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Magneto-, and isotope stratigraphy around the Jurassic/Cretaceous boundary in the Vysoká Unit (Malé Karpaty Mountains, Slovakia): correlations and tectonic implications

JACEK GRABOWSKI[1], JOZEF MICHALÍK[2], ANDRZEJ PSZCZÓŁKOWSKI[3] and OTÍLIA LINTNEROVÁ[4]

[1]Polish Geological Institute, National Research Institute, Rakowiecka 4, 00 975 Warszawa, Poland; jacek.grabowski@pgi.gov.pl
[2]Geological Institute, Slovak Academy of Sciences, Dúbravská cesta 9, P.O. Box 106, 840 05 Bratislava, Slovak Republic; jozef.michalik@savba.sk
[3]Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Warsaw, Twarda 51/55, 00-818 Warszawa, Poland; apszczol@twarda.pan.pl
[4]Department of Economic Geology, Faculty of Science, Comenius University, Mlynská dolina G, 842 15 Bratislava, Slovak Republic; lintnerova@fns.uniba.sk

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Abstract: Magneto- and isotope stratigraphic studies in the Vysoká Nappe (Hlboča section, Fatric Unit, Malé Karpaty Mts, Slovakia) were performed. A generally decreasing $\delta^{13}C$ isotope curve is interpreted as a primary trend from the Late Oxfordian (3.3 ‰ V-PDB) to the Late Tithonian (1.8–1.4 ‰ V-PDB). Data from the Tithonian part of the Tegernsee Formation probably reflect "local" basin processes connected with the breccia formation in the latest Tithonian/earliest Berriasian and/or with possible diagenetic overprint. The C-isotope record of the Berriasian Padlá Voda Formation is more homogeneous (1.4–1.8 ‰ V-PDB) and assumed to be primary. Magnetostratigraphic investigations were focused on the Jurassic/Cretaceous (J/K) boundary strata. Upper Tithonian nodular limestones of the Tegernsee Formation differ substantially from Lower Berriasian calpionellid limestones of the Padlá Voda Formation in rock magnetic properties. Hematite is present in the Tegernsee Formation, while magnetite is the only magnetic mineral of the Padlá Voda Formation. Additionally, the latter formation contains superparamagnetic magnetite, which significantly influences its magnetic susceptibility. Correlation of normal and reversed magnetic intervals with the Late Tithonian global polarity time scale was supported by microfossil stratigraphy. M21n to M20n magnetozones were distinguished, including the short reversed Kysuca (M20n1r) Subzone within M20n. Interpretation of Lower Berriasian magnetostratigraphy was more complex due to presence of breccia horizons and a stratigraphic gap at the J/K boundary in the lower part of the Padlá Voda Formation embracing M19r and most of M19n magnetozones. This formation was also partially affected by remagnetization. Detailed correlation between the isotope- and magnetic stratigraphy of the Tithonian–Berriasian interval between Hlboča and Brodno sections is also complex due to J/K stratigraphical gap within the Hlboča section. The primary B component accounts for counter-clockwise rotation of the Vysoká Unit with a magnitude of ca. 50°. Since the paleodeclination of Paleogene and Karpatian–Eggenburgian rocks in the area is similar, the rotation must have taken place after Early Miocene. The paleoinclinations of several Upper Tithonian–Berriasian sections of the Central Western Carpathians and western part of the Pieniny Klippen Belt are consistent and indicate paleolatitude of 27–30°N.

Key words: J/K boundary, Western Carpathians, paleomagnetism, magnetostratigraphy, magnetic susceptibility, stable isotopes, microfossil stratigraphy.

Introduction

The Jurassic/Cretaceous (J/K) boundary interval offers good correlation possibilities for marine sections in the Tethyan region because of the established (micro- and nanno-) biostratigraphy, C-isotope stratigraphy and magnetostratigraphy. The magnetic zones are relatively easy to identify, due to the specific pattern of two long normal magnetozones (M20n and M19n), containing short reversed polarity subzones (M20n1r and M19n1r), named by Houša et al. (1996, 1999) as the Kysuca and the Brodno respectively. Microbiostratigraphic callibration of Late Tithonian/Berriasian magnetozones was successfully performed in south Tethyan sections of the Apennines and Southern Alps (Channell et al. 1987; Channell & Grandesso 1987; Ogg et al. 1991). Detailed magnetostratigraphic studies in the Apennines, Tatra Mts and Transdanubian Mts were published recently (Houša et al. 2004; Speranza et al. 2005; Grabowski & Pszczółkowski 2006; Grabowski et al. 2010) and pilot results were reported from the Eastern Alps (Pruner et al. 2009). The Brodno section in the Pieniny Klippen Belt (PKB) is currently proposed as the J/K regional stratotype in the Carpathians (Michalík et al. 2009).

As the integrated bio- and magnetostratigraphic framework of the J/K boundary interval is now well known, the magnetic method becomes a tool in identification of paleoenvironmental changes on a global or regional scale, akin to those in Quaternary loess sequences (e.g. Heller & Evans 1995) or Middle–Upper Devonian shallow water carbonates (e.g. Jackson et al. 1993; Hladil et al. 2006; Nawrocki et al. 2008). Grabowski & Pszczółkowski (2006) and Grabowski

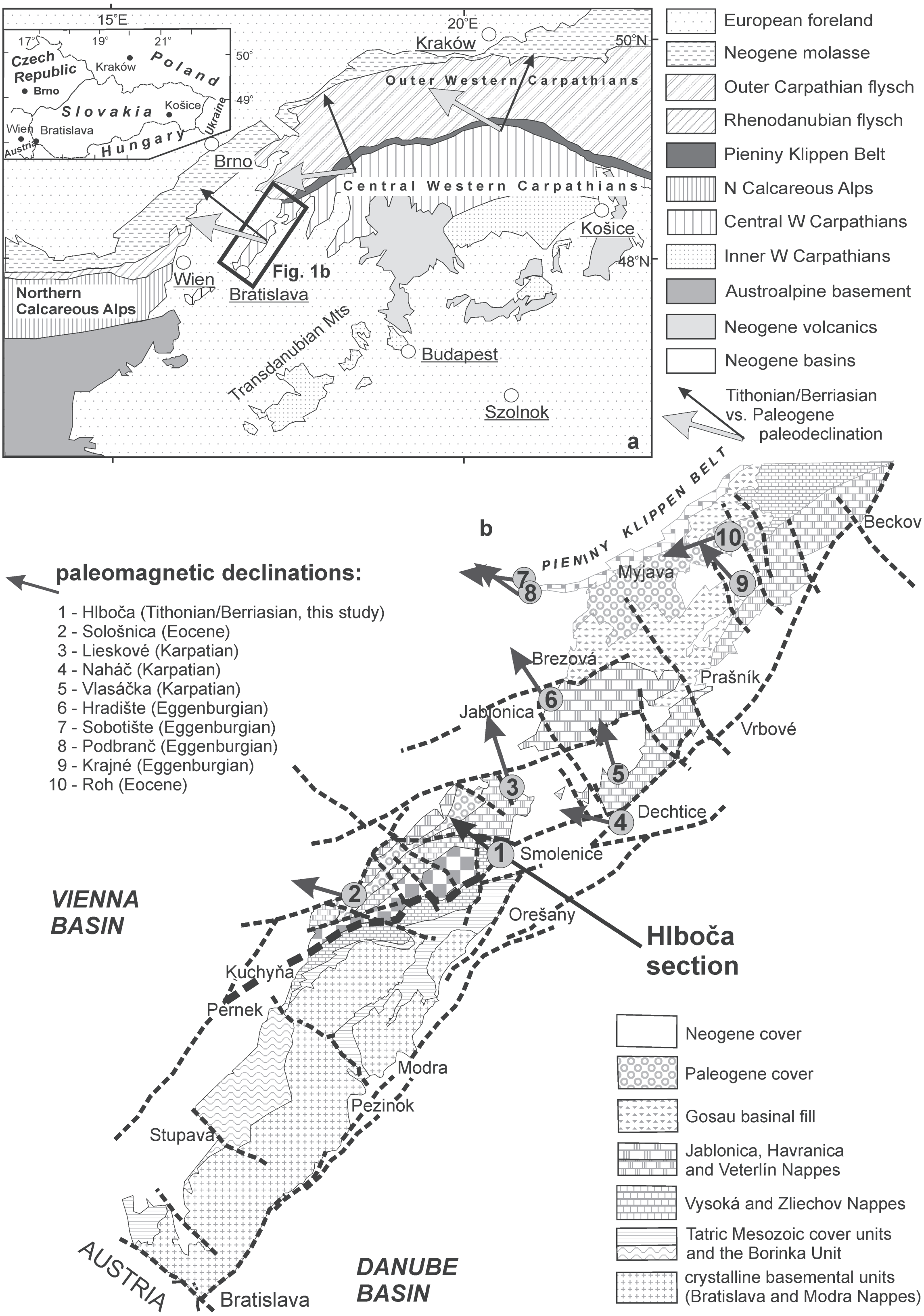

Fig. 1. a — Tectonic sketch map of the Western Carpathians and Eastern Alps showing Tithonian–Berriasian (single arrow) and Paleogene (double arrow) paleodeclinations from the Malé Karpaty Mts (Paleogene — Márton et al. 1992; Berriasian — this study), from the Strážovské Vrchy Mts (Paleogene — Túnyi & Márton 1995; Berriasian — Grabowski et al. 2009 — 1) and from the Tatra Mts (Paleogene — Márton et al. 1999; Berriasian — Grabowski 2005 — 2). The rectangle indicates the area of Fig. 1b. **b** — Geological sketch map of the Malé Karpaty Mts with declinations of Mesozoic and Tertiary paleomagnetic directions: **1** — this study, 2–10 — after Márton et al. (1992), and Kováč & Túnyi (1995).

et al. (2010) attempted to link petromagnetic properties of formations in the Tatra Mts (Poland) and central part of the Transdanubian Mts (Hungary) with changing sedimentary conditions.

Isotopic research in the J/K boundary sequences in various parts of the world (but mainly in the Tethyan area) confirmed a correlative shape of the $\delta^{13}C$ curve, reflecting relationship between global oceanic and atmospheric conditions and the extent of production and deposition of organic matter in oceanic sediments (Scholle & Arthur 1980; Weissert et al. 1985; Weissert & Channell 1989; Price et al. 2000; Gröcke et al. 2003; Michalík et al. 2009, and many others). The $\delta^{13}C$ record in carbonates is becoming an important stratigraphic tool, because it integrates information on evolution both in the organic and inorganic part of the carbon cycle. As the total range of fluctuations usually does not exceed 1 or 2 ‰ (exceptionally 2 to 3 ‰), the significance of isotopic curve changes is interpretable in biostratigraphically or magnetostratigraphically well characterized sections.

In this paper, new paleomagnetic, magnetostratigraphic, magnetic susceptibility and stable isotope data from the Hlboča section (Vysoká Nappe, Malé Karpaty Mts) are presented. This section was biostratigraphically correlated with the regional J/K stratotype section at Brodno and with other magnetostratigraphically studied sections in the Western Carpathians. The global vs. diagenetic trend of the Oxfordian–Berriasian C-isotope curve in the Hlboča section was discussed. Magnetostratigraphic, biostratigraphic and isotope stratigraphic scales were compared. The significance of paleomagnetic results for sedimentary and paleotectonic reconstructions of the Central Western Carpathians was also briefly discussed.

Geological setting

The Malé Karpaty Mts form the westernmost part of the Central Western Carpathians close to the junction with the Northern Calcareous Alps (Fig. 1). Its structure joins elements of the Alpine and Carpathian architecture. The lowermost unit exposed is the Borinka Unit of Ultra-Tatric appurtenance, covered by the thick Tatric Bratislava granitoid nappe with its Mesozoic sedimentary cover (Fig. 1). The Alpine superficial nappe system lies above it. Its basal part belongs to the Vysoká Nappe, derived from the northern, marginal part of the Fatric Domain, where slope and ridge facies prevailed (Plašienka et al. 1997). Thrusting of the Vysoká Nappe over Tatric Mesozoic cover and crystalline basement (Mahel' 1987) might have taken place around the Turonian/Coniacian boundary (Plašienka et al. 1991). Higher tectonic units are represented by the Hronic nappe system (the Jablonica, Havranica and Veterlin Nappes).

The Hlboča section is located in the Vysoká Nappe, in the NE part of the Malé Karpaty Mts, in a half-blind karstic valley (with the only small waterfall in the area called the Padlá Voda) close to the Smolenice village, ca. 50 km to the NNE from Bratislava (Fig. 1). The closure of the valley is formed by steep rock walls called the Mníchove Diery ("Monk's holes"); they comprise almost complete Upper Jurassic–Lower Cretaceous sequence, dipping monoclinally to the NW (Borza & Michalík 1987b).

Sampling and methods of study

A total of 106 samples have been taken from the sequence in 0.5 m (in the upper part of section in 1 meter) intervals for thin sectioning and microfacies study. Allochems (clastic grains, calcareous and siliceous plankton tests, shell fragments of benthic organisms) and micrite have been evaluated under optical microscope in percent using the optical charts of Bacelle & Bosellini (1965). The data obtained have been applied in graphic representation of mutual changes, illustrating transport and sedimentation changes during eustatic sea level fluctuations (Michalík 2007).

Fourty-seven limestone beds were sampled for magnetostratigraphic study. Samples were taken either with a gasoline powered drill (38 beds) or as hand samples (9 beds). Sampling resolution was higher within the Tegernsee Formation: approximately three samples per one meter were taken. For comparison, in the difficult conditions of the Padlá Voda Formation, forming steep walls of the karstic valley, only lower resolution sampling (one sample per one meter) was performed. Most of the sampled beds (36) were also studied in thin sections for microfossil stratigraphy.

Standard cylindrical specimens 2.2 cm high and 2.5 cm in diameter were prepared from drill cores and hand samples. Paleomagnetic experiments were performed in the Paleomagnetic Laboratory of the Polish Geological Institute. Natural remanent magnetization (NRM) was measured with the JR6a spinner magnetometer and the KLY2 kappabridge was used for magnetic susceptibility measurements. Specimens were demagnetized exclusively by the thermal method using a MMTD1 oven. The results of measurements were further processed using the Remasoft software (Chadima & Hrouda 2006). A fold test was applied using the method of Watson & Enkin (1993). Rock magnetic investigations comprised measurements of isothermal remanent magnetization (IRM) applied along the Z axis in the field of 1 T, and then antiparallel in the field of 100 mT (using a MMPM pulse magnetizer). The S parameter calculated as a ratio of IRM intensities applied in both fields was indicative for proportions of low and high coercivity minerals. In samples from selected beds, stepwise acquisition of the IRM (in the maximum field of 1.4 T) was performed, followed by thermal demagnetization of three axes IRM acquired in the fields of 1.4 T, 0.4 T and 0.1 T (Lowrie 1990). Low and high frequency susceptibility of selected beds was studied by means of the Bartington MS2 susceptibility meter to estimate the contribution of the very fine (close to superparamagnetic state — SP) magnetic fraction (Forster et al. 1994).

Carbon and oxygen isotope analyses were carried out on 47 bulk carbonate samples from the Oxfordian- to Lower Berriasian part of the Hlboča section using the Finnigan MAT-2 mass spectrometer. The values are reported in terms of the Vienna-PDB (V-PDB) in the standard δ notation in ‰, with a precision of ± 0.01 ‰. The total organic (TOC) and inorganic carbonate content (TIC) was measured on the C-MAT 550.

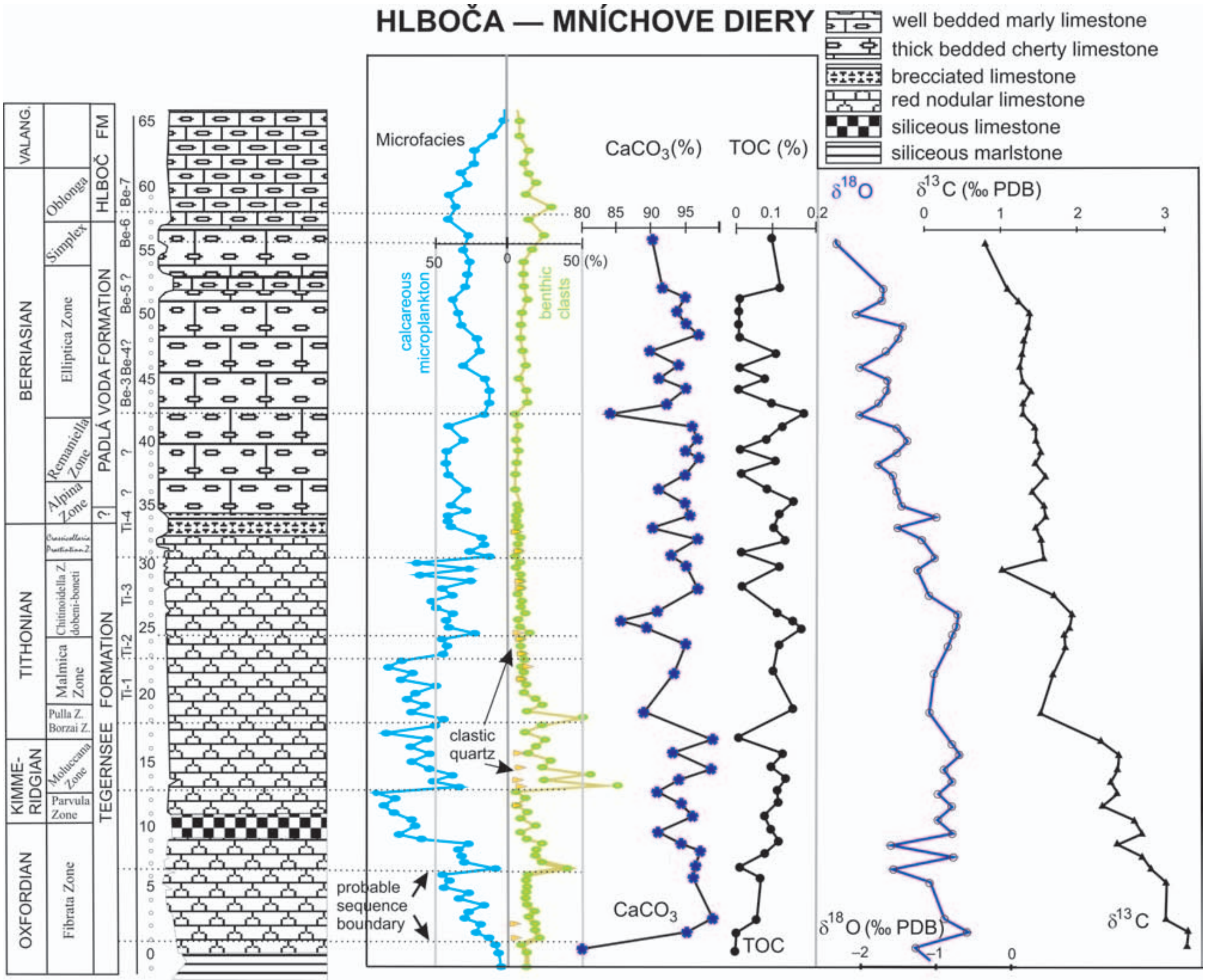

Fig. 2. Lithology, distribution of allochems in microfacies, $CaCO_3$ content, TOC, isotopes of O and C in the Hlboča section.

TIC values were recalculated to the $CaCO_3$ content in order to assess the carbonate content of the samples.

Lithology, sequence stratigraphy and isotope data

The lower part of the section sampled (between 25 and 34 m, see Fig. 2) is formed by reddish and pink nodular limestones attributed to the Tegernsee Formation (Borza & Michalík 1987a,b; Vašíček et al. 1994; probable equivalent of the Czorsztyn Limestone Formation of Birkenmajer 1977; Lefeld et al. 1985). The limestones are irregularly, sometimes thin lenticularly, or even schistose bedded, with layers of intraclasts. The clasts are formed by pale rosa micrite, the matrix consists of reddish brown more marly micrite. Ammonite and belemnite fragments are relatively common, but they have been heavily corroded and broken prior to deposition.

The amount of allochems fluctuates in the more or less regular deepening upward cycles. Seven such cycles have been recognized in the Tegernsee Formation. Their lowstand part contains more clastic quartz; an increase of fragments of benthic organisms in biomicrosparite to biomicrite is observed during shallowing upward. The representation of biomicrite accompanied by amount of planktonic tests increases towards highstand (Fig. 2).

Generally, the Padlá Voda Formation consists of thick (poorly)-bedded grey calpionellid limestones. However, the boundary of the Tegernsee- and the Padlá Voda Formations coincides with (several) limestone breccia beds between 32 and 35 m of the section (Borza & Michalík 1987b; Michalík et al. 1990, 1995). The stratigraphic extent and thickness of breccias appears as a true problem within the section, as the breccia is hardly visible on the weathered surface of rock, and is clearly recognizable only on large polished slabs (Fig. 3). The limestone extraclasts attain 10–30 mm, rarely up to 70 mm, they were derived from underlying Tithonian and lowermost Berriasian strata. The erosion of 12 m of the uppermost Tithonian limestone sequence was postulated by Borza &

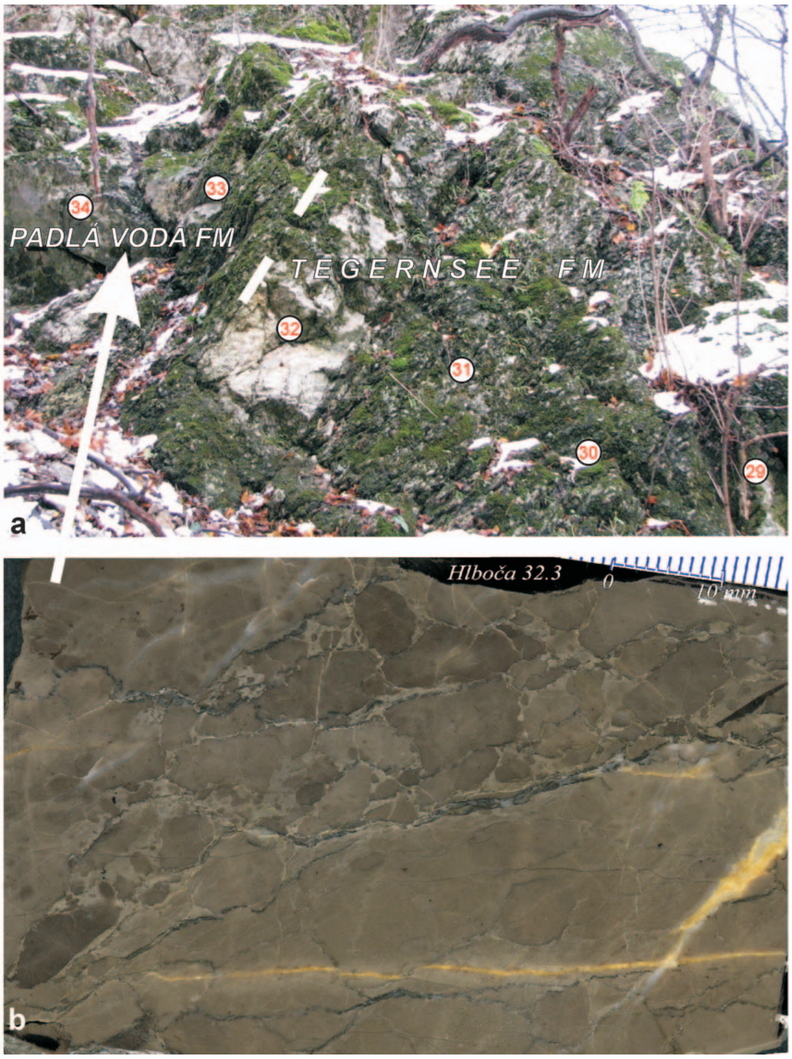

Fig. 3. Hlboča Valley — the Mníchove Diery section. **a** — Beds 29–35 around the J/K boundary; **b** — Macrophotography of the brecciated limestone at the base of the Padlá Voda Formation.

Michalík 1987b (see also Michalík et al. 1995). It probably originated during several extensional pulses, which denivelated the sea bottom (as in the Upper Valanginian Nozdrovice Breccia in more distal parts of the Fatric Zliechov Basin, see Michalík 2007). The higher part of the Padlá Voda Formation consists of massive limestone with large (up to 25 cm in diameter) cherts. A marly bedded interval with weak silicification occurs near the top of the sequence. The Padlá Voda Formation is covered by the bedded to schistose marly Hlboč Formation (Valanginian–Hauterivian) at 57 m of the section.

Geochemical analyses illustrate a small increase in carbonate content in each eustatic cycle from lowstand to highstand, correlatable with periodically fluctuating carbonate micro- and nannoplankton bioclasts (Fig. 2). On the other hand, the accumulation rate of organic carbon in the Hlboča section was very low, comparable to the Brodno section, or other sections studied (Weissert & Channell 1989; Michalík et al. 2009).

The $\delta^{13}C$ curve shows a decreasing trend from Oxfordian values often above 3 ‰ to Berriasian values below 2 ‰ (Fig. 2). A similar trend was documented elsewhere and it is interpreted as a global trend (Jenkyns & Clayton 1986; Weissert & Channel 1989; Jenkyns 1996; Price & Rogov 2009).

The influence of diagenetic and post-sedimentary processes was tested using $\delta^{13}C$ and $\delta^{18}O$ plots of bulk samples (Fig. 4). Values of $\delta^{13}C$ and $\delta^{18}O$ from the lower, Oxfordian–Kimmeridgian part of the section ($\delta^{13}C > 2$) do not show a positive covariance (Fig. 4a). Therefore, these limestones were not modified during diagenesis or deep burial (e.g. Föllmi et al. 2006; Duchamp-Alfonse et al. 2007).

The elongated shape of the Tithonian data cluster (18–32 m) from the Tegernsee Formation seems to indicate a relatively high positive correlation (Fig. 4b) — which could be regarded as evidence for diagenetic transformation of the limestone bed studied. However, when the sample with the most extreme $\delta^{13}C$ value (29.5: +0.87 ‰) is removed from the set, the degree of covariance decreases. Moreover, $\delta^{18}O$ value change is less distinct than the change in $\delta^{13}C$ in this sample (Figs. 2, 4), which is striking if we assume higher diagenetic "sensitivity" of the oxygen isotope. Therefore, the $\delta^{13}C$ composition of the 30.5 m sample could have been affected by local conditions in the basin indicated by sedimentary breccia occurrence. It is a matter of discussion, whether the above mentioned extensional pulses, which triggered erosion, redeposition and mixing of sediment could have resulted in local $\delta^{13}C$ value decrease both in the water column and in the carbonate deposited. On the other side, physical changes evoked by sediment mixing could have produced different diagenetic $\delta^{13}C$ ratio formed in sediment.

The more compact cluster of data from the Berriasian Padlá Voda Formation (33–55) reveals a negative trend and rather co-variance of $\delta^{13}C$ and $\delta^{18}O$ values (Figs. 2 and 4c). Although diagenetic overprint cannot be excluded, the level of co-variation is lower than in the Tithonian set. The uppermost sample (55.5 m) from transitional beds between the Padlá Voda- and the Hlboč Formations shows the most negative values of both isotope ratios. From the point of view of diagenetic overprint of Berriasian samples this datum represents a rather extreme value and it may be excluded from the graphic plot.

Regular fluctuation of $\delta^{18}O$ values in the Berriasian Padlá Voda Formation resembles similar cyclic changes in calcareous plankton content and the general sequence stratigraphic arrangement of these beds (Tremolada et al. 2006). Although the most negative $\delta^{18}O$ peaks are associated with sequence boundaries, connection with meteoric diagenesis (Weissert & Mohr 1996) in these deeper water conditions seems improbable.

For comparison, crossplots of $\delta^{13}C$ and $\delta^{18}O$ values from the Brodno section which embraces a similar stratigraphic

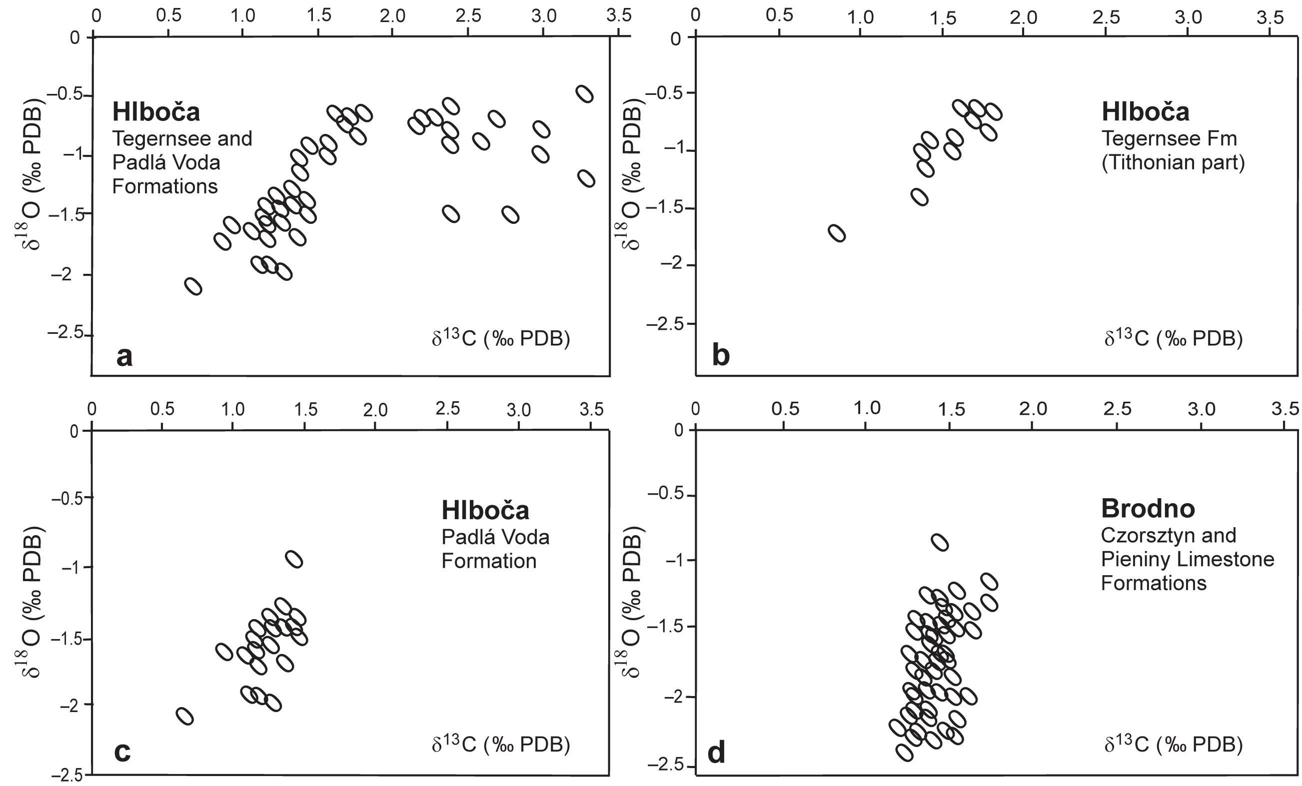

Fig. 4. Crossplot of carbon and oxygen isotopic data: **a** — Total Oxfordian–Berriasian data; **b** — Tithonian part of the Tegernsee Formation; **c** — Berriasian Padlá Voda Formation from the Hlboča section; **d** — Total data from the Brodno section.

interval do not show any co-variation (Fig. 4d). Therefore, primary isotopic ratios were preserved (Michalík et al. 2009). Either slight diagenetic modification of both oxygen and carbon isotopic values, or a significant local overprint in the Hlboča section should be included in the interpretation of deviation from the global trend (Weissert & Channell 1989; Marshall 1992; Morante & Hallam 1996; Weissert & Mohr 1996; Price & Rogov 2009, etc.).

Microbiostratigraphy

Biostratigraphy of Upper Jurassic–Lower Cretaceous formations in the Mníchove Diery section have been performed by Michalík et al. (1990), Reháková & Michalík (1992), or by Vašíček et al. (1994). Michalík et al. (1990) reported six Kimmeridgian to Early Berriasian microfossil zones (Pop 1976, 1986, 1994; Remane et al. 1986). The Moluccana-, Malmica-, Chitinoidella- and Crassicollaria Zones were distinguished in the Tegernsee Formation. The boundary between the Tegernsee- and the Padlá Voda Formations has been put below the Early Berriasian Calpionella alpina Subzone. The Calpionella Standard Zone, subdivided into the Alpina- and the Remaniella Subzones, was identified in the lower part of the Padlá Voda Formation.

Current biostratigraphic study of the Hlboča (Mníchove Diery) section was integrated with sampling for magnetostratigraphic investigations. It was based on 36 samples taken from the Tithonian–Middle Berriasian limestones (Fig. 5). In this part of the section, Chitinoidella-, Crassicollaria- and Calpionella biozones have been recognized. However, the studied section is not complete, as a breccia occurs at the boundary between the Crassicollaria and Calpionella Zones (= Tithonian/Berriasian boundary).

The interval examined starts in the middle part of the Tegernsee Formation. The typical red nodular limestone described by Michalík et al. (1990) is rich in *Saccocoma* ossicles. The 25-3 sample consists of *Globochaete-Saccocoma* biomicrite, containing rare *Borziella slovenica* (Borza) merely visible in thin section. This sample belongs to the Early Tithonian Dobeni Subzone of the Chitinoidella Zone (Fig. 5). Better preserved chitinoidellids occur in the 25-8 sample: *Daciella svinitensis* Pop, *D.* cf. *svinitensis* Pop, *Daciella almajensis* Pop, *D. banatica* Pop, *Daciella danubica* Pop, and *Borziella slovenica* (Borza). In other samples, scarce chitinoidellids like *Dobeniella* sp. cf. *D. cubensis* (Furrazola-Bermúdez), *Daciella banatica* Pop, *D. rumanica* Pop and also *Borziella slovenica* (Borza) occur.

The boundary of Dobeni/Boneti Subzones is located between samples No. 26 and 26-8 (Fig. 5). *Almajella cristobalensis* (Furrazola-Bermúdez), *Dobeniella colomi* (Borza) and *Dobeniella* cf. *cubensis* (Furrazola-Bermúdez) have been recorded in the sample 26-8. *Saccocoma–Globochaete* biomicrite (27-1) contains frequent *Chitinoidella* sp. (cf. *Ch. boneti* Doben), *"Chitinoidella" pinarensis* (Furrazola-Bermúdez & Kreisel), *Dobeniella* sp., *Borziella slovenica* (Borza), *Dobeniella bermudezi* (Furrazola-Bermúdez) and *Carpathella rumanica* Pop. This assemblage is correlated with the Late

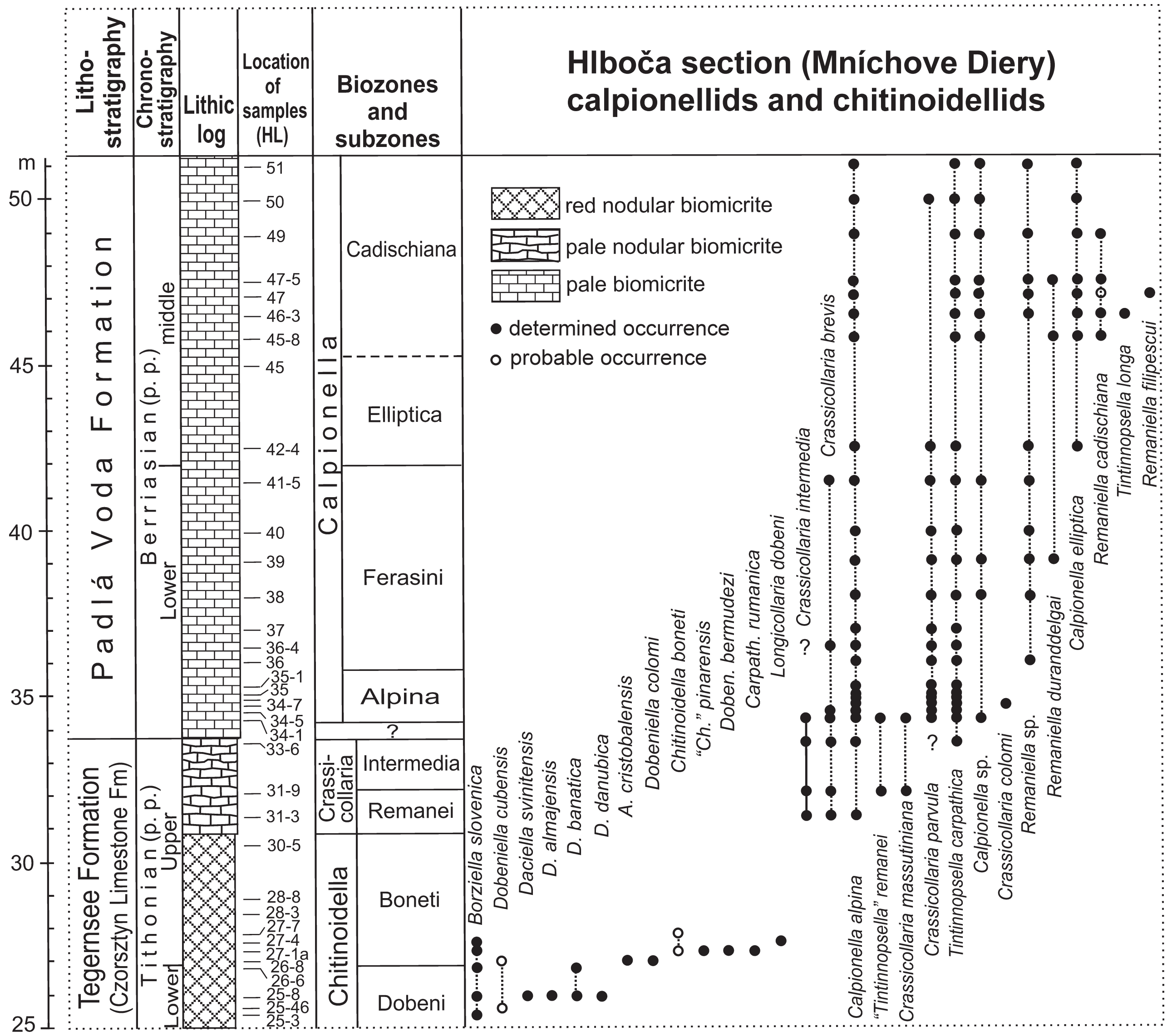

Fig. 5. Distribution of identified microfossils in the Hlboča section sequence.

Tithonian Boneti Subzone in the upper part of the Chitinoidella Zone. Up section, chitinoidellids are still present, although poorly preserved. *Borziella slovenica* (Borza) and *Longicollaria dobeni* (Borza) have been recognized in the 27-4 sample (Fig. 5). This assemblage is characteristic rather of the Dobeni Subzone (Reháková 2002), but according to Pop (1996, 1997) both taxa occur throughout the Chitinoidella and Praetintinnopsella Zones. Unidentified chitinoidellids also occur in the 27-7 and 30-5 samples (also in the bed 31 according to Reháková & Michalík 1992), whereas fully hyaline calpionellids are found in 31-3. Therefore, the boundary of Chitinoidella/Crassicollaria Zones is located below the latter sample, perhaps close to the contact of the red nodular limestone with reddish to light grey biomicrites (Fig. 5). According to Michalík et al. (1990, text-fig. 2), the Chitinoidella/Praetintinnopsella zonal boundary is located between beds 31 and 32. The Praetintinnopsella Zone was not recognized in our study, nevertheless this zone has been reported by Michalík et al. (1990) and Reháková & Michalík (1992) from a limestone interval about one meter thick.

The Late Tithonian Crassicollaria Standard Zone comprises 3 m thick biomicrite beds. This zone is subdivided into Remanei and Intermedia Subzones. The Intermedia Subzone is represented by light grey biomicrites and microbreccias with calpionellids. The calpionellid assemblages observed in the dark grey limestone clasts and the light grey cement (33-6 sample) have similar composition (Fig. 5): *Calpionella alpina*, *Crassicollaria brevis*, *Cr. intermedia* and *Cr. parvula*(?). Thus, Upper Tithonian calcareous sediments were eroded and redeposited along the basinal slope (Michalík et al. 1990).

The limestones of the Padlá Voda Formation are about 24 m thick. Clast-bearing calpionellid-*Globochaete* biomicrite at the base of this formation (34-1 sample) contains abundant *Calpionella alpina,* frequent *Crassicollaria parvula* and rare *Calpionella* sp., *Crassicollaria intermedia* and *Cr. brevis.* This assemblage may represent either the Tithonian/Berriasian

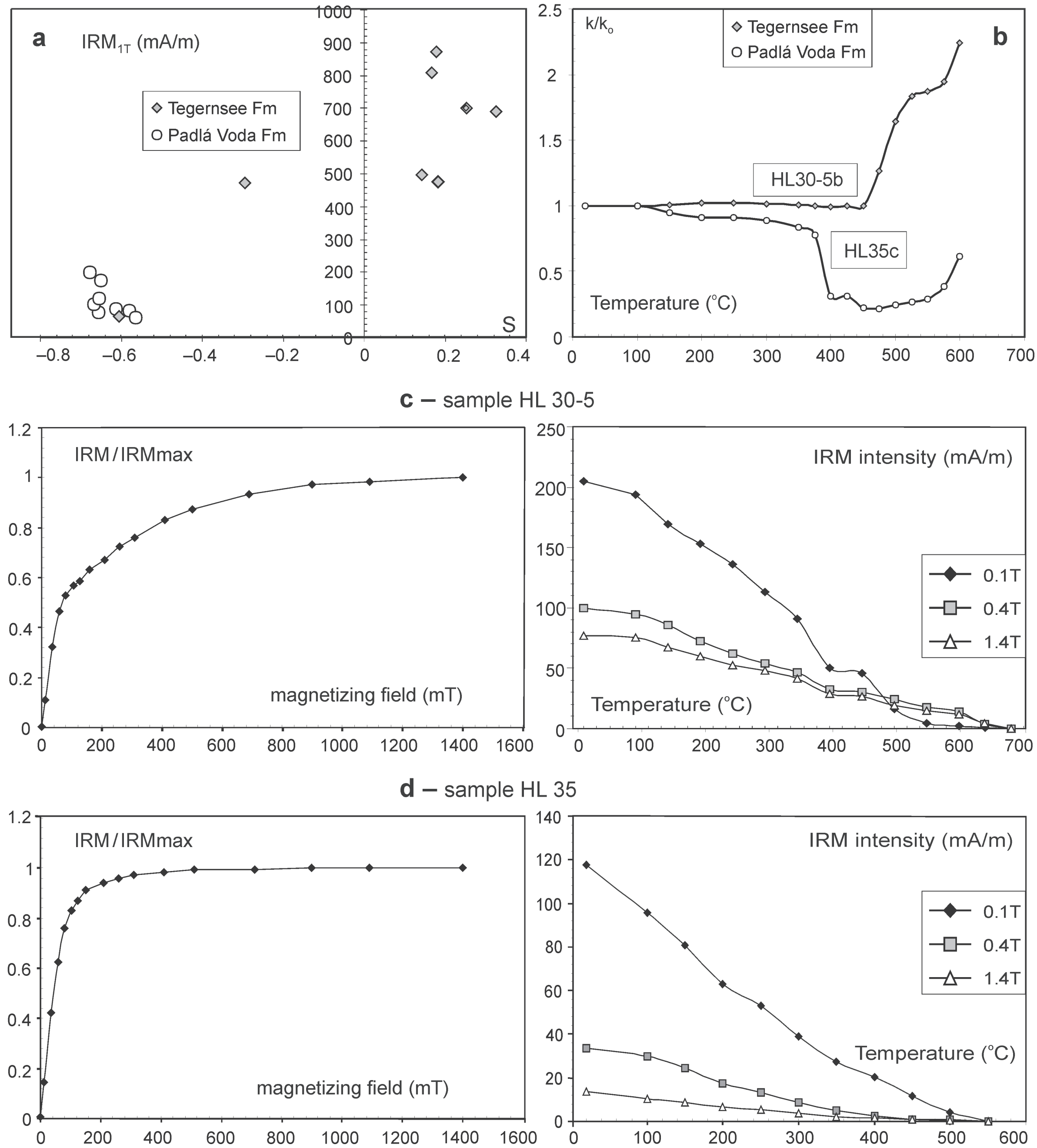

Fig. 6. Rock magnetic properties of the Tegernsee- and the Padlá Voda Formations. **a** —Crossplot of S ratio and IRM_{1T}; **b** — magnetic susceptibility changes during thermal treatment; **c,d** — IRM acquisition curve and thermal demagnetization of the 3 axes IRM acquired in the fields of 0.1 T, 0.4 T and 1.4 T for representative specimens of the Tegernsee (c) and the Padlá Voda Formations (d).

boundary interval (Crassicollaria/Calpionella Zones) or, alternatively, redeposited Upper Tithonian *Crassicollaria* loricas in the earliest Berriasian *Calpionella alpina*-*Cr. parvula* assemblage. The latter explanation seems to fit the results of thin section analysis better.

A typical Lower Berriasian association of *C. alpina, Cr. parvula* and *T. carpathica* with rare (less than 0.5 % of all identified calpionellid specimens) *Crassicollaria colomi* Doben, 1963 is contained in the 34-7 sample (Fig. 5). In the standard zonation (Remane et al. 1986) this calpionellid assemblage indicates Early Berriasian Alpina Subzone.

The index taxon of the Ferasini Subzone (Pop 1994; Reháková 1998), *Remaniella ferasini* (Catalano 1965) has been found in our sample 39, only. In 40–41-5 samples, limestone clasts with *Cr. intermedia* and *Cr. brevis* occur, sometimes with oncolitic crusts.

The boundary of the Ferasini- and Elliptica Subzones was recognized between samples 41-5 and 42-4. Limestones of the middle Berriasian Elliptica Subzone are 3.3 m thick (Fig. 5). The index of the Cadischiana Subzone, *Remaniella cadischiana* (Colom, 1948), along with *Remaniella duranddelgai* Pop, *Calpionella elliptica* Cadisch and *Tintinnopsella* sp. ex

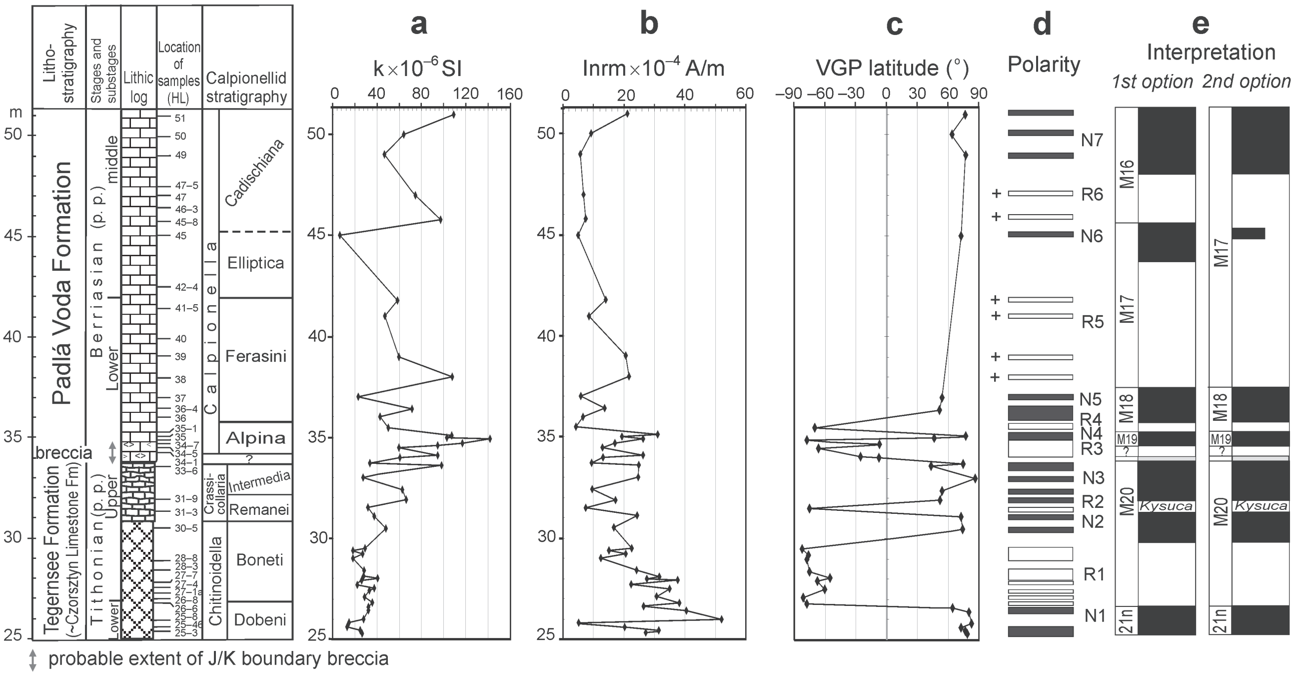

Fig. 7. The Hlboča section. (**a**) k — Magnetic susceptibility. (**b**) NRM intensities (Inrm). (**c**) Computed VGP latitude. (**d**) Magnetic polarity: black — normal polarity, white — reversed polarity; crosses — reversed polarity determined from great circle trends. (**e**) Correlation with global polarity time scale (two options, second option preferred).

gr. *T. longa-subacuta* was found in four samples from 6 m thick beds above (Fig. 5).

Rock magnetic properties

Measurements of magnetic parameters revealed distinct differences in rock magnetic properties between the Tegernsee and the Padlá Voda Formations (Fig. 6a,b). High coercivity minerals occur in high amounts in the Tegernsee Formation. Its maximum unblocking temperature close to 700 °C (Fig. 6c) proves its identification with hematite. The hematite is accompanied by a low coercivity magnetite with unblocking temperatures between 550 and 600 °C. The magnetite is the only magnetic mineral in the Padlá Voda Formation: only a low coercivity fraction is observed and the maximum unblocking temperature does not exceed 600 °C (Fig. 6d). Magnetic susceptibility of nodular limestones of the Tegernsee Formation rises within the section from ca. 20×10^{-6} SI Units in the lowermost part (the Dobeni Subzone) up to 70×10^{-6} SI in the Crassicollaria Zone (Fig. 7). Within the Padlá Voda Formation, large variations of magnetic susceptibility are observed (between 20 and 130×10^{-6} SI Units). Susceptibility values higher than 100×10^{-6} SI, occurring within the Padlá Voda Formation, are related to superparamagnetic (SP) fraction which is indicated by a frequency dependent diagram (Fig. 8a). Differences in magnetic susceptibility changes during thermal treatment between two formations, especially large decrease between 350 and 450 °C in samples from the Padlá Voda Formation (Fig. 6b), must also be attributed to alterations of the SP fraction. Similar differences in magnetic susceptibility behaviour were observed in the Strážovce section (Grabowski et al. 2009), between the Jasenina- and the Osnica Formations (no SP magnetite), and the Mráznica Formation (abundant SP magnetite). NRM intensities are the highest in the lowermost part of Tegernsee Formation, up to 50×10^{-4} A/m, and decrease below 10×10^{-4} A/m in the Padlá Voda Formation (Fig. 7). In the latter case, a good correlation is observed between susceptibility and NRM and IRM intensity, which is not the case in the Tegernsee Formation (Fig. 8b and c). These observations account for different carriers of magnetic susceptibility signal in the two formations: mostly paramagnetic in the Tegernsee Formation and mostly ferro- + superparamagnetic in the Padlá Voda Formation. It should be noted that the magnetic susceptibility pattern across the J/K boundary is exactly opposite to that noted typically in the Tethyan sections. There is a general tendency of magnetic susceptibility decrease from the Upper Tithonian to Lower Berriasian strata; it is known from sections of Val Bosso (Houša et al. 2004), Brodno (Houša et al. 1996, 1999), Pośrednie (Tatra Mts; Grabowski & Pszczółkowski 2006), Nutzhof (Eastern Alps; Pruner et al. 2009), and Lókút (Transdanubian Range; Grabowski et al. 2010). The opposite trend, observed in the Hlboča section only, is related to relative abundance of SP magnetite in the Padlá Voda Formation. Calpionellid limestones from other sections mentioned did not reveal evidence of SP particles and their susceptibility is rather dominated by ferro- or paramagnetic matrix (Grabowski & Pszczółkowski 2006; Grabowski et al. 2010).

Thermal demagnetization revealed mostly two components of magnetization. The A labelled component was demagnetized between 20 and 300 °C in most samples (Fig. 8d). In present-day coordinates, its direction is close to the expected

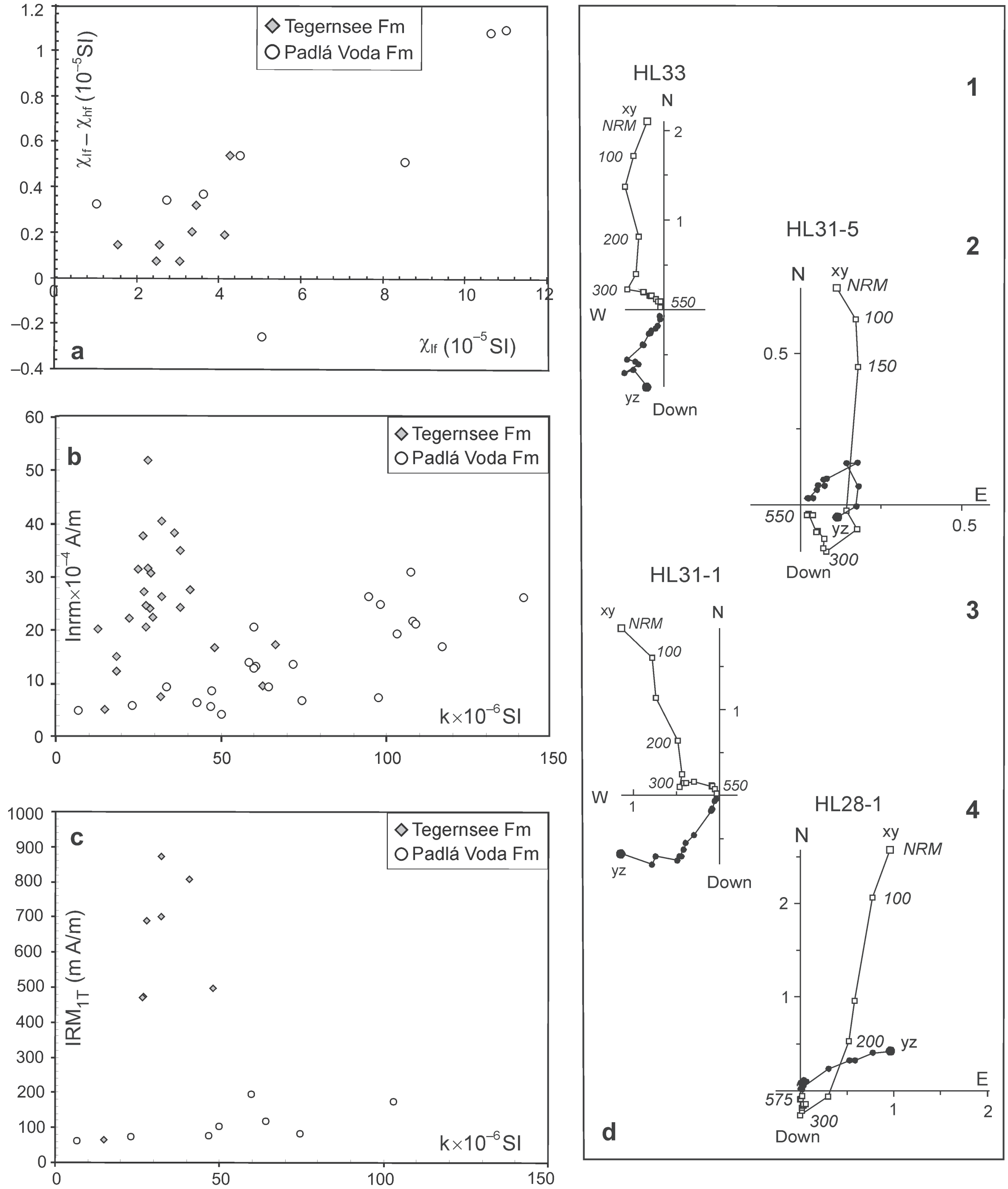

Fig. 8. **a** — Susceptibility differences χ_{lf}–χ_{hf} measured at low (0.47 kHz; χ_{lf}) and high frequency (4.7 kHz; χ_{hf}) plotted as a function of a low frequency susceptibility χ_{lf}; **b** — magnetic susceptibility (k) vs. NRM intensity (Inrm); **c** — magnetic susceptibility (k) vs. IRM_{1T} intensity; **d** — Thermal demagnetization of typical samples. Orthogonal projection (Zijderveld diagram). 1 — HL33, Upper Tithonian, magnetozone M20n1n; 2 — HL31-5, Upper Tithonian, magnetosubzone M20n1r (Kysuca); 3 — HL31-1, Upper Tithonian, magnetozone M20n2n; 4 — HL28-1, Upper Tithonian, magnetozone M20r. All projections after tectonic correction. Open squares — horizontal (xy) plane; solid circles — vertical (yz) plane. NRM intensities in 10^{-3}A/m.

present-day geomagnetic field of the area and the application of tectonic correction results in poorer clustering (Table 1). These observations, as well as unblocking temperature range account for interpretation of the A component as the recent viscous remanent magnetization. The second, B component, is unblocked between 300 and 550–575 °C (Fig. 8d). It reveals dual polarity. Therefore, the B component might be interpreted as the primary magnetization.

The directions of characteristic components are presented in Table 1 and in Fig. 9. As the B component between 33.6 and 34.9 m of the section is greatly dispersed, it is inferred that samples in this interval were taken from the breccia interval at

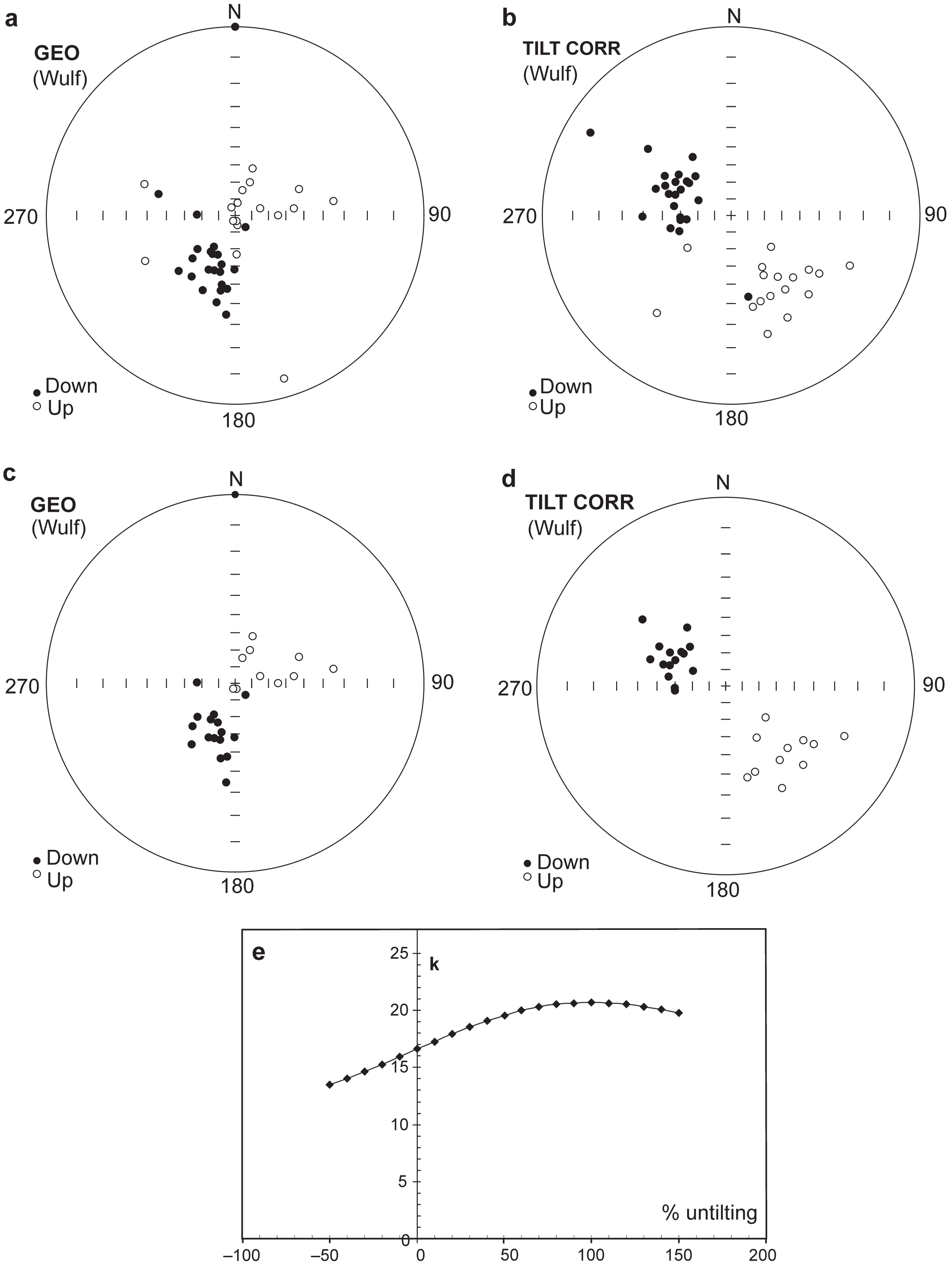

Fig. 9. Stereographic projection of component B from all samples (**a**, **b**) and excluding directions from brecciated zone (**c**, **d**). Entrance data, see Table 1. Full (open) symbols, lower (upper) hemisphere projection. (**e**) Tilt test for normal and reversed component B (without data from brecciated zone). **k** — Fisherian precision parameter.

the J/K boundary (Michalík et al. 1990, 1995). Indeed, thin section study indicates occurrence of microbreccias within this interval (see above). Clustering of the B component improves when results from the breccia interval are not taken into account (Table 1, Fig. 9c,d). This indicates that the B component pre-dates the breccia, and as the breccia is of sedimentary origin, it is an argument supporting the primary nature of the B component. However, a reversal test for the B component is negative. It can be seen also from the Fig. 9 and Table 1, that difference in declination of normal and reversed polarity directions differ by ca 30°. Negative results of the reversal test are not unusual in magnetostratigraphy (e.g.

Table 1: Characteristic paleomagnetic components from the Hlboča section (Malé Karpaty Mts). In bold: components used for geological interpretation.

Component	D/I	α_{95}	k	Dc/Ic	α_{95}	k	N/N$_o$
A	**23/58**	2.9	56.3	0/16	3.7	35.6	43/47
B_{nor} *(all)*	207/57	7.3	19.1	292/53	6.7	22.2	22/47
B_{nor} *(breccia excluded)*	204/57	6.3	27.5	**293/54**	5.7	33.4	20/47
B_{rev} *(all)*	84/–82	15.8	5.7	151/–38	14.1	7.0	18/47
B_{rev} *(breccia excluded)*	67/–74	10.6	15.0	**142/–39**	8.7	22	14/47
$B_{nor+rev}$ *(breccia excluded)**	215/65	6.6	15.0	**307/49**	6.1	17.4	34/47
$B_{nor+rev}$ *(breccia excluded)***	218/67	–	–	**310/47**	–	–	N = 2

Mean paleopole for the section: **Paleopole*:** latitude 46.0°N, longitude 282.5°E, dp = 5.3, dm = 8.1. **Paleopole**:** latitude 46.9°N, longitude 278.2°E. ***Explanations:*** **D/I** — declination/inclination before bedding correction; **Dc/Ic** — declination/inclination after bedding correction; **α_{95}, k** — Fisher statistics parameters; **N/N$_o$** — number of beds used for calculation of characteristic direction/number of beds sampled; **dp, dm** — confidence oval of paleopole estimation. * — calculated as mean of all normally and reversely magnetized beds; ** — calculated as mean of normal and reversed sets.

Speranza et al. 2005) but need to be explained. Normal directions of the B component are better clustered than reversed polarity directions, although both populations pass the fold test (Fig. 9e). Moreover, not all reverse polarity directions might be calculated in some samples (mostly from the Padlá Voda Formation): their reverse polarity was inferred from great circle trends (Fig. 7d). To explain this, we suggest that the B component is contaminated by a normal polarity overprint which is close to the normal direction of the calculated B component. The unblocking temperatures of the overprint and primary magnetization overlap and therefore, isolation of "purely" primary direction is not possible. This is a very common situation observed in the paleomagnetism of Mesozoic carbonate rocks from the Carpathians (e.g. Márton & Márton 1981; Grabowski 2005; Lewandowski et al. 2005) and Apennines (Houša et al. 2004; Speranza et al. 2005). Normal polarity overprint was acquired most probably during the Cretaceous Quiet Zone, when maximum burial and overthrusting processes took place (see the "Geological setting").

Magnetic stratigraphy

Normal (N) and reversed (R) polarity intervals within the Hlboča section (according to polarity of the B component) were numbered (Fig. 7d). Three normal (N1–N3) and two reversed intervals (R1–R2, between Tithonian Dobeni and Intermedia Subzones) were noted within the sampled part of the Tegernsee Formation, between beds 25-3 and 33-6. The lowermost beds sampled, between bed 25-3 and 26-6 reveal normal magnetization (N1) and belong to the Dobeni Subzone. Magnetozone N1 is interpreted as M21n. This is in accordance with the data of Ogg et al. (1991) and Grabowski et al. (2010), where the base of the Chitinoidella Zone occurs mostly within this magnetozone. The following R1 reversed polarity interval (between 26-8 and 29-5) belongs to the Boneti Subzone and might correspond to the M20r magnetozone. It should be mentioned that the first occurrence (FO) of chitinoidellids in the Brodno- and in the Pośrednie III sections (Boneti Subzone) takes place within this magnetozone.

A short R2 reversed polarity interval, documented by sample 31-5 falls within the Remanei Subzone. It must be correlated with the Kysuca (M20n1r) magnetosubzone. Indeed, the position of the Kysuca magnetosubzone is the same within all studied Carpathian sections (Fig. 10): the Brodno (Houša et al. 1999; Michalík et al. 2009), Pośrednie III (Grabowski & Pszczółkowski 2006) and Lókút (Grabowski et al. 2010): just above the base of the Crassicollaria Standard Zone. Consequently, normal interval N3, situated within the Intermedia Subzone (between samples 31-9 and 33-6) should correspond to the M20n1n magnetozone. It must represent the lower part of the Intermedia Subzone, since the upper part of this subzone usually embraces the M19r and large part of the M19n2n magnetozones (Grabowski & Pszczółkowski 2006; Grabowski et al. 2010).

The correlation of upper part of the section to the GPTS is rather speculative. The R3 magnetozone (sample 34 to 34-9, Alpina Zone), is situated largely within the probably brecciated interval. The B component in this interval reveals consistent negative inclinations, but its declinations are dispersed. This might indicate that the Brodno magnetosubzone (M19n1r) is represented in clastic beds.

As the beginning of the Ferasini Subzone coincides with the bottom of our N5 interval, it is assumed that N5 corresponds to the M18n magnetozone. The first appearance datum (FAD) of *Remaniella ferasini* usually falls within the M18n magnetozone (Ogg et al. 1991; Houša et al. 2004), although it should be noted, that this index is rare in our section (Fig. 5). In this case, the R4 and N4 intervals should be correlated with the M18r and topmost part of the M19n, respectively.

As the M19r and a large part of the M19n magnetozones are apparently missing in the Hlboča section, it is assumed, that the sediments deposited during those magnetochrons were eroded and deposited in another part of the basin.

The reversed R5 magnetozone embraces samples 41 to 41-8 (boundary of Remaniella/Elliptica Subzones). It must be interpreted as the M17r magnetozone, since that is where the lower boundary of the Elliptica Subzone is situated within the standard Italian sections (Ogg et al. 1991), as well as in the Tatra Mts (Grabowski & Pszczółkowski 2006). Magnetostratigraphic interpretation of the uppermost part of the section again poses some problems. N6 normal polarity magnetozone (based on only single sample no. 45), most probably within the lower part of the Cadischiana Subzone, might correspond

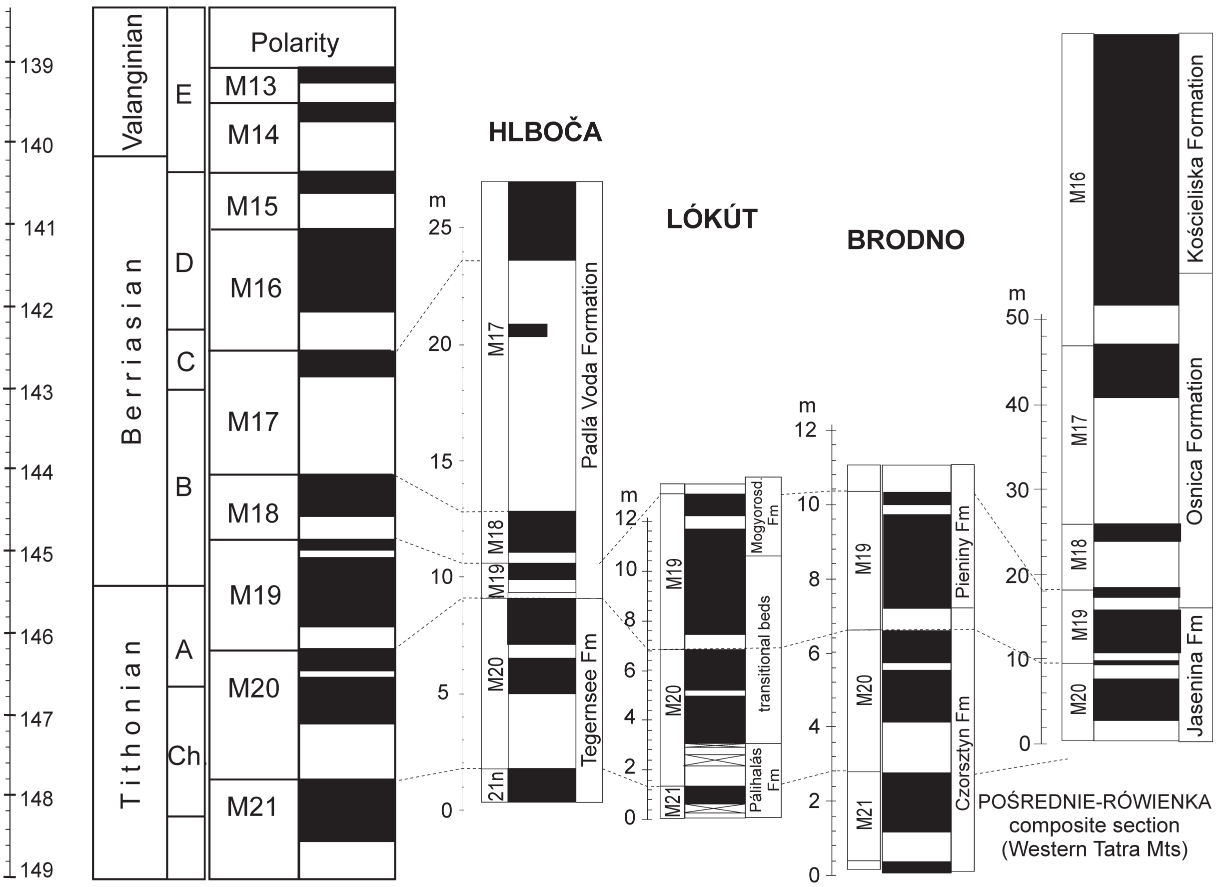

Fig. 10. Summary of the current magnetostratigraphic studies of the J/K boundary sections in the Carpathians. Reference GPTS time scale and correlation to calpionellid zones after Gradstein et al. (2004). Section references: Hlboča (this study); Lókút (Grabowski et al. 2010); Brodno (Houša et al. 1999; Michalík et al. 2009); Western Tatra (Grabowski & Pszczółkowski 2006, composite section).

to M17n. Indeed, the position of this magnetozone in the Tatra Mts in the Pośrednie II section is similar, and this is the only normal magnetozone situated entirely within the C calpionellid Zone (Ogg et al. 1991; Grabowski & Pszczółkowski 2006). However, following this pattern, the R6 magnetozone (documented by samples 45-8 and 47), situated within the Cadischiana Subzone, should correspond to the M16r. In the Tatra Mts, this magnetozone embraces the upper part of the Cadischiana Subzone and lower part of the Simplex Subzone. The problem in interpretation is that the last subzone was not confirmed in the highest part of the section sampled by us. The highest N7 magnetozone should start within the Simplex Subzone and it should be interpreted as M16n (Ogg et al. 1991; Grabowski & Pszczółkowski 2006), but in fact only the Cadischiana Subzone was documented as far as bed 51. This might imply that:

1. The bottom part of the Simplex Subzone is difficult to document (its presence is documented between 54 and 57 m of the section — see Fig. 2).

2. The N6 magnetozone, based on a single sample 45, cannot be interpreted as a real magnetozone, but it represents either a geomagnetic excursion or an effect of remagnetization.

In our opinion, the second explanation is more plausible. High resolution magnetostratigraphic studies prove that magnetic intervals based on single samples often cannot represent magnetozones. Speranza et al. (2005) documented previously unrecognized geomagnetic excursions within M16n and M16r magnetic chrons in the Bosso section. They also report a normal polarity excursion within the Kysuca (M20n1r) magnetosubzone. Therefore, the N6 interval in our section might be interpreted as an excursion, although it might be strange that excursion was documented with rather low resolution of sampling. Remagnetization effect perhaps represents a more likely explanation. As can be seen from Fig. 7d, all reversed polarity samples between 36 and 47 m of the section reveal great circle trends towards the reversed direction, during thermal demagnetization. This indicates that this part of the Padlá Voda Formation is more strongly remagnetized than the Tegernsee Formation. This is also consistent with the relative abundance of the SP magnetite within the Padlá Voda Formation: the presence of SP magnetite is usually accompanied by remagnetization phenomena (e.g. Jackson et al. 1993), sometimes very strong, as is the case of the Mráznica Formation in the Strážovce section (Borza et al. 1980; Grabowski et al. 2009). Thin section analysis of sample 45 revealed that it is particularly strongly silicified consisting mostly of chert concretions. Therefore, primary magnetization might be affected by diagenesis in this sample. Whatever the reason for the origin of the N6 interval, in this case both reversed R5 and R6 intervals should be interpreted rather as the M17r magnetozone, and the

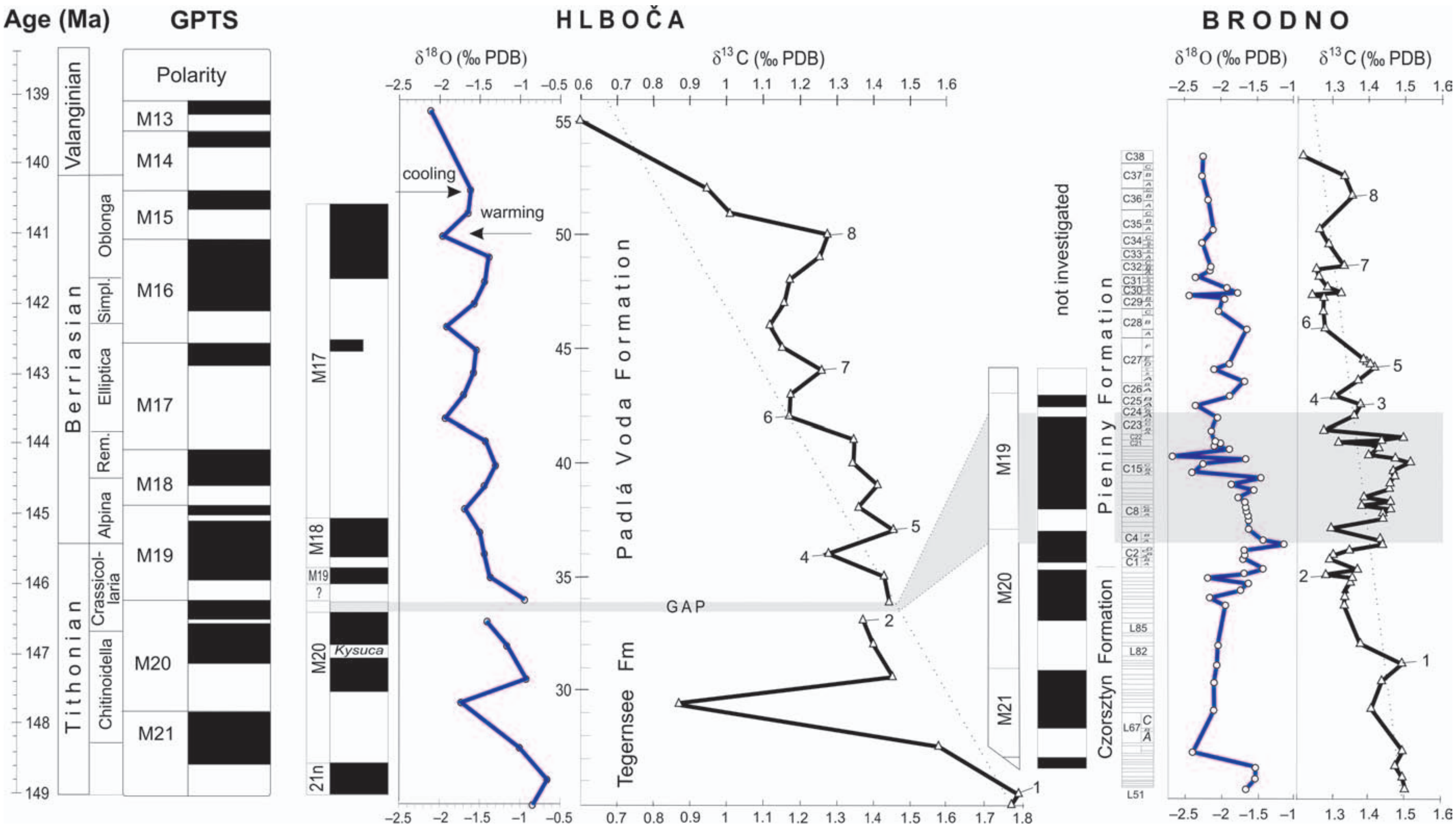

Fig. 11. Correlation of magnetostratigraphy and $\delta^{18}O$ and $\delta^{3}C$ isotope stratigraphy in the Hlboča and the Brodno sections (negative and positive spikes are numbered for correlation).

N7 normal interval as the M17n. This interpretation is also presented in the Fig. 7e (2nd option). It is in agreement with the integrated bio- and magnetostratigraphic scheme (Ogg et al. 1991; Grabowski & Pszczólkowski 2006), where the M17n magnetozone falls into the Cadischiana Subzone, and to put the base of the M16n magnetozone into this subzone is not necessary.

The resolution of our magnetostratigraphic data is not high enough to calculate changes of sedimentation rate for each magnetozone. However, estimations are possible for the M20r (4.59–6.22 m/Myr), M20n (3.1–4.5 m/Myr) and M17r (7.58–9.83 m/Myr) magnetozones. Sedimentation rates for M20n and M17r should be treated as the minimum values, since both these magnetozones are not complete in the Hlboča section. The values obtained are in better agreement with estimations of sedimentation rates by Michalík et al. (1995; 3–3.7 m/Myr for the Tegernsee Formation and 7–11 m/Myr for the Padlá Voda Formation) than by Vašíček et al. (1994; 0.23–1.56 m/Myr for the Tegernsee Formation and 5.5–9 m/Myr for the Padlá Voda Formation). Anyhow, the typical trend of sedimentation rate increase across the J/K boundary (Grabowski & Pszczółkowski 2006; Grabowski et al. 2010) is observed in this section, too.

The state of the art in magnetic stratigraphy of the Carpathian sections is presented in the Fig. 10. Until now, four J/K boundary sections in the Carpathians have been calibrated magnetostratigraphically, the magnetostratigraphic divisions being controlled by microfossil stratigraphy. They embrace the interval between the uppermost part of M22n (Lower Tithonian, Brodno section) and M16n (Upper Berriasian, Western Tatra Mts) magnetozones.

Both short reversed (Kysuca and Brodno) magnetosubzones are located in similar positions in the Brodno and the Lókút sections. The position of the Brodno magnetosubzone in the Western Tatra section is fairly similar to those in the Brodno and the Lókút sections. In the Hlboča section, part of the Brodno magnetosubzone might be situated in the stratigraphic gap at the J/K boundary. In the Western Tatra sections, the position of the Kysuca magnetosubzone is not well constrained (Grabowski & Pszczółkowski 2006). Its location in the uppermost part of the M20n zone is probably an artifact due to previously unrecognized thrust contact within a part of the section, between M20 and M19 (Fig. 10).

The J/K boundary, indicated at the Crassicollaria/Calpionella zones boundary, is traditionally placed in the middle part of M19n2n (Gradstein et al. 2004). In the Brodno section, this boundary was recently designated in the topmost part of the M19n2n, just below the Brodno (M19n1r) magnetosubzone (Michalík et al. 2009).

Isotope stratigraphy

Weissert & Channell (1989) documented a decreasing trend of $\delta^{13}C$-values from 2.07 ± 0.14 in the Oxfordian (CM 24–22) to 1.16 ± 0.16 ‰ near to the Tithonian/Berriasian boundary (CM18–CM14) in four Italian sections.

A trend, observable in the Hlboča section, was accompanied by a decrease of organic C content in sediments. High positive $\delta^{13}C$ values in the lowermost part of this section belonging to the dinoflagellate Fibrata Acme Zone (Reháková in Michalík et al. 1990; Reháková 2000) are comparable to the Oxfordian $\delta^{13}C$ event of Jenkyns (1996) located in the Transversarium ammonite Zone (Padden et al. 2002). Due to low sedimentary rate and oxidic environment with effective organic matter biocycling, the water equilibrium has been shifted more to a negative value as a part of the decreasing $\delta^{13}C$ trend in the Kimmeridgian and Tithonian part of the Tegernsee Formation (Fig. 11). This global trend was interrupted by more negative spikes at 18.5 (1.4 ‰), or at 29.5 (0.87 ‰). Diagenetic alteration of sediment seems to be the most acceptable interpretation of these spikes on the $\delta^{13}C$ curve. Transport of limestone clasts from disintegrated shallower gentle slope environment of "Ammonitico Rosso" type could evoke input of solutions with a higher content of light ^{12}C isotope during the sediment lithification.

Detailed correlation between $\delta^{13}C$ and $\delta^{18}O$ isotopes and magnetic stratigraphy between the Hlboča and Brodno sections in the Tithonian–Berriasian boundary interval is also difficult due to a stratigraphical gap within the Hlboča section, embracing the uppermost part of the Intermedia Subzone and the lower part of the Alpina Subzone (the uppermost part of the M20n1n-, entire M19r and M19n2n magnetozones) (Fig. 11). The gap in the isotopic record in the Hlboča section coincides with a warming trend and elevated values of $\delta^{13}C$ in the Brodno section (Michalík et al. 2009). Both oxygen and carbon isotopic values in this part of the Hlboča section were at least partially modified by diagenesis or were significantly affected by local sedimentary conditions.

Paleotectonic implications

Paleoinclination of paleomagnetic directions around the J/K boundary from Central Western Carpathians (PKB and Transdanubian Mts) are in good agreement (45–49°, Table 2) which indicates a 27–30°N paleolatitude. The primary Tithonian/Berriasian direction from the Hlboča section is counterclockwise rotated if compared with the expected European reference directions by about 50° (Table 2). Evidence for counter-clockwise tectonic rotation of Tertiary units in the Malé Karpaty Mts has been known since the 1990s (Márton et al. 1992; Kováč & Túnyi 1995). They were documented in the basal Paleogene sediments in Sološnica and in several localities in Miocene depressions (Fig. 1b). The rotations were in-

Table 2: Comparison of the Tithonian–Berriasian declinations and inclinations from the Hlboča section (this study) with coeval directions from adjacent areas and European reference data. For explanations see Table 1.

Locality	Dc/Ic	α_{95}	k	References
Hlboča	307/49	6.1	17.4	This study
Strážovce	338/49	4.0	75.3	Grabowski et al. 2009
Western Tatra	23/47	5.5	499.1	Grabowski 2005
Brodno	236/45	5.6	9.8	Houša et al. 1996
Lókút	270/38	3.6	25.7	Grabowski et al. 2010
European reference direction				
Berriasian stratotype	0/47	2.9	15.75	Galbrun 1985

terpreted as the result of tectonic escape of the Central Western Carpathians from the domain of the Alpine collision. The overall rotation of 40–60° took place, mostly at the end of the Early Miocene (Kováč & Túnyi, l.c.). Variegated magnitudes of Tertiary tectonic rotation in the Malé Karpaty Mts were interpreted as the result of local block rotations in the zones of ENE–WSW trending dislocations during the Middle Miocene (Kováč & Túnyi, l.c.). Our data reveal that essentially no rotation occurred between the Tithonian–Berriasian and Eocene in the area: paleodeclinations for these two time intervals in the Malé Karpaty Mts are virtually the same (Fig. 1b). In contrast, a large difference between Mesozoic and Paleogene declinations exists in the N part of the Central Western Carpathians (Tatra Mts — Podhale region, Grabowski & Nemčok 1999; Márton et al. 1999; Grabowski 2005). Declination difference amounts to 90° (Fig. 1a). The difference in the Strážovske Vrchy Mts, situated halfway between the Malé Karpaty- and the Tatra Mts is ca. 75°, taking into account angular difference between primary magnetization of the Tithonian–Berriasian strata in the Strážovce section (Grabowski et al. 2009) and Paleogene rocks in the Omastiná locality (Bánovská Kotlina Basin, Túnyi & Márton 1996). Our conclusion is that the counter-clockwise rotation of Tithonian–Berriasian paleodeclinations in the Krížna Unit tends to increase westwards along the strike of the Central Western Carpathians. A similar observation was reported by Kruczyk et al. (1992) and Pruner et al. (1998) who studied paleomagnetism of Jurassic rocks from different parts of the Central Western Carpathians (between Ružbachy and the Malá Fatra Mts).

Conclusions

1. Tithonian magnetozones, from the top of M21n to M20n1n, embracing the Dobeni to the Intermedia Subzones, were documented within the uppermost part of the Tegernsee Formation in the Hlboča section. The magnetostratigraphy of the overlying Padlá Voda Formation is not well constrained due to breccias and a stratigraphic gap at the J/K boundary and more intense remagnetization of this formation. Nevertheless, it is assumed that sediments deposited during the M19r and a large part of the M19n magnetochrons were mostly eroded. Above the breccia, magnetozones from the topmost part of M19n to M17n were identifed within the Padlá Voda Formation.

2. The magnetic susceptibility values of the Berriasian Padlá Voda Formation are higher than for the Tithonian Tegernsee Formation, which differs from typical magnetic susceptibility trends across the J/K boundary in the Tethyan region. The anomalously high magnetic susceptibility of the Padlá Voda Formation is related to the presence of superparamagnetic magnetite, which occurs commonly in remagnetized carbonates.

3. Primary C isotopic data were preserved in limestones within the Oxfordian–Kimmeridgian part of the Tegernsee Formation with typically decreasing C-isotope trend. Data from the Tithonian part of the Tegernsee Formation probably reflect "local" basin processes connected with the breccia formation and/or with possible diagenetic overprint. The C-isotope record of the Berriasian Padlá Voda Formation is more homogeneous (1.4–1.8 ‰ V-PDB) and assumed to be primary. Detailed correlation between isotope and magnetic stratigraphy of the Tithonian–Berriasian interval between the Hlboča and Brodno sections is also complex due to a J/K stratigraphic gap within the Hlboča section.

4. Tithonian-Berriasian paleodeclinations reveal counter-clockwise rotation of the Vysoká Unit by an amount of ca. 50°. As the Eocene-Miocene paleodeclinations from the cover rocks of the area are comparable, the counter-clockwise rotation must have taken place mostly after the Early Miocene (after Karpatian).

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References

Bacelle L. & Bosellini A. 1965: Diagrammi per la stima visiva della composizione percentuale nelle rocce sedimentarie. *Ann. Univ. Ferrara, N.S., sez. IX., Sci. Geol. Paleont.* 1, 3, 59–62.

Birkenmajer K. 1977: Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Stud. Geol. Pol.* 41, 7–159.

Borza K. & Michalík J. 1987a: On stratigraphy and lithology of Czorsztyn Limestone Formation in Central West Carpathians (Jurassic, Malm). *Geol. Zbor. Geol. Carpath.* 38, 3, 259–284.

Borza K. & Michalík J. 1987b: Microbiostratigraphy of Upper Jurassic to Lower Cretaceous sequence in Vysoká Nappe, Malé Karpaty Mts. *Knihovnička ZPN, Miscellanea micropalaeontologica* 6a, 2, 1, 203–214 (in Slovak, with English summary).

Borza K., Gašparíková V., Michalík J. & Vašíček Z. 1980: Upper Jurassic–Lower Cretaceous sequence of the Krížna Nappe (Fatric) in the Strážovce section, Strážovské Vrchy Mts. (Western Carpathians). *Geol. Zbor. Geol. Carpath.* 31, 4, 541–562.

Chadima M. & Hrouda F. 2006: Remasoft 3.0 — a user-friendly paleomagnetic data browser and analyzer. Travaux Geophysiques, 27, 20–21. Abstracts of the 10th "Castle Meeting". *New Trends in Geomagnetism.* Castle of Valtice, September 3–8th, 2006.

Channell J.E.T. & Grandesso P. 1987: A revised correlation of Mesozoic polarity chrons and calpionellid zones. *Earth Planet. Sci. Lett.* 85, 222–240.

Channell J.E.T., Bralower T.J. & Grandesso P. 1987: Biostratigraphic correlation of Mesozoic polarity chrons CM1 to CM23 at Capriolo and Xausa (Southern Alps, Italy). *Earth Planet. Sci. Lett.* 85, 203–221.

Duchamp-Alfonse S., Gardin S., Fiet N., Bartolini A., Blamart D. & Pagel M. 2007: Fertilization of the northwestern Tethys (Vocontian Basin, SE France) during Valanginian carbon isotope perturbation: evidence from calcareous nannofossils and trace element data. *Paleogeogr. Paleoclimatol. Paleoecol.* 243, 132–151.

Forster Th., Evans M.E. & Heller F. 1994: The frequency dependence of low field susceptibility in loess sediments. *Geophys. J. Int.* 118, 636–642.

Föllmi K.B., Godet A., Bodin S. & Linder P. 2006: Interactions between environmental change and shallow water carbonate build-up along the northern Tethyan margin and their impact on the Early Cretaceous carbon isotope record. *Palaeoceanography* 21, 4, PA 4211.

Galbrun B. 1985: Magnetostratigraphy of the Berriasian stratotype section (Berrias, France). *Earth Planet. Sci. Lett.* 74, 130–136.

Grabowski J. 2005: New Berriasian palaeopole from the Central West Carpathians (Tatra Mts, southern Poland): does it look Apulian? *Geophys. J. Int.* 161, 65–80.

Grabowski J. & Nemčok M. 1999: Summary of paleomagnetic data from the Central West Carpathians of Poland Slovakia: evidence for the Late Cretaceous–Early Tertiary transpression. *Physics and Chemistry Earth* A24, 8, 681–685.

Grabowski J. & Pszczółkowski A. 2006: Magneto- and biostratigraphy of the Tithonian-Berriasian pelagic sediments in the Tatra Mountains (central Western Carpathians, Poland): sedimentary and rock magnetic changes at the Jurassic/Cretaceous boundary. *Cretaceous Research* 27, 398–417.

Grabowski J., Michalík J., Szaniawski R. & Grotek I. 2009: Synthrusting remagnetization of the Krížna Nappe: high resolution palaeo- and rock magnetic study in the Strážovce section, Strážovské vrchy Mts, Central West Carpathians (Slovakia). *Acta Geol. Pol.* 59, 137–155.

Grabowski J., Haas J., Márton E. & Pszczółkowski A. 2010: Magneto- and biostratigraphy of the Jurassic/Cretaceous boundary in the Lókút section (Transdanubian Range, Hungary). *Stud. Geophys. Geodet.* 54, 1–26.

Gradstein F.M., Ogg J.G. & Smith A. 2004: A geologic time scale 2004. *Cambridge University Press*, 1–589.

Gröcke D.R., Price G.D., Ruffell A.H., Mutterlose J. & Baraboshkin E. 2003: Isotopic evidence for the Late Jurassic–Early Cretaceous climate change. *Paleogeogr. Paleoclimatol. Paleoecol.* 202, 97–118.

Heller F. & Evans M.E. 1995: Loess magnetism. *Rev. Geophys.* 33, 211–240.

Hladil J., Geršl M., Strnad L., Frana J., Langrová A. & Spišiak J. 2006: Stratigraphical variation of complex impurities in platform limestone and possible significance of atmospheric dust: a study with emphasis on gamma-ray spectrometry and magnetic susceptibility outcrop logging (Eifelian–Frasnian, Moravia, Czech Republic). *Int. J. Earth Sci.* 95, 703–723.

Houša V., Krs M., Krsová M. & Pruner P. 1996: Magnetostratigraphy of Jurassic-Cretaceous limestones in the Western Carpathians. In: Morris A. & Tarling D.H. (Eds.): Paleomagnetism and tectonics of the Mediterranean region. *Geol. Soc. Spec. Publ.* 105, 185–194.

Houša V., Krs M., Krsová M., Man O., Pruner P. & Venhodová D. 1999: High-resolution magnetostratigraphy and micropaleontology across the J/K boundary strata at Brodno near Žilina, western Slovakia: summary of results. *Cretaceous Research* 20, 699–717.

Houša V., Krs M., Man O., Pruner P., Venhodová D., Cecca F., Nardi G. & Piscitello M. 2004: Combined magnetostratigraphic, palaeomagnetic and calpionellid investigations across the Jurassic/Cretaceous boundary strata in the Bosso Valley, Umbria, central Italy. *Cretaceous Research* 25, 771–785.

Jackson M., Rochette P., Fillion G., Banerjee S. & Marvin J. 1993: Rock magnetism of remagnetized Paleozoic carbonates: low temperature behavior and susceptibility characteristics. *J. Geophys. Res.* 98, B4, 6217–6225.

Jenkyns H.C. 1996: Relative sea-level change and carbon isotopes: data from the Upper Jurassic (Oxfordian) of central and southern Europe. *Terra Nova* 8, 1, 75–85.

Jenkyns H.C. & Clayton C.J. 1986: Black shales and carbon isotopes in pelagic sediment from Tethyan Lower Jurassic. *Sedimentology* 33, 87–106.

Kováč M. & Túnyi I. 1995: Interpretation of the paleomagnetic data from the western part of the Central West Carpathians. *Miner. Slovaca* 27, 213–220.

Kruczyk J., Kądziałko-Hofmokl M., Lefeld J., Pagáč P. & Túnyi I. 1992: Paleomagnetism of Jurassic sediments as evidence for oroclinal bending of the Inner West Carpathians. *Tectonophysics* 206, 315–324.

Lefeld J. (Ed.), Gaździcki A., Iwanow A., Krajewski K. & Wójcik K. 1985: Jurassic and Cretaceous lithostratigraphic units of the Tatra Mountains. *Stud. Geol. Pol.* 84, 3–93.

Lewandowski M., Krobicki M., Matyja B.A. & Wierzbowski A. 2005: Paleogeographic evolution of the Pieniny Klippen Basin using stratigraphic and palaeomagnetic data from the Veliky Kamenets section (Carpathians, Ukraine). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 216, 53–72.

Lowrie W. 1990: Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophys. Res. Lett.* 17, 2, 159–162.

Maheľ M. 1987: The Malé Karpaty Mts — constituent of the transitional segment between the Carpathians and Alps; important tectonic window of the Alpides. *Miner. Slovaca* 19, 1–27.

Marshall J.D. 1992: Climatic and oceanographic isotopic signals from carbonate rock record and their preservation. *Geol. Mag.* 192, 143–160.

Márton E. & Márton P. 1981: Mesozoic palaeomagnetism of the Transdanubian Central Mountains and its tectonic implications. *Tectonophysics* 72, 129–140.

Márton E., Pagáč P. & Túnyi I. 1992: Paleomagnetic investigations on Late Cretaceous–Cenozoic sediments from the NW part of the Pannonian Basin. *Geol. Carpathica* 43, 363–368.

Márton E., Tokarski A.K. & Mastella L. 1999: Paleomagnetic results from Tertiary Podhale flysch, Polish West Carpathians. *Phys. Chem. Earth* (A), 24(8), 645–649.

Michalík J. 2007: Rock record and microfacies indicators of the latest Triassic to mid-Cretaceous tensional development of the Zliechov Basin (central Western Carpathians). *Geol. Carpathica* 58, 5, 443–453.

Michalík J., Reháková D. & Halásová E. 1990: Stratigraphy of the Jurassic/Cretaceous boundary beds in the Hlboč Valley (Vysoká Unit of the Krížna Nappe, Malé Karpaty Mts). *Knihovnička ZPN* 9a, 183–204 (in Slovak, with English summary).

Michalík J., Reháková D. & Vašíček Z. 1995: Early Cretaceous sedimentary changes in west Carpathian area. *Geol. Carpathica* 46, 285–296.

Michalík J., Reháková D., Halásová E. & Lintnerová O. 2009: The Brodno section — a potential regional stratotype of the Jurassic/Cretaceous boundary (Western Carpathians). *Geol. Carpathica* 60, 3, 213–232.

Morante R. & Hallam A. 1996: Organic carbon isotopic record across the Triassic-Jurassic boundary in Austria and its bearing on the cause of mass extinction. *Geology* 24, 5, 391–394.

Nawrocki J., Polechońska O. & Werner T. 2008: Magnetic susceptibility and selected geochemical-mineralogical data as proxies for Early to Middle Frasnian (Late Devonian) carbonate depositional settings in the Holy Cross Mountains, southern Poland. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 269, 176–188.

Ogg J.G., Hasenyager R.W., Wimbledon W.A., Channell J.E.T. & Bralower T.J. 1991: Magnetostratigraphy of the Jurassic-Cretaceous boundary interval—Tethyan and English faunal realms. *Cretaceous Research* 12, 455–482.

Padden M., Weissert H., Funk H., Schneider S. & Gansner C. 2002: Late Jurassic lithological evolution and carbon isotope stratigraphy of the western Tethys. *Eclogae Geol. Helv.* 95, 333–346.

Plašienka D., Michalík J., Kováč M., Gross P. & Putiš M. 1991: Paleotectonic evolution of the Malé Karpaty Mts — an overview. *Geol. Carpathica* 42, 195–208.

Plašienka D., Havrila M., Michalík J., Putiš M. & Reháková D. 1997:

Nappe structure of the western part of the Central Carpathians. In: Alpine evolution of the Western Carpathians and related areas. *International Conference. Abstracts and Introductory articles to the excursion*, Bratislava, September, 11–14th, 1997, 139–161.
Pop G. 1976: Tithonian-Valanginian calpionellid zones from Cuba. *Dari Seama Sedintelor* 62, 237–266.
Pop G. 1986: Calpionellids and correlation of Tithonian-Valanginian formations. *Acta Geol. Hung.* 29, 93–102.
Pop G. 1994: Calpionellid evolutive events and their use in biostratigraphy. *Romanian J. Stratigr.* 76, 7–24.
Pop G. 1996: Trois nouvelles espéces de genre *Remaniella* (*Calpionellidae* Bonet, 1996). *Paléontologie. C.R. Acad. Sci. Paris* 332, IIa, 317–323.
Pop G. 1997: Révision systématique des chitinoïdelles tithoniennes des Carpathes méridionales (Roumanie). *C.R. Acad. Sci. Paris* 324, IIa, 931–938.
Price G.D. & Rogov M.A. 2009: An isotopic appraisal of the Late Jurassic greenhouse phase in the Russian Platform. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 273, 41–49.
Price G.D., Ruffell A.H., Jones C.E., Kalin R.M. & Mutterlose J. 2000: Isotopic evidence for temperature variation during the Early Cretaceous (late Ryazanian–mid Hauterivian). *J. Geol. Soc. London* 157, 335–343.
Pruner P., Venhodová D. & Slepičková J. 1998: Palaeomagnetic and palaeotectonic studies of selected areas of Tatricum, Manin and Krížna units. In: Rakús M. (Ed.): Geodynamic development of the Western Carpathians. *Slovak Geol. Surv.*, Bratislava, 281–290.
Pruner P., Schnabl P. & Lukenender A. 2009: Preliminary results of magnetostratigraphic investigations across the Jurassic/Cretaceous boundary strata at Nutzhof, Austria. *Ann. Naturhist. Mus. Wien* 110A, 331–344.
Reháková D. 1998: Calpionellid genus *Remaniella* Catalano, 1965 in Lower Cretaceous pelagic deposits of Western Carpathians. *Miner. Slovaca* 30, 443–452.
Reháková D. 2000: Calcareous dinoflagellate and calpionellid bioevents versus sea-level fluctuations recorded in the West Carpathian (Late Jurassic/Early Cretaceous) pelagic environments. *Geol. Carpathica* 51, 4, 229–243.
Reháková D. 2002: *Chitinoidella* Trejo, 1975 in Middle Tithonian carbonate pelagic sequences of the West Carpathian Tethyan area. *Geol. Carpathica* 53, 6, 369–379.
Reháková D. & Michalík J. 1992: Notes to ultrastructure study of Upper Jurassic–Lower Cretaceous calpionellids. *Acta Univ. Carolinensis Pragensis, Geol.* 3–4, 107–110.
Remane J., Borza K., Nagy I., Bakalova-Ivanova D., Knauer J., Pop G. & Tárdi-Filácz E. 1986: Agreement on the subdivision of the standard calpionellid zones defined at the IInd Planktonic Conference, Roma 1970. *Acta Geol. Hung.* 29, 1–2, 5–14.
Scholle P.A. & Arthur M.A. 1980: Carbon isotopic fluctuations in pelagic limestones: potential stratigraphic and petroleum exploration tool. *Amer. Assoc. Petrol. Geol. Bull.* 64, 67–87.
Speranza F., Satolli S., Mattioli E. & Calamita F. 2005: Magnetic stratigraphy of Kimmeridgian–Aptian sections from Umbria-marche (Italy): New details on the M polarity sequence. *J. Geophys. Res.* 110, B12109.
Tremolada F., Bornemann A., Bralower T., Koeberl C. & van de Schootbrugge B. 2006: Paleooceanographic changes across Jurassic/Cretaceous Boundary: the calcareous phytoplankton response. *Earth Planet. Sci. Lett.* 241, 361–371.
Túnyi I. & Márton E. 1996: Indications for large Tertiary rotation in the Carpathian–northern Pannonian region outside the North Hungarian Paleogene Basin. *Geol. Carpathica* 47, 43–49.
Vašíček Z., Michalík J. & Reháková D. 1994: Early Cretaceous stratigraphy, palaeogeography and life in Western Carpathians. *Beringeria* 10, 3–169.
Watson G.S. & Enkin R.J. 1993: The fold test in paleomagnetism as a parameter estimation problem. *Geophys. Res. Lett.* 20, 2135–2137.
Weissert H. & Channell J.E.T. 1989: Tethyan carbonate carbon isotope stratigraphy across the Jurassic/Cretaceous Boundary: An indicator of decelerated Global Carbon Cycling. *Paleoceanography* 4, 4, 483–494.
Weissert H. & Mohr H. 1996: Late Jurassic climate and its impact on carbon cycling. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 122, 27–43.
Weissert H., McKenzie J.A. & Channell J.E.T. 1985: Natural variation on the C-cycle during the Early Cretaceous. In: Sundquist E.T. & Broecker W.S. (Eds.): The Carbon cycle and atmospheric CO_2: Natural variations Archean to Present. *Geophys. Monogr. Ser*. 32, 531–545.