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# The stratigraphy of Zechstein strata in the East European Craton of Poland: an overview

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The sedimentary and stratigraphic patterns established for Zechstein of the western part of the Peribaltic Syneclise (and in particular the eastern Łeba Elevation) were applied to other parts of the East European Craton (EEC) in Poland: the eastern Peribaltic Syneclise and the Podlasie region. A very large number of mostly fully-cored borehole sections in the Puck Bay region certainly predestines the eastern Łeba Elevation area to use it as a model. The most part of the EEC, except of its part adjacent to the Teisseyre-Tornquist Zone, during the Zechstein deposition represents the marginal parts of the basin. The fauna occurring in the Zechstein carbonate deposits of the EEC makes it possible to distinguish between the Zechstein Limestone and the younger carbonate strata, but certainly not between the Main Dolomite and the Platy Dolomite and hence the facies models for the Zechstein that have been previously developed in the western part of the Peribaltic Syneclise augmented by sequence stratigraphic approach seem to be the best tool to apply in other peripheral areas in the EEC area. The Zechstein sequence in the western part of the Peribaltic Syneclise consists, in general terms, of three parts: (1) carbonate platform of the Zechstein Limestone (occurring only in the north-westernmost corner of the study area and passing into basin facies dominant in the most part of the area); (2) the PZ1 evaporite platform system composed of sulphate platforms and adjacent basin system and constituting the major part of the Zechstein sequence; and (3) the Upper Anhydrite-PZ3 cover. There is a consensus, as far as the western part of the Peribaltic Syneclise is concerned, that the Platy Dolomite platform is wider than the Main Dolomite platform. In the easternmost part of the Peribaltic Syneclise, the stratigraphical interpretations are diverse. We have included the anhydrite overlying the Zechstein Limestone into the Upper Anhydrite, and concluded that the overlying interbedded mudstone and anhydrite also belong to the Upper Anhydrite. When above the Upper Anhydrite one carbonate unit occurs, it is assigned either to the Main Dolomite and Platy Dolomite, or to the Platy Dolomite. The same conclusion is proposed for the marginal parts of the Podlasie Bay. The deposition of Zechstein Limestone resulted in the origin of carbonate platforms along the basin margins which changed an inherited topographic setting. The Lower Anhydrite deposits are lowstand systems tracts (LST) deposits, lacking in more marginal parts of the western and eastern Peribaltic Syneclise and in the major part of the Podlasie Bay. The accommodation space existed and/or created during the Lower Anhydrite and the Oldest Halite deposition in the Baltic and Podlasie bays was filled and at the onset of the Upper Anhydrite deposition, a roughly planar surface existed except in the area adjacent to the main Polish basin. The Upper Anhydrite deposits are transgressive systems tracts deposits and then highstand systems tracts deposits and they encroached the Zechstein Limestone platforms. The Upper Anhydrite deposition was terminated by sea level fall, and the Upper Anhydrite deposits in the marginal areas became subject to karstification. The Main Dolomite transgression took place in several phases but its maximum limit did not reach the Upper Anhydrite limit. The deposition of the PZ2 chlorides (LST deposits) resulted in the filling of the accommodation space that was inherited after the deposition of the Main Dolomite and the Basal Anhydrite. Subsequently, the area became exposed, and marine deposits (Grey Pelite and Platy Dolomite) related to the last major transgression during the life of the Zechstein basin that resulted in a flooding of the exposed surface of older Zechstein deposits, including the area that was emergent during deposition of the PZ2 cycle. Microbial carbonates, being stromatolites and thrombolites, are a common feature of all Zechstein carbonate units but in particular this is the case of the Platy Dolomite. There are no direct premises allowing for convincing settlement doubts regarding the stratigraphical position of the upper carbonate unit in many cases, but several lines of evidence suggest that, as in the entire Zechstein basin, the Main Dolomite considerably shifted basinward, and the Platy Dolomite – landward, although it is difficult to ascertain whether the original Platy Dolomite extent was similar to or greater than the limit of the Zechstein Limestone as elsewhere in the Zechstein Basin.

Key words: Zechstein, stratigraphy, palaeogeography, East European Craton, Main Dolomite, Platy Dolomite, Poland

## INTRODUCTION

The Southern Permian Basin (SPB) was an intracontinental basin that by the beginning of the Late Permian had apparently subsided below global sea level, and was inundated during the

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Late Permian (middle-late Wuchiapingian – cf. Szurlies, 2020) by Arctic seas (Fig. 1A). It extends across the Paleozoic Platform of western and central Europe and encroaches east- and north-eastwards onto the Precambrian East European Craton (Fig. 1B; Guterch et al., 2010 with references therein). The boundary between these major basement provinces, referred to as the Trans-European Suture Zone (TESZ), is a broad and complex zone of Early Paleozoic terrane accretion (Pharaoh et al., 2010 with references therein). Teisseyre-Tornquist Line (TTL) was conceived as a linear feature is border of crystalline, "granitic" upper crust of the EEC, and the Teisseyre-Tornquist Zone (TTZ) is a few tens of kilometres wide zone related to craton edge (Grad, 2019). In Poland, north-east of the TTL the East European Platform occurs (Fig. 1B, C). The first borehole in the Polish part of EEC reaching the Zechstein strata, Łeba 1, was drilled in 1936 (Dahlgrün and Seitz, 1944). Then, as the result of the intensive borehole program in the Polish Lowland related to the first phase of regional geological study of the Polish Lowland in the sixth and seventh decades of the 20th century, numerous publications dealing with the Zechstein parts of the EEC area (e.g., Szaniawski, 1966, 1970; Wagner, 1971, 1972; Stolarczyk, 1972; Werner, 1972; Czajor and Wagner, 1974) or particular borehole sections (Krasowska, 1973, 1977; Areń, 1974, 1975, 1978; Modliński, 1974, 1975, 1977, 1982, 1989; Lendzion, 1975; Witkowski, 1976, 1986; Tomczyk, 1977; Dembowska and Marek, 1988) have originated. Certainly, the area of EEC was also included in the first syntheses of the whole Zechstein basin in Poland that were summarizing the results gained due to the ongoing borehole program (Poborski, 1960, 1968; Pawłowska, 1968; Pokorski and Wagner, 1975).

A recognized milestone in the Zechstein research in Poland was the publication of cartographical synthesis and correlation schemes for particular regions in Poland (Depowski, 1978) that were summarized by Wagner et al. (1978c). The subsequent synthetic publications by Wagner (1988, 1994, 1997, 1998a–f) did not change the stratigraphical and palaeogeographical concepts for the EEC that were presented in Depowski (1978) although some updating and reinterpretation in the southern part of the Warsaw Trough and the Podlasie Depression (see Wagner, 1983, 2007a, b) occurred.

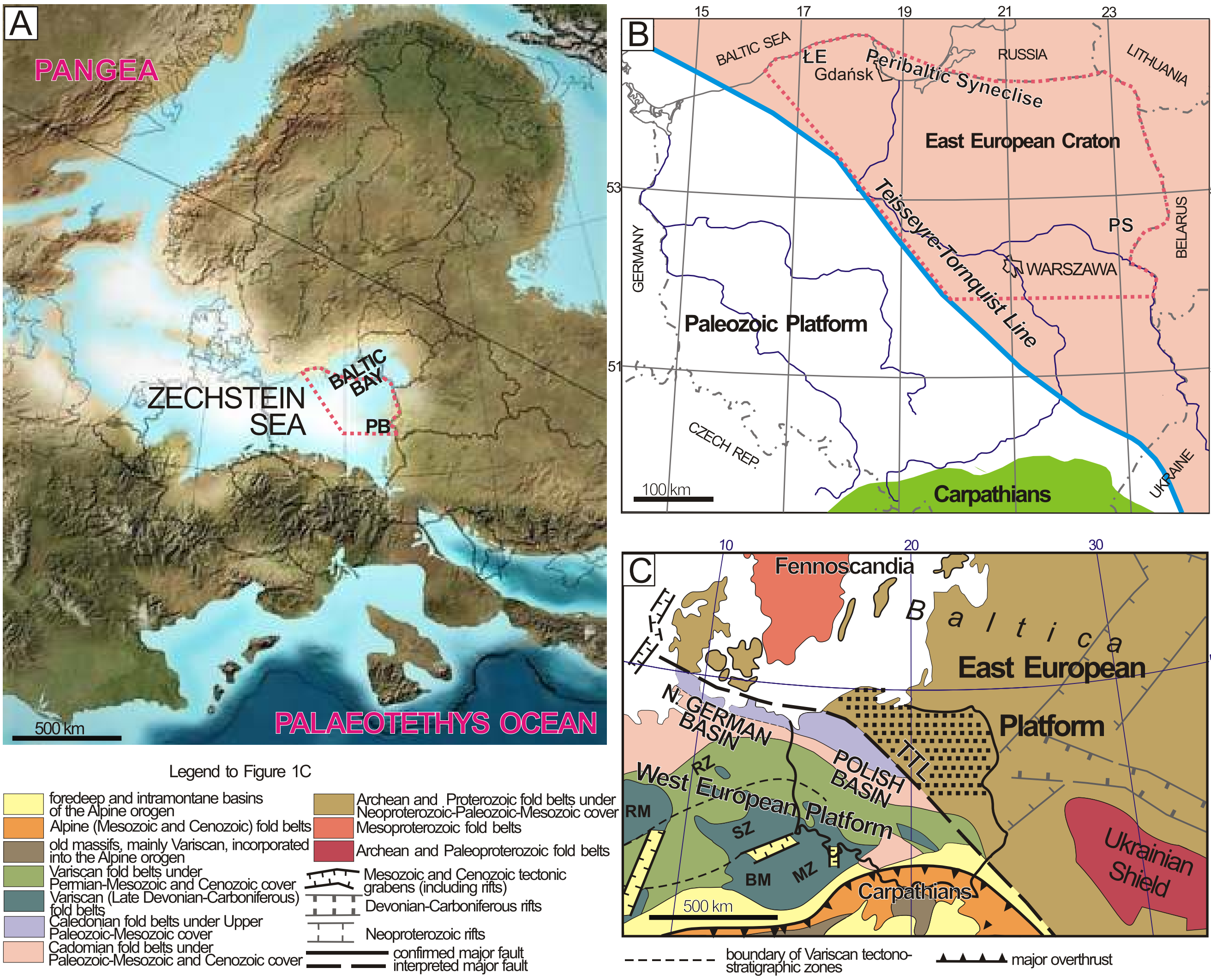



**Fig. 1A – palaeogeography of Europe during the Late Permian (after Blakey, 2016) showing the boundary (red dots) of area discussed in this paper: PB – Podlasie Bay; B – major tectonic units of sub-Permian basement of Poland (after Guterch et al., 2010, simplified); ŁE – Łeba Elevation, PS – Podlasie Syncline; red dots show the boundary of area studied; C – tectonic map of Poland and adjacent countries (after Aleksandrowski, 2020, simplified); the Polish part of the East European Craton discussed in this paper is dotted; BM – Bohemian Massif, MZ – Moldanubian Zone, RM – Rhenish Massif, RZ – Rhenohercynian Zone, SZ – Saxothuringian Zone, TTL – Teisseyre-Tornquist Line**

In the post-1978 time new important information arose from the borehole drilled in the area adjacent to the TTZ, and seismic data from that area, that was included in the syntheses (Wagner, 1988, 1994, 1997, 1998a–f) and papers dealing with particular borehole sections (e.g., Leszczyński, 2011, 2019; Podhalańska and Sikorska-Jaworowska, 2018; Krzywiec et al., 2019). However, these new data, although very important for the understanding of the basin centre – basin margins relations, could not, and did not, contribute to the earlier-established concepts, often presenting different interpretations, for the marginal part of the Zechstein basin. In addition, updated sections of boreholes drilled more than a half of century ago have been published during two last decades (Modliński, 2007, 2011; Podhalańska, 2007, 2008, 2011, 2012, 2014; Podhalańska and Sikorska-Jaworowska, 2015; Waksmundzka and Wójcik, 2019).

The aim of this paper is to apply the sedimentary and stratigraphic patterns established for the western part of the Peribaltic Syneclise (summarized by Peryt et al., 1992; cf. Dębski, 1983) to other parts of the EEC: the eastern Peribaltic Syneclise in Poland and the Podlasie region. Such a possibility was already suggested by Peryt and Czapowski (1988), Gąsiewicz and Peryt (1989a), and Peryt (1989) for the eastern Peribaltic Syneclise and Peryt (1990a) for the Podlasie Depression. A very large number of mostly fully-cored borehole sections in the Puck Bay region certainly predestines the eastern Łeba Elevation area to use it as a model. In fact, the stratigraphical concepts developed in the Łeba Elevation were applied to the easternmost, marginal part of the Peribaltic Syneclise already at the beginning of its intensive exploration (Orska, 1960, 1962). The number of new boreholes drilled in the eastern part of the Podlasie Depression is limited; no new material is available from the eastern part of the Peribaltic Synecise.

The marine facies of the PZ3 are followed and/or replaced, in the Peribaltic Syneclise and Podlasie Depression, by the uppermost Permian clastics of the Top Terrigenous Zechstein (PZt) that are not, however, subject to analysis in this paper.

## PRINCIPLES OF ZECHSTEIN LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

A regional stratigraphic correlation within the Zechstein follows the classical model of cyclic chemical precipitation in a giant saline basin (Richter-Bernburg, 1955a, b). This correlation, initially established by Richter-Bernburg (1955a) and Lotze (1957), has been soon after applied in Poland (cf. Tokarski, 1959a, b), although with some important modifications introduced by Wagner (1978a, 1994), in particular for the central part of the basin (Table 1). The alternative, sequence stratigraphic approach, has been proposed by Tucker (1991) and then his scheme was modified for the Zechstein of Germany (Strohmenger et al., 1996a, b; Leyrer et al., 1999; Becker and Bechstädt, 2006) and Poland (Wagner and Peryt, 1997; Peryt, 2010).

The lithostratigraphic nomenclature of the Zechstein Group distinguishes between marine and evaporitic sediments in the basin itself and terrestrial sediments of the basin margins (Paul, 2020a). The basinal facies in Germany consists of seven formations (Z1–Z7) coined after their main occurrences (Table 1). First three (Z1–Z3) are equivalent to three cyclothems (PZ1–PZ3) distinguished in Poland (e.g., Wagner et al., 1978c; Wagner, 1994) and the formations Z4–Z7 correspond to the cyclothem PZ4 with its 5 subcyclothems in Poland (Wagner, 1994; Wagner and Peryt, 1997). The formations in Germany are subdivided into members named after their main lithologic component and eventually the position in the Zechstein profile (i.e., lower, upper – cf. Paul, 2020a), and then into horizons and salt beds.

As advocated by Wagner (1986, 2009), establishing of formal subdivision seems pointless when aimed to match formal requirements only although its use is justified in the case of marginal zone of the Zechstein basin dominated by terrestrial sediments. In Poland, such local subdivisions were proposed for the North-Sudetic Synclinorium (Fijałkowska-Mader et al., 2018) and the Holy Cross Mts. (Kuleta and Zbroja, 2006; Jewuła et al., 2020). We concur with the view of Wagner (1986, 2009).

The boundary between the Rotliegend Group and the Zechstein Group in Germany is traditionally defined with the occurrence of first marine deposits but based on practical grounds it is now placed at the base of the Kupferschiefer (T1) or its equivalents (Paul, 2020b; Paul et al., 2020; cf. Peryt, 1976 and Pokorski and Wagner, 1978). The term Zechstein in such an approach loses the facies meaning and gains a lithostratigraphic one, what causes that the deposits occurring below the Kupferschiefer (or its equivalents) and genetically related to the transgression can have an unspecified lithostratigraphic position (see Paul, 2020b). However, from the sequence stratigraphy point of view they undoubtedly represent the transgressive systems tracts (TST) deposits of the first Zechstein sequence (Table 1).

The lithostratigraphic boundary between the Zechstein and the Buntsandstein in Germany is defined at the base of the Calvörde Formation (or correlative units) and is linked to the change of facies (Hug-Diegel, 2020). Since Pokorski and Wagner (1975), it is accepted that there are no PZ4 deposits in the East European Craton and hence this paper does not discuss the strata overlying the PZ3 deposits.

The greater part of the EEC, with the exception of its part adjacent to the TTZ, during the Zechstein deposition represents the marginal parts of the basin. The emphasis in the cycle philosophy is on events in the basin centre and hence there is no advantage in using either the cycle or sequence concept in the basinal succession, where deposition is more or less continuous (see Tucker, 1991). Quite a different situation occurs in the case of the basin margins where, as pointed out by Tucker (1991), evaporites may be precipitated during the early stages of the TST before the salinity returns to normal and carbonates are deposited in the mid-late TST and highstand systems tracts (HST). Accordingly, "...the late evaporites simply pass up into the carbonates without any major time gap..." (Tucker, 1991). This is certainly not the case of the Upper Anhydrite (A1g)–Main Dolomite (Ca2) boundary that is characterized by subaerial exposure and karstification of the A1g platform and the platform margin during sea level lowstand (e.g., Peryt, 1992; Leyrer et al., 1999). A stratigraphic boundary on top of the first Zechstein cycle evaporites does represent a significant time gap and consequently, Leyrer et al. (1999) proposed that the base of the Ca2 is bounded by a sequence boundary (ZSB3; cf. Strohmenger et al., 1996a). Peryt and Wagner (1998) admitted that although in fact the A1g/Ca2 boundary can be treated as a sequence boundary covered by evident TST deposits (e.g., Peryt, 1992), it should rather be regarded as a result of lower order sea level oscillations analogous to those recognized later during Ca2 deposition (e.g., Peryt and Dyjaczynski, 1991; Peryt and Scholle, 1996; Strohmenger and Strauss, 1996; Strohmenger et al., 1996a; Piske et al., 2020). In the peripheral part of the basin the Zechstein Limestone deposits are overlain by the distinctive Anhydrite Breccia – a TST sediments covered by massive anhydrites representing HST deposits (Peryt et al., 1996a; Peryt and Wagner, 1998).

Table 1

**Zechstein lithostratigraphy and sequence stratigraphy in the Polish Basin after Wagner and Peryt (1997) and Peryt (2010)**

| | | | Lithostratigraphy | | Sequences | | |
|---|---|---|---|---|---|---|---|
| | | Polish Basin | | | | | GB |
| Changhsingian | Z E C H S T E I N | Zechstein 4 PZ4 | for the PZ4 lithostratigraphy see Wagner (1994) | | LST | PZS4 | ZS8 ? ZS7 |
| | | Zechstein 3 PZ3 | Na3t | Younger Clay Halite | | | |
| | | | Na3 ⟨K3⟩ | Younger Halite (Younger Potash) | | | ZS6 |
| Wuchiapingian | | | A3 | Main Anhydrite | | | |
| | | | Ca3 | Platy Dolomite | HST | | ZS5 |
| | | | T3 | Grey Pelite | | mfs | |
| | | Zechstein 2 PZ2 | A2r | Screening Anhydrite | TST | PZS3 | |
| | | | Na2r | Screening Older Halite | | | |
| | | | K2 | Older Potash | LST | | |
| | | | Na2 | Older Halite | | | ZS4 |
| | | | A2 | Basal Anhydrite | | | |
| | | | Ca2 | Main Dolomite | HST | | ZS3 |
| | | Zechstein 1 PZ1 | A1g ⟨BrA1⟩ | Upper Anhydrite ⟨Anhydrite Breccia⟩ | TST | mfs PZS2 | |
| | | | Na1 | Oldest Halite | LST | | ZS2 |
| | | | A1d | Lower Anhydrite | | | |
| | | | Ca1 | Zechstein Limestone | HST | | ZS1 |
| | | | T1 | Kupferschiefer | TST | mfs | |
| | | | Ca0 | Basal Limestone | | PZS1 | |
| | | | Zs1 | Zechstein Sandstone | | | |
| | | | Zc1 | Zechstein Conglomerate | LST/TST | | |

GB – German Basin (sequence stratigraphy after Strohmenger et al., 1996b); the Changhsingian-Wuchiapingian boundary is put in the middle of the PZ3 cycles after Szurlies (2020); previously it was regarded as equivalent to the Z2/Z3 boundary; HST – highstand systems tract, LST – lowstand systems tract, mfs – maximum flooding surface, TST – transgressive systems tract

Leyrer et al. (1999) placed the next sequence boundary at the boundary between the sabkha and salina deposits of the Basal Anhydrite (A2) as it is assumed that the transgressive surface of Zechstein sequence ZS4 marks the change from carbonate to evaporitic sedimentation (salina-type anhydrites; Leyrer et al., 1999). In turn, Strohmenger and Strauss (1996) and Strohmenger et al. (1996a) and then Peryt and Wagner (1998) placed the sequence boundary in places of rapid transitions from sub- to peritidal facies which is quite frequently recorded on slopes of the Ca2 carbonate platforms.

In the western part of the Peribaltic Syneclise the Ca2 deposits are covered by re-crystallized laminated sulphates indicative of a deposition in a salina environment (Peryt et al., 1985), however, local cryptalgal deposits in the uppermost part of Ca2 indicating an intertidal environment imply a sea level fall at the end of Ca2 deposition followed by a sea level rise at the beginning of the A2 deposition (Peryt, 1986a). The topmost part of the Ca2 sequence was eroded on most parts of the carbonate platform prior to the deposition of the Platy Dolomite (Ca3), and is preserved only in the outer part of the carbonate platform, where peloidal packstones and rare ooid grainstones top the sequence (Peryt, 1986a). When the Ca3 overlies the Ca2, only one carbonate unit occurs above the PZ1. Such a unit can represent either (1) partly Ca2 and partly Ca3, as in the area along the Baltic Sea coast between Dębki in the west and Władysławowo in the east, or (2) Ca3, as in the longitudinal zone including boreholes Bytów IG 1 and Lębork IG 1 and further west, or (3) Ca2 when the Ca3 is eroded as is observed along the Baltic Sea coast west of Dębki to Łeba (cf. Peryt, 1986a).

The fauna occurring in the Zechstein carbonate deposits of the EEC makes it possible to distinguish between the Zechstein Limestone and the younger carbonate strata, but certainly not between the Ca2 and the Ca3 (Woźny, 1976; Karczewski, 1986; Woszczyńska, 1987). Karczewski (1986: table 1) indicated that in the western part of the Peribaltic Syneclise the composition of the bivalve assemblages in the Ca2 and the Ca3 are basically the same although particular species occur more commonly in the Ca2. The most common species, *Liebea squamosa* (Sowerby), was recorded in 23 boreholes in the case of Ca2 and in 19 boreholes in the Ca3, *Schizodus schlotheimi* (Geinitz) and *Schizodus obscurus* (Sowerby) in 20 boreholes in the Ca2 and in either 12 or 6 boreholes in the Ca3, and *Permophorus costatus* (Brown) in 14 boreholes in the Ca2 and 5 boreholes in the Ca3 (Karczewski, 1986).

Therefore, the facies models for the Zechstein that have been previously developed in the western part of the Peribaltic Syneclise augmented by a sequence stratigraphic approach seem to be the best tool to apply in other peripheral areas in the EEC area.

## MATERIAL

Carbonate and sulphate deposits have been investigated in 107 boreholes in the western part of the Peribaltic Syneclise (Appendix 1*). With some exceptions these were fully cored in the Zechstein interval although the core recovery in the Ca3 was generally moderate (see Gąsiewicz and Peryt, 1989b). Of these, 53 borehole sections with the Ca2 (Peryt, 1986a) and 38 borehole sections with the Ca3 deposits (Gąsiewicz and Peryt, 1989b; Gąsiewicz, 1990a, b; Peryt et al., 1992), have been studied in detail.

In the central and eastern parts of the Peribaltic Syneclise, 8 boreholes drilled by the (Polish) Geological Institute and 1 Polish Oil and Gas Company (POGC) borehole were sedimentologically and petrologically examined. Their location is shown in Figure 2. In the Podlasie Depression, 12 boreholes (whose location is shown in Fig. 2) have been studied. In addition, the Zechstein carbonate and sulphate deposits have been sedimentologically and petrologically studied in a number of boreholes (see Fig. 2 for location) in the area adjacent to the TTZ (Fig. 2).

The Zechstein sections in the boreholes located in the eastern and central parts of the Peribaltic Syneclise, Podlasie Depression and the area adjacent to the TTZ have been earlier studied, and in a majority of cases published, in the series "Profile głebokich otworów wiertniczych (Państwowego) Instytutu Geologicznego" (Table 2). The Zechstein carbonate deposits in many of those boreholes were subject to petrographical study [Czajor 1972; Czajor and Wagner, 1974; Piekarska and Kwiatkowski, 1975; and numerous publications in the series "Profile głebokich otworów wiertniczych (Państwowego) Instytutu Geologicznego" – Table 2]. Peryt and Czapowski (1988) characterized the upper Zechstein carbonate unit in the Kętrzyn IG 2 borehole and subsequently, its upper part (also in the Barciany 4 borehole) was studied in detail by Gąsiewicz and Peryt (1989a), and Peryt (1990a) studied petrographically the upper Zechstein carbonate unit in the Podlasie Depression. Peryt (1992) published results of the Ca2 study in the Płońsk IG 2 borehole.

The depth intervals and the thickness of particular Zechstein units in many boreholes that will be discussed in detail further in this paper, often differ even in the publications (co)authored by particular authors. For example, the thickness of the PZ1, PZ2 and PZ3 deposits in the Wyszków IG 1 borehole is, respectively, 24.5, 34.5 and 13.0 m according to Czajor and Wagner (1974) and 31.0, 27.5 and 13.5 m after Wagner (2007a), and in the Żebrak IG 1 borehole the thickness of the PZ1 strata is either 58.0 m (Pawłowska, 1968) or 49.1 m (Czajor and Wagner, 1974). Those differences are partly due to various stratigraphical concepts and different calculation methods applied in the case of a poor core recovery.

## RESULTS AND INTERPRETATION

Results of examination and data interpretation of the boreholes studied are presented for three areas of the Polish East European Craton: westernmost part of the Peribaltic Syneclise, eastern part of the Peribaltic Syneclise and the Podlasie Depression. For the characterization of each area, several key boreholes have been selected based on the existing controversies regarding their stratigraphy and/or palaeogeographical location.

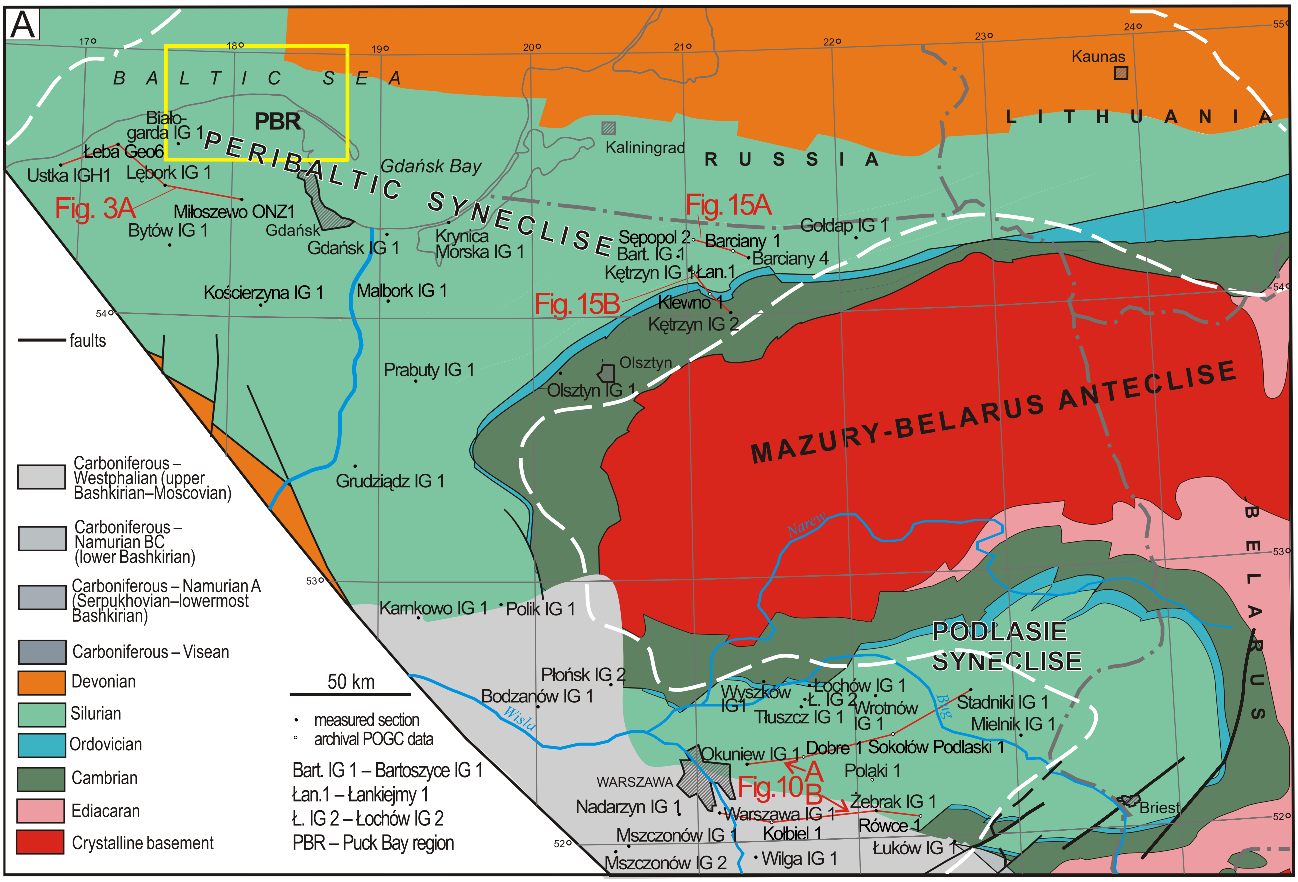
### WESTERN PART OF THE PERIBALTIC SYNECLISE

The Zechstein sequence in the western part of the Peribaltic Syneclise consists, in general terms, of three parts:

– carbonate platform of the Zechstein Limestone (Ca1) occurring only in the north-westernmost corner of the study area and passing into basin facies dominant in the most part of the area (Peryt et al., 1992);
– the PZ1 evaporite platform system composed of sulphate platforms and adjacent basin system (Czapowski, 1983, 1987, 1998; Peryt et al., 1992; Peryt, 1994) and constituting the major part of the Zechstein sequence;
– the A1g–PZ3 cover (Fig. 3).

The distribution pattern of the Ca2 facies established in the eastern part of the Łeba Elevation is characterized by a basin margin sequence deposited on a relatively uniform and gentle slope of a homoclinal ramp (Read, 1985) which has modern counterparts in the Persian Gulf and Shark Bay, Australia (Peryt, 1986a). Argillaceous wackestones/mudstones containing whole fossils characteristic of the deeper ramp are passing shoreward to peloidal and peloidal-bioclastic and lump deposits (possibly representing lagoonal facies), and then to a fringing oolite flat facies and a tidal-flat complex of the coastal oolitic barrier system (see Peryt, 1986a). The latter was adjacent to the sabkha facies recorded in the vicinity of Łeba town where two carbonate units predominantly consisting of intertidal deposits are separated by a sulphate unit representing a sabkha environment (see Peryt, 1986a: fig. 4). South of the Łeba VI borehole where the shift of carbonate deposition was recorded, in the Białogarda IG 1 and Lębork IG 1 boreholes only sulphates were deposited during the Ca2 time (Peryt, 1986a). Wagner (2015) considered that these sulphates represent "extremely

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1617



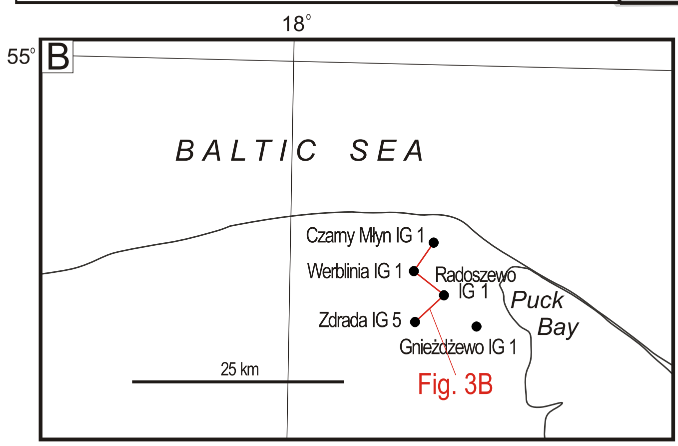




**Fig. 2A – subcrop map of the sub-Permian-Mesozoic unconformity of the East European Craton in Poland (simplified after Waksmundzka, 2010) showing the limit of occurrence of Zechstein deposits (white broken line; after Czajor and Wagner, 1974; Peryt, 1989, 1990a) and the location of boreholes referred to in this paper; yellow frame shows the area shown in B; B – enlargement of a fragment of A showing the area where >90% of boreholes listed in Appendix 1 were drilled**

shallow-water" lithofacies called coastal anhydrite – a facies analogue of the Ca2 and A2 (Wagner et al., 1978c: fig. 1).

The Ca3 deposits occur in much wider area than the Ca2 deposits do (Peryt et al., 1992; Wagner, 2015). Wagner (2015) concluded that the Pomeranian Peninsula was mostly inundated by the transgressing sea of the Ca3. In addition, the palaeogeographical patterns of both carbonate units were different. During the Ca2 the coastal oolitic barrier system occurring along the Baltic Sea shore east of Łeba and then, south of Łeba, showing a roughly longitudinal direction, was gradually passing into the open basin facies (see Peryt, 1986a). During the Ca3 deposition, open basin facies was separated from a wide restricted platform zone by a narrow zone of arched platform edge (running from the Jastarnia IG 1 borehole – Peryt et al., 1978: p. 13–14, through Mechelinki – Gąsiewicz, 1985 and Wejherowo and the further towards the north-west) where ooid sands occurred (Peryt, 1983; Gąsiewicz, 1985, 1990a; Gąsiewicz and Peryt, 1989b). In the southern part of platform laminoids are accompanied by relatively rare bioclastic intercalations, and in its northern part, north of the Werblinia IG 1 borehole, the bioclastic and muddy intercalations are common and the laminoids are poorly developed (Gąsiewicz et al., 1987; Gąsiewicz and Peryt, 1989b; Gąsiewicz, 1990a, b).

Facies and sequence stratigraphic correlation and interpretation of the PZ2-PZ3 strata in the western part of the Peribaltic Syneclise along a transect A of Peryt and Wagner (1998) shows that (1) the most part of the Zechstein sequence are lowstand systems tracts (LST) deposits and (2) wedge-shape pile of TST+HST deposits of the Zechstein sequence 3 is shifted basinward regarding the same pile of Zechstein sequence 2 (cf. Fig. 3B). On the other hand, there is a consensus, as far as the western part of the Peribaltic Syneclise is concerned (cf. Peryt

Table 2

**Publications reporting the previous research on the Zechstein in PGI boreholes located in the East European Craton**

| Author | Published in | Subject |
|---|---|---|
| E. Czajor | Modliński (1974), Areń (1978) | petrography of carbonate rocks |
| K. Pawłowska | Krasowska (1973), Lendzion (1975) | lithology and stratigraphy |
| L. Piątkowska | Modliński (1982) | petrography of carbonate rocks |
| T. Piątkowski | Dembowska and Marek (1988), Modliński (1989) | petrography of carbonate rocks |
| R. Wagner | Krasowska (1973, 1977), Areń (1974, 1975, 1978) Modliński (1974, 1975, 1977, 1982, 1989, 2007, 2011), Lendzion (1975), Witkowski (1976, 1986), Tomczyk (1977), Dembowska and Marek (1988), Podhalańska (2007, 2008, 2011, 2012, 2014), Leszczyński (2011, 2019); Podhalańska and Sikorska-Jaworowska (2015, 2018), Waksmundzka and Wójcik (2019) | lithology and stratigraphy |
| M. Wichrowska | Leszczyński (2011), Matyja (2011), Modliński (2011), Podhalańska (2011, 2012, 2014), Podhalańska and Sikorska-Jaworowska (2015, 2018) | petrography of carbonate rocks |

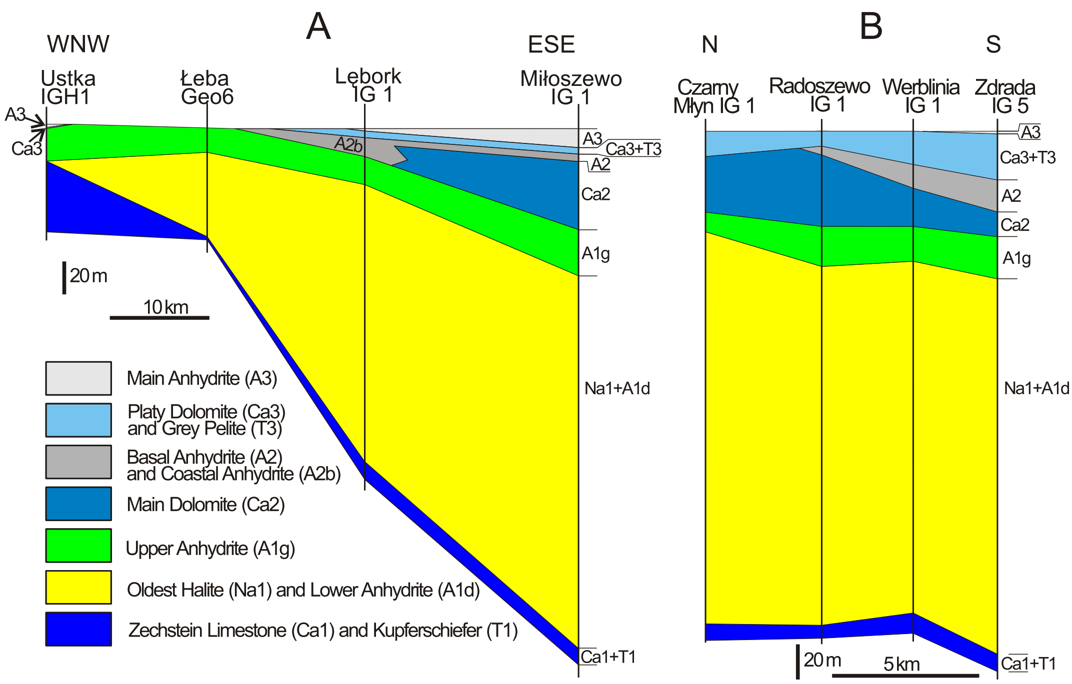



**Fig. 3. Cross-sections showing Zechstein strata along the lines shown in Figure 2**

The reference level is the top of PZ3 deposits
(except of Łeba Geo6 where younger than A1g strata are lacking)

et al., 1992; Wagner, 2015), that the Ca3 platform is wider than the Ca2 platform (see Peryt, 1986a; Gąsiewicz and Peryt, 1989 for details). In addition, because the palaeogeographical patterns of the Ca2 and Ca3 are in fact divergent – facies zones of the Ca2 are controlled to some extent by the Pomeranian Peninsula and in the Ca3 they are oblique against it – the carbonate unit occurring above the PZ1 cycle can represent the Ca3 as in the case of the Ustka IGH1 (Fig. 4), Lębork IG 1 and Bytów IG 1 boreholes (Figs. 5 and 6).

The Ustka IGH1 borehole is located between the Łeba Geo3 and Łeba Geo4 boreholes that were characterized by Szaniawski (1970) who supposed that the Zechstein strata in the area represent only the PZ1 cycle. In the borehole, the Ca1 is overlain by sulphate-siliciclastic deposits included by Wagner (2008b) to an unspecified PZ1 Anhydrite. In the upper part of the sulphate-siliciclastic complex a 70 cm thick dolomite intercalation occurs (Fig. 4). It consists of dolomite-sulphate laminite of sabkha type accompanied by possibly pedogenic carbonates (Fig. 4B) similar to those occurring at the top of the Ca1 (Fig. 4C) and laminoids (Fig. 4A). The sulphate-siliciclastic strata below the dolomite are regarded as the A1g (Peryt et al., 1992) – facies zone 1 *sensu* Peryt (1990b). The 70 cm thick dolomite

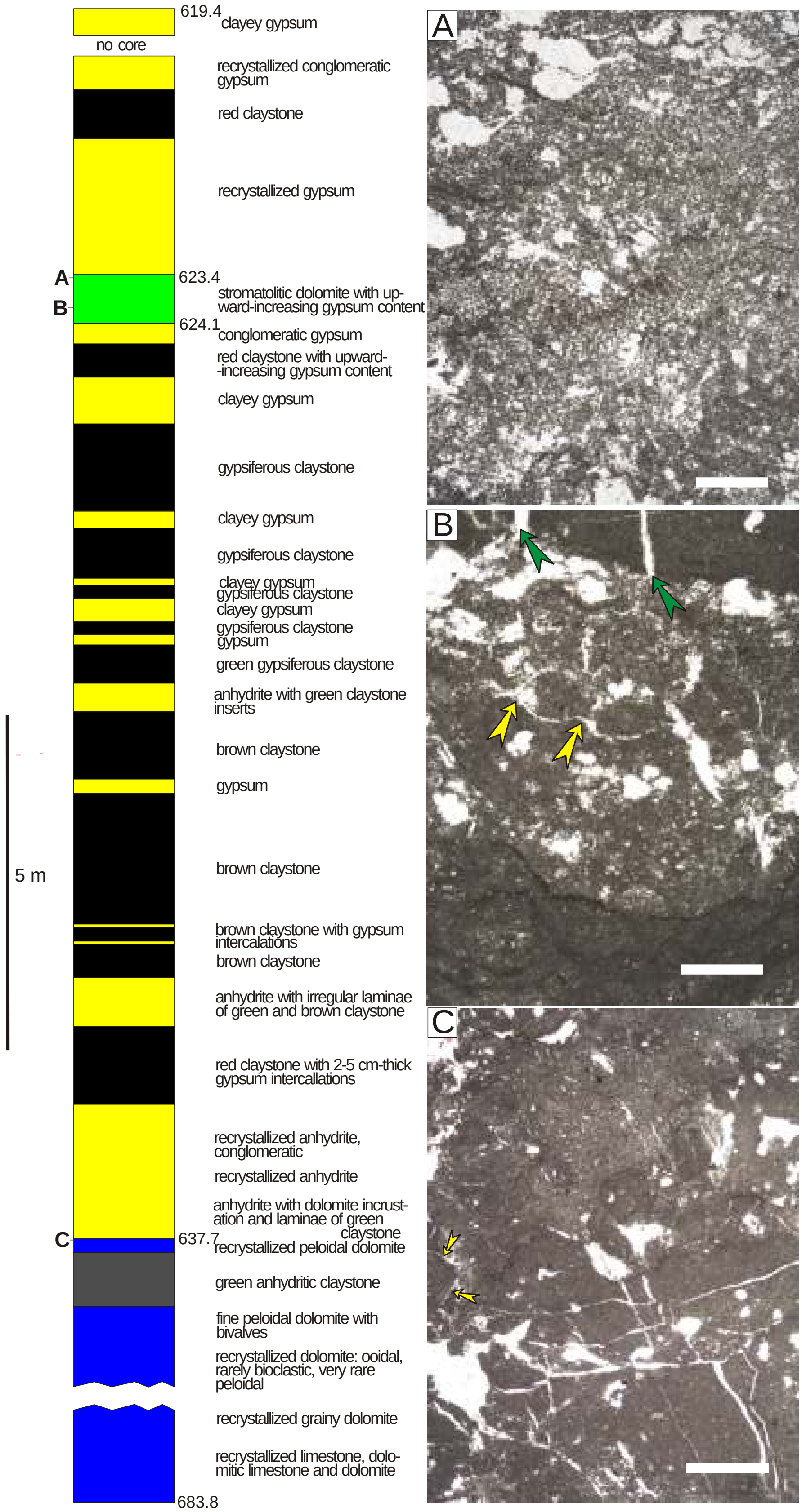
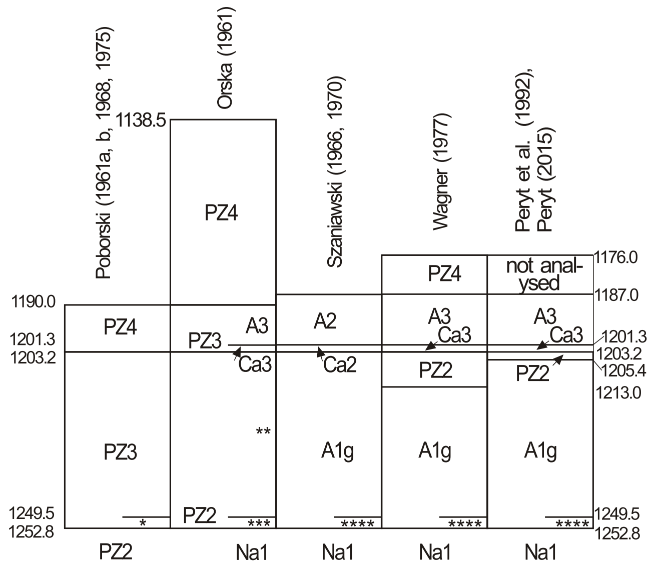



**Fig. 4. The Zechstein section of the Ustka IGH1 borehole**

**A** – biolaminoidal dolomite with abundant fenestrae in the upper part; **B** – calichefied granular dolomite; irregularly bent and branching voids filled with anhydrite (pedotubules – yellow arrows) possibly corresponding to decayed root system and fine small desiccation cracks (green arrows); **C** – recrystallized peloidal dolomite showing subhorizontal and subvertical cracks, possible circumgranular cracks (yellow arrows), and granular texture (particularly well seen in the upper part of the photo) – possibly calichefied deposit. The carbonate deposits in the depth interval 637.7–683.8 m represent the Zechstein Limestone, the stratigraphic position of the overlying strata is subject to discussion (see the text); the scale bar is 1 mm




* anhydritic dolomarl; ** mostly anhydrite; *** anhydritic dolomite; **** anhydrite breccia

**Fig. 5. Development of ideas on stratigraphy of the upper part of the Zechstein deposits in the Bytów IG 1 borehole**

Current abbreviations of particular members as shown in Table 1 are used for the presentation of concepts of various authors

was first assumed to be the Ca2 (Peryt, 1986a) and then the Ca3 (Peryt et al., 1992), and the latter interpretation is accepted. The anhydrite above this dolomite would represent the Main Anhydrite (A3).

Interpretations of stratigraphy in the Lębork IG 1 and Bytów IG 1 boreholes differ although they mostly refer to the upper part of the sections, above the Oldest Halite (Na1), except of the concept presented by Poborski (1961a, b, 1968, 1975) (Fig. 5; see a review by Wagner, 1977). Wagner (1977) distinguished the PZ2 cycle developed in the entirely sulphate facies based on the existence of lateral transition of Ca2 deposits into the sulphate deposits (Pokorski and Wagner, 1975) and the continual sedimentation between the A1g and PZ2 including the lack of erosion. Then, however, Peryt (1990b) indicated that in the Peribaltic Syneclise prior to the onset of the Ca2 deposition, the PZ1 evaporite platform with the A1g cover, became exposed and subject to karstification as indicated by the occurrence of filling of cavities in the anhydrite by green-coloured clay-dolomitic material (cf. Peryt, 1986b). In the Lębork IG 1 above the karstified A1g deposits the Ca3 occurs (Fig. 6; Peryt, 2015). In the borehole Bytów IG 1 karstified strata of the A1g are overlain by recrystallized anhydrite (0.9 m thick) and nodular anhydrite (1.1 m thick). These deposits – covered by the Ca3 – are included into the PZ2 cycle (Figs. 5 and 6). Further to the north, in the Białogarda IG 1 the A1g is overlain by red claystone (0.25 m thick) that in turn is covered by nodular anhydrite (Fig. 6; Peryt et al., 1992).

## EASTERN PART OF THE PERIBALTIC SYNECLISE

There are only 17 boreholes east of the Bartoszyce meridian, and only 2 of them: Gołdap IG 1 and Kętrzyn IG 2 are located in more marginal part of the basin. The Bartoszyce IG 1 section itself is characterized by the occurrence of the basinal facies of the PZ2 and PZ3 cycles: the Ca2 (5.2 m thick) is followed by the PZ2 evaporites (including the Older Halite) with a total thickness of 22 m, and the Ca3 (5.5 m) is overlain by the A3 (18.5 m) (Wagner, 1974). The Younger Halite (Na3) deposits are known to occur some 25 km SW of the Bartoszyce IG 1 borehole and then further to the west (Peryt, 1989). In turn, the PZ1 cycle consisting of the T1 (1.0 m), Ca1 (46.0 m), A1d (75.7 m), and A1g (5.1 m) have originated at the slope of the Ca1 carbonate platform (Wagner, 1974).

East of the Bartoszyce IG 1 borehole, the Barciany region is subject to diverse interpretations (see discussion in Gąsiewicz and Peryt, 1989a). The case of the Gołdap IG 1 borehole section is a remarkable example of varied stratigraphical interpretations (Fig. 7). Each of those interpretations had its strong and weak points, and each had important implications for palaeogeographical reconstructions.

An upper part of the lower carbonate complex assigned by Orska (1962) and Pawłowska (1968) to the Ca2 and by other authors to the upper part of the Ca1 consists of recrystallized dolomites that show the former presence of fine spherical or subspherical grains (0.2 mm or less) (Fig. 8E). These grains have been dissolved and only the cement (and possibly matrix) was left behind, and the pores were then filled by anhydritic cement (Fig. 8E). The shells of probably bivalves accompanying the dissolved spherical or subspherical grains were not subject to dissolution what suggest a different primary mineralogy. Below this part of the section, calcitic dolomites occur that are mostly composed of millimetric coated grains showing mostly a grainstone texture (Fig. 8F).

Wagner (1974) and Czajor (1974) reported a gradual transition from the "oncolitic" dolomite (shown in Fig. 8E) into a massive anhydrite (5.2 m thick) that was included by them in the A1d but considering the replacive and displacive nature of anhydrite in the highest part of the discussed carbonate unit such a transition does not imply a continual deposition. There is no doubt that the carbonate deposition was followed by meteoric diagenesis related to the subaerial exposure of the carbonate platform of the Ca1 both during the final stages of the Ca1 and after (cf. Clark, 1980). As already concluded by Czajor (1972), the sea level fall leading to the basinward migration of the coastline already occurred during the Ca1 deposition. There is a consensus that in the Zechstein Basin the marginal carbonate platforms of the Zechstein Limestone (and its equivalents) became subaerially exposed after the sea level fall due to the evaporite drawdown (e.g., Smith, 1979; Peryt, 1984; Tucker, 1991; Becker and Bechstädt, 2006; Peryt et al., 2010). They could become the place of deposition only after the seawater/brine level was high enough again which often occurred after the transgression related to the sequence boundary at the base of the ZS3; cf. Table 1). Therefore, there is no reason to assume the presence of A1d in the Gołdap IG 1 as well as in other boreholes in similar palaeogeographical location. The anhydrite overlying the Zechstein Limestone is hence included into the A1g (Fig. 7). To the A1g belong also the overlying interbedded mudstone and anhydrite (Peryt, 1990b). In the upper part of the unit, in the dolomitic inserts possibly related to the subaerial diagenesis of sulphate deposits, calcified filaments are common (Fig. 8D).

Above the A1g, the 3.5 m thick dolomite unit occurs that was regarded as the Ca3 or Ca2 (Fig. 7). It consists of biolaminoidal dolomite with abundant fenestrae and calcified filaments (Fig. 8A) and the deposits showing weakly developed lamination consisting of thicker and muddy laminae, possibly biolaminoid, alternated with organic laminae (Fig. 8B); in addition, rare dolomitized algal boundstone occur in the lower part (Fig. 8C; cf. Czajor, 1974).

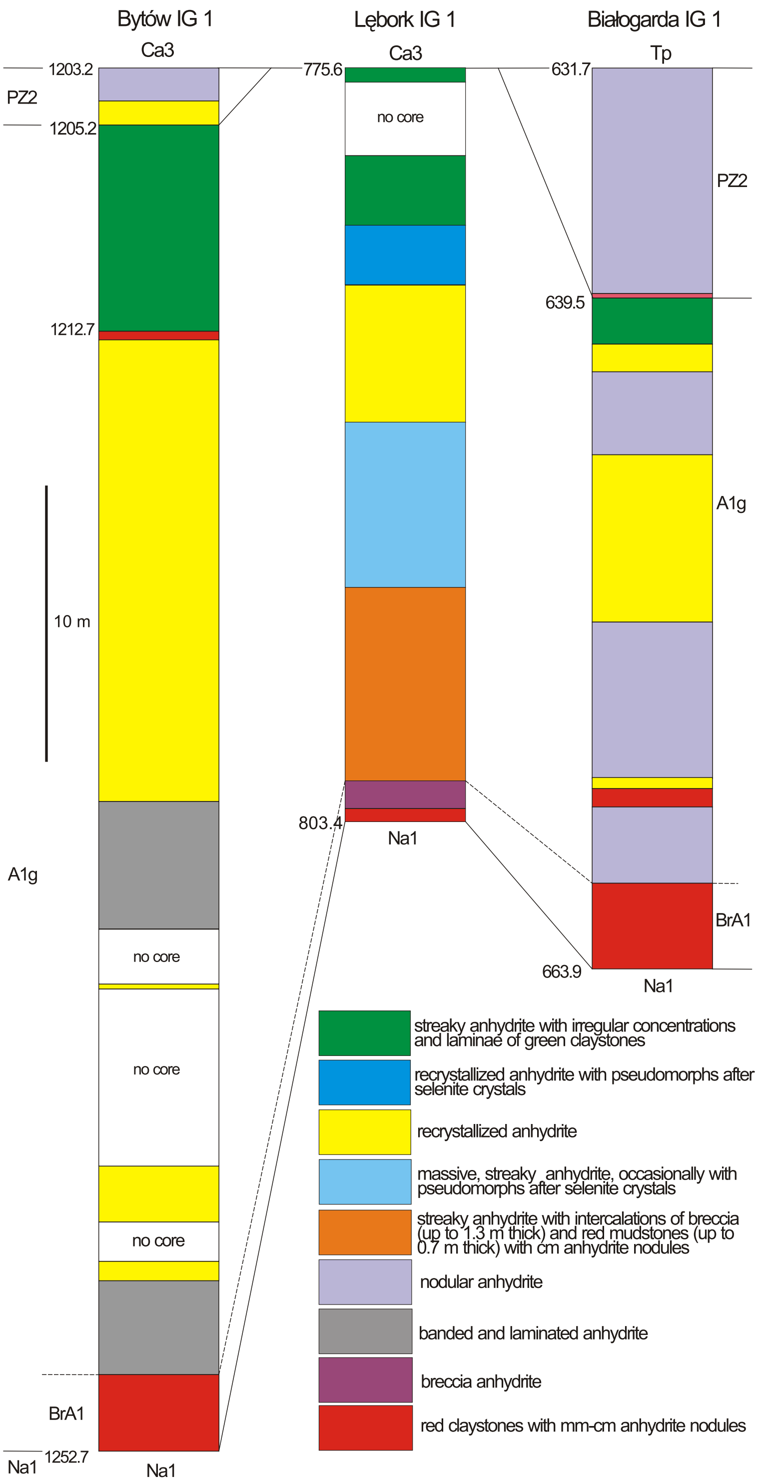



**Fig. 6. The lithology of the Upper Anhydrite and PZ2 deposits in the Bytów IG 1**

Lębork IG 1 and Białogarda IG 1 boreholes

In the Kętrzyn IG 2 borehole, 15.1 m thick dolomites showing ooid packstone and grainstone textures, partly recrystallized and, in their upper part, oomouldic, are covered by 1.5 m thick dolomite containing large admixture of non-carbonate grains (Peryt and Czapowski, 1988). Czajor (1972) indicated, in this part of the section, a concentration of heavy minerals characterized by the highest density what was interpreted as a proof for beach zone (Czajor and Wagner, 1974). This carbonate sequence representing the Ca1 (Fig. 7) is covered by 3.5 m thick complex of sandy mudstones and sandstones of arkosic composition (Czajor and Wagner, 1974). The siliciclastic complex was characterized by Czapowski (in Peryt and Czapowski, 1988) and interpreted as deposited in a lagoonal environment passing upward into a nearshore envi-

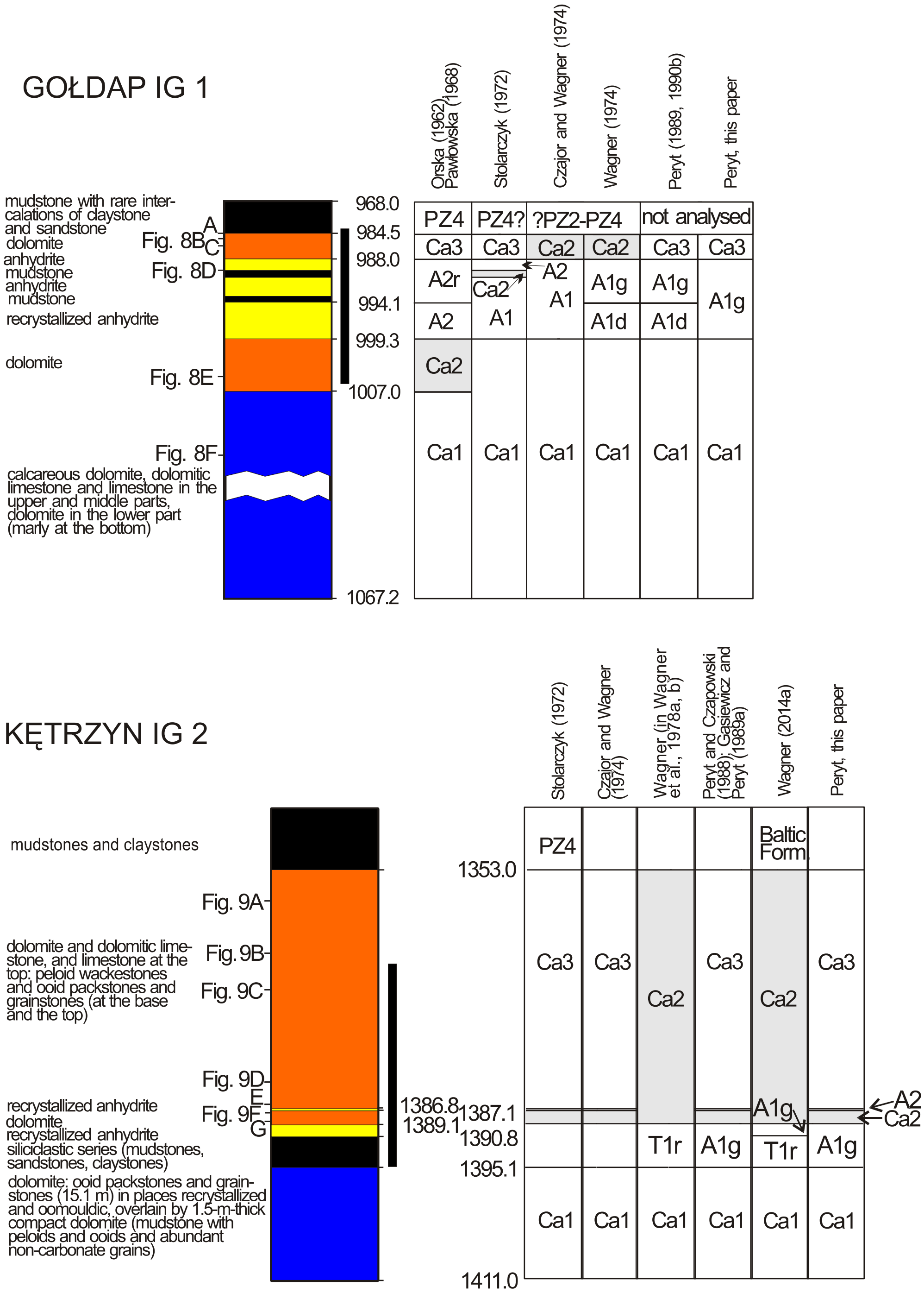



**Fig. 7. Development of ideas on stratigraphy of Zechstein deposits in the Gołdap IG 1 and Kętrzyn IG 2 boreholes (current abbreviations of particular members as shown in Table 1 are used for the presentation of concepts of various authors**

The entire Zechstein was cored, and the black bar right of stratigraphic column shows the almost full core recovery (otherwise core recovery was poor in the Kętrzyn IG 2 borehole)

ronment. Then, 1.5 m thick recrystallized anhydrite occurs. The siliciclastic complex and the overlying anhydrite bed were included into the A1g by Peryt and Czapowski (1988) based on analogy with the development of the A1g in the Puck Bay region (Peryt, 1990b), and the transgressive nature of the A1g (Peryt and Czapowski, 1988). Finally, a concept of such a nature of A1g was accepted by Wagner (2014b).

Peryt and Czapowski (1988) concluded that the 30 cm thick anhydrite bed occurring in the lower part of the upper carbonate complex (lying above the A1g) shows pseudomorphs after upright-growth gypsum crystals indicating salina environment, is the A2, and thus the overlying carbonate strata represent the Ca3 what have been previously accepted by Stolarczyk (1972) and Czajor and Wagner (1974). Then, however, Wagner

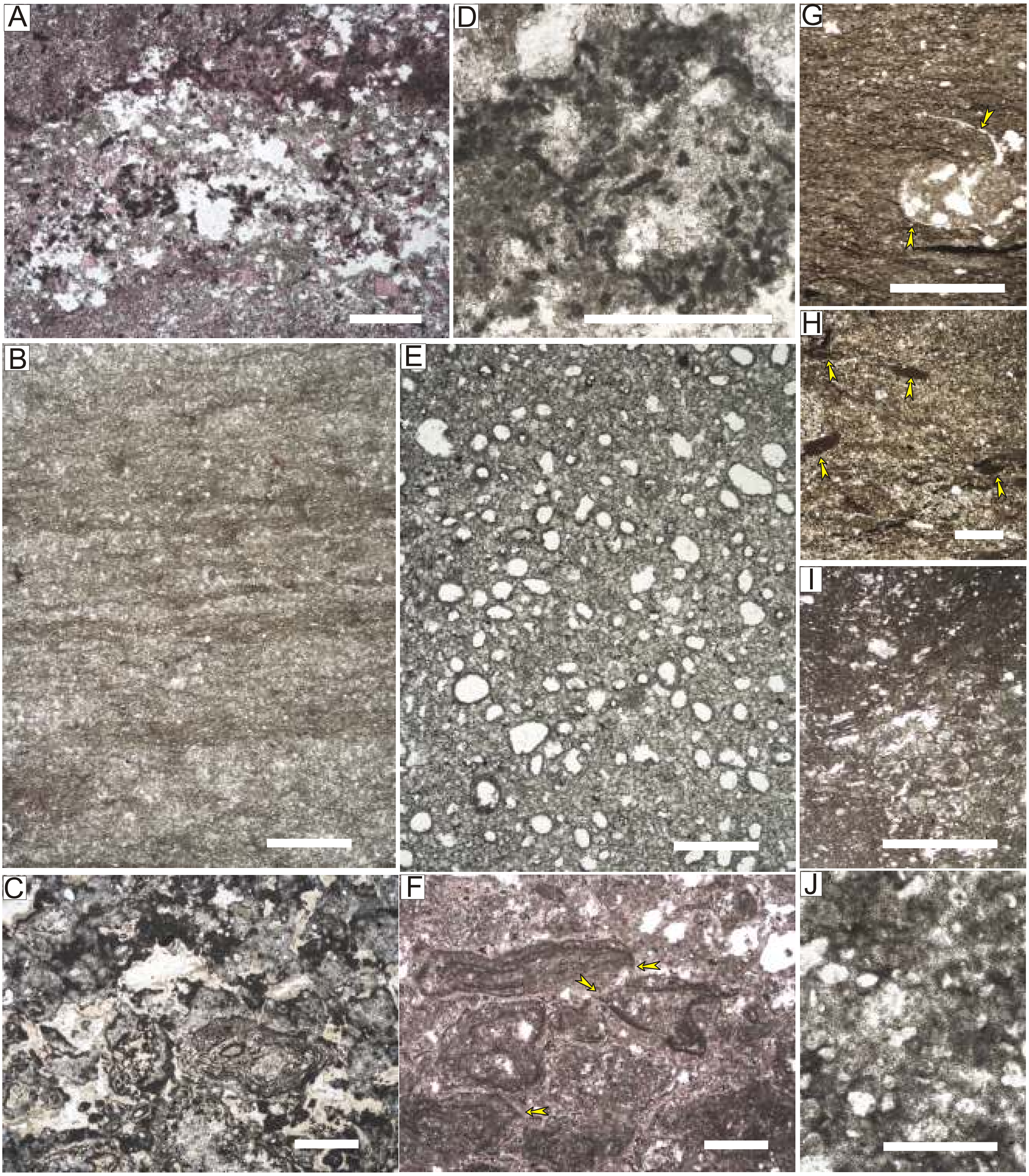



**Fig. 8. Microfacies of the Zechstein carbonate rocks in Gołdap IG 1 (A–F; see the location of samples in Fig. 7) and Olsztyn IG 1 (Platy Dolomite: G – 1891.6 m, H – 1892.1 m and Main Dolomite: I – 1912.2 m, K – 1913.6 m)**

**A** – biolaminoidal dolomite with abundant fenestrae and calcified filaments in the middle part; **B** – weakly developed lamination consisting of thicker and muddy laminae, possibly biolaminoid, alternated with organic laminae; **C** – dolomitized algal boundstone; **D** – calcified filaments, each of coating of micrite; **E** – fine oomoldic packstone, with porosity occluded by anhydrite; **F** – recrystallized pisolitic grainstone composed of large, irregularly-coated composite grains, with an over-packed texture due to vadose compaction (arrows); **G** – recrystallized mudstone-wackestone with thin bivalve shells (arrows) and streaks of organic matter; **H** – recrystallized wackestone with clasts of mudstone (arrows); **I** – recrystallized peloidal-bioclastic dolomite with abundant thin-shelled bivalves; **J** – recrystallized oolitic dolomite; the scale bar is 1 mm

(1978b, 2014b) assumed that similar anhydrite intercalations are common in the basal part of the Ca2 and thus its stratigraphic importance in the Kętrzyn IG 2 borehole is questionable. On the other hand, in his description of the Kętrzyn IG 2 borehole, Wagner (2014a) stresses that the contact of anhydrite intercalation with the underlying dolomite is "clearly erosional" (Wagner, 2014a: p. 73).

Gąsiewicz and Peryt (1989a) put the Ca2-Ca3 boundary within the part of the Zechstein section included by Wagner (in Depowski, 1978) to the Ca2. Wagner (2014b) raised the point that in the section a break in sedimentation should be observed and in the core of 100% recovery, no proof of such a break exists (although his core description states, as noted above, erosional nature of anhydrite-dolomite boundary).

The Ca3 section was characterized by Gąsiewicz and Peryt (1989a) and Wichrowska (2014), although the latter author accepted the stratigraphical concept of Wagner (2014a) and hence it is regarded by her as the Ca2. At the bottom of the unit, recrystallized ooidal-bioclastic grainstone (Fig. 9E) followed by recrystallized bioclastic-peloidal wackestone-packstone (ostracod shell in the upper left corner of Fig. 9D) occur. Then a complex of mostly biolaminoids with intercalations of mudstones and bioclastic wackestones (thin-shelled bivalves, foraminifers) (Fig. 9C). The top of the unit consists of recrystallized ooidal grainstone with common composite grains (Fig. 9A, B).

The Ca3 in the central part of the Peribaltic Bay shows a different development (cf. Figs. 8G, H and 9H, I).

## PODLASIE DEPRESSION

The Zechstein Sea in the area of the Podlasie Depression extended up to westernmost Belarus where the carbonate rocks (up to 40 m thick) of the Kamenetsk Suite occur (Golubtsov and Monkevich, 2001). Its lower part contains abundant fossils: brachiopods (among others *Horridonia* ex gr. *horrida)*, pelecypods, crinoids, corals, bryozoans, ostracods, foraminifers (*Nodosaria*, *Dentalina*, *Geinitzina*) and flora remains, and the upper part, occasionally oolitic and containing rare intercalations of marls and clays, contains rare pelecypods (*Schizodus*, *Pseudobakewellia*) and abundant flora (Golubtsov, 1961). Very similar characteristics are shown by the 31 m thick calcareous-dolomitic strata with abundant fossils in the Mielnik IG 1 borehole that are included into the Ca1 (Pawłowska, 1968). They are overlain by the 9.5 m thick marly-mudstone series with intercalations of barren carbonates that were regarded as the PZ2 deposits by Pawłowska (1968).

Towards the west the inventory of stratigraphical units increases and near the connection with the main basin the PZ1–PZ3 sequence is complete in the Nadarzyn IG 1 borehole (Wagner, 1983). East, NE and SW of the borehole, the total thickness of the Zechstein and of the particular cycles decrease (Fig. 10), and in particular the evaporite members gradually disappear (Czajor and Wagner, 1974; Wagner, 1983). For example, the Na1 is 159.0 m thick in the Warszawa IG 1 borehole and ~20 m thick in the Polaki 1 borehole (Czajor and Wagner, 1974: fig. 43). As already concluded by Czajor and Wagner (1974), the Na1 fills the earlier existing depressions in the basin and the A1g was deposited almost independent of the earlier facies zones.

In the Nadarzyn IG 1 borehole, the Ca2 (8.3 m thick) are thin peloidal-intraclast-bioclastic wackestones and packstones (2.3 m) overlain by a 1.8 m thick series of columnar stromatolites followed by bedded clayey bivalve and gastropod wackestones (4.2 m) (Piątkowski, 1988). It is followed by the A2 (first recrystallized anhydrite with pseudomorphs and pores after upright-growth gypsum crystals, then laminated anhydrite), the Older Halite (Na2) and the Screening Anhydrite (A2r); the total thickness of the PZ2 is 99 m (Wagner, 1983). The T3 (0.7 m) consists of dolomitic mudstones and sandstones containing clasts of claystones and mudstones. It is followed by the Ca3 (2.9 m) that contains peloidal packstones (10 cm) at the base followed by bedded mudstones (30 cm) and bryozoan-bivalve packstones (including 10 cm thick coquina – 1.55 m). The packstones are overlain by bedded mudstones (1.15 m) that near the boundary with the A3 become clayey and contain rare bivalves (Piątkowski, 1988). The Ca3 is overlain by the A3 (26.7 m) – anhydrite with mm-cm pores, presumably after halite crystals. The total thickness of PZ3 deposits is 30.3 m (Wagner, 1983).

In the Okuniew IG 1, the thickness of PZ2 deposits decreases to 26.0 m (although the thickness of Ca2 remains the same as in the Nadarzyn IG 1 borehole), and the thickness of the PZ3 is almost the same as in the Nadarzyn IG 1 (T3: 1.0 m; Ca3: 3.5 m; A3: 28.5 m; in total: 33.0 m – Wagner, 2008b). Then, towards the north (Wyszków IG 1) and the south (Wilga IG 1), PZ2 and PZ3 evaporites disappear and above the PZ1 deposits only one basically carbonate complex (albeit with siliciclastic intercalations) occurs (Fig. 11).

The Ca2 deposits in the Wilga IG 1 borehole are 33.5 m thick and consist of mudstones and wackestones (10.2 m) overlain by peloidal (microbial?) recrystallized dolomite (9.1 m), then bioclastic wackestones with bivalves, foraminifers and ostracods (4.2 m) with two 10–20 cm thick intercalations of oncolites (1–3 mm across), and 10 m thick oncoid grainstones (Fig. 12A, B) with common possibly microbial laminae and rare bivalve shells that are chaotically arranged (Wagner, 2019). Then, a 1.5 m thick quartz mudstone with common clasts (up to 5 mm across) of the T3 occurs. It is followed by 3.5 m thick bioclastic wackestones-grainstones (Fig. 12D, E) with two intercalations (30–40 cm thick) of dolomitic mudstones; in the top extraclasts (fine clasts of claystone) appear (Fig. 12F). Bivalves and gastropods quite often form coquinas, and in addition encrusting bryozoans occur. Wagner (2019) interpreted the Ca3 deposits as formed in a shallow lagoon and considered that the microfacies and a small thickness of the Ca3 as the proof of a smaller extent of the Ca3 than the Ca2 along the Potycz 1–Wilga IG 1–Izdebna IG 1 line.

In the Wyszków IG 1 borehole, above the peloidal-ooidal grainstones of the Ca2 (Fig. 12C) recrystallized dolomite with filaments (Fig. 12I) of microbial origin occur. They are accompanied by encrusting foraminifers (Fig. 12H) and bivalves. At the top ooidal grainstones occur (Fig. 12G).

In several boreholes (including Wyszków IG 1, Tłuszcz IG 1 and Łochów IG 1) above the Ca1, mudstone with laminae of sandstone occurs with common dolomite clasts derived from the Ca1. This series in the Tłuszcz IG 1 borehole was included into the PZ2 detrital deposit (Pawłowska, 1968; Wagner, 1971), and subsequently to the T1r (Wagner, 1974) and the A1g (Peryt, 1990b; Fig. 11). The overlying carbonate complex was regarded by Pawłowska (1968) and Wagner (1974) as belonging to the Ca2, but Peryt (1990a) concluded that its uppermost part composed of microbial mats with bryozoan fragments (Czajor, 1978) is the Ca3 (Fig. 11). It clearly differs from the underlying "oncoidal" deposits – thus the analogy with the Wyszków IG 1 borehole is striking. This difference in sedimentary conditions was already noticed by Czajor (1978) although she explained it as due to a considerable shallowing or subaerial exposure of an "oncolitic ridge" that protected the lagoon from wave action.

In the Łochów IG 1 borehole, above the cored interval (Fig. 11) occur mudstones with dolomite intercalations (up to 2 m

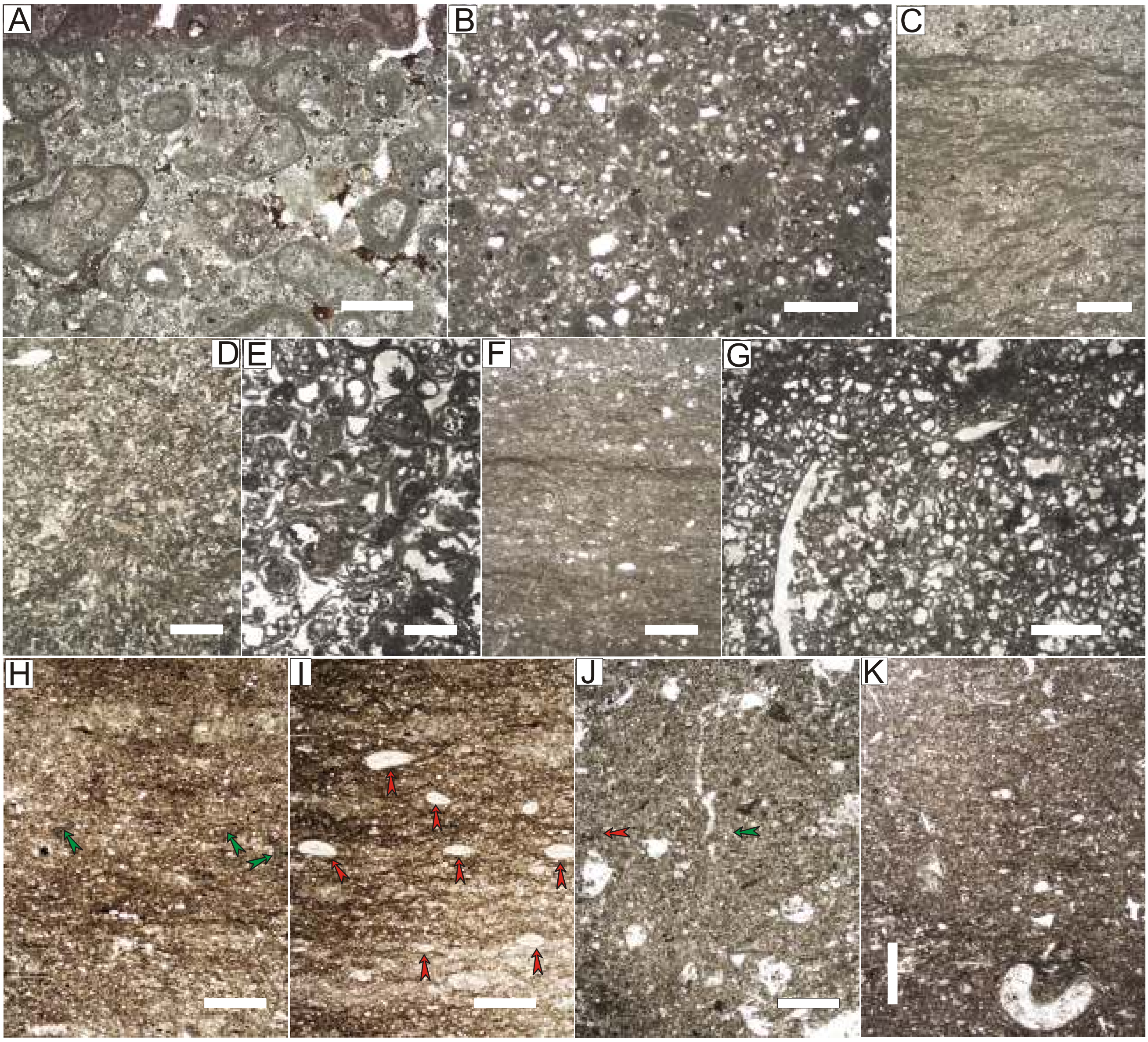



**Fig. 9. Microfacies of the Zechstein carbonate rocks in Kętrzyn IG 2 (A–H; see the location of samples in Fig. 7) and Kętrzyn IG 1 (Platy Dolomite: H – 1319.6 m, I – 1325.1 m and Main Dolomite: J – 1333.5 m, K – 1334.0 m)**

**A**, **B** – recrystallized ooidal grainstone with common composite ooids (in A); **C** – recrystallized dolomite showing the occurrence of granular texture, with micritic flasers of enigmatic origin; **D** – recrystallized bioclastic-peloidal packstone (ostracod shell in the upper left corner of the photo); **E** – recrystallized ooidal-bioclastic grainstone; **F** – recrystallized granular grainstone; **G** – oomoldic grainstone with bioclasts (bivalves, ostracods), with porosity occluded by anhydrite; **H**, **I** – sparsely fossiliferous (foraminifers – green arrows, ostracods – red arrows), organic matter-rich micrite; **J** – recrystallized wackestone-packstone with uniserial foraminifers (green arrow) and tubular microfossils (red arrow); **K** – recrystallized bioclastic wackestone-packstone; gastropod in the lower right corner; the scale bar is 1 mm

thick) that can be equivalent to the Ca3 (Wagner, 1978b). Peryt (1990a) assumed, based on the correlation of geophysical logs, that the Ca3–Ca2 boundary is in the middle of carbonate complex. However, the microfacies suggest that this boundary should be placed at the base of a mudstone intercalation containing clasts of dolomite that is possibly an equivalent of the T3 (Fig. 11). The Ca2 would be represented, in the upper part, by microbial dolomite (Fig. 13E, F), recrystallized ooidal grainstone (Fig. 13D) and, in the uppermost part, recrystallized granular dolomite, possibly pedogenic in origin (Fig. 13C). The Ca3 consists of recrystallized dolomite showing, in the lowermost part, common silt-size quartz grains and clasts of mudstone (Fig. 13B) and recrystallized fenestral dolomite with micritic concentrations, possibly filaments (Fig. 13A). Such an interpretation is also supported by reinterpretation of the geophysical logs (cf. Peryt, 1990a: fig. 3).

In the Żebrak IG 1 borehole, the T1 (0.15 m thick) is overlain by 8.6 m thick Ca1 and then 41.2 m thick anhydrite of the PZ1 cycle occurs (Fig. 11; Pawłowska, 1968) followed by clayey anhydrite with claystone intercalations included in the A1g (Peryt, 1990a; Wagner, 2008b). The 4.0 m thick dolomites with fossils occurring at the Zechstein top was put into undivided PZ3 + PZ4, Ca2 or Ca3 (Fig. 11). The latter interpretation was based on striking similarity to the microbial "more grainy" facies of the eastern

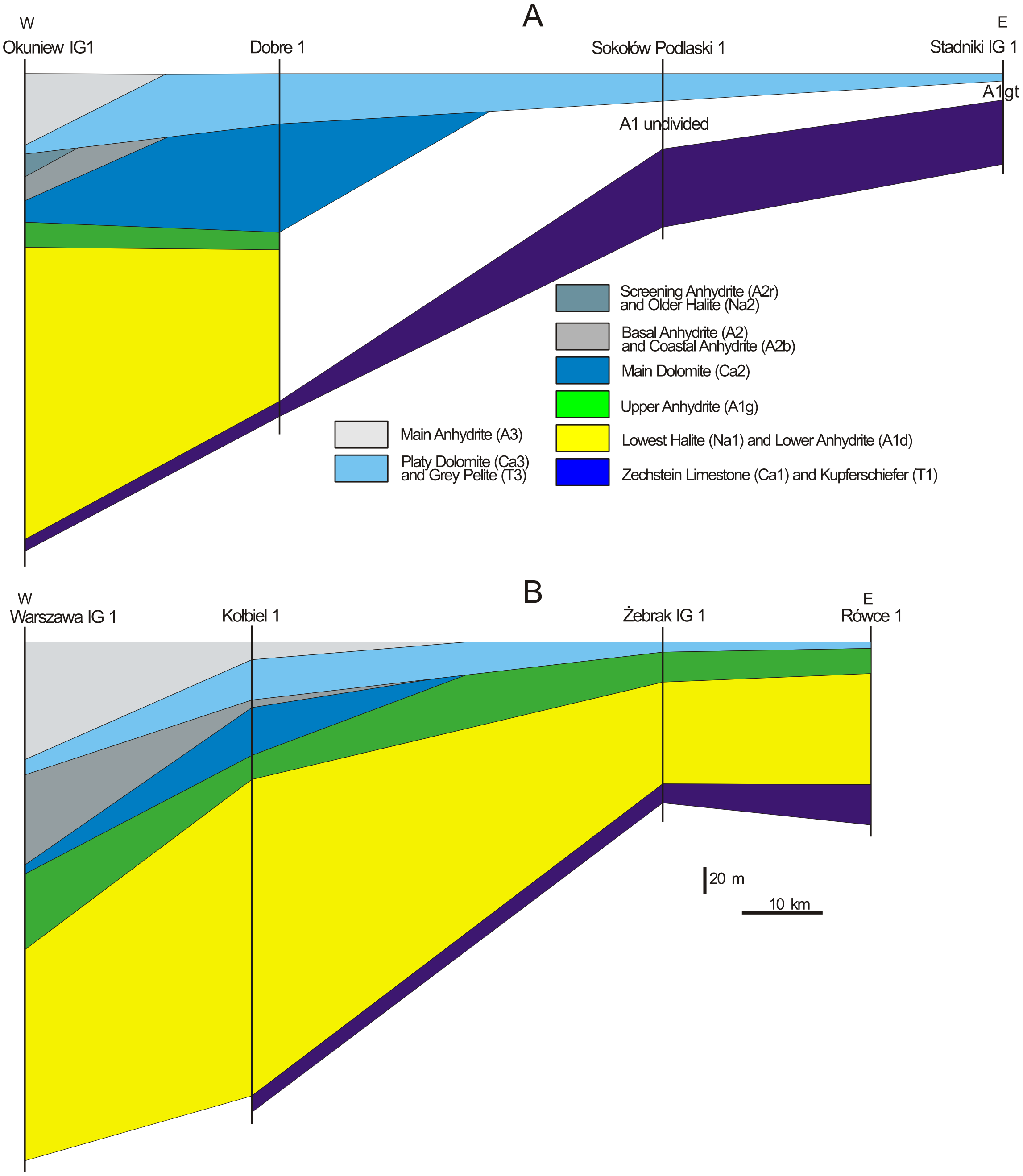



**Fig. 10. Cross-sections showing PZ1–PZ3 strata along the lines shown in Figure 2A**

A is modified and simplified figure 5 of Peryt (1990a)

part of the Peribaltic Syneclise (Gąsiewicz and Peryt, 1989a) and the occurrence of anhydrite nodules (up to 20 mm).

In the Wrotnów IG 1 borehole, the Ca1 (23.5 m thick) is covered by massive anhydrite (12.5 m) and then anhydrite with mudstone intercalations (7.0 m). According to Wagner (2008a), they both represent the Lower Anhydrite. Our interpretation is that the massive anhydrite is the Lower Anhydrite, and the overlying anhydrite with mudstone intercalations is the A1g. It is covered by a 5 m thick dolomite, mostly marly, with bivalves (very often in convex-up position – Fig. 14C, E) and plant detritus. Laminated bindstones (Fig. 14D, F), more rare fenestral bindstones (Fig. 14B), with intercalations of peloidal packstone with bioclasts (Fig. 14C, E) and quartz grains (Fig. 14A) are composing the unit that represents Ca2 after Wagner (2008a) and Ca3 after Peryt (1990a).

In the Stadniki IG 1 borehole, the Zechstein Limestone (25.5 m thick) is overlain by the recessive terrigenous series (7.5 m) composed of mudstones with intercalations of fine-grained sandstones (Wagner, 2011a). Then, 3 m thick dolomite occurs that is assumed to be a fragment of the basal Ca2 by Wagner (2011b) or Ca3 by Peryt (1990a). These are laminoid bindstones with fenestral fabrics (Fig. 14H–J) with intercalations of organodetrital rocks composed of bivalve and gastropod shells and peloidal packstone with quartz grains (Fig. 14G).

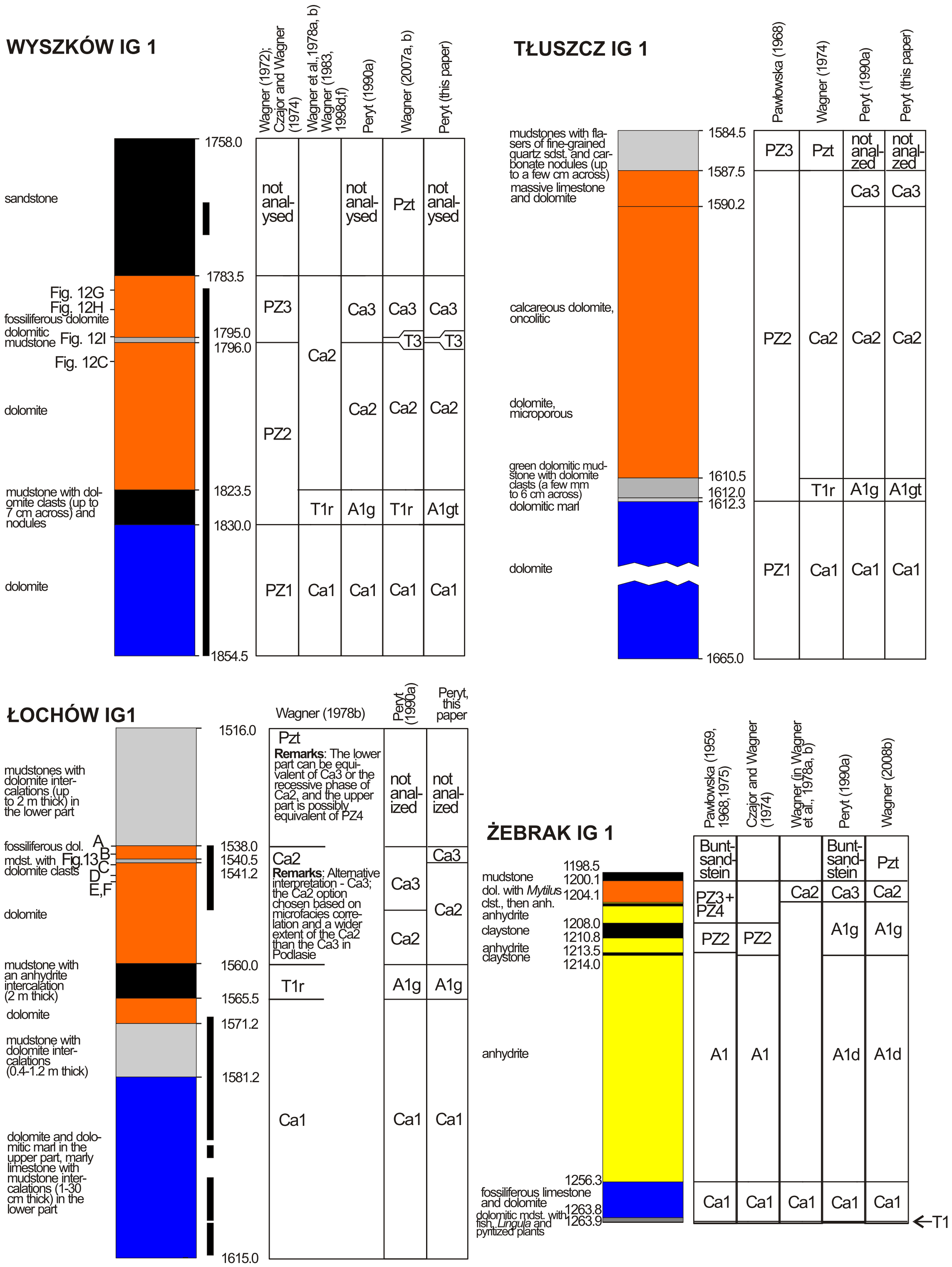



**Fig. 11. Development of ideas on stratigraphy of Zechstein deposits in the Wyszków IG 1, Tłuszcz IG 1, Łochów IG 1 and Żebrak IG 1 boreholes (current abbreviations of particular members as shown in Table 1 are used for the presentation of concepts of Pawłowska, 1959, 1968, 1975; Wagner, 1972, 1974, 1978b, 1983, 1998d, f, 2007a, b, 2008b; Czajor and Wagner, 1974; Wagner et al., 1978a, b; Peryt, 1990a)**

The black bar right of stratigraphic columns in the Wyszków IG 1 and Łochów IG 1 boreholes shows the cored intervals (in the Wyszków IG 1 borehole, the core recovery is very good except of boundary intervals between the particular units)

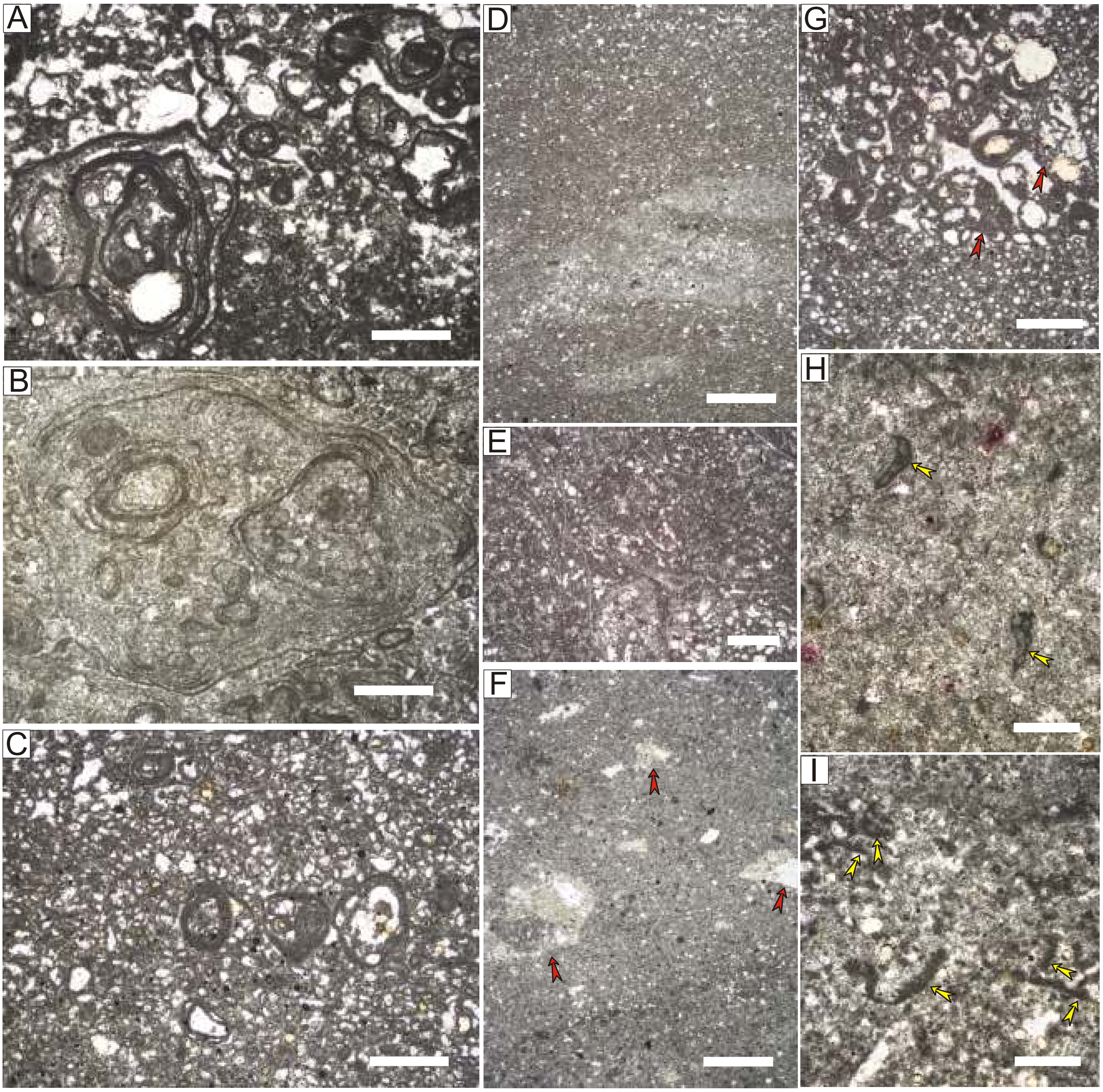



**Fig. 12. Microfacies of the Main Dolomite (A–C) and Platy Dolomite (D–I), Wilga IG 1 (A – 2084.7 m, B – 2085.1 m, D – 2080.2 m, E – 2083.1 m, F – 2084.3 m) and Wyszków IG 1 (C, G–I, see the location of samples in Fig. 11)**

**A**, **B** – recrystallized pisolitic grainstone composed of large, irregularly-coated composite grains; **C** – peloidal-ooidal grainstone; **D** – recrystallized peloidal packstone-grainstone; **E** – recrystallized peloidal-bioclastic (thin-shelled bivalves) packstone-grainstone; **F** – recrystallized packstone with extraclasts (red arrows); **G** – ooidal grainstone – fine ooids in the lower part, accompanied by large ooids and intraclasts of ooidal grainstones (red arrows) in the upper part; **H** – recrystallized dolomite with tubular microfossils (possibly encrusting foraminifers; yellow arrows); **I** – recrystallized dolomite with filaments (yellow arrows); the scale bar is 1 mm

## DISCUSSION

Outside the EEC in Poland the Ca3 deposits (and thus PZ3 deposits) had much wider extent than the Ca2 deposits (and thus PZ2 deposits) (e.g., Wagner, 1976; Peryt, 1977; Kowalczewski and Rup, 1989). The same was recorded in Germany (e.g., Kulick, 1991; Paul, 2020c; Hug-Diegel and Heggemann, 2020; Paul and Huckriede, 2020) as well as in the Netherlands and England (see Peryt et al., 2010 with references therein). For the EEC area, Wagner (1988, 1994, 1998d, f) presented the view that the present and primary extents of the Ca3 were smaller than those characteristic of the Ca2, which was explained by the "general palaeogeographical situation". This "general palaeogeographical situation" was in fact the conviction that the factors controlling the Zechstein deposition in the EEC were different than those characteristic for other parts of the basin; but no proof for this has been presented. In addition,

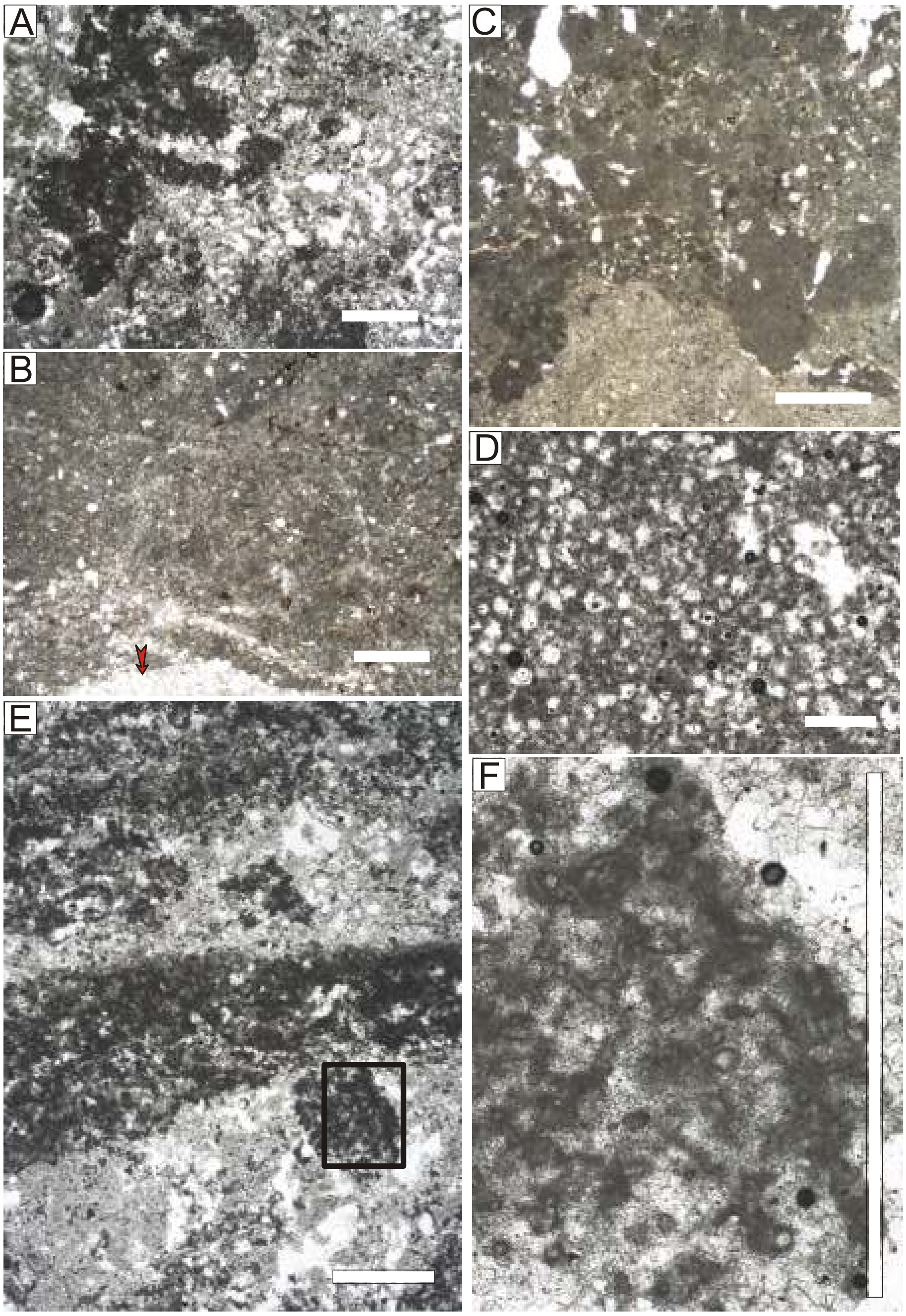



**Fig. 13. Microfacies of the Platy Dolomite, Łochów IG 1 (see the location of samples in Fig. 11)**

**A** – recrystallized fenestral dolomite with micritic concentrations, possibly filaments; **B** – recrystallized dolomite showing, in the lowermost part, common silt-size quartz grains and a clast of mudstone (red arrow); **C** – recrystallized granular dolomite, possibly pedogenic in origin; **D** – recrystallized fine ooidal grainstone, with ooids commonly dissolved and pores occluded by anhydritic cement; **E** – microbial dolomite with very common filaments, in places thoroughly recrystallized, quadrangle outlines a fragment shown in enlargement in F; **F** – enlarged view of part of E showing common filaments; the scale bar is 1 mm

the same argument (i.e., general palaeogeographical situation) was applied – for example in the case of the Wyszków IG 1 borehole – either to neglect the presence of the Ca3 (e.g., Wagner et al., 1978a, b; Wagner, 1983, 1998d, f) or to confirm its occurrence (Wagner, 1972, 2007a, b; Czajor and Wagner, 1974). Certainly one could speculate that the cratonic part of the Zechstein basin could have a different depositional history during the PZ2 and PZ3 times than the part of the basin having Cadomian, Caledonian and Variscan fold belts in the basement (Fig. 1B) but on the other hand there is no doubt that the NW part of the EEC, west of the Puck Bay area, shows exactly the same trend as in the West European Platform (see Peryt, 1989; Peryt et al., 1992; Wagner, 2015). Therefore, the concept that only a part of the EEC adjacent to the Mazury Land (Wagner,

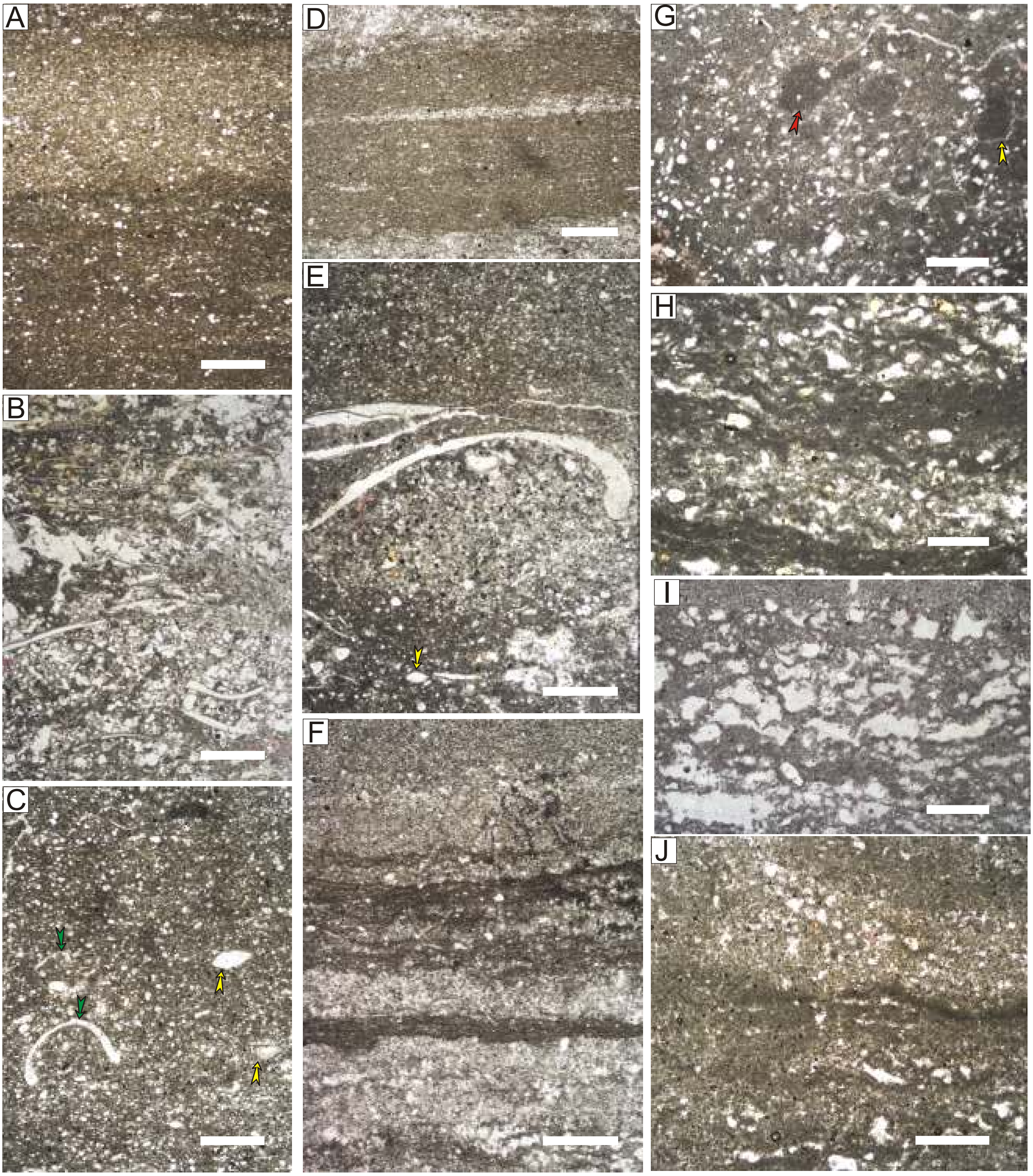


**Fig. 14. Microfacies of the Platy Dolomite, Wrotnów IG 1 (A–F) and Stadniki IG 1 (G–I, K): A – 1256.8 m, B – 1257.7 m, C – 1257.8 m, D – 1259.5 m, E – 1259.7 m, F – 1260.8 m, G – 794.9 m, H – 799.1 m, I – 799.3 m, J – 799.7 m**

**A** – recrystallized peloidal packstone with common quartz grains; **B** – fenestral bindstone and bioclastic-peloidal packstone; **C** – peloidal packstone with bioclasts (ostracods – yellow arrows, bivalves – green arrows); bivalves in convex-up position; **D** – laminated bindstone consisting of alternated thin light laminae with rare fenestrae and possible porostromate microstructures and thick micritic laminae; **E** – laminated peloidal packstone with bivalve shells in convex-up position and ostracods (yellow arrow); **F** – laminated bindstone consisting of alternated thicker light laminae with rare fenestrae and possible porostromate microstructures and thin micritic laminae; **G** – peloidal packstone with quartz grains and irregularly bent and branching voids filled with anhydrite (pedotubules – yellow arrow) and possible caliche nodules (red arrow); **H–J** – laminoid bindstone with fenestral fabrics; the scale bar is 1 mm

1988) shows a different behaviour compared to the Variscan Platform is unreasonable considering the stability of the area (as stressed otherwise by Wagner, 1988) and low rate of subsidence (that was ~6 times lower than in the Mid-Polish Trough and twice lower than in the Variscan platform – Wagner, 1988).

The inundation of the pre-existing depression in which the Upper Rotliegend deposits have accumulated by the Zechstein sea resulted in that the marginal parts of the EEC became the loci of marine sedimentation except for the Mazury Land where essentially crystalline rocks occurred (Fig. 2A). North of the Mazury Land, a wide Baltic Bay developed, and south of the Land, less indented Podlasie Bay was formed; they both had mostly Lower and Middle Paleozoic deposits in the substrate.

The PZ1 deposits in the Polish part of Baltic Bay are mostly 200–300 m thick except in its marginal parts (Wagner, 1998a; Peryt et al., 2010). In the Podlasie Bay the thickness is much smaller – only in the Warszawa region does it exceed 200 m, and is more than 100 m thick only in its westernmost part (Peryt, 1990a).

The deposition of Ca1 resulted in the origin of carbonate platforms along the basin margins that changed the inherited topographic setting. The A1d deposits are LST deposits and hence they are lacking in more marginal parts of the western (Fig. 4) and eastern Peribaltic Syneclise (Figs. 7 and 15) as well as in the major part of the Podlasie Bay (Fig. 11). In turn, they occur in the central, basinal parts of the bays. The accommodation space existed and/or created during the A1d and the Na1 deposition in the Baltic and Podlasie bays was filled and at the onset of the A1g deposition, a roughly planar surface existed except in the area adjacent to the main Polish basin (cf. Peryt, 2010).

The A1g deposits are TST and then HST deposits (Wagner and Peryt, 1997) and they encroached the Ca1 platforms (Figs. 4, 7, 11 and 15). In addition to the sulphate deposits, siliciclastics are a common (sometimes main) constituent of the A1g sections. Rarely, as in the Wyszków IG 1 and Tłuszcz IG 1 boreholes (Fig. 11), no anhydrite is associated with mudstones which contain dolomite clasts (up to 7 cm across) and nodules (Wagner, 1974, 2007a, b). We suggest to use the term Terrigenous Upper Anhydrite (A1gt) for such cases. Previously they were considered by Wagner (1978a) as Recessive Terrigenous Series (T1r) equivalent to the PZ1 evaporites. Wagner et al. (1978c) stressed that the Anhydrite Breccia (BrA1) is passing shoreward into mudstones of the T1r; evidently, the time relation of those strata with the A1g seemed the most probable.

The A1g deposition was terminated by sea level fall, and the A1g deposits in the marginal areas became subject to karstification, as well demonstrated in the Puck Bay region (Peryt, 1990b). The Ca2 transgression occurred in several phases but its maximum limit did not reach the A1g limit (e.g., Peryt, 1986a, 1992; Fig. 16). In the Puck Bay region, Peryt (1986a) documented that deeper ramp zone is passing into a lagoonal zone (both facies zones being separated by a narrow hypothetical barrier zone). Further shoreward a prograding coastal oolitic barrier system, coastal oolitic barrier system and sabkha facies zone occurred. In NW Poland and in NE Germany an inner platform (lagoonal) zone (separated by a narrow mostly oolitic barrier from the platform slope) is dominated by carbonate muddy lithofacies, locally (bio)laminated with rare microbialite and grainy deposits (e.g., Gąsiewicz, 2013; Piske et al., 2020).

In the eastern part of the Peribaltic Syneclise and Podlasie Bay, in a deeper part of the basin, marly dolomites of the Ca2 3.0–10.0 m thick occur (Figs. 8I, K and 9K, L; Czajor and Wagner, 1974; Piątkowski, 1988). They are passing into carbonate platform deposits. In the NW part of the Podlasie Bay ooid-

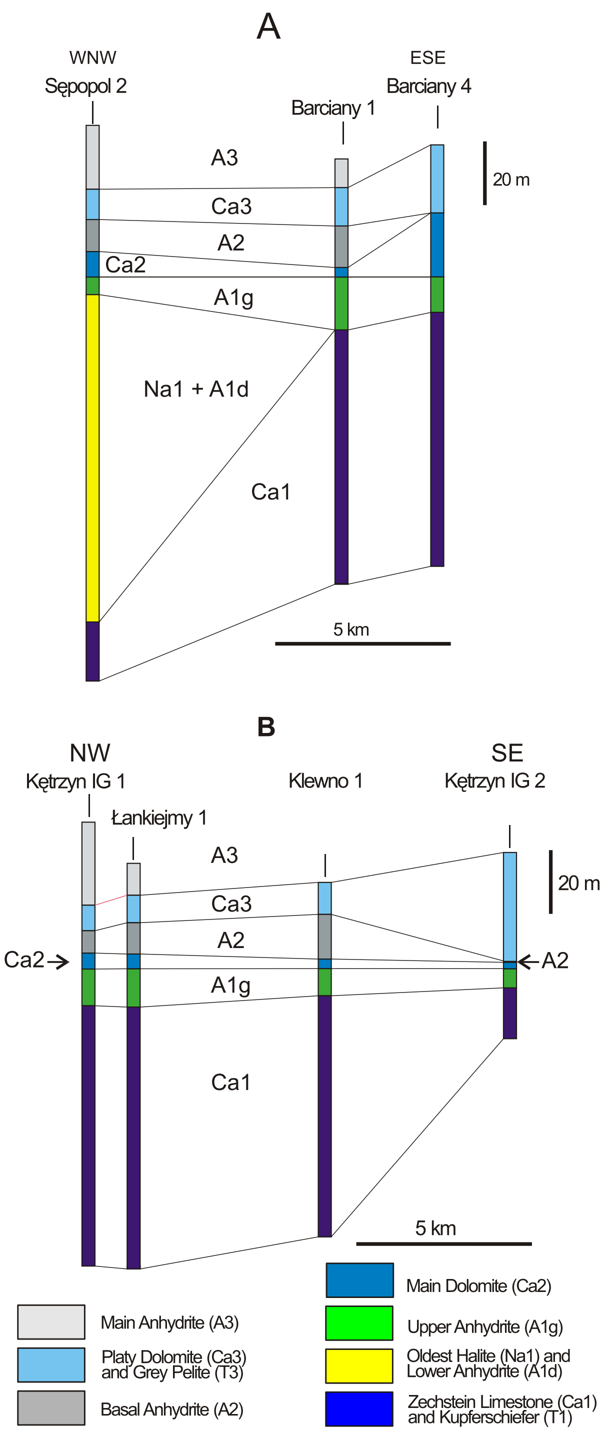



**Fig. 15. Cross-sections showing PZ1–PZ3 strata along the lines shown in Figure 2A**

The reference level is the top of the Upper Anhydrite

bioclastic grainstones of the transgressive beach occur in the Wyszków IG 1 borehole (Peryt, 1990a) and their equivalents in other boreholes (Tłuszcz IG 1, Łochów IG 2 – Czajor, 1978: fig. 37). They are followed by mudstones, then peloid packstones and finally ooid grainstones (Czajor, 1978; Peryt, 1990a). Such a succession is characteristic for a lagoonal zone with a pro-

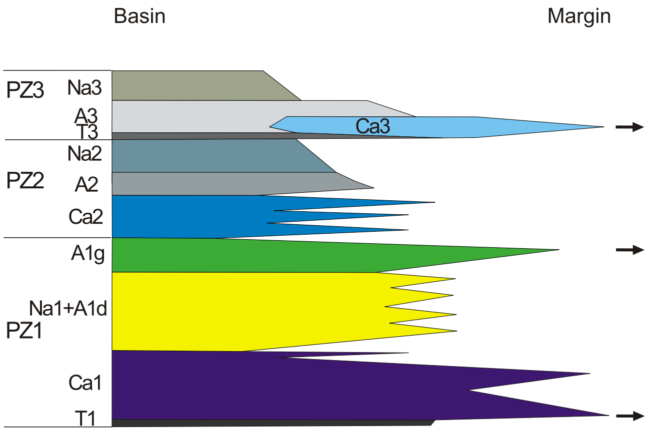



**Fig. 16. PZ1–PZ3 strata in the EEC showing the basin-margin relations in time (the figure concept after Paul, 2020c: time axis is arbitrary, white colour – mostly no deposition or minor terrestrial sedimentation, black arrows indicates maximum flooding surface)**

grading coastal oolitic barrier system (cf. Peryt, 1986a), and thus it is reasonable to expect that the limit of the Ca2 is not distant from those boreholes. In the SW part of the Podlasie Bay, in the Wilga IG 1 and Warka IG 1 boreholes, bedded mudstones followed by mudstones and bioclastic wackestones-packstones with intercalations of ooid grainstones in the uppermost part (Peryt, 1990a), and forming the top 10 m of the Ca2 section in the Wilga IG 1 borehole (cf. Wagner, 2019). Wagner (2019: fig. 30) interpreted that the occurrence of platform-edge barrier is documented in the borehole (Wagner, 2019).

In the eastern part of the Peribaltic Syneclise, very few boreholes show the Ca2 in other facies than the basinal one. In the Barciany 4 borehole, in the lowest part of the Ca2 transgressive deposits showing a great similarity to those in the Puck Bay region occur. Then, mudstones with thin intercalations of wackestones and packstones (either bioclastic or ooid) occur, and in places mudstones are passing into laminoids (Gąsiewicz and Peryt, 1989a). Those characteristics suggest a lagoonal environment within a homoclinal ramp that existed there. Eventual barrier zone (or coastal oolitic barrier system passing into a sabkha zone) of the Ca2 can be located east of the Barciany 4 borehole and between the Klewno 1 and Kętrzyn IG 2 boreholes. Accordingly, the assumed relatively small width of the marginal carbonate platform of the Ca2 agrees well with the narrow carbonate shelf in the northern rim of the Southern Permian Basin during the Ca2 (Peryt et al., 2010; Piske et al., 2020).

A2 deposits originated in shallow subaqueous environments. In the Puck Bay area, their deposition resulted in elimination of the relief that was previously created owing to a different rate of carbonate deposition in the carbonate platform and adjacent basin during the Ca2 sedimentation. It was estimated (Peryt, 1986a) that by the end of the Ca2 the difference in depth between the northernmost and southernmost part of the Puck Bay region it was ~40 m. The Na2 deposits occurred in the deeper, basinal parts of the Baltic and Podlasie Bays, and are developed in an open salt basin facies (e.g., Prabuty IG 1 and Krynica Morska IG 1 boreholes – Czapowski, 1989; Czapowski et al., 1990) although the case of the Bartoszyce IG 1 borehole where a pan facies was recorded (Czapowski, 1989; Czapowski et al., 1990) indicates that a series of shallow salinas or salt pans along the basin margins (Peryt, 1989). The deposition of the PZ2 chorides resulted in the elimination of the accommodation space that was inherited after the deposition of the Ca2 and the A2.

Subsequently, the area became exposed, and in the lowest areas playa deposits, developed as green siltstones/claystones with irregularly distributed anhydrite nodules, formed. Although they are rarely recorded (e.g., in Gnieżdżewo IG 1 borehole – Czapowski et al., 1991), initially they probably were much more widespread. The A2r is the TST deposit of the next Zechstein sequence (Peryt et al., 1996b), followed by marine deposits (T3) related to the last major transgression during the life of the Zechstein basin that resulted in a flooding of the exposed surface of older Zechstein deposits, including the area that was emergent during deposition of the PZ2 cycle.

The thickness of Ca3 deposits in the EEC exceeds 40 m in the Puck Bay area (Gąsiewicz and Peryt, 1989b). In most marginal parts of the Ca3 basin the deposits of the unit are eroded at least partly and this explains why no transitional environments to continental one have been recorded despite the occurrence of a wide microbial platform. In the Ca3 of Hesse a transition of the microbial mats facies (up to 50 km wide) to a sabkha zone was recorded by Möller (1985). A similar width of the microbial platform assumed for the EEC.

Microbial carbonates (benthic microbial carbonates *sensu* Burne and Moore, 1987), being stromatolites and thrombolites (Kennard and James, 1986; Burne and Moore, 1987), are a common feature of all Zechstein carbonate units but in particular this is the case of the Ca3. This was at least partly related to a general decline, in the Late Permian, of skeletal biota coinciding with a further increase in microbial carbonates (Flügel and Kiessling, 2002). Although microbialites are opportunistic forms that may develop even in normal marine, subtidal seafloor, seasonal hypersalinity is among the mechanisms playing a fundamental role in the abundance and distribution of microbialite deposits in some environmentally stressed settings (see Mercedes Martín and Buatois, 2021 with references). This stressed environments have caused, among others, a poorly diversified faunal composition in the eastern part of the Baltic Bay (Table 3).

In the Barciany region and Kętrzyn IG 2 boreholes the microbial platform deposits occur, and they continue farther to the east. Peryt (1989, 1990a; Peryt and Wagner, 1998; Peryt et al., 2010) consistently presented a view of the wider Ca3 extent than that of the Ca2 in the cratonic part of the Zechstein basin (Figs. 16 and 17). This concept was also accepted for the Lithuanian part of the basin (V. Kadunas and P. Raczyński in Peryt et al., 2010), although previously it was assumed (e.g., Suveizdis, 1975) that the Ca2 limit was much bigger greater than that of the Ca3, and the occurrence of the Galinda Suite (=Leine) was restricted to the southern part of the Kaliningrad region (Russia).

Summarizing, there are no direct premises allowing for the convincing settlement of doubts regarding the stratigraphical position of the upper carbonate unit in many cases. Several lines of evidence suggest that, as in the entire Zechstein basin, the Ca2 considerably shifted basinward, and the Ca3 – landward (Fig. 16), although it is difficult to ascertain whether the original Ca3 extent was similar to or greater than the limit of the Ca1 as elsewhere in the Zechstein Basin (e.g., Smith, 1980). The Ca2 and Ca3 show different facies patterns, though, and in the Puck Bay region it can be demonstrated that the limit of the Ca3 is clearly greater than in the Ca2 but platform-edge sands of the Ca3 are shifted basinward compared to the Ca2 (Fig. 3).

Table 3

**Taxa reported by Woźny (1976) in the strata assigned to the Platy Dolomite (Ca3)**

| Borehole | Depth [m] | Taxa | Platy Dolomite according to: |
|---|---|---|---|
| Bartoszyce IG 1 | 1294.50 | *Liebea squamosa* (Sowerby)<br>*Schizodus schlotheimi* (Geinitz) | Wagner (1974) |
| Kętrzyn IG 1 | 1320.00 | *Schizodus rotundatus* Brown | Wagner (2014b) |
| | 1323.70 | *Schizodus rotundatus* Brown | |
| Kętrzyn IG 2 | 1357.20 | *Liebea squamosa* (Sowerby) | Gąsiewicz and Peryt (1989a) |
| | 1360.20 | *Liebea squamosa* (Sowerby) | |
| | 1366.40 | *Schizodus schlotheimi* (Geinitz) | |
| | 1367.40 | *Liebea squamosa* (Sowerby) | |
| | 1368.40 | *Schizodus schlotheimi* (Geinitz)<br>*Permophorus costatus* (Brown)<br>*Liebea squamosa* (Sowerby) | |
| | 1370.40 | *Liebea squamosa* (Sowerby) | |
| | 1371.60 | *Liebea squamosa* (Sowerby) | |
| | 1373.60 | *Liebea squamosa* (Sowerby) | |
| | 1375.60 | *Liebea squamosa* (Sowerby) | |
| | 1376.60 | *Liebea squamosa* (Sowerby) | |
| | 1383.10 | *Liebea squamosa* (Sowerby) | |

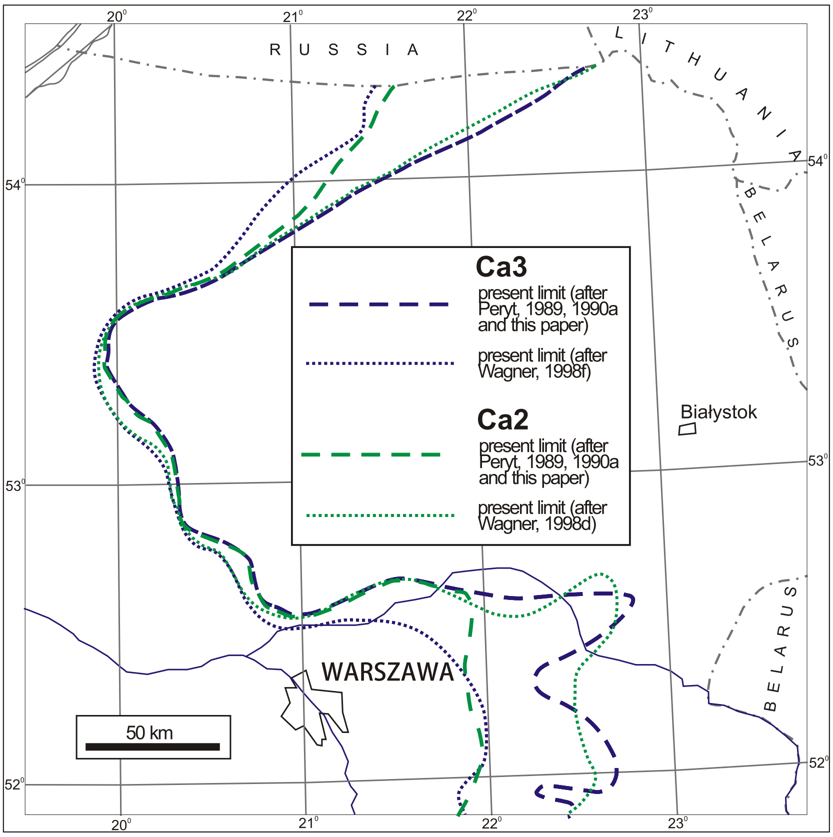



**Fig. 17. Present limits of the Ca2 and Ca3 deposits in the EEC of Poland after Wagner (1998d, f) and Peryt (1989, 1990, present paper)**

## IMPLICATIONS

An implication of the stratigraphic concept as outlined in this paper is that the limit of the Ca3 is greater that the limit of the Ca2 in the entire EEC area (Figs. 16 and 17), and not only in some its parts, as was assumed by Wagner (1983, 2015). Consequently, such a general pattern of relative changes of the limit of coastline is characteristic for the entire Zechstein basin, as already proposed by Peryt et al. (2010).

The presented concept is based largely on the results derived from the study of the Puck Bay region although definitely it is characterized by its own specifics. In the Ca3, it is characterized by predominant microbial facies (Gąsiewicz et al., 1987; Gąsiewicz and Peryt, 1989b; Gąsiewicz, 1990a, b) that for example in the area to the west (e.g., Żarnowiec 6k – Gąsiewicz in Peryt et al., 1992) become more rare and poorer developed while skeletal facies are more abundant and are accompanied by mudstones occasionally containing laminoids. A similar development was also recorded in the eastern part of the Baltic Bay (Gąsiewicz and Peryt, 1989a) and in the Podlasie Bay.

## CONCLUSIONS

1. The stratigraphic and palaeogeographic patterns of the Zechstein strata in the entire EEC area are the same as in other parts of the Zechstein basin.

2. The Lower Anhydrite and Oldest Halite form the greater part of the Zechstein section except in the most marginal parts of the basin dominated by the Zechstein Limestone.

3. In those parts, the Zechstein Limestone is overlain by the A1g, in places (Terrigenous Upper Anhydrite) in entirely siliciclastic lithologies.

4. The limit of the Ca3 deposits (very often showing microbial development) is greater that the limit of the Ca2 in the entire EEC area.

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