Geological Quarterly, 2021, 65: 21
DOI: http://dx.doi.org/10.7306/gq.1589

Depositional architecture of the Upper Cretaceous succession in central Poland (Grudziądz-Polik area) based on regional seismic data

Aleksandra STACHOWSKA[1, *] and Piotr KRZYWIEC[1]

[1] Polish Academy of Sciences, Institute of Geological Sciences, Twarda 51/55, 00-818 Warszawa, Poland

Stachowska, A., Krzywiec, P., 2021. Depositional architecture of the Upper Cretaceous succession in central Poland (Grudziądz-Polik area) based on regional seismic data. Geological Quarterly, 2021, 65: 21, doi: 10.7306/gq.1589

Interpretation of the regional high-resolution seismic data of the PolandSPAN™ survey in the Grudziądz-Polik area revealed a new depositional architecture of the Upper Cretaceous succession that differs substantially from the previously assumed layer-cake model, commonly applied to Permian-Mesozoic sequences. A previously unrecognized regional unconformity, dividing the Upper Cretaceous succession into two units characterized by very different internal geometries, was identified and mapped. The lower unit, with a generally layer-cake internal pattern, is overlain by an upper unit composed of a regionally low-angle succession that pinches out toward the south. This newly revealed regional pattern remained unrecognized in previous regional compilations based on borehole data, which suggested that a layer-cake depositional architecture prevailed throughout the entire Upper Cretaceous. This new image of Upper Cretaceous depositional patterns has far-reaching consequences for understanding of the evolution of the Polish Basin in the Late Cretaceous, including its subsidence and burial history, deposition, and tectonic development. A re-evaluation of the chronostratigraphy of the Upper Cretaceous of the Polish Basin is needed to temporally constrain the succession of sedimentary and tectonic events revealed here.

Key words: central Poland, depositional architecture, layer-cake stratigraphy, regional seismic data, seismic stratigraphy, Upper Cretaceous.

INTRODUCTION

Recognizing the internal geometry of subsurface sedimentary rock successions is often difficult, due to limited coverage or resolution of the available seismic or borehole data. This is particularly true in areas where interpretations of subsurface geology are entirely based on long-distance correlations of scattered boreholes, with no other geological and geophysical data – in particular, seismic profiles – located between them. In such situations, certain assumptions about inter-borehole correlations, rock unit thickness, and stratigraphic geometry must be made before a final geological model can be constructed. In areas with relatively simple geology devoid of any significant tectonic disturbances, a classic layer-cake geology model can be applied. This model assumes that rock layers are traceable over large distances (tens and hundreds of kilometres), and do not show any substantial changes in lithology, fossil content, and relative thickness over their entire extent (Levorsen, 1943; Brett, 1982, 2000; Brett et al., 2007; Gjelberg and Steel, 2012). Consequently, synchronous lithostratigraphic boundaries are expected; in other words, the lithostratigraphy should effectively mirror the chronostratigraphy, at least in a regional, basin-scale context (Ainsworth et al., 1999). The classic areas where layer-cake geometry models have been successfully applied for stratigraphic correlation are platform and cratonic basins (e.g., Armitage and Allen, 2010; Allen and Armitage, 2012): for instance, the Anglo-Paris Basin (Mortimore and Pomerol, 1987; Perrodon and Zabek, 1990; Bristow et al., 1997), the West Siberian Basin (Vyssotski et al., 2006; Kontorovich et al., 2014), the Parnaiba Basin (Tozer et al., 2017; Daly et al., 2018), some of the intra-cratonic basins on the North American Craton (Sloss, 1963; Merriam, 2006; Burgess, 2019), and intra-cratonic basins in Africa (Burollet, 1984).

A system of Upper Cretaceous basins dominated by pelagic carbonates, such as chalk, "chalk-like" limestone, gaize (carbonate-siliceous rock containing detrital quartz and sponge spicules), and opoka (carbonates containing biogenic silica), is well-known over extensive areas of the East European Craton and the West European Platform (e.g., Ziegler, 1990; Voigt et al., 2008; Vejbæk et al., 2010; Mortimore, 2011; Torsvik and Cocks, 2016). In these basins, a pattern of horizontal layers with broadly layer-cake patterns can be anticipated, for the most part; in many cases, however, the depositional architecture of the Upper Cretaceous succession is more complex due to regional Late Cretaceous basin inversion and associated reactivation of salt structures, which led to stratigraphic pinch-outs, incisions, and lateral thickness changes (e.g., Ziegler, 1990; Vejbæk and Andersen, 2002; Esmerode et al., 2007; Surlyk and Lykke-Andersen, 2007; Krzywiec et al., 2009, 2018a; Gennaro et al., 2013; Larsen et al., 2014; Arfai et al., 2016; Krzywiec and Stachowska, 2016; van der Voet et al., 2018; Hübscher et al., 2019).

* Corresponding author, e-mail: aleksandra.stachowska@twarda.pan.pl

Received: December 18, 2020; accepted: February 20, 2021; first published online: April 29, 2021

The layer-cake geology model has commonly been applied to the Permian-Mesozoic Polish Basin, especially the portion deposited above the East European Craton. The Upper Cretaceous of central and north-east Poland has almost exclusively been interpreted through unevenly scattered boreholes, supported by limited seismic coverage of generally poor quality (e.g., Bac-Moszaszwili and Morawska, 1975; Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 1997, 2010, 2012, 2017a). In most cases, the available local 2D seismic surveys from that area were intended to target Paleozoic and older units, and as such were insufficient to properly depict the basin-scale depositional architecture of the Permo-Mesozoic basin infill (cf. Krzywiec et al., 2018a). Major advancements in this field have only recently become possible, with the acquisition of modern, high-resolution regional seismic data through the PolandSPAN™ project (cf. https://www.iongeo.com/Data_Library; cf. Krzywiec et al., 2014a, b). The regional seismic profiles of the PolandSPAN™ (Fig. 1, inset) survey have yielded a high-quality image of the entire Phanerozoic sedimentary cover of the East European Craton in Poland, including the Upper Cretaceous succession (cf. Krzywiec et al., 2014a, b). Unparalleled spatial coverage coupled with excellent seismic imaging, including shallow intervals (the topmost few hundred metres), has allowed the recognition of previously unknown seismostratigraphic features that, in some cases, have enabled a significant re-evaluation of the regional Mesozoic history (Krzywiec et al., 2018a).

In this article, we present the results of a detailed seismostratigraphic analysis of the Upper Cretaceous succession and its internal geometry in the Warsaw Segment of the Kościerzyna-Puławy Synclinorium (Fig. 1; Żelaźniewicz et al., 2011), from PolandSPAN™ regional seismic profiles. A hitherto unknown regional unconformity, and other lateral variations within the depositional architecture of the Upper Cretaceous succession incompatible with the layer-cake depositional model, have been detected. We examine the relationship of this regional unconformity with the borehole-based stratigraphy, and propose a preliminary, qualitative model for the development of the Upper Cretaceous sedimentary succession.

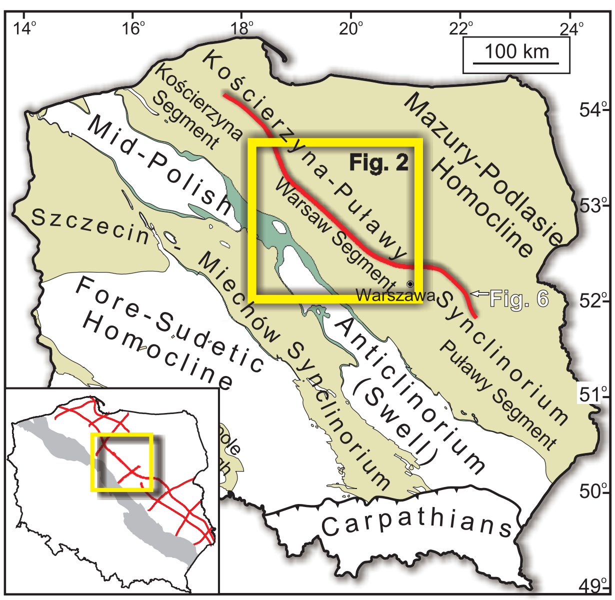

Fig. 1. Tectonic and geologic sketch-map of Poland (without Cenozoic; compiled after Dadlez et al., 2000 and Żelaźniewicz et al., 2011)

Light green – Upper Cretaceous; dark green – Lower Cretaceous; white – pre-Cretaceous; yellow rectangle – study area (see Fig. 2); red line – regional seismic profile studied herein (see Fig. 6); the extent of the PolandSPAN™ seismic profiles is shown in the inset

GEOLOGICAL SETTING

The study area is located in central Poland, within the Warsaw Segment of the Kościerzyna-Puławy Synclinorium located along the north-east flank of a major inversion structure, the Mid-Polish Swell (Anticlinorium) (Fig 1; Żelaźniewicz et al., 2011; cf. Krzywiec et al., 2018a). Palaeogeographically, the Upper Cretaceous of the study area constitutes the north-central part of the Polish Basin, which in turn formed the easternmost part of the Permian-Mesozoic Central European Basin System (Ziegler, 1990; Marek and Pajchlowa, 1997; Scheck-Wenderoth et al., 2008; Doornenbal and Stevenson, 2010). The Teisseyre-Tornquist Zone, located within the thinned, marginal edge of the East European Craton, had considerable influence on the evolution of the Polish Basin (cf. Kutek and Głazek, 1972; Dadlez et al., 1995; Dadlez, 1998; Mazur et al., 2015; Mikołajczak et al., 2019). The study area is located north-east of this zone, with its Upper Cretaceous succession forming part of the sedimentary cover of the East European Craton.

During the Permian and Mesozoic, the Polish Basin underwent several pulses of accelerated tectonic subsidence in the Zechstein–Scythian, Oxfordian–Kimmeridgian and Early Cenomanian (Dadlez et al., 1995; Stephenson et al., 2003), and was filled with a thick siliciclastic-carbonate succession, underlain by basal Zechstein (Upper Permian) evaporites (for regional overview and numerous further references see Krzywiec et al., 2017b). The basin depocentre was located axially, within the so-called Mid-Polish Trough (e.g., Pożaryski and Brochwicz-Lewiński, 1978; Dadlez, 2003). During the Late Cretaceous–Paleogene, due to the Alpine-Carpathian collision and/or the Africa-Iberia-Europe convergence, the Polish Basin underwent inversion (cf. Kutek and Głazek, 1972; Dadlez, 1998; Kutek, 2001; Krzywiec, 2002, 2006; Mazur et al., 2005), together with many other basins in Europe (Ziegler, 1987, 1990; Kley and Voigt, 2008; Voigt et al., 2020; von Eynatten et al., 2020). Consequently, the Mid-Polish Trough was uplifted and transformed into a positive structure, the Mid-Polish Swell. As a consequence of this regional uplift, the Upper Cretaceous succession was largely eroded from the area, including any growth strata that may have documented the progressive uplift of the Mid-Polish Swell. The inversion led to the development of marginal troughs subparallel to the swell (e.g., Krzywiec and Stachowska, 2016), with well-preserved Upper Cretaceous successions. Near to the Mid-Polish Swell, these marginal troughs are filled with inversion-related syntectonic deposits, which gradually disappear farther away from the inversion axis (Krzywiec et al., 2009, 2018a). The syntectonic deposits also accompany salt structures (diapirs, pillows) and other salt-related structures on both sides of the Mid-Polish Swell (Leszczyński, 2000, 2002; Krzywiec, 2006, 2012; Rowan and Krzywiec, 2014).

UPPER CRETACEOUS OF THE POLISH BASIN – AN OVERVIEW

The Late Cretaceous Basin in Poland formed part of an extensive, relatively warm, and shallow Central European epicontinental sea (e.g., Hallam, 1985; Hay, 2008; Thibault et al., 2016), characterized by siliciclastic, carbonate, and siliceous carbonate sedimentation (Voigt et al., 2008; Leszczyński, 2010, 2012). Assuming that the chalk represents the deepest facies of this basin (Walaszczyk and Remin, 2015; Machalski and Malchyk, 2019), and taking 100–250 m as the estimated depth at which the European chalk was deposited (Håkansson et al., 1974; Boussaha et al., 2017), the supposed maximum depth of the Polish Basin did not exceed 250 m (Abdel-Gawad, 1986; Świerczewska-Gładysz, 2006; Dubicka and Peryt, 2012). Most of the basin, however, was much shallower, as suggested by studies in south-east Poland (Abdel-Gawad, 1986; Walaszczyk and Remin, 2015; Machalski and Malchyk, 2019).

The general facies pattern of the Late Cretaceous Polish Basin was strongly controlled by eustatic sea-level changes (Haq et al., 1988; Hancock, 1989; Haq, 2014). The mid-Cretaceous transgression began towards the end of the Early Cretaceous, in the Middle/Late Albian, and continued to the end of the Cretaceous (Haq et al., 1988; Hancock, 1989; Haq, 2014). Initially, the sea covered the axial part of the basin (i.e. the Mid-Polish Trough), successively encroaching onto flanking areas towards the north-east and south-west, and ultimately covering most of present-day Poland (e.g., Cieśliński, 1959; Marcinowski and Radwański, 1983). The sea disappeared from the Polish Basin in the Early Paleocene (e.g., Ziegler, 1987; Piwocki et al., 2004; Jarosiński et al., 2009).

Although relatively uniform in facies, the Upper Cretaceous succession of the Polish Basin shows quite distinct lateral and vertical lithological changes, controlled by (1) proximity to the source area(s), (2) basin depth, and (3) local inversion-related tectonic movements (e.g., Jaskowiak-Schoeneichowa and Krassowska, 1988; Krassowska, 1997; Leszczyński, 2010, 2012). The pattern revealed in published lithofacies maps (Jaskowiak-Schoeneichowa and Krassowska, 1988; Leszczyński, 2010, 2012) demonstrates the presence of sandy facies within the proximal zones of the basin (best preserved farther to the north and in the south-west of Poland), and carbonates (limestone, marl, opoka, chalk, with locally abundant cherts and flints) prevailing in central pelagic zones far away from surrounding lands. Mudstone and claystone facies, often calcareous, constitute the transition zones. The study area (Fig. 1), located within the north-east flank of the Mid-Polish Trough, was in a transition zone between the peripheral regions of the basin and the open, pelagic sea.

Siliciclastic sedimentation also occurred in the centre of the basin, where it was associated with compressionally-reactivated salt or local inversion structures. Syntectonic, inversion-related Upper Cretaceous deposits have been identified in numerous boreholes and imaged by seismic data (Jaskowiak-Schoneichowa, 1979; Leszczyński, 2000, 2002; Krzywiec et al., 2003, 2009, 2018a; Krzywiec, 2006, 2012; Krzywiec and Stachowska, 2016).

DATA AND METHODS

SEISMIC DATA

This study was based on the PL1-1100 seismic profile (Fig. 1), one of the regional NW–SE oriented seismic reflection profiles acquired as a part of the PolandSPAN™ survey. The part of this profile studied is located between the Grudziądz IG 1 and Polik IG 1 deep research boreholes (Fig. 2), where the entire Upper Cretaceous succession was captured in great detail. Some seismic profiles were acquired in this part of the basin in previous decades, mostly in the late 1980s, but they did not allow a detailed recognition of internal structure in the Upper Cretaceous succession. This was mostly due to sparse seismic data coverage, the relatively short length of particular seismic profiles, their insufficient resolution, and generally poor imaging quality within the upper parts of these profiles covering the Upper Cretaceous succession (Fig. 3); in fact, in some cases, parts of the Upper Cretaceous and Cenozoic were not been imaged at all (Fig. 3A). The PL1-1100 regional seismic profile has sufficient length and is characterized by good quality, high-resolution imaging of the shallowest part; it revealed various seismostratigraphic features within the Upper Cretaceous succession precisely, including local and regional unconformities, local incisions, and lateral changes of thickness.

The PolandSPAN™ survey was acquired in 2012 by ION Geophysical as a part of their global BasinSPAN ™ Project (https: //www.iongeo.com/Data_Library). It consists of ~2200 km of seismic profiles acquired using high-end parameters: long offsets (12 km), tight station spacing (25 m), long record lengths (12 sec), and high nominal fold (480) and broadband sweep (2–150 Hz) (cf. Krzywiec et al., 2014a, b, 2017a, 2018a, b; Mazur et al., 2015). All these data have been prestack time and pre-stack depth migrated. The seismic profiles of PolandSPAN™ provide unparalleled insight into the deep subsurface, and have already been used to decipher various aspects of the Precambrian, Paleozoic, and Mesozoic structure and evolution of north-east and south-east Poland (e.g., Mazur et al., 2015, 2016; Krzywiec et al., 2018a, b; Mikołajczak et al., 2019; Kufrasa et al., 2020).

In this study, interpretation of seismic data was focused on the internal geometry of the Upper Cretaceous sedimentary succession. Due to the absence of any discernible tectonic deformation in this part of the basin, special attention was paid to a detailed analysis of the pattern of seismic reflections and their terminations, interpreted to depict details of the Upper Cretaceous depositional architecture (cf. Vail et al., 1977; Catuneanu et al., 2011), hitherto regarded as mostly adhering to the layer-cake depositional model.

BOREHOLE DATA

The PL1-1100 seismic reflection line was calibrated using two deep research boreholes: Grudziądz IG 1 and Polik IG 1 (Leszczyński, 2011a; Podhalańska and Sikorska-Jaworowska, 2018a). The boreholes, drilled by the Polish Geological Institute in 1972 (Grudziądz IG 1) and 1987 (Polik IG 1), are located in the immediate vicinity of the interpreted seismic profile (<230 m apart). Both have a sufficient set of geophysical data that, after appropriate corrections and processing, allowed for precise borehole-to-seismic ties. Additionally, both boreholes penetrated the entire Upper Cretaceous succession.

Data on the stratigraphic and lithological characteristics of the Upper Cretaceous succession have been retrieved from the Central Geological Database of the Polish Geological Institute (CBDG; http://baza.pgi.gov.pl/), and from various publications (Jaskowiak-Schoeneichowa and Krassowska, 1983; Gawor-Biedowa, 2011, 2018a, b, 2019; Leszczyński, 2011a, b, c, 2012, 2017a, b, 2018a, b, 2019; Podhalańska and Sikorska-Jaworowska, 2018a, b). Stratigraphic surfaces from the borehole reports broadly correspond to the standard stratigraphic subdivision of the Upper Cretaceous (Gale et al., 2020). Although both the Grudziądz IG 1 and Polik IG 1 boreholes have the status of research boreholes, core recovery of the Upper Cretaceous section was rather sparse: 8.3% for Grudziądz IG 1, and only 1.2% for Polik IG 1. Consequently, any biostratigraphic studies, which require rock material retrieved from these boreholes, may have a limited scope. The available stratigraphic framework for these two boreholes should therefore be regarded as approximate.

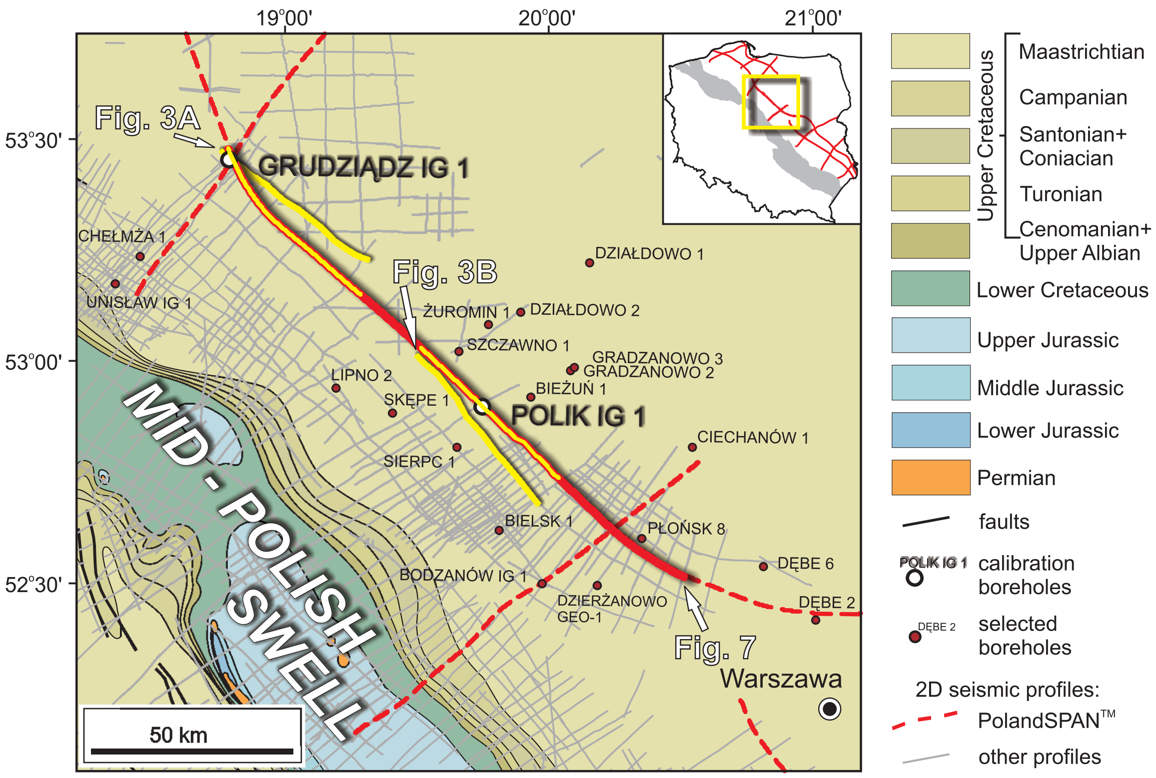

Fig. 2. Location of the PolandSPAN™ seismic profile (red lines) on the geological map of Central Poland (without Cenozoic; simplified after Dadlez et al., 2000)

Grey lines – other, mostly older seismic profiles (compiled after Central Geological Database, http://baza.pgi.gov.pl/); yellow lines – seismic profiles shown in Figure 3; insert as in Figure 1

BOREHOLE-TO-SEISMIC TIE

In order to correlate the borehole depth data with seismic time data, 1D seismic forward modelling was conducted for the Grudziądz IG 1 and Polik IG 1 boreholes to predict the seismic response of the Upper Cretaceous succession (cf. Onajite, 2014). Synthetic seismograms were calculated following the procedure described below.

First, the quality of the well logs used as an input data was thoroughly checked. For both boreholes, resistivity (EN10) and sonic (DT) logs were analysed. In Grudziądz IG 1, the resistivity log covered the 123–1075 m interval, and the sonic log the 948–1075 m interval; in Polik IG 1, the resistivity log extended through the 0–1250 m interval, and the sonic log the 297–1250 m interval. The sonic log intervals absent from the Grudziądz IG 1 (123–948 m) and the Polik IG 1 (0–297 m) succession were calculated by converting the resistivity log to a sonic log using the Kim-Rudman equation (cf. Rudman et al., 1975). In both boreholes studied, the density of the Upper Cretaceous succession was obtained by converting sonic logs to density with the Gardner equation (cf. Gardner et al., 1974).

The sonic logs were subsequently calibrated by check-shot data. Finally, synthetic seismograms were calculated using sonic and density logs (Sheriff and Geldart, 1995) and seismic wavelets extracted from seismic data using frequency matching. A synthetic seismogram for the Grudziądz IG 1 borehole was calculated using a zero-phase seismic wavelet, with an average dominant frequency of ~35 Hz, extracted from the PL1-1100 seismic profile and 10 nearby seismic traces in the window-extraction time range 0.36–1.26 s. Similarly, a synthetic seismogram for the Polik IG 1 borehole was constructed using a zero-phase wavelet with a dominant frequency of 27 Hz, extracted from the PL1-1100 seismic profile with a window-extraction time range of 1–2 s. To support the 1D seismic stratigraphic analysis, natural gamma ray logs (GR) yielded generalized information on vertical lithological changes in the Upper Cretaceous succession studied.

UPPER CRETACEOUS SUCCESSION IN THE STUDY AREA – SUMMARY OF PREVIOUS RESULTS BASED ON BOREHOLE DATA

The Upper Cretaceous of the study area has been recognized in several boreholes drilled in the 1960s–1990s (Fig. 2). The macro- and microfauna recovered from cores and drill cuttings has suggested the presence of complete (at the stage level) stratigraphic sequences of the Upper Cretaceous succession over most of the study area (Jaskowiak-Schoeneichowa and Krassowska, 1983; Gawor-Biedowa, 2011, 2018a, b, 2019; Leszczyński, 2011b, c, 2012, 2017a, b, 2018a, b, 2019; Podhalańska and Sikorska-Jaworowska, 2018b). Only a few studies from the southeasternmost part of the study area reported hardgrounds and other discontinuity surfaces; these were described from the Campanian-Maastrichtian boundary of the Dębe 6 borehole and from the Lower/Upper Maastrichtian boundary of the Płońsk 8 and Dębe 2 boreholes (Leszczyński,

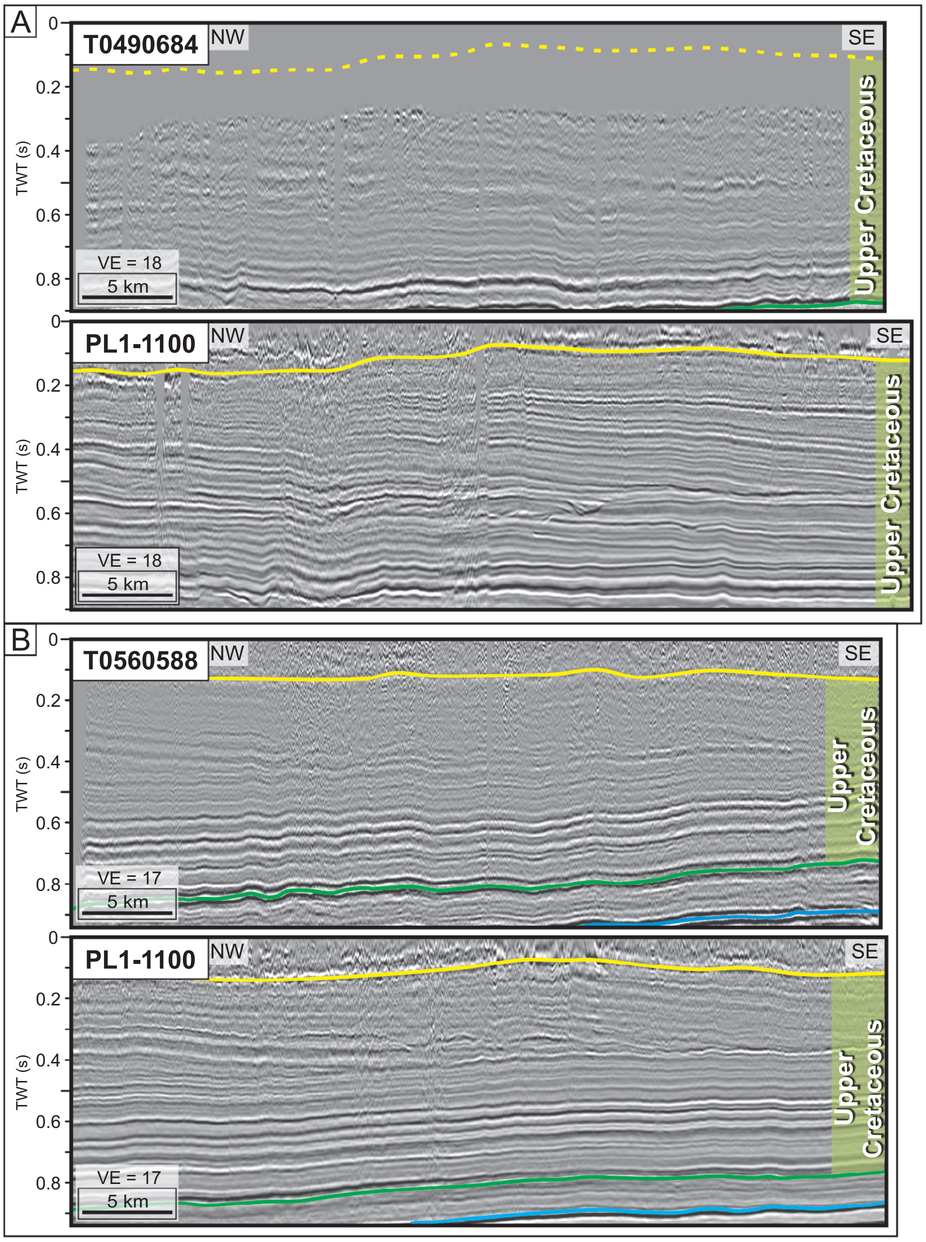

Fig. 3. Comparison of PolandSPAN™ and older seismic profiles

A – on the T0490684 profile (acquired in 1984) the first ~300 m (~0.3 s) are not imaged at all, and details of the Upper Cretaceous geometry are not visible even deeper; in contrast, the entire Upper Cretaceous succession is precisely imaged on PL1-1100; **B** – on the T0560588 profile (acquired in 1988), the entire Upper Cretaceous succession is imaged, although the resolution is much poorer compared to the PolandSPAN™ profile; yellow line: Cretaceous-Cenozoic boundary; dark green line – top of the Lower Cretaceous; blue line – top of the Jurassic; the location of particular seismic profiles is shown on Figure 2

1997, 2012, 2017a; Fig. 2). A stratigraphic gap spanning the uppermost Campanian–Lower Maastrichtian was reported from the area between the Bodzanów IG 1, Ciechanów 1, and Dębe 2 boreholes (Jaskowiak-Schoeneichowa and Krassowska, 1983; Fig. 2).

Some doubts about the precision of the stratigraphic framework were already raised by various authors such as Jaskowiak-Schoeneichowa and Krassowska (1983), Leszczyński (1997, 2011c, 2017a, 2018a, b, 2019) and Gawor-Biedowa (2018a, b, 2019), and attributed to incomplete coring, poor knowledge of the true nature of the stratigraphic record (due to mass redeposition and/or a poor palaeontological record), subsequent mixing of the cored material, and the lack of easily recognizable correlative peaks in the well logs. Consequently, the standard stratigraphy available either in the CBDG database or in various publications and reports should not be treated as "rock-solid", and the existence of substantial error bars for all of the stratigraphic boundaries examined here must be kept in mind while working with seismic data.

UPPER ALBIAN–CENOMANIAN

The Upper Albian succession begins with quartz-glauconitic sandstones with phosphates, reflecting basin-wide transgression. Within most of the study area, the topmost Albian sandstones pass upwards into marls (Unisław IG 1, Chełmża 1 and Grudziądz IG 1 boreholes; Fig. 2), and only in the north-west part of the area do the sandstones continue higher up-section. The Albian succession does not exceed 10 m in thickness. The Cenomanian is characterized by a gradual upwards increase in carbonate content: consequently, clay-marly limestones appear in the Grudziądz area and limestones in the Polik area (Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 2011c, 2018b). The Cenomanian is up to 90 m thick, with the thickest Cenomanian recorded in the northwestern part of the study area and near the axis of the Warsaw Segment of the Kościerzyna-Puławy Synclinorium, close to the Lipno 2–Bodzanów IG 1 line (Fig. 2).

The Albian lacks any biostratigraphic indices. In contrast, the Cenomanian is quite well-documented by both micro- and macrofauna [foraminifers: *Gavelinella cenomanica* (Brotzen) in the Polik IG 1 and Bodzanów IG 1 boreholes (Gawor-Biedowa, 2018b, 2019), *Rotalipora greenhornensis* (Morrow) and *Praeglobotruncana stephani* (Grandolfi) in the Bodzanów IG 1 borehole (Gawor-Biedowa, 2019); inoceramid bivalves: *Gnesioceramus crippsi* (Mantell) in the Bielsk 1, Gradzanowo 2, Polik IG 1, and Żuromin 1 boreholes (CBDG, http://baza.pgi.gov.pl/; Jaskowiak-Schoeneichowa and Krassowska, 1983; Gawor-Biedowa, 2018b) and *Inoceramus etheridgei* Woods in the Gradzanowo 2 borehole (CBDG, http://baza.pgi.gov.pl/)].

TURONIAN–LOWERMOST CONIACIAN

The Turonian-lowermost Coniacian interval is characterized by a lithofacies transition from limestone in the north-east, to marly limestone in the synclinorium axis (close to the Lipno 2 – Bodzanów IG 1 line), and opoka in the north-west of the study area (Fig. 2). In the vicinity of Grudziądz IG 1, the basal Turonian consists of light grey limestone, which changes upward into grey marly opoka and opoka. In the Polik area, the entire unit is dominated by marly limestone and limestone, with cherts and flints (Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 2010, 2012). The thickness of the interval gradually increases towards the synclinorium axis, reaching up to 162 m in the Sierpc 1 borehole. Reductions in thickness are noted in the vicinity of local tectonic structures (e.g., the Lipno structure in the Lipno 2 borehole, with an observed thickness of ~124.5 m). A few biostratigraphic indices of the interval have been reported from the Polik region: namely, the inoceramid bivalves [*Inoceramus lamarcki* Parkinson and *Cremnoceramus crassus inconstans* (Woods) from the Żuromin 1 borehole; Jaskowiak-Schoeneichowa and Krassowska, 1983)], and foraminifers (identified in a few cored intervals; e.g., Gawor-Biedowa, 2019). Some foraminifers have also been reported from the Grudziądz area; however, most are characterized by long ranges that do not provide precise stratigraphic constraint (Gawor-Biedowa, 2011, 2018a). A Late Turonian–Early Coniacian age was indicated by reports of *Stensioeina praeexculpta* (Keller) (Jaskowiak-Schoeneichowa and Krassowska, 1983).

UPPER PART OF CONIACIAN

Dark grey and grey muddy opoka and claystone, as well as marly limestone, from boreholes located near the part of the seismic profile interpreted (Fig. 2) were identified as being within the upper part of the Coniacian, with a total thickness of up to 60 m (Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 2011c, 2018b). The boundary between the siliceous and carbonate lithofacies lies west of the Żuromin 1–Polik IG 1–Bielsk 1–Bodzanów IG 1 borehole line and east of the Skępe 1–Sierpc 1 borehole line, and extends farther south-east along the Mid-Polish Swell (Jaskowiak-Schoeneichowa and Krassowska, 1983). Due to poor coring, the scarcity of macrofossils, and the presence of foraminifers characterized by long stratigraphic ranges, recognition of the upper part of the Coniacian in most of the study area is of very low confidence and was primarily based on often questionable lithological similarities derived from well log data. Due to the absence of clear lithologic differences, available geophysical well logs – such as natural GR logs – are of little use.

SANTONIAN

The Santonian is dominated by siliceous lithofacies in the north-west, and by siliceous-carbonate lithofacies (mostly opoka with cherts and flints) in the central and south-east parts of the study area (Fig. 2; Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 2010, 2012). The lithofacies boundary in the northern and central portions of the study area is similar to that observed in the upper part of the Coniacian, while in the south the boundary reaches the Mid-Polish Swell. The thickness distribution observed in this interval is similar to the thickness distribution in the Turonian-lowermost Coniacian described above: it increases from the north-east (91 m in the Działdowo 1 borehole) to the south-west, towards the synclinorium axis (166 m in the Bielsk 1 borehole), with local reductions near local tectonic structures. The Santonian age of the opoka in the Polik region has been demonstrated by the inoceramid bivalves *Sphenoceramus patootensiformis* (Seitz) (Bieżuń 1 borehole; CBDG, http://baza.pgi.gov.pl/), *S. cardissoides* (Goldfuss) (Gradzanowo 3 borehole; CBDG, http://baza.pgi.gov.pl/), and *S.* cf. *pinniformis* (Willett) (Szczawno 1 borehole; cf. Jaskowiak-Schoeneichowa and Krassowska, 1983). The Santonian age of the opoka in the Grudziądz area is less certain, and is suggested only by a few foraminiferal species (Gawor-Biedowa, 2011).

CAMPANIAN

In the study area, the Campanian is mostly represented by marly limestone with limestone, marl, and opoka intercalations, with numerous cherts and flints. North-west of the Skępe 1 borehole, the siliceous lithofacies consist mainly of light grey opoka (Jaskowiak-Schoeneichowa and Krassowska, 1983). The greatest Campanian thicknesses, of up to 277 m (Skępe 1 borehole), are noted in the synclinorium axis (close to the Lipno-Bodzanów line). In the southern part of the study area, the Lower Campanian age of the marly limestone is indicated by the belemnite *Gonioteuthis quadrata* (Blainville) (Dzierżanowo GEO-1 borehole; Jaskowiak-Schoeneichowa and Krassowska, 1983). In the Grudziądz region, a few foraminifers characteristic of the Campanian and Maastrichtian were identified [*Cibicidoides involutus* (Reuss), *Angulogavelinella grodnensis* (Akimez), *Gavelinella monterelensis* (Marie); Gawor-

-Biedowa, 2011, 2018a)], and in the Polik region, a Campanian age is indicated by a characteristic foraminiferal assemblage (Jaskowiak-Schoeneichowa and Krassowska, 1983).

MAASTRICHTIAN

The Maastrichtian is dominated by siliceous carbonates, which become sandier in the northwestern part of the study area; calcareous sandstones and sandy limestone appear in the Unisław IG 1 borehole (Leszczyński, 2018a), and sandy marly limestone intercalations appear within the opoka in the Chełmża 1 and Grudziądz IG 1 boreholes (Leszczyński, 2011c). In the vicinity of Grudziądz IG 1, the uppermost part of the Cretaceous succession is more marly, with sandy limestone intercalations containing flints and cherts (Leszczyński, 2018a). In the Upper Maastrichtian of the central and southeastern parts of the study area, chalk-like limestones (the Bieżuń 1, Ciechanów 1, Działdowo 2, and Szczawno 1 boreholes) and gaizes (e.g., Działdowo 1 borehole) also occur (Fig. 2; cf. CBDG, http://baza.pgi.gov.pl/; Jaskowiak-Schoeneichowa and Krassowska, 1983). The greatest Maastrichtian thickness, locally ranging up to 400 m (in the vicinity of the Lipno 2 borehole), is known from near the synclinorium axis.

In the Grudziądz and Polik areas, the Maastrichtian was documented by a few macro- and microfauna finds obtained from fragmentary cores. In the Polik region, the foraminifer *Angulogavelinella gracilis* (Marsson) shows the presence of the Lower Maastrichtian, while *Gavelinella complanata* (Reuss), *Bolivinoides draco* (Marsson), and *Karreria fallax* Rzehak are characteristic of the Upper Maastrichtian (Gawor-Biedowa, 2018b). In the same region, the ammonite genus *Hoploscaphites* was reported from the Bieżuń 1 borehole (CBDG, http://baza.pgi.gov.pl/), and the bivalves *Chlamys acuteplicatus* (Alth) and *Entolium* cf. *membranaceum* (Nilsson) from the marly limestone of the Działdowo 1 borehole (Jaskowiak-Schoeneichowa and Krassowska, 1983). The Lower Maastrichtian age of the sandy-marly limestone in the Grudziądz IG 1 borehole has been demonstrated by the belemnite *Belemnella* cf. *lanceolata* (Schlotheim) (Leszczyński, 2019) and the foraminifers *Gavelinella complanata* (Reuss), *Cibicidoides bembix* (Marsson), *Osangularia navarroana* (Suchman), and *Karreria fallax* Rzehak (Gawor-Biedowa, 2011).

DEPOSITIONAL ARCHITECTURE OF THE UPPER CRETACEOUS SUCCESSION BASED ON SEISMIC DATA

1D SEISMIC STRATIGRAPHIC ANALYSIS AND BOREHOLE-TO-SEISMIC TIE

Borehole-to-seismic ties enabled the correlation of stratigraphic tops, well log data, and lithological logs with seismic data (Figs. 4 and 5). Based on borehole reports, all of the Upper Cretaceous stratigraphic stages have been documented in the Grudziądz IG 1 and Polik IG 1 boreholes (Leszczyński, 2011a; Podhalańska and Sikorska-Jaworowska, 2018a). It should be remembered, however, that due to incomplete coring and other problems with establishing the detailed stratigraphy described above, the exact location of stage boundaries in both boreholes should be treated as approximate, with a certain margin of error associated with the depth of each chronostratigraphic boundary. Nevertheless, in the absence of more reliable stratigraphic data, a 1D seismic stratigraphic analysis was carried out using the stratigraphic descriptions from the borehole reports (Leszczyński, 2011a; Podhalańska and Sikorska-Jaworowska, 2018a).

A synthetic seismogram constructed for Grudziądz IG 1 (Fig. 4) revealed several clear positive and negative reflections. The negative reflector in the lower part of the Cretaceous succession (1038–1040 m), in sandstones and sandy marls with glauconite, corresponds to an Upper Albian phosphorite horizon (which is recognized widely in the Polish Basin; e.g., Cieśliński, 1959). This horizon is associated with a strong positive peak on the natural GR log. Higher up, a high-amplitude positive reflector is associated with the intra-Cenomanian organodetrital limestone/clay marl transition (drilled at 1026.5 m). Above, a Cenomanian positive reflector corresponds to the marl/claystone boundary (drilled at 979 m) located within the marly-claystone lithological succession, which is characterized by relatively high values on the natural GR log. A clear transition from a negative to a positive reflector would be expected slightly higher, at the claystone-limestone transition marking the Cenomanian-Turonian boundary. Unfortunately, the expected reflectors are not present, probably due to the lack of a measured sonic log in this interval and the substitution of a calculated sonic log instead. High-amplitude negative reflectors are noted distinctly higher, within the opokas and clayey opokas just above the Santonian-Campanian boundary, and positive and negative reflectors are recorded at the sandy limestone – gaize transition at the Maastrichtian-Danian boundary. Additionally, several low-amplitude reflectors are visible, corresponding to subtler changes in lithology. In general, it can be concluded that there is a relatively good match between the synthetic seismogram calculated for the Grudziądz IG 1 borehole and the seismic data (Fig. 4).

The synthetic seismogram calculated for Polik IG 1 shows an even better correlation with seismic data than the synthetic seismogram for Grudziądz IG 1. The major reflectors in the synthetic seismogram correspond to key lithological boundaries (Fig. 5). The first high-amplitude negative reflector corresponds to the boundary between marly sandstones/sandy marls with glauconite phosphates in the Upper Albian (1214.5 m). Due to signal interference and tuning effects (the so-called thin bed effect; Widess, 1973), this negative reflector may correspond to the transition between marls and limestones at the Albian-Cenomanian boundary. Similar to the Grudziądz IG 1 borehole, the horizon with phosphorites and glauconite in the Upper Albian succession is associated with a positive peak on the GR log. In the Cenomanian succession, both high-amplitude positive and negative reflectors are observed. The positive reflector corresponds to a boundary between limestone characterized by high resistivity and marls characterized by lower resistivity (1178 m). The negative reflector, in contrast, corresponds to the transition between marls and marly limestones at the Cenomanian-Turonian boundary. A strong positive reflector, corresponding to a boundary between marly limestone and limestone with numerous cherts, is observed higher (1055 m), in the Turonian-lowermost Coniacian interval. Stratigraphically higher (946 m), a positive reflector is related to the lithological contrast between marly limestones and opokas at the Coniacian-Santonian boundary. Within the Santonian interval, two strong negative and positive reflectors may indicate vertical lithological variations: that is, alternating transitions from soft to harder layers, characterized by an increased content of cherts and flints. An accompanying increase in the GR log may suggest an increase in clay components in the opokas. In the Campanian-Maastrichtian succession, the synthetic seismogram only reveals a few positive and negative reflections. In the

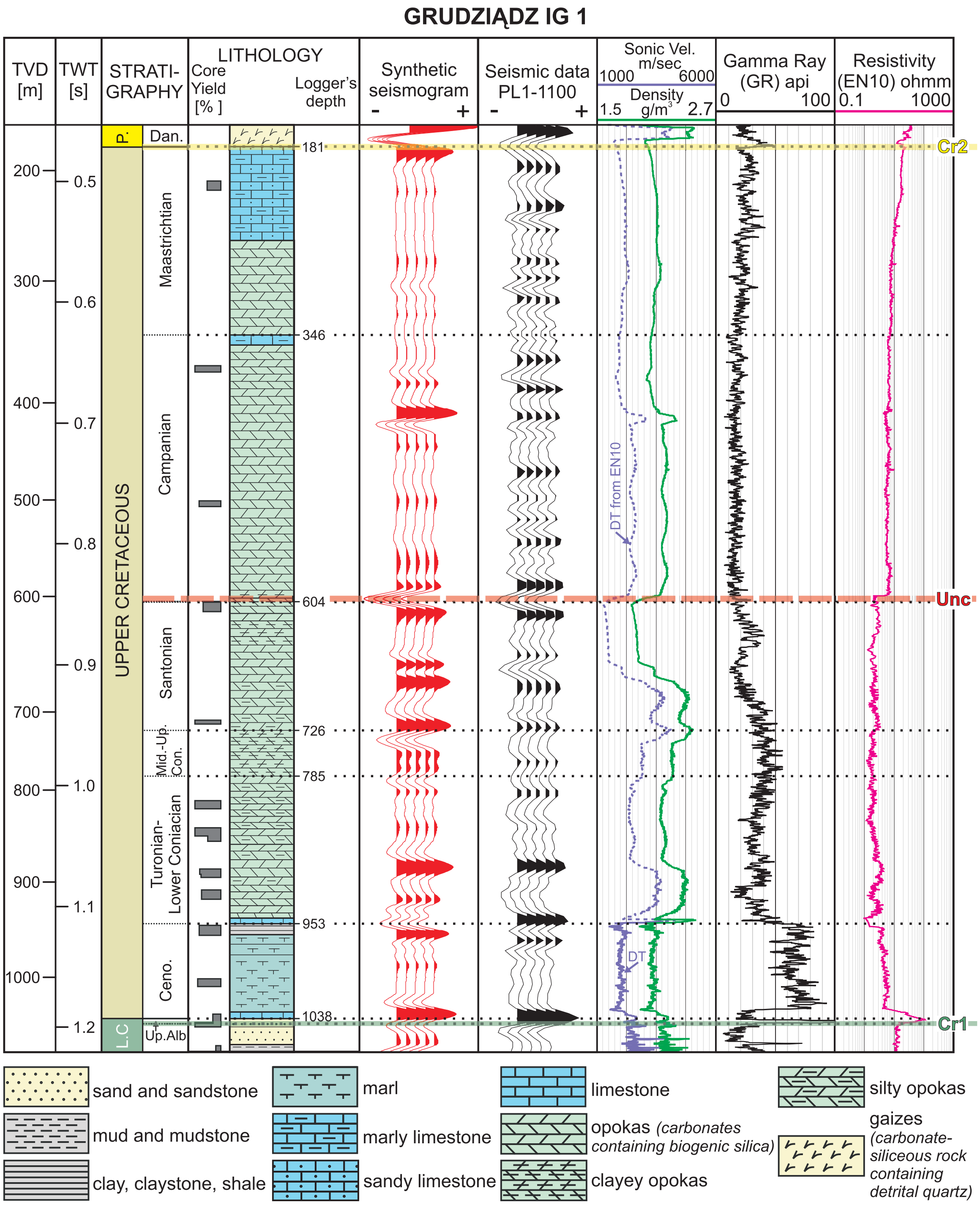

Fig. 4. Borehole-to-seismic tie for the Upper Cretaceous succession of the Grudziądz IG 1 borehole

For location, see Figure 2; TVD – true vertical depth, TWT – two-way time; stratigraphy: L.C – Lower Cretaceous, P. – Paleogene, Ceno. – Cenomanian, Mid.-Up. Con. – Middle and Upper Coniacian, Dan. – Danian, Up. Alb. – Upper Albian; Log: Sonic Vel. – sonic velocity, DT – sonic log; seismic horizons: Cr1 – Top Lower Cretaceous; Unc – unconformity, Cr2 – Top Upper Cretaceous; stratigraphic and lithological logs are after Leszczyński (2011b)

lower part of the Campanian, the strong positive reflection may correspond to marly limestones with cherts, which are harder (seismically "faster") than the under- and overlying rocks. A transition from a weakly visible positive reflector into a negative one is noted within the marly limestones at the Campanian-Maastrichtian boundary (609 m). High values on the GR log show that the Maastrichtian marly limestone may be characterized by higher clay content than the Campanian marly limestone. Most of the Maastrichtian succession does not contain any clear reflectors, suggesting similar acoustic impedance of

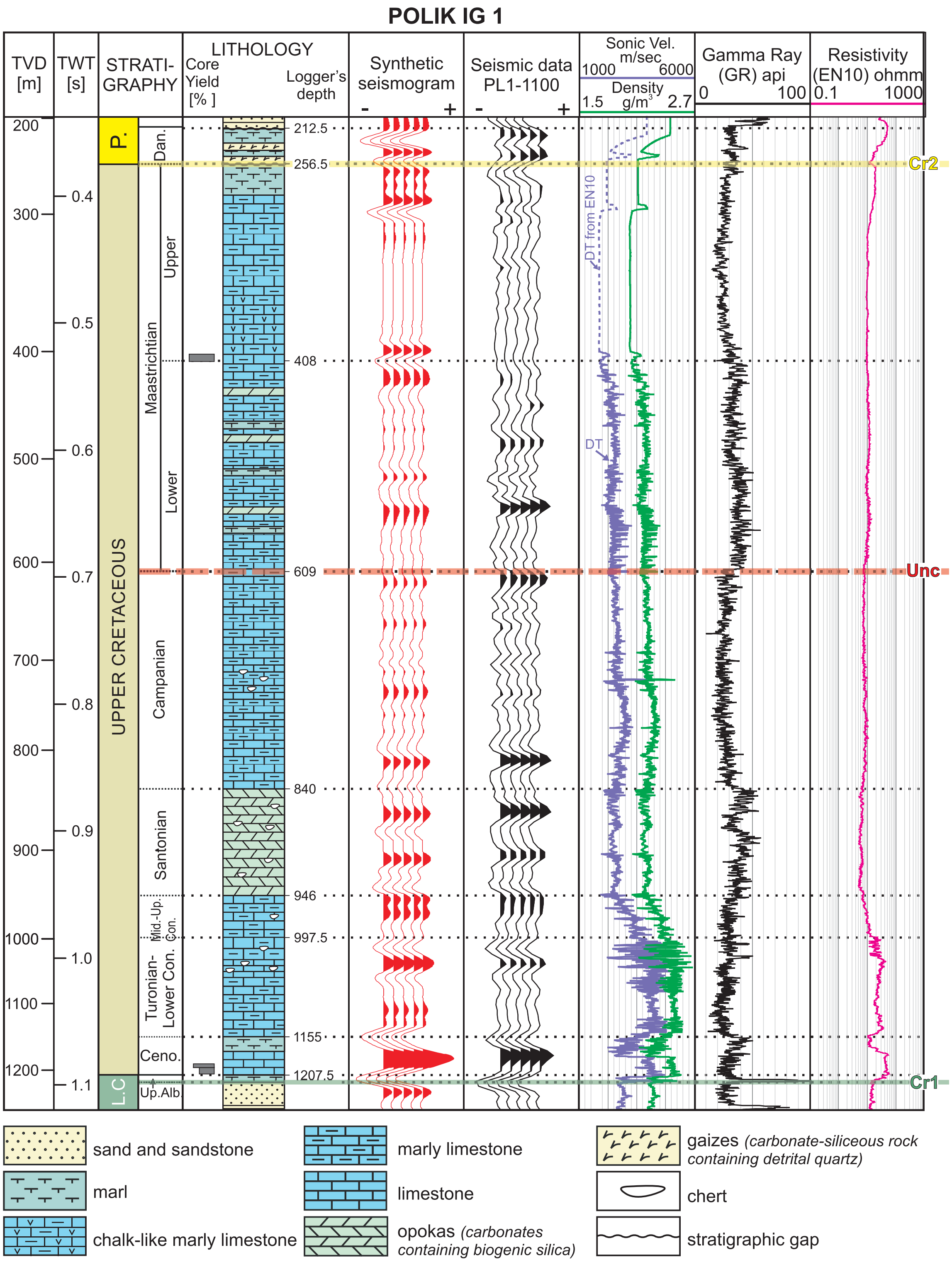

Fig. 5. Borehole-to-seismic tie for the Upper Cretaceous succession of the Polik IG 1 borehole

For location see Figure 2, for other explanations see Figure 4; stratigraphic and lithological logs are after Podhalańska and Sikorska-Jaworowska (2018b)

lithological successions within this stratigraphic interval. It is dominated by marly limestones with intercalation of marls and opokas; chalk-like marly limestones are also common. The high-amplitude negative reflector related to the Lower-Upper Maastrichtian boundary (408 m) does not reflect any significant geological changes, and may be an artifact caused by well log processing. The highest (256.5 m) negative reflection is associated with the marl-gaize transition and unconformity at the Maastrichtian-Danian boundary.

RESULTS OF SEISMIC DATA INTERPRETATION

In general, the depositional architecture of the Mesozoic sedimentary cover on the East European Craton can be described by a stratigraphic layer-cake model. In the Upper Cretaceous portion of this succession, however, some important deviations from this model are observed (Fig. 6; cf. also Krzywiec et al., 2018a).

As illustrated by seismic data, one of the key features of the Upper Cretaceous succession between the Grudziądz IG 1 and Polik IG 1 boreholes – and also north-west and south-east of this line – is the presence of a very prominent regional mid-Late Cretaceous unconformity (Figs. 6 and 7), which subdivides the Upper Cretaceous interval into two distinct units (Fig. 7). In the Polik area, the lower unit (labelled – 1 on Fig. 7) is characterized by an almost horizontal seismic horizon pattern. The horizons are rather continuous, with relatively high amplitude and frequency. As suggested by borehole-to-seismic correlation (Fig. 5), this unit is composed of carbonate and siliceous carbonate lithofacies. Near Grudziądz IG 1, however, seismic data reveal local changes in thickness and local pinch-outs of horizons of medium-amplitude and frequency (labelled – 1a on Fig. 7). Based on borehole-to-seismic ties, this interval corresponds to the carbonate-siliceous lithofacies, within which the silty and clayey opoka dominates (Fig. 4).

The regional unconformity surface within the part of the PolandSPAN™ 1100 seismic profile interpreted, labelled as “Unc” on Figure 7, is highlighted by the low angle downlap of seismic horizons located above it, and erosional truncation beneath it. According to borehole data, this unconformity is neither related to any prominent feature on geophysical well logs nor reflected by any significant lithological change, despite its regional character and basin-scale extent. In both calibration boreholes, this regional unconformity is associated with only slightly decreased values on the resistivity logs. In the Grudziądz IG 1 borehole, this surface is close to the clayey opoka-opoka boundary (Fig. 4), and within the marly limestone interval in the Polik IG 1 borehole (Fig. 5).

In the upper unit (labelled – 2 on Fig. 7) overlying the regional unconformity, oblique seismic reflections downlapping onto the regional unconformity at a low but noticeable angle (~0.7°) are clearly visible. Most of this succession pinches out towards the south. A comparison of lithological data from the Grudziądz IG 1 borehole with seismic data shows that parallel, mostly continuous, medium and high-amplitude seismic horizons correspond to a siliceous carbonate lithofacies (Fig. 4). On the other hand, in the Polik area this interval is dominated by semi-continuous reflections with medium-amplitude frequency, in places with a wavy to parallel pattern. These reflections correspond to carbonate-siliceous lithofacies, as suggested by borehole-to-seismic correlation (Fig. 5).

Correlation of seismic and borehole data suggests the unconformity is diachronous: in the north (Grudziądz IG 1 borehole), it approximately corresponds to the Santonian-Campanian boundary, and in the south (Polik IG 1 borehole) it lies close to the Campanian-Maastrichtian boundary. The PL1-1100 seismic profile clearly illustrates that there are Upper Cretaceous intervals (labelled – A on Fig. 8A) that can be identified in the north-west part of the Warsaw Segment (Grudziądz area), but do not have equivalents in the Polik area. Similarly, there is an interval in the Polik area (labelled – B on Fig. 8B) which does not have a stratigraphic counterpart in the Grudziądz area. As a consequence, a significant stratigraphic gap is inferred for the Polik IG 1 borehole, spanning at least a large part of the Lower Maastrichtian, and possibly also the highest part of the Campanian: i.e., the interval identified in the Grudziądz IG 1 borehole (Fig. 8A). Results of the seismic-stratigraphic correlation between Grudziądz IG 1 and Polik IG 1 suggest that, in contrast to the available borehole stratigraphy, the Lower Maastrichtian may not be present in Polik IG 1 borehole. While the foraminifers *Angulogavelinella gracilis* (Marsson) reported from Polik IG 1 does suggest the presence of the Lower Maastrichtian in this borehole (Gawor-Biedowa, 2018b), it may potentially be redeposited. On the other hand, the uppermost part of the Upper Cretaceous succession in the Polik IG 1 borehole, which includes part of the Upper Maastrichtian according to biostratigraphic studies, has no equivalent in the Grudziądz IG 1 borehole (Fig. 8A). The stratigraphic adjustments inferred from seismic data seem viable, taking into account the relatively wide margin of error for particular stratigraphic tops described above. However, the modified stratigraphic correlation of the Upper Cretaceous succession derived from interpretations of regional high-resolution seismic data is in sharp contrast with the classic layer-cake model used for the sedimentary infill of the Polish Cretaceous Basin, based as it is on the simple correlation of stratigraphic surfaces between boreholes (Fig. 8B).

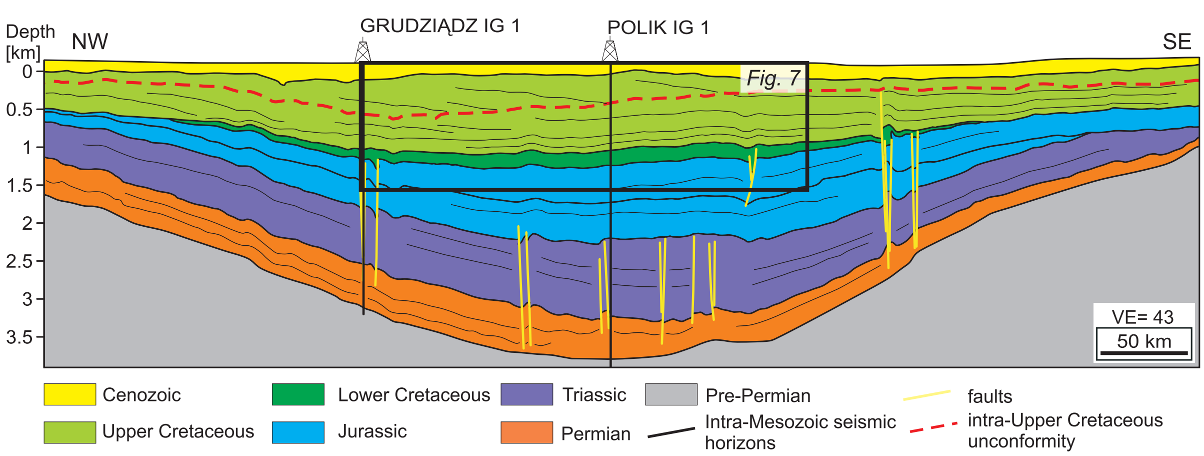

Fig. 6. Geologic cross-section based on the part of the P1-1100 seismic profile interpreted, showing the main structures and stratigraphic features of the Permo-Mesozoic infill of the marginal East European Platform

For location see Figure 1

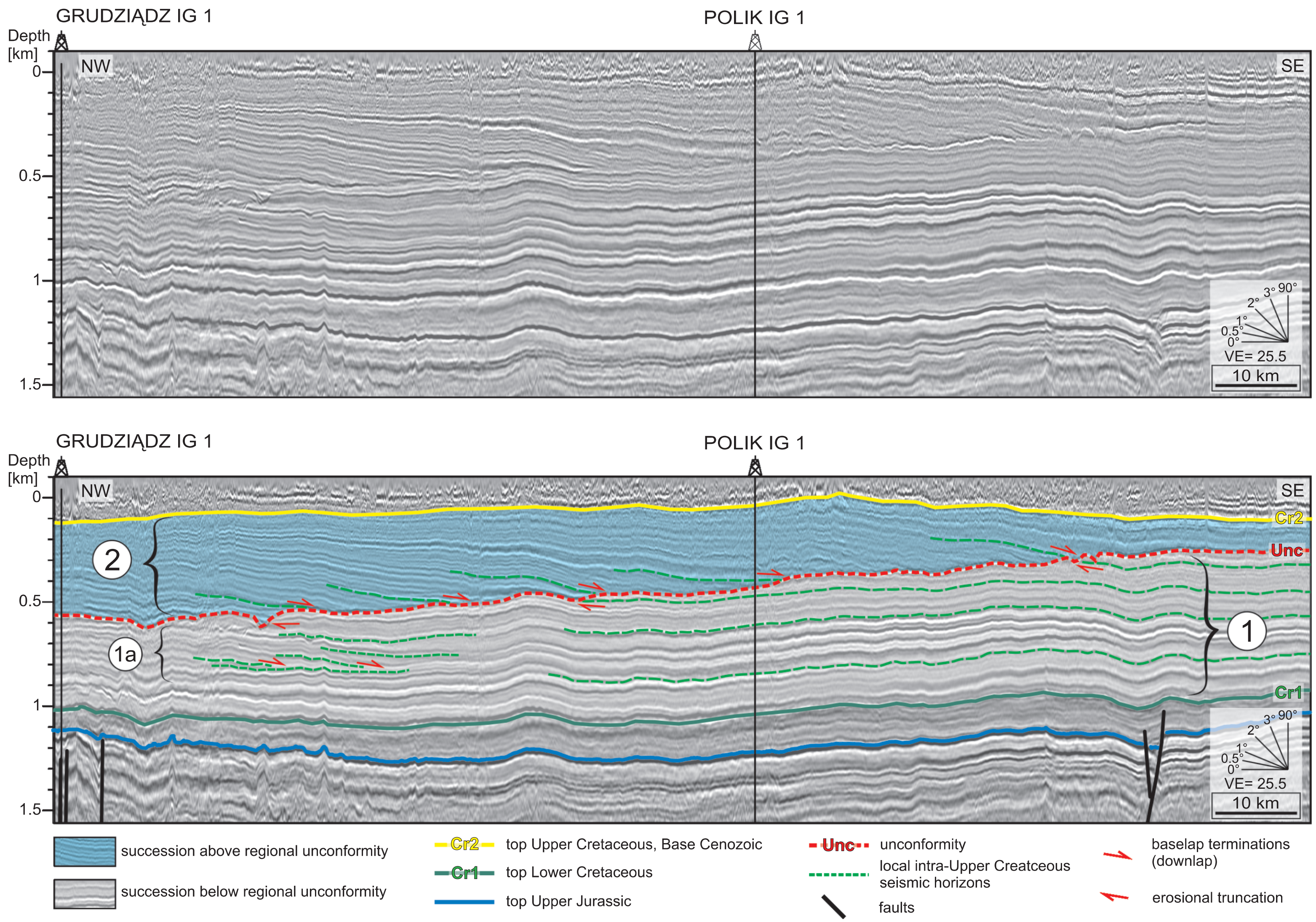

Fig. 7. Uninterpreted and interpreted portion of the regional PolandSPAN™ seismic profile PL1-1100, documenting a regional unconformity (Unc) and the depositional architecture of the Upper Cretaceous

Lower illustration: 1 – lower unit, with layer-cake geometry and local pinch-outs (1a) below regional unconformity; 2 – upper unit, with regional pinch-out above regional unconformity; for location of the profile, see Figure 2

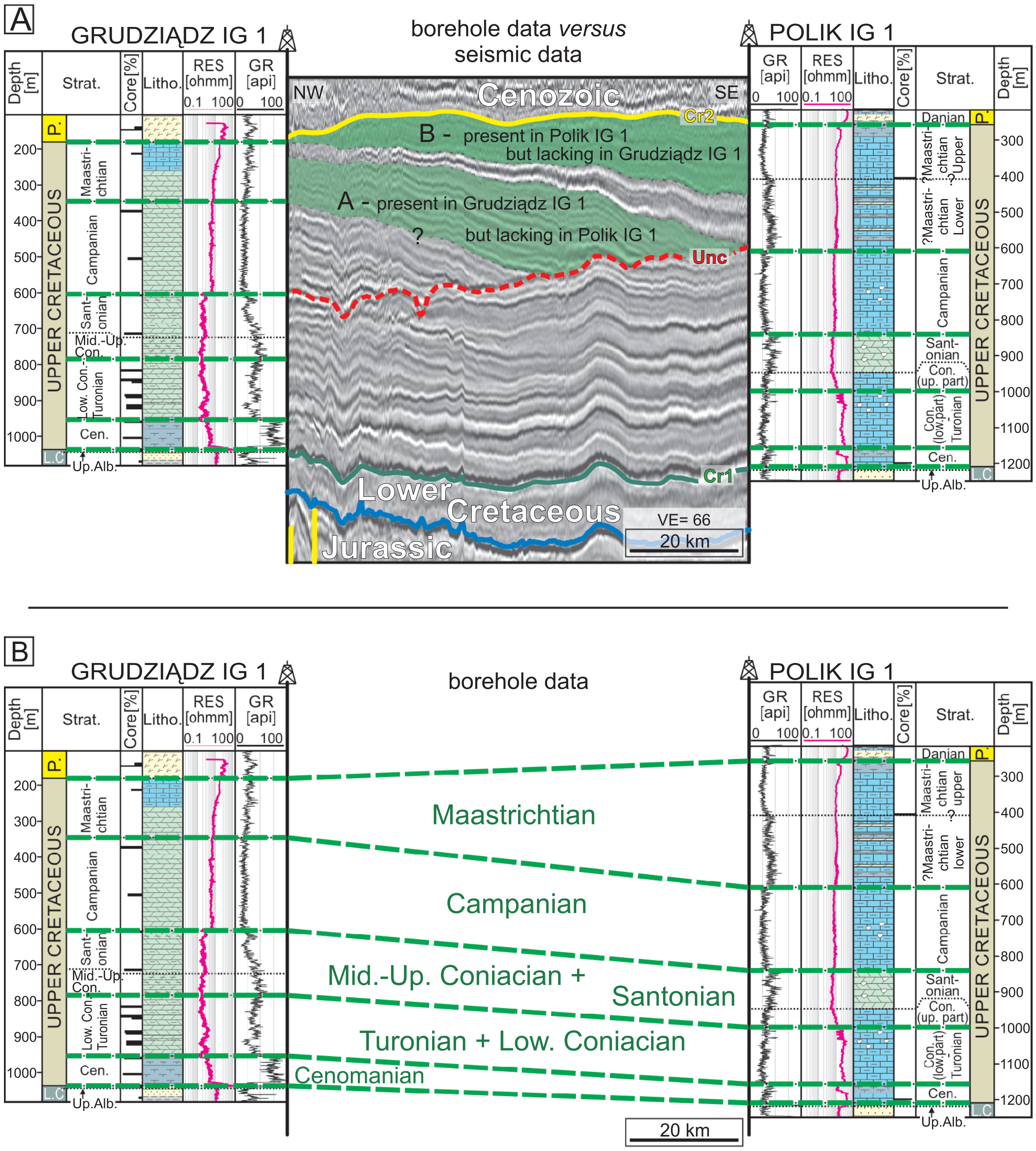

Fig. 8. Correlation between the Grudziądz IG 1 and Polik IG 1 boreholes

A – seismostratigraphic correlation, above unconformity, (A) interval present in Grudziądz IG 1 and absent from Polik IG 1, (B) interval present in Polik IG 1 and absent from Grudziądz IG 1; **B** – chronostratigraphic correlation based on well-log data. Stratigraphical and lithological logs after Leszczyński (2011b) and Podhalańska and Sikorska-Jaworowska (2018b). Strat. – stratigraphy, Litho. – lithology, RES – resistivity, GR – gamma ray; other explanations as in Figures 4, 5 and 7; please note very substantial exaggeration (66x) of seismic profile that has significantly oversteepened the clinoform of the unit [2] located above the regional unconformity marked by a red hatched line

DISCUSSION

Interpretation of the PolandSPAN™ 1100 seismic profile in the area between the Grudziądz IG 1 and Polik IG 1 boreholes revealed a depositional architecture of the Upper Cretaceous succession that differed substantially from the previously assumed layer-cake model, as based on long-distance borehole correlations (cf. Fig. 8B). The main element of this new seismic-based model is the presence of a previously unrecognized mid-Late Cretaceous regional unconformity, which subdivides the Upper Cretaceous succession into two units: a lower one (unit – 1 on Fig. 7) characterized mostly by layer-cake geometry, and an upper one (unit – 2 on Fig. 7) characterized by a regional low-angle clinoform pattern.

A simple, stage-level correlation of stratigraphic surfaces between the Grudziądz IG 1 and Polik IG 1 boreholes (Leszczyński, 2011a; Podhalańska and Sikorska-Jaworowska, 2018a) illustrates very similar successions in both boreholes with regards to both their stratigraphic completeness and thickness pattern (Fig. 8B). This is particularly evident in the Cenomanian-Campanian interval; the Maastrichtian has a much greater thickness in the Polik IG 1 borehole (Fig. 8B). In the absence of other information, these data would fully justify a simple stage-by-stage correlation between the boreholes, built upon an assumption that a classic layer-cake geological model, indicating continuous and undisturbed sedimentation in the Late Cretaceous, is applicable. However, this model is inconsistent not only with the seismic interpretation described in this paper, but also with the results of previous sedimentological studies conducted on selected borehole cores and well logs from the southeastern part of the study area (the region between Bodzanów IG 1, Ciechanów 1, and Dębe 2), which identified the presence of hardgrounds and other discontinuity surfaces, associated with a stratigraphic gap spanning the uppermost Campanian–Lower Maastrichtian (Jaskowiak-Schoeneichowa and Krassowska, 1983; Leszczyński, 1997, 2012, 2017a). This stratigraphic gap might correspond to the unconformity surface recognized in the PolandSPAN™ seismic profile.

A question then arises: supposing that better documentation had been available, would it have been possible to discern the actual architecture as revealed by the PolandSPAN™ seismic profile interpreted herein based on prior datasets? Not necessarily. There is still a lot of space to interpret the Upper Cretaceous succession based on a layer-cake stratigraphic model.

In order to explain the Late Cretaceous evolution of the segment of the Polish Basin studied, a simple conceptual model based on seismic data was constructed (Fig. 9). During the Late Albian–early Late Cretaceous, siliciclastic-carbonate sedimentation prevailed and a layer-cake stratigraphic succession (unit 1), typical of cratonic basins characterized by uniform subsidence, formed (Fig. 9A). To an extent, this simple geometry was complicated by local progradation, lateral thickness changes, and pinch-outs (unit – 1a in Fig. 7) related to local tectonic movements driven by the thin-skinned inversion of local structures that are detached in Zechstein evaporites and located along the northeastern flank of the Mid-Polish Swell (Fig. 9B; e.g., Jaskowiak-Schoeneichowa and Krassowska, 1983; Krzywiec, 2006, 2012). Then, in approximately the Campanian–Early Maastrichtian, regional erosion took place that may have followed regional uplift of the northeastern part of the Polish Basin located above the marginal part of the craton. Similar Late Jurassic and earliest Late Cretaceous regional uplifts have been previously reported using PolandSPAN™ seismic data in south-east Poland (Krzywiec et al., 2018a). The exact nature of these uplifts remains enigmatic: one candidate is regional buckling of the cratonic edge, caused by a regional compressive stress field that led to the inversion of sedimentary basins in many parts of Europe (e.g., Cloetingh et al., 1999; Cloetingh and Van Wees, 2005). The progressive formation of a related regional unconformity was followed by the establishment of the ensuing sedimentary system, characterized by low-angle (<1°) carbonate and siliceous carbonate sedimentation, which gradually progressed southeastwards (Fig. 9C). This new depositional system (approx. Campanian–Maastrichtian), controlled by inversion tectonics and Late Cretaceous sea-level changes, lasted at least until the end of the Cretaceous. After the final stage of basin inversion, ensuing erosion led to the removal of the topmost part of the Upper Cretaceous tectonic succession (Fig. 9D). Subsequently, the Cretaceous succession was capped by a relatively thin, mostly horizontal, post-inversion Cenozoic sequence (Fig. 9E).

The new Upper Cretaceous depositional architecture demonstrated here, based on regional high-resolution seismic data calibrated by research boreholes, differs significantly from the previously used model based on a layer-cake approach. As such, it seems natural that the regional Upper Cretaceous stratigraphy should be re-evaluated using hard and reliable stratigraphic facts – that is, biostratigraphic data from cores, seismic data, and well logs. A re-evaluated stratigraphic framework will result in, at a minimum, revised Upper Cretaceous regional depositional models (Leszczyński, 2012), palaeogeography (e.g., Ziegler, 1990; Leszczyński, 1998), thickness trends (e.g., Jaskowiak-Schoeneichowa and Krassowska, 1988; Świdro-

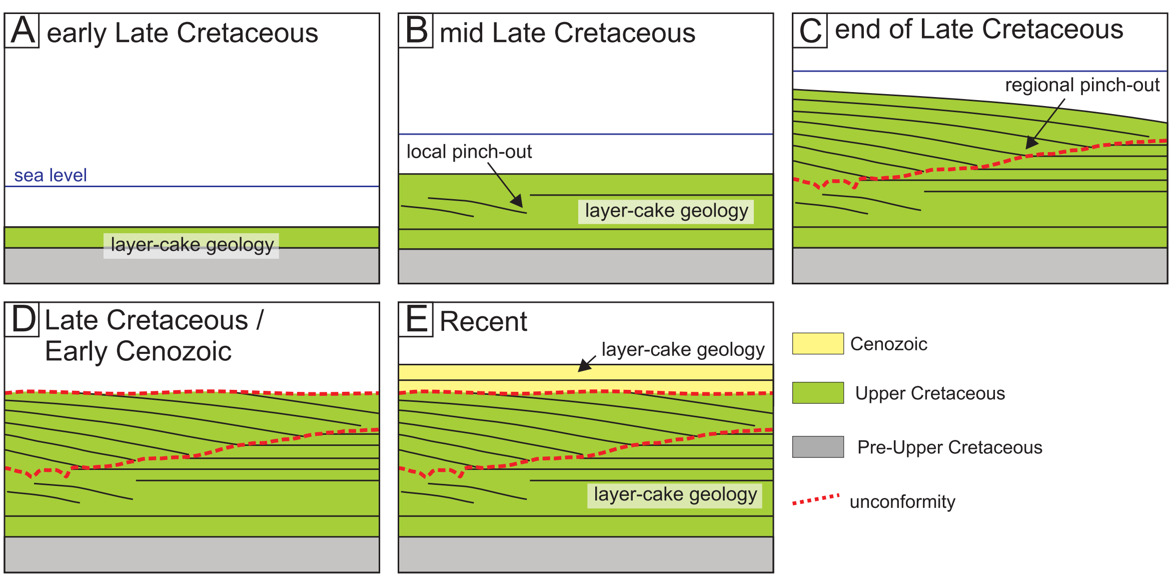

Fig. 9. A qualitative, conceptual model for the development of Late Cretaceous depositional architecture in the Grudziądz-Polik area

wska and Hakenberg, 1999), and facies distribution (e.g., Jaskowiak-Schoeneichowa and Krassowska, 1988; Leszczyński, 1998, 2010, 2012). Additionally, modified models of tectonic subsidence, burial history, and thermal evolution for the part of the Polish Basin studied might be expected (cf. Dadlez et al., 1995; Poprawa, 2019).

SUMMARY AND CONCLUSIONS

This paper provides a new model of Upper Cretaceous depositional architecture in central Poland (Polik-Grudziądz area) *via* an interpretation of regional high-resolution seismic data from the PolandSPAN™ survey. The newly acquired seismic profiles provide a unique glimpse into the true architecture of the regional Upper Cretaceous succession – including a hitherto unrecognized regional unconformity that subdivides the studied succession into two units. The lower unit is mostly characterized by a layer-cake geometry with local changes in thickness, while the upper unit, characterized by low-angle seismic clinoforms, progressively pinches out toward the south. Correlation of seismic and borehole data showed that the regional unconformity in the Grudziądz–Polik area is of Campanian age. Moreover, the results of the seismic-stratigraphic correlation suggest a significant stratigraphic gap in the Polik IG 1 borehole, spanning at least a large part of the Lower Maastrichtian and possibly also the uppermost part of the Campanian, an interval robustly identified in the Grudziądz IG 1 borehole. The depositional architecture and stratigraphic correlation of the Upper Cretaceous succession based on interpretations of regional seismic data do not correspond to a layer-cake model, which has been previously applied to the entire Upper Cretaceous succession within the margins of the East European Craton. The formation of the regional unconformity discovered here is tentatively associated with regional buckling of the East European Craton during Late Cretaceous inversion of the Polish Basin.

The new stratigraphic interpretation presented herein may have a profound influence on understanding of the Late Cretaceous evolution of the marginal part of the East European Platform, an area previously considered as characterized mostly by a "layer cake" depositional architecture.

Acknowledgements. ION Geophysical is thanked for granting access to PolandSPAN™ seismic data, and IHS Markit for providing an academic license of their seismic interpretation software. K. Leszczyński (Polish Geological Institute – National Research Institute), T. Voigt (University of Jena) and an anonymous reviewer provided useful comments that helped to finally shape this paper. This study was supported by Polish National Science Centre (NCN) grant No 2015/17/B/ST10/03411.

REFERENCES

Abdel-Gawad, G.I., 1986. Maastrichtian non-cephalopod mollusks (Scaphopoda, Gastropoda and Bivalvia) of the Middle Vistula valley, central Poland. Acta Geologica Polonica, **36**: 69–224.

Ainsworth, B.R., Sanlung, M., Duivenvoorden, S.T.C., 1999. Correlation techniques, perforation strategies, and recovery factors: an integrated 3-D reservoir modeling study. Sirikit field, Thailand. AAPG Bulletin, **83**: 1535–1551.

Allen, P.A., Armitage, J.J., 2012. Cratonic basins. In: Tectonics of Sedimentary Basins: Recent Advances (eds. C. Busby and A.A. Pérez): 602–620. John Wiley and Sons, Chichester.

Arfai, J., Lutz, R., Franke, D., Gaedicke, C., Kley, J., 2016. Mass-transport deposits and reservoir quality of Upper Cretaceous Chalk within the German Central Graben, North Sea. International Journal of Earth Sciences, **105**: 797–818.

Armitage, J.J., Allen, P.A., 2010. Cratonic basins and the long-term subsidence history of continental interiors. Journal of the Geological Society, **167**: 61–70.

Bac-Moszaszwili, M., Morawska, A., 1975. Tectonic structures in the Cretaceous formations of the Warsaw Basin and their relation to the substratum dislocations (in Polish with English summary). Acta Geologica Polonica, **25**: 577–586.

Boussaha, M., Thibault, N., Anderskouv, K., Moreau, J., Stemmerik, L., 2017. Controls on upper Campanian–Maastrichtian chalk deposition in the eastern Danish Basin. Sedimentology, **64**: 1998–2030.

Brett, C.E., 1982. Stratigraphy and facies relationships of Silurian (Wenlockian) Rochester Shale: layer cake geology reinterpreted. AAPG Bulletin, **66**: 1165–1165.

Brett, C.E., 2000. A slice of the "layer cake": the paradox of "frosting continuity". Palaios, **15**: 495–498.

Brett, C.E., McLaughlin, P.I., Baird, G.C., 2007. Eo-Ulrichian to Neo-Ulrichian views: the renaissance of "layer-cake stratigraphy". Stratigraphy. USGS Publications Warehouse, **4**: 201–215.

Bristow, R., Mortimore, R., Wood, C., 1997. Lithostratigraphy for mapping the Chalk of southern England. Proceedings of the Geologists' Association, **108**: 293–315.

Burgess, P.M., 2019. Phanerozoic evolution of the sedimentary cover of the North American Craton. In: The Sedimentary Basins of the United States and Canada. Second Edition (ed. A.D. Miall): 39–75. Elsevier, Toronto.

Burollet, P.F., 1984. Intracratonic and pericratonic basins in Africa. Sedimentary Geology, **40**: 1–11.

Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. Newsletters on stratigraphy, **44**: 173–245.

Central Geological Database. URL: http://baza.pgi.gov.pl/

Cieśliński, S., 1959. Commencement of Upper Cretaceous transgression in Poland (without Carpathians and Silesia) (in Polish with English summary). Kwartalnik Geologiczny, **3** (4): 943–964.

Cloetingh, S., Van Wees, J.D., 2005. Strength reversal in Europe's intraplate lithosphere: transition from basin inversion to lithospheric folding. Geology, **33**: 285–288.

Cloetingh, S.A.P.L., Burov, E., Poliakov, A., 1999. Lithosphere folding: primary response to compression? (from central Asia to Paris basin). Tectonics, **18:** 1064–1083.

Dadlez, R., 1998. Devonian to Cretaceous epicontinental basins in Poland: relationship between their development and structure (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **165**: 17–30.

Dadlez, R., 2003. Mesozoic thickness pattern in the Mid-Polish Trough. Geological Quarterly, **47** (3): 223–240.

Dadlez, R., Narkiewicz, M., Stephenson, R.A., Visser, M.T.M., Van Wees, J.D., 1995. Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, **252**: 179–195.

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

Daly, M.C., Fuck, R.A., JuliB, J., Macdonald, D.I., Watts, A.B., 2018. Cratonic basin formation: a case study of the Parnaíba Basin of Brazil. Geological Society Special Publications, **472**: 1–15.

Doornenbal, J.C., Stevenson A.G. eds., 2010. Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. Houten.

Dubicka, Z., Peryt, D., 2012. Latest Campanian and Maastrichtian palaeoenvironmental changes: implications from an epicontinental sea (SE Poland and western Ukraine). Cretaceous Research, **37**: 272–284.

Esmerode, E.V., Lykke-Andersen, H., Surlyk, F., 2007. Ridge and valley systems in the Upper Cretaceous chalk of the Danish Basin: contourites in an epeiric sea. Geological Society Special Publications, **276**: 265–282.

Gale, A.S., Mutterlose, J., Batenburg, S., Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Petrizzo, M.R., 2020. The Cretaceous Period. In: Geologic Time Scale 2020 (eds. F.M. Gradstein, J.G. Ogg, M.D. Schmitz and G.M. Ogg): 1023–1086. Elsevier.

Gardner, G.H.F., Gardner, L.W., Gregory, A.R., 1974. Formation velocity and density – the diagnostic basics for stratigraphic traps. Geophysics, **39**: 770–780.

Gawor-Biedowa, E., 2011. Biostratygrafia kredy górnej i paleocenu dolnego na podstawie otwornic (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **129**: 71–73.

Gawor-Biedowa, E., 2018a. Biostratygrafia skał kredy górnej na podstawie otwornic (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **148**: 101–106.

Gawor-Biedowa, E., 2018b. Biostratygrafia utworów górnokredowych i dolnego paleogenu na podstawie otwornic (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **150**: 89–93.

Gawor-Biedowa, E., 2019. Biostratygrafia utworów paleocenu dolnego i kredy górnej na podstawie otwornic (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **156**: 136–139.

Gennaro, M., Wonham, J.P., Gawthorpe, R., Sælen, G., 2013. Seismic stratigraphy of the Chalk Group in the Norwegian Central Graben, North Sea. Marine and Petroleum Geology, **45**: 236–266.

Gjelberg, J., Steel, R., 2012. Depositional model for the Lower Cretaceous Helvetiafjellet Formation on Svalbard – diachronous vs. layer-cake models. Norwegian Journal of Geology, **92**: 41–54.

Hallam, A., 1985. A review of Mesozoic climates. Journal of the Geological Society, **142**: 433–445.

Håkansson, E., Bromley, R., Perch-Nielsen, K., 1974. Maastrichtian chalk of north west Europe – a pelagic shelf sediment. IAS Special Publication, **1**: 211–233.

Hancock, J.M., 1989. Sea-level changes in the British region during the Late Cretaceous. Proceedings of the Geologists' Association, **100**: 565–594.

Haq, B.U., 2014. Cretaceous eustasy revisited. Global and Planetary Change, **113**: 44–58.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. SEPM Special Publication, **42**: 71–108.

Hay, W.W., 2008. Evolving ideas about the Cretaceous climate and ocean circulation. Cretaceous Research, **29**: 725–753.

Hübscher, C., Hseinat, M.A.A., Schneider, M., Betzler, C., 2019. Evolution of contourite systems in the late Cretaceous Chalk Sea along the Tornquist Zone. Sedimentology, **66**: 1341–1360.

ION Geophysical Company. URL: https://www.iongeo.com/Data_Library

Jarosiński, M., Poprawa, P., Ziegler, P., 2009. Cenozoic dynamic evolution of the Polish Platform. Geological Quarterly, **53** (1): 3–26.

Jaskowiak-Schoeneichowa, M., 1979. Stratygrafia, litologia i paleogeografia. Kreda górna (łącznie z albem górnym) (in Polish). Prace Instytutu Geologicznego, **96**: 77–89.

Jaskowiak-Schoeneichowa, M., Krassowska, A., 1983. Upper Cretaceous (in Polish with English summary). Prace Instytutu Geologicznego, **103**: 177–197.

Jaskowiak-Schoeneichowa, M., Krassowska, A., 1988. Palaeothickness, lithofacies and palaeotectonic of the epicontinental Upper Cretaceous in Poland (in Polish with English summary). Geological Quarterly, **32** (1): 177–198.

Kley, J., Voigt, T., 2008. Late Cretaceous intraplate thrusting in central Europe: effect of Africa-Iberia-Europe convergence, not Alpine collision. Geology, **36**: 839–842.

Kontorovich, A.E., Ershov, S.V., Kazanenkov, V.A., Karogodin, Y.N., Kontorovich, V.A., Lebedeva, N.K., Nikitenko, B.L., Popova, N.I., Shurygin, B.N., 2014. Cretaceous paleogeography of the West Siberian sedimentary basin. Russian Geology and Geophysics, **55**: 582–609.

Krassowska, A., 1997. Kreda górna. Sedymentacja, paleogeografia i paleotektonica (in Polish). Prace Państwowego Instytutu Geologiczego, **153:** 386–402.

Krzywiec, P., 2002. Mid-Polish Trough inversion – seismic examples, main mechanisms and its relationship to the Alpine–Carpathian collision. EGU Stephan Mueller Special Publication Series, **1**: 151–165.

Krzywiec, P., 2006. Structural inversion of the Pomeranian and Kuiavian segments of the Mid-Polish Trough – lateral variations in timing and structural style. Geological Quarterly, **50** (1): 151–168.

Krzywiec, P., 2012. Mesozoic and Cenozoic evolution of salt structures within the Polish basin: an overview. Geological Society Special Publications, **363**: 381–394.

Krzywiec, P., Stachowska, A., 2016. Late Cretaceous inversion of the NW segment of the Mid-Polish Trough – how marginal troughs were formed, and does it matter at all? Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, **167**: 107–119.

Krzywiec, P., Kramarska, R., Zientara, P., 2003. Strike-slip tectonics within the SW Baltic Sea and its relationship to the inversion of the Mid-Polish Trough – evidence from high-resolution seismic data. Tectonophysics, **373**: 93–105.

Krzywiec, P., Gutowski, J., Walaszczyk, I., Wróbel, G., Wybraniec, S., 2009. Tectonostratigraphic model of the Late Cretaceous inversion along the Nowe Miasto-Zawichost Fault Zone, SE Mid-Polish Trough. Geological Quarterly, **53** (1): 27–48.

Krzywiec, P., Malinowski, M., Mazur, S., Buffenmyer, V., Lewandowski, M., 2014a. Structure and Phanerozoic evolution of the SW edge of the East European Craton in Poland – new insight from high-effort seismic reflection data (project Poland SPAN). Geologia Sudetica, **42**: 46–48.

Krzywiec, P., Malinowski, M., Lis, P., Buffenmyer, V., Lewandowski, M., 2014b. Lower Paleozoic Basins developed above the East European Craton in Poland: new insight from regional high-effort seismic reflection data. SPE/EAGE European Unconventional Resources Conference and Exhibition, Vienna, Austria, 25–27.02: 7.

Krzywiec, P., Mazur, S., Gągała, Ł., Kufrasa, M., Lewandowski, M., Malinowski, M., Buffenmyer, V., 2017a. Late Carboniferous thin-skinned compressional deformation above the SW edge of the East European Craton as revealed by reflection seismic and potential fields data-correlations with the Variscides and the Appalachians. GSA Memoir, **213**: 352–372.

Krzywiec, P., Peryt, T.M., Kiersnowski, H., Pomianowski, P., Czapowski, G., Kwolek, K., 2017b. Permo-Triassic evaporites of the Polish Basin and their bearing on the tectonic evolution and hydrocarbon system, an overview. In: Permo-Triassic Salt Provinces of Europe, North Africa and the Central Atlantic: Tectonics and Hydrocarbon Potential (eds. J. Soto, J. Flinch and G. Tari): 243–261. Elsevier.

Krzywiec, P., Stachowska, A., Stypa, A., 2018a. The only way is up – on Mesozoic uplifts and basin inversion events in SE Poland. Geological Society Special Publications, **469**: 33–57.

Krzywiec, P., Poprawa, P., Mikołajczak, M., Mazur, S., Malinowski, M., 2018b. Deeply concealed half-graben at the SW margin of the East European Craton (SE Poland) – evidence for Neoproterozoic rifting prior to the break-up of Rodinia. Journal of Palaeogeography, **7**: 88–97.

Kufrasa, M., Krzywiec, P., Gągała, Ł., Mazur, S., Mikołajczak, M., 2020. Sequence of deformation at the front of an orogen: Lublin basin case study (Poland). Journal of Structural Geology, **141.**

Kutek, J., 2001. The Polish Permo-Mesozoic Rift Basin. Mémoires du Muséum national d'histoire naturelle, **186**: 213–236.

Kutek, J., Głazek, J., 1972. The Holy Cross area, central Poland, in the Alpine cycle. Acta Geologica Polonica, **22**: 603–651.

Larsen, C., Ineson, J., Boldreel, L.O., 2014. Seismic stratigraphy and sedimentary architecture of the Chalk Group in south-west Denmark. Geological Survey of Denmark and Greenland Bulletin, **31**: 23–26.

Leszczyński, K., 1997. The Upper Cretaceous carbonate-dominated sequences of the Polish Lowlands. Geological Quarterly, **41** (4): 521–532.

Leszczyński, K., 1998. Upper Cretaceous (including Upper Albian) – thickness. In: Paleogeographic Atlas of the Epicontinental Permian and Mesozoic in Poland (1:2 500 000) (in Polish with English summary) (eds. R. Dadlez, S. Marek and J. Pokorski): Plate 71. Polish Geological Institute, Warszawa.

Leszczyński, K., 2000. The Late Cretaceous sedimentation and subsidence south-west of the Kłodawa Salt Diapir, central Poland. Geological Quarterly, **44** (2): 167–174.

Leszczyński, K., 2002. Late Cretaceous inversion and salt tectonics in the Koszalin-Chojnice and Drawno-Czlopa-Szamotuly zones, Pomeranian sector of the Mid-Polish Trough. Geological Quarterly, **46** (3): 347–362.

Leszczyński, K., 2010. Lithofacies evolution of the Late Cretaceous basin in the Polish Lowlands (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **443**: 33–54.

Leszczyński, K. ed., 2011a. Grudziądz IG 1 (in Polish with English summary). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **129**: 5–138.

Leszczyński, K., 2011b. Profil litologiczno-stratygraficzny otworu wiertniczego Grudziądz IG 1 (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **129**: Fig. 4.

Leszczyński, K., 2011c. Sukcesja kredowa (z paleocenem dolnym) pogranicza niecek pomorskiej i płockiej oraz syneklizy perybałtyckiej w otworze wiertniczym Grudziądz IG 1 (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **129**: 67–71.

Leszczyński, K., 2012. The internal geometry and lithofacies pattern of the Upper Cretaceous-Danian sequence in the Polish Lowlands. Geological Quarterly, **56** (2): 363–386.

Leszczyński, K., 2017a. The significance of Upper Cretaceous hardgrounds and correlative discontinuity surfaces for basin-wide correlations, based on drillcore data from boreholes in northern Poland. Geological Quarterly, **61** (4): 825–844.

Leszczyński, K., 2017b. Evolution of the Nasielsk–Dębe Graben (eastern central Poland) during Cretaceous times (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **470**: 49–62.

Leszczyński, K., 2018a. Stratygrafia i litologia utworów kredy (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **148**: 95–100.

Leszczyński, K., 2018b. Litologia i stratygrafia (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **150**: 82–86.

Leszczyński, K., 2019. Stratygrafia i litologia (bez beriasu dolnego) oraz regionalne tło paleogeograficzne (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **156**: 132–136.

Levorsen, A.I., 1943. Discovery thinking. AAPG Bulletin, **27**: 887–928.

Machalski, M., Malchyk, O., 2019. Relative bathymetric position of opoka and chalk in the Late Cretaceous European Basin. Cretaceous Research, **102**: 30–36.

Marcinowski, R., Radwański, A., 1983. The mid-Cretaceous transgression onto the Central Polish Uplands (marginal part of the Central European Basin). Zitteliana, **10**: 65–95.

Marek, S., Pajchlowa, M. eds., 1997. The epicontinental Permian and Mesozoic in Poland (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **153**: 1–452.

Mazur, S., Scheck-Wenderoth, M., Krzywiec, P., 2005. Different modes of inversion in the German and Polish basins. International Journal of Earth Sciences, **94**: 782–798.

Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Buffenmyer, V., Lewandowski, M., 2015. Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica? Tectonics, **34**: 2465–2477.

Mazur, S., Mikołajczak, M., Krzywiec, P., Malinowski, M., Lewandowski, M., Buffenmyer, V., 2016. Pomeranian Caledonides NW Poland – a collisional suture or thin-skinned fold-and-thrust belt? Tectonophysics, **692**: 29–43.

Merriam, D.F., 2006. Layer-cake stratigraphy from the geobakery or the classic flatland geology of the Midcontinent (USA). The Shale Shaker, **56**: 171–176.

Mikołajczak, M., Mazur, S., Gągała, Ł., 2019. Depth-to-basement for the East European Craton and Teisseyre-Tornquist Zone in Poland based on potential field data. International Journal of Earth Sciences, **108**: 547–567.

Mortimore, R., 2011. A chalk revolution: what have we done to the Chalk of England. Proceedings of the Geologists' Association, **122**: 232–297.

Mortimore, R.N., Pomerol, B., 1987. Correlation of the Upper Cretaceous White Chalk (Turonian to Campanian) in the Anglo-Paris Basin. Proceedings of the Geologists' Association, **98**: 97–143.

Onajite, E., 2014. Seismic Data Analysis Techniques in Hydrocarbon Exploration. Elsevier, Amsterdam.

Perrodon, A., Zabek, J., 1990. Paris Basin. AAPG Memoir, **51:** 633–680.

Piwocki, M., Badura, J., Przybylski, B., 2004. Niż Polski i jego południowe obrzeżenie – Neogen (in Polish). In: Budowa Geologiczna Polski (eds. T. Peryt and M. Piwocki). Kenozoik, Paleogen, Neogen, 3a: 71–118. Państwowy Instytut Geologiczny, Warszawa.

Podhalańska, T., Sikorska-Jaworowska, M. eds., 2018a. Polik IG 1 (in Polish with English summary). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **150:** 7–184.

Podhalańska, T., Sikorska-Jaworowska, M. eds., 2018b. Profil litologiczno-stratygraficzny otworu wiertniczego Polik IG 1 (in Polish). Profile Głębokich Otworów Wiertniczych Państwowego Instytutu Geologicznego, **150**: Fig. 4.

Poprawa, P., 2019. Geological setting and Ediacaran–Palaeozoic evolution of the western slope of the East European Craton and adjacent regions. Annales Societatis Geologorum Poloniae, **89:** 347–380.

Pożaryski, W., Brochwicz-Lewiński, W., 1978. On the Polish Trough. Geologie en Mijnbouw. **57**: 545–557.

Rowan, M.G., Krzywiec, P., 2014. The Szamotuły salt diapir and Mid-Polish Trough: decoupling during both Triassic-Jurassic rifting and Alpine inversion. Interpretation, **2**: SM1–SM18.

Rudman, A.J., Whaley, J.F., Blakely, R.F., Biggs, M.E., 1975. Transform of resistivity to pseudovelocity logs. AAPG Bulletin, **59**: 1151–1165.

Scheck-Wenderoth, M., Krzywiec, P., Zülke, R., Maystrenko, Y., Frizheim, N., 2008. Permian to Cretaceous tectonics. In: The Geology of Central Europe, **2**: Mesozoic and Cenozoic (ed. T. McCann): 999–1030. Geological Society, London.

Sheriff, R.E., Geldart, L.P., 1995. Exploration Seismology. Cambridge University Press, Cambridge.

Sloss, L.L., 1963. Sequences in the cratonic interior of North America. GSA Bulletin, **74**: 93–114.

Stephenson, R.A., Narkiewicz, M., Dadlez, R., Van Wees, J.D., Andriessen, P., 2003. Tectonic subsidence modelling of the Polish Basin in the light of new data on crustal structure and magnitude of inversion. Sedimentary Geology, **156**: 59–70.

Surlyk, F., Lykke-Andersen, H., 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. Sedimentology, **54**: 405–422.

Świdrowska, J., Hakenberg, M., 1999. Subsidence and the problem of incipient inversion in the Mid-Polish Trough based on thickness maps and Cretaceous lithofacies analysis (in Polish with English summary). Przegląd Geologiczny, **47**: 61–68.

Świerczewska-Gładysz, E., 2006. Late Cretaceous siliceous sponges from the Middle Vistula River Valley (Central Poland) and their palaeoecological significance. Annales Societatis Geologorum Poloniae, **76**: 227–296.

Thibault, N., Harlou, R., Schovsbo, N.H., Stemmerik, L., Surlyk, F., 2016. Late Cretaceous (late Campanian–Maastrichtian) sea-surface temperature record of the Boreal Chalk Sea. Climate of the Past, **12**: 429–438.

Torsvik, T.H., Cocks, L.R.M., 2016. Earth History and Palaeogeography. Cambridge University Press.

Tozer, B., Watts, A.B., Daly, M.C., 2017. Crustal structure, gravity anomalies, and subsidence history of the Parnaíba cratonic basin, Northeast Brazil. Journal of Geophysical Research, Solid Earth, **122**: 5591–5621.

Vail, P.R., Mitchum Jr., R.M., Todd, R.G., Widmier, J.M., Thompson III, S., Sangree, J.B., Bubb, J.N., Hatlelid, W.G., 1977. Seismic stratigraphy and global changes of sea level. AAPG Memoir, **26**: 49–212.

Vejbæk, O.V., Andersen, C., 2002. Post mid-Cretaceous inversion tectonics in the Danish Central Graben-regionally synchronous tectonic events? Bulletin of the Geological Society of Denmark, **49**: 139–144.

Vejbæk, O.V., Andersen, C., Dusa, M., Herngreen, W., Krabbe, H., Leszczyński, K., Lott, G.K., Mutterlose, J., Van der Molen, A.S., 2010. Cretaceous. In: Petroleum Geological Atlas of the Southern Permian Basin Area (eds. J. C Doornenbal and A.G. Stevenson): 195–209. EAGE Publications b.v. Houten.

Van der Voet, E.V.A., Heijnen, L., Reijmer, J.J., 2018. Geological evolution of the Chalk Group in the northern Dutch North Sea: inversion, sedimentation and redeposition. Geological Magazine, **156**: 1265–1284.

Voigt, S., Wagreich, M., Surlyk, F., Walaszczyk, I., Uličny, D., Cech, S., Voigt, T., Wiese, F., Wilmsen, M., Niebuhr, B., Reich, M., Funk, H., Michalik, J., Jagt, J.W.M., Felder, P.J., Schulp, A.S., 2008. Cretaceous. In: The Geology of Central Europe*:* Mesozoic and Cenozoic (ed. T. McCann): 923–997. Geological Society, London.

Voigt, T., Kley, J., Voigt, S., 2020. Dawn and dusk of Late Cretaceous basin inversion in Central Europe. Solid Earth Discuss: https://doi.org/10.5194/se-2020-188

Von Eynatten, H., Kley, J., Dunkl, I., Hoffmann, V.-E., Simon, A., 2020. Late Cretaceous to Paleogene exhumation in Central Europe – localized inversion vs. large-scale domal uplift. Solid Earth Discuss: https://doi.org/10.5194/se-2020-183

Vyssotski, A.V., Vyssotski, V.N., Nezhdanov, A.A., 2006. Evolution of the West Siberian basin. Marine and Petroleum Geology, **23**: 93–126.

Walaszczyk, I., Remin Z., 2015. Kreda obrzeżenia Gór Świętokrzyskich (in Polish). LXXXIV Zjazd Naukowy Polskiego Towarzystwa Geologicznego 2015 (eds. S. Skompski and W. Mizerski): 41–50. Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa.

Widess, M.B., 1973. How thin is a thin bed? Geophysics, **38**: 1176–1180.

Ziegler, P.A., 1987. Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland – a geodynamic model. Tectonophysics, **137**: 389–420.

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe (2nd edition). Shell Internationale Petroleum Maatschappij BV – Geological Society Publishing House, Bath.

Żelaźniewicz, A., Aleksandrowski, P., Buła, Z., Karnkowski, P.H., Konon, A., Oszczypko, N., Ślączka, A., Żaba, J., Żytko, K., 2011. Regionalizacja tektoniczna Polski (in Polish). Komitet Nauk Geologicznych PAN, Wrocław.