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Integrated palynostratigraphy and magnetostratigraphy of the Middle and Upper Buntsandstein in NE Poland – an approach to correlating Lower Triassic regional isochronous horizons

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Despite years of research, Lower Triassic deposits of the epicontinental Central European Basin still lack a detailed stratigraphy that would allow regional correlation of isochronous horizons. The best chronostratigraphic results have up to now been achieved by microspore-based biostratigraphy and magnetostratigraphy. Integrated palynostratigraphic and magnetostratigraphic investigations, carried out on Buntsandstein cores from northeastern Poland representing the eastern margin of the basin, have made precise correlations with the better-explored basin centre. The Lidzbark and Malbork formations of the Bartoszyce IG 1 borehole were examined by means of palynology and palaeomagnetic studies. Further palaeomagnetic studies were applied to the Lidzbark, Malbork and Elbląg formations of the Nidzica IG 1 borehole and the Elbląg Fm. of the Pasłęk IG 1. Two spore-pollen assemblages were distinguished representing the *Densoisporites nejburgii* Subzone of the *D. nejburgii* Zone within the lower part of the Lidzbark Fm. and the lowermost part of the Malbork Fm. Mostly reversed polarity was detected within the lower part of the succession investigated, whereas normal polarity prevailed within its upper part. A normal polarity local zone was correlated with the undivided Tbn6–Tbn7 standard magnetozones of western Poland. The reversely polarized part of the succession corresponds most probably to the Tbr5 standard magnetozone. The base of the Tbn6–Tbn7 magnetozone can serve as a good correlation horizon for regional reconstructions.

Key words: Buntsandstein, Lower Triassic, northeastern Poland, palynostratigraphy, magnetostratigraphy.

INTRODUCTION

The stratigraphy of the Lower Triassic Buntsandstein Group of the Polish part of the epicontinental Central European Basin, since the work of Senkowiczowa (1997) and Szyperko-Teller (1997), still belongs among the main research topics of the regional Mesozoic succession (e.g., Nawrocki et al., 2003; Kuleta and Zbroja, 2006; Ptaszyński and Niedźwiedzki, 2006; Becker, 2014; Szulc et al., 2015). A precise chronostratigraphic framework, delivering key horizons, enabling reliable detailed reconstructions of basin development independent of lithostratigraphic correlation, is still lacking. So far, the best results in chronostratigraphic research have been achieved by palynostratigraphy and magnetostratigraphy. The biostratigraphy based on conchostracans seems to be controversial and is still insufficiently tested (Becker, 2014, 2015; Schneider and Scholze, 2016). In addition, the taxonomic problems with the index species *Falcisca eotriassica* Kozur et Seidel, 1983, *F. postera* Kozur et Seidel, 1983 and *F. verchojanica* Molin, 1965, (e.g., Scholze et al., 2015, 2016), undermine their credibility as a stratigraphic tool. Studies utilizing ostracods have also played a subordinate role in the biostratigraphy of the Polish Buntsandstein (Styk, 1982).

The most comprehensive investigation has been palynostratigraphic, extending across the whole area of the Polish Basin (e.g., Fuglewicz, 1973, 1979, 1980; Marcinkiewicz, 1976, 1982; Orłowska-Zwolińska 1977, 1988; Fijałkowska 1994a, b, 1995, 2006a, b; Fijałkowska-Mader, 1999, 2013; Fijałkowska-Mader et al., 2015), resulting in palynozonations based on mio- (Orłowska-Zwolińska, 1984, 1985) and megaspores (Marcinkiewicz, 1992; Marcinkiewicz et al., 2014).

Nawrocki (1997; Nawrocki et al., 1993) has developed the magnetostratigraphic reference scale for the Buntsandstein of

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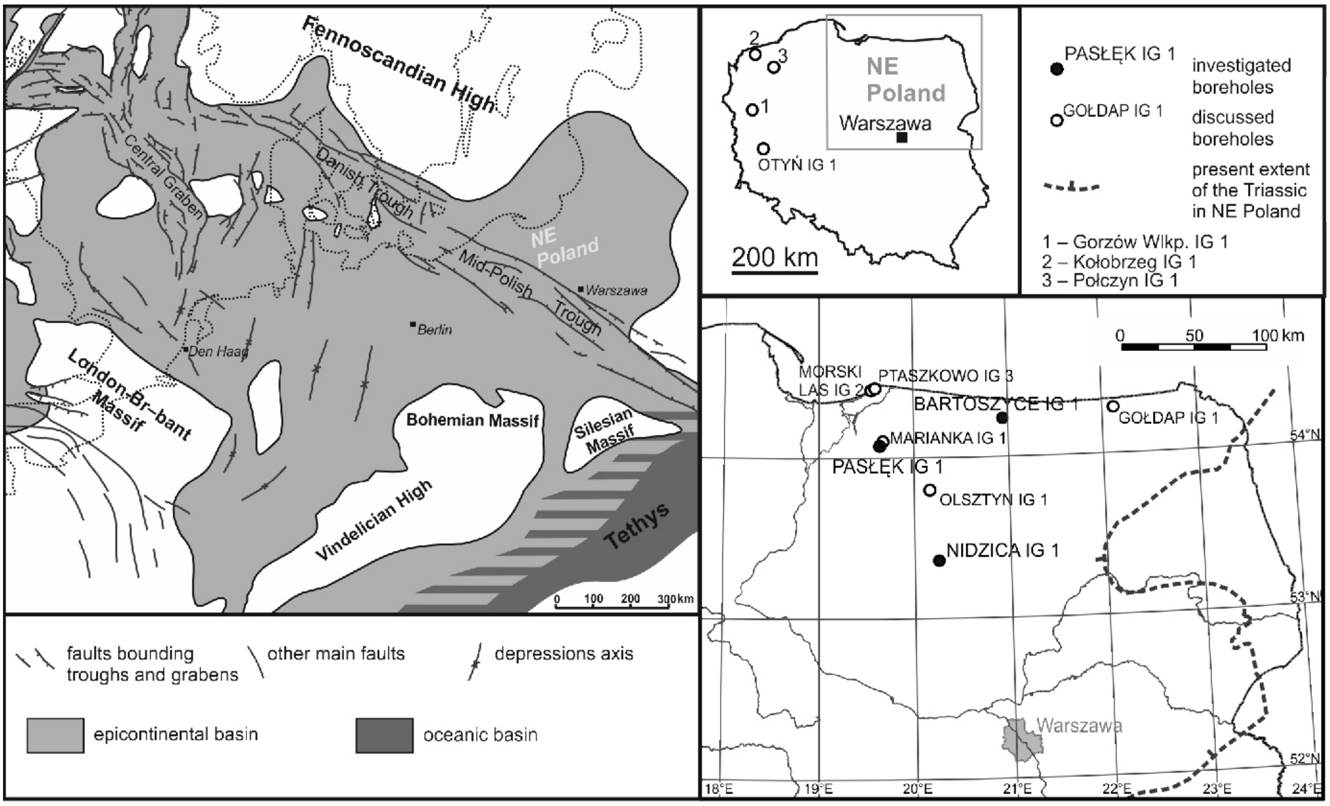


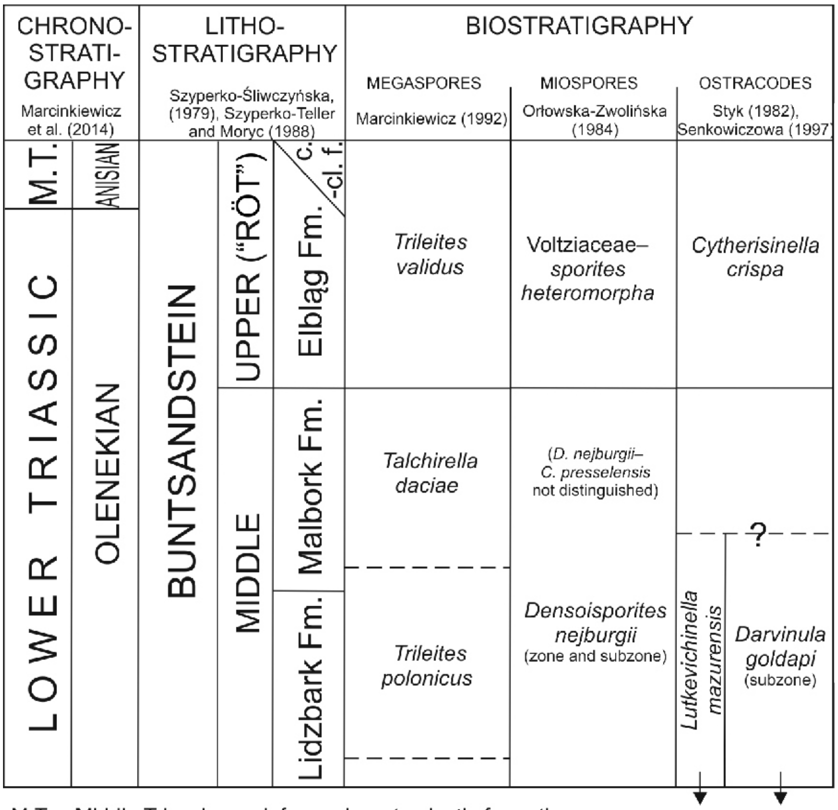
Fig. 1. Palaeogeography of the Central European Basin of the Early Triassic with its main tectonic structures (after Ziegler, 1990, modified), locality of the research area and of the boreholes investigated

western Poland and has carried out magnetostratigraphic research in other parts of the Polish Basin (Nawrocki et al., 2003; Nawrocki, 2004; Becker and Nawrocki, 2014).

The relative scarcity of fossils within the Buntsandstein deposits, especially in the basin margin successions, has limited the usefulness of biostratigraphy, and neither that nor magnetostratigraphy alone have allowed interpretion of their results in terms of chronostratigraphy. Biostratigraphy can determine the approximate chronostratigraphic position of the sections, while magnetostratigraphy is able to correlate isochronous horizons, by means of identifying polarity changes. The greatest advantage of magnetostratigraphy is that it has the potential to yield a continuous record for whole available sections. Without a precise stratigraphic model for the entire Buntsandstein basin, including its margins, it is difficult to reconstruct and understand its palaeogeography. Due to the lack of detailed interdisciplinary regional chronostratigraphic studies of the basin margins, such as in northeastern Poland, lithostratigraphy has remained the only method for stratigraphic correlations and for palaeogeographic reconstruction. Within the scope of a comprehensive program of the State Geological Survey of Poland, designated to protect and comprehensively study stratotype sections in borehole cores, palaeomagnetic and palynological studies had been conducted on the Middle and Upper Buntsandstein of the Bartoszyce IG 1 and Pasłęk IG 1 boreholes (Fig. 1; Fijałkowska-Mader, 2015; Sobień and Becker, 2015), that serve as stratotypes for the Lidzbark, Malbork and Elbląg formations (Szyperko-Śliwczyńska, 1979). Earlier magnetostratigraphic research on the neighbouring Nidzica IG 1 borehole (Fig. 1; Nawrocki in Krzywiec, 2000) helped to provide a preliminary magnetostratigraphic scale for the Middle and Upper Buntsandstein of northeastern Poland. The present study constitutes the first step towards establishing an integrated magneto-biostratigraphic framework for the Lower Triassic of the northeastern margins of the Central European Basin (Fig. 1).

GEOLOGICAL SETTING

During the Triassic the study area was located north-east of the Mid-Polish Trough, i.e. in the local subsidence centre of the Polish Basin. The basin belongs to the eastern part of the Central European Basin (CEB; Fig. 1) – an epicontinental basin that originated in the Early Permian due to thermal subsidence of the continental crust after the Variscan orogeny (e.g., Dadlez et al., 1995; Bachmann et al., 2008; Pharaoh et al., 2010). Its main depocentres stretched NW–SE (e.g., Central Graben, Danish and Mid-Polish troughs) or NNE–SSW (e.g., the main depressions in north Germany and the Netherlands, e.g., Ziegler, 1990; Fig. 1). The Mid-Polish Trough and the Danish Trough developed in the border zone of two large tectonic structures (units), the Variscan West European Platform and the Precambrian East European Craton, the crystalline basement of which formed the Fennoscandian High limiting the CEB to the north (Fig. 1; Dadlez et al., 1995). The main subsidence phase of the CEB and its Polish part took place in the Permian to Early Triassic (Dadlez et al., 1995; Pharaoh et al., 2010). Tectonic inversion of the Mid-Polish Trough during the late Cretaceous and early Paleogene, induced by the collision of Eurasia and Africa, terminated the development of the Polish Basin (Dadlez et al., 1995; Dadlez and Marek, 1997; Krzywiec, 2006; Pharaoh et al., 2010). The basin was filled alternately with terrestrial clastic and marine carbonate deposits, depending on the state of the connection with the Tethys Ocean to the south or boreal oceanic realm to the north. The Lower Triassic infill consists mostly of



M.T. – Middle Triassic; c.-cl. f. – carbonate-clastic formation

Fig. 2. Stratigraphy of the Middle and Upper Buntsandstein of northeastern Poland

terrestrial to very shallow marine clastic deposits up to 2000 m in thickness in the basin centre. The thickness decreases with increasing distance to the depocentre, and does not exceed 400 m in the region of northeastern Poland (Dadlez et al., 1998; Bachmann et al., 2010). The study area is located within a part of the basin encroaching onto the margins of the Precambrian East European Craton.

The Middle and Upper Buntsandstein section of the northeastern Poland is composed of the Lidzbark, Malbork and Elbląg formations (Szyperko-Śliwczyńska, 1979; Szyperko-Teller, 1997; Becker et al., 2008; Fig. 2). To the west and south of the study area the uppermost part of the Buntsandstein is formed by a carbonate-clastic formation (c.-cl. f.), not included into the Elbląg Fm. The Middle Buntsandstein consists of the Lidzbark and Malbork formations and the Upper Buntsandstein of the Elbląg Formation and in some regions of the carbonate-clastic formation. Each formation constitutes one large scale fining-upward succession.

According to Szyperko-Śliwczyńska (1979), the Lidzbark Formation in the study area is composed of grey, green-grey to violet-grey and violet-brown calcareous mudstones with intercalations or laminae of limestone. Sandy intervals are concentrated at the base of the unit, but constitute only a subordinate component. In the Bartoszyce IG 1 borehole these occur at depths of 987.9–1049.2 m (Szyperko-Śliwczyńska, 1979; Fig. 3). Within the formation, horizontal and leticular lamination in mudstones was observed, highlighted by streaks of marl or marly limestone. Root traces, fish remains as well as lenses or cracks filled with ooids occur within the succession. Limestone intercalations are mostly <0.5 m thick, reaching 2 m. They are represented by sandy oolites with flaser mudstone lamination. The sandstones are very fine grained to silty, flaser or horizontal laminated, calcareous. The Lidzbark Formation occurs at 2005.0–2072.0 m depth in the Nidzica IG 1 borehole (Szyperko-Śliwczyńska, 1979; Fig. 4). It is developed as described above though with a greater amount of sandy-oolitic intervals throughout the succession (Szyperko-Śliwczyńska, 1979) and with more pronounced flaser, wavy and leticular lamination, rare anhydrite nodules and erosive basal surfaces of thicker sandy beds (CBDG, 2008).

The Malbork Formation of northeastern Poland is formed by red to red-brown calcareous mudstones with subordinate sandy intercalations that are concentrated in the lowermost part of the succession (Szyperko-Śliwczyńska, 1979). In the Bartoszyce IG 1 borehole, where it occurs at 898.0–987.9 m depth (Fig. 3), mudstones are horizontally laminated or structureless, very rarely rippled and bear clay intraclasts or calcareous nodules. Plant and fish remains occur occasionally. Siltstone or fine-grained sandstone intercalations are mostly grey and often mottled. Rare marl intercalations occur. The formation was described from 1962.0–2005.0 m depth in the Nidzica IG 1 borehole (Szyperko-Śliwczyńska, 1979; Fig. 4). It consists of sandy mudstones, mostly red, partly variegated, with sandstone intercalations concentrated in the lowermost part of the formation, partly cross-laminated (CBDG, 2008).

The lowermost part of the Elbląg Formation is mostly grey, sandy and conglomeratic; it is overlain by red mudstones and fine-grained sandstones (Szyperko-Śliwczyńska, 1979). In the Pasłęk IG 1 borehole it occurs at 1090.0–1170.0 m depth (Szyperko-Śliwczyńska, 1979; Fig. 5). It starts with light grey sandy conglomerates built of marl and dolomite clasts up to 7 cm across, which are overlain by a mudstone succession with very fine sandstone intercalations, grey at the bottom and pale red in its upper part. Root traces, plant remains and fish plates are occasionally present. The coarser bottom deposits are cross-stratified, whereas a massive structure dominates in the

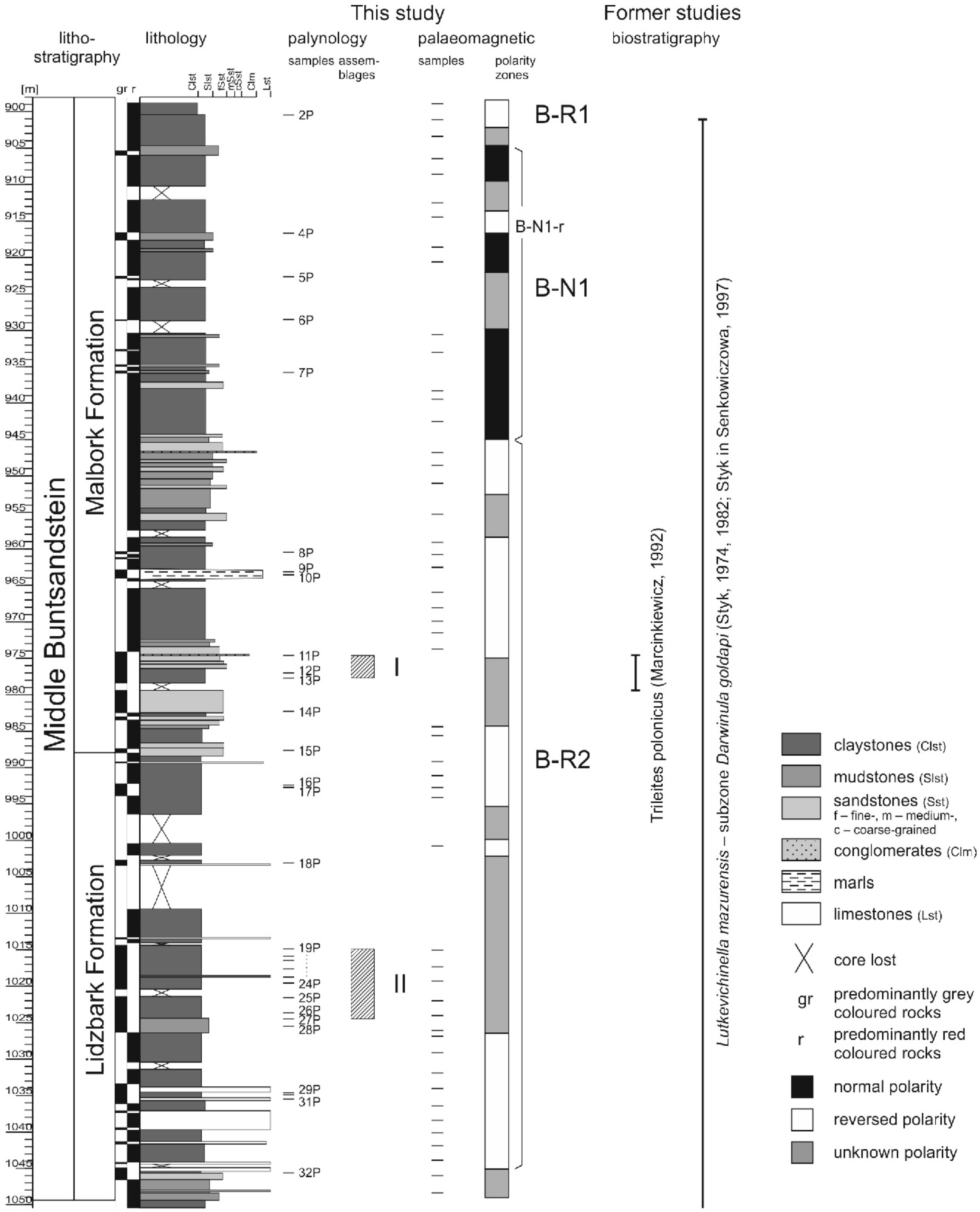


Fig. 3. Middle Buntsandstein section of the Bartoszyce IG 1 borehole with the main results of the present studies together with earlier biostratigraphic result

Lithostratigraphy after Szyperko-Śliwczyńska (1979)

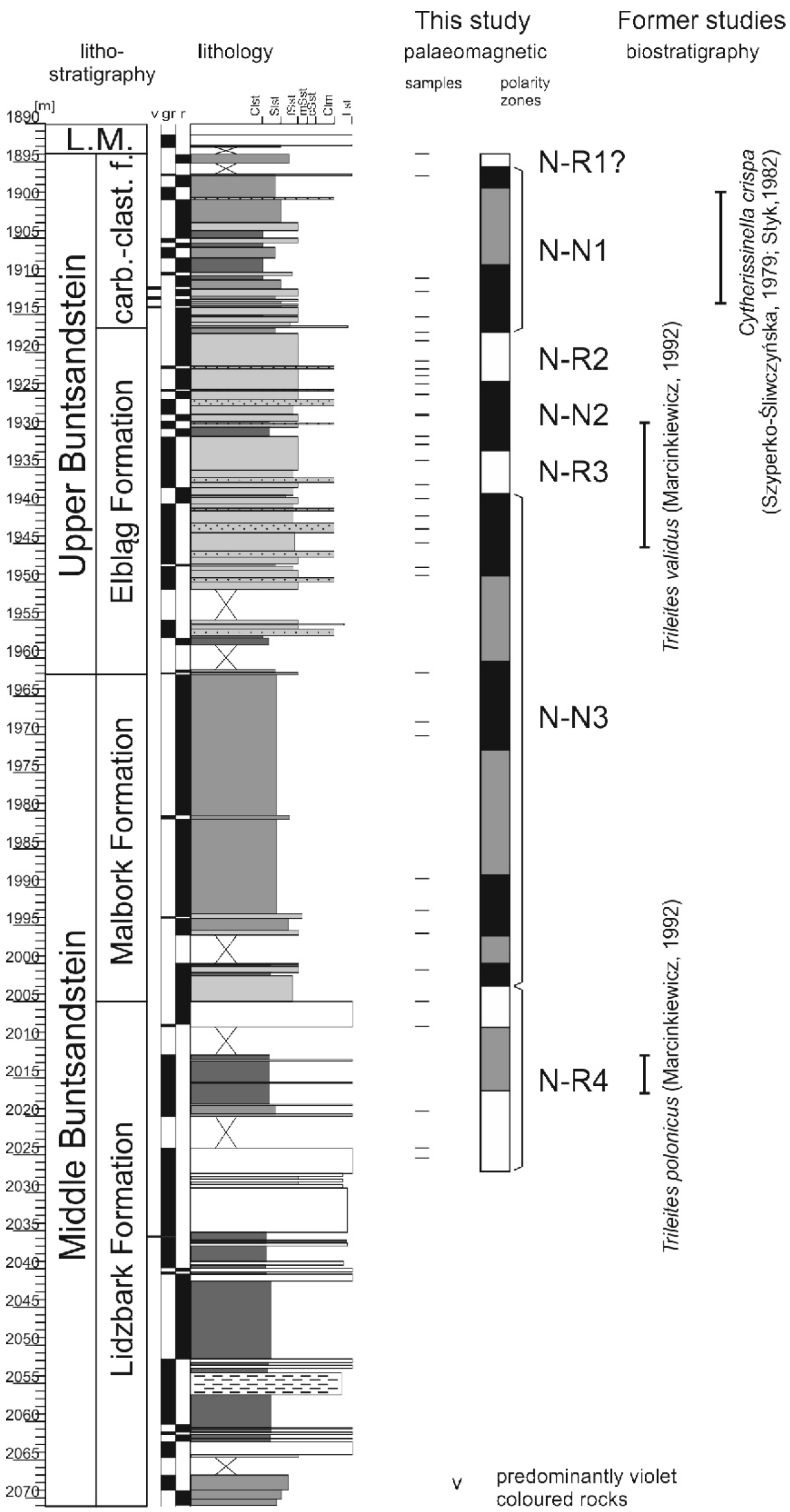


Fig. 4. Middle and Upper Buntsandstein section of the Nidzica IG 1 borehole with the main results of the present studies

Lithostratigraphy after Szyperko-Śliwczyńska (1979), lithology after Szyperko-Śliwczyńska (1966) and CBDG (2008); explanations as in Figure 3

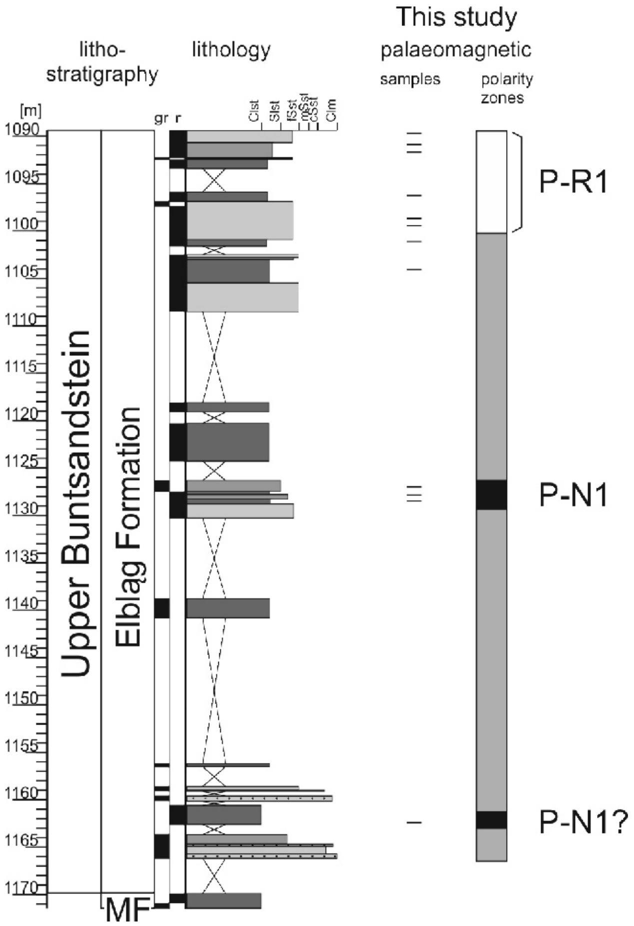


Fig. 5. Upper Buntsandstein section of the Pasłęk IG 1 borehole with the main results of the present studies

Lithostratigraphy after Szyperko-Śliwczyńska (1979); explanations as in Figure 3

fine-grained part of the formation. The Upper Buntsandstein succession of the Nidzica IG 1 borehole can be subdivided into its lower part (depth 1916.0–1962.0 m) built of fine-grained sandstones, and its upper part (depth 1895.0–1916.0) where mudstones, rarely intercalated with thin limestone beds, dominate (Fig. 4). The lower part is distinctly thicker than the upper one (CBDG, 2008). Calacareous conglomerates of pedogenic origin are regularly interbedded within the succession (CBDG, 2008). The upper part was recognized as "Röt" by Szyperko-Śliwczyńska (1979), and further described as informal carbonate-clastic formation (c.-cl. f.; Szyperko-Teller, 1997).

Stratigraphic zonations for the Buntsandstein succession of northeastern Poland were developed by Fuglewicz (1980) and Marcinkiewicz (1992) on the base of megaspores and by Orłowska-Zwolińska (1984) on the base of miospores. Styk (1982) provided an ostracod zonation without age interpretation. Chronostratigraphic dating of megaspore zones was mostly provided using correlation with the best dated microspore zonations (e.g., Marcinkiewicz, 1992). Only a few sections of northeastern Poland have been investigated in terms of microspore analysis (Orłowska-Zwolińska, 1984). No results have been published from the Bartoszyce IG 1, Pasłęk IG 1 and Nidzica IG 1 boreholes, which gave the rationale for the present studies.

Three megaspore zones have been distinguished within the Middle and Upper Buntsandstein section of the region: the *Trileites polonicus* Zone extending from the Lidzbark to the lowermost Malbork Formation, the *Talchirella daciae* Zone occurring in the Malbork Formation and the *Trileites validus* Zone corresponding to the Elbląg Formation (Marcinkiewicz, 1992; Fig. 2). The megaspore zone *Trileites polonicus* has been detected within the uppermost Lidzbark Fm. of the Nidzica IG 1 borehole and the lowermost Malbork Fm. of Bartoszyce IG 1 (Marcinkiewicz, 1992, Figs. 3 and 4) and the *Trileites validus* Zone has been determined in the lower Elbląg Fm. of Nidzica IG 1 (Marcinkiewicz, 1992; Fig. 4).

Orłowska-Zwolińska (1984) identified the *Densoisporites nejburgii* miospore Zone within the Lidzbark Fm. and found no miospores within the Malbork Fm. The Elbląg Formation comprises a microspore assemblage corresponding to the *Voltziaceaesporites heteromorpha* Zone (Orłowska-Zwolińska, 1984; Fig. 2). As mentioned above, miospore zones have not been reported from the boreholes investigated up to now.

The ostracod zones have shown the widest stratigraphic range, which makes them unsuitable for detailed geological reconstructions. Nevertheless, two zones have been established: of *Lutkevichinella mazurensis*, extending from the Lower to the Middle Buntsandstein, subdivided into the *L. mazurensis* Subzone below and the *Darvinula goldapi* Subzone above; and the *Cytherissinella crispa* Zone, characterizing the Upper Buntsandstein (Styk, 1982; Senkowiczowa, 1997; Figs. 2–4). An ostracod assemblage corresponding to the *Lutkevichinella mazurensis Zone* has been recognized in the Bartoszyce IG 1 and Pasłęk IG 1 sections, extending from the Lower Buntsandstein up to the uppermost Malbork Fm. (Styk, 1974, 1982; Fig. 3). Within the uppermost Upper Buntsandstein of the Nidzica IG 1 section an assemblage representing the *Cytherissinella crispa* Zone was detected (Styk in Szyperko-Śliwczyńska, 1979; Fig. 4). The chronostratigraphic interpretation of the biostratigraphic results showed that the Middle Buntsandstein of northeastern Poland corresponds to the Olenekian (Marcinkiewicz et al., 2014 and references therein; Fig. 2). The Upper Buntsandstein was placed less precisely around the Olenekian-Anisian boundary (Marcinkiewicz et al., 2014).

As noted above, until now magnetostratigraphy has been applied only in western and central Poland (Nawrocki, 1997; Nawrocki et al., 2003; Becker and Nawrocki, 2014).

MATERIAL AND METHODS

PALYNOSTRATIGRAPHY

32 samples from the Bartoszyce IG 1 core interval of 892.48–1045.75 m were examined, of which 15 yielded palynological material (Figs. 3 and 6). The rock material was treated with HF according to the method described by Orłowska-Zwolińska (1983). For quantitative analysis 200 palynomorphs were counted per slide. Only in very sparse spectra were all palynomorphs counted.

MAGNETOSTRATIGRAPHY

50 mudstone samples, oriented as regards way-up, were taken from the Bartoszyce IG 1 core section: 22 from the Lidzbark Fm. and 28 from the Malbork Fm. (Fig. 3). 12 samples were collected from the Elbląg Fm. of the Pasłęk IG 1 section

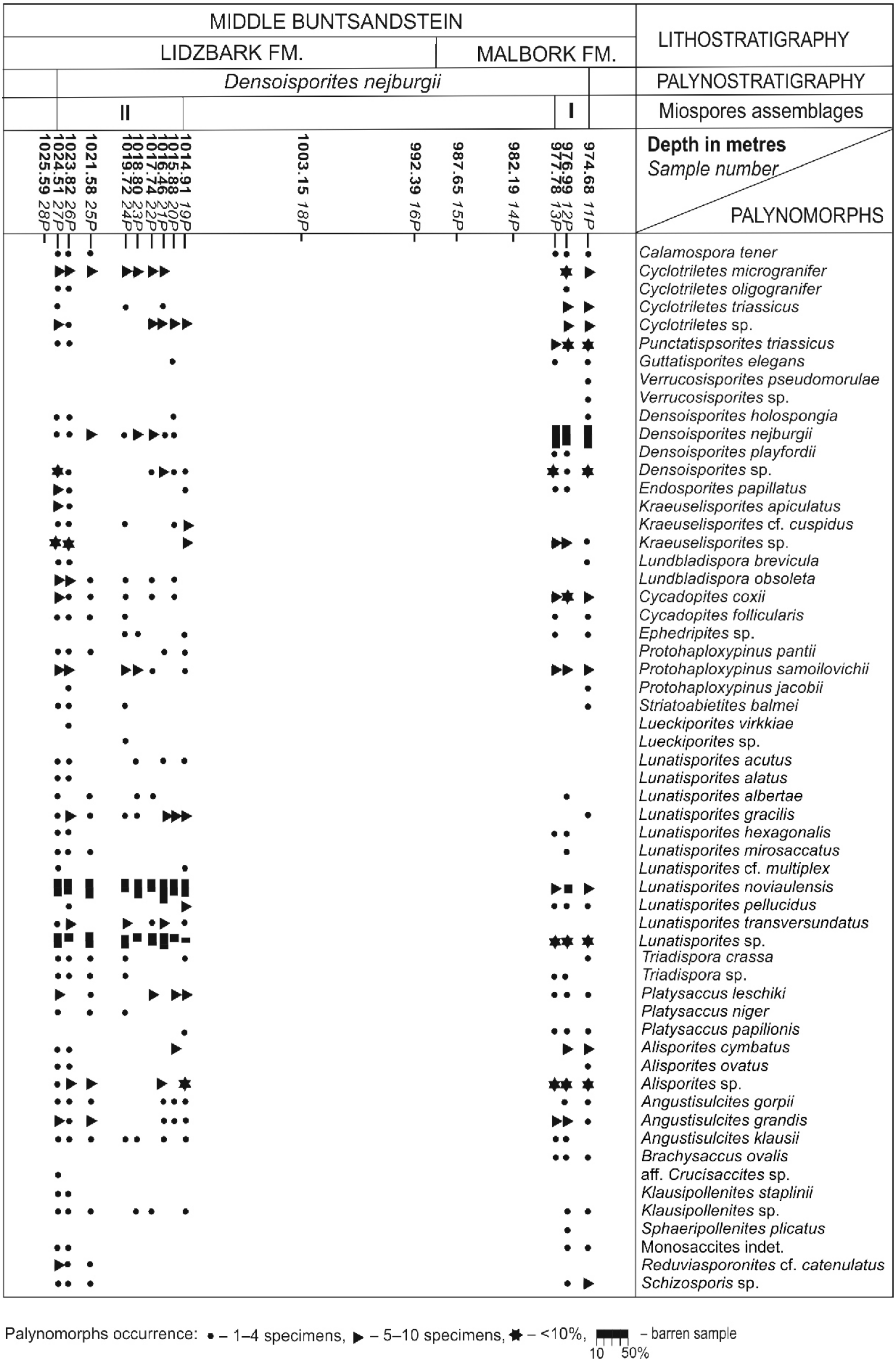


Fig. 6. Occurrence of selected palynomorphs in the Middle Buntsandstein of the Bartoszyce IG 1 borehole

For lithology see Figure 2

(Fig. 5). Investigations into the Nidzica IG 1 borehole were made on 40 samples from the depth interval of 1894.0–2025.0 m (Fig. 4).

Two cubic specimens of 8 cm^3 volume were cut off from each sample from the Bartoszyce IG 1 and Pasłęk IG 1 cores, yielding 124 specimens for palaeomagnetic studies. At least two cylindrical specimens were cored and cut off from each sample of the Nidzica IG 1 borehole.

Magnetic susceptibility was monitored using a KLY-2 susceptibility bridge for each specimen subjected to stepwise demagnetization in an MMTD1 oven up to temperatures at or below 680°C. The natural remanent magnetization (NRM) of specimens was measured using a *JR6A* magnetometer on the Bartoszyce IG 1 and Pasłęk IG 1 specimens, or a JR5 spinner magnetometer on Nidzica IG 1 samples. Components of natural remanent magnetization (NRM) for the Nidzica IG 1 specimens were calculated using the software developed by Lewandowski et al. (1997), based on principal component analysis (Kirshvink, 1980), and for the Bartoszyce IG 1 and Pasłęk IG 1 specimens using the *Remasoft 3.0* software (AGICO, Brno, Chadima and Hrouda, 2006). Diagrams representing the results were prepared using Remasoft 3.0 software. Magnetic polarity was interpreted using the reliability criteria of Nawrocki (1997).

RESULTS

PALYNOSTRATIGRAPHY

Seventy palynomorph taxa which comprise spores, pollen grains and algae were identified in the samples from the Bartoszyce IG 1 borehole (Appendix 1*). Two spore-pollen assemblages were distinguished: assemblage I at 974.68–977.78 m depth and assemblage II at 1014.91–1024.51 m depth (Figs. 3 and 6).

ASSEMBLAGE I

Characteristics: The assemblage is dominated by spores (50–70% of the spectra in the samples analysed), mainly of the lycopsid spores *Densoisporites nejburgii* (Fig. 7A–C). Less commonly, fern spores of the *Cyclotriletes* (Fig. 7E–G), *Punctatisporites* (Fig. 7H) genera occur, as well as lycopsid spores of the species *Densoisporites playfordii* (Fig. 7D) and *Endosporites papillatus* (Fig. 7I, J) and the genus *Kraeuselisporites* (Fig. 7K). These are accompanied by individual spores of the ferns *Guttatisporites* (Fig. 7L) and *Verrucosisporites* (Fig. 7M), the equisetalean spores *Calamospora* (Fig. 7N, O), and the moss spores *Sphagnumsporites* (Fig. 7P). Pollen grains (30–50% of the spectra examined) are strongly dominated by conifer pollen of *Alisporites* (Fig. 7R), *Lunatisporites* (Fig. 7S–U) and *Protohaploxypinus* (Fig. 8A, B). Pteridosperm pollen of *Platysaccus* (Fig. 8C, D), the conifer pollen *Brachysaccus ovalis* (Fig. 8E) and *Angustisulcites grandis* (Fig. 8F) as well as cycadalean pollen of *Cycadopites* (Fig. 8G, H) are abundant. These are accompanied by rare conifer pollen of the genera *Klausipollenites, Lueckisporites* (Fig. 8I), *Striatoabietites, Triadispora* (Fig. 8J) and *Sphaeripollenites* (Fig. 8K), as well as gnetacean pollen of *Ephedripites* sp. (Fig. 8L). Algae (1–2% of the spectra) are represented mainly by the *Schizosporis* (Fig. 8M) and *Reduviasporonites*. In addition, a few undetermined forms were found (Fig. 8N–P).

Occurrence: depth 974.68 m, 976.99 m and 977.78 m; Malbork Fm., Middle Buntsandstein (Figs. 3 and 6).

ASSEMBLAGE II

Characteristics: The assemblage is strongly dominated by conifer pollen (60–90% of the spectra examined), whereas spores are less abundant (10–40%). The latter are represented mainly by lycopsid spores of the *Densoisporites* (Fig. 9A, B), *Kraeuselisporites* (Fig. 9C–H) and *Lundbladispora* (Fig. 9I, J) genera, as well as *Cyclotriletes* fern spores (Fig. 9K). Relatively numerous occurrences of spores in tetrads is a characteristic feature of this assemblage (Fig. 9H, L). Specimens of *Lunatisporites* (Fig. 9M-U) are most abundant among the pollen (40–60% of the spectra examined), whereas pollen of *Protohaploxypinus* (Fig. 10A–C), *Alisporites* (Fig. 10E), *Platysaccus* (Fig. 10F), *Angustisulcites* (Fig. 10G, H) and *Cycadopites* occur less abundantly. They are accompanied by individual pollen of *Klausipollenites* (Fig. 10I), *Striatoabietites, Lueckisporites* (Fig. 10D) and *Triadispora* (Fig. 10J, K), as well as mono- and polysaccate pollen (Fig. 10L).

Occurrence: depth 1014.91 m, 1015.88 m, 1016.46 m, 1017.74 m, 1018.80, 1019.72 m, 1021.58 m, 1023.82 m and 1024.51 m; Lidzbark Fm., Middle Buntsandstein (Figs. 3 and 6).

Comparisons and correlations: Both assemblages represent the *Densoisporites nejburgii* Subzone of the *Densosiporites nejburgii* Zone distinguished by Orłowska-Zwolińska (1977, 1984, 1985; Fig. 2) in the middle part of the Middle Buntsandstein (Olenekian), although a significant dominance of striatite conifer pollen in assemblage II suggests affinity to the older *Lundbladispora obsoleta–Protohaploxypinus pantii* Zone (e.g., Fijałkowska, 1994a, b). This assemblage also contains a few miospores characteristic of the younger *Voltziaceaesporites heteromorpha* Zone, such as *Guttatisporites* sp., *Lapposisporites* sp., *Angustisulcites* sp. and *Microcachryidites* sp. (e.g., Orłowska-Zwolińska, 1984, 1985), that makes it similar to the *nejburgii–heteromorphus* Zone recognized in the Southern Alps and Transdanubian Mts. in the Tethyan realm (e.g., Nowak et al., 2018); however, the index species *Voltziaceaesporites heteromorphus* Klaus was not found.

MAGNETOSTRATIGRAPHY

The NRM is mostly carried by hematite with unblocking temperatures >600°C in specimens from the Bartoszyce IG 1 and Pasłęk IG 1 boreholes. In specimens from Nidzica IG 1 this temperature was >550°C but it was impossible to define it precisely because of a substantial increase in magnetic susceptibility, sometimes associated with the formation of an artificial component of remanent magnetization. This phenomenon was most probably connected with high temperature oxidation of some clay minerals to magnetite while heating the samples in air. Examples of demagnetizing diagrams for samples of normal and reversed polarity are shown in Figures 11–13. Polarity interpretation adequate for magnetostratigraphy was achieved for 60% of specimens from the Bartoszyce IG 1 section (Fig. 14), 71% of specimens from the Pasłęk IG 1 section (Fig. 15) and 72% of Nidzica IG 1 specimens (Fig. 16). One of the problems was the lack of orientation of sample tops, especially from the Pasłęk IG 1 core, caused by poor core preservation. Fortunately, in most cases the viscous low-temperature component of NRM was present in the samples studied. We assumed its recent origin and consequently this magnetization is directed to the bottom of sample. Results achieved from each borehole are shown in Figures 14–16. Simplified polarity logs showing local zones are compared with other data on Figures 3–5.

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1533

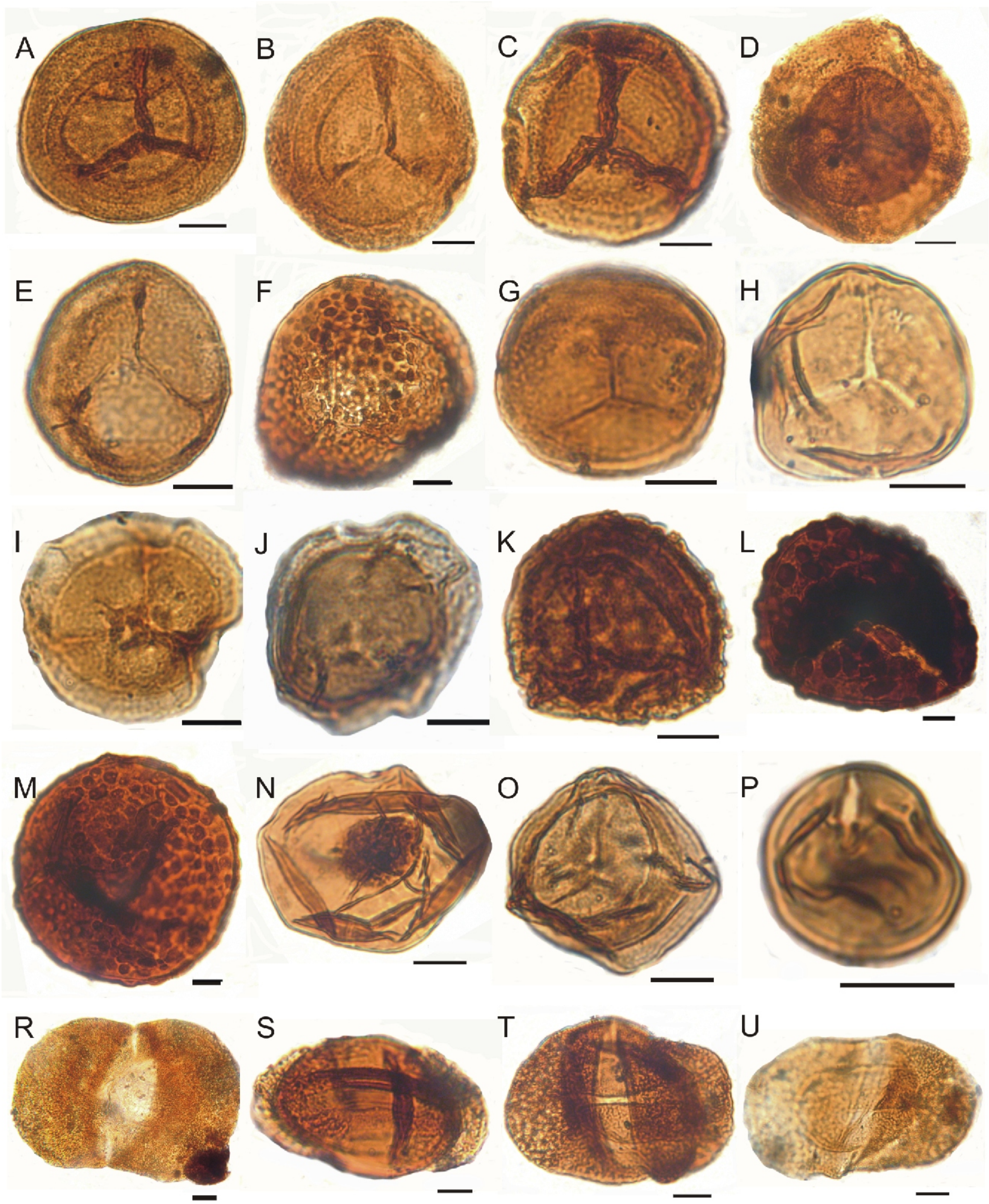


Fig. 7. Miospores from the Middle Buntsandstein (Malbork Fm.) of the Bartoszyce IG 1 borehole (Assemblage I)

A–**C** – *Densoisporites nejburgii* (Schulz) Balme; **D** – *D. playfordii* (Balme) Dettmann; **E** – *Cyclotriletes microgranifer* Mädler; **F** – *C. oligogranifer* Mädler; **G** – *C. triassicus* Mädler; **H** – *Punctatisporites triassicus* Schulz; **I, J** – *Endosporites papillatus* Jansonius; **K** – *Kraeuselisporites* sp.; **L** – *Guttatisporites elegans* Visscher; **M** – *Verrucosisporites pseudomorulae* Visscher; **N** – *Calamospora tener* (Leschik) de Jersey; **O** – *C.* sp.; **P** – *Sphagnumsporites* sp.; **R** – *Alisporites cymbatus* Venkatachala, Beju et Kar; **S** – *Lunatisporites gracilis* (Jansonius) Fijałkowska; **T** – *L. noviaulensis* (Leschik) Scheuring; **U** – *L. pellucidus* (Goubin) Helby; A, F, G, L, M, P, R, S – depth 974.68 m; B, C, E, H, I, K, U – depth 976.99 m; D, J, N, O, T – depth 977.78 m; scale bar 10 μm

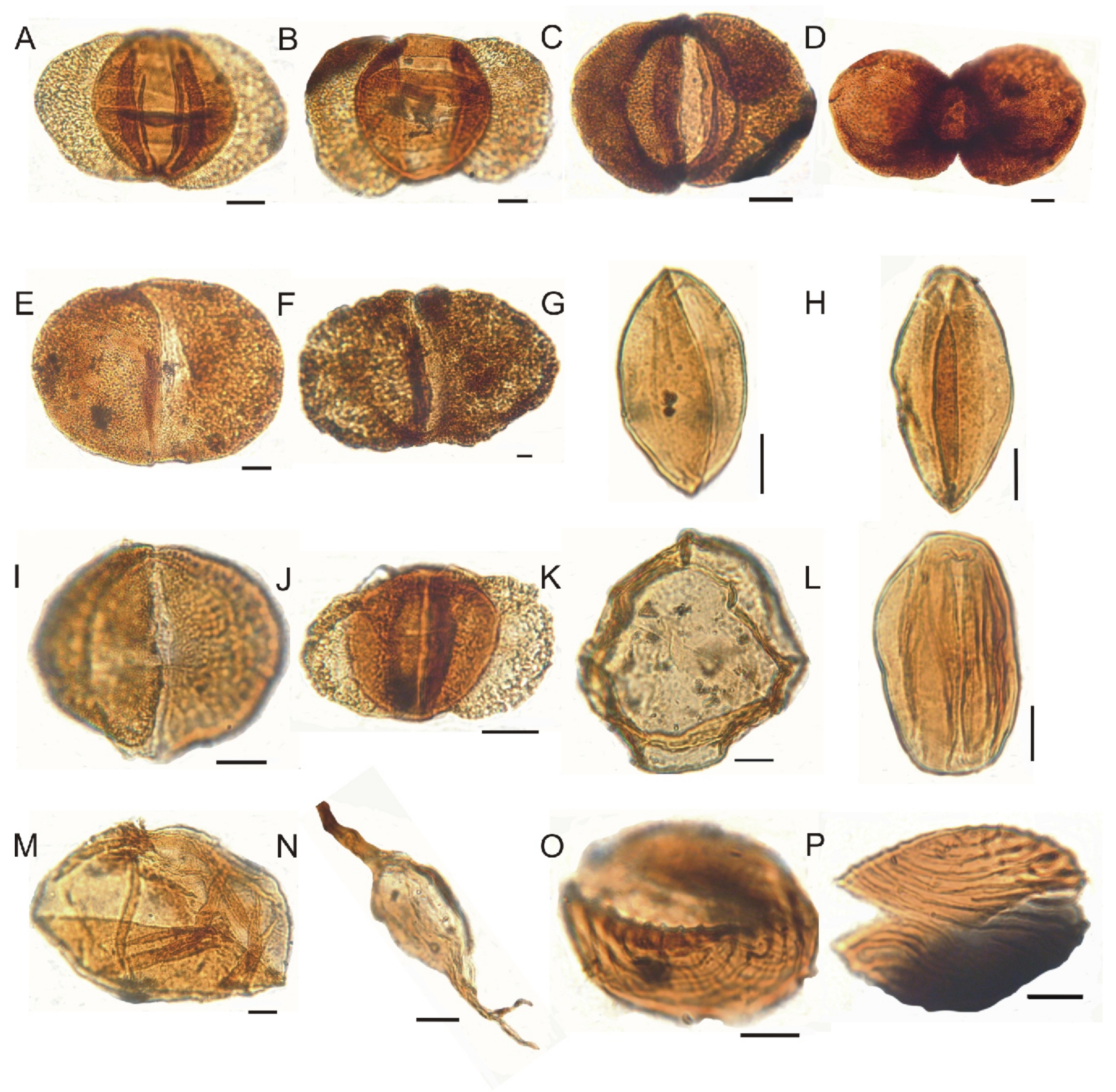


Fig. 8. Palynomorphs from the Middle Buntsandstein (Malbork Fm.) of the Bartoszyce IG 1 borehole (Assemblage I)

A – *Protohaploxypinus jacobii* (Jansonius) Hart**;** **B** – *P. samoilovichii* (Jansonius) Hart; **C** – *Platysaccus leschiki* Hart; **D** – *P. papilionis* Potonié et Klaus; **E** – *Brachysaccus ovalis* Mädler*;* **F** – *Angustisulcites grandis* (Freudenthal) Visscher; **G** – *Cycadopites coxii* Visscher; **H** – *C. follicularis* Wilson et Webster; **I** – *Lueckisporites* sp.; **J** – *Triadispora* sp.; **K** – *Sphaeripollenites plicatus* Orłowska-Zwolińska; **L** – *Ephedripites* sp.; **M** – *Schizosporis* sp.; **N, O, P** – ?algae; A, B, D, E, G, H, L, M, P – depth 974.68 m; C, F, I, J, K, M, N, O – depth 976.99 m; L, P – depth 977.78 m; scale bar 10 μm, E – 25 μm

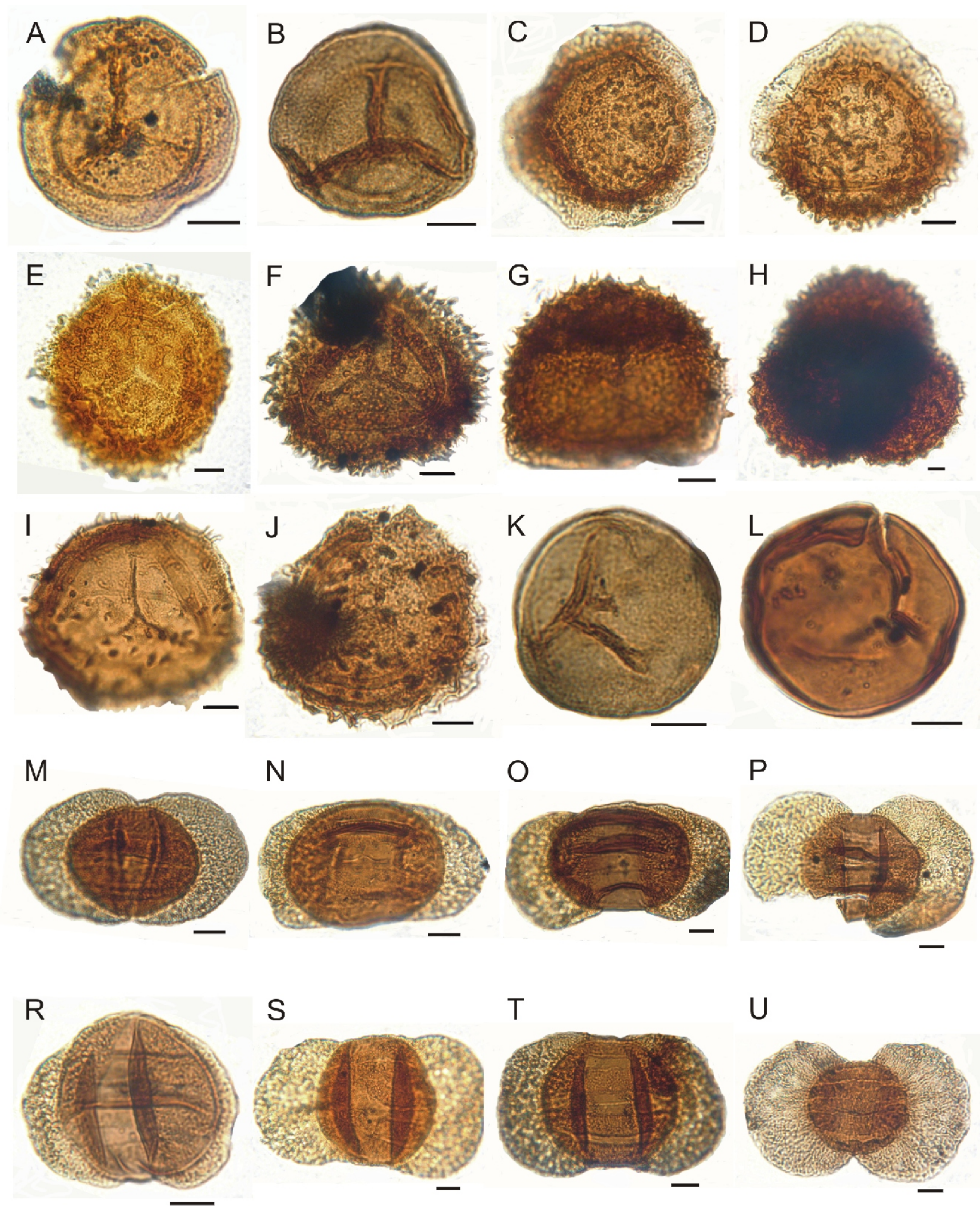


Fig. 9. Miospores from the Middle Buntsandstein (Lidzbark Fm.) of the Bartoszyce IG 1 borehole (Assemblage II)

A, B – *Densoisporites nejburgii* (Schulz) Balme; **C, D** – *Kraeuselisporites apiculatus Jansonius*; **E** – *Kraeuselisporites* cf. *cuspidus* Balme; **F**– *Kraeuselisporites* cf. *ullrichi* Reinhardt et Schmitz; **G** – *K.* sp.; **H** – tetrad of *Lapposisporites* sp.; **I, J** – *Lundbladispora obsoleta* Balme; **K** – *Cyclotriletes microgranifer* Mädler; **L** – *Punctatisporites triassicus* Schulz; **M** – *Lunatisporites acutus* Leschik; **N** – *L. alatus* (Klaus) Scheuring; **O** – *L. gracilis* (Jansonius) Fijałkowska; **P** – *L. hexagonalis* (Jansonius) Fijałkowska; **R** – *L. microsaccatus* Fijałkowska; **S** – *L.* cf. *multiplex* (Visscher) Scheuring; **T** – *L. noviaulensis* (Leschik) Scheuring; **U** – *L. transversundatus* (Jansonius) Fijałkowska; A, E, L – depth 1015.88 m; B, C, D, F, G, I, J, K, O, P, R, S – depth 1024.51 m; H, M, T – depth 1014.91 m; N, U – depth 1023.82 m; scale bar 10 μm

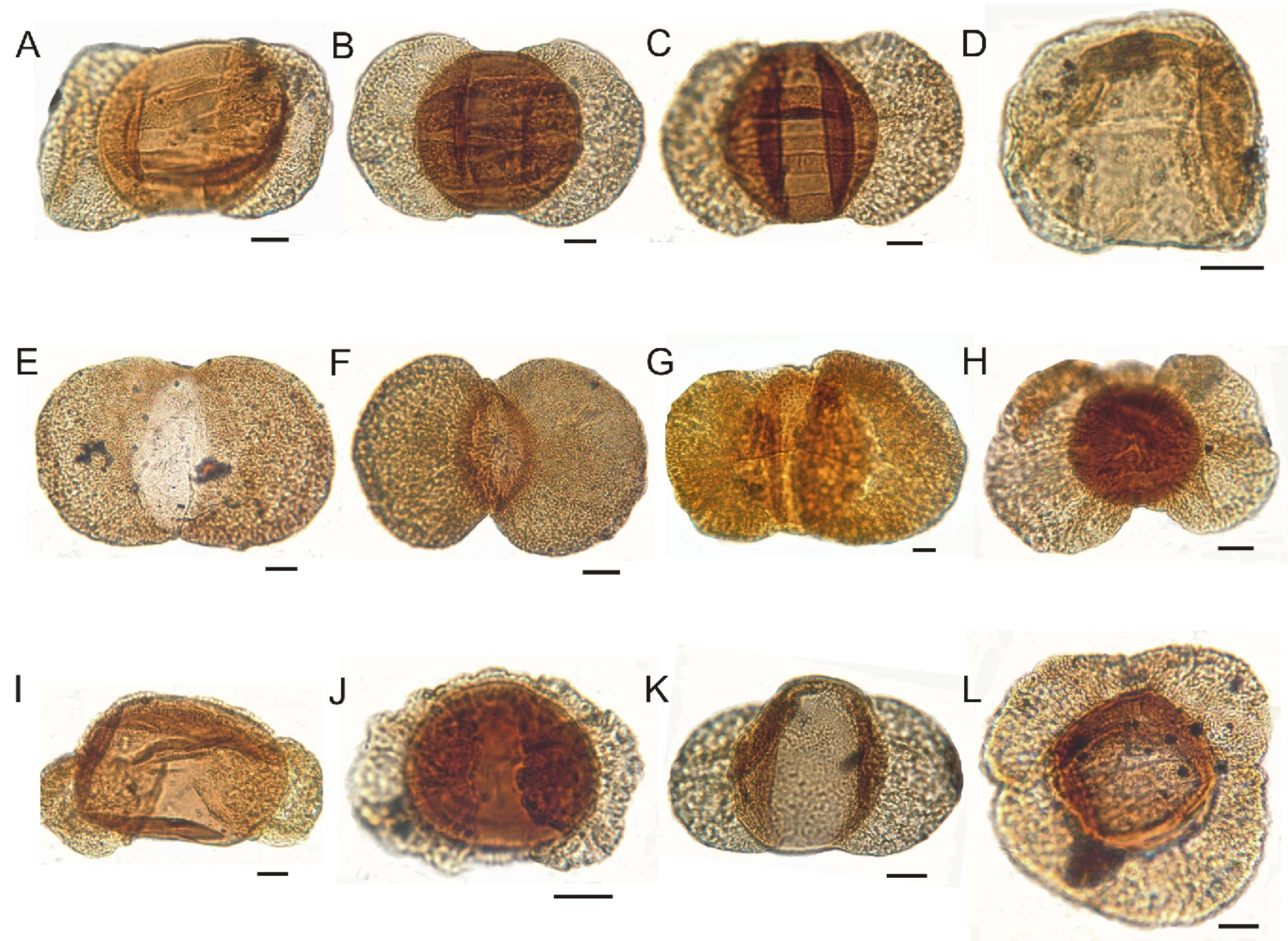


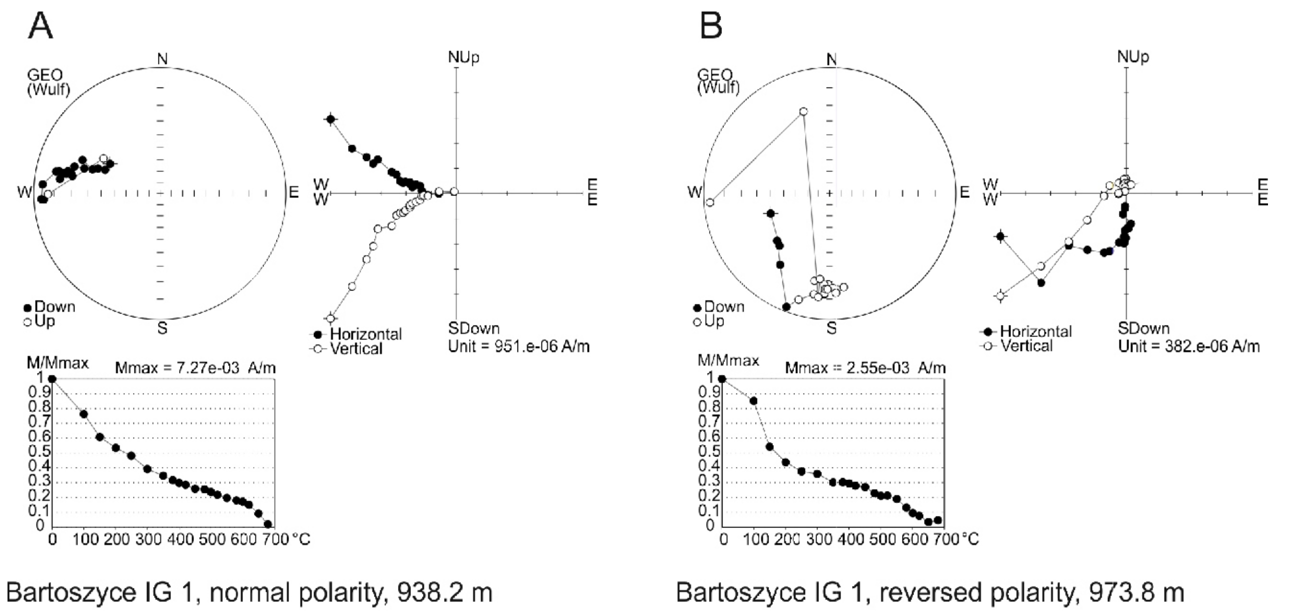
Fig. 10. Miospores from the Middle Buntsandstein (Lidzbark Fm.) of the Bartoszyce IG 1 borehole (Assemblage II)

A, **B** – *Protohaploxypinus pantii* (Jansonius) Orłowska-Zwolińska; **C** – *Protohaploxypinus samoiolovichii* (Jansonius) Hart; **D** – *Lueckisporites virkkiae* Potonié et Klaus; **E** – *Alisporites* sp.; **F** – *Platysaccus leschiki* Hart; **G** – *Angustisulcites grandis* (Freudenthal) Visscher; **H** – *A. klausi* Freudenthal; **I** – *Klausipollenites* sp.; **J** – *Triadispora crassa* Klaus; **K** – *T.* sp.; **L** – aff. *Crucisaccites* sp.; A, D, – depth 1021.58 m; B, C, E, H, J, K, L – depth 1024.51 m; F – depth 1014.19 m; G – depth 1015.88 m; I – depth 1023.82 m; scale bar 10 µm

The two uppermost samples of the Bartoszyce IG 1 borehole show reversed polarity, composing the first reversed polarity local zone (B-R1) within the uppermost Malbork Fm. (Fig. 14). Within the underlying 40 m of the profile the samples show mostly normal polarity or the polarity was undeterminable. Only in one sample was reversed polarization detected. This succession forms the first local normal polarity zone (B-N1) located in the upper Malbork Fm. with one short reversed subzone (B-N1-r). All samples from the depth interval 946.9–1048.3 m show reversed polarity or the polarity was not determinable. They form the second local reversed polarity zone (B-R2) encompassing the lower Malbork and all of the Lidzbark formation (Figs. 3 and 14). Most results were interpreted as first category of reliability after the criteria of Nawrocki (1997; Fig. 14).

Within the Elbląg Formation of the Pasłęk IG 1 borehole, 9 samples delivered results enabling polarity interpretation (Fig. 15). Five of them, located in the uppermost part of the formation, show reversed polarity (reversed local zone P-R1, Figs. 5 and 15). Three samples from the middle part of the formation and one from the lower part of it show normal polarity (normal local zone P-N1). Most of the polarities were interpreted as first reliability class, though 4 of these were detected in reversed core samples (Figs. 12 and 15).

The uppermost sample from the Upper Buntsandstein section of the Nidzica IG 1 borehole (Fig. 16) shows reversed polarity of first reliability class. This suggests the occurrence of a reversed polarity interval (assumable N-R1? local zone). The next 4 samples interpreted show normal polarity and compriset the first normal local polarity zone N-N1. Because of the low quality of the results (only one result of first reliability class) zone N-N1 has to be considered with caution. The lower part of the Upper Buntsandstein shows a changing polarity pattern. Local zones N-R2, N-N2, N-R3 and N-N3 were distinguished. The normal local zone N-N3 continues down to the base of the Malbork Formation of the Middle Buntsandstein. The samples from the upper Lidzbark Formation show reversed polarity and form the lowermost local reversed zone N-R4. Eighteen of the 33 results interpreted were of the first category of reliability after the criteria of Nawrocki (1997; Figs. 13 and 16). In all samples from the Bartoszyce IG 1 and Pasłęk IG 1 boreholes the characteristic component of NRM was disclosed in a wide range of demagnetizing temperatures starting from 300°C. Because of this and because linear segments of the orthogonal diagrams were directed to the centre of the Zijderveld diagrams we inferred that the Triassic characteristic components of NRM isolated in the Nidzica IG 1 borehole are credible despite incomplete demagnetization (Fig. 16).



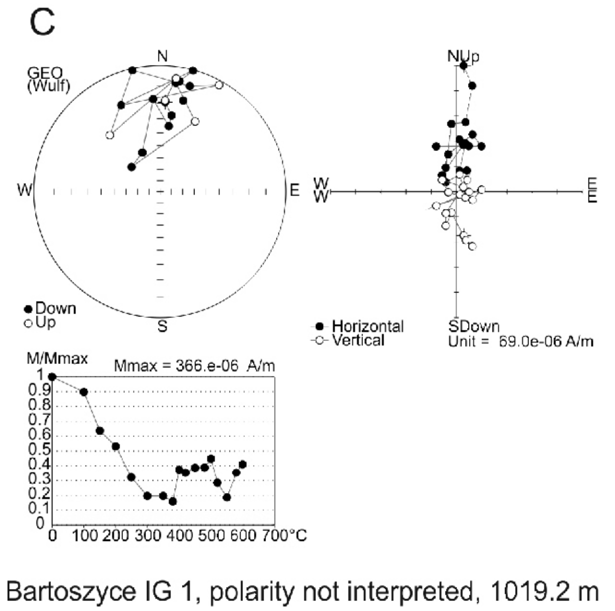


Fig. 11. Details of thermal demagnetization of specimens from the Middle Buntsandstein of the Bartoszyce IG 1 borehole

A – normal polarity, depth 938.2 m, Malbork Fm.; **B** – reversed polarity, depth 973.8 m, Malbork Fm.; **C** – polarity allocation not possible, depth 1019.2 m, Lidzbark Fm.

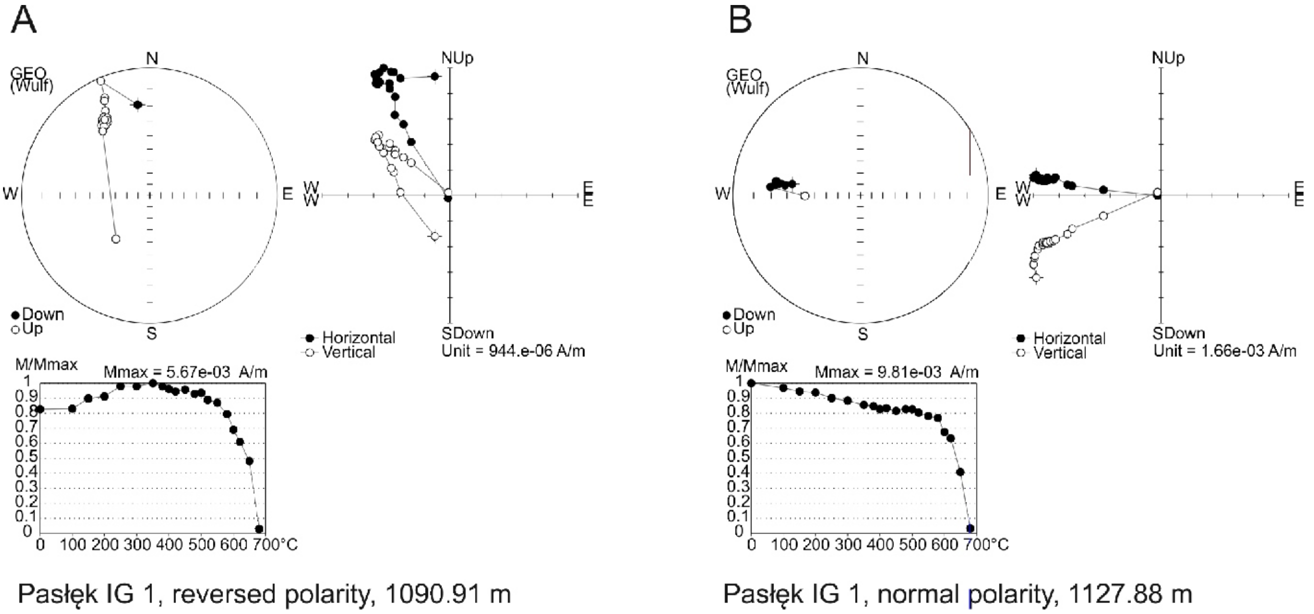


Fig. 12. Details of thermal demagnetization of specimens from the Upper Buntsandstein (Elbląg Fm.) of the Pasłęk IG 1 borehole

A – reversed polarity, depth 1090.91 m; **B** – normal polarity, depth 1127.88 m

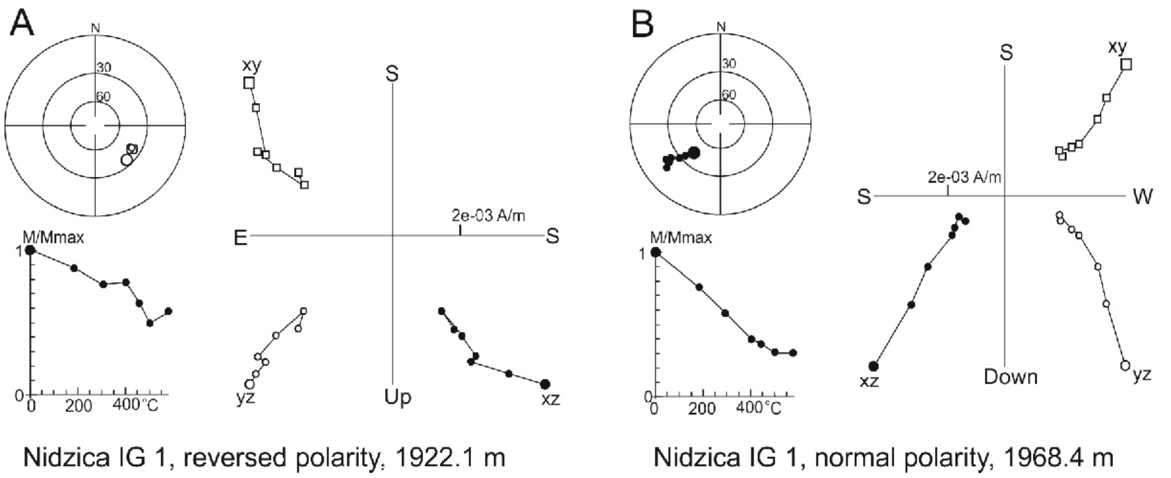


Fig. 13. Details of thermal demagnetization of specimens from the Upper and Middle Buntsandstein of the Nidzica IG 1 borehole

A – reversed polarity, depth 1922.0 m (Elbląg Fm.), **B** – normal polarity, depth 1968.0 m (Malbork Fm.)

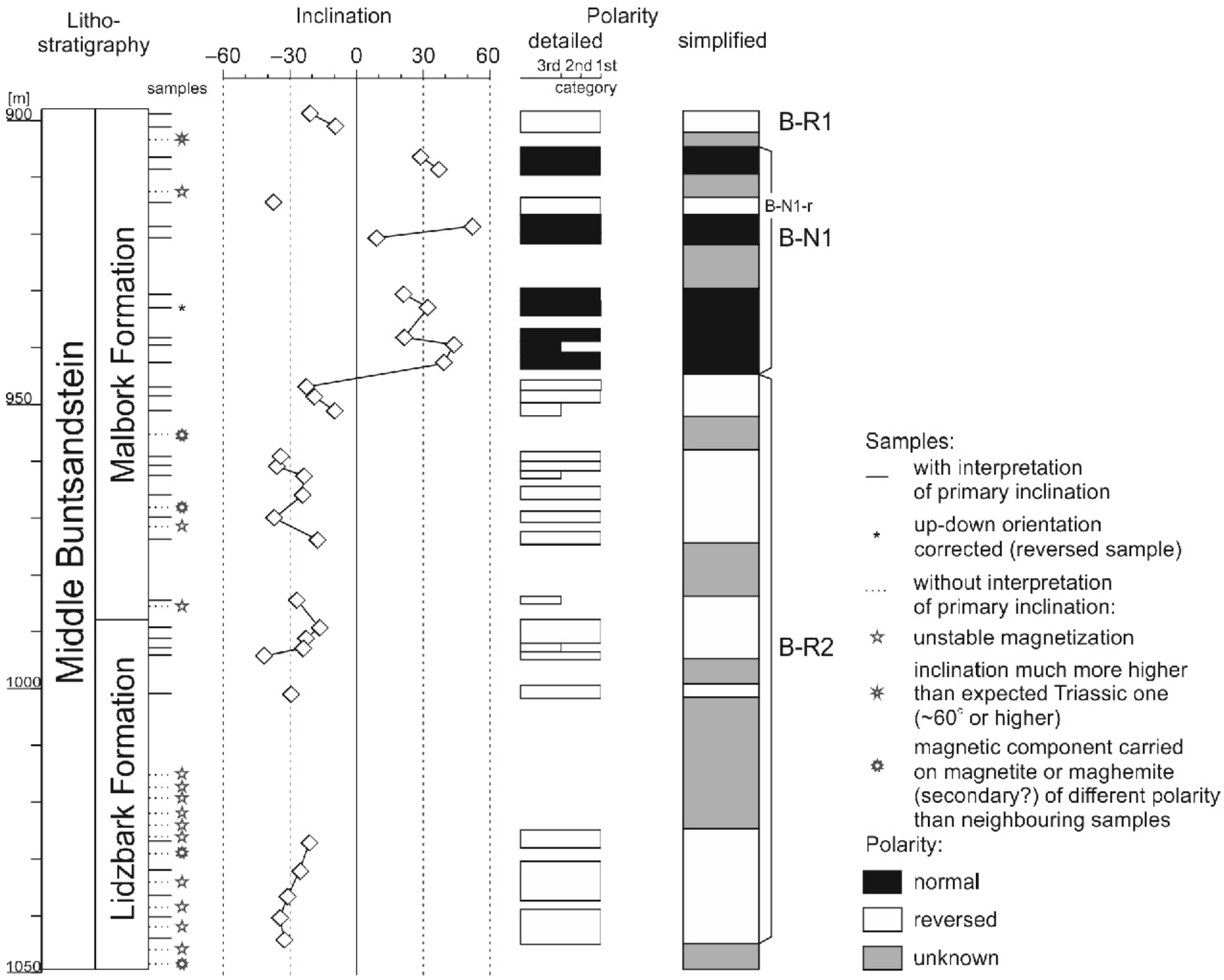


Fig. 14. Magnetostratigraphic analysis of the Middle Buntsandstein of the Bartoszyce IG 1 borehole

Dotted line for samples means specimens without interpretation of the primary inclination; categories of polarity data after Nawrocki (1997); for lithology see Figure 3

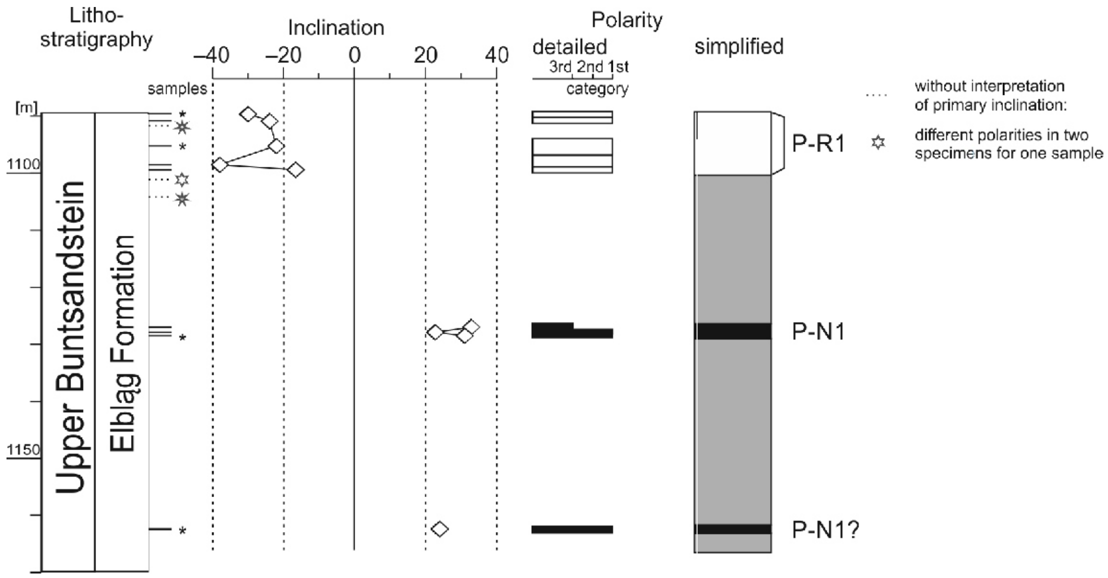


Fig. 15. Magnetostratigraphic analysis of the Upper Buntsandstein of the Pasłęk IG 1 borehole

Dotted line for samples means specimens without interpretation of the primary inclination; categories of polarity data after Nawrocki (1997); for lithology see Figure 5; other explanations as in Figure 14

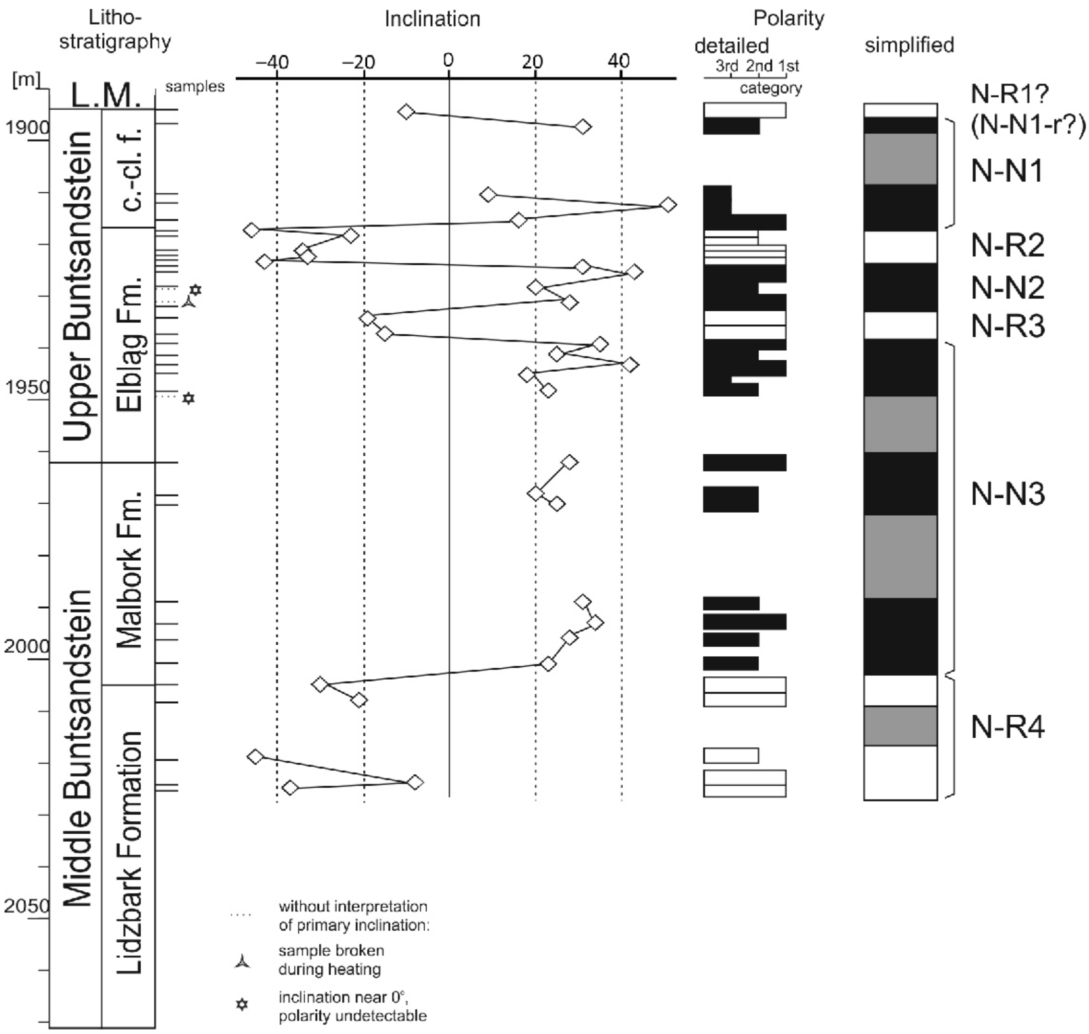


Fig. 16. Magnetostratigraphic analysis of the Middle and Upper Buntsandstein of the Nidzica IG 1 borehole

Dotted line for samples means specimens without interpretation of the primary inclination; categories of polarity data after Nawrocki (1997); for lithology see Figure 4; c.-cl. f. – carbonate-clastic formation; other explanations as in Figure 14

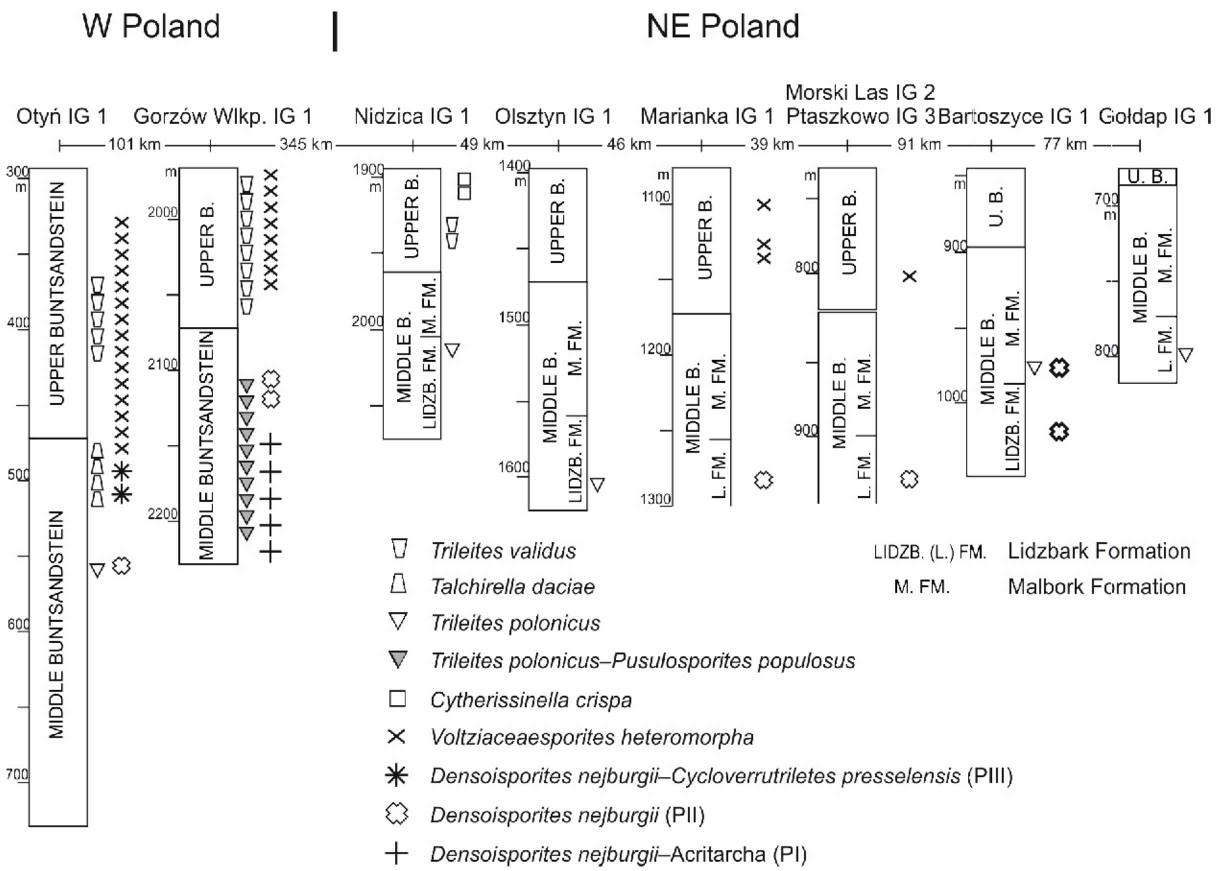


Fig. 17. Biostratigraphy of the Buntsandstein of northeastern Poland and its correlation to the Otyń IG 1 and Gorzów Wielkopolski IG 1 sections of western Poland

Lithostratigraphy after Szyperko-Śliwczyńska (1979), Orłowska-Zwolińska (1977), and Feldman-Olszewska (2014), biostratigraphy after Styk (1974, 1982), Fuglewicz (1979, 1980), Szyperko-Śliwczyńska (1979), Orłowska-Zwolińska (1977, 1984), and Marcinkiewicz (1992); results of this study are highlighted with thicker line; for locality see Figure 1

DISCUSSION

According to the results of palynostratigraphic analysis, the *Densoisporites nejburgii Zone*, *D. nejburgii* Subzone (PII) occurs within the succession discussed (Orłowska-Zwolińska 1984, 1985). The *Densoisporites nejburgii* Zone was defined in western Poland as the total range of *D. nejburgii* (Orłowska-Zwolińska, 1977, 1984). The zone stretches there through the whole Middle Buntsandstein as e.g. in the Gorzów Wielkopolski IG 1 and Otyń IG 1 boreholes (see Fig. 17). The zone was subdivided into three subzones (from bottom to top): *D. nejburgii*–Acritarcha, *D. nejburgii* and *D. nejburgii–Cycloverrutriletes presselensis* (Orłowska-Zwolińska, 1984). The lowermost subzone occurs in the lower to middle part of the Middle Buntsandstein of western Poland. The *D. nejburgii* Subzone was determined in the middle to upper part of the subgroup and the third subzone is characteristic of the upper Middle Buntsandstein of western Poland (see Fig. 17). In northeast Poland only the *D. nejburgii* Subzone was detected within the lower to middle part of the Middle Buntsandstein by Orłowska-Zwolińska (1984), as well as in this study (Fig. 17). This is significantly nearer the base of the Middle Buntsandstein subgroup than in the western part of the basin. A similar position within the Middle Buntsandstein section of NE Poland is occupied by the *Trileites polonicus* Zone, co-occurring with the *D. nejburgii* Subzone in the Polish basin (Marcinkiewicz, 1992; Marcinkiewicz et al., 2014). This suggests that Middle Buntsandstein sedimentation started in western Poland one palynological subzone earlier than at the northeastern basin margin. On the other hand the two palynological assemblages recognized in Bartoszyce IG 1 as the *D. nejburgii* Subzone are slightly different. The lower assemblage shows some similarities to the *Volziaceaesporites heteromorpha* or *nejburgii–heteromorphus* zones, known respectively from the marine Upper Buntsandstein of the Polish basin and from the Southern Alps and Transdanubian Mts. of the Tethyan realm (Orłowska-Zwolińska, 1984; Nowak et al., 2018). The presence of the algae *Schizosporis* and *Reduviasporonites* in the lower *D. nejburgii* assemblage of the Bartoszyce IG 1 borehole may indicate the acritarch acme defining the *D. nejburgii*–Acritarcha subzone of western Poland. Additionally, the assemblage discussed lies below the *T. polonicus* macrospore Zone in Bartoszyce IG 1 as could be expected for the lowermost subzone of the *D. nejburgii* Zone. On the other hand, there is a co-occurrence of the *Trileites polonicus–Pusulosporites populosus* megaspore Zone with both subzones, of *D. nejburgii*–Acritarcha and *D. nejburgii*, in the Gorzów Wielkopolski IG 1 borehole (Fig. 17). The *T. polonicus–P. populosus* Zone of Fuglewicz (1980) corresponds to the undivided *Trileites polonicus* and *Talchirella daciae* zones of Marcinkiewicz (1992). This demonstrates that co-occurrence of the *T. polonicus* Zone with the lowermost subzone of the *D. nejburgii* Zone is possible and this may be the case in the study area as well. Unequivocal definition of the palynological zones and subzones of northeastern Poland will need further investigations.

The Middle Buntsandstein succession of the Bartoszyce IG 1 borehole can be subdivided into two main palaeomagnetic local zones: a lower zone of reversed polarity (B-R2) and an upper zone of normal polarity (B-N1; Fig. 14). The boundary between both main local zones is located within the middle

Malbork Fm., which means that normal polarity is characteristic of the upper part of the Middle Buntsandstein. Such a pattern corresponds well to the magnetostratigraphic scale of western Poland in which the magnetozones Tbn6 and lowermost Tbn7 have been defined within the upper Middle Buntsandstein (Fig. 18; Nawrocki, 1997). The lower Middle Buntsandstein is dominated by reverse polarization of the uppermost part of the Tbr3 magnetozone and Tbr4–Tbr5 magnetozones (Fig. 18; Nawrocki, 1997). A similar magnetostratigraphic pattern is also known from Germany (Menning and Käding, 2013: fig. 6.7.4 therein). The boundary between the interval of predominant reversed polarization and of predominant normal polarization depicted in the Bartoszyce IG 1 borehole has been correlated with the boundary of the Tbr5 and Tbn6 zones of western Poland. The relatively low precision of polarity interpretation did not allow separation of the Tbn6 and Tbn7 zones. Thus, the whole normally polarized succession was defined as an undivided Tbn6–Tbn7 zone. The local B-R1 zone could be correlated either with the standard zone Tbr6 or with the reversed subzones occurring within the standard Tbn7 zone of western Poland (Fig. 18). The palynostratigraphic *Densoisporites nejburgii* Zone, *D. nejburgii* Subzone (PII) is connected with the boundary interval between the reversely and normally polarized parts of the Middle Buntsandstein in western Poland (Orłowska-Zwolińska, 1977, 1984; Nawrocki, 1997; Becker and Nawrocki, 2014). The base of the *D. nejburgii* Subzone (PII) lies within the uppermost Tbr5 magnetozone, whereas the base of the entire *D. nejburgii* Zone (PI-PIII) lies within the uppermost Tbr3 magnetozone in the Gorzów Wielkopolski IG 1 section (Orłowska-Zwolińska, 1977; Becker and Nawrocki, 2014). The local B-R2 magnetozone can also be correlated with the Tbr5 standard magnetozone or with the succession of the Tbr3 to Tbr5 magnetozones, considering the disputable stratigraphic interpretation of the lower palynomorph assemblage.

Only a few results from the Elbląg Fm. of the Pasłęk IG 1 have allowed a polarity interpretation. Nevertheless, those achieved from the lower part of the formation show normal polarity, whereas others obtained from its upper part indicate reversed polarity. This corresponds well with the standard scale. The lower and middle Upper Buntsandstein of western Poland shows mainly normal polarity and belongs to the Tbn7 magnetozone, whereas the upper part is mainly reverse magnetized (Tbr7

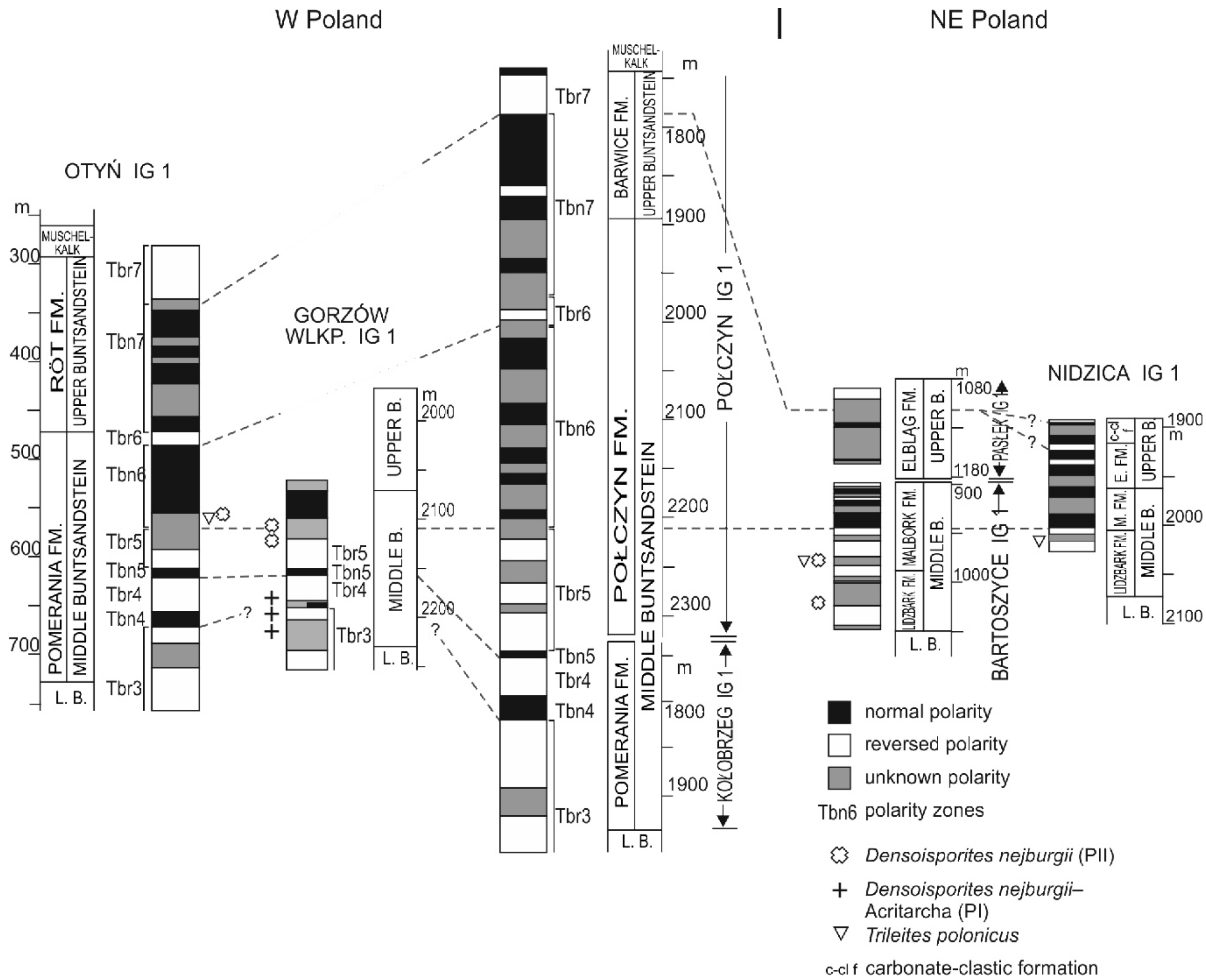


Fig. 18. Integrated magneto- and biostratigraphic correlation of the Buntsandstein of northeastern and western Poland

Magnetostratigraphy of western Poland after Nawrocki (1997) and Becker and Nawrocki (2014), miospore zones of Otyń IG 1 and Gorzów Wlkp. IG 1 after Orłowska-Zwolińska (1977, 1984), *T. polonicus* megaspore Zone after Marcinkiewicz (1992); for locality see Figure 1 magnetozone, Fig. 18; Nawrocki, 1997). Despite the lack of polarity data within the lower Elbląg Fm. of the Pasłęk IG 1 it is highly probable that the section can be included into the composite Tbn6–Tbn7 zone. The reversed local zone P-R1 of the uppermost Elbląg Fm. (Fig. 15) would be interpreted as the Tbr7 zone (Fig. 18). Results achieved from the Nidzica IG 1, discussed below, strengthen such an interpretation.

A similar pattern of polarity changes within the Middle and Upper Buntsandstein section has been detected in the Nidzica IG 1 section. The lower part of the Middle Buntsandstein shows reversed polarity (local zone N-R4), whereas the upper part of the subgroup is normally magnetized (local zone N-N3). The boundary between both zones is located in the lowermost Malbork Formation, i.e. distinctly nearer the base of the formation than in the Bartoszyce IG 1 section. The lowermost, reversely magnetized part of the Malbork Fm. detected in the latter section is lacking in the Nidzica IG 1 borehole, which suggests a stratigraphic gap, as suggested already by Szyperko-Śliwczyńska (1979: fig. 5 therein). Such an interpretation is supported by the thickness difference of the formation, which is significantly thicker in Bartoszyce IG 1 than in Nidzica IG 1. The occurrence of the megaspore *Trileites polonicus* Zone in both sections (Marcinkiewicz, 1992), in addition to the palaeomagnetic results given in this paper, enables another interpretation. The *Trileites polonicus* Zone coincides in both sections with the upper part of the reverse magnetized succession of the Middle Buntsandstein. But, it lies within the Lidzbark Fm. in Nidzica IG 1 in contrast to Bartoszyce IG 1, where the zone is located within the Malbork Fm. (see Figs. 3, 4 and 17). This allows the conclusion that the uppermost Lidzbark Fm. of Nidzica IG 1 is a lateral equivalent of the lowermost Malbork Fm. of the Bartoszyce IG 1 section. A stratigraphic gap at the base of the Malbork Fm. in the Nidzica IG 1 section cannot be confirmed. Nevertheless, considering the marginal position of the study area within the Buntsandstein basin, the presence of stratigraphic gaps is very possible in general.

The predominant part of the Upper Buntsandstein of Nidzica IG 1 is characterized by normal polarity (Fig. 16: local zone N-N3, beginning in the Middle Buntsandstein, and zones N-N2 and N-N1). The uppermost sample from the Elbląg Fm. showed reversed polarity, which possibly points to a polarity change detected in Pasłęk IG 1 as well, and also known from western Poland (the Tbr7 zone of Nawrocki, 1997). Further investigation should show if the reversed polarity continues up-section, forming a magnetozone, or not. The results of the Nidzica IG 1 borehole showed the presence of a long normal polarity zone stretching from the upper part of the Middle Buntsandstein towards the upper Upper Buntsandstein, which corresponds very well with the standard scale of western Poland and which can be correlated with the undivided magnetozone Tbn6–Tbn7. No correlation of the reversed local zones N-R3 and N-R2 with the standard scale can be proposed. Within the long normally magnetized succession of Tbn6–Tbn7 zones, Nawrocki (1997) defined a short reversed zone Tbr6, and a reversed subzone above it. A reversed subzone has also been detected in a similar position in Bartoszyce IG 1. This record indicates repeated short episodes of polarity changes. An even more complicated polarity pattern was demonstrated by Szurlies (2007) for the German part of the basin, who found 9 short reversed intervals (zones, subzones or undefined reversals) within the analoguous, predominantly normally polarized CG8n to CG11n succession. He was not able to correlate any of the German short reversed intervals with the Polish Tbr6 zone. It seems that the local zones N-R3 and N-R2 are located higher in the stratigraphic record than the Tbr6 zone, when the palynostratigraphic proxies are considered. The reversed zone N-R3 of Nidzica IG 1 co-occurs with the *Trileites validus* megaspore Zone (Marcinkiewicz, 1992), which corresponds with the middle to upper part of the Tbn7 magnetozone in Otyń IG 1 (Figs. 17 and 18; Marcinkiewicz, 1992; Nawrocki, 1997). The base of reversed zone Tbr7 is located just above the top of the *T. validus* Zone in the same borehole. The base of the local N-R2 zone is located directly above the top of *T. validus* Zone in the Nidzica IG 1 borehole. Thus, the N-R2 zone may correlate with the Tbr7 standard magnetozone. Summarizing, the base of standard Tbr7 zone can be correlated in the Nidzica IG 1 borehole either with the base of the N-R2 local zone or with the base of the tentative N-R1? reversal, located only slightly higher. The documented occurrence of numerous short episodes of reversed polarity in the part of the stratigraphic section discussed additionally impedes precise correlation. The local zone N-R4 can be correlated with the Tbr5 standard zone based on the correlation of the *Trileites polonicus* Zone of Marcinkiewicz (1992) between the Nidzica IG 1, Bartoszyce IG 1 and Otyń IG 1 boreholes.

CONCLUSIONS

Combined palynological and palaeomagnetic investigations on the Lower Triassic Buntsandstein sections of northeastern Poland have allowed construction of a more detailed chronostratigraphic framework.

The two palynomorph assemblages of the lower Lidzbark Formation and of the lowermost Malbork Formation can be correlated with the *Densoisporites nejburgii* Zone, *D. nejburgii* Subzone (PII). The lower assemblage might correlate with the *D. nejburgii*–Acritarcha Subzone (PI).

The palynostratigraphic results suggest diachronity of the base of the Middle Buntsandstein between western and northeastern Poland. The deposition of the Middle Buntsandstein would start one palynomoprh subzone later in northeastern Poland than in the western part of the Polish Basin. Developing a more precise framework of palynostratigraphic zones and subzones in NE Poland will test this conclusion.

The polarity pattern of the sections investigated in northeastern Poland correlate well with the standard magnetostratigraphic scale from western Poland, despite the marked thickness differences of the sections.

A long normal magnetic polarity zone containing two small reversed local magnetozones was detected within the upper Malbork Formation and in the lower and middle Elbląg Formation, which can be correlated with the undivided Tbn6–Tbn7 magnetozone of the standard scale (Nawrocki, 1997). Local reversed zones and subzones are incorporated into the normal polarity interval, as in western Poland and Germany.

The magnetostratigraphic results support a postulated quasi-isochroneity of the lithostratigraphic units of the Lower Triassic within the Polish Basin, which may be caused by a very high sedimentation rate in the Early Triassic and a very shallow depth of the entire basin as expected at a time of very high subsidence rate. Nevertheless, the boundaries of the units cannot serve as marker horizons because they may be diachronous as demonstrated for the base of the Malbork Fm. and possibly the base of the Middle Buntsandstein.

The base of the combined Tbn6–Tbn7 magnetozone is a good marker horizon throughout the basin. Usefulness of its top needs to be tested by further research. The magnetostratigraphic correlation showed that the upper Middle Buntsandstein and the lower Röt formation of the northwestern Fore-Sudetic Homocline (~250 m in thickness), the upper Połczyn Formation and the lower Barwice Formation of northwestern Poland (~400 m in thickness), as well as the Malbork Formation and the lower Elbląg Formation of northeastern Poland (~100 m in thickness) were deposited synchronously (see Fig. 18).

A stratigraphic gap between the Lidzbark and Malbork formations inferred by Szyperko-Śliwczyńska (1979) in the Nidzica IG 1 borehole can be only partly supported based on magnetostratigraphic correlation. Combination of the current magnetostratigraphic results with the published biostratigraphy allowed documention of lateral changes in parts of both formations, in contrast to a previously interpreted large stratigraphic gap between them.

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