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VARIATION IN CLASTIC INPUT IN THE BERRIASIAN OF THE LOWER SUB-TATRIC (KRÍŽNA) SUCCESSION IN THE TATRA MOUNTAINS (CENTRAL WESTERN CARPATHIANS, POLAND): DATA FROM MAGNETIC SUSCEPTIBILITY AND INORGANIC GEOCHEMISTRY

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Abstract: The paper deals with the age and palaeoenvironment interpretation of the Late Berriasian sedimentary transition from micritic calpionellid limestones to marls, corresponding to the passage from the Osnica Formation to the Kościeliska Marl Formation, Lower Sub-Tatric succession, Tatra Mts., Central Western Carpathians. Since only reliably dated sections are an appropriate basis for palaeoenvironmental study, the following pelagic and hemipelagic sections were chosen owing to enrichment in fine, clastic material and the existing biostratigraphic and magnetostratigraphic frameworks: Pośrednie III, Rówienka, Gładkie Upłaziańskie and Gęsia Szyja. The authors integrated and interpreted new, detailed data on magnetic susceptibility (MS), rock magnetism and element geochemistry from all of the sections. Well defined biostratigraphy permitted the testing of the potential of MS as a stratigraphic method. Owing to its close connection to selected terrigenous elements (e.g., Al, Th, Zr), MS could be used here as a proxy for detrital input into the basin. Its value as a correlation tool in a pelagic and hemipelagic setting was confirmed. MS permitted not only detailed correlation of the outcrops studied, but also the comparison of them with the Barlya section (Western Balkans) of the same age.

This study proves that increased detrital input began in the Calpionellopsis simplex Subzone and continued into the lower part of the Calpionellopsis oblonga Subzone. It might be regarded as synchronous event within the Zliechov Basin and it is not everywhere correlated with the formation boundaries. The change in sedimentation was not only a local phenomenon. The onset of deposition of the terrigenous fraction can be identified in many sections of the Western Tethys. Two independent factors, regional regression and an increase in humidity might have contributed simultaneously to the increased detrital input in Late Berriasian time. However, this picture is further complicated by tectonic activity on local and regional scales.

Key words: Magnetic susceptibility, geochemistry, Berriasian, Lower Sub-Tatric succession, detrital input, palaeoenvironmental changes, Tatra Mts.

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INTRODUCTION

The dating and quantification of clastic input into ancient marine basins provide important information about relative sea level changes (e.g., Haq, 2014; Wendler *et al.*, 2014), tectonic activity (e.g., McCann and Saintot, 2003) and climatic events (e.g., Adatte *et al.*, 2002; Tucker, 2003). Magnetic susceptibility (MS), which is a measure of the amount of para- and ferromagnetic minerals, usually distributed within the diamagnetic matrix (e.g., SiO_2 or $CaCO_3$), has often been applied in recent years as a useful parameter for the estimation of terrigenous influx (e.g., Ellwood *et al.*, 2000; Riquier *et al.*, 2010; Da Silva *et al.*, 2012, 2013). The application of MS as a correlation and palaeoenvironmental tool requires reliable dating of the sections studied. The Berriasian pelagic sections of the Lower Sub-Tatric (Krížna) succession offer a good basis for testing the potential of MS for use as stratigraphic method. The sections in the Polish part of the Tatra Mts. are well dated bio- and magnetostratigraphically (Pszczółkowski, 1996; Grabowski and Pszczółkowski, 2006). As well, they are relatively rich in fine clastic material and the first results from the Pośrednie III section

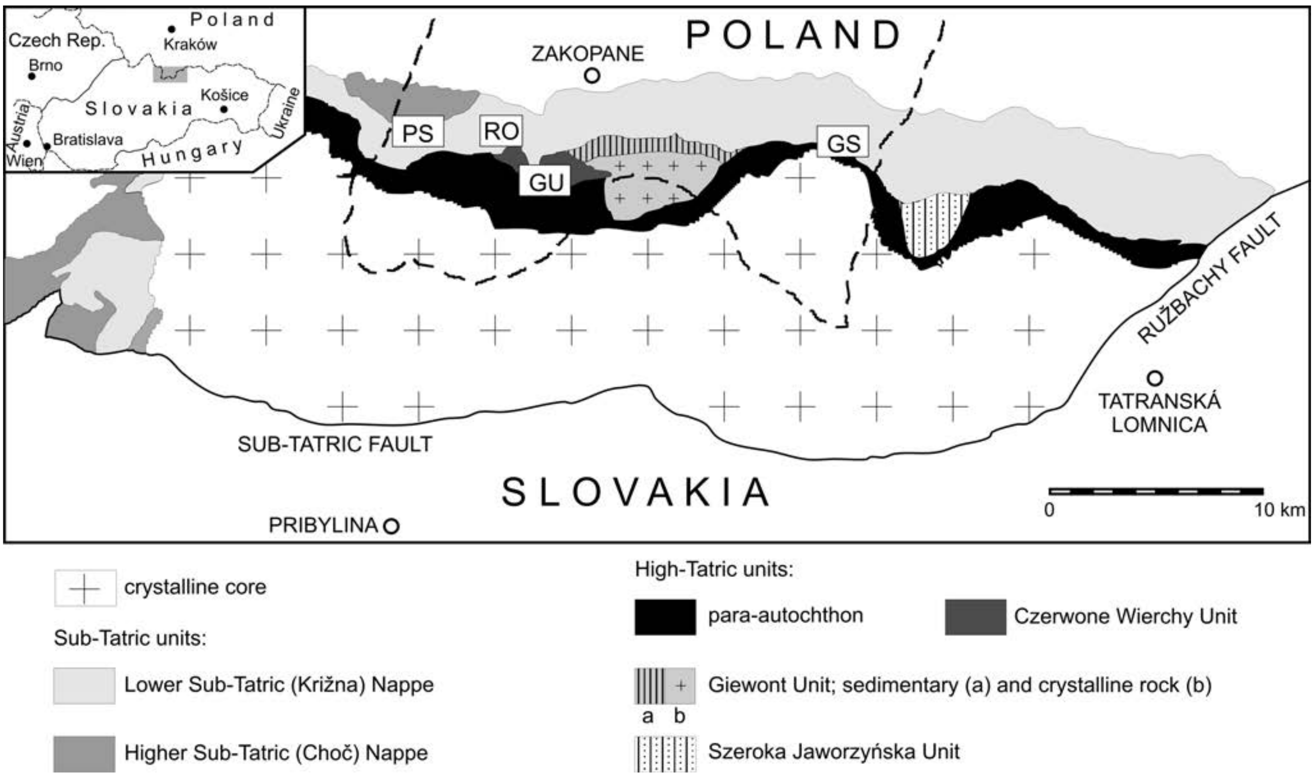

Fig. 1. Tectonic sketch map of the Tatra Mts. and localization of the sections studied: PS – Pośrednie III, RO – Rówienka, GU – Gładkie Upłaziańskie, GS – Gęsia Szyja.

(Grabowski *et al.*, 2013) indicate that long-term changes in MS might be correlated with sea level trends (Hardenbol *et al.*, 1998) and/or climatic events (Schnyder *et al.*, 2006, 2009; Tremolada *et al.*, 2006). In this paper, the authors present the integrated results of a new MS and geochemical study of three new Berriasian sections and compare them with the Pośrednie III section. The authors focus on dating and determination of the palaeoenvironment of a change in sedimentation, which occurred in the Late Berriasian and was manifested in the transition between micritic calpionellid-rich limestones (Osnica Fm) and widespread marls (Kościeliska Marl Fm).

GEOLOGICAL SETTING AND STRATIGRAPHY

The sections studied are located in the Tatra Mts. (Poland) and belong to the Krížna Nappe (Fig. 1; Fatric domain, Lower Sub-Tatric succession; see e.g., Bac-Moszaszwili, 1998; Plašienka, 1997; Lefeld, 1999). They are (from west to east): Pośrednie III (PS), Rówienka (RO), Gładkie Upłaziańskie (GU) and Gęsia Szyja (GS). They were primarily situated within the extensional Zliechov Basin, which was the site of deep-water pelagic and hemipelagic sedimentation in the Late Jurassic and Early Cretaceous (Lefeld, 1974; Vašíček *et al.*, 1994; Michalík *et al.*, 1995a, b; Michalík, 2007). After the Cenomanian, the Zliechov Basin was closed and thrusted northwards, together with other tectonic elements of Fatric-Hronic nappe system (e.g., Plašienka, 1997, 2003a, 2012; Prokešova *et al.*, 2012; Jurewicz, 2005). During thrusting, the Krížna Nappe became differentiated into numerous smaller units (partial nappes, duplexes; see Guzik and Kotański, 1963; Prokešová *et al.*, 2012).

The stratigraphy of the Berriasian in the Lower Sub-Tatric succession of the Tatra Mts. is well established, owing to micropalaeontological (Lefeld, 1974; Pszczółkowski, 1996) and magnetostratigraphic studies (Grabowski and Pszczółkowski, 2006). The Jurassic/Cretaceous (Tithonian/Berriasian) boundary is situated close to the bottom of Osnica Fm (Michalík *et al.*, 1990) which is seen as well bedded greyish micritic limestones with abundant calpionellids. The Osnica Fm in the Tatra Mts. attains a thickness of up to 25–37 m (Pszczółkowski, 1996). It is overlain by the Kościeliska Marl Fm (Lefeld *et al.*, 1985). The boundary between the two formations is diachronous and ranges from the Remaniella cadischiana Subzone in the Gładkie Upłaziańskie section to the Calpionellopsis oblonga Subzone in the Gęsia Szyja section (Pszczółkowski, 1996, 2003). In the Bobrowiec Unit in the Western Tatra Mts., the boundary is situated in the upper part of the Calpionellopsis simplex Subzone, in the lower part of the magnetozone M16n (Grabowski and Pszczółkowski, 2006).

An estimation of the sedimentation rate revealed a marked contrast between the two formations: 10–17 m/My in the Osnica Fm and at least 18–23 m/My in the Kościeliska Marl Fm (Upper Berriasian) (Grabowski and Pszczółkowski, 2006).

An attempt at palaeoenvironmental interpretation of the Tithonian–Berriasian succession was performed by Grabowski *et al.* (2013) for the Pośrednie III section. Abrupt

MS variations apparently correlate well with relative sea-level changes and indicate regressive intervals (MS highs) in the Upper Tithonian/lowermost Berriasian (magnetozones M20r to M19n2n) and Upper Berriasian (M16n) and a transgressive interval (MS low) in the Lower Berriasian (M18r to M17r). Long-term MS variations might be linked to enhanced continental run-off, controlled by palaeoclimate. Geochemical data (P, Th/U, Mn, Cd, Ni, Mo and TOC content) indicate an increase in biological productivity and a slight oxygen deficiency in the Lower Berriasian, which correspond to MS low values and typical nannofossil-calpionellid limestone sedimentation. The timing of major palaeoenvironmental changes might be correlated also with general palaeoclimatic trends in the Western Tethys and Western Europe: cooling in the late Tithonian followed by a temperature increase throughout the Berriasian and an important humidity increase in the upper part of the Lower Berriasian (M17n; Grabowski *et al.*, 2013).

MATERIAL

The Gładkie Upłaziańskie (GU) section (Upłaziańska Kopa in Jach *et al.*, 2014) is located within a separate small tectonic slice (Kotański, 1965), on the southern slope of the Gładkie Upłaziańskie hill (GPS coordinates: N 49°14'22.1", E 19°53'22.7"). It is almost 85 m thick and covers a large part of the Lower and Upper Berriasian from the Alpina up to the Murgeanui subzones (Fig. 2). The section presented in the Fig. 2 is a composite section, based on the data of Pszczółkowski (1996, 2003). The boundary of the Osnica/Kościeliska formations occurs in the Lower Berriasian, in the Cadischiana Subzone.

The Gęsia Szyja (GS) section, 46 m thick, is situated on the tourist trail leading from the Rusinowa Polana (Rusinowa Glade) to Gęsia Szyja Hill (GPS coordinates: N49° 15'32.4", E20°04'49.86") in the eastern part of the Tatra Mts. (Pszczółkowski, 1996). It belongs to a tectonic slice, called the Gęsia Szyja Cretaceous Slab (Lefeld, 1999) or the Gęsia Szyja Partial Nappe (Sokołowski, 1978; Birkenmajer, 2000). It covers the upper part of the Lower Berriasian (the upper part of the Alpina Subzone) up to the Oblonga Subzone of the Upper Berriasian. The contact between the Osnica and Kościeliska Marl formations is situated in the uppermost part of the section, in the upper part of the Oblonga Subzone (Fig. 3).

The Pośrednie III and Rówienka sections (Grabowski and Pszczółkowski, 2006) are situated in the Bobrowiec Unit (Bac, 1971; Bac-Moszaszwili, 1998) in the Western Tatra Mts.

The Rówienka (RO) section (Grabowski and Pszczółkowski, 2006) lies in the lower part of the Lejowa Valley, in a gully on its south-eastern slopes (beginning of the section: N49°16'14.0", E19°50'51.8"; end of the section: N49°16' 11.8", E19°50'54.3"). The section, 37 m thick, comprises continuous exposure from the uppermost Lower Berriasian (Elliptica Subzone, M16r) up to the upper part of the Upper Berriasian (upper part of the Calpionellopsis Zone, M16n). A continuous transition between the Osnica and Kościeliska Marl fms is well exposed there (Fig. 4).

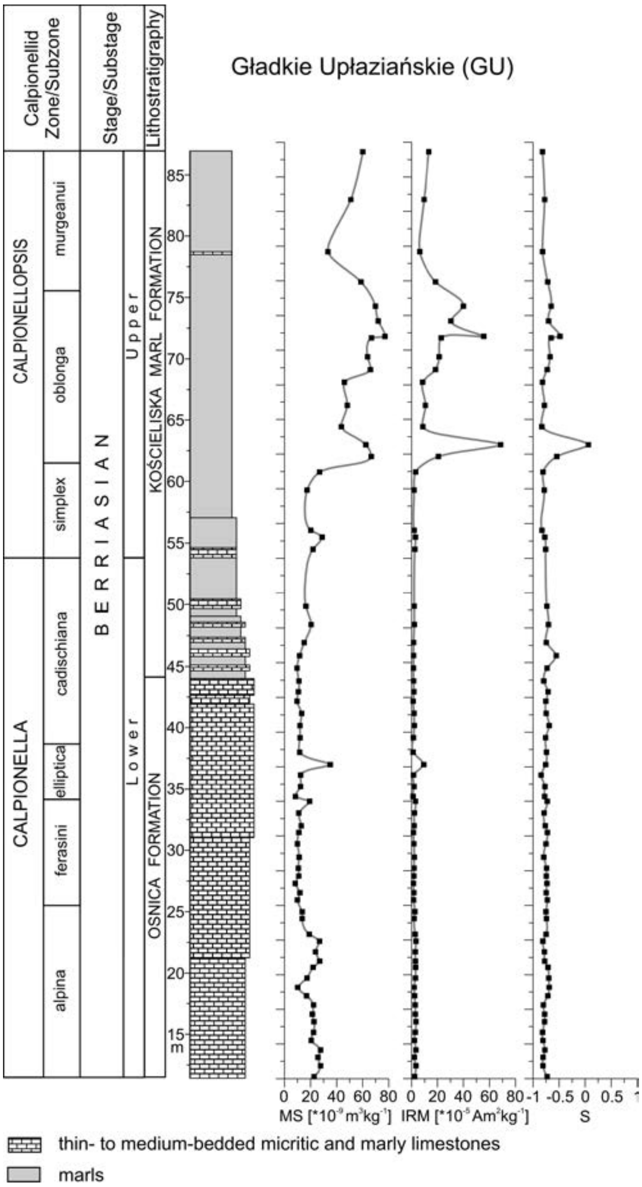

Fig. 2. Gładkie Upłaziańskie section: lithology and biostratigraphy (slightly modified after Pszczółkowski, 1996, 2003), magnetic susceptibility (MS), isothermal remanent magnetization acquired in the field of 1 T (IRM_{1T}), and S-ratio.

The Pośrednie III (PS) section is localized to the west of the Chochołowska Valley, on the ridge between the Kryta and Długa valleys (beginning of the section: N49°15'37.1", E19°48'05.5"; end of the section: N49°15'38.5", E19°48' 05.8"). The entire section covers interval from the uppermost part of the Lower Tithonian up to the Upper Berriasian (Grabowski and Pszczółkowski 2006; Grabowski *et al.*, 2013). In this study, only the upper part of the section is considered and comprises the upper part of the Lower Berriasian (topmost part of the Calpionella alpina Subzone; M17r) up to the Upper Berriasian (Calpionellopsis oblonga Subzone, M16n), about 22.5 m in thickness (see Fig. 5). Unfortunately, the contact between the Osnica and Kościeliska Marl fms is covered in that section and most probably is tectonic in character (Grabowski *et al.*, 2013).

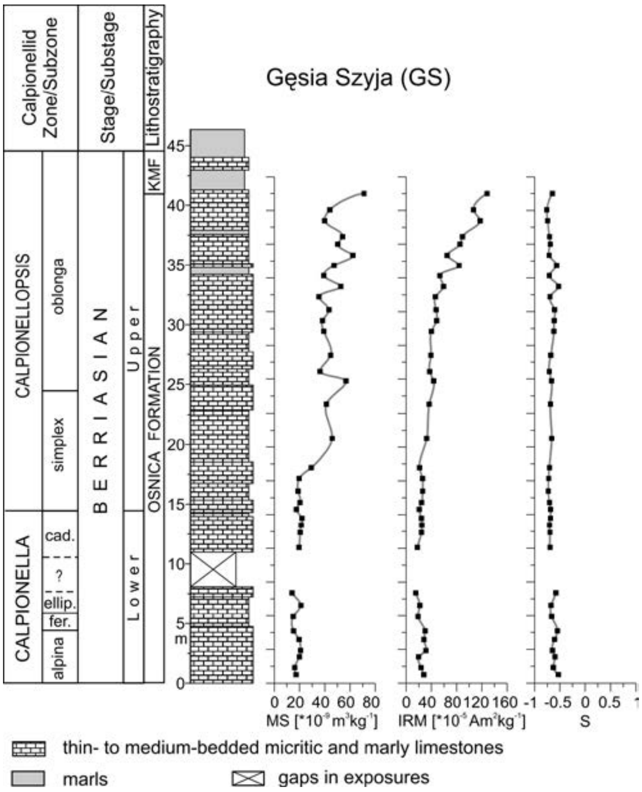

Fig. 3. Gęsia Szyja section: lithology and biostratigraphy (slightly modified after Pszczółkowski, 1996), magnetic susceptibility (MS), isothermal remanent magnetization acquired in the field of 1 T (IRM_{1T}), and S-ratio. Abbreviations: fer. – ferasini; ellip. – elliptica; cad. – cadischiana.

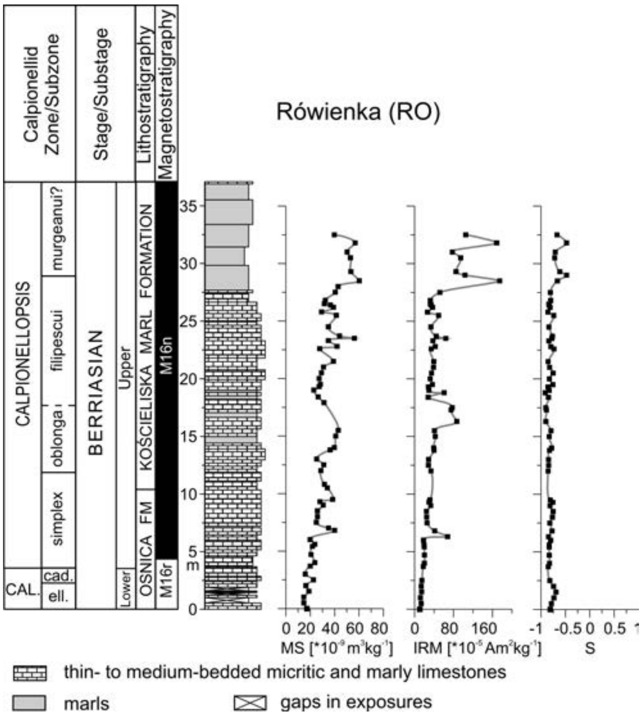

Fig. 4. Rówienka section: lithology, biostratigraphy, magnetic susceptibility (MS), isothermal remanent magnetization acquired in the field of 1 T (IRM_{1T}), and S-ratio (slightly modified after Grabowski and Pszczółkowski, 2006). Abbreviations: CAL. – Calpionella; ell. – elliptica; cad. – cadischiana.

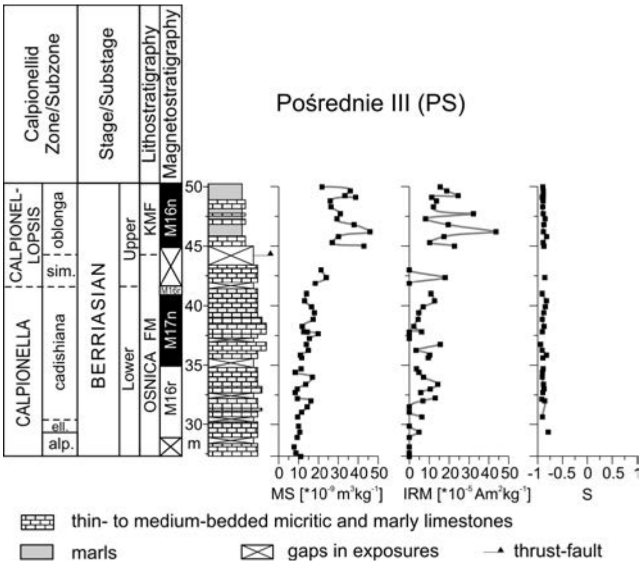

Fig. 5. Pośrednie III section: lithology, biostratigraphy, magnetic susceptibility (MS), isothermal remanent magnetization acquired in the field of 1 T (IRM_{1T}), and S-ratio (slightly modified after Grabowski *et al.*, 2013). Abbreviations: alp. – alpina; ell. – elliptica; sim. – simplex; KMF – Kościeliska Marl Formation.

SAMPLING AND METHODS

In the present study, the authors used the archival samples of Pszczółkowski (1996) from the Gładkie Upłaziańskie and Gęsia Szyja sections. The authors also used the archival samples of Grabowski and Pszczółkowski (2006) for the Rówienka section. Additionally, the results were compared with the data from the Pośrednie III section, published by Grabowski *et al.* (2013). Bulk magnetic susceptibility (MS) was measured in three positions for 162 samples using a KLY-2 kappabridge (AGICO, Brno, sensitivity 10^{-8} SI), in the Paleomagnetic Laboratory of the Polish Geological Institute – National Research Institute in Warsaw. Isothermal remanent magnetization (IRM) was acquired using a MMPM pulse magnetizer, in the fields of 1T (IRM_{1T}) and then anti-parallel in the field of 100mT (IRM_{100mT}). The S parameter (S-ratio), calculated as a ratio of IRM intensities applied in both fields (IRM_{100mT}/IRM_{1T}), was indicative for proportions of low- and high-coercivity minerals. All magnetic measurements were normalized for mass. The quantities of samples from particular sections were as follows: 64 from the Gładkie Upłaziańskie, 36 samples from the Gęsia Szyja and 62 samples from the Rówienka sections. All samples previously had been investigated biostratigraphically (Pszczółkowski, 1996, 2003; Grabowski and Pszczółkowski, 2006). The Pośrednie III and Rówienka sections were calibrated with the magnetostratigraphy (Grabowski and Pszczółkowski, 2006). Chemical analyses of 114 whole-rock samples (RO – 42, PS – 32, GU – 19, GS – 21) were performed at the Acme Analytical Laboratories, Vancouver, British Columbia. The concentrations of major and trace elements were measured by inductively coupled plasma mass spectrometry (ICP-MS). Measurement precision was as follows: 0.02% for Al, Ca, K, and Fe; 0.001% for Ti, 0.1 ppm for Sc, Rb, Th, Ni, and U; 0.02 ppm for Ga;

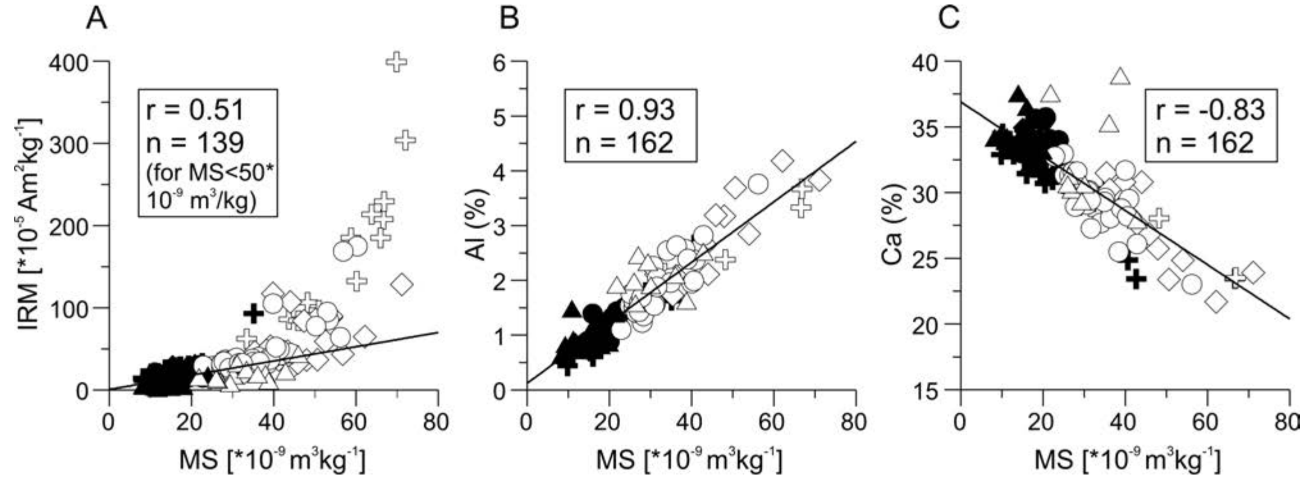

Fig. 6. Correlation between magnetic susceptibility (MS) and: (**A**) isothermal remanent magnetization acquired in the field of 1 T (IRM_{1T}), (**B**) aluminium, and (**C**) calcium. Black and white symbols: data before (up to the last MS low value = lower end of the arrows in Fig. 7) and after MS increase in Simplex Subzone (see Fig. 7). GU – crosses, GS – diamonds, RO – circles, PS – triangles.

0.001 ppm for P; 0.2 ppm for Co, Zr, and Zn; and 1 ppm for Cr. In this paper, only elements related to the detrital input are discussed. Aluminium content was selected as a normalizing factor, on the assumption that it is hosted solely in the lithogenous sediment fraction (e.g., Calvert and Pedersen, 1993; Brumsack, 2006; Tribovillard *et al.*, 2006; see also Grabowski *et al.*, 2013).

RESULTS

Magnetic susceptibility

MS in the **Gładkie Upłaziańskie** section (Fig. 2) revealed a decreasing pattern in the lower part, from 30 × 10^{-9} m^3/kg in the Alpina Subzone to 10 × 10^{-9} m^3/kg in the Remaniella ferasini Subzone, the C. elliptica Subzone and the lower part of the R. cadischiana Subzone. A gradual increase to 20–25 × 10^{-9} m^3/kg was observed in the upper part of the Cadischiana Subzone and the lower part of the Simplex Subzone. A noticeable increase to 60–70 × 10^{-9} m^3/kg occurs in the uppermost part of the Simplex Subzone and these values, with minor variations, are preserved up to the top of the section (Murgeanui Subzone).

In the **Gęsia Szyja** section (Fig. 3), the Ferasini, Elliptica and Cadischiana subzones are reduced in thickness (about 10 m) by comparison with the Gładkie Upłaziańskie section (almost 30 m). Nevertheless, similar MS trends were observed. A subtle MS decrease was observed between the Alpina and Elliptica subzones (between 20 and 15 × 10^{-9} m^3/kg). Throughout the Cadischiana Subzone and the lower part of the Simplex Subzone the MS returns to values of 20 × 10^{-9} m^3/kg and in the middle part of the Simplex Subzone it rises sharply to 45–50 × 10^{-9} m^3/kg. Even higher values of MS were observed in the upper part of the Oblonga Subzone (up to 70 × 10^{-9} m^3/kg).

In the **Rówienka** section (Fig. 4), the MS rises gently from 10 to about 20 × 10^{-9} m^3/kg between the Elliptica Subzone and the lower part of the Simplex Subzone and then rather sharply to 40 × 10^{-9} m^3/kg in the upper part of the Simplex Subzone. Also in this section, the highest MS values occur in the upper part of the Oblonga Subzone. In the **Pośrednie III** section (Fig. 5), MS fluctuated between 10 and 20 × 10^{-9} m^3/kg in the Elliptica and Cadischiana subzones. A continuous transition towards the Simplex Subzone is not exposed; however, in the Oblonga Subzone MS values amount already to 40–50 × 10^{-9} m^3/kg.

Magnetic mineralogy and geochemistry

The previous rock magnetic investigations, performed for the Pośrednie III and Rówienka sections (Grabowski and Pszczółkowski, 2006), proved that magnetite is the main magnetic mineral in the Osnica and Kościeliska Marl fms. The subordinate presence of hematite was noted only in the lower part of the Osnica Fm.

The predominance of low-coercivity minerals also was confirmed in the present study. The S-ratio revealed almost exclusively low negative values, which confirmed the presence of magnetite. The only horizon with a slightly positive value of S-ratio (higher-coercivity minerals, possibly hematite?) is represented by sample GU 73 in the Gładkie Upłaziańskie section (lower part of the Oblonga Subzone; Fig. 2). Magnetite contributes to the MS, which is evidenced in a generally good correlation between MS and IRM_{1T} (Fig. 6A). An MS increase from 10 to 50 × 10^{-9} m^3/kg is accompanied by only a slight positive shift of the IRM_{1T}. For samples with MS values higher than 50 x 10^{-9} m^3/kg, the slope of correlation is much steeper, so that even a slight increase in MS results in a large increase in IRM_{1T}. This is especially well demonstrated in the Gładkie Upłaziańskie and Rówienka sections (Fig. 6A). This indicates that in those samples (mostly in the Kościeliska Marl Fm) the ferromagnetic contribution to the MS might be more significant.

An excellent positive correlation is observed between MS and Al, as well as the other detrital elements (Ti, Zr, Th, and other; see Table 1 and Fig. 6B). There is also a good negative correlation between MS and Ca (Fig. 6C). This is proof that MS might be regarded as a good proxy for

Table 1

Cross-correlations between Al and selected elements

	K	Rb	Ti	Th	Ga	Zr	V	Sc	Fe	U	P	Co	Ni	Cr	Zn	Ca
GU	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.98**	**0.91**	0.86	0.86	0.89	0.55	-0.98
GS	**0.98**	**0.94**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.97**	**0.93**	**0.94**	**0.95**	**0.92**	**0.98**	**0.96**	-0.98
RO	**0.99**	**0.99**	**0.99**	**0.99**	**1.00**	**0.99**	**0.99**	**0.99**	**0.97**	**0.95**	**0.94**	0.82	**0.93**	**0.91**	**0.97**	-0.83
PS	**0.98**	**0.98**	**0.97**	**0.99**	**0.99**	**0.98**	**0.99**	**0.98**	**0.98**	**0.91**	0.87	0.88	-0.09	0.58	0.89	-0.45

Very good correlation (r > 0.9) is indicated in bold.

lithogenic input in all four sections, independently of the relative para- and ferromagnetic contribution. Previous investigations revealed that detrital material is abundant in both the Osnica and Kościeliska Marl fms of the PS section (Grabowski *et al.*, 2013). It comprises quartz, chlorite, albite, muscovite, apatite, rutile and in places also biotite. Titanium oxides are apparently more common in the Kościeliska Marl Fm than in the Osnica Fm, which might indicate that also detrital magnetites and/or titanomagnetites are more abundant in the former.

DISCUSSION

The four studied sections reveal quite similar pattern of MS variation. General low MS predominates from the upper part of the Alpina, through the Ferasini, Elliptica and Cadischiana subzones, up to the lower part of the Simplex Subzone (lower part of M16n). Higher up in the latter subzone, a major increase in MS occurs, which is persistent with some small-scale variations also in the Oblonga and Murgeanui subzones. An interval of MS increase is located in the upper part of Simplex Subzone (lower part of M16n) in the Rówienka and Gęsia Szyja sections, and at the boundary between the Simplex and Oblonga subzones in the Gładkie Upłaziańskie section. Unfortunately, detailed dating of this interval is impossible in the Pośrednie III section, because it is located in a gap in the section (between the lower part of the Simplex and the Oblonga subzones). As the MS increases, a relatively higher amount of ferromagnetic particles is present in the sediment.

A contrast in terrigenous input between the Osnica and Kościeliska fms was well known and quite obvious (Lefeld, 1974; Lefeld *et al.*, 1985). The present study proves that the major increase in terrigenous input between the Simplex and Oblonga subzones might be a synchronous event within the Zliechov Basin and the formation boundaries do not always correlate with it. In the Gładkie Upłaziańskie section, it occurs in the Kościeliska Marl Fm (about 17 m above the base), while in the Gęsia Szyja section, still in the Osnica Fm (about 24 m below the top). This observation indicates that correlation of clastic events on the basis of field observations might be misleading. Therefore, the authors regard MS as an appropriate tool for the quantification of fine clastic input in such pelagic and hemipelagic sediments. An increase in clastic input in the Lower Sub-Tatric succession in the Tatra Mts. (based on MS logging and gamma-ray spectrometry in the Pośrednie III section) between the Lower and Upper Berriasian was already documented by Grabowski *et al.* (2013).

The results obtained in sections from the Lower Sub-Tatric succession in the present study might be compared to magnetostratigraphic and MS data from the Barlya section in Bulgaria (Western Balkans, Grabowski *et al.*, 2014b). It is evident that there too, an increase in marly sedimentation is observed between the upper part of the Simplex Subzone and the lower part of the Oblonga Subzone (the transition between Glozhene and Salash fms; see Lakova *et al.*, 2007; Lakova and Petrova, 2013), in the lower part of magnetozone M16n. The MS increase is not as sharp as in the sections of the Lower Sub-Tatric succession and its magnitude is lower. Nevertheless, the MS increase in Barlya, between 110 and 114 m in the lower part of M16n, corresponds exactly to the positive MS shift in the Rówienka section (Fig. 7). It is noteworthy that the range of the Simplex Subzone in the Rówienka and Barlya sections is slightly different. The bottom of the Simplex Subzone falls in the uppermost part of M16r in the Rówienka and in the middle part of M16r in the Barlya sections.

The increased supply of fine clastic material in the Late Berriasian might be interpreted as a result of the interplay between at least three factors:

1 – general regression in the Tethyan domain (Hardenbol *et al.*, 1998; Pszczółkowski and Myczyński, 2010);

2 – an increase in climate humidity at the northwestern margin of the Tethys and the surrounding areas of the European platform (Abbink *et al.*, 2001; Schnyder *et al.*, 2006; Morales *et al.*, 2013);

3 – regional tectonic phenomena, related to rifting processes in the Vahic-Magura Ocean (Golonka and Krobicki, 2001; Golonka *et al.*, 2003; Plašienka, 2003b; Krobicki *et al.*, 2010).

Detrital supply as a result of regression

Grabowski *et al.* (2013) noted similarities between T-R cycles in the Tethyan realm and the long-term MS pattern in the Pośrednie III section. The MS increase in the Upper Berriasian would represent a maximum regression in the uppermost part of magnetozone M16n (Fig. 8). The influence of eustatic events on sedimentary and biotic changes in the Western Carpathians was suggested by Reháková (2000) and Michalík (2007). An increase in fine clastic input and a shallowing tendency in the Upper Berriasian of the Western Tethys seems to be a regional phenomenon. In the Western Carpathians, marly sedimentation started at the

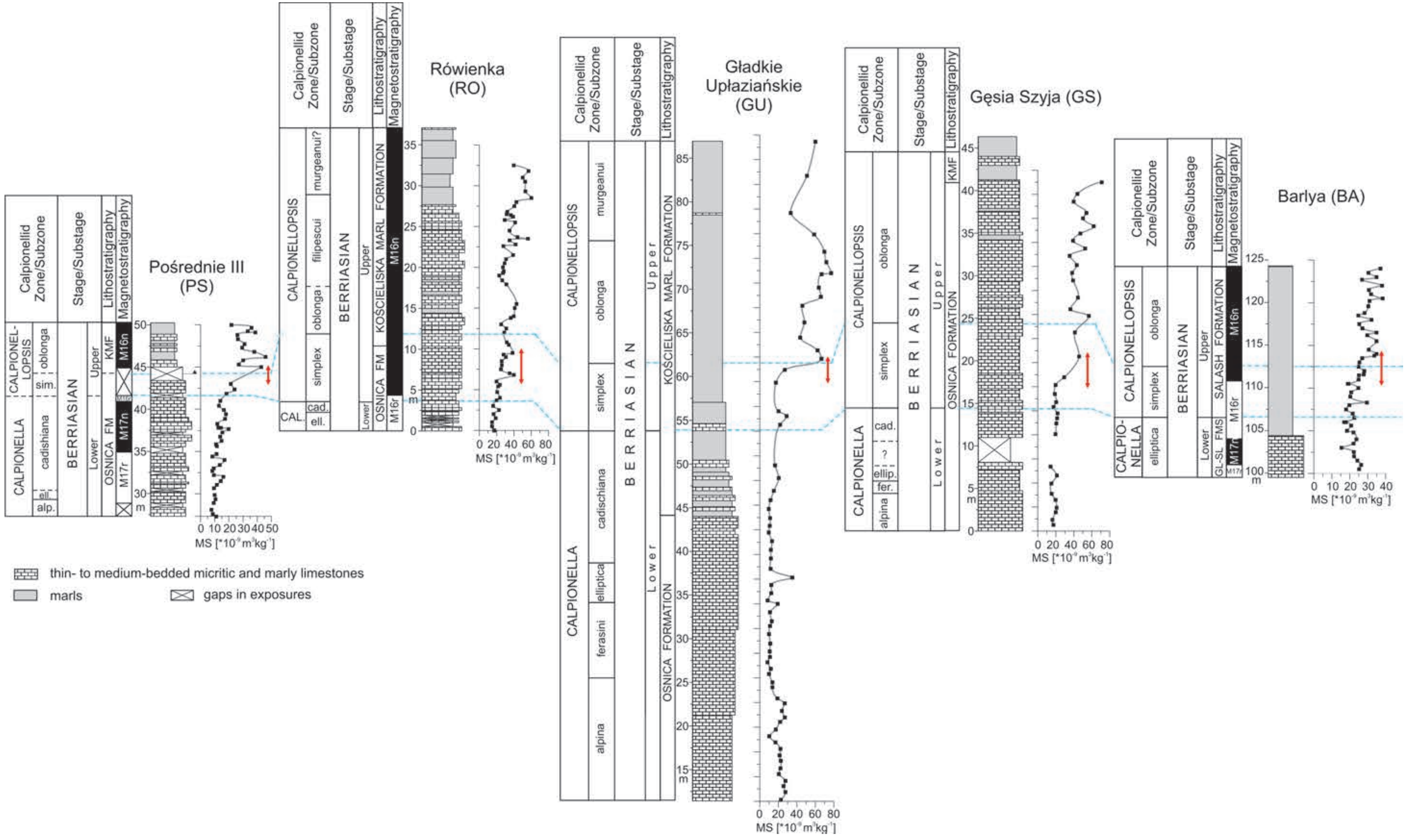

Fig. 7. Correlation of the sections studied in the Lower Sub-Tatric succession with the Barlya section (Western Balkan, Bulgaria, after Grabowski *et al.*, 2014b) using bio-, magneto-stratigraphy and magnetic susceptibility. Arrows indicate the level of MS increase within the Simplex Subzone and lower part of Oblonga Subzone (lower part of M16n). Abbreviations: fer. – ferasini; ellip. – elliptica; cad. – cadischiana; CAL. – Calpionella; ell. – elliptica; alp. – alpina; sim. – simplex; KMF – Kościeliska Marl Formation; GL-SL – the transition between Glozhene and Salash fms.

Simplex/Oblonga subzonal boundary, as in the Hlboča section in the Male Karpaty (Hlboč Fm – Grabowski *et al.*, 2010) and in the lower part of the Calpionellopsis Zone in the Strážovce section in the Strážov Mts. (Mráznica Fm – Michalík *et al.*, 1995a).

An onset of marly sedimentation in the early Late Berriasian, manifested in the transition between the Oberalm and Schrambach fms, is well known also in the Northern Calcareous Alps (e.g., Faupl *et al.*, 1997; Rasser *et al.*, 2003; Krische *et al.*, 2013). In Western Cuba, an important lithologic change takes place in the Upper Berriasian in the Guaniguanico successions, where radiolarian limestones of the Artemisa Fm are overlain by clastic-rich sediments of the Polier Fm in the Northern Rosario succession (Pszczółkowski and Myczyński, 2010). Pale red pelagic biomicrites of Tumbitas Member rest on the dark limestones of Tumbadero Member in the Los Organos succession. The authors correlated this sedimentary change with a significant sea-level fall in the scheme of Haq *et al.* (1987).

Detrital supply as a result of climate humidity increase

Recently, the timing of a climate humidity change in the Upper Berriasian was documented in the Vocontian Basin (SE France, Montclus section). Its onset (first kaolinite occurrences) falls in the calpionellid D1 (Simplex) Subzone, but kaolinite becomes more abundant in the calpionellid D3 Subzone (Morales *et al.*, 2013). Also in the Mount Salève section (E France), the climatic change occurred in the calpionellid D2 Subzone (Bover-Arnal and Strasser, 2013).

The MS event in the Simplex Subzone broadly coincided in time with the humidity change in the Late Berriasian. However, data on clay minerals (kaolinite content), which are of crucial importance in postulating the climatic nature of this event, are not available from the Lower Sub-Tatric succession. It is well known that clay minerals in the Mesozoic rocks of the Tatra Mts. were significantly transformed during deep tectonic burial, owing to the Late Cretaceous thrusting, and preservation of primary kaolinite was hardly possible. Almost all data revealed the presence of less than 15% of smectite (Środoń *et al.*, 2006), while unpublished data from the Tithonian–Berriasian strata in the area of the Kryta section (Western Tatra Mts., Lower Sub-Tatric succession – P. Brański, pers. comm., 2013) indicated the presence of illite (56–64%) and chlorite (36–44%).

Detrital supply as an effect of regional tectonics

Krobicki *et al.* (2010) point to the importance of tectonic phenomena as the main factors controlling detrital input into the Carpathian basins. The idea was especially well documented in the Czorsztyn succession of the Pieniny Klippen Belt. The Walentowa Breccia Member (Birkenmajer, 1977), interpreted as a product of synsedimentary mass movements along submarine scarps (Birkenmajer, 1958, 1975), is dated as Upper Berriasian (Calpionellopsis Zone; see Wierzbowski and Remane, 1992).

The shallowing-upward trend in various parts of the Czorsztyn succession of the Pieniny Klippen Belt was proved throughout the Berriasian (from the Jurassic/Cretaceous boundary to the upper part of the Calpionellopsis Zone) by analysis of brachiopod assemblages (Krobicki, 1994, 1996). These phenomena were interpreted as an effect of "Neo-Cimmerian" events, which in fact were related to extension and rifting in the Magura Ocean, on the northern side of the Czorsztyn Ridge (Walentowa Phase of Plašienka, 2003b). Increase of marly sedimentation in the Upper Berriasian (at the simplex/oblonga subzonal boundary) is observed in the Branisko succession of the PKB (Łysonka Marl Bed; Pszczółkowski and Myczyński, 2004).

It is not easy to decide to what extent each of the factors mentioned exerted an influence on the increased terrigenous influx into the Zliechov Basin in the Late Berriasian, documented in this paper. Both climatic changes and eustatic regression in the Late Berriasian are well documented and their effects might have been superposed, contributing to a wide regional sedimentary change. The sequence of events presented in Figure 8 does not appear to be synchronous, although a concentration of events in the lower part of the Upper Berriasian is evident. It must be kept in mind that integrated magnetostratigraphic, MS and calpionellid studies were performed only in the Tatra Mts. and Western Balkans. However, in these localities the beginning of marly sedimentation coincides very clearly (see Fig. 7). The MS event is situated in the regressive interval of both reference sea level curves (Fig. 8), but it does not correlate with the maximum regression in the Hardenbol *et al.* (1998) scheme. The situation is additionally complicated by local and regional tectonic activity in the Late Berriasian: rifting phases and vertical tectonic movements manifested by breccias in the Central Western Carpathians and the Pieniny Klippen Belt (see Michalík *et al.*, 1995a; Reháková, 2000; Golonka and Krobicki, 2001; Golonka *et al.*, 2003: Nozdrovice and Walentowa breccias).

In the opinion of the authors, however, the Czorsztyn Ridge and surrounding areas definitely could not be the source of the fine siliciclastic material supplied to the Zliechov Basin. The MS values in the Berriasian and Valanginian of the Pieniny Limestone Fm are an order of magnitude lower than in the coeval deposits of the Lower Sub-Tatric succession (the Osnica Fm and the Kościeliska Marl Fm; see Grabowski *et al.*, 2014a). This indicates that the source area must have been situated south of the Zliechov Basin, most probably in the area of the Meliata-Hallstatt suture zone (see also Świerczewska and Pszczółkowski, 1997; Faupl *et al.*, 1997; Jablonský *et al.*, 2001; Michalík, 2007). The tectonic phenomena responsible for the formation of the carbonate breccias were most probably superposed on the eustatic and/or climatic trends.

CONCLUSIONS

Four Berriasian sections in the Lower Sub-Tatric succession in the Polish part of the Tatra Mts. were correlated by means of magnetic susceptibility. MS reflects the amount of influx of clay particles and detrital magnetite into the basin. This is evidenced by very good positive correlation with lithogenic elements (Al, Th, Zr and others) and a negative correlation with Ca. A sharp increase in MS was observed be-

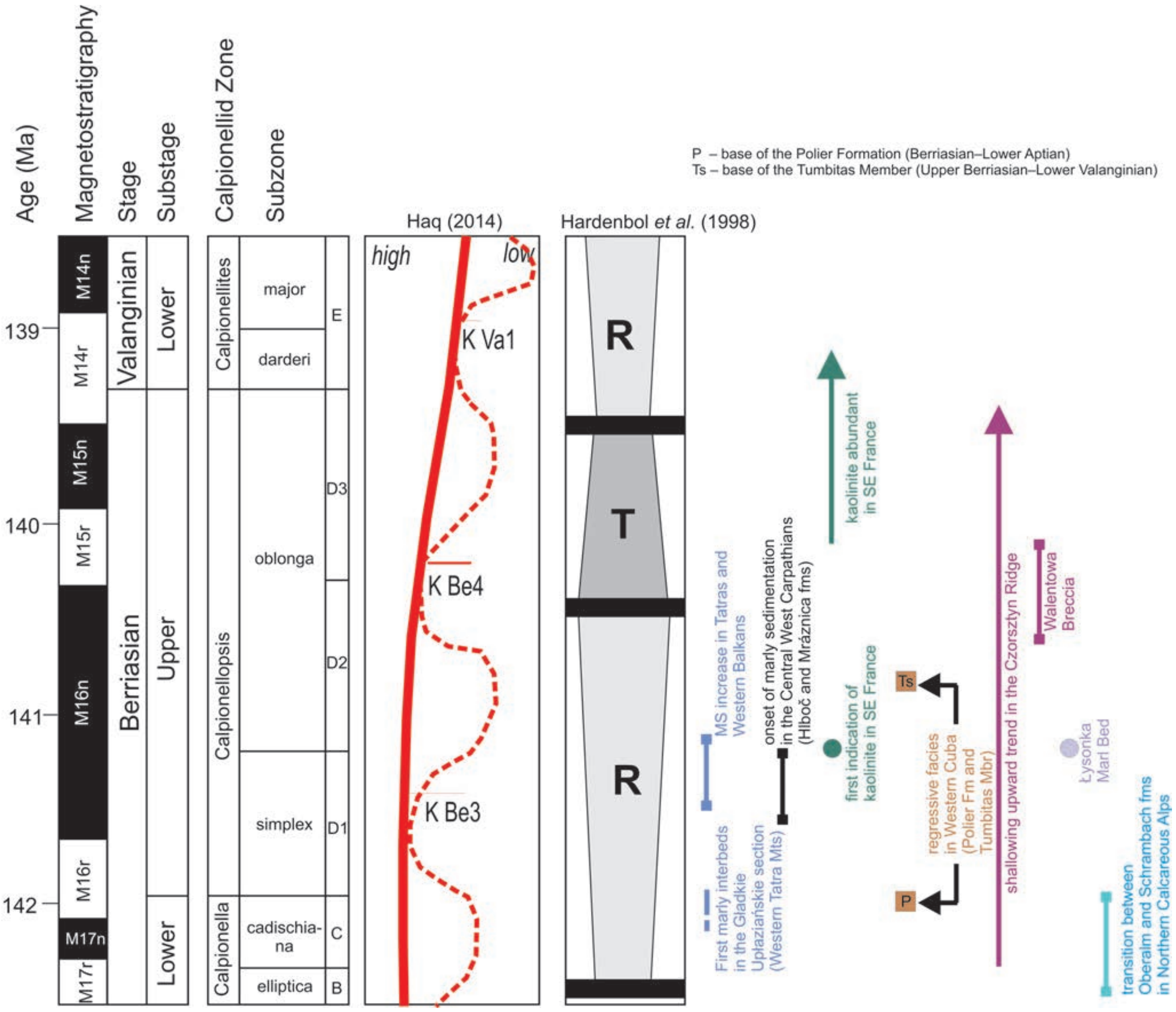

Fig. 8. Integrated Late Berriasian bio- and magnetostratigraphical scheme, its correlation with eustatic sea level changes after Haq (2014) and Hardenbol *et al.* (1998, only T-R cycles in Tethyan domain) and Berriasian clastic and climatic events discussed in this study. Stratigraphic positions of events after Morales *et al.* (2013; SE France), Pszczółkowski and Myczyński (2010; W Cuba), Wierzbowski and Remane (1992; Walentowa Breccia), Golonka and Krobicki (2001; Czorsztyn Ridge), Pszczółkowski and Myczyński (2004; Łysonka Marl Bed), Krische *et al.* (2013; Northern Calcareous Alps), Grabowski *et al.* (2010; Hlboč Fm) and Michalík *et al.* (1995a; Mráznica Fm).

tween the Calpionellopsis simplex and the Calpionellopsis oblonga subzones, in the lower part of the Upper Berriasian magnetozone M16n.

The increase in MS does not correspond everywhere to the lithostratigraphical boundary between the Osnica Fm and the Kościeliska Marl Fm.

An increase in marl sedimentation in the early Late Berriasian was documented and magnetostratigraphically dated also in the Western Balkans (Barlya section). It seems that an increase in clastic input might have been a regional phenomenon, at least in the Western Tethys (e.g., in the Austro-Alpine domain and in western Cuba).

The palaeoenvironmental interpretation of this late Berriasian MS event is not clear. It might have been controlled either by regional regression in the Western Tethyan domain and by climatic change (increase in humidity). A joint contribution of both of these factors (eustatic and climatic) also is likely.

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