Geological Quarterly, 2017, **61** (4): 946–961
DOI: http://dx.doi.org/10.7306/gq.1381

Keuper magnetostratigraphy in the southern Mesozoic margin of the Holy Cross Mts. (southeastern edge of the German Basin)

Krystian WÓJCIK[1, *], Dorota KOŁBUK[2], Katarzyna SOBIEŃ[1], Olga ROSOWIECKA[1], Joanna ROSZKOWSKA-REMIN[1], Jerzy NAWROCKI[1] and Andrzej SZYMKOWIAK[1]

[1] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland

[2] University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland

Wójcik, K., Kołbuk, D., Sobień, K., Rosowiecka, O., Roszkowska-Remin, J., Nawrocki, J., Szymkowiak, A., 2017. Keuper magnetostratigraphy in the southern Mesozoic margin of the Holy Cross Mts. (southeastern edge of the German Basin). Geological Quarterly, **61** (4): 946–961, doi: 10.7306/gq.1381

Magnetostratigraphy of the Keuper succession in the southern Mesozoic margin of the Holy Cross Mountains is presented based on investigations of two sections of Brzeziny and Wolica. They cut an ~60 m thick succession of variegated siltstones and claystones, which overlies the Reed Sandstone (Stuttgart Formation). The succession has been correlated with the Patoka Member of the Grabowa Formation, defined in the Upper Silesia region as an equivalent of the Steinmergelkeuper (Arnstadt Formation). The primary Late Triassic magnetization was obtained from component B carried by fine-grained haematite. Twelve magnetic polarity zones, six of normal and six of reversed polarity, have been defined. The obtained polarity pattern corresponds to the Norian (E13–E16 Newark zones) according to the Long-Rhaetian option of the Late Triassic Magnetic Polarity Time Scale. The mean normal polarity characteristic direction (N = 24, D/I = 31/62, k = 28.24, $\alpha95$ = 6.04) differs significantly from the reversed one (N = 18, D/I = 223/-25, k = 16.38, $\alpha95$ = 8.65): the primary magnetic signal is partly overlapped by component A carried by magnetite of recent viscous remanent magnetization. Some samples do contain also coarse-grained haematite that, however, does not form any clustered magnetization. The palaeopole position calculated from the transposed reversed and normal polarity directions of component B corresponds to the Late Triassic (Norian) segment of the reference Baltica/Europe Apparent Polar Wander Path.

Key words: Triassic, Keuper, German Basin, Holy Cross Mountains, magnetostratigraphy, rock magnetism.

INTRODUCTION

The Keuper succession in the German Basin (Fig. 1) is divided into several lithostratigraphic units: the Lettenkeuper (Erfurt Formation), Lower Gipskeuper (Grabfeld Formation), Schlifsandstein (Stuttgart Formation), Upper Gipskeuper (Weser Formation), Steinmergelkeuper (Arnstadt Formation) and Rhätkeuper (Exter Formation) (Stratigraphische Tabelle von Deutschland 2012; Fig. 2). The eustatic and climate control on sedimentation enables the correlation of the continental and shallow-marine Germanic successions with the marine Alpine record in terms of sequence stratigraphy (Szulc, 2000). As a result, the general chronostratigraphic position of the German lithostratigraphic units was established (Szulc, 2000, 2007; Bachmann and Kozur, 2004; Feist-Burkhardt et al., 2008; Stratigraphische Tabelle von Deutschland 2012; Fig. 2). The units are separated by different-ranging stratigraphic gaps. Its range, stratigraphic position or even presence is still under discussion (see summary in Szulc et al., 2015a: p. 581, 582). On the one hand, the duration of the Late Triassic depositional activity calculated in the German successions sum up only to several My in relation to ~35.5 My of the Late Triassic timespan, and the presence of discontinuities are assumed to occur in these successions (Nitsch et al., 2005). On the contrary, Szulc et al. (2015a: p. 582) concluded that "Instead of spectacular depositional breaks, lasting for millions of years,… the cumulative temporal effect of numerous, superimposed minor and irregular erosion and starvation episodes is proposed as the main cause of the total time gap evident in the… Keuper succession".

In the Polish part of the German Basin, the Keuper succession is divided into the Border Dolomite, Lower Gypsum Beds, Reed Sandstone, Upper Gypsum Beds, Jarkowo Beds, Zbąszynek Beds and Wielichowo Beds (Szulc, 2007; Fig. 2). This succession includes the "humid" interval, in which the Reed Sandstone fluvial clastics were deposited, and the arid Lower Gypsum Beds and Upper Gypsum Beds (Szulc, 2007). A gradual decline of evaporites and dominance of the ephemeral and perennial fluvial sediments occur higher in the succession, in the Jarkowo and Zbąszynek beds. These seem to be the result of gradual pluvialization (Szulc, 2007), which favoured the development of vascular plants, and, as a consequence, appearance of the first dinosaurs (Dzik et al., 2000). Detailed chronostratigraphic research of the Polish Keuper was provided by Orłowska-Zwolińska (1983, 1985), Marcinkiewicz et al. (2014) and Fijałkowska-Mader (2015) on the basis of palyno-

* Corresponding author, e-mail: krystian.wojcik@pgi.gov.pl
Received: April 12, 2017; accepted August 30, 2017; first published online: September 18, 2017

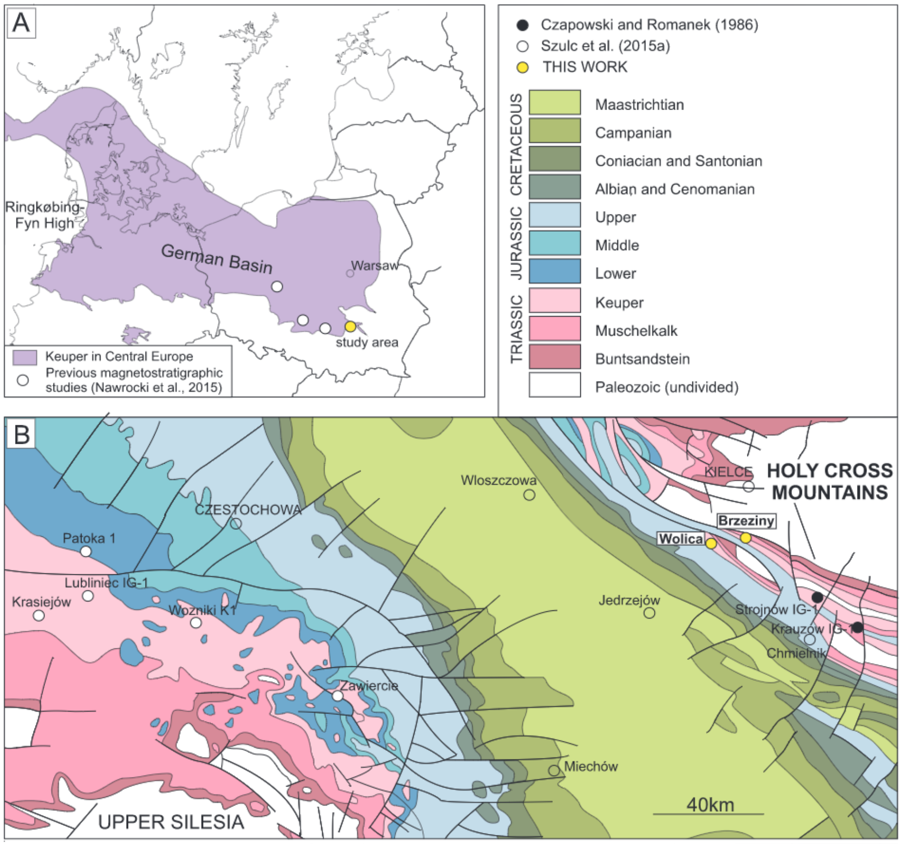

Fig. 1A – distribution of the Keuper sediments (Upper Gypsum Beds) in Central Europe (after Szulc, 2008) with location of the study area and sections previously investigated for magnetostratigraphy (Nawrocki et al., 2015); B – distribution of the Keuper sediments in the southern Mesozoic margin of the Holy Cross Mountains and in the Upper Silesia region with location of the studied sections in comparison to the previous investigations of Czapowski and Romanek (1986), Szulc et al. (2015a) and Nawrocki et al. (2015); geological map after Dadlez et al. (2000)

stratigraphy. According to these data, the Lower Gypsum Beds and Reed Sandstone belong to the Upper Longobardian–Cordevolian *longdonensis* (assemblage) Zone and Julian *astigmosus* (assemblage) Zone, respectively, while the upper part of the Upper Gypsum Beds belongs to the Tuvalian *meyeriana a* (interval) Subzone, upper part of the Jarkowo Beds belongs to the Alaunian–Sevatian *meyeriana b* (assemblage) Subzone, and the Zbąszynek Beds belong to the Upper Norian–Lower Rhaetian interval from the *meyeriana b* Subzone to the *meyeriana c* (assemblage) Subzone (Fig. 2). Nawrocki et al. (2015) used magnetostratigraphy as a tool for the composition of the magnetic polarity time scale for the Polish Keuper succession, which was correlated with the standard Composite Late Triassic Magnetic Polarity Time Scale (Kent and Olsen, 1999; Hounslow and Muttoni, 2010; Hüsing et al., 2011; Ogg, 2012). This was the only published work dedicated to Keuper magnetostratigraphy in Poland, so far.

Due to lack of the age-diagnostic fossils and scarcity of the magnetostratigraphic data, lithostratigraphy remains the principal method for the Keuper stratigraphic correlation in the German Basin. The Keuper lithostratigraphic subdivision is broadly uniform throughout the basin only in the lower part of the succession. The Lower Keuper, Lower and Upper Gypsum beds and Reed Sandstone of Poland correspond well to their German equivalents in terms of lithostratigraphy (Fig. 2). In contrast, the upper part of the succession is difficult for even local correlation. This is an effect of climate changes and tectonic movements that resulted in strong lateral lithological variety (Szulc, 2007; Szulc and Racki, 2015 and discussion therein). This is especially well-visible along the SE margin of the German Basin, in which the standard German Keuper units cannot be clearly distinguished. Such a problem occurs in the Upper Silesia sections, in which the Grabowa Formation (divided into the Ozimek, Patoka and Woźniki members) was defined instead of the Upper Gypsum, Jarkowo and Zbąszynek beds (Bilan, 1976; Gajewska et al., 1997; Deczkowski et al., 1997; Szulc and Racki, 2015; Szulc et al., 2015a). Similar difficulties occur also in the southern Mesozoic margin of the Holy Cross

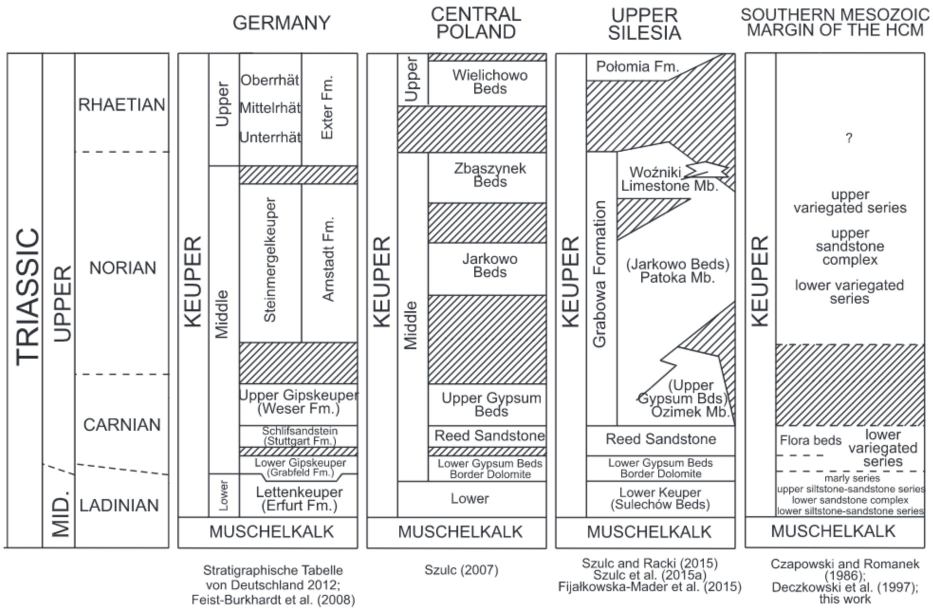

Fig. 2. Keuper lithostratigraphy in the Central and SE parts of the German Basin

Mountains (HCM). Palynostratigraphic investigations conducted in the nearby area in the Krauzów and Strojnów boreholes (Czapowski and Romanek, 1986) and in the Nida Basin (Fijałkowska-Mader, 2013; Fijałkowska-Mader et al., 2015) brought no information about the age of the units younger than the Reed Sandstone. For these reasons we used the magnetostratigraphy as an opportunity for effective stratigraphic correlation in the SE part of the German Basin.

Due to lack of natural outcrops, the Keuper succession in the southern Mesozoic margin of the HCM (SE margin of the German Basin; Fig. 1) is still poorly recognized in terms of lithology and stratigraphy. Moreover, poor biostratigraphic documentation, stratigraphic gaps, and informal lithostratigraphical subdivision, do not favour the HCM sections as promising ones for worldwide magnetostratigraphic correlation. However, the succession contains red beds usually providing a reliable primary palaeomagnetic signal, which enables at least the correlation with the Silesian successions described in details by Szulc and Racki (2015), Szulc et al. (2015a, b) and dated magnetostratigraphically by Nawrocki et al. (2015). This correlation is especially important since vertebrate remains were discovered in the Opole region (Dzik et al., 2000; see also Dzik and Sulej, 2007) and several other bone-bearing sections were also found in Upper Silesia (Dzik et al., 2008; Niedźwiedzki et al., 2014).

GEOLOGICAL SETTING

The area of the present southern Mesozoic margin of the HCM constituted the SE margin of the Keuper German Basin (Fig. 1). However, the succession remained poorly recognized and only known fragmentarily from a few outcrops (Senkowiczowa, 1957; Pawłowska, 1962; Filonowicz, 1968) until Czapowski and Romanek (1986) described the Keuper deposits in the Krauzów IG-1 and Strojnów IG-1 boreholes near Chmielnik (Figs. 1 and 2). Due to different lithological characteristics and merely general palynostratigraphy, the correlation of these sections with the standard Keuper lithostratigraphic units still is difficult.

The Keuper succession in the Krauzów IG-1 and Strojnów IG-1 boreholes reaches 377 m in thickness, and was divided into seven informal lithological units (Fig. 2): lower siltstone-sandstone series (26 m thick), lower sandstone complex (28 m), upper siltstone-sandstone series (27 m), marly series (36 m), lower variegated series (173 m) with the Flora beds (44 m) in the middle part, upper sandstone complex (28 m), and upper variegated series (57 m). The first three units correspond lithologically to the Lower Keuper in central Poland and to the lower part of the Lettenkeuper (Erfurt Fm.) in Germany, while the overlying marly series can be correlated with the Border Dolomite (Pawłowska, 1979; Czapowski and Romanek, 1986; Fig. 2). The age of the Flora beds is also well-constrained. The palynostratigraphic data indicated this plant-rich interval as the equivalent of the Reed Sandstone. The upper part of the succession, which overlies the Flora beds, belongs to the interval from the Upper Gypsum Beds to the Wielichowo Beds. Gajewska et al. (1997) suggested that this part of the Keuper resembles the Grabowa Formation in the Upper Silesian region. The succession described by Czapowski and Romanek (1986) was traced in the northern limb of the Ostrów Syncline and the southern limb of the Zbrza Anticline – in the Brzeziny and Wolica sections (Fig. 1; Appendix 1 and 2).

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1381

BRZEZINY SECTION

The Keuper deposits in the Brzeziny section were investigated in a 300 m long and 2–3 m deep cross-cut, in which an ~175 m thick succession have been recognized. Sixty metres of the upper part of the section was examined for magnetostratigraphy (Fig. 3). In this interval, the succession is divided into four lithological units that correspond well to the succession from the Krauzów IG-1 and Strojnów IG-1 boreholes described by Czapowski and Romanek (1986).

The **Flora beds**, at least 5 m thick, are composed of thinly laminated greyish and greenish siltstones and claystones intercalated with thin (up to 5 cm thick) layers of black claystones (Fig. 3). Plant detritus occurs in the whole unit, but is especially abundant in the black layers. Lamination is flat and continuous. The unit is a clear equivalent of the upper part of the Flora beds of Czapowski and Romanek (1986; Fig. 2). Adopting the palynostratigraphic data from the two boreholes, the Flora beds can be correlated with the Reed Sandstone (Schilfsandstein, Stuttgart Fm.; see Szulc, 2007 and Fijałkowska-Mader, 2015).

The **lower variegated series** (43 m thick) is composed of numerous sets of variegated (“mottled”), mostly red to brownish and greenish parallel-laminated siltstones and mudstones intercalated with layers of plane- and cross-bedded fine-grained yellow sandstones (Fig. 3). Numerous light grey to light green kaolinite-rich intercalations (up to 10 cm thick) occur in the middle part of the unit. Plant-root structures are also abundant. Plant remains are dispersed in the fine-grained clastics. Single coal-rich layers of sandstones with plant-detritus also occur.

Two 4.5 m thick horizons of brown nodular marls and marly siltstones occur in the lower variegated series. The nodules are from several mm up to 10 cm across and have micritic to fine-grained (vadoid wackestones and packstones) microstructure. In general, the larger nodules are concentrated in the bottom part of the unit, while the smaller-nodular texture predominates upper in the succession (Fig. 3). This is especially visible in the lower horizon. Both also contain some irregular greenish flasers. Similar deposits were described as the “Lisów breccias” in Upper Silesia (Maliszewska, 1972; Bilan, 1976; Szulc, 2007; Szulc and Racki, 2015; Szulc et al., 2015a). They are interpreted as horizons of reworked pedogenic nodules, frequently associated with a debris-flow fabric (Szulc et al., 2015a). Unfortunately, according to Szulc (2007) and Szulc et al. (2015a), the Lisów breccia horizons are diachronous within the Keuper succession and cannot be used as correlation markers.

The unit corresponds well to the upper part of the lower variegated series of Czapowski and Romanek (1986; Fig. 2). Gajewska et al. (1997) suggested its correlation with the Grabowa Formation in the sense of Bilan (1976).

The **upper sandstone complex** (9 m thick) is composed of yellow parallel- to cross-laminated fine-grained sandstones (Fig. 3). The sandstone beds are up to 0.5 m thick in the upper part of the unit; thinner sandstone beds, usually intercalated with violet and green siltstones, occur in the lower part. A 2 m thick package of variegated fine-grained clastics with abundant plant detritus also occurs there. The unit corresponds to the upper sandstone complex of Czapowski and Romanek (1986; Fig. 2) and the so-called upper “Rhaetian” *sensu* polonico (= lithostratigraphic unit of the Upper Norian) in Deczkowski et al. (1997).

The **upper variegated series** (6 m thick) is composed of variegated (red to violet) parallel-laminated siltstones intercalated with thin beds of fine-grained sandstones (Fig. 3). They are erosively overlain by the Middle Jurassic sandstones. The unit corresponds to the upper variegated series of Czapowski and Romanek (1986; Fig. 2) and the so-called upper “Rhaetian” *sensu* polonico in Deczkowski et al. (1997).

Gajewska et al. (1997) indicated that the Upper Gypsum Beds were not deposited in the investigated region. Following this interpretation, the succession recognized in the Brzeziny section above the Flora beds is an equivalent of the Upper Silesian Patoka Member of the Grabowa Formation (in its present sense defined by Szulc and Racki, 2015, and Szulc et al., 2015a; see Fig. 2). Such a correlation seems to be evident if to emphasize the lithological similarities between the HCM and Upper Silesia sections (cf. the Brzeziny section to the interval between 65 and 120 m in the Patoka 1 drill core; see Szulc et al., 2015a: fig. 11), and lack of evaporites and limestones indicating the absence of the Ozimek and Woźniki members. The Patoka Member corresponds to the Jarkowo and Zbąszynek beds in the Polish part of the German Basin (Gajewska et al., 1997; Deczkowski et al., 1997; Szulc et al., 2015a) and to the Arnstadt Formation (Steinmergelkeuper) in Germany (Fig. 2). Additionally, Fijałkowska-Mader et al. (2015) indicated that the Patoka Member belongs to the Middle Norian *meyeriana b* palynostratigraphic Subzone, which can be correlated with the upper part of the Norian *Granuloperculatipollis rudis* Zone (see Ogg, 2012; Lucas et al., 2012; Szulc et al., 2015a).

WOLICA SECTION

The Wolica section is located 6 km SW from the Brzeziny section (Fig. 1). The uppermost part of the Keuper succession is exposed in the quarry road-cut, in which variegated sandstones and siltstones are overlain by the Middle Jurassic succession. The Wolica section, including the Keuper sediments, was described in detail by Kozłowska et al. (2016). They assigned the whole Keuper succession to unit I, in which variegated, horizontally bedded mudstones are followed by thick layers of horizontally laminated sandstones in the middle part and red-brownish horizontally laminated mudstones at the top (Fig. 4). Characteristic green intercalations with plant-root structures also occur in the section.

The Keuper of the Wolica section can be clearly correlated with the uppermost part of the Brzeziny section (see Fig. 10). The thick layers of sandstones correspond well to the upper sandstones complex, while the overlying succession correlates with the upper variegated series.

MATERIAL AND METHODS

A total of 99 cylindrical drill core samples for palaeomagnetic studies were collected from the Brzeziny section (Fig. 3). Another 19 samples were collected from the Wolica section (Fig. 4). Two or three specimens were cut from each sample. The natural remanent magnetization (NRM) of the specimens was measured using a JR-6A dual-speed spinner magnetometer with a noise level of ~0.3×10^{-5} A/m. The samples were thermally demagnetized in the following steps: 100, 150, 200, 250, 300, 350, 400, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675, 700°C using an MMTD oven. After each thermal demagnetization step, the magnetic susceptibility (MS) was monitored on a *Kappabridge KLY-2*. Least-square line fit methods of Kirschvink (1980) were used to calculate the components of the characteristic remanence and their unblocking temperature spectra. Magnetic mineralogy in selected samples was determined from isothermal magnetic remanence (IRM) acquisition and three-axes IRM thermal demagnetization experiments (Lowrie, 1990; Fig. 5). The laboratory measurements were performed in the Palaeomagnetic Laboratory of the Polish Geological Institute – National Research Institute.

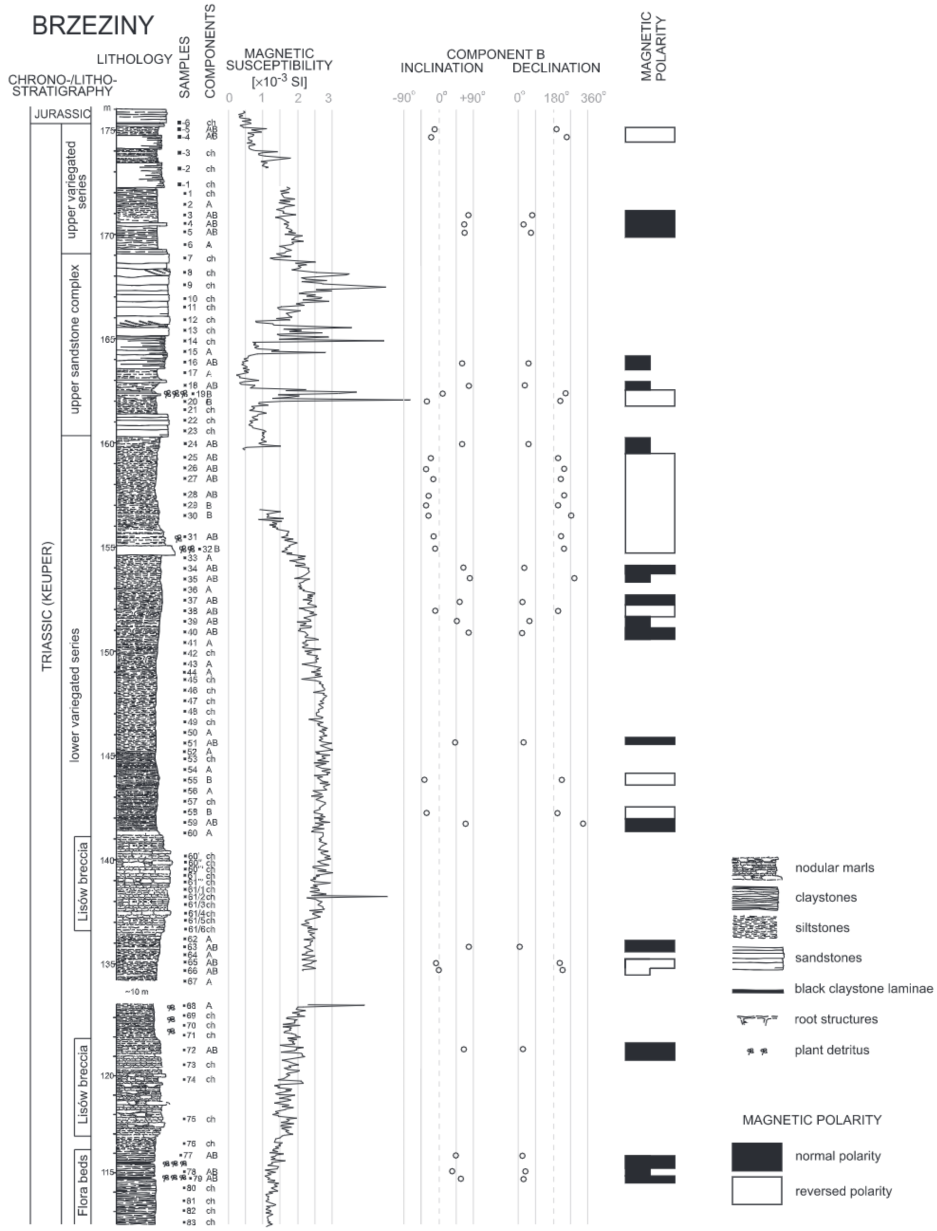

Fig. 3. Lithostratigraphy of the Keuper sediments in the Brzeziny section and the results of magnetic susceptibility measurements and palaeomagnetic investigations

Characteristic inclination and declination directions isolated from component B (fine-grained haematite); Half bar/full bar – magnetic polarity obtained from one/two specimen/s cut from the sample; ch – chaotic demagnetization with no components obtained

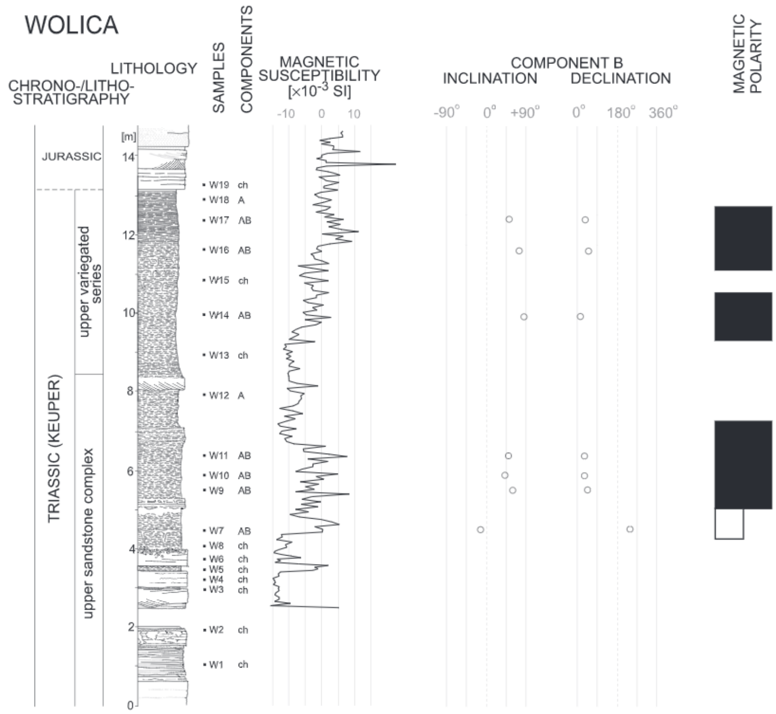

Fig. 4. Lithostratigraphy of the Keuper sediments in the Wolica section and the results of magnetic susceptibility measurements and palaeomagnetic investigations

For explanations see Figure 3

Besides the palaeomagnetic study in the laboratory, magnetic susceptibility (MS) was measured in the field with 5 cm vertical spacing using a *Bartington MS3* device. The MS curves were used for a general correlation of the Brzeziny and Wolica sections.

RESULTS

MAGNETIC CARRIERS

Three-axis IRM thermal demagnetization curves (Lowrie, 1990) indicate that there are at least three different magnetic minerals in the samples (Fig. 5). These minerals have unblocking temperatures of 500–550°C, ~600–650 and 700°C. They are related most probably to magnetite and fine- and coarse-grained haematite, respectively, since pigmentary haematite usually has lower unblocking temperatures than specular haematite (Dunlop and Özdemir, 1997: p. 456).

The IRM-acquisition curves indicate the dominance of the high-coercivity minerals (pigmentary and specular haematite) in the investigated samples: the saturation of the IRM was not achieved even in the applied field of 1.5 T (Fig. 5A–C). This is typical in samples dominated by haematite, like in the Triassic Buntsandstein deposits in the German Basin (Nawrocki, 1997; Szurlies, 2004, 2007). The examples illustrated in and C are similar with a slow increase of magnetization between 0 and 0.2 T, unachieved saturation, stable decrease of MS, and complete removal of IRM at ~600–650°C. These samples are probably dominated by pigmentary haematite. On the contrary, the example illustrated in Figure 5B characterizes a rapid increase of magnetization between 0 and 0.2 T, unachieved saturation, rapid decrease of MS between 450 and 500°C, increase of MS between 650 and 700°C, and complete removal of IRM at ~700°C. The increase of magnetization can be interpreted as a result of admixture of magnetite in the sample dominated by haematite, like in the Middle Triassic from the Iberian Ranges (Rey et al., 1996) and in the Buntsandstein deposits from the German Basin (Szurlies, 2004, 2007; see also experiments with mixture of haematite and magnetite provided by Frank and Nowaczyk, 2008). The presence of low-coercivity mineral can be clearly interpreted from the three-axes thermal demagnetization curves (Fig. 5B – right side). However, the presence of specular haematite should also be considered due to high unblocking temperatures (700°C) of high-coercivity fraction. According to Borradaile (1999; see also Dunlop, 1971, 1981) the IRM acquisition curve in the interval between 0 and 0.2 T is characteristic for coarse-grained haematite rather than for magnetite (Fig. 5D). The MS increase >650°C is probably an effect of high-temperature magnetite formation (e.g., Dunlop, 1972; Dunlop and Özdemir, 1997).

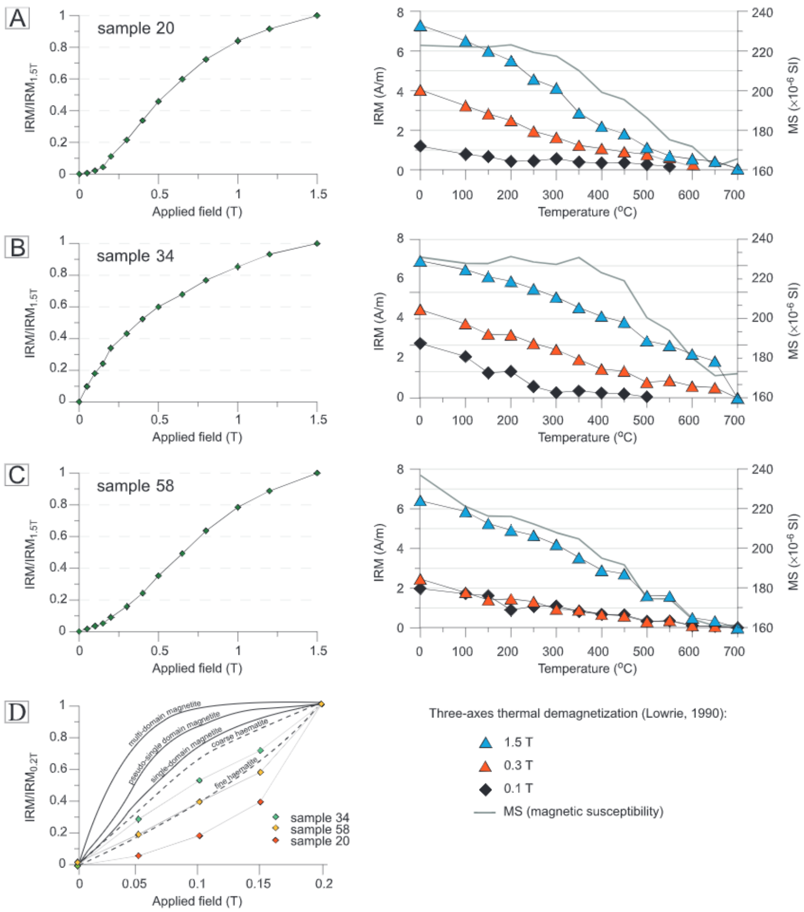

Fig. 5. Results of the IRM acquisition and three-axes IRM thermal demagnetization (Lowrie, 1990) in three selected samples

A – sample 20 with an interpreted mixture of magnetite and fine-grained haematite; **B** – sample 34 with an interpreted mixture of magnetite and coarse-grained haematite; **C** – sample 58 with an interpreted mixture of fine- and coarse-grained haematite; **D** – IRM acquisition curves of the three selected samples in relation to magnetic behaviour of multi-domain, pseudo-single-domain, and single-domain magnetite and fine- and coarse-grained haematite (after Borradaile, 1999; see also Dunlop 1971, 1981)

COMPONENTS OF NATURAL REMANENT MAGNETIZATION

Forty-two samples (42% of population) derived from the Brzeziny section and 10 samples (52% of population) from the Wolica section show chaotic demagnetization. These samples were taken mostly from the sandstone layers and Lisów breccia horizons and show no stable component even within low temperature ranges (Figs. 6E and 7E). In the remaining samples, two magnetization components A and B were isolated.

Component A was isolated in 55 samples (47% of the total samples), of which 46 were derived from Brzeziny and 9 from Wolica (Table 1; Figs. 3 and 4). The component is characterized by unblocking temperatures between 475 and 520°C, and most probably it is carried by magnetite. Component A has a stable magnetic direction of only normal magnetic polarity of 4° declination and 61° inclination (k = 13.42, α95 = 5.15) in geographic system coordinates (Table 1; Figs. 6–8). This can be interpreted as a post-folding (Brunhes?) magnetic direction corresponding to a pole position of 357.9° longitude and –80° latitude (Fig. 9) according to the southern hemisphere projection (Torsvik et al., 2012).

The stable magnetic direction of component B was observed between 475/520°C and 600/650°C. This component is probably carried by fine-grained haematite. Component B was isolated in 42 samples (36% of the total samples), of which 35 were derived from Brzeziny and 7 from Wolica (Table 1; Figs. 3 and 4). This collection includes 24 samples with normal polarity

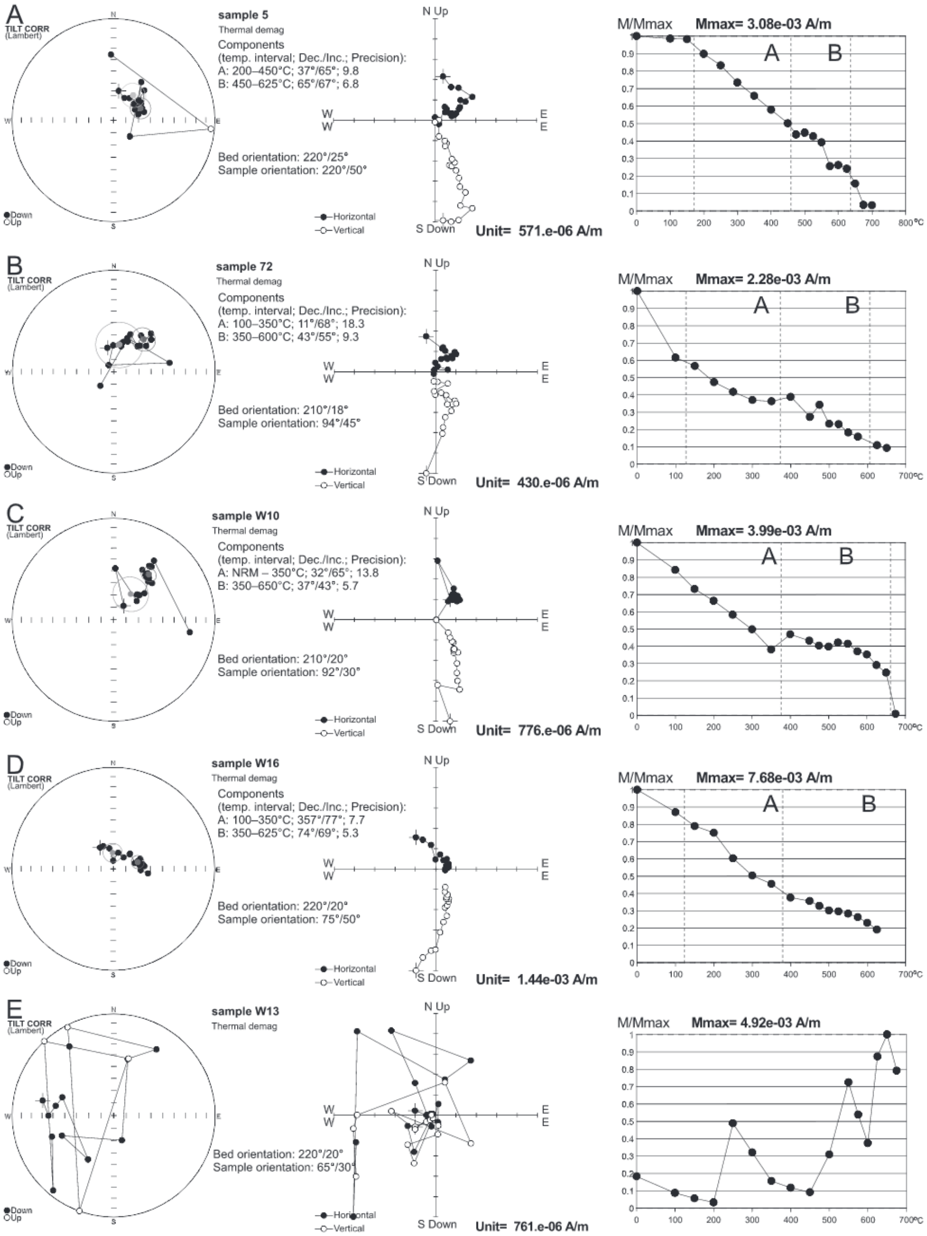

Fig. 6. Typical demagnetization characteristics (orthogonal plots, demagnetization paths and intensity decay curves) of the Keuper from the southern Mesozoic margin of the Holy Cross Mountains

Part I. **A–D** – normal polarity samples; **E** – chaotic demagnetization sample. Open circles in the orthogonal plots represent vertical projection, full circles represent horizontal projection. M – intensity of remanent magnetization; Mmax – initial intensity of natural remanent magnetization; A, B – components of magnetization. Diagrams prepared in *Remasoft 3.0* (Chadima and Hrouda, 2006)

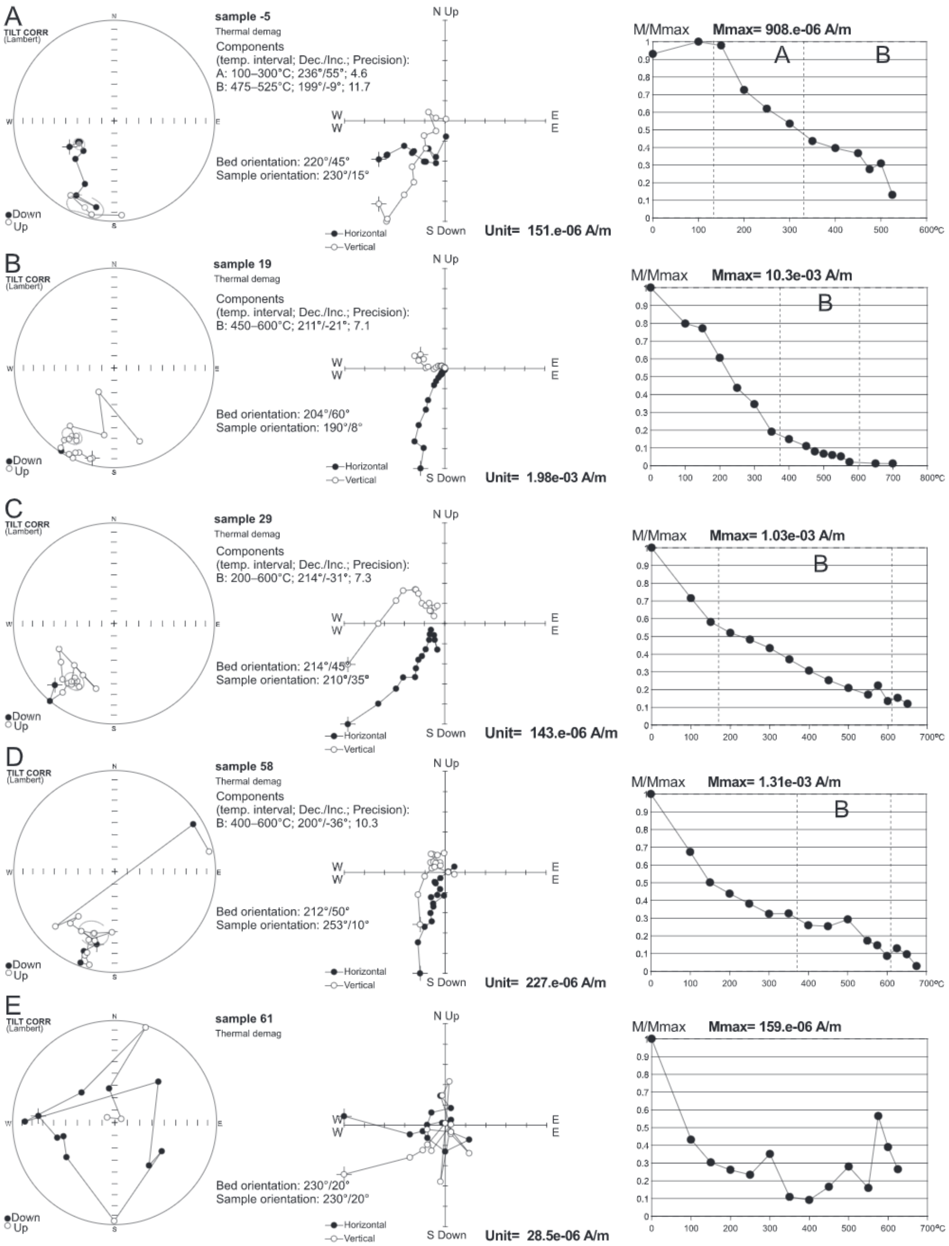

Fig. 7. Typical demagnetization characteristics (orthogonal plots, demagnetization paths and intensity decay curves) of the Keuper from the southern Mesozoic margin of the Holy Cross Mountains

Part II. **A–D** – reversed polarity samples; **E** – chaotic demagnetization sample; for other explanations see Figure 6

Table 1

Summary statistics of characteristic palaeomagnetic directions obtained from the Keuper successions in the Brzeziny and Wolica sections in the southern Mesozoic margin of the Holy Cross Mts.

Components	Number of samples	Geographic system coordinates						Tilt system coordinates					
		Polarity	Mean Dec.	Mean Inc.	k	$\alpha95$	VGP (Long./Lat.)	Polarity	Mean Dec.	Mean Inc.	k	$\alpha95$	VGP (Long./Lat.)
A	55	normal	4	61	13.4	5.4	358/-80	–	288	70	10.3	6.4	–
B	42	–	359	79	1.6	30.5	–	normal (24 samples)	31	62	28.2	6.4	311/-53
								reversed (18 samples)	223	–25	16.4	9.4	

Long. – longitude; Lat. – latitude; Decl. – declination; Incl. – inclination; VGP – Virtual Geomagnetic Pole Position; k – precision parameter, $\alpha95$ – 95% confidence limit

of mean 31° declination and 62° inclination (k = 28.24, $\alpha95$ = 6.04) and 18 samples with reversed polarity of mean 223° declination and –25° inclination (k = 16.38, $\alpha95$ = 8.65) in tectonic system coordinates (Table 1; Figs. 6–8). Although the normal and reversed magnetizations are not exactly antiparallel, they are interpreted as the primary Late Triassic magnetic signal. Shallower reversed and steeper normal polarities are probably related to the overlapping by the younger secondary magnetization. About 25° of syndepositional inclination shallowing is also observed in modern, fluvial, haematite-bearing sediments (Tan and Kodama, 2002 and citations therein).The palaeopole position calculated from the transposed reversed and normal polarity samples is 311° longitude and –52.8° latitude (Fig. 9) according to the southern hemisphere projection (Torsvik et al., 2012). These values correspond well to the Late Triassic (Norian) segment of the reference Phanerozoic Apparent Polar Wander Path for Baltica/Europe (Torsvik et al., 2012). Similar values of ~305–311° declination and ~–50° have been obtained from the 215–226 Ma European Upper Triassic (Walderhaug, 1993; Torsvik et al., 2008).

In 33 samples (28% of the total samples; Figs. 6 and 7), dispersed directions with no clustered magnetization were observed above 600/650°C up to complete demagnetization at 700°C. This magnetization is carried probably by coarse-grained haematite.

Similar two-component behaviour of magnetization, carried by magnetite and haematite, is typical for the Triassic redbeds. This is especially visible in the Buntsandstein deposits in the German Basin (Nawrocki, 1997; Szurlies 2004, 2007) and in the Middle Triassic from Spain (Rey et al., 1996). In the Keuper deposits from Poland, the primary Triassic magnetization was described as carried by haematite (Nawrocki et al., 2015). Only in few cases, the magnetite or a mixture of magnetite and haematite bring the primary magnetization.

LOCAL MAGNETOSTRATIGRAPHY

The polarities obtained from component B are used for magnetostratigraphy in the investigated sections (Figs. 3, 4, 10 and 11). The normal and reversed polarity samples occur in regular sets – up to eight succeeding samples of the same polarity, which also proves the primary character of the magnetization.

Twelve magnetic polarity zones – six of normal and six of reversed polarity are interpreted in the Brzeziny section (Figs. 3 and 10). However, thick intervals with no preserved Triassic magnetization occur in the lower (Lisów breccia horizons) and upper (upper sandstone complex) parts of the section (Fig. 3). Two magnetic polarity zones are distinguished in the Wolica section (Fig. 4). Like in the Brzeziny section, a primary magnetic signal was not recognized in the sandstone complex.

The correlation of both sections seems quite obvious: the upper normal polarity zone in the Brzeziny section corresponds to that recognized in the Wolica section (Fig. 10). This correlation broadly matches also the magnetic susceptibility fluctuations and lithological correlation (Fig. 10).

DISCUSSION

The Late Triassic Magnetic Polarity Time Scale is well-established both in the terrestrial succession in the Newark Basin (Kent and Olsen, 1999; Hüsing et al., 2011; see also Kent et al., 2017) and in the biostratigraphically well-dated marine successions in the Tethyan domain (Gallet et al., 1993, 1996, 2000, 2003, 2007; Channell et al., 2003; Hounslow et al., 2004; Krystyn et al., 2007; Muttoni et al., 2010; Hounslow and Muttoni, 2010; Maron et al., 2017). Their global magnetostratigraphic correlation can be found in Hüsing et al. (2011), while the Composite Late Triassic Magnetic Polarity Time Scale is presented in Hounslow and Muttoni (2010) and Ogg (2012). The Upper Carnian (Tuvalian) to Rhaetian magnetic polarity time scale in the Newark Basin includes 24 polarity zones (Kent and Olsen, 1999; Hounslow and Muttoni, 2010; Hüsing et al., 2011; Ogg, 2012: long-Rhaetian option), in which nine – from the top of the E7n Zone (~226.6 Ma) to the top of the E16n Zone (~209.8 Ma) – correspond to the Norian (Hüsing et al., 2011; see also Ogg, 2012).

Assuming the lack of long-lasting stratigraphic gaps and similar sedimentation rates along the entire section, the magnetic polarity zones distinguished in our study characterize relatively thick normal polarity intervals. Such behaviour is characteristic of the Mid-Late Norian (latest Lacian–Sevatian), opposite to the long-lasting reversed polarity zones in the Early Norian (Lacian) interval (Ogg, 2012). We propose to correlate the twelve magnetic polarity zones distinguished in the Brzeziny and Wolica sections with the latest Lacian–Sevatian interval of the Composite Late Triassic Time Scale, which corresponds to the E13n–E16r Newark zones. In this interpretation, the HCM sections include the interval of ~8 My – from ~218 to ~210 Ma. This is in agreement with palynostratigraphic data of Fijałkowska-Mader et al. (2015), who indicated the Patoka Member in the Upper Silesia region belongs to the Middle to Upper Norian

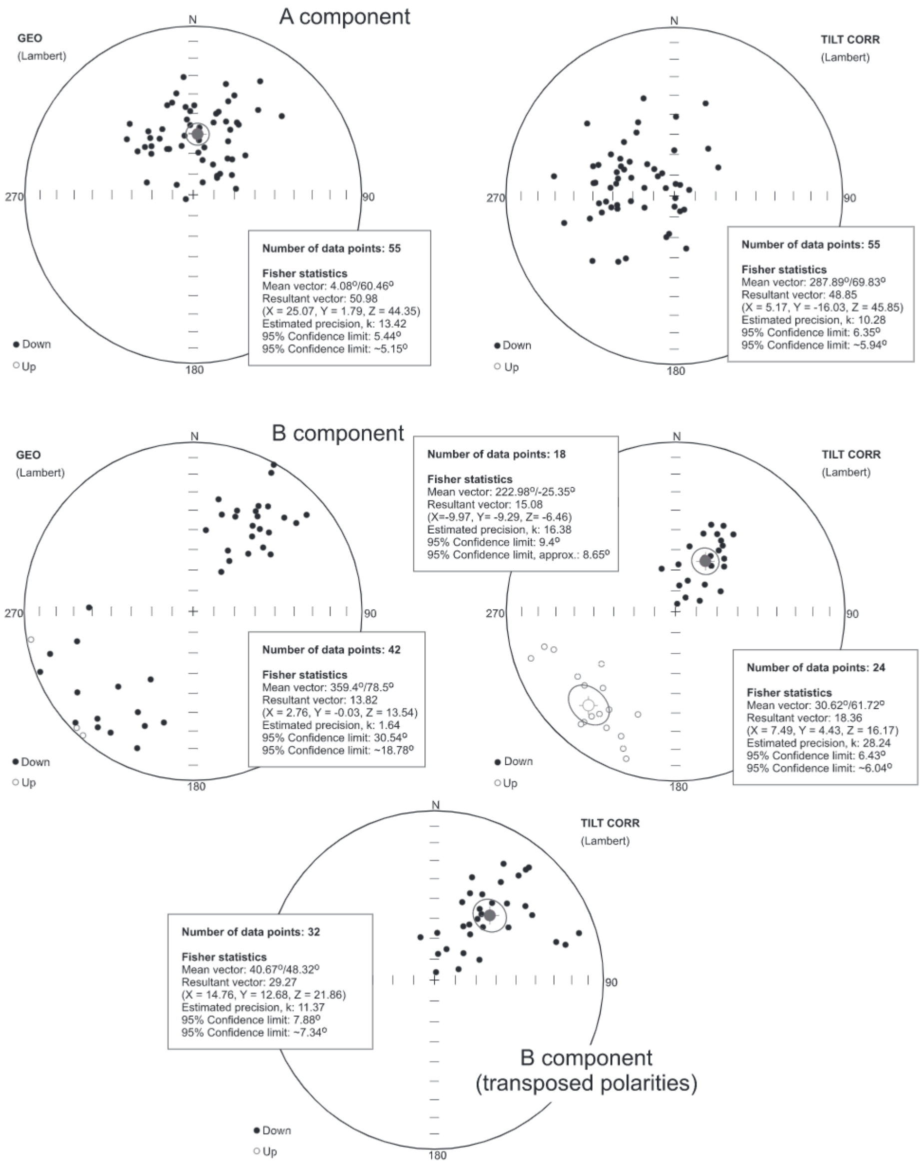

Fig. 8. Group statistics of characteristic magnetic directions of components A and B in the Keuper successions of the southern Mesozoic margin of the Holy Cross Mountains

The projections are prepared in a geographic coordinate system (before tectonic correction) and a tilt coordinate system (after tectonic correction); diagrams prepared in *Remasoft 3.0* (Chadima and Hrouda, 2006)

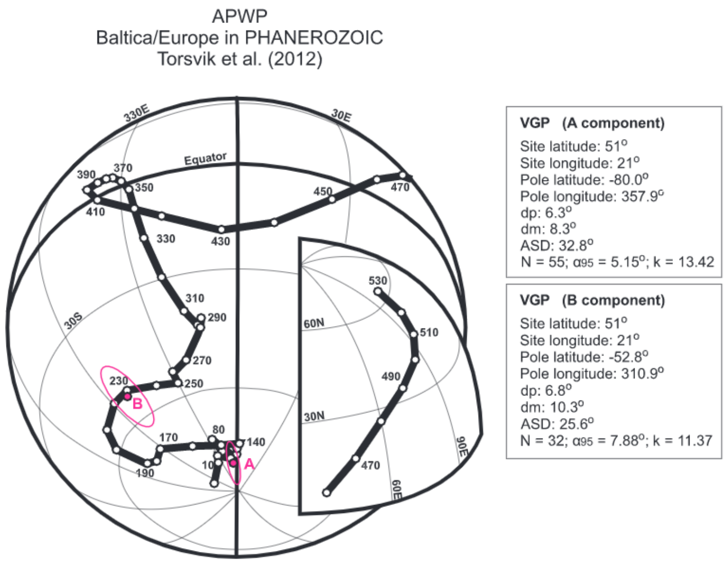

Fig. 9. Palaeopole projections (VGP) of components A and B on the reference Phanerozoic Apparent Polar Wander Path for Baltica/Europe (Torsvik et al., 2012)

Poles calculated from 55 samples of component A and 32 samples (from all normal polarity samples and selected transposed reversed polarity samples) of component B. Dp – semi-axis of the confidence ellipse along the great-circle path from site to pole, dm – semi-axis of the confidence ellipse perpendicular to that great-circle path, ASD – angular standard deviation, k – precision parameter, α95 – 95% confidence limit, N – number of samples used for calculation

meyeriana b palynostratigraphic Subzone. This Subzone corresponds to the upper part of the *Granuloperculatipollis rudis* European Zone, which ranges from the base to the top of the Norian stage (Orłowska-Zwolińska, 1983; Cirilli, 2010; Ogg, 2012; Marcinkiewicz et al., 2014; Szulc et al., 2015a: fig. 8).

The magnetostratigraphic scale compiled by Nawrocki et al. (2015) for the Keuper of Poland includes 22 magnetic polarity zones, in which six were distinguished in the Patoka Member of the Grabowa Formation. Nawrocki et al. (2015: fig. 9) proposed two options of their correlation with the Late Triassic Composite. According to the first option, the six magnetic polarity zones distinguished in the Patoka Member correspond to the E6 to E8 Newark magnetic polarity zones (from the uppermost Tuvalian to the lowermost Norian). The second hypothesis assumes the E8 to E10 Newark zones (Lower Norian). Both correlations seem to be in contradiction with the palynostratigraphic data of Fijałkowska-Mader et al. (2015), who proved the Middle to Late Norian age of the Patoka Mb. Also the thick normal-polarity intervals interpreted in this part of the succession indicate rather the E12 to E13 Newark magnetic polarity zones, similar as in the HCM sections. The present state of the Keuper magnetostratigraphy at the southeastern margin of the German Basin is presented in Figure 11.

CONCLUSIONS

1. An ~60 m thick succession of variegated siltstones and claystones intercalated with sandstones and breccia horizons was recognized and investigated for magnetostratigraphy in two sections at the southern Mesozoic margin of the Holy Cross Mountains.

2. The investigated interval overlies the Reed Sandstone and corresponds to the Upper Silesian Patoka Member of the Grabowa Formation.

3. A primary Late Triassic magnetic magnetization of normal and reversed polarity was isolated in 42 samples out of 118 samples. This magnetization is carried by fine-grained haematite. The primary Late Triassic magnetic signal is partly overlapped by the low- and high-coercivity younger components. Because of this the normal and reversed magnetizations are not antiparallel.

4. Twelve magnetic polarity zones have been distinguished and correlated with the Middle–Upper Norian (latest Lacian–Sevatian) interval of the Composite Late Triassic Magnetic Polarity Time Scale.

5. The mean palaeopole calculated from the transposed reversed and normal directions corresponds well with the ex-

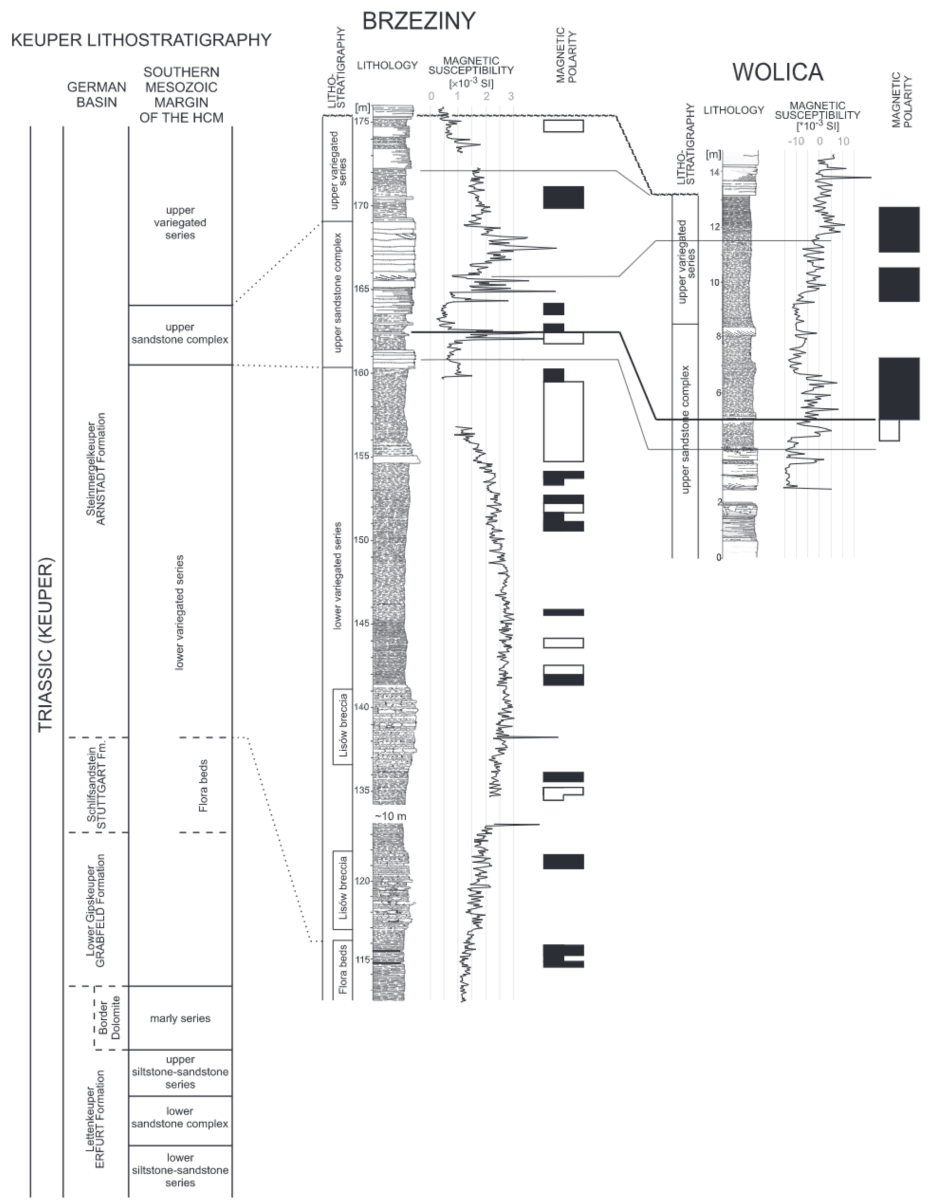

Fig. 10. Correlation of the two Keuper sections at the southern Mesozoic margin of the Holy Cross Mts. in terms of lithostratigraphy, magnetic susceptibility record, and magnetic polarities. Keuper lithostratigraphy in the HCM and Germany after Czapowski and Romanek (1986) and Feist-Burkhardt et al. (2008), respectively

For explanations see Figures 3 and 4

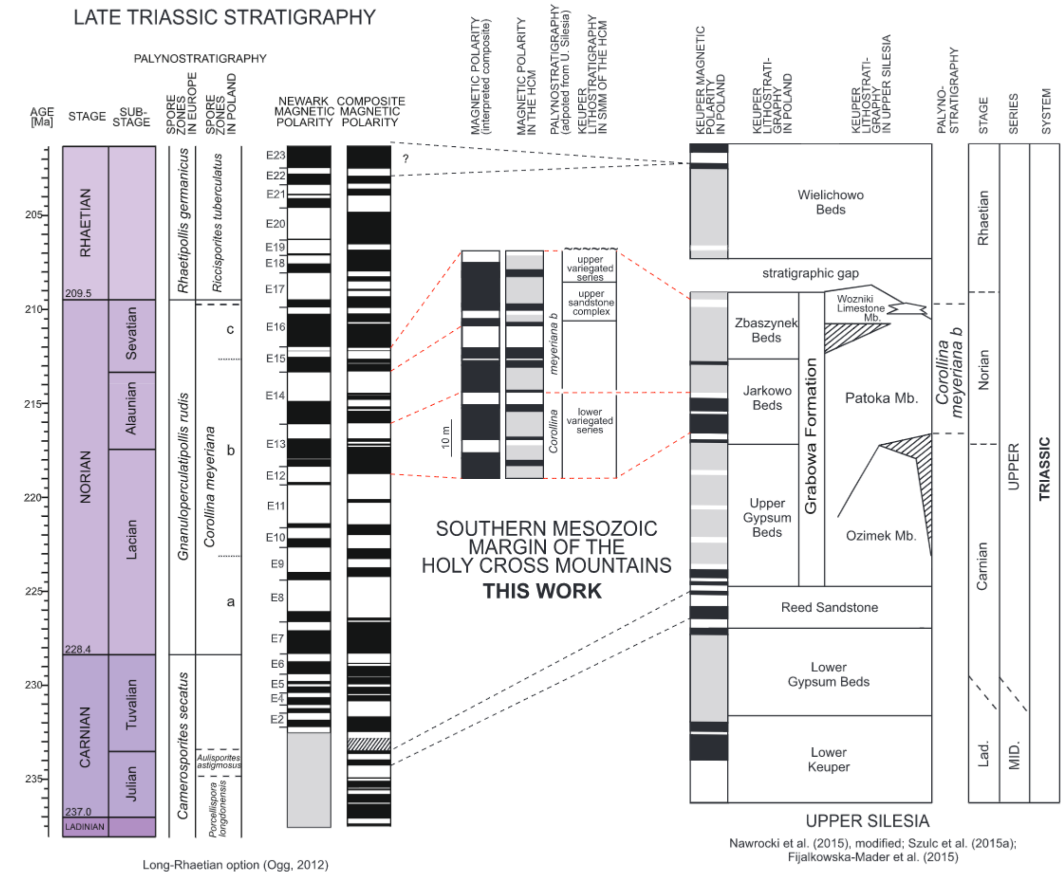

Fig. 11. Keuper magnetostratigraphy in the southeastern margin of the German Basin and its correlation with the Composite Late Triassic Magnetic Polarity Time Scale (according to a "Long-Rhaetian" option of stratigraphy; Ogg, 2012)

SMM – southern Mesozoic margin; C. – Carnian; red dotted line – correlation proposed in this work; black dotted line – correlation after Nawrocki et al. (2015)

pected (Norian, Late Triassic) segment of the Baltica/Europe Phanerozoic Reference Apparent Polar Wander Path.

Acknowledgements. This work was financed by Statutory Project No. 61.2401.1502.00.0 of the Polish Geological Institute – National Research Institute, entitled "The Upper Triassic magnetostratigraphy at the southern Mesozoic border of the Holy Cross Mountains". We are greatly indebted to two reviewers: M. Hounslow and J. Szulc for their insightful comments and help in preparation of the final version of this manuscript. The remarks and suggestions of J. Grabowski and T. Peryt are also greatly appreciated.

REFERENCES

Bachmann, G.H., Kozur, H.W., 2004. The Germanic Triassic: correlations with the international chronostratigraphic scale, numerical ages and Milankovitch cyclicity. Hallesches Jahrbuch für Geowissenschaften, **26**: 17–62.

Bilan, W., 1976. The stratigraphy of the Upper Triassic deposits of the eastern margin of the Upper Silesian Coal Basin (in Polish with English summary). Zeszyty Naukowe AGH, Geologia, **2**: 4–73.

Borradaile, G.J., 1999. Viscous remanent magnetization of high thermal stability in limestone. Geological Society Special Publications, **151**: 27–42.

Chadima, M., Hrouda, F., 2006. Remasoft 3.0 a user-friendly paleomagnetic data browser and analyzer. Travaux Géophysiques, **27**: 20–21.

Channell, J.E.T., Kozur, H.W., Sievers, T., Mock, R., Aubrecht, R., Sykora, M., 2003. Carnian–Norian biomagnetostratigraphy at Silická Brezová (Slovakia): correlation to other Tethyan sections and to the Newark Basin. Palaeogeography, Palaeoclimatology, Palaeoecology, **191**: 65–109.

Cirilli, S., 2010. Upper Triassic–lowermost Jurassic palynology and palynostratigraphy: a review. Geological Society Special Publications, **334**: 221–262.

Czapowski, G., Romanek, A., 1986. Lithostratigraphy and sedimentary environment of the Upper Triassic deposits near Chmielnik (in Polish with English summary). Przegląd Geologiczny, 34: 635–643.

Dadlez, R., Marek, S., Pokorski, S., 2000. Geological Map of Poland without Cainozoic Deposits 1:100 000. Państwowy Instytut Geologiczny, Warszawa.

Deczkowski, Z., Marcinkiewicz, T., Maliszewska, A., 1997. Norian and Rhaetian. Sedimentation, paleogeography and paleotectonics (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **153**: 150–194.

Dunlop, D.J., 1971. Magnetic properties of fine particle hematite. Annales Geophysicale, **27**: 269–293.

Dunlop, D.J., 1972. Magnetic mineralogy of unheated and heated red sediments by coercivity spectrum analysis. Geophysical Journal International, **27**: 37–55.

Dunlop, D.J., 1981. The rock magnetism of fine particles. Physics of the Earth and Planetary Interiors, **26**: 1–26.

Dunlop, D.J., Özdemir, Ö., 1997. Rock Magnetism: Fundamentals and Frontiers. Cambridge University Press.

Dzik, J., Sulej, T., 2007. A review of the early Late Triassic Krasiejów biota from Silesia, Poland. Palaeontologia Polonica, **64**: 3–27.

Dzik, J., Sulej, T., Kaim, A., Niedźwiedzki, R., 2000. A late Triassic tetrapod graveyard in the Opole Silesia (SW Poland) (in Polish with English summary). Przegląd Geologiczny, **48**: 226–235.

Dzik, J., Sulej, T., Niedźwiedzki, G., 2008. A dicynodont-theropod association in the latest Triassic of Poland. Acta Palaeontologica Polonica, **53**: 733–738.

Feist-Burkhardt, S., Götz, A.E., Szulc, J., Borkhataria, R., Geluk, M., Hass, J., Hornung, J., Jordan, P., Kempf, O., Michalik, J., Nawrocki, J., Reinhardt, L., Ricken, W., Röhling, H.G., Rüffer, T., Török, Á., Zühlke, R., 2008. Triassic. In: The Geology of Central Europe (ed. T. McCann), **2** (Mesozoic and Cenozoic): 749–822, Geological Society, London.

Fijałkowska-Mader, A., 2013. Palynostratigraphy, palaeoecology and palaeoclimate of the Late Permian and Triassic of the Nida Basin (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **454**: 15–70.

Fijałkowska-Mader, A., 2015. A record of climatic changes in the Triassic palynological spectra from Poland. Geological Quarterly, **59** (4): 615–653.

Fijałkowska-Mader, A., Heunisch, C., Szulc, J., 2015. Palynostratigraphy and palynofacies of the Upper Silesian Keuper (Southern Poland). Annales Societatis Geologorum Poloniae, **85**: 637–661.

Filonowicz, P., 1968. Objaśnienia do Szczegółowej Mapy Geologicznej Polski 1:50 000, arkusz Morawica (in Polish). Wyd. Geol., Warszawa.

Frank, U., Nowaczyk, N., 2008. Mineral magnetic properties of artificial samples systematically mixed from haematite and magnetite. Geophysical Journal International, **175**: 449–461.

Gajewska, I., Marcinkiewicz, T., Maliszewska, A., Deczkowski, Z., 1997. Norian and Rhaetian. Sedimentation, paleogeography and paleotectonics (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **153**: 150–194.

Gallet, Y., Besse, J., Krystyn, L., Théveniaut, H., Marcoux, J., 1993. Magnetostratigraphy of the Kavur Tepe section (southwestern Turkey): a magnetic polarity time scale for the Norian. Earth and Planetary Science Letters, **117**: 443–456.

Gallet, Y., Besse, J., Krystyn, L., Marcoux, J., 1996. Norian magnetostratigraphy from the Scheiblkogel section, Austria: constraint on the origin of the Antalya Nappes, Turkey. Earth and Planetary Science Letters, **140**: 113–122.

Gallet, Y., Besse, J., Krystyn, L., Marcoux, J., Guex, J., Théveniaut, H., 2000. Magnetostratigraphy of the Kavaalani section (southwestern Turkey): consequence for the origin of the Antalya Calcareous Nappes (Turkey) and for the Norian (Late Triassic) magnetic polarity timescale. Geophysical Research Letters, **27**: 2033–2036.

Gallet, Y., Krystyn, L., Besse, J., Marcoux, J., 2003. Improving the Upper Triassic numerical time scale from cross-correlation between Tethyan marine sections and the continental Newark basin sequence. Earth and Planetary Science Letters, **212**: 255–261.

Gallet, Y., Krystyn, L., Marcoux, J., Besse, J., 2007. New constraints on the end-Triassic (Upper Norian–Rhaetian) magnetostratigraphy. Earth and Planetary Science Letters, **255**: 458–470.

Hounslow, M., Muttoni, G., 2010. The geomagnetic polarity timescale for the Triassic: linkage to stage boundary definitions. Geological Society Special Publications, **334**: 61–102.

Hounslow, M.W., Posen, P.E., Warrington, G., 2004. Magnetostratigraphy and biostratigraphy of the Upper Triassic and lowermost Jurassic succession, St. Audrie's Bay, UK. Palaeogeography, Palaeoclimatology, Palaeoecology, **213**: 331–358.

Hüsing, S.K., Deenen, M.H.L., Koopmans, J.G., Krijgsman, W., 2011. Magnetostratigraphic dating of the proposed Rhaetian GSSP at Steinbergkogel (Upper Triassic, Austria): implications for the Late Triassic time scale. Earth and Planetary Science Letters, **302**: 203–216.

Kent, D.V., Olsen, P.E., 1999. Astronomically tuned geomagnetic polarity timescale for the Late Triassic. Journal of Geophysical Research, **104**: 12831–12841.

Kent, D.V., Olsen, P.E., Muttoni, G., 2017. Astrochronostratigraphic polarity time scale (APTS) for the Late Triassic and Early Jurassic from continental sediments and correlation with standard marine stages. Earth-Science Reviews, **166**: 153–180.

Kirschvink, J.L., 1980. The least square line and plane and the analysis of paleomagnetic data. Geophysical Journal of the Royal Astronomical Society, **62**: 699–718.

Kozłowska, M., Barski, M., Mieszkowski, R., Antoszewska, K., 2016. A new Triassic-Jurassic section in the southern part of the Holy Cross Mts. (Poland) – implications for palaeogeography. Geological Quarterly, **60** (2): 365–484.

Krystyn, L., Richoz, S., Gallet, Y., Bouquerel, H., Kürschner, W.M., Spötl, C., 2007. Updated bio-and magnetostratigraphy from Steinbergkogel (Austria), candidate GSSP for the base of the Rhaetian stage. Albertiana, **36**: 164–173

Lowrie, W., 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. Geophysical Research Letters, **17**: 159–162.

Lucas, S.G., Tanner, L.H., Kozur, H.W., Weems, R.E., Heckert, A.B., 2012. The Late Triassic timescale: age and correlation of the Carnian–Norian boundary. Earth-Science Reviews, **114**: 1–18.

Maliszewska, A., 1972. The origin of Lisów Breccia on the basis of petrographic studies (in Polish with English summary). Biuletyn Instytutu Geologicznego, **261**: 33–54.

Marcinkiewicz, T., Fijałkowska-Mader, A., Pieńkowski, G., 2014. Megaspore zones of the epicontinental Triassic and Jurassic deposits in Poland – overview (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **457**: 15–42.

Maron, M., Muttoni, G., Dekkers, M.J., Mazza, M., Roghi, G., Breda, A., Krijgsman, W., Rigo, M., 2017. Contribution to the magnetostratigraphy of the Carnian: new magneto-biostratigraphic constraints from Pignola-2 and Dibona marine sections, Italy. Newsletters on Stratigraphy, **50**: 187–203.

Muttoni, G., Kent, D.V., Jadoul, F., Olsen, P.E., Rigo, M., Galli, M.T., Nicora, A., 2010. Rhaetian magneto-biostratigraphy from the Southern Alps (Italy): constraints on Triassic chronology. Palaeogeography, Palaeoclimatology, Palaeoecology, **285**: 1–16.

Nawrocki, J., 1997. Permian to Early Triassic magnetostratigraphy from the Central European Basin in Poland: implications on regional and worldwide correlations. Earth and Planetary Science Letters, **152**: 37–58.

Nawrocki, J., Jewuła, K., Stachowska, A., Szulc, J., 2015. Magnetic polarity of the Upper Triassic sediments of the German Basin in Poland. Annales Societatis Geologorum Poloniae, **85**: 663–674.

Niedźwiedzki, G., Brusatte, S.L., Sulej, T., Butler, R.J., 2014. Basal dinosauriform and theropod dinosaurs from the mid-late Norian (Late Triassic) of Poland: implications for Triassic dinosaur evolution and distribution. Palaeontology, **57**: 1–22.

Nitsch, E., Seegis, D., Vath, U., Hauschke, N., 2005. Sedimente und Sedimentationspausen im deutschen Keuper: Wie vollständig ist die Überlieferung der späten Triaszeit? Newsletters on Stratigraphy, **41**: 225–251.

Ogg, G., 2012. The Triassic Period. In: The Geologic Time Scale 2012 (eds. F.M. Gradstein, J.G. Ogg, M. Schmitz and G. Ogg), **2**: 681–730. Elsevier, Amsterdam.

Orłowska-Zwolińska, T., 1983. Palynostratigraphy of the Upper part of Triassic epicontinental sediments in Poland (in Polish with English summary). Prace Instytutu Geologicznego, **104**: 1–89.

Orłowska-Zwolińska, T., 1985. Palynological zones of the Polish epicontinental Triassic. Bulletin Polish Academy of Sciences, Earth Sciences, **33**: 107–119.

Pawłowska, K., 1962. The Rhaetian and the Lias of the southern periphery of the Święty Krzyż Mountains (in Polish with English summary). Kwartalnik Geologiczny, **6** (3): 436–446.

Pawłowska, K., 1979. Triassic rocks of south-eastern Góry Świętokrzyskie Mts. (in Polish with English summary). Kwartalnik Geologiczny, **23** (2): 337–361.

Rey, D., Turner, P., Ramos, A., 1996. Palaeomagnetism and magnetostratigraphy of the Middle Triassic in the Iberian Ranges (Central Spain). Geological Society Special Publications, **105**: 59–82.

Senkowiczowa, H., 1957. The Muschelkalk on the southern slope of the Święty Krzyż Mts. between Czarna Nida and Chmielnik (in Polish with English summary). Biuletyn Instytutu Geologicznego, **122**: 5–81.

Szulc, J., 2000. Middle Triassic evolution of the northern Peri-Tethys area as influenced by early opening of the Tethys Ocean. Annales Societatis Geologorum Poloniae, 70: 1–48.

Szulc, J., 2007. Keuper. In: International Workshop on the Triassic of southern Poland, Fieldtrip guide, September 3–8, 2007 (eds. J. Szulc and A. Becker): 33–41.

Szulc, J., 2008. Climate evolution in the Tehys area and its controls. In: The Geology of Central Europe (ed. T. McCann), **2** (Mesozoic and Cenozoic): 751–752. Geological Society, London.

Szulc, J., Racki, G., 2015. Grabowa Formation – the basic lithostratigraphic unit of the Upper Silesian Keuper (in Polish with English summary). Przegląd Geologiczny, **63**: 103–113.

Szulc, J., Racki, G., Jewuła, K., 2015a. Key aspects of the stratigraphy of the Upper Silesian middle Keuper, southern Poland. Annales Societatis Geologorum Poloniae, **85**: 557–586.

Szulc, J., Racki, G., Jewuła, K., Środoń, J., 2015b. How many Upper Triassic bone-bearing levels are there in Upper Silesia (southern Poland)? A critical overview of stratigraphy and facies. Annales Societatis Geologorum Poloniae, **85**: 587–626.

Szurlies, M., 2004. Latest Permian to Middle Triassic cyclo-magnetostratigraphy from the Central European Basin, Germany: Implications for the geomagnetic polarity timescale. Earth and Planetary Science Letters, **261**: 602–619.

Szurlies, M., 2007. Magnetostratigraphy: the key to a global correlation of the classic Germanic Trias – case study Volpriehausen Formation (Middle Buntsandstein), Central Germany. Earth and Planetary Science Letters, **227**: 395–410.

Tan, X., Kodama, K.P., 2002. Magnetic anisotropy and paleomagnetic inclination shallowing in red beds: evidence from the Mississippian Mauch Chunk Formation, Pennsylvania. Journal of Geophysical Research, **107**: EPM 9-1–EPM 9-17.

Torsvik, T.H., Müller, R.D., van der Voo, R., Steinberger, B., Gaina, C., 2008. Global plate motion frames: toward a unified model. Reviews of Geophysics, **46**, **RG3004**: 1–44.

Torsvik, T.H., van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tovher, E., Meert, J.G., McCausland, P.J., Cocks, L.R.M., 2012. Phanerozoic polar wander, paleogeography and dynamics. Earth-Science Reviews, **114**: 325–368.

Walderhaug, H., 1993. Rock magnetic and magnetic fabric variations across three thin alkaline dykes from Sunnhordland, western Norway; influence of initial mineralogy and secondary chemical alterations. Geophysical Journal International, **115**: 97–108.