Jurassic planktic foraminifera from the Polish Basin

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Abstract. Jurassic (Bathonian–Oxfordian) planktic foraminifera from the epicontinental strata of the Polish Basin have been investigated. The palaeoecology, palaeobiogeography, and biostratigraphical potential of the recorded taxa are discussed. Four species are recorded: Conoglobigerina helvetojurassica (Haeusler, 1881), Globuligerina balakhmatovae (Morozova, 1961), G. bathoniana (Pazdrowa, 1969), and G. oxfordiana (Grigelis, 1958). This assemblage is probably the most diverse of those described to date from the epicontinental areas of Europe. The recorded taxa are thought to represent three different ecological morphotypes. The clear relationship between transgressive–regressive facies and the palaeobiogeography of the recorded planktic foraminifera indicates a morphotype-related depth–distribution pattern in which small, simple, globular-chambered morphotypes occupied shallow waters whereas slightly larger, more complex forms, or those with hemispherical chambers, inhabited deeper and more open-water environments.

1 Introduction

Foraminifera constitute an unique group of marine protists that are used extensively as biostratigraphical and palaeoenvironmental proxies in the Earth sciences. Planktic foraminifera are especially useful due to their very wide, near-global, distribution (Masters, 1977; Hart, 1999; Premoli Silva and Sliter, 1999; Gradstein et al., 2017a). The adaptation to a planktic lifestyle took place relatively late in the history of the foraminifera, as benthic forms may have appeared in the Neoproterozoic (Pawlowski et al., 2003). It is suggested that planktic taxa appeared in the late Early Jurassic (Toarcian, ~180 Ma) following work by Wernli (1988, 1995), Simmons et al. (1997), Hart et al. (2003), Hudson et al. (2009), Leckie (2009), Gradstein et al. (2017a, b). The origin of planktic foraminifera, from benthic ancestors, is a key question in the evolutionary history of the foraminifera and in biological oceanography in general.

Shelf environments, probably close to continental margins, were the preferred habitat for the first appearance of primitive planktic foraminifera (Gordon, 1970; Gradstein et al., 2017b). Because the area of extra-Carpathian Poland was covered during the Middle and Late Jurassic by a relatively shallow, epicontinental, sea that extended from the northern part of the Tethys (northern Tethyan shelf), it appears to be a favourable ecological niche for planktic foraminifera and contains an important fossil record (Olszewska and Wiecezorek, 1988; Wierzbowski et al., 2009) in both the deeper waters of the Inner and Outer Carpathians and the shallower waters of the foreland region of the Polish Basin (north of Kraków). What is more, the rather low degree of diagenetic modification, and the high content of clay minerals in the sediments of the Polish Basin, enabled the preservation of aragonite foraminiferal tests. These mudstones also allow specimens to be extracted with little difficulty. This procedure is essential for morphological analysis and taxonomic identification of the planktic taxa, as compared to the thin section studies of Görög (1994) and Wernli and Görög (2000). Wernli and Görög (1999) also resorted to acid reductions of limestones from Hungary in order to study their material in 3-D. Despite these uniquely favourable research conditions in the Polish Basin, Jurassic planktic foraminifera have been described by very few authors, mostly during the 1960s and 1970s (Bielecka, 1960; Bielecka and Styk, 1967; Pazdrowa, 1969; Fuchs, 1973; Olszewska and Wiecezorek, 1988). The aim of our research was to summarize the present
knowledge of the planktic foraminifera from the studied area as well as to analyse newly collected material. Therefore, our research objectives were to understand the taxonomy, evolution, and palaeoecology of the Jurassic planktic foraminifera and demonstrate their utility in Late Jurassic stratigraphy and palaeoenvironmental interpretations.

Before discussion of our procedures it is important to record that both Oberhauser (1960) and Fuchs (1967, 1970) were interested in the origins of the planktic foraminifera and, in major investigations of Triassic and Lower Jurassic successions in Austria and northern Italy, erected a suite of both genera and species that were based on washed residues that provided 3-D material. Malcolm B. Hart, with the assistance of Holger Gebhardt, studied the Oberhauser and Fuchs material in the collections of the Geological Survey of Austria (including all of the type slides of the new taxa). This investigation concluded that, almost certainly, none of the taxa were planktic, and this was the same conclusion as that of Simmons et al. (1997). There are some taxa in the collection (Oberhauserella and Praegubkinella) that look to be very close to developing a planktic morphotype but may still be benthic in palaeoecology. Also in the collections are the taxa erected by Fuchs (1973) based on material collected by Manfred E. Schmid (Geological Survey of Austria) during the 10th European Micropalaeontological Colloquium. These meetings were held on a regular basis for many years and allowed “invited” geoscientists to visit key localities in Europe and collect, under local guidance, material for their institutions. The samples for the study by Fuchs (1973) appear to have come from the upper Callovian and lowermost Oxfordian of the “Kalksteinbruch von Wiek” near Ogrodzieniec. Both of the samples used by Fuchs (1973) – from beds 21 and 26 – are recorded as coming from the glauconitic marls that are present at the Callovian–Oxfordian boundary. In his paper, Fuchs (1973, p. 462, 474) describes his specimens as being “glauconitkern”, an internal cast composed of the Fe-rich clay mineral glauconite. This preservation was also noted by Loeblich and Tappan (1987) in their discussion of some of Fuchs’ new genera. Based on glauconitic steinkerns and with no test material or apertures preserved, all of the new taxa erected by Fuchs (1973) are, almost certainly, invalid.

The full significance of this style of preservation only became apparent when Plymouth-based PhD student Wendy Hudson attended the 7th International Congress on the Jurassic System in September 2006. The field excursion guidebook (Matyja and Wierzbowski, 2006) illustrates (op. cit., Fig. B1.8) an excavated section in the Ogrodzieniec Quarry in which the Ogrodzieniec Glauconitic Marls Formation (of latest Callovian and earliest Oxfordian age) is illustrated. Samples from this temporary exposure were collected, processed in Plymouth, and used by Hudson (2007) in her PhD thesis. Both samples contain almost no residue (when washed on a 63 µm sieve) aside from grains of glauconite, a very high proportion of which are the internal casts of both benthic – but mainly planktic – foraminifera. A study of the Fuchs (1973) collection in Vienna confirmed that the material is probably identical and that the samples collected by Manfred E. Schmid are from the same formation.

This comparison did resolve one problem with the illustrations displayed in Fuchs (1973). Despite being a good likeness of the material, Malcolm B. Hart could not understand the “double” lines in many of the drawings which, in places, are almost suggestive of marginal keels. Many of the specimens in our material have a different colour (dark green) of glauconite within the chambers and a slightly paler green where septa or chamber edges would have been located.

On a return visit to the Ogrodzieniec Quarry in 2011, with Jarosław Tyszka and Eiichi Setoyama, the temporary exposure created for the Jurassic symposium had been infilled and the Glauconitic Marls Formation was only exposed in

Figure 1. Glauconitic steinkerns of Globigerina sp. cf. G. oxfordiana from the Callovian–Oxfordian boundary section, Ogrodzieniec, Poland. All scale bars represent 50 µm except 3 and 8 in which scale bars are 100 µm.
Figure 2. Glauconitic steinkerns of (1–8) *Globuligerina* sp. cf. *G. oxfordiana* and (9–11) *Conoglobigerina helvetojurassica* from the Callovian–Oxfordian boundary section, Ogrodzieniec, Poland. All scale bars represent 50 µm except 3, 4, 5, 6, and 11 in which scale bars are 100 µm.

a track-side area (50°46'46.5" N, 19°51'86.2" E) with limited stratigraphical thickness visible. Samples from this very small section yielded the same type of residue with only glauconitic steinkerns present when washed on a 63 µm sieve. This material is exceptionally rich in planktic foraminifera with benthic foraminifera represented by only 10%–15% of the assemblage (Figs. 1, 2).

2 Material and methods

In total, 43 samples were examined for foraminiferal studies. The samples came from the Wrzosowa (6), Kawodrza (3), Stare Gliny (19), Ogrodzieniec (4), Gnaszyn (7), Bolecin (1), Czatkowice (1), Gorenice (1), and Podlże (1) quarries located in the Polish Jura (Fig. 3), which, combined, expose strata from the Morrisi Zone (middle Bathonian) to the Bifurcatus Zone (upper Oxfordian). We have sampled all available stratigraphical divisions (ammonite zones). Specifically, the Morrisi Zone (middle Bathonian) was sampled in the Kawodrza (50°48'09.8" N, 19°04'01.2" E) and Gnaszyn (50°48'05.5" N, 19°02'42.3" E) clay pits. These locations display a rather homogenous succession of black clays, with the sporadic occurrence of siderite nodule horizons (Matyja and Wierzbowski, 2003; Matyja et al., 2006b; Leonowicz, 2012; Parent and Zatoń, 2016).

Upper Bathonian and lower to middle and middle Callovian deposits that developed as clays and glauconitic marls respectively were sampled in Ogrodzieniec (50°27'54.6" N, 19°31'17.2" E) by Dembicz in 2006 (Dembicz and Praszkier, 2003; Matyja and Głowniak, 2003; Barski et al., 2004; Dembicz et al., 2006; Wierzbowski et al., 2009, 2013). The Glauconitic Marls Formation (uppermost Callovian to lowermost Oxfordian) was, as reported above, sampled by Hudson in 2006 and by Malcolm B. Hart in 2011. At the present time, the lower part of the outcrop is unavailable.

An incomplete succession from the Jason Zone (middle Callovian) to the Bifurcatus Zone (middle to upper Oxfordian) was sampled exclusively in the Stare Gliny Quarry (50°21’00.8” N, 19°35’29.2” E) (Wierzbowski et al., 2009, before declining to 50°16’50.7” N, 19°28’55.0” E) by Wierzbowski et al. (2013). The Glauconitic Marls Formation (uppermost Callovian to lowermost Oxfordian) was, as reported above, sampled by Hudson in 2006 and by Malcolm B. Hart in 2011. At the present time, the lower part of the outcrop is unavailable.
2021). This important Jurassic section is about 21 m thick and includes middle to upper Callovian marl–limestone rhythmites (10 samples; 9 m) and lower to upper Oxfordian clay strata (9 samples; 12 m).

Jurassic strata in the Wrzosowa Quarry (50°45′25.4″N, 19°08′51.9″E) are represented by a succession, approximately 5 m thick, of Cordatum Zone (lower Oxfordian) marl–limestone rhythmites with the dominant limestone of the Jasna Góra beds, yielding numerous sponges, belemnites, ammonites, and brachiopods (Trammer, 1985; Matyja et al., 2006a; Wierzbowski et al., 2009; Głowniak, 2012). Some isolated samples of Callovian and Oxfordian strata were additionally collected from little-known sections such as Bołćin (lower Callovian) (Różycki, 1953), Czatkowice (Lamberti Zone, upper Callovian) (Dayczak-Calikowska and Kopik, 1973a; Salata, 2013), Gorenice (lower Oxfordian) (Różycki, 1953), and Podłęże (middle Oxfordian) (Gizejewska and Wieczorek, 1977; Jurkowska and Kołodziej, 2013).

All of the collected samples are characterized by high clay content, which provides excellent conditions for fossil preservation, enabling the acquisition of isolated free specimens from the sediments (Hart et al., 2019). The use of 3-D specimens instead of thin sections (see the work of Hudson et al., 2009, on material from the Inner Carpathians) afforded us improved data for detailed morphological analysis. Selectively collected clay-rich samples were disintegrated using Glauber’s salt (Na₂SO₄ × 10H₂O) or detergent (Witwicka et al., 1958). The material was then washed in an ultrasonic cleaner and sieved using two sieves: 0.071 mm (lower) and 0.6 mm (upper). Samples that required additional cleaning were treated with liquid nitrogen (Remin et al., 2012). Foraminifera were manually picked from the residue and studied with the use of a Nikon SMZ18 stereoscopic microscope. Taxonomic observations and images were generated using a Zeiss Sigma VP scanning electron microscope at the Faculty of Geology, University of Warsaw.

3 Results

In general, planktic foraminifera in the samples were abundant, if not very numerous, and variably preserved. In all of the samples from Wrzosowa and some from Gnaszyn (G1252, G1264, G1318), Kawodrza (K1), Ogrodzieniec (O1, O2, O3), and Stare Gliny (ST6B, ST6F, ST6H, ST18, ST0, ST60, ST560), planktic forms were absent. The scarcity of foraminifera was almost certainly caused by the dissolution of their aragonitic tests, as all of the aragonitic benthic foraminifera had also been lost and the foraminiferal assemblages were represented only by benthic foraminifera with calcitic wall structures. Planktic foraminifera were recorded in the other studied samples, although their state of preservation was variable. Rather poorly preserved specimens with obscure morphological features, such as ornamentation or apertures (some of the specimens were preserved as glauconitic internal moulds, as described above in material from Ogrodzieniec) were collected from the Callovian of Stare Gliny (samples 2, 4, 16), Czatkowice, Gorenice, and Podłęże, whereas very well-preserved specimens were obtained mostly from samples that came from Gnaszyn (sample 1330), Kawodrza (samples 2, 3), and Stare Gliny (samples 140, 320, 500).

In our material, four species from two genera were recorded: Conoglobigerina helvetojurassica (Haueuler, 1881), Globuligerina balakhmatovae (Morozova, 1961), Globuligerina bathoniana (Pazdrowa, 1969), and Globuligerina oxfordiana (Grigels, 1958) (Fig. 4). C. helvetojurassica is characterized by a low to medium-high trochospiral large test; the mean diameter measured on 10 randomly selected specimens was 260 μm. The almost spherical chambers are much larger in the last whorl than those in the previous whorl, and they sit close to each other. Well-preserved pseudomuricae are visible on the surface of the test. G. balakhmatovae has a much smaller and low trochospiral test with oval, almost petaloid chambers. The chamber flattening, commonly observed in the studied specimens, is apparently a primary feature and is not produced during taphonomy. The main diagnostic features of G. bathoniana are a high trochospiral test, spherical chambers, and a test surface almost covered by pustulose ornamentation. The mean diameter of G. bathoniana, measured on 10 randomly selected specimens, was 160 μm. Similarly, G. oxfordiana is characterized by pustulose ornamentation. The coiling of the test is, however, that of a relatively low trochospiral. The last chamber is significantly larger than earlier ones and is often more elongated. The mean size of 10 randomly selected specimens of G. oxfordiana was 150 μm.

The most common taxa in our material were G. bathoniana and G. oxfordiana. G. bathoniana was the most numerous in Bathonian strata, especially in the Morrisi Zone (middle Bathonian) of Gnaszyn and Kawodrza, and in the Callovian and Oxfordian sediments of Bołćin, Czatkowice, Ogrodzieniec, Podłęże, and Stare Gliny. A relatively similar stratigraphical distribution was observed for G. oxfordiana, which was a dominant component of the Czatkowice, Podłęże, and Stare Gliny assemblages but rare in the Bathonian samples from Gnaszyn and Kawodrza. Specimens of C. helvetojurassica were recorded exclusively in the upper Oxfordian (Bifurcatus Zone) sediments from Stare Gliny (samples 140, 200, 380). Well-preserved specimens retained the characteristic pseudomuricae ornamentation, which is a diagnostic feature of the genus Conoglobigerina (Simmons et al., 1997; Gradstein et al., 2017a). Specimens of G. balakhmatovae were found in four samples from Kawodrza (Morrisi Zone, middle Bathonian) and from the Bifurcatus Zone (of Stare Gliny (upper Oxfordian) samples 140, 320, 380). No hemispherical forms were recorded from any Callovian (Jason–Lamberti zone) sediments.
Figure 4. SEM images of studied planktic foraminifera. **Globuligerina balakhmatovae** (Morozova, 1961) specimens: (1a–b) Stare Gliny, sample 140, MWGUW ZI/67/MG4.65 and (2a–b) Stare Gliny, sample 140 MWGUW ZI/67/ZD64ST14. **Globuligerina bathoniana** (Pazdrowa, 1969) specimens: (3, 4) Gnaszyn, sample 1324, MWGUW ZI/67/MG1.01 and (5) Stare Gliny, sample 140, MWGUW ZI/67/ZD64ST02. **Globuligerina oxfordiana** (Grigelis, 1958) specimens: (6) Podłęż, sample 1, MWGUW ZI/67/MG1.42; (7) Podłęż, sample 1, MWGUW ZI/67/MG1.20; (8) Stare Gliny, sample 6, MWGUW ZI/67/MG4.62; and (9) Stare Gliny, sample 140, MWGUW ZI/67/ZD64ST03. **Conoglobigerina helvetojurassica** (Haeusler, 1881) specimens: (10) Stare Gliny, sample 380, MWGUW ZI/67/MG3.12; (11) Stare Gliny, sample 120, MWGUW ZI/67/MG4.57; (12) Stare Gliny, sample 140, MWGUW ZI/67/MG4.07. Characteristic wall ornamentation (13-14) of genus: (13) **Globuligerina**, Graszyn, sample 1312, MWGUW ZI/67/MG1.02 and (14) **Conoglobigerina**, Stare Gliny, sample 140, MWGUW ZI/67/MG4.49. All scale bars represent 100 µm.

4 Discussion

4.1 Species variability of Jurassic planktonic foraminifera in extra-Carpathian Poland

Beginning in the second half of the 20th century, Jurassic planktic foraminifera have been investigated worldwide (Gradstein et al., 2017a), although few investigations have been undertaken in extra-Carpathian Poland. The first records derive from the Polish Jura where, in the late 1960s, **Globuligerina sp. cf. G. oxfordiana** and **Globuligerina sp. cf. G. helvetojurassica** (Bielecka and Styk, 1967) were found in middle–upper Callovian (Jason–Lamberti zones) and Mariae Zone (lower Oxfordian) strata of Ogrodzieniec. In 1969, Olga Pazdrowa described **G. bathoniana** from the Morrisi Zone (middle Bathonian) exposed in this quarry. It should be remembered, however, that her work was carried out in 1959 as that is the date written (by her) on the slides in the collections of the institute in Kraków. Several years later, Fuchs (1973) published his description of planktic foraminifera from the Polish Jura, identifying many new species. As all of this material is illustrated by line drawings of moulds, without original test walls, ornamentation, and apertures, none of these new taxa are valid (Loeblich and Tappan, 1987; Hudson, 2009; Gradstein et al., 2017a); see earlier discussion.

Subsequently, several sites from extra-Carpathian Poland were studied in terms of Jurassic planktic foraminifera (Kraków region, by Olszewska and Wieczorek, 1988; Ogrodzieniec, by Hudson, 2009, and Hart et al., 2012; and Gnaszyn, by von Hillebrandt, 2012, Smoleń, 2012, and Kendall et al., 2020). Moreover, planktic foraminifera were recorded in microfossil assemblages from boreholes in northern Poland (Chrzanów, by Bielecka, 1960; Kcynia, by Bielecka and Styk, 1964; Pasłęk, by Bielecka and Styk, 1966; Bartoszyce, by Bielecka and Styk, 1966, and Bielecka, 1974; Grzybnica, by Bielecka and Styk, 1981; and Wolin, by Bielecka and Styk, 1981) where, apart from **G. bathoniana** from Wolin (Fig. 5), **G. oxfordiana** was the only recorded planktic taxon.

To summarize, planktic foraminifera from extra-Carpathian Poland are rather scarce and require additional investigation. In fact, to date, only two species of planktic foraminifera, **G. bathoniana** and **G. oxfordiana**, have been described with certainty from this region. It is worth mentioning that Bielecka and Styk (1967, 1981) recorded **C. helvetojurassica** in this area of Poland, although it is clearly indicated in their papers that this record is uncertain. There is only one very poor illustration of this species included in the work of Bielecka and Styk (1981), and this is probably inadequate for a reliable taxonomic identification.

**G. oxfordiana** is commonly regarded as a cosmopolitan Jurassic planktic form (Hudson et al., 2009), but this is probably the result of many authors naming any mid-Jurassic planktic form as this species. The newly studied Oxfordian
assemblage from Stare Gliny is quite species-rich and probably one of the most diverse in the previously described area of epicontinental extra-Carpathian Poland and Europe in general. In this regard it is similar to the rather diverse assemblage seen as glauconitic steinkerns in the material from Ogrodzieniec described here. Specifically, this assemblage is composed of common *G. bathoniana* and *G. oxfordiana* but also includes the typical Tethyan *C. helvetojurassica* and *G. balakhmatovae*. These four taxa represent three different morphotypes: a small globular-chambered morphotype, represented by *G. bathoniana* and *G. oxfordiana*; the hemispherically chambered *G. balakhmatovae*; and the often larger and more complex *C. helvetojurassica*.

4.2 Biostratigraphical remarks

Gradstein et al. (2017a, b) show that the rate of speciation and evolutionary diversification of the first planktonic foraminifera was rather slow, confirming earlier suggestions by Simmons et al. (1997), Premoli Silva and Sliter (1999), Hart (1999), and Hart et al. (2002). Consequently, even the later Jurassic forms were characterized by a low level of morphological and taxonomic variability, which is, unfortunately, a serious disadvantage for stratigraphical studies. Additionally, the low preservation potential of the aragonitic tests of Jurassic planktic foraminifera very often results in their poor preservation or complete absence from the fossil record.

Not many species of Jurassic foraminifera are unquestionably considered as planktic. Gradstein et al. (2017a) described only 10 different species: *Globuligerina dagestanica* (Morozova), *G. avariformis* (Kasimova), *G. balakhmatovae* (Morozova), *G. oxfordiana* (Grigelis), *G. bathoniana* (Pazdrowa), *G. jurassica* (Hofman), *G. oxfordiana* (Grigelis) *calloviensis* Kuznetsova, *G. tojeiraensis* Gradstein, *Conoglobuligerina helvetojurassica* (Haeusler), *C. grigelisi* Gradstein, and *C. gulekhensis* (Gorbachik and Poroshina). Recently, however, Apthorpe (2020) described three new planktic taxa: *Globuligerina bathoniana australiana* n. ssp., *Globuligerina altissapertura* n. sp., and *Mermaidogerina loopae* n. gen. n. sp. from the Bajocian of the southern Tethys (northwest Australia). These records, from dredge samples, lack precise dating, as the Jurassic material is entomed in Pleistocene sediments, but the occurrence – so far away from the otherwise European and North Atlantic Ocean locations – creates problems for palaeogeographical reconstructions (see Hudson et al., 2009). This assemblage is, perhaps, more reminiscent of the Bathonian–Oxfordian interval than the Bajocian.

This rather low level of taxonomic diversity, the scattered occurrence and rather poor taphonomic potential of Jurassic planktics, and the lack of extensive sampling have resulted in a rather low level of resolution for standard biostratigraphical zonation (see Ogg et al., 2016). The most recent and exhaustive zonation of Jurassic planktonic foraminifera presented by Gradstein et al. (2017b) includes six zones (from J1 to J6). Unfortunately, the total ranges of specific zones have been established only tentatively and are still uncertain; no links to ammonite zones have been assigned. Nonetheless, Jurassic planktic foraminifera possess significant interregional correlative potential, as described from a wide palaeogeographical area including the eastern part of North America, Europe, the North Atlantic Ocean, the Gulf of Mexico, North Africa, the Middle East, and Australia. Additional investigations are,
therefore, definitely needed in order to create a robust biostratigraphical zonation correlated with other groups of index fossils (especially calcareous nanofossils and ammonites).

The stratigraphical distribution of the studied taxa from the Polish Basin closely matches the biostratigraphical scheme of Gradstein et al. (2017b). In the studied area, the earliest forms recorded are *G. bathoniana* and *G. balakhmatovae*, which occurred in the Morrisi Zone (middle Bathonian) of Gnazytn (see also Pazdrowa, 1969; Bielecka and Styk, 1981; Hart et al., 2012; Smoleń, 2012; Kendall et al., 2020) and Kawdrz (Fig. 6). *G. bathoniana* occurs frequently in the Morrisi Zone (middle Bathonian) of the ore-bearing Czestochowa clays in which it was originally described (Pazdrowa, 1969). Both *G. bathoniana* and *G. balakhmatovae* are known from the late Bathonian of other locations on the margins of the Tethys, namely, Grand Banks in Eastern Canada (Gradstein, 1979; Stam, 1986) and the lower Bathonian (Zigzag Zone) of central Dagestan (Morozova and Moskalenko, 1961). In general, *G. bathoniana* appeared slightly earlier than *G. balakhmatovae* and is characterized by a wider stratigraphical range (Gradstein et al., 2017b) encompassing the interval from the early Bajocian to the late Tithonian, whereas the latter appeared from the middle Bajocian to the end of the Kimmeridgian (Fig. 5). Whereas *G. bathoniana* was constantly recorded from the Bathonian up to the Oxfordian in the studied area, *G. balakhmatovae* was missing from the Callovian samples (Fig. 6).

The general stratigraphical range of *G. oxfordiana* is assessed as early Bajocian–late Tithonian – i.e. exactly the same range as that of *G. bathoniana* (Gradstein et al., 2017b). The first appearances of both taxa were established as the basis for the Jurassic planktic foraminiferal zone J2. Its lower Bajocian and Bathonian occurrence has been confirmed from, for example, Hungary (Humphriesianum and Niortense zones; Wernli and Görög, 1999) and Eastern Canada (Stam, 1986) respectively. These records challenge the hypothesis that the range of this taxon is restricted to the Oxfordian stage (Simmons et al., 1997).

In the studied area, *C. helvetojurassica* has been found only in the upper Oxfordian (Bifurcatus Zone) of Stare Gliny (Fig. 6); this is the first record of this taxa in extra-Carpathian Poland. *C. helvetojurassica* has been typically described from Tethyan strata, e.g. the middle Oxfordian Transversarium Zone of Switzerland (Gradstein et al., 2017a) and the lower Kimmeridgian Planula–Platynta zones of Portugal (Stam, 1986; Gradstein, 2017; Gradstein et al., 2017a) and France (Görög and Wernli, 2013). In general, *C. helvetojurassica* ranges from the middle Oxfordian to the early Kimmeridgian; its first appearance defines the beginning of the planktonic foraminiferal zone J5.

The co-occurrence of the four species *C. helvetojurassica*, *G. balakhmatovae*, *G. bathoniana*, and *G. oxfordiana* in the marls of the Stare Gliny section indicate zone J5 of Gradstein et al. (2017b) (Fig. 6). This zone, ranging from the middle Oxfordian to the early Kimmeridgian, is defined by the first appearance of the genus *Conoglobigerina* as well as the common occurrence of typical simple and hemispherical forms such as *G. balakhmatovae*, *G. bathoniana*, and *G. oxfordiana*. Regrettably, due to the wide stratigraphical ranges of Jurassic planktic forms and the lack of characteris-

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**Figure 6.** Chronostratigraphy, lithological columns, and ranges of recorded species of planktonic foraminifera in the studied sections, including a comparison with their total Tethyan ranges (Gradstein et al., 2017b).
tic events, no other zones were identified from the remainder of the sampling material.

4.3 Distribution of Jurassic planktonic foraminifera in extra-Carpathian Poland and their palaeoenvironmental potential

Planktic foraminifera are undoubtedly very useful palaeoenvironmental and palaeoecological proxies due to their close relationship with test morphology (morphotype) and with the habitat they occupied. Moreover, their tests constitute a useful medium for recording stable (carbon and oxygen) isotopes or ratios of trace elements such as Mg and Sr.

The geographical distribution of Holocene planktic foraminifera is restricted to fully marine habitats from the Equator to relatively high latitudes. These organisms occur in the water column from the surface water to several hundred metres in the water column (Bé and Hamlin, 1967; Bé, 1977; Schiebel and Helmeleen, 2005, 2017). Thus, the union of Tethys and the proto-Atlantic with adjacent epicontinental seas during the mid-Late Jurassic apparently resulted in the expansion of planktic forms (Hart et al., 2002; Hudson et al., 2009; BouDagher-Fadel, 2015). Planktic foraminifera, having originated in the Tethys Zone, subsequently migrated into adjacent epicontinental seas, and a brief review of their development follows.

The earliest planktic foraminifera appear to be those described by Wernli (1995) from the Creux de l’ours section in the area of Teyssachaux (Swiss Prealps, Fribourg, Switzerland). The mudstones from which the planktic foraminifera were recovered are located within a few metres of the Toarcian Oceanic Anoxic Event (OAE), an event recently re-interpreted by Ruebsam et al. (2019) as possibly related to warming and sea level rise following a glacial (or cold) event. In the UK, Hylton (2000) and Hart et al. (2003) recorded a flood of inflated Oberhauerella or Rheinholdella at the same stratigraphical level immediately above the Toarcian OAE (Whitby Mudstone Formation). Planktic foraminifera are rare in the overlying Aalenian (Wernli, 1988), becoming more abundant (and widespread) in the Bajocian (Gradstein et al., 2017b). Many of the mid-Jurassic occurrences are in “Ammonitico Rosso” facies in which ammonites and calcite “filaments” are the only other fossils. The important questions are as follows:

1. Are these mid-Jurassic planktic foraminifera with simple test arrangements surface-dwelling forms?
2. Do all of these Jurassic planktic foraminifera have aragonitic tests and are they, therefore, a completely unrelated lineage to most Cretaceous taxa?
3. Why are Jurassic assemblages so species-poor and why did they never developed greater diversity?

In answer to question 1, the simple “globigerine” forms, which often have only three to four chambers in the final whorl, appear comparable to many Cretaceous taxa in which stable isotope analysis (Wendler et al., 2013) indicates the occupation of surface waters (above the thermocline). In a recent study of Globuligerina spp. from Poland and Portugal, Kendall et al. (2020) – using micro computed tomography (micro-CT) analysis – suggest that this morphology reflects short life cycles and potentially rapid reproduction in nutrient-rich coastal environments.

In the Czorsztyn Limestone Formation (Oxfordian) of the Pienniny Klippen Belt of Poland, Hudson et al. (2009) described thin sections full of simple, globigerina, forms (often with a maximum of four chambers in the final whorl) and very few associated benthic taxa. These were thought to represent open-ocean environments in which a 99 : 1 P : B ratio indicates planktic ooze deposition above a Jurassic aragonite compensation depth (ACD), although the actual water depth is impossible to estimate. The palaeoenvironmental evidence of Hudson et al. (2009) and Hart et al. (2012), coupled with the morphological analysis of Kendall et al. (2020), is suggestive of a surface-water dwelling habitat for most Jurassic planktic foraminifera.

These species were, therefore, able to spread into shelf seas only during sea level highstands (Gordon, 1970), which resulted in the minimum seawater depth required for these organisms to thrive. It is also believed that foraminiferal migration farther into the shelves was additionally associated with the occasional incursion of warm currents (Gordon, 1970; Riegraf, 1987; Hudson et al., 2009). Therefore, it is possible that planktic foraminifera first appeared in the Polish epicontinental seas during a transgressive interval in the late Bathonian (Morrisi Zone) (Dayczak-Calikowska and Kopik, 1973b; Leonowicz, 2016), where they were recorded (Fig. 5) in the Polish Jura (Pazdrowa, 1969; Fuchs, 1973; Smoleń, 2012) as well as in northern Poland (Bielecka and Styk, 1981). No planktic foraminifera have been recorded in the Aalenian and Bajocian, as these stages are represented by very shallow, although transgressive, facies only as the Aalenian sea entered the Polish Basin (Dayczak-Calikowska, 1997). Until the late Bajocian, the basin in the Polish Lowlands was very narrow (elongated in a north-western–south-eastern direction) and had not expanded towards the north-eastern part of Poland (Dayczak-Calikowska and Kopik, 1973b). During the late Bathonian, a significant expansion took place and, as a result, the sea covered nearly all of the Polish Lowlands (Dayczak-Calikowska and Kopik, 1973b; Leonowicz, 2016). The first planktic foraminifera from the area of Poland are actually recorded from the Bathonian: G. bathoniana and G. oxfordiana (e.g. Pazdrowa, 1969; Smoleń, 2012; Hart et al., 2012; Kendall et al., 2020).

A short-term, relatively rapid, regression occurred in the early Callovian, particularly affecting the basin in the Polish Lowlands (Dayczak-Calikowska and Kopik, 1973b): G. bathoniana and G. oxfordiana have rarely been recorded subsequently, even in the southern parts of the Polish Basin (Bielecka and Styk, 1967; Bielecka, 1960; Bielecka and...
Styk, 1981). Similarly, as in their early Callovian distribution, both species occurred sporadically in the middle and upper Callovian samples from Stare Gliny and Ogrodzieniec. Contrastingly, during the late Callovian–Oxfordian interval, planktic foraminifera expanded to attain their widest distribution, described as the “foraminiferal flood” across Europe (Hudson et al., 2009), which was apparently connected with global oceanographical and climatic changes occurring at the transition between the Middle and Upper Jurassic (Callovian to Oxfordian). Specifically, a marked transgression, beginning in the late Callovian and continuing until the Kimmeridgian (Dadlez et al., 1998), resulted in the appearance of widespread epicontinental seas, which communicated with the Tethys covering much of Europe, as well as in climate warming. Mediterranean ammonites began to be found instead of boreal taxa in the Oxfordian strata of the Polish Lowlands in relation to the sea level curve as well as to facies distribution and the palaeogeographical map (distance from the ocean) (Hudson et al., 2009; Wierzbowski et al., 2009; Leonowicz, 2016), the depth–distribution pattern of Jurassic planktonic foraminifera appeared comparable to that of the Cretaceous. Specifically, the shallow shelf facies and the areas quite distant from the open ocean yielded only small, simple morphotypes such as G. bathoniana and G. oxfordiana. Planktic foraminiferal assemblages composed of only these two morphologically simple forms have been collected mostly from the Bathonian and Callovian, as these strata were deposited in a still relatively shallow sea. Only monospecific G. oxfordiana planktonic assemblages have been recorded in the Oxfordian strata of the northern part of the Polish Basin, implying that, in the Oxfordian, the northern margin of the basin was invaded by only shallow-dwelling forms, in contrast to the southernmost part of the basin, which represented a deeper-shelf environment, where planktic foraminiferal assemblages were slightly more diverse and represented by more complex and larger forms, such as G. balakhmatovae and C. helvetojurras- sica. This is suggestive of a deepening of the environment towards the outer shelf and open ocean. To summarize, assemblages composed of only simple forms such as G. bathoniana and G. oxfordiana were typical of rather shallow- and mid-shelf environments, and, by analogy to Holocene counterparts, may have been characterized by short life cycles which may have unfolded in relatively shallow waters beyond the open ocean. The Oxfordian of the Stare Gliny outcrop, deposited in an outer-shelf environment, closer to the Tethys (actually, Stare Gliny represents the southernmost available Jurassic strata of the Polish epicontinental basin), contains more diverse planktic foraminiferal assemblages. In addition to simple G. bathoniana and G. oxfordiana, it contains hemispherical G. balakhmatovae and the larger morphotype C. helvetojur- sica. The latter was the most evolutionarily advanced species of all those reported in this study and may have needed a much greater water column to establish favourable conditions for its life cycle.
5 Conclusions

Four species of Jurassic planktonic foraminifera, Conoglobigerina helvetojurassica (Haesleur, 1881), Globuligerina balakhatmatovae (Morozova, 1961), Globuligerina bathoni-ana (Pazdrowa, 1969), and Globuligerina oxfordiana (Grig- lis, 1958), were identified in material from extra-Carpathian Poland. In general, the level of richness of the studied assemblages was rather low and undifferentiated. The majority were represented by only two common taxa, G. batho-ana and G. oxfordiana. Nevertheless, an assemblage from the middle–upper Oxfordian clays and marls of the Stare Gliny Quarry includes all four of the species mentioned above, making it currently the most diverse planktonic foraminiferal assemblage of the European epicontinental Jurassic.

The stratigraphical distributions of all of the studied taxa closely match the general biostratigraphical zonation for Jurassic planktic foraminifera (Gradstein et al., 2017b). The first planktic foraminifera from the Polish Basin, G. batho- niana and G. balakhatmatovae, derive from middle Bathonian (Morrisi Zone) transgressive deposits of the Polish Jura. In the middle–upper Callovian (Jason–Lamberti zones) of the Polish Jura, planktic foraminifera, represented by G. batho- niana and G. oxfordiana, are discontinuously and rather sparsely recorded. Due to the late Callovian–Oxfordian transgression, planktic foraminifera migrated to the northern part of the Polish area, where they are represented mostly by monospecific assemblages of G. oxfordiana, in contrast to the southern part, where assemblages are more diverse and contain complex Tethyan forms.

Three separate test morphotypes within the studied Jurassic planktic foraminifera were distinguished: a small and simple globular-chambered morphotype represented by G. bathoniana (the mean diameter of all the studied specimens is ca. 160 µm) and G. oxfordiana (the mean diameter of the studied specimens is ca. 150 µm), a hemispherically chambered morphotype by G. balakhatmatovae, and a large and complex morphotype by C. helvetojurassica (the mean diameter of all the studied specimens is ca. 260 µm). These morphotypes apparently reflect the close relationship between the settled habitat and test morphology. The deeper the environment, the more diverse the foraminiferal assemblages that occurred there, with a significant share of large and complex forms. Contrastingly, small and simple foraminifera dominated the shallow inner-shelf environments. This distribution pattern would have some similarities to depth–distribution models created for younger forms such as Late Cretaceous planktic foraminifera (Leckie, 1987; Caron and Homewood, 1983). Thus, beyond doubt, Jurassic planktic foraminifera may also be regarded as useful depth indicators for palaeoenvironmental studies.

In general, our studies provide new insight into the palaeoecology, evolution, and distribution of Jurassic planktic foraminifera from the Polish Jura. However, the group still requires more investigation.

Author contributions. ZD conceived this research project. MG processed and analysed the samples. All authors interpreted results and wrote and edited the article.

Competing interests. Malcolm B. Hart reviewed the first version of this paper and suggested substantive improvements. He then participated as a co-author when the paper was revised.

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