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

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Abstract

Tithonian–Berriasian pelagic limestones were sampled in the Krížna (= lower Sub-Tatric) Nappe of the Tatra Mountains, central West Carpathians, Poland (19°49′E, 49°16′N). Palaeomagnetic, rock magnetic and biostratigraphical investigations were performed on four partially overlapping sections. Although remagnetised in part, the limestones yielded reliable magnetic polarity stratigraphy. Sections were correlated with the global polarity time-scale by means of calpionellid stratigraphy. Magnetozones from M20r up to M16n were identified. The Jurassic/Cretaceous boundary, defined as the boundary between Calpionellid Biozones A and B, lies within Magnetozone M19n, below the Brodno (M19n-1r) Magnetozone. Sedimentation rate apparently increases up-section, from 5–7 m/my in the Upper Tithonian—lowermost Berriasian (M20n–M18n), up to 10–17 m/my in the Lower and Middle Berriasian (M17), and 18–23 m/my in the Upper Berriasian (M16n). Environmental changes are reflected by changes in the rock magnetic properties of the sediments. Slow accumulation in the Upper Tithonian and around the J/K boundary favoured hematite precipitation. In the Berriasian strata, magnetite mineralogy dominates. Sedimentation increase in the Lower and Middle Berriasian sequence is accompanied by a decrease in magnetic susceptibility, probably related to higher carbonate productivity of micro- and nannoplankton. A stepwise increase in magnetic susceptibility, and an even higher sedimentation rate, in Upper Berriasian beds probably reflects a higher influx of detrital clay minerals to the basin.

Keywords: Tithonian; Berriasian; Magnetostratigraphy; Biostratigraphy; Calpionellids; Tatra Mountains; Poland

1. Introduction

The magnetostratigraphy of the Jurassic/Cretaceous boundary in the Tethyan Realm is relatively well known since the pioneering works of Cirilli et al. (1984), Lowrie and Channell (1984), and Ogg and Lowrie (1986). Although placement of the boundary within the various biostratigraphical schemes has been disputed, correlation of the magnetozones with oceanic anomalies, as well as with calpionellid biostratigraphy, have been made (Channell and Grandesso, 1987; Channell et al., 1987; Ogg et al., 1991). Almost all data were derived from the Southern Alps and Apennines, from a widespread pelagic Maiolica facies. These sections have good biostratigraphical
(calpionellid and nannofossil) control and favourable palaeomagnetic properties. Recently, the Brodno section of the Pieniny Klippen Belt in Slovakia (Houša et al., 1996, 1999) and Bosso Valley section of Umbria (Italy) (Houša et al., 2004) have been documented. They yielded a very detailed magnetostratigraphy, with two short magnetosubzones in the Upper Tithonian and lowermost Berriasian. The combination of magneto- and biostratigraphical data is consistent, and confirms that the Jurassic/Cretaceous boundary, as defined by calpionellid biostratigraphy (between zones A and B), is situated within Magnetozone M19n (Houša et al., 1996, 1999).

Integration of magneto- and biostratigraphical methods offers an excellent tool for calibration and correlation of sedimentological or geochemical events (e.g., Channell et al., 1993) and for further development of more detailed (e.g., astrochronological) time-scales (e.g., Mayer and Appel, 1999). In the present paper, the first magnetostratigraphical data from the Tithonian–Berriasian calpionellid limestones of the Fatric Zone in the central Western Carpathian area are presented, supported by microfossil study. The nature of the sedimentary changes within the studied basin is discussed.

2. Geological setting and sampling

The sections studied are located in the western part of the Tatra Mountains (19°49'E, 49°16'N), within the Krížna Nappe (Fig. 1A) which forms a weakly deformed NNE-dipping monocline (Bac, 1971). The 2000-m-thick succession of the Krížna Nappe reveals a shallow-water Triassic development but during Jurassic–Early Cretaceous, deep-water formations prevailed, which were deposited in an extensional regime on thinned continental crust (e.g., Vašíček et al., 1994; Plašienka, 2003). The litho- and biostratigraphy

Fig. 1. A, location of the studied sections in the Western Tatra Mountains, southern Poland (partly after Bac-Moszaszwili in Bac-Moszaszwili et al., 1979). B, detail showing simplified geological map of Kryta Valley, west of Chocholowska Valley (partly after Guzik in Guzik and Guzik, 1958, modified). Krížna Nappe: J, Jurassic (pre-Kimmeridgian); JA, Jasenina Formation (Kimmeridgian—earliest Berriasian); OS (shaded), Osnica Formation (Berriasian); MK, Kościelska Marl Formation (Late Berriasian—Aptian); Choč Nappe: T, Triassic. C, detail of simplified geological map of the Rówienka gully area in Lejowa Valley (after Guzik in Guzik et al., 1958). Krížna Nappe: J, JA, OS, MK as for B, above; Choč Nappe: T, Triassic; E, Eocene; Q, Quaternary.
of the Tithonian and Berriasian strata in the Tatra Mountains and other central Western Carpathian massifs have been studied by Lefeld (1974), Lefeld et al. (1985), Michałik et al. (1990) and Pszczółkowski (1996). Green, and sometimes reddish, siliceous radiolarian limestones belong to the lower part of the Jasenina Formation (Kimmeridgian—lower Tithonian; see Fig. 2). Shaly marls and olive grey, thinly bedded micritic limestones occur in the upper part of the Jasenina Formation (Upper Tithonian—lowermost Berriasian). The light grey, calpionellid-bearing pelagic limestones of the Osnica Formation (Berriasian) overlie the Jasenina Formation deposits (Fig. 2). These pelagic limestones are 25–37 m thick in various sections (Pszczółkowski, 1996) and pass gradually into the overlying strata of the Kościeliska Marl Formation (Lefeld et al., 1985). This formation, of Late Berriasian—Aptian age, comprises marls and limestones about 260 m thick (Lefeld et al., 1985).

During the mid-Cretaceous, the compression started that resulted in thrusting of the Krížna basement below the Veporic Unit. In the Late Turonian, the sedimentary Krížna succession was finally detached and thrust northward, in the form of a thin-skinned nappe (e.g., Plašienka and Prokešova, 1996; Plašienka, 1997).

Four sections were selected for magnetostratigraphical studies, all of them in the area of the Tatra National Park. The Kryta, Pośrednie II, and Pośrednie III sections (Fig. 1 B) are located to the west of the Chochołowska Valley. Both Pośrednie sections occur on the southern slope of the Pośrednie Ridge, while the Kryta section lies in the bottom of the Kryta Valley, continuously exposed along the creek and road. The Rówienka section is situated in the lower part of the Lejowa Valley, in a gully on its southeast slopes (Fig. 1 C). All beds accessible for sampling were marked with numbers in white paint. Most samples were taken using a gasoline-powered drilling machine at an interval of 0.3–1 m. Occasionally, hand-samples were also collected.

3. Methods

Natural remanent magnetisation (NRM) was measured by means of a JR-5 spinner magnetometer (AGICO, Brno; noise level 10⁻⁵ A/m) in the palaeomagnetic laboratory of the Polish Geological Institute (PGI) in Warsaw. Most samples were demagnetised thermally using the non-magnetic oven MMTD (Magnetic Measurements, UK; maximum demagnetisation temperature 700 °C). For a small set of samples, alternating field (AF) demagnetisation was performed with the Molspin demagnetiser (maximum demagnetisation field 100 mT). NRM measurements and demagnetisation experiments were carried out in a magnetically-shielded space (a low-field cage from Magnetic Measurements, UK, reducing the ambient geomagnetic field by about 95%). Magnetic susceptibility was monitored with a KLY-2 bridge (AGICO, Brno; sensitivity 10⁻⁸ SI units) after each thermal demagnetisation step.

### Table: Microfossil zonations published by various authors

<table>
<thead>
<tr>
<th>Stages and Substages</th>
<th>Studied sections</th>
<th>Microfossil zonations published by various authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Berrissian</td>
<td>Calpionellopsis oblonga</td>
<td>Calpionellopsis longa</td>
</tr>
<tr>
<td>Kosielska Marl FM</td>
<td>simplex</td>
<td>simplex</td>
</tr>
<tr>
<td>Middle</td>
<td>Calpionella</td>
<td>Calpionella elliptica</td>
</tr>
<tr>
<td>Osnica FM</td>
<td>Röwienka</td>
<td>Remaniella alpina</td>
</tr>
<tr>
<td>Lower</td>
<td>Crassicollaria</td>
<td>Crassicollaria intermedia</td>
</tr>
<tr>
<td>Jaseinia Fm</td>
<td>Kryta</td>
<td>Chitinoidella boneti dobeni</td>
</tr>
<tr>
<td>Tithonian</td>
<td>Praetintinnopessella</td>
<td>Praetintinnopessella</td>
</tr>
<tr>
<td>Lower</td>
<td>Chitinoidella boneti dobeni</td>
<td>Chitinoidella boneti dobeni</td>
</tr>
</tbody>
</table>

Fig. 2. Stratigraphical position of the studied sections within the framework of previously published lithostratigraphical divisions and microfossil (mainly calpionellid) biozonations.
Characteristic remanence magnetisation (ChRM) directions were calculated, based on principal component analysis (Kirschvink, 1980) and great circle analysis, following the method of McFadden and McElhinny (1988). Rock magnetic studies of representative samples included stepwise acquisition of the isothermal remanent magnetisation (IRM) and thermal demagnetisation of the IRM, acquired along three perpendicular axes (Lowrie, 1990). IRM was acquired using the MMPM1 pulse magnetiser produced by Magnetic Measurements (UK). The following magnetic parameters were measured for each sample in the section: mean magnetic susceptibility; IRM intensity after 1 T ($I_{1T}$, field applied along Z axis); IRM intensity after 100 mT ($I_{100mT}$ field applied antiparallel to Z axis). The parameter, $S$, was calculated as $S = I_{100mT}/I_{1T}$, in order to evaluate the relative contributions of low- and high-coercivity minerals (Opdyke and Channell, 1996). The value $S = -1$ indicates absence of a high-coercivity fraction.

The biostratigraphy of the studied Tithonian and Berriasian limestones is based on praeacalpionellids and calpionellids (Fig. 2). Usually, the limestones contain common to abundant specimens of these microfossils, although their preservation is moderate to poor. In the studied sections (Figs. 3–6), chitinoidellids are the more poorly preserved microfossils. The frequencies of calpionellid taxa were counted in each thin-section if the total number of identified specimens exceeded 100 ($>200$ in many cases). The relative frequency of each recognised taxon was established as a percentage of a total number of identified specimens in a given thin-section. The following percentage groups are shown in the figured sections (Figs. 4–6): 1, rare ($<1\%$); 2, infrequent (1–5\%); 3, frequent (5–20\%); 4, common (20–40\%); and 5, abundant ($>40\%$). In the Kryta section (Fig. 3), low numbers of microfossils (mainly chitinoidellids) identified in the thin-sections did not allow us to fully follow this subdivision. The number of investigated thin-sections was constrained by palaeomagnetic-orientated sampling density and completeness of the studied exposures.

4. Results

4.1. Biostratigraphy

Chitinoidellids are usually not very well preserved in the studied sections, nevertheless, we have been able to apply the taxonomy of Pop (1997a). We follow the subdivision of the Tithonian Chitinoidella Zone into the dobeni and boneti subzones (Fig. 2), as proposed by Borza (1984). We retain the original position of the Praeintinnopsella Zone above (not within) the Chitinoidella Zone (Borza, 1984; Pop, 1997b, 1998). Also, we follow the calpionellid standard zones established by Allemann et al. (1971). We have adopted the subzones of the Crassicollaria and Calpionella Standard Zones, as proposed by Remane et al. (1986) and Grün and Blau (1997), respectively (Fig. 2). The position of the Early Berriasian Remaniella ferasini Subzone (Pop, 1994a, 1997b) is indicated in the Pośrednie II section (Fig. 5). The scheme of Remane (1963, 1964, 1971) is also used, principally to allow a comparison of the studied sections with the calpionellid data published in some papers (Le Hégarat and Remane, 1968; Ogg and Lowrie, 1986; Channell et al., 1987; Channell and Grandesso, 1987; Le Hégarat and Ferry, 1990; Ogg et al., 1991; Houša et al., 1999, 2004).

The ca. 6-m-thick Kryta section comprises Tithonian limestones and marls of the Jasenina Formation (Fig. 3). These deposits belong mainly to the Chitinoidella boneti Subzone of the Chitinoidella Zone (see Fig. 7A, B for the index-taxon of this subzone). The base of the Praeintinnopsella Zone lies in the uppermost part of the section (sample K-17 in Fig. 3). Specimens of the index-taxon ($Praeintinnopsella$ sp.) are scarce and poorly preserved. In the two-fold subdivision of the Tithonian, the (early) Late Tithonian age of this zone has been established (Pop, 1994a, 1998; Grün and Blau, 1997; Blau and Grün, 1997), as shown in Fig. 2. According to Borza (1984) and Borza and Michalík (1986), the Praeintinnopsella Zone occupies the interval across the Middle/Upper Tithonian boundary.

In the ca. 48-m-thick Pośrednie III section (Fig. 4), Praeintinnopsella andrusovi (Fig. 7C) has been found in sample POS-19. The Tithonian/Berriasian boundary (= Jurassic/Cretaceous
boundary) is placed at the *Crassicollaria*/*Calpionella* zonal boundary, between samples POS-37 and 42 (Fig. 4). In this respect, we follow Remane et al. (1986), Borza and Michalik (1986), Houša et al. (1999), Grün and Blau (1997), Blau and Grün (1997) and other authors. However, according to Tavera et al. (1994) and Olóriz et al. (1995), in Spain the base of the *Berriasella jacobi* Zone falls within the *Crassicollaria* Zone, close to the A2/A3 boundary. Our sample POS-37 contains *Calpionella alpina* (Fig. 7D), *Crassicollaria massutiniana* (Fig. 7E), *Crassicollaria brevis* (Fig. 7F) and *Crassicollaria intermedia*; this assemblage belongs to Subzone A3 (Fig. 4).

In the Berriasian part of the section, the species *Remaniella cadischiana* (Fig. 7H) occurs from sample POS-72 upwards; this is the index-taxon for the *R. cadischiana* Subzone (Fig. 2). The first occurrence (FO) of *Calpionellopsis oblonga* (Fig. 7J) was recorded in sample POS-102 (Fig. 4).

The 28-m-thick *Pośrednie II* section (Fig. 5) comprises the lower part of the Osnica Formation (Lower–Middle Berriasian), ranging from the *Calpionella alpina* Subzone up to the *Remaniella cadischiana* Subzone. The Jurassic/Cretaceous boundary is not accessible in this section. The species *Calpionella elliptica* (Fig. 7G) occurs from sample P-17 upward,
whereas the FO of *Remaniella cadischiana* was recorded in sample P-21 (Fig. 5).

The 38-m-thick Rówienka section is a continuous outcrop exposing limestones of the Osnica Formation (upper part) and marlstones and limestones of the Kościeliska Marl Formation (Fig. 6). The boundary between the Osnica and Kościeliska Marl formations lies at the base of the first, thicker marlstone bed (following Lefeld et al., 1985) in the upper part of the *Calpionellopsis simplex* Subzone, characterised by frequent occurrence of the index-taxon (Fig. 7I). The index-taxa for the younger subzones of the *Calpionellopsis* Standard Zone, e.g., *Praecalpionellites filipescui* (Fig. 7K) and *P. gr. murgeanui*, are rare in the studied thin-sections. The well-preserved specimens of *Lorenziella hungarica* (Fig. 7L), the index-taxon for the Subzone D3 (Fig. 2), are also scarce.

4.2. Rock magnetism

Measurements of magnetic parameters throughout the sections revealed distinct differences in the magnetic properties between lithologies. In the Jasenina Formation, strong variations in magnetic susceptibility were observed: between 50 and $150 \times 10^{-6}$ SI (Fig. 8). These are accompanied by high peaks of IRM$_{1T}$ intensity and high positive values of parameter S, especially above the *Chitinoïdella* Zone (Tithonian). The complex magnetic mineralogy of the Jasenina Formation is clearly visible in Fig. 9A, where two end-members might be distinguished: (1) samples with high negative values of parameter S and low values of IRM$_{1T}$ (<100 mA/m); and (2) samples with positive values of parameter S and very high values of IRM$_{1T}$ (several hundred mA/m). Group 1 samples revealed the predominance of a low-coercivity mineral with unblocking temperatures of $500-550^\circ$C (Fig. 9B), which is interpreted as magnetite. Group 2 samples contain a variable admixture of a high-coercivity mineral (Fig. 9C). Its maximum unblocking temperatures of >600 $^\circ$C are characteristic for hematite. Group 2 samples also occur sporadically in the lower part of the Osnica Formation (Figs. 8, 10A, B). However, the bulk of the Osnica Formation reveals monotonous magnetic mineralogy with magnetite (Figs. 8, 10C). It also yields systematically lower susceptibilities than the Jasenina Formation, usually no more than $50 \times 10^{-6}$ SI (see Fig. 8). Within the uppermost part of the Osnica Formation, a stepwise increase of magnetic susceptibility was observed, which continues into the Kościeliska Formation (Fig. 11). The mean susceptibility increases up to $120-160 \times 10^{-6}$ SI within the middle part of the *Praecalpionellites filipescui* Subzone (Late Berriasian),
with the same magnetite-related magnetic mineralogy. Susceptibility shifts conform to an increasing admixture of clay in the carbonate rocks. In the uppermost sampled beds (above 28 m in the Rówienka section), again a change in petromagnetic properties is observed, manifested by a greater amount of a harder magnetic fraction (Fig. 11) and still higher susceptibilities. This correlates with a distinct lithological change, wherein micritic and marly limestones are replaced by marls and shales (see Fig. 6).

4.3. Demagnetisation and characteristic components

Most samples were thermally demagnetised, which is now a routine technique applied in palaeomagnetic studies of the Maiolica facies (Channell and Grandesso, 1987; Houša et al., 1999; Channell et al., 2000). AF demagnetisation was not efficient; in particular, it did not lead to isolation of reversed components. Most NRM intensities varied between 1 and 5 $\times 10^{-4}$ A/m, and maximum values never exceeded 10 $\times 10^{-3}$ A/m. Two groups of samples were distinguished during thermal demagnetisation. In the first group, a normal polarity component, S, was observed, which was stable up to 350–400 °C (Figs. 12A, C, 13A, B). Then, a reversed polarity component, R, appeared. However, the samples could not be fully demagnetised because, between 475 and 525 °C, they became unstable due to mineralogical changes, and magnetic susceptibility increased during thermal treatment. In this temperature range, component R was still contaminated by component S. Component S was present in all sections and might be calculated using the fitted line method (Kirschvink, 1980). It revealed a pre-folding geometry in each locality (Table 1). A tilt test between localities was not fully positive: the vectors cluster better before tectonic correction. This apparent contradiction...
might be explained by assuming that component S is, in fact, synfolding; it was acquired during or after Late Cretaceous thrusting but before the Neogene uplift of the Tatra lithospheric block. During acquisition of component S, the strata were parallel within a single locality but the tectonic position of beds was already diversified between localities. However, component S is poorly represented in the Kryta and Rówieńka sections and its apparent synfolding nature
Fig. 8. Rock magnetic parameters in the Pośrednie III section. K, magnetic susceptibility; IRM$_{1T}$, isothermal remanent magnetisation, acquired in the field of 1T; S, ratio of low- to high-coercivity minerals.

Fig. 9. Rock magnetic properties of the Jasenina Formation, Pośrednie III section. A, crossplot of S ratio and IRM$_{1T}$. B, C, IRM experiments for samples POS-2 (0.31 m) and POS-37 (12.26 m): 1, stepwise acquisition of the IRM; 2, thermal demagnetisation of the three axes IRM, acquired in the fields of 0.2 T, 0.5 T and 1.7 T.
might also be an artefact. It should be noted that a component similar to S is also ubiquitous in the Upper Triassic—Upper Jurassic limestones directly underlying our Tithonian—Berriasian strata, and has been interpreted as Late Cretaceous/pre-Eocene remagnetisation (Grabowski and Nemčok, 1999; Grabowski, 2000). Component R is most probably a primary, reversed magnetisation. Because samples of this group were not demagnetised to the origin, the direction of component R was calculated using a combination of the stable end-point and remagnetisation circle methods of McFadden and McElhinny (1988). After tectonic correction, it is situated in the south-west quarter of the stereonet, roughly antipodal to component S but with shallower inclination (Table 2). Component R clusters better after tectonic correction (Table 2). The second group of samples revealed mostly univectorial decay of a normal polarity component, N, up to 500 °C (Figs. 12B, 13C, 14), sometimes accompanied by a small, low-stability component demagnetised at 150–300 °C. Component N might always be calculated using the fitted line method (Kirschvink, 1980), and is interpreted as pre-folding because: (1) its very steep inclination in present-day coordinates (Table 2) cannot be accepted; and (2) clustering of component N between the four studied sections improves after tectonic correction.

We assume that component N indicates the presence of primary magnetisation of normal polarity. However, it is very likely that it represents a composite vector, being a sum of normal primary magnetisation and a normal overprint, S, which is most probably present also in this group of samples. The overprint, S, is close to the normal polarity primary component, and that is why demagnetisation of “normal” samples is apparently univectorial. The entire dataset of normal and reversed directions (N + R; see Table 2) clusters better after tectonic correction, which is further evidence for the primary nature of the N + R directions.
4.4. Magnetostratigraphy

Although partially remagnetised, the sections yielded a reliable and consistent record of normal and reversed magnetozones. Normal magnetisation prevails within the Kryta section (Jasenina Formation), comprising the bulk of the *Chitinoidella boneti* Subzone (late Early and earliest Late Tithonian; see Fig. 2), except its lowermost part (Fig. 15).

The Pośrednie III section embraces the Jasenina and Osnica formations and the lowermost part of the Kościeliska Formation (Fig. 16). The primary magnetisation within the Jasenina Formation is mostly normal, with reversed intervals between 0 and 2 m (at the bottom of the *Chitinoidella Zone*, Tithonian in age), 7 and 8 m, 8.5 and 9.5 m (both within the *Crassicollaria intermedia* Subzone of Late Tithonian age).

The base of the Osnica Formation lies at the top of a normal interval, which ends at 15 m (lower part of the *Calpionella alpina* Subzone, Early Berriasian in age). Further normal polarity intervals occur between 16 and 17.5 m, still in the lower part of the *Calpionella alpina* Subzone, in the middle part of the *C. alpina* Subzone between 20.5 and 24 m, and between 36 and 42 m within the upper part of the *Remaniella cadischiana* Subzone (mid-Berriasian). The uppermost normal magnetozone within the section covers the Kościeliska Marl Formation, high into the *Calpionellopsis oblonga* Subzone (sensu Remane et al., 1986). The bottom of the section, containing the boundary between the *Remaniella cadischiana* (mid-Berriasian) and *Calpionellopsis simplex* (early Late Berriasian) subzones, is reversely magnetised.

In the Rówienka section, almost exclusively normal magnetisation was revealed (Fig. 18), starting in the uppermost part of the Osnica Formation, in the lowermost *Calpionellopsis simplex* Subzone (at 2.5 m; earliest Late Berriasian), and continuing throughout the Kościeliska Marl Formation, high into the *Calpionellopsis oblonga* Subzone. The bottom of the section, containing the boundary between the *Remaniella cadischiana* (mid-Berriasian) and *Calpionellopsis simplex* (early Late Berriasian) subzones, is reversely magnetised.

Table 1

Secondary component, S, in the studied sections. D/I, declination/inclination before tectonic correction; $a_{95}$, Fisher statistics parameters; $D/L$, declination/inclination after tectonic correction; $n$, number of specimens; $N$, number of localities.

<table>
<thead>
<tr>
<th>Section</th>
<th>D/I</th>
<th>$a_{95}$</th>
<th>k</th>
<th>$D/L$</th>
<th>$a_{95}$</th>
<th>k</th>
<th>n</th>
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<tbody>
<tr>
<td>Posrednie III</td>
<td>186/72</td>
<td>8.3</td>
<td>19.5</td>
<td>46/66</td>
<td>6.3</td>
<td>33.1</td>
<td>17</td>
</tr>
<tr>
<td>Posrednie II</td>
<td>162/83</td>
<td>6.9</td>
<td>23</td>
<td>31/58</td>
<td>6.7</td>
<td>24.4</td>
<td>20</td>
</tr>
<tr>
<td>Kryta</td>
<td>230/66</td>
<td>—</td>
<td>—</td>
<td>76/73</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>Rówienka</td>
<td>201/77</td>
<td>37.9</td>
<td>11.2</td>
<td>26/51</td>
<td>31.6</td>
<td>15.9</td>
<td>3</td>
</tr>
</tbody>
</table>

$S_{mean}$: D/I = 203/76, $a_{95} = 11.5$, k = 64.6, N = 4, $D/L_k = 39/63$, $a_{95} = 15.1$, k = 37.5.

Fig. 11. Rock magnetic parameters in the Rówienka section. K, magnetic susceptibility; IRM$_{1T}$, isothermal remanent magnetisation, acquired in the field of 1T; S, ratio of low- to high-coercivity minerals.
5. Correlation of the sections

Correlation between the praecalpionellid and calpionellid biostratigraphy and the magnetostratigraphy was carried out, using schemes and databases provided by Channell et al. (1987), Channell and Grandesso (1987) and Ogg et al. (1991). This is briefly summarised in Fig. 19.

Additionally, the data of Houša et al. (1999) were consulted, especially for correlations around the Jurassic/Cretaceous boundary. The detailed correlation is presented in Fig. 20.

The lowest reversed magnetozone, at the base of the Kryta and Pośrednie III sections, is identified as M20r. It contains the base of the Chitinoidella Zone and the preceding Saccocoma.
Zone. The (documented) FO of chitinoidellids in our sections is higher than the first appearance datum (FAD) of these praecalpionellids in the Italian sections, where the base of the Chitinoidella Zone falls within Magnetozone M21n (Ogg et al., 1991; see also Fig. 19). However, the first chitinoidellids in the Brodno section were found in the upper part of M20r (Housá et al., 1999), similarly to their level in the Po/C19srednie III section.

Magnetozone M20n contains a reversed magnetozone, M20n-1r (= the Kysuca Magnetosubzone of Houša et al., 1999, 2004). The Kysuca Magnetosubzone corresponds, in our opinion, to a reversed polarity interval at 7–8 m in the Po/C19srednie section, within the lower part of Calpionellid Zone A. This position of the Kysuca Magnetosubzone is approximately concordant with Ogg et al. (1991), and occupies a similar position in the Brodno section (Houša et al., 1999). Normally magnetised beds at 2–7 m and 8–8.5 m in the Po/C19srednie III section represent the pre- and post-Kysuca parts of M20n. The pre-Kysuca part of M20n contains a large part of the Chitinoidella Zone, as well as the boundaries between the Chitinoidella and Praetintinopsella zones and the Praetintinopsella and Crassicollaria zones. The base of Calpionellid Zone A also occurs within this magnetozone in Tethyan sections (see Fig. 19).

The normal magnetozone in the Kryta section (Chitinoidella Zone) must also correspond to the pre-Kysuca part of M20n. The next normal magnetozone, M19n, also has a complex structure. Within its upper part, a short reversed magnetozone, M19n-1r, occurs (= the Brodno Magnetosubzone of Houša et al., 1999, 2004). The Brodno Magnetosubzone in the Tethyan sections falls into the lower part of Calpionellid Zone B (Ogg and Lowrie, 1986; Houša et al., 1999). Here, we interpret a reversed polarity interval between 14.5 and 16 m in the Po/C19srednie section (in the lowermost part of Calpionellid Zone B) as the Brodno Magnetosubzone. Magnetozone M19n would thus embrace the intervals 9.5–14.5 m (pre-Brodno) and 16–18 m (post-Brodno). The boundary between Calpionellid zones A and B (i.e., the Jurassic/Cretaceous boundary) is situated in the pre-Brodno part of M19n, at a similar level to that in the Brodno section. It should be noted that such positioning of the A/B zonal boundary is seen in most other Tethyan sections (Ogg and Lowrie, 1986; Ogg et al., 1991) but it occasionally occurs higher (e.g., at Xausa, close to the CM19n/CM18r boundary; see Channell and Grandesso, 1987). A thin reversed magnetozone, occurring between 8.5 and 9.5 m in the Po/C19srednie II, is interpreted as M19r. This magnetozone is situated entirely within Calpionellid Zone A (Ogg et al., 1991; Houša et al., 1999; see also Fig. 19).

Normal Magnetozone M18n was identified between 4.5 and 6.5 m in the Po/C19srednie II section, and 20.5 and 24 m in the Po/C19srednie III section. According to Channell and Grandesso (1987) and Ogg et al. (1991), it is the only normal magnetozone situated in Zone B (Fig. 19). Reversed Magnetozone M18r is the lowermost in the Po/C19srednie II section (at 0–4.5 m). In the Po/C19srednie III section, this magnetozone starts between 17 and 19 m, still in the lower part of Zone B.

The normal magnetozone in the Po/C19srednie II section, between 21 and 24 m, and Po/C19srednie III section between 36 and 42 m, is interpreted as M17n. This is supported by the magnetostratigraphy of the Tethyan sections (Ogg et al., 1991; Opdyke and Channell, 1996), where M17n is the only normal magnetozone situated within Zone C (Fig. 19). The underlying reversed magnetozone (6.5–21 m in Po/C19srednie II and 24–36 m in Po/C19srednie III) is unambiguously defined as M17r; this magnetozone lies around the
B/C calpionellid zonal boundary and contains the FO of *Calpionella elliptica* in our sections and in the Italian reference sections (Figs. 19, 20).

The reversed magnetozone at the base of the Rówieńka section, positioned around the boundary between Calpionellid zones C and D, is interpreted as M16r. The position of the C/D zonal boundary in M16r is supported in numerous Tethyan sections (Ogg et al., 1991; see also Fig. 19). A thin reversed interval, at 42.5–44.5 m in the Pośrednie III section, is interpreted as the upper part of CM16r (within the *Calpionellopsis simplex* Subzone). The uppermost reversed magnetozone in the Pośrednie II section (between 24.5 and 28 m), falling in the upper part of the *Remaniella cadischiana* Subzone (= upper part of Calpionellid Zone C; see Fig. 2), is correlated with the lower part of M16r. In comparison with the Rówieńka and Pośrednie II sections, the reduced thicknesses

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$R_{\text{mean}}$: D/I = 163/−86, $a_{95}$ = 13.5, $k$ = 32.8, $N$ = 5. D/Ic = 202/-48, $a_{95}$ = 9.6, $k$ = 64.6.

$N_{\text{mean}}$: D/I = 226/85, $a_{95}$ = 16.2, $k$ = 27.5, $N$ = 5. D/Ic = 24/56, $a_{95}$ = 7.1, $k$ = 116.1.

$(N + R)_{\text{mean}}$: D/I = 254/87, $a_{95}$ = 14.8, $k$ = 27.5, $N$ = 5. D/Ic = 22/53, $a_{95}$ = 8.0, $k$ = 92.3.

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**Table 2**

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 Declination

Inclination

Polarity

**Fig. 15.** Magneto- and biostratigraphy of the Kryta section. Black, normal polarity; white, reversed polarity. For other explanations, see Fig. 3.
of M16r and the *C. simplex* Subzone in the Pośrednie III section implies the likely presence of a thrust fault, between 42 and 42.5 m.

The youngest magnetozone in our sections is a long normal magnetozone in the Rówienka section, falling into the *Calpionellopsis* Standard Zone (Zone D). As the FO of *Calpionellopsis oblonga* occurs in this magnetozone (between 10 and 15 m; see Figs. 6, 20), it is identified as Magnetozone M16n. The FAD of *C. oblonga* in the Italian sections (Ogg et al., 1991) falls exclusively within this magnetozone (Fig. 19). The specimens of *C. oblonga* appear in the uppermost normal magnetozone (at 45.5 m) of the Pośrednie III section, so this magnetozone must also be interpreted as M16n (see Figs. 4, 20). It should be noted that *Lorenziella*
hungarica appears in our sections soon after the FO of C. oblonga (see Figs. 4, 6, 20), within Magnetozone M16n. This is significantly earlier than in the Italian and French sections, where its earliest appearance is noted at the bottom of Magnetozone M15r (Ogg et al., 1991; see also Fig. 19). In contrast, in the Subbetic Zone (south-east Spain), Aguado et al. (2000) noted the presence of L. gr. hungarica in the upper interval of Magnetozone M16n. This observation seems to confirm the opinion of Remane et al. (1986), that the actual stratigraphic distribution of L. hungarica is poorly known. According to Aguado et al. (2000), scarcity and identification difficulties of this calpionellid taxon have led some authors to reject its FO as a valid biostratigraphical datum.

6. Sedimentation rate

Identification of the magnetozones enables a rough estimation of sedimentation rates to be made for the studied sections. These calculations should not be treated as absolute because there are many uncertainties, producing significant errors. Among them, the most important are: (1) the sections contain several gaps, probably of tectonic origin, therefore the calculated sedimentation rates are mostly minimum values; (2) the numerical ages of the Jurassic/Cretaceous boundary are variable according to different authors. At present, two timescales are available, which differ in placing the boundary at levels 2.6 my apart (Gradstein et al., 1994; Channell et al., 1995); and (3) dating of the magnetozones is dependent on assumptions of spreading rates (see Opdyke and Channell, 1996).

To calculate the sedimentation rate within a specific magnetozone, the section containing the magnetozone with maximum thickness has been chosen. Sedimentation rates were estimated using the time-scales of Gradstein et al. (1994) and Channell et al. (1995). The results are presented in Table 3 and Fig. 21.
The overall sedimentation rate in our sections is much higher than in Brodno, where its mean value amounts to 2.27 m/my (Housˇa et al., 1999). Although most of our data represent minimum values, it seems that the sedimentation rate generally increases upwards. Relatively low values (3–7 m/my) are recorded in Magnetozones M20n–M19n, representing the Jasenina Formation. Variable, but mostly higher, values are observed within Magnetozones M18r–M16r: 8–18 m/my (with the exception of M18n), which embrace the Osnica Formation. The highest values (probably >20 m/my) occur within long Magnetozone M16n, in the lower part of the Kościeliska Marl Formation. These rates are quite similar to those suggested by Vasˇi´cek et al. (1994), on the basis of biostratigraphical and sedimentological data. They gave values of 6.6–7 m/my for the Jasenina Formation, 5.5–7.5 m/my for the Osnica Formation, and 15–30 m/my for the Koscieliska Marl Formation. Our data indicate a bigger contrast between the Jasenina and Osnica formations. In light of this, estimations given by Michalik et al. (1995) (>16 m/my for the Jasenina and <3 m/my for the Mráznicza formations, the latter a more calcareous counterpart of the Kościeliska Marl Formation) seem less realistic. Low sedimentation rates for the Jasenina Formation gain support from our rock magnetic data. The abundance of hematite in carbonate sediments is often interpreted as an indicator of a low sedimentation rate (e.g., Channell et al., 1982, 2000). Slow accumulation of sediments establishes more oxidising conditions at the sediment/water interface, and primary hematite originates from goethite or clay minerals. Hematite was also noted in Magnetozone M18n (lower part of the Osnica Formation) in the Pośrednie II section, which correlates with a low sedimentation rate within this magnetozone.

An increasing sedimentation rate in Magnetozones M17r and M17n (middle part of the Osnica Formation) correlates with a change in magnetic mineralogy, where magnetite becomes the only magnetic mineral. As the sediment becomes more carbonaceous, it might be suggested that increased carbonate productivity is here a primary cause of faster sedimentation. This process corresponds to phenomena already described in the Tethyan sections, where red Ammonitico Rosso-type sediments are replaced by the grey Maiolica facies, which also results from higher sedimentation rates (Ogg et al., 1991). Apparently, the low sedimentation rate in Magnetozone M16r (Fig. 20) must be treated as an artefact, since in all sections investigated only parts of this magnetozone occur. An even higher sedimentation rate in Magnetozone M16n (at the boundary of the Osnica and Kościeliska formations)
is accompanied by a stepwise increase of magnetic susceptibility and IRM1T values, but without any change in magnetic mineralogy (Fig. 11). An increased frequency of marly layers is observed; thus an influx of detrital clay minerals and magnetite is most probably responsible for this change. The change from carbonate to marly sedimentation in the Upper Berriasian seems to be a regional phenomenon, not only in the Tatra Mountains (Pszczółkowski, 1996) but also in the other Fatric sections (Vasiček et al., 1994). Its cause is not well understood; we believe that this change might be related to the oncoming collision at the southern edge of the central Carpathian area (Vasiček et al., 1994; Plasienka, 1997, 2003). However, a high-latitude cooling is postulated for the Late Berriasian (Price and Mutterlose, 2004; Weissert and Erba, 2004, fig. 2), and a major cold, or significantly cool, period occurred at the Berriasian/Valanginian boundary (Pucéat et al., 2003). Therefore, climate change, combined with a sea-level fall (Haq et al., 1987), also could have had some bearing on triggering marly deposition during the Late Berriasian.

Acknowledgements

We are grateful to Ing. T. Szytryk for invaluable help in the field. The investigations were supported by the Polish Committee for Scientific Research (Grant 6 P04D 071 18). Thanks are also due to authorities of the Tatra National Park for permission to carry on the investigations in protected areas. Critical reviews of the manuscript by Jozef Michalik and Jim Ogg are gratefully acknowledged.

References


Appendix

Microfossils identified (this study)

- *Almajella cristobalensis* (Furrazola-Bermúdez, 1965)
- *Borziella atava* Grün and Blau, 1996
- *Cadonina fusca* Wanner, 1940
- *Calpionella alpina* Lorenz, 1902
- *Calpionella elliptica* Cadisch, 1932
- *Calpionella* sp. (genus *Calpionella* Lorenz, 1902)
- *Calpionellopsis oblonga* (Cadisch, 1932)
- *Calpionellopsis simplex* (Colom, 1939)
- *Calpionellopsis* sp. (genus *Calpionellopsis* Colom, 1948)
- *Chitinoidella boneti* Doben, 1963
- *Colomisphaera carpathica* (Borza, 1964)
- *Committosphaera pulla* (Borza, 1964)
- *Crassicollaria brevis* Remane, 1962
- *Crassicollaria intermedia* (Durand-Delga, 1957)
- *Crassicollaria massatiana* (Colom, 1948)
- *Crassicollaria parvula* Remane, 1962
- *Crassicollaria* sp. (genus *Crassicollaria* Remane, 1962)
- *Longicollaria dobeni* (Borza, 1966)
- *Lorenziella dacica* (Filipescu and Dragastan, 1970)
- *Lorenziella hungarica* Knauer and Nagy, 1963
- *Lorenziella plicata* Remane, 1968
- *Lorenziella* sp. (genus *Lorenziella* Knauer and Nagy, 1963)
- *Praecalpionellites filipescu* (Pop, 1994)
- *Praecalpionellites gr. murgeanui* (Pop, 1974)
- *Praecalpionellites* sp. (genus *Praecalpionellites* Pop, 1986)
- *Praetintinnopsella andrusovi* Borza, 1969
- *Praetintinnopsella* sp. (genus *Praetintinnopsella* Borza, 1969)
- *Remaniella cadischiana* (Colom, 1948)
- *Remaniella catalanoi* Pop, 1996
- *Remaniella colomi* Pop, 1996
- *Remaniella duranddelga* Pop, 1996
- *Remaniella* sp. (genus *Remaniella* Catalano, 1965)
- *Saccocoma* sp. (genus *Saccocoma* Agassiz, 1836)
- *Stomiosphaera moluccana* Wanner, 1940
- *Sturiella oblonga* Borza, 1981
- *Tintinnopsella carpatica* (Murageau and Filipescu, 1933)
- *Tintinnopsella longa* (Colom, 1939)
- *Tintinnopsella subacuta* (Colom, 1948)