (2007) and Ruckwied (2008).

In the framework of the IGCP 458 Project "Triassic/Jurassic boundary events: Mass extinction, global environmental change, and driving forces" Michalík et al. (2007a) focussed on environmental changes recorded in the Triassic/Jurassic boundary series of the Western Carpathians. An integrated study of sedimentary and organic facies as well as clay mineralogy points to a sudden increase of humidity during the boundary interval (Michalík et al. submitted). The present study focuses on the palynology of the Furkaska section (Tatra Mts) with respect to changes within the microfloral assemblage of the boundary interval.

Geological setting

During Late Triassic times, the study area was located on the NW Tethyan shelf, bordering the Neotethys Ocean Branch. The Tatra Mountains represent a part of the Tatro-Veporic Unit, which was located close to the Upper Austroalpine Unit (Michalík 1994; Haas 2001). During the Early Jurassic the European shelf was influenced by the extensional Penninic rift, creating small pull-apart basins in the W Carpathian-E Alpine crustal block (Michalík 1993; Fig. 1). The Zliechov Basin comprises a latest Triassic to mid-Cretaceous sedimentary record (Plašienka 2001; Michalík 2007a). The Upper Rhaetian series is composed of dark coloured carbonates and shales (Fatra Formation), displaying ten facies zones (Michalík 1973, 1974, 1977). The depositional environments varied from salt marshes through carbonate ramp to deeper neritic slope, and were populated by characteristic benthic associations (Michalík 1978a; Michalík & Jendrejáková 1978) dominated by brachiopods and bivalves (Michalík et al. 2007a). The Upper Rhaetian carbonate succession is overlain by dark brown clays, the so-called "Boundary Clay" and sandstones named "Cardinia Sandstone" ("Cardinien Sandstein"; Goetel 1917) of the Lower Jurassic (Hettangian) Kopienec Formation (Michalík 2003). The stratigraphic boundary was placed near the lithological boundary on the basis of microfacies analyses and a striking negative excursion of the $\delta^{13}C_{carb}$ isotopic curve (Michalík et al. 2007a).

Biostratigraphy

In the Western Carpathian Tatra Mountains, Late Triassic microfossils of biostratigraphical use, mainly foraminifers and conodonts, are rare (Gaździcki 1974, 1978, 1983; Gaździcki et al. 1979, 2000; Gaździcki & Michalík 1980; Błaszyk & Gaździcki 1982; Michalík & Gaździcki 1983; Fijałkowska & Uchman 1993). A detailed foraminiferal zonation is based on the rapid evolutionary changes of *Involutinidae, Ammodiscidae* and *Ophthalmidiinae.* The sequence of the Rhaetian *Glomospirella friedli-Triasina hantkeni* Assemblage Zone and the Hettangian-Sinemurian *Ophthalmidium leischneri-Ophthalmidium walfordi* Assemblage Zone was detected by Gaździcki (1978). The *Glomospirella friedli-Triasina hantkeni* Zone was correlated with both the *Choristoceras haueri* and *Ch. marshi* ammonoid Zones (Rhaetian), and its extent also corresponds to that of the *Misikella posthernsteini* conodont Zone. The extent of the Early Jurassic *Ophthalmidium leischneri-Ophthalmidium walfordi* Zone may correspond to the *Planorbis* to *Angulata,* and possibly also the *Bucklandi* Standard ammonite Zones of the Hettangian–Sinemurian, defining the age of the basal Jurassic strata in the Tatra Mountains (Michalík et al. 2007a).

Material and methods

The Furkaska section is situated in the Furkaska Valley east of the village of Oravice (Fig. 2). The W slope of the Mt Veľká Furkaska exposes a succession of Upper Triassic to Lower Cretaceous sediments of the Krížna Nappe. The investigated Triassic/Jurassic boundary interval is exposed in a small cascade section, revealing a continuous, ca. 25 m thick depositional series. Palynofacies analysis was carried out on a total of 12 samples from limestones, shales and sandstones. All samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for dissolution of carbonates and silicates, and saturated $ZnCl_2$ solution ($D \approx 2.2$ g/ml) for density separation. Residues were sieved at 15 μm mesh size. Slides have been mounted in Eukitt, a commercial, resin-based mounting medium. The relative percentages of sedimentary organic constituents are based on counting at least 500 particles per slide. The classification of terrestrial and marine particles follows Steffen & Gorin (1993). Cluster analysis of the palynological data set has been carried out using PAST (PAleontological STatistics), a free software by Hammer, Harper & Ryan (Hammer et al. 2001).

Palynofacies data

The palynofacies of the Furkaska section is dominated by terrestrial particles (Fig. 3). The marine fraction is very small and mainly composed of the dinoflagellate cyst species *Dapcodinium priscum* (Fig. 4) and *Rhaetogonyaulax rhaetica*; acritarchs and prasinophytes are rare. Degraded organic matter (DOM) attains percentages of up to 35 % of the palynofacies assemblage. Amorphous organic matter (AOM) is only abundant in the lowermost part of the studied sedimentary series. The phytoclast group is dominated by equidimensional opaque particles.

The sedimentary organic matter content of the samples studied points to shallow marine conditions. The sporomorph dominance within the palynomorph group indicates a close proximity to fluvio-deltaic sources (cf. Tyson 1995: p. 448). Due to the extremely small amount of marine components, the ratio of terrestrial to marine particles is not very meaningful with respect to sea-level changes within this interval. The relatively high amount of degraded organic matter points to a high-energy depositional system. In the lower part of the Furkaska section, which belongs to the Rhaetian Fatra Formation, the relative percentages of pollen grains and spores are almost equal. From bed 408 spores become more abundant and are dominant within the sporomorph assemblage of the lowermost Hettangian.

Palynomorph assemblage

In the Furkaska section of the Slovak Tatra Mountains palynomorphs are fairly well-preserved (Fig. 4) and show characteristic changes within the Triassic/Jurassic boundary interval. The lower part of the section is characterized by high abundance of *Ricciisporites tuberculatus* (Fig. 5; samples 405, 406, 406/407, 407/408). The sudden increase in the abundance of trilete spores (Fig. 3), the decrease in the abundance of *Ovalipollis* spp., the last appearance of *Alisporites minimus* and *Corollina* spp., and the first appearance of *Concavisporites rhaetoliassicus*, *Cyatidites australis*, *Callialasporites dampieri*, *Pinuspollenites minimus*, *Platysaccus* spp. and *Zebrasporites fimbriatus* are features for the subdivision of two palynomorph assemblages (Fig. 5). *Cerebropollenites thiergartii*, a marker species for the base of the Hettangian in the Northern Calcareous Alps (Kuerschner et al. 2007) was not identified.

The Rhaetian/Hettangian palynomorph assemblages of the Furkaska section can be distinguished by means of multivariate statistical analysis, which allows the quantification of similarity/dissimilarity of a variety of samples that were examined according to different attributes. A cluster analysis was performed for the data set of 11 samples and 70 sporomorph species (variables). Sample 410 was excluded from cluster analysis due to the small number of identifiable palynomorphs and their overall poor preservation. Fig. 6 shows the subdivision of the sam-

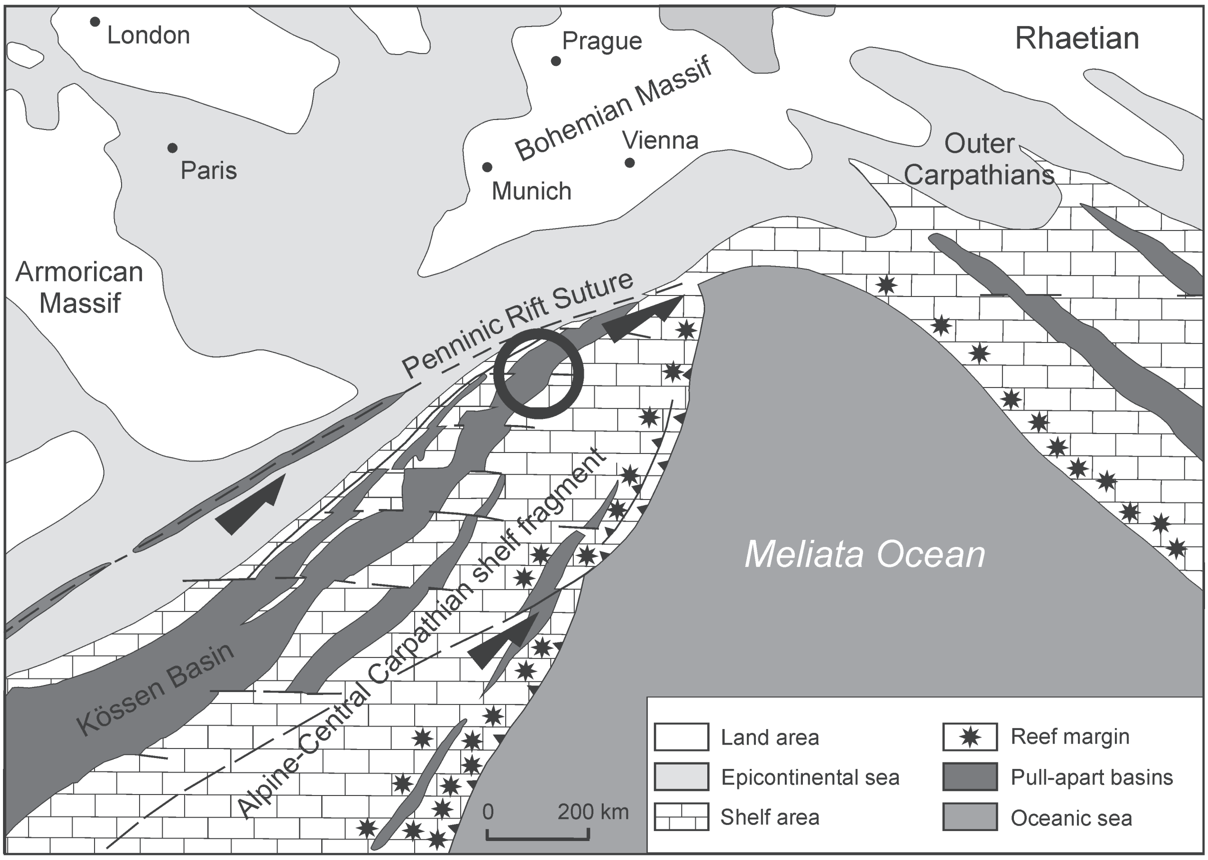

Fig. 1. Paleogeography of the NW Tethyan realm during Rhaetian times (modified from Michalík 1993). Circle marks the study area.

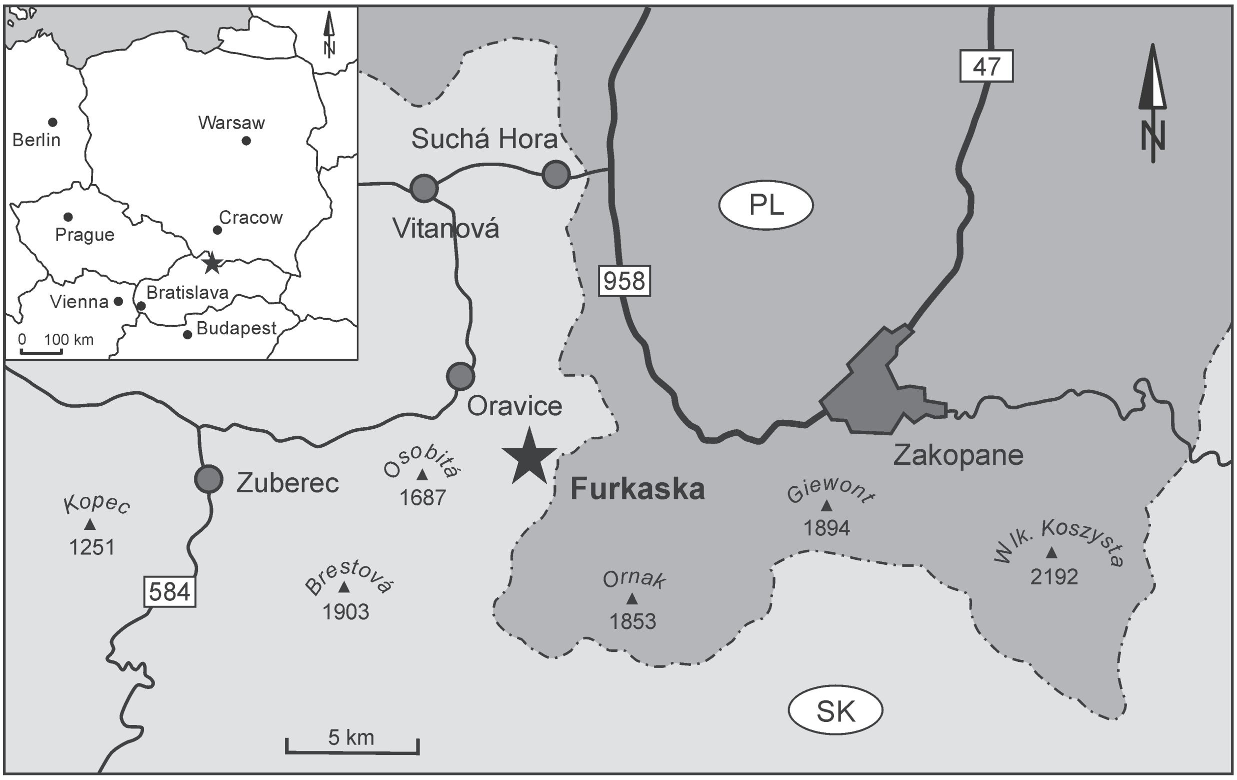

Fig. 2. Location map of the study area. Star marks the studied Furkaska section (49°16′ N; 19°47′ E) southeast of Oravice (Tatra Mts, Slovakia).

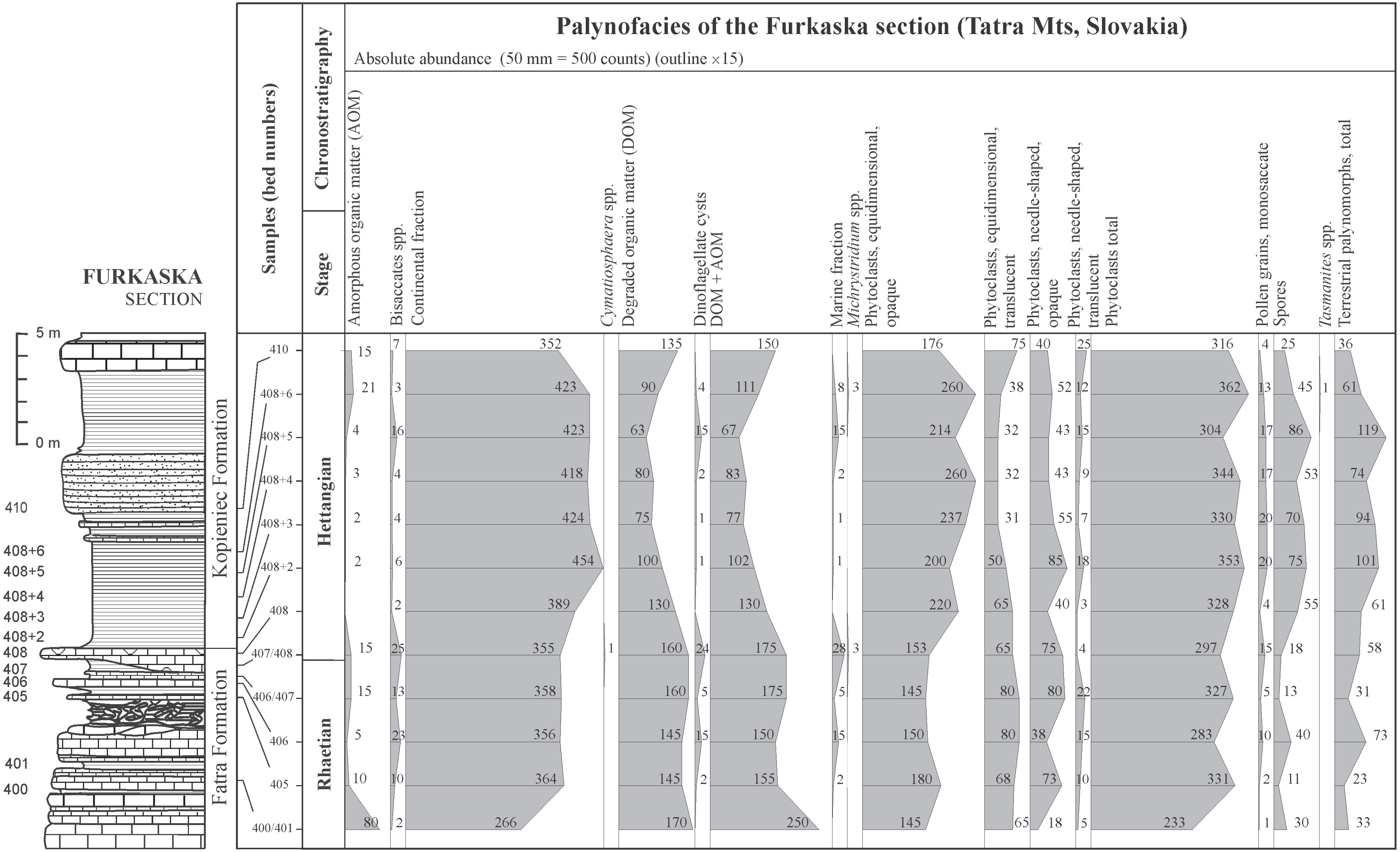

Fig. 3. Palynofacies of the Triassic/Jurassic boundary interval of the Furkaska section (Tatra Mts, Slovakia). The sample numbers correspond to the bed numbers by Michalík et al. (2007a). The sudden increase in the abundance of trilete spores in bed number 408 marks the Triassic/Jurassic boundary.

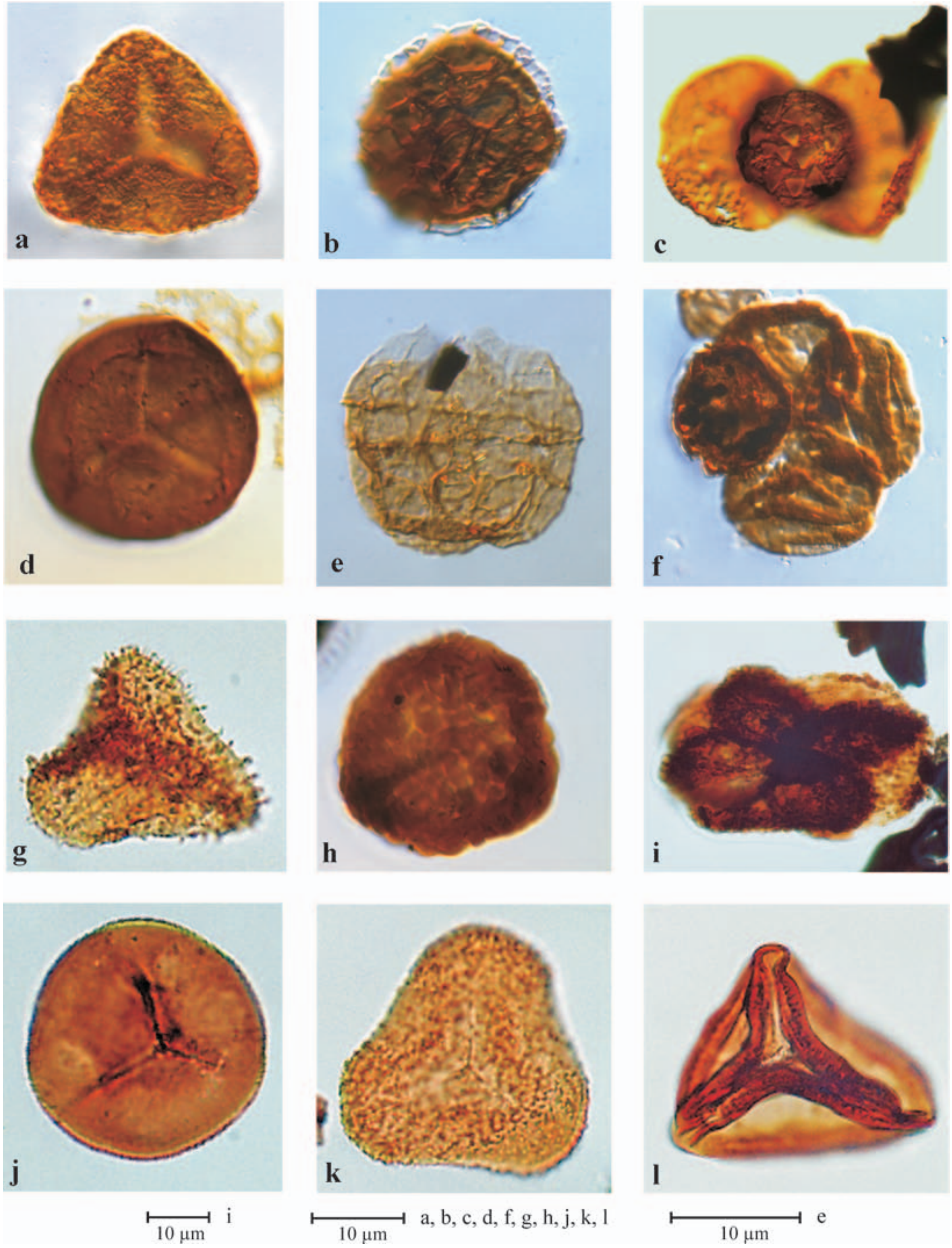

Fig. 4. Palynomorphs of the Triassic/Jurassic boundary interval of the Furkaska section (Tatra Mts, Slovakia). **a** — *Trachysporites fuscus* (sample 408 + 3); **b** — *Kraeuselisporites* sp. (sample 406); **c** — Bisaccate pollen grain (sample 406/407); **d** — *Punctatisporites* sp. (sample 408); **e** — *Dapcodinium priscum* (sample 408 + 1); **f** — *Corollina meyeriana* (sample 406); **g** — *Acanthotriletes varius* (sample 408 + 1); **h** — *Verrucosisporites* sp. (sample 408 + 4); **i** — *Ricciisporites tuberculatus* (sample 406); **j** — *Todisporites minor* (sample 408); **k** — *Conbaculatisporites mesozoicus* (sample 408 + 4); **l** — *Concavisporites crassexinus* (sample 408).

ples into two clusters: the samples of the lower part of the section studied (400/401 to 407/408) form one cluster whereas the samples of the upper part (408 to 408 + 6) group into a second cluster. It is necessary to point out, that the number of samples must be considered very low for a multivariate analysis. Regarding the minimum size of the sample population there are no general rules except that the sample population should be "large enough and representative" (Bortz 1999). Though the results of the cluster analysis are based on a small sample population their results are interpretable. Due to the fact that the change within the assemblage is not isochronic with the lithofacies change from limestone to clay but some centimeters lower in the section, the microfloral change is supposed to be independent of this lithologic change.

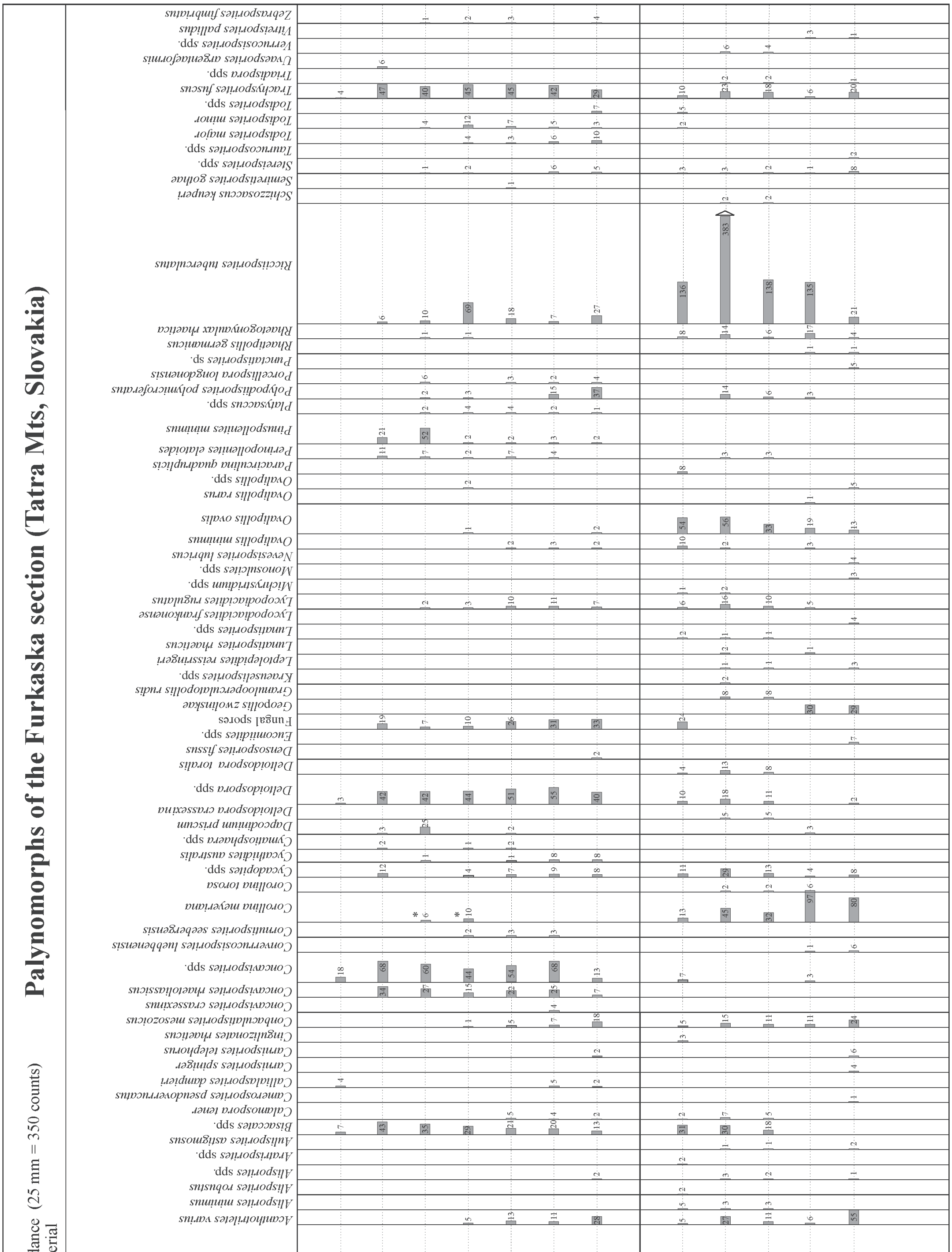

Fig. 5. Distribution of palynomorphs within the Triassic/Jurassic boundary interval of the Furkaska section (Tatra Mts, Slovakia). The decrease in the abundance of *Ovalipollis* spp., the last appearance of *Alisporites minimus* and *Corollina* spp., and the first appearance of *Concavisporites rhaetoliassicus*, *Cyatidites australis*, *Callialasporites dampieri*, *Pinuspollenites minimus*, *Platysaccus* spp. and *Zebrasporites fimbriatus* are striking features for a subdivision of two palynomorph assemblages.

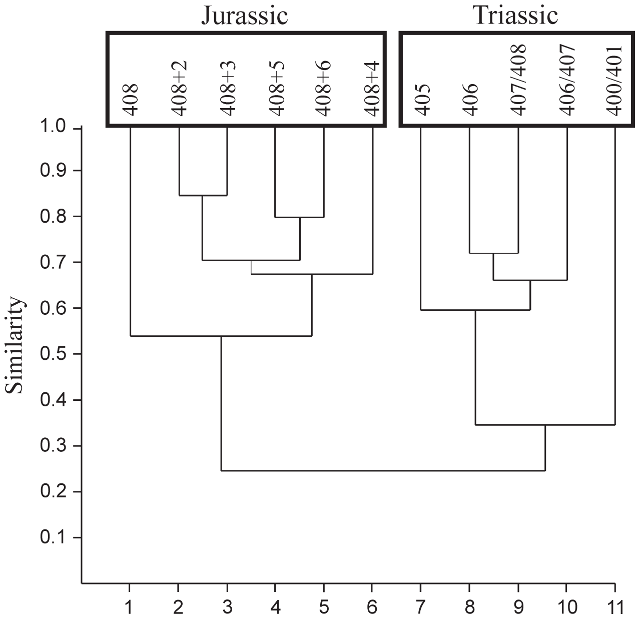

Fig. 6. Hierarchical tree plot of the palynological data set of the Furkaska section. The samples of the lower part of the section studied (400/401 to 407/408) form one cluster whereas the samples of the upper part (408 to 408 + 6) group into a second cluster.

Palynostratigraphy

Latest Triassic and Early Jurassic palynological assemblages are well documented by a number of studies in the German and Danish parts of the Germanic Basin (e.g. Schulz 1967; Herngreen & De Boer 1974; Lund 1977, 2003; Guy-Ohlson 1981; Brenner 1986) and the British Rhaetian-Hettangian (e.g. Orbell 1973; Warrington 1974; Hounslow et al. 2004). A compilation of the stratigraphically important marker species identified by these authors and their zonations is given in Fig. 7.

Lund (1977) divided the Rhaetian of the North Sea into a *Rhaetipollis-Limbosporites* Zone and a *Ricciisporites-Polypodiisporites* Zone; the Hettangian is represented by the *Pinuspollenites-Trachysporites* Zone. Orbell (1973) has distinguished a Late Triassic *Rhaetipollis* Zone and an Early Hettangian *Heliosporites* Zone in British sections. The latter is characterized by an acme of *Naiaditaspora* spp. (*Naiaditaspora harrisii* is considered by Morbey (1975) as a junior synonym of *Porcellispora longdonensis*) following the rapid decline of palynomorphs characterizing the *Rhaetipollis* Zone (*Rhaetipollis germanicus* and *Ovalipollis pseudoalatus*) and a marked increase in the abundance of *Heliosporites*. Kuerschner et al. (2007) separate a *Rhaetipollis-Porcellispora* Zone and a *Trachysporites-Porcellispora* Zone within the Rhaetian of the Northern Calcareous Alps. The Hettangian is defined by palynomorphs of the *Trachysporites-Heliosporites* Zone. Kuerschner et al. (2007) suggested *Cerebropollenites thiergartii* as a marker species for the base of the Hettangian. Weiss (1989) divided the Rhaetoliassic of S Germany into a Rhaetian *Concavisporites-Duplexisporites problematicus-Ricciisporites tuberculatus* Zone and a Hettangian *Concavisporites-Duplexisporites problematicus* Zone. Brenner (1986) described sporomorph assemblages of SW Germany, but did not define zones. Sediments of the Polish part of the Germanic Basin were investigated by Orłowska-Zwolinska (1983). She distinguished a Rhaetian Assemblage (Assemblage V) and a Hettangian Assemblage (Assemblage VI). Fowell & Olsen (1993) worked on Triassic/Jurassic boundary sections of the Newark Basin (Eastern North America), while Ashraf et al. (1999) studied the Rhaetian Haojiagou Formation and the Liassic Badaowan Formation of the Chinese Junggar Basin.

Figure 7 shows the stratigraphical occurrence of the most important palynomorphs in the Furkaska section in comparison with the previous works mentioned above. The sporomorph assemblage of the Tatra Mountains is very similar to the assemblages of the Polish part of the Germanic Basin (Orłowska-Zwolinska 1983) and to the assemblages of the Austrian Kössen Beds of the Northern Calcareous Alps (e.g. Kuerschner et al. 2007). The close paleogeographic relation of these areas during Rhaetian and Hettangian times is the cause of this resemblance.

In the Newark Supergroup of North America (Newark Basin) palynomorphs and conchostracans were used as biostratigraphic index fossils. Until a few years ago, the Triassic/Jurassic boundary was drawn with the beginning of the high increase of *Corollina meyeriana* (Cornet 1977) immediately below the first basalt flow. Recently, Kozur & Weems (2005) investigated the conchostracans and placed the boundary within the so-called Newark igneous extrusive zone at the base of the *Bulbilimnadia sheni* Zone. This position of the boundary is confirmed by vertebrate findings and Lucas & Tanner (2007) interpreted the sudden dominance of *Corollina meyeriana* within the palynomorph assemblage as a result of regional climate change caused by uplift or volcanism, not as a biostratigraphical datum. Since biostratigraphical identification of the Triassic/Jurassic boundary in the Newark Basin is still under discussion, correlation with marine sections of similar age in the Tethyan realm remains difficult.

Discussion

The most striking change in the microfloral assemblage of the Furkaska section is the sudden increase in the abundance of trilete spores within the last limestone bed of the uppermost Rhaetian Fatra Formation (bed 408). Spores are produced by plants such as ferns and horsetails, which require moist conditions to reproduce. Therefore, the relative abundance of spores can serve as a proxy for humidity changes. In the present study the spore spike is interpreted as an indication of increasing humidity at this time. Other significant features are the decrease of *Ricciisporites tuberculatus* and the LAD of *Corollina* spp. In contrast to other marine sections of the NW Tethyan realm, a prasinophyte bloom was not detected in the Furkaska section.

Since the Triassic/Jurassic boundary marks one of the five biggest biotic extinctions during the Phanerozoic, the lack of mass extinction within the microfloral assemblages of the NW Tethyan realm is surprising. However, a prasinophyte bloom

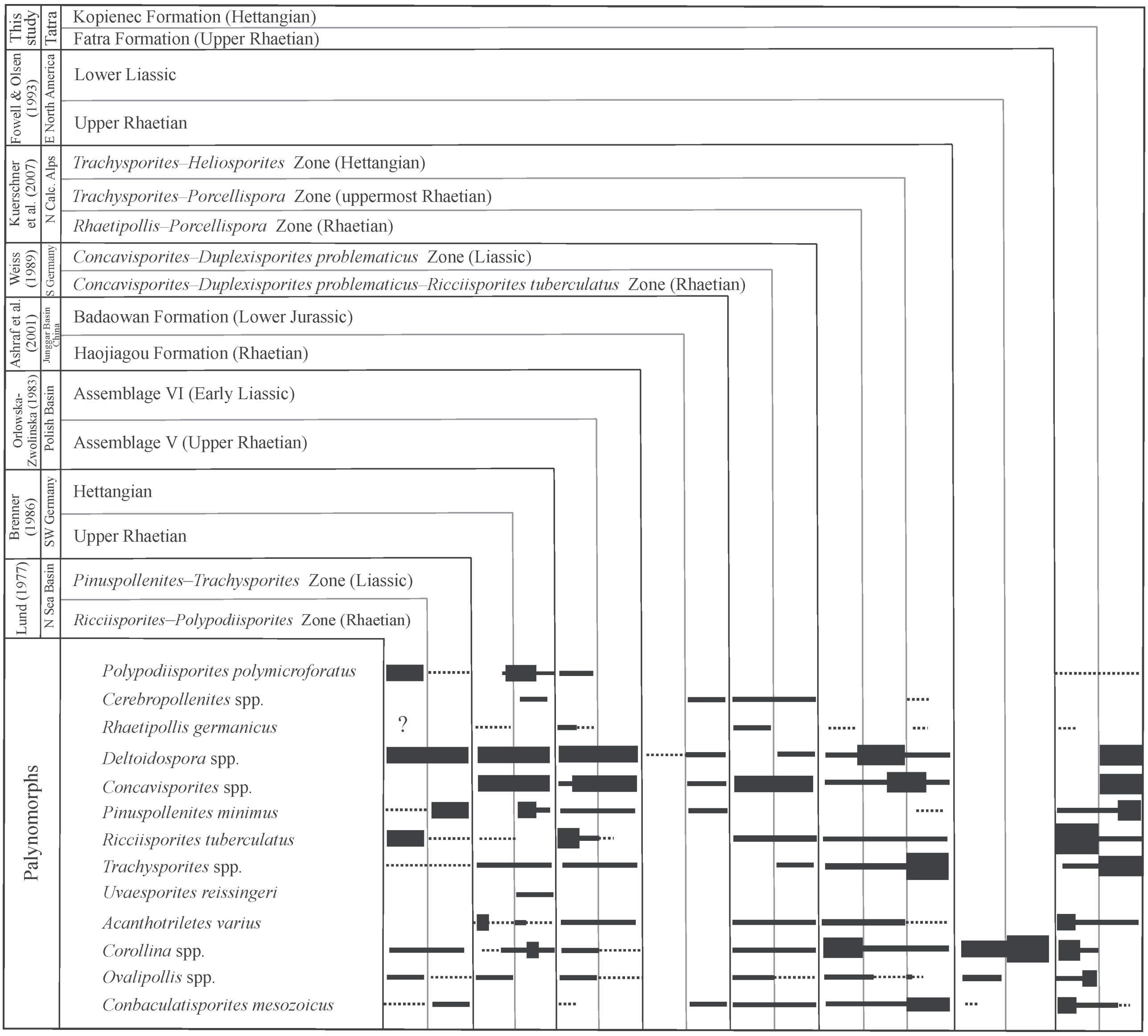

Fig. 7. Marker species of Triassic/Jurassic boundary sections of the NW Tethys region (Tatra Mountains, Northern Calcareous Alps), of the Germanic Basin (North Sea, Germany, Poland), the Newark Basin (USA), and Junggar Basin (China).

recognized in sections of the Northern Calcareous Alps (Tiefengraben; Kuerschner et al. 2007), Great Britain (St. Audrie's Bay; Van de Schootbrugge et al. 2007) and the Transdanubian Range (Csővár; Ruckwied 2008; Götz et al. submitted) in association with a prominent negative shift in $\delta^{13}C_{org}$ values (Hesselbo 2002, 2004; Kuerschner et al. 2007; Michalík et al. 2007a; Pálfy et al. 2007) points to a major perturbation in ocean chemistry.

The ultimate cause of these biotic and environmental changes is still under discussion. Three main possible drivers are considered: The first is the emplacement of a large igneous province (the Central Atlantic Magmatic Province, CAMP) that was associated with the initial break up of Pangaea (Wilson 1997), the second is the possible impact of a large meteorite (Olsen et al. 2002) similar in size (10 km in diameter) to the one that is inferred to have impacted Earth 65 Ma ago at the K-Pg boundary. The third involves the sudden dissociation of large amounts of methane hydrate (Beerling & Berner 2002).

Hesselbo et al. (2002) discussed a causal relation of the negative $\delta^{13}C$ excursion and the initial volcanic activity of the Pangaean Atlantic rifting and recently, $^{40}Ar/^{39}Ar$-datings of plateau basalts in Morocco and Portugal (Nomade et al. 2007; Verati et al. 2007) confirmed the isochroneity of CAMP volcanism and major changes in marine and terrestrial ecosystems at the Triassic/Jurassic boundary. The palynological data of the present study support this hypothesis. Phases of intense rifting and high volcanic activity are associated with changes in oceanic and atmospheric circulation patterns, regionally resulting in increasing precipitation and/or humidity, documented in the detected spore signal. Furthermore, clay mineralogical analyses reveal a striking dominance of kaolinite within the Boundary Clay of the Furkaska section (Ruckwied et al. 2006; Michalík et al. 2007b) which is interpreted as a reflection of high chemical weathering in the hinterland due to humid climate.

Nevertheless, the influence of any one of the three mechanisms under discussion would not necessarily rule out the operation of the others. Therefore, further studies should focus on precise quantifications of the environmental effects that took place across the Triassic/Jurassic boundary to identify and understand the most likely cause of the global changes at that time (Cohen & Coe 2007).

Conclusions

The palynological data presented here contribute to the discussion of the driving mechanism(s) of globally documented changes in marine and terrestrial ecosystems at the Triassic/Jurassic boundary. Striking changes in the palynomorph assemblages of the Triassic/Jurassic boundary interval of the Furkaska section (Tatra Mts, Slovakia) clearly reflect a major climatic change during that period. The detected spore shift is interpreted as evidence of a sudden increase in humidity most probably caused by the volcanic activity of the Central Atlantic Magmatic Province (CAMP).

Acknowledgments: This study is part of a project on microfloral changes within the Triassic/Jurassic boundary interval of key sections in the NW Tethyan realm supported by the German Research Foundation (DFG Project GO 761/2-1). Joint field work and fruitful discussions with Jozef Michalík and Otília Lintnerová (Bratislava) are gratefully acknowledged. We also thank Susanne Feist-Burkhardt (London) and Stephen Hesselbo (Oxford) for their very constructive reviews.

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Appendix 1

Alphabetical list of palynomorphs identified in the Furkaska section.

Spores

Acanthotriletes varius Nilsson, 1958
Aratrisporites sp.
Aulisporites astigmosus Klaus, 1960
Calamospora tener (Leschik, 1955) Mädler, 1964
Camerosporites pseudoverrucatus Leschik, 1956
Carnisporites ornatus Mädler, 1964
Carnisporites spiniger (Leschik, 1955) Morbey, 1975
Carnisporites telephorus Pautsch, 1958
Conbaculatisporites mesozoicus Klaus, 1960
Concavisporites crassexinus Nilsson, 1958
Concavisporites rhaetoliassicus Achilles, 1981
Concavisporites spp.
Cingulizonates rhaeticus (Reinhardt, 1961) Schulz, 1967
Converrucosisporites luebbenensis Schulz, 1967
Cornutisporites seebergensis Schulz, 1967
Cycathidites australis Couper, 1953
Deltoidospora crassexina Lund, 1977
Deltoidospora spp.
Deltoidospora toralis (Leschik, 1955) Lund, 1977
Densosporites fissus (Reinhardt, 1964) Schulz, 1967
Kraeuselisporites spp.
Leiotriletes sp.
Leptolepidites reissringeri (Reinhardt, 1961) Achilles, 1981
Lycopodiacidites frankonense Achilles, 1981
Lycopodiacidites rugulatus Schulz, 1967
Nevesisporites lubricus Orłowska-Zwolinska, 1983
Polypodiisporites polymicroferatus Orłowska-Zwolinska, 1983
Porcellispora longdonensis (Clarke, 1965) Scheuring, 1970
Porcellispora sp.
Punctatisporites sp.
Semiretisporites gothae Reinhardt, 1964
Stereisporites spp.
Taurucosporites spp.
Todisporites major Couper, 1958
Todisporites minor Couper, 1958
Todisporites spp.
Trachysporites fuscus Nilsson, 1958
Uvaesporites argentaeformis (Bolkovitina, 1953) Schulz, 1967
Verrucosisporites spp.
Zebrasporites fimbriatus Klaus, 1960

Pollen grains

Alisporites sp.
Alisporites minimus Leschik, 1955
Alisporites robustus Nilsson, 1958
Bisaccates sp.
Callialasporites dampieri (Balme, 1957) Dev, 1961
Corollina meyeriana (Klaus, 1960) Venkatachala & Góczán, 1964
Corollina torosa (Reissinger, 1950) Klaus, 1960
Cycadopites spp.
Eucomiidites spp.
Geopollis zwolinskae (Lund, 1977) Brenner, 1987
Granuloperculatopollis rudis Venkatachala & Gózcán, 1964
Lunatisporites rhaeticus Leschik, 1955
Lunatisporites spp.
Monosulcites spp.
Ovalipollis minimus Scheuring, 1970
Ovalipollis ovalis (Krutzsch, 1955) Scheuring, 1970
Ovalipollis rarus Klaus, 1960
Ovalipollis spp.
Paracirculina quadruplicis Scheuring, 1970
Perinopollenites elatoides Couper, 1958
Pinuspollenites minimus (Couper, 1958) Kemp, 1970
Platysaccus spp.
Rhaetipollis germanicus Schulz, 1967
Ricciisporites tuberculatus Lundblad, 1964
Schizzosaccus keuperi Mädler, 1964
Triadispora spp.
Vitreisporites pallidus (Reissinger, 1950) Nilsson, 1958

Dinoflagellate cysts

Rhaetogonyaulax rhaetica (Sarjeant, 1963) Loeblich & Loeblich, 1968, emend. Below, 1987
Dapcodinium priscum Evitt, 1961, emend. Below, 1987

Acritarchs

Michrystridium spp.

Prasinophytes

Cymatiosphaera spp.
Tasmanites spp.