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Upper Cretaceous contourites from northwestern Poland in the vicinity of the Szamotuły salt diapir

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ABSTRACT:

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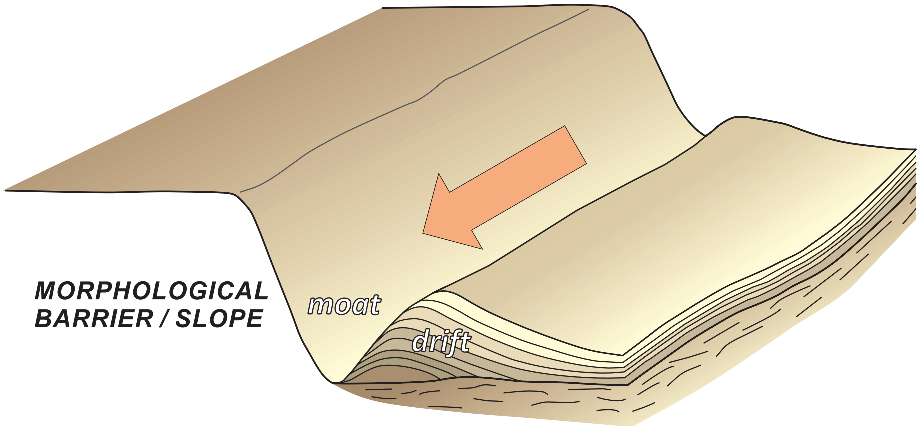
This paper presents the results of seismostratigraphic interpretation of the Upper Cretaceous sedimentary succession preserved within two synclines flanking the Szamotuły diapir in northwestern Poland. This succession is characterized by a complex Santonian–Campanian internal geometry characteristic of contourites – that is, deposits formed by contour (bottom) currents. The aim of the present paper is to document these contourites using 2D seismic reflection profiles calibrated by the Obrzycko 1 well. The contourite drifts in the immediate vicinity of the Szamotuły structure exhibit elongated mounded shapes, with adjacent concave moats. At greater distances from the diapir, gradual aggradational patterns are observed. The formation of these Santonian–Campanian contourites was associated with growth of the Szamotuły diapir during regional compression and Polish Basin inversion. These contour currents and associated contourites formed an integral part of a regional axial depositional system developed within the flanks of the Mid-Polish Anticlinorium. Furthermore, this paper discusses the potential role of contourites as palaeomorphological indicators of palaeoslopes in varied geodynamics settings, such as inverting sedimentary basins, as opposed to the passive margins upon which they have been most commonly documented.

Key words: Contourites; Late Cretaceous; Polish Basin; Inversion; Salt tectonics.

INTRODUCTION

Bottom current activity is characterized by localized erosion and the formation of depositional structures at the sea-floor of sedimentary basins (e.g., Faugères and Stow 1993; Viana *et al.* 1998, 2007; Stow *et al.* 2002; Rebesco and Camerlenghi 2008; Shanmugam 2017). Contour (bottom) currents can affect not only bathymetry, but also can, in turn, reflect morphological changes caused by the tectonic evolution of the basin. Originally, the term *contour current* was used to describe currents (1) driven by density gradients and the Coriolis force, (2) flowing along continental edges, and (3) almost exclusively representing deep-water environments (i.e., geostrophic contour current; Heezen *et al.* 1966). However, currently this term is increasingly used to describe currents that develop along all types of smaller and/or larger (regional) slopes and morphological barriers, for instance in shelf environments (e.g., Verdicchio and Trincardi 2008; Hübscher *et al.* 2019; Hong *et al.* 2022).

Contour currents form depositional systems consisting of elongated depressions (moats) and associated mound-shaped sediment accumulations (drifts; 1–10s km large); generally, these sedimentary deposits are referred to as *contourites* (Text-fig. 1; e.g., Rebesco *et al.* 2014). Contourite shapes are characterized by asymmetric geometries and depend primarily on flow velocities, which affects erosional and depositional potentials, and on the steepness of adjacent slopes along which the currents develop



Text-fig. 1. Schematic model depicting key contourite drift features (redrawn from Rebesco *et al.* 2014). Contour (bottom) currents (depicted by arrow) flow along a morphological barrier at the sea-floor. The contourite depositional system is characterized by an asymmetric moat and mound geometry (drift) which can be observed on seismic reflection data.

(Wilckens *et al.* 2021, 2023). Characteristic contourite depositional patterns can be revealed by seismic reflection data, which often provide the only evidence for ancient moat-drift systems. In addition to numerous unconformities, changes in thickness, and incisions, seismic data may also depict (1) progradational reflector patterns within the drift towards the moat (i.e., clinoforms) and (2) continuous and/or discontinuous, sub-parallel and wavy reflectors of moderate to low amplitude (e.g., Faugères *et al.* 1999; Rebesco and Stow 2001).

Numerous examples of Upper Cretaceous–Palaeogene contour currents flowing along inversion-related uplifts have been reported from several European epicontinental sedimentary basins, such as the Norwegian-Danish Basin, the North German Basin, and the Polish Basin (e.g., Esmerode *et al.* 2007; Surlyk and Lykke-Andersen 2007; Krzywiec *et al.* 2009, 2018, 2022a; Gennaro *et al.* 2013; Larsen *et al.* 2014; Hübscher *et al.* 2019; Stachowska and Krzywiec 2023). These currents were responsible for variations in lateral thickness, local incisions, the development of local unconformities, and stratigraphic pinch-outs, and profoundly influenced associated depositional architectures.

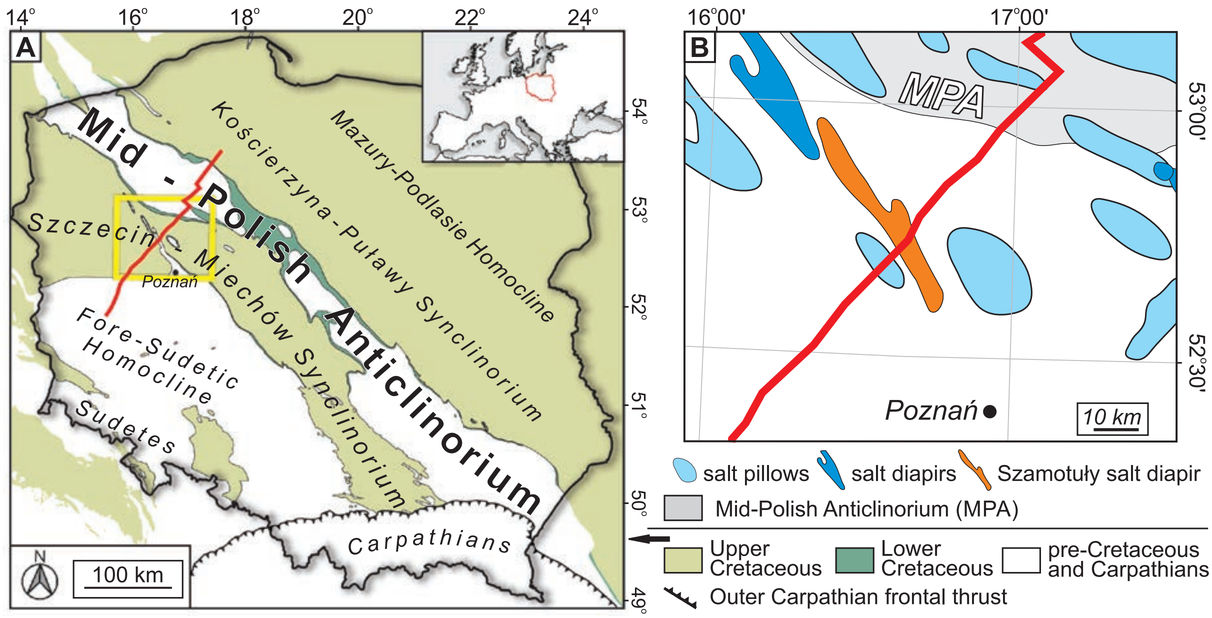
Contourite formation along modern continental margins is, by definition, related to continental slopes that focus and direct contour current flow. Therefore, the formation of contourites is directly related to the sea-floor morphology. For ancient contourites, the slopes that focused contour current development may no longer exist due to subsequent geological processes, such as uplift and erosion. However, identified contourites may be used to suggest slopes must have existed during their formation. As such, contourites can be conceivably used as reliable palaeomorphologic indicators.

The aim of the present paper is to document contourites in the vicinity of the Szamotuły salt diapir in northwestern Poland (Text-fig. 2), based on well-calibrated seismostratigraphic analysis of the associated Upper Cretaceous sedimentary succession; the study focuses on the analysis of two 2D seismic reflection profiles calibrated by the Obrzycko 1 well. A key feature is the complex internal geometry of Santonian–Campanian deposits within the diapir flanks. These geometries indicate contourite drifts and moats, interpreted here as resulting from an active contour current along the flanks of this diapir. These structures are discussed in the context of diapir evolution and the regional axial depositional system that developed along both sides of the Mid-Polish Anticlinorium, the main regional inversion structure in Poland (cf. Mazur *et al.* 2005; Krzywiec *et al.* 2018; Stachowska and Krzywiec 2023).

GEOLOGICAL SETTING

An overview of the Polish Basin

The Polish Basin constituted the easternmost extension of the Southern Permian Basin, a Permian–Mesozoic epicontinental basin system in western and central Europe (Ziegler 1990; Marek and Pajchlowa 1997; Scheck-Wenderoth *et al.* 2008; Pharaoh *et al.*

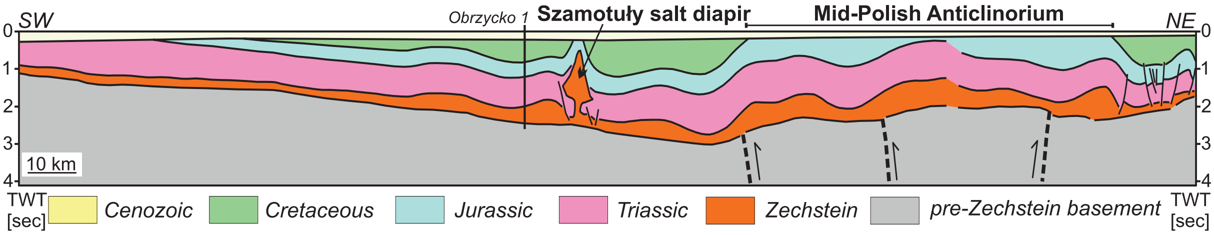


Text-fig. 2. Location of the study area. A – Simplified geological map of Poland (without Cenozoic) with main Mesozoic structural units, compiled after Pożaryski (1979), Dadlez *et al.* (2000), and Żelaźniewicz *et al.* (2011); inset shows location of Poland; yellow rectangle marks the study area; B – Zechstein salt structures in the study area (from Dadlez and Marek 1998). Red line: location of regional cross-section shown in Text-fig. 3.

2010). The axial, most subsiding portion of the Polish Basin, the Mid-Polish Trough, developed along the Teisseyre-Tornquist Zone, which formed the boundary between the East European Craton and the Western European Platform (cf. Kutek and Głazek 1972; Pożaryski and Brochwicz-Lewiński 1978; Dadlez *et al.* 1995; Dadlez 1997a, b, 1998; Kutek 2001; Mazur *et al.* 2015; Mikołajczak *et al.* 2019).

Long-term thermal subsidence of the Polish Basin, which lasted from the late Permian to the earliest Late Cretaceous, combined with several pulses of increased tectonic subsidence in the late Permian–Early Triassic, Late Jurassic, and earliest Late Cretaceous, significantly influenced the sedimentary infill of the Mid-Polish Trough, which consisted of a thick series of siliciclastic-carbonate deposits underlain by Zechstein evaporites (Pożaryski 1977; Tarka 1992; Dadlez *et al.* 1995; Kiersnowski *et al.* 1995; Marek and Pajchlowa 1997; Dadlez 1998; Stephenson *et al.* 2003). Salt remobilization in the Early Triassic significantly modified subsidence patterns in the central and northwestern Mid-Polish Trough, leading to the development of a complex salt structure system (cf. Krzywiec 2004a, b, 2006b, 2012; Krzywiec *et al.* 2017).

The Polish Basin inverted in the Late Cretaceous–Palaeogene, triggered by a regional compressional stress field, in turn driven by the Africa-Iberia-Europe convergence and/or collisions in the Alpine-Carpathian orogenic belt (Ziegler 1990; Kley and Voigt 2008). This led to (1) the development of the Mid-Polish Anticlinorium along the axis of the former Mid-Polish Trough (Text-figs 2A and 3; Mazur *et al.* 2005; Krzywiec 2006a, b; Krzywiec *et al.* 2006, 2009; Resak *et al.* 2008; Scheck-Wenderoth *et al.* 2008; Pharaoh *et al.* 2010) and (2) the compressional reactivation of thin-skinned and salt structures. Due to this regional uplift, Upper Cretaceous sediments are missing within the axial portion of the Anticlinorium, and are only preserved within marginal troughs on both sides of the Anticlinorium (Pożaryski 1977; Marek and Pajchlowa 1997; Krzywiec and Stachowska 2016). Well (e.g., Leszczyński 2000, 2002, 2012) and seismic (Krzywiec 2002a, b, 2004b, 2006b, 2009a, b; Krzywiec *et al.* 2009) data suggest that Polish Basin inversion may have begun in the Late Turonian, peaking in the Campanian–Maastrichtian and post-Maastrichtian. The basal Cenozoic succession (?Eocene–Oligocene), which uncomfortably overlies Upper Cretaceous and stratigraphically older deposits, defines the end of Mid-Polish Trough inversion tectonics (Piwocki 2004).



Text-fig. 3. Regional cross-section along the central part of the inverted Polish Basin (after Krzywiec 2006a; Krzywiec *et al.* 2006, modified).

The Late Cretaceous in northwest Poland

Eustatic sea-levels – the highest during the Mesozoic and Cenozoic – and associated transgressive-regressive fluctuations had a significant impact on sedimentary records within Central and Western European epicontinental basins (Cieśliński 1959; Haq *et al.* 1988; Hancock 1989; Ziegler 1990; Haq 2014). For instance, unique pelagic facies, such as chalk and opoka (i.e., pelagic carbonates enriched with biogenic silica – see Jurkowska *et al.* 2019 and references therein), were formed during this interval. In the Late Cretaceous of the Polish Basin, shallower, proximal deposits were largely composed of siliciclastic facies, whereas deeper, more distal zones were dominated by carbonate-siliceous facies (Leszczyński 2010, 2012). Despite high sea-levels (c. 200–250 m higher than modern), these depositional systems formed in relatively shallow sedimentary environments (< 250 m; Håkansson *et al.* 1974; Abdel-Gawad 1986; Świerczewska-Gładysz 2006; Dubicka and Peryt 2012; Boussaha *et al.* 2017).

The northwestern Polish Basin was first submerged in the ?Middle–Late Albian (Early Cretaceous), was likely emergent in the Late Maastrichtian (Jaskowiak-Schoeneichowa 1979, 1981), and flooded again in the Oligocene (Piwocki 2004; Widera *et al.* 2019). Siliciclastic sediments (mainly sandstones) were prevalent in the Late Albian, and were overlain by carbonate and carbonate-siliceous sediments in the Cenomanian to Maastrichtian; in the Maastrichtian, limestones, marly limestones, marls, and opokas were the main deposits (Jaskowiak-Schoeneichowa 1979, 1981; Leszczyński 2002). The significant increase in carbonate sedimentation in the Cenomanian and Early Turonian resulted from the significant Late Cretaceous transgression and an associated unification of carbonate and siliceous facies over most of the Polish Basin (Pożaryski 1960, 1964; Jaskowiak-Schoeneichowa and Krassowska 1988; Walaszczyk 1992; Leszczyński 2010, 2012). In addition to eustatic sea-level changes, sedimentation patterns were also controlled by local variations in subsidence rate, the intensity of inversion tectonics, and salt tectonics. Turonian–Maastrichtian syn-tectonic deposits have been documented in the marginal troughs and the vicinity of diapirs and salt pillows, and are characterized by local and regional unconformities, changes in thickness, and elevated terrigenous quartz content (Leszczyński 2000, 2002; Krzywiec 2006b, 2012; Rowan and Krzywiec 2014; Krzywiec and Stachowska 2016).

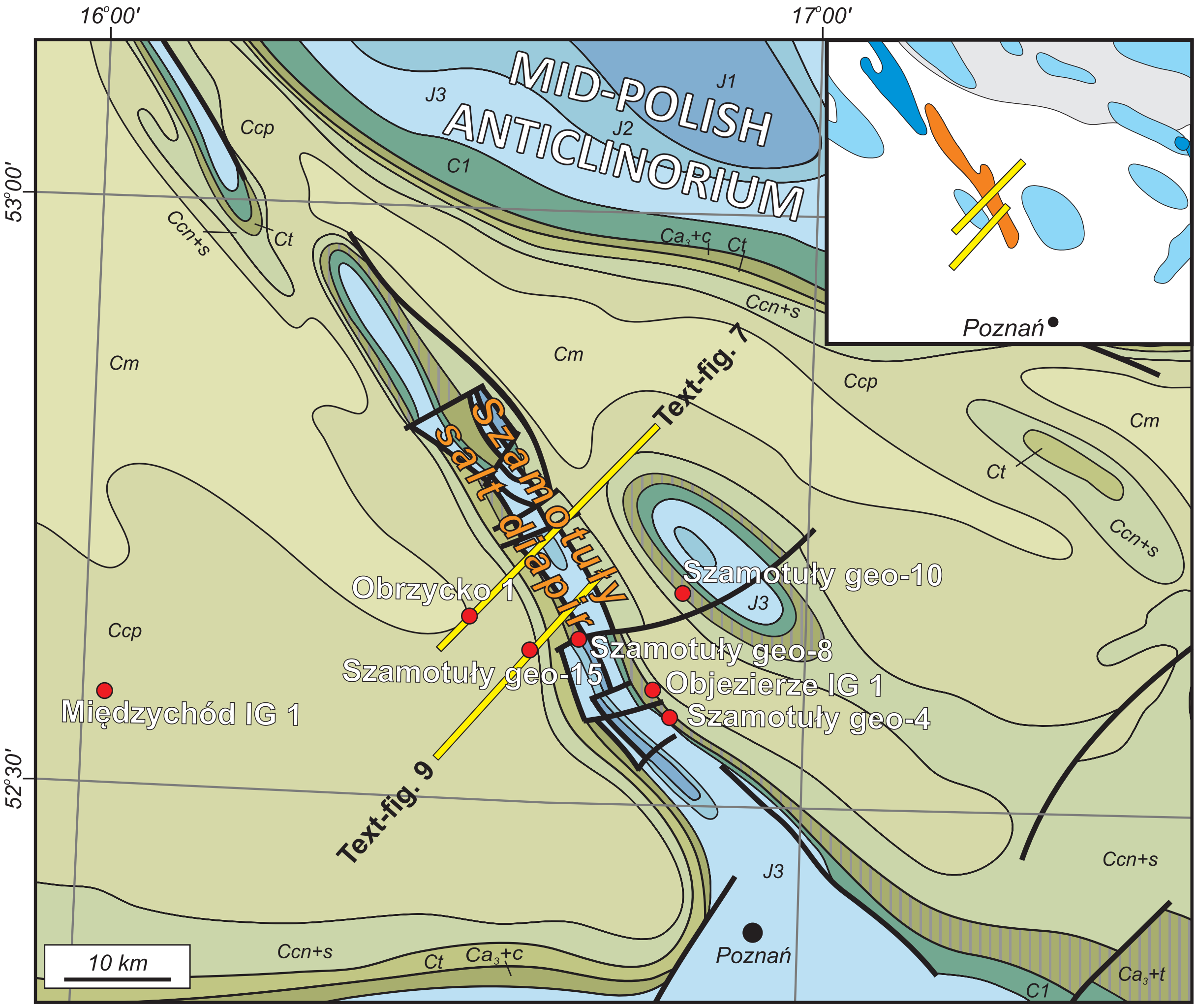
Szamotuły salt diapir

The study area is located southwest of the Mid-Polish Anticlinorium in the northwestern Szczecin-Miechów Synclinorium (northwestern Poland; Text-fig. 2). The Szamotuły salt diapir is composed of Zechstein (Wuchiapingian–Changhsingian) evaporites. It is located within the southwestern flank of the Polish Basin, approximately 40 km west from the major basement fault that controlled subsidence of the Mid-Polish Trough and the subsequent inversion and formation of the Mid-Polish Anticlinorium (Rowan and Krzywiec 2014). This salt diapir developed in the Early to Middle Triassic as a reactive diapir, and from the Late Triassic onwards as a passive diapir; furthermore, it was compressionally reactivated during widespread Late Cretaceous basin inversion (Rowan and Krzywiec 2014). Inversion-related growth of the Szamotuły diapir and other salt diapirs within the Polish Basin, and associated buckling of their overburden, was partly syn-depositional and led to the formation of Upper Cretaceous growth strata characterized by localized reductions in thickness and formations of progressive unconformities (cf. Krzywiec 2006b, 2012; Krzywiec and Stachowska 2016). Due to regional post-inversion erosion, inversion-related growth strata have not been preserved directly above the Szamotuły salt diapir; however, they are present within synclines developed along its edges. In the vicinity of the diapir, the deformed and eroded Mesozoic succession is capped by an unconformity that formed after inversion ceased. Above this unconformity, relatively thin (100–200 m) Oligocene and younger strata were deposited (Piwocki 2004; Widera *et al*. 2019).

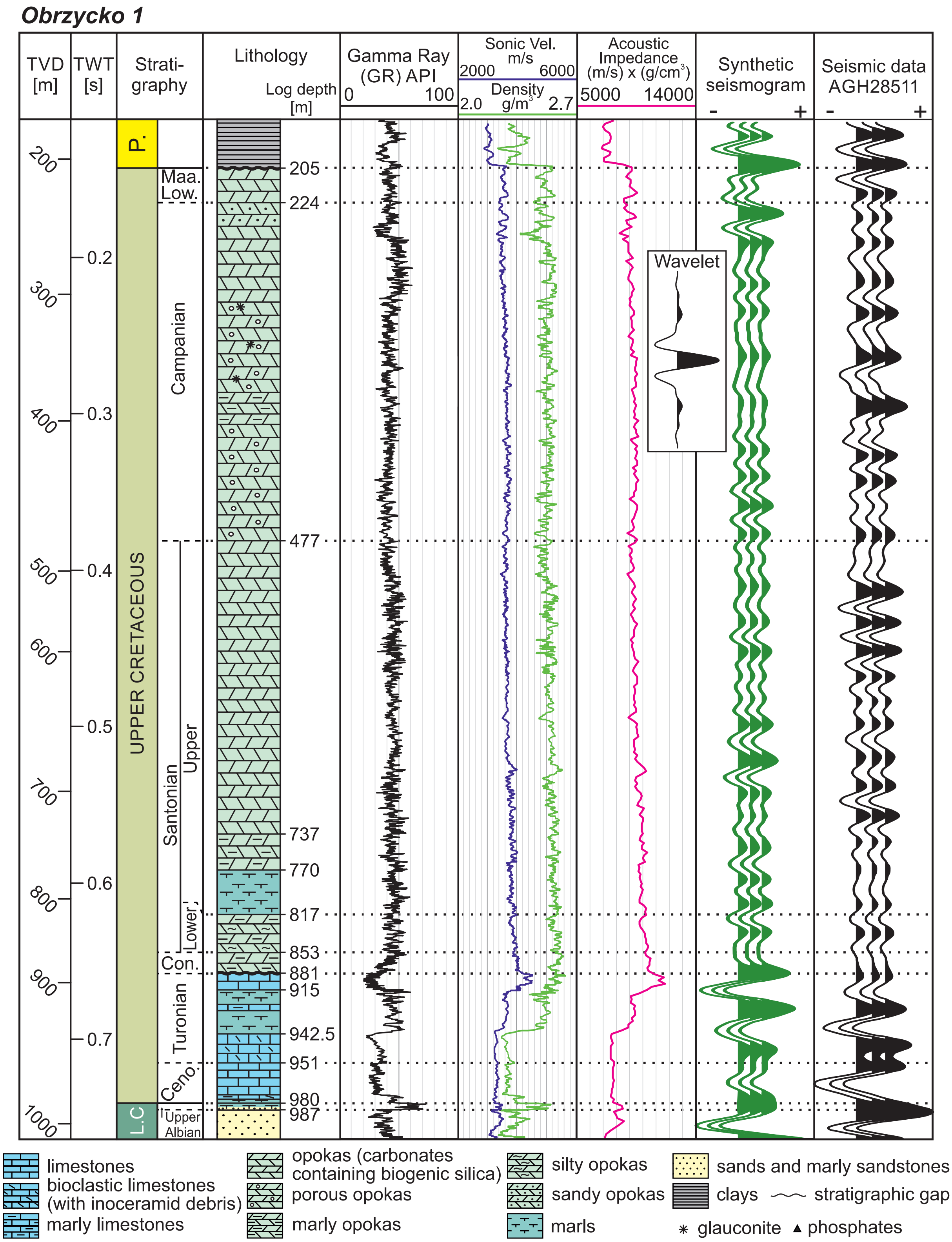
DATA AND METHODS

Seismic and well data

Two seismic reflection profiles were used to examine Upper Cretaceous internal geometry in the vicinity of the Szamotuły salt diapir (Text-fig. 4). The first is part of the regional SW-NE oriented profile AGH28511, which was acquired and pre-stack time migrated in 2011 by a joint Geofizyka Toruń and AGH University of Mining and Metallurgy team. This part of the seismic profile is located c. 40 km northwest of Poznań and captures the Szamotuły diapir and troughs on its northeastern and southwestern sides. The entire depth-migrated line (114-km-long profile) was published by Rowan and Krzywiec (2014; their fig. 4). The second (T0074207 profile), which also has a SW-NE orientation, is located 6.5 km southeast of the AGH28511 profile. This profile was acquired in 2007 and depicts part of the Szamotuły diapir, including the southwestern trough (see Krzywiec *et al.* 2022a; their fig. 13). The vertical seismic resolution for the Upper Cretaceous succession was estimated, based on a well-to-seismic tie, as c. 25–35 m.



Text-fig. 4. Geological map (without Cenozoic) of the study area (after Dadlez *et al.* 2000), with location of seismic profiles shown in Text-figs 7 (AGH28511 profile), 9 (T0074207 profile), and wells. C_m – Maastrichtian, C_{cp} – Campanian, C_{cn+s} – Coniacian + Santonian, C_t – Turonian, C_{a3+t} – Upper Albian + Turonian, C_{a3+c} – Upper Albian + Cenomanian, C1 – Lower Cretaceous, J3 – Upper Jurassic, J2 – Middle Jurassic, J1 – Lower Jurassic, Pz – Permian (Zechstein).



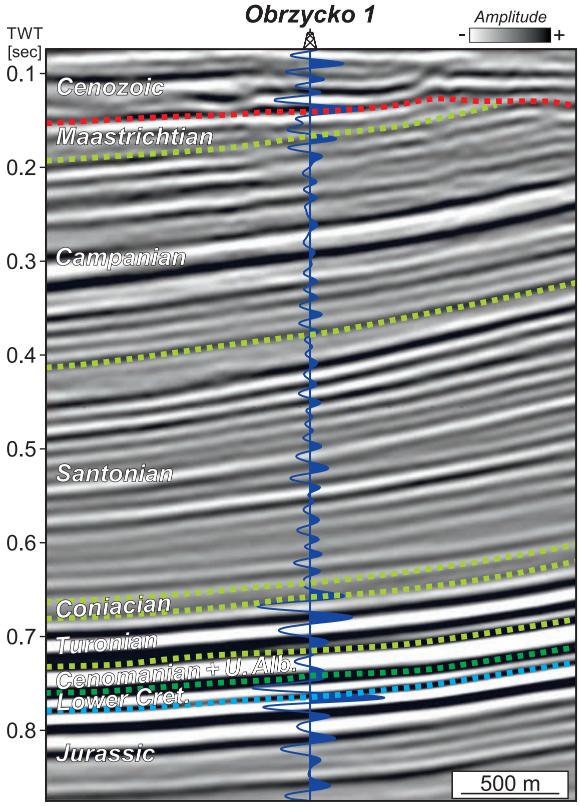
Text-fig. 5. Obrzycko 1 – synthetic seismogram, well log, and lithologic log. TVD – true vertical depth, TWT – two-way time; stratigraphy: L.C. – Lower Cretaceous, P. –Palaeogene, Ceno. – Cenomanian, Con. – Coniacian, Maa. Low. – Lower Maastichtian; Log: Sonic Vel. – sonic velocity. Stratigraphic and lithologic logs after Jaskowiak-Schoeneichowa (1981).

As in other parts of the Polish Basin, deep wells in the study area are mostly located on the crests and flanks of various deep subsurface anticlinal structures, often caused by salt. Our well database provides Upper Cretaceous lithologic and stratigraphic data in the vicinity of the Szamotuły diapir, and consists of eight wells drilled by the Polish Geological Institute between 1958 and 1987 (Text-fig. 4). The Obrzycko 1 borehole, located immediately adjacent to one of the interpreted seismic profiles, has a sufficient wireline log suite (i.e., sonic, density, and check shot data) to enable a precise well-to-seismic tie. For other wells, only basic geophysical data were available, with no sonic and check shot data. Previously published stratigraphic correlations and lithological descriptions by Jaskowiak-Schoeneichowa (1979, 1981) and data from the Central Geological Database of the Polish Geological Institute (CBDG, http://baza.pgi.gov.pl/) were used in the Discussion section. Most of the cores used by Jaskowiak-Schoeneichowa were not preserved and so cannot be re-evaluated.

Data integration and interpretation

The AGH28511 seismic profile is calibrated by the Obrzycko 1 borehole, which penetrated the entire Upper Cretaceous succession. Stratigraphic correlation of the Obrzycko 1 borehole with this seismic profile is based on a synthetic seismogram calculated using sonic and density logs (Text-fig. 5). The calculated impedance log was convolved with a zero-phase wavelet extracted from the seismic data from the window-extraction time range 0.02–2.4 s, using frequency matching. The basic attributes of this statistical wavelet are an average dominant frequency of c. 35 Hz and a signal length of 125 ms. The synthetic seismogram was then correlated with seismic data for stratigraphic interpretation (Text-figs 5 and 6). The correlation of well to seismic data is satisfactory; a synthetic seismogram revealed several clear reflectors that precisely fit the reflection patterns. The main lithologic and stratigraphic boundaries within the studied Upper Cretaceous strata can therefore be easily identified on seismic data.

Seismic data interpretations were carried out with special emphasis on the internal geometry of Upper Cretaceous strata adjacent to the Szamotuły salt diapir. Particular attention was paid to the analysis of seismic reflection patterns and terminations, as well as other seismic reflector characteristics such as amplitude, frequency, and lateral continuity (cf. Mitchum *et al.* 1977; Taner and Sheriff 1977; Veeken and van Moerkerken 2014). Seismostratigraphic interpretations on the seismic profiles are shown with a black-to-white scale, where black indicates a positive amplitude (peak) and white indicates a negative amplitude (trough).



Text-fig. 6. Correlation of the Obrzycko 1 well with seismic data. Cret. – Cretaceous; U. Alb. – Upper Albian.

RESULTS

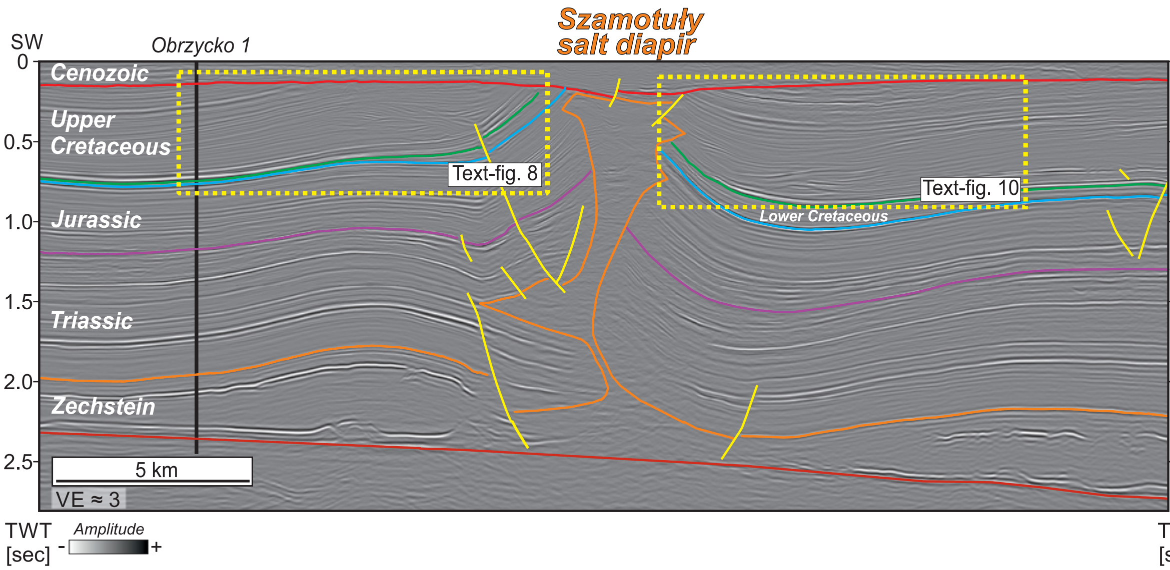
1D seismostratigraphic analysis

A 1D seismostratigraphic analysis was carried out for the Obrzycko 1 well based on a well-to-seismic tie, using stratigraphic and lithologic descriptions (CBDG, http://baza.pgi.gov.pl/; Jaskowiak-Schoeneichowa 1979, 1981). For the most part, this analysis showed a clear relationship between Upper Cretaceous lithologies and seismic patterns (Text-figs 5 and 6). As such, detailed seismic characterization of the Upper Cretaceous in the vicinity of the Szamotuły diapir were obtained.

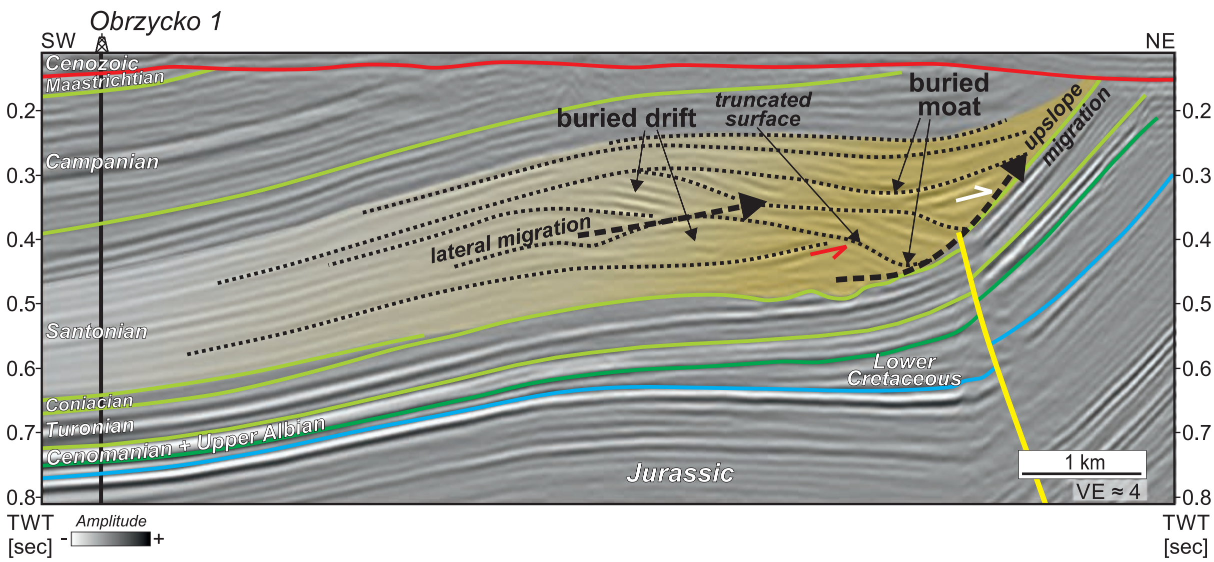
In addition to the Upper Cretaceous succession, the detailed well-to-seismic tie also includes Upper Albian (Lower Cretaceous) sandstones that mark the onset of the mid-Cretaceous transgression (Cieśliński 1959; Pożaryski 1960; Jaskowiak-Schoeneichowa 1979, 1981). In the Obrzycko 1 well, the Upper Albian is represented by fine- and medium-grained calcareous sandstones, with a characteristic basal horizon containing gravel, glauconite, and phosphorites. This horizon is clearly distinguished by a significant spike in the GR log (peak at 987 m; Text-fig. 5). The upper Upper Albian succession is more marly, and is overlain by Cenomanian deposits dominated by light gray, pure limestones. The Albian/Cenomanian boundary is associated with a positive high-amplitude seismic horizon (at 980 m/741 msec TWT; Text-figs 5 and 6). However, due to (i) the seismic tuning effect associated with thin layers characterized by different acoustic impedance (cf. Widess 1973) and (ii) the relatively thin (c. 7 m) Albian interval that is below the vertical resolution of our seismic data, the high-amplitude seismic horizon at the Albian/Cenomanian boundary also extends to the base of the Upper Albian. The next high-amplitude seismic horizon is associated with the contact between Cenomanian limestones and Turonian bioclastic limestones (limestones with abundant inoceramid shell debris) at 951 m/715 msec TWT. Above this reflector, the synthetic seismogram reveals two seismic horizons with high negative amplitudes (troughs) within the Turonian that are dominated by carbonate facies, comparable to the Cenomanian facies. The first horizon represents the lithological contact between the underlying bioclastic limestones and the overlying marls at 942.5 m/695 msec TWT, while the second one corresponds to the contact between these marls and marly limestones and the overlying pure limestones. In the Obrzycko 1 well, the Turonian is stratigraphically incomplete and is capped by a discontinuity surface, which is expressed seismically as a moderate-amplitude positive horizon at 881 m/657 msec TWT. This surface is covered by marly opokas that Jaskowiak-Schoeneichowa (1979, 1981) classified as Coniacian. Above, the Santonian succession in Obrzycko 1 is mainly represented by pure opokas, although in the lower Santonian marls, marly and silty opokas are recognized. According to the well-to-seismic tie, the lowermost Santonian is characterized by parallel, continuous reflections of low to medium amplitude and medium frequency. In turn, the overlying Santonian pure opokas are captured by parallel reflections of medium to high amplitude and medium frequency. The transition from marly and silty opokas to overlying marls corresponds to a negative low-amplitude seismic horizon (at 817 m/620 msec TWT). Negative seismic horizons of similar amplitudes also represent marl/marly opoka (at 770 m/591 msec TWT) and marly opoka/pure opoka boundaries (at 737 m/568 msec TWT). The transition from pure Santonian opokas to overlying porous Campanian opokas is poorly highlighted on the seismic data due to the marginal differences in acoustic impedances of these facies; this boundary is represented by a positive, low amplitude seismic horizon (at 477 m/382 msec TWT). Like the Santonian, the Campanian is represented by opokas. According to well logs, these opokas are porous in the lowest Campanian, marly in the Middle Campanian, and pure and sandy in the Upper Campanian. Campanian opokas are mostly represented by parallel and semiparallel continuous and semicontinuous reflections of low to medium amplitude and low to medium frequency (Text-fig. 6). In the Middle Campanian, however, high-amplitude reflectors were also observed in seismic data. These reflectors do not correspond to significant changes in the well logs and can only partially be related to marly opoka alternations within this interval. In the Obrzycko 1 well, the youngest documented Upper Cretaceous strata are c. 20 m of opoka, which Jaskowiak-Schoeneichowa (1979, 1981) placed in the Lower Maastrichtian (Text-fig. 5). This succession is capped by a regional unconformity which separates Upper Cretaceous carbonates from overlying Palaeogene (?Oligocene) siliciclastics. In seismic data, this regional surface is correlated with a positive high-amplitude seismic horizon (at 205 m/143 msec TWT; Text-figs 5 and 6).

Contourites on seismic data

The seismic profile across the Szamotuły salt diapir shows the internal geometry of the entire Zechstein–Mesozoic and Cenozoic sedimentary succession (Text-fig. 7). To the southwest of the Szamotuły diapir, the Santonian succession can reach up to 400 m thickness, as evidenced by the Obrzycko 1 well and seismic data, and certainly constitutes the thickest Upper Cretaceous stage (Text-figs 5 and 6). However, the Santonian strata are characterized by a peculiar reflection pattern (Text-figs 8 and 9). At larger distance from the diapir (more than c. 7 km), a gradual aggradational pattern can be observed within this succession. This pattern is characterized by parallel, laterally continuous seismic reflectors of low-to-high amplitude and medium frequency. The well-to-seismic correlation (Text-fig. 5) indicates this succession is composed of marls and opokas. However, within a <7 km zone in the vicinity of the diapir, this pattern is replaced by a complex set of oblique and convex-up seismic horizons (Text-figs 8 and 9). These mound-

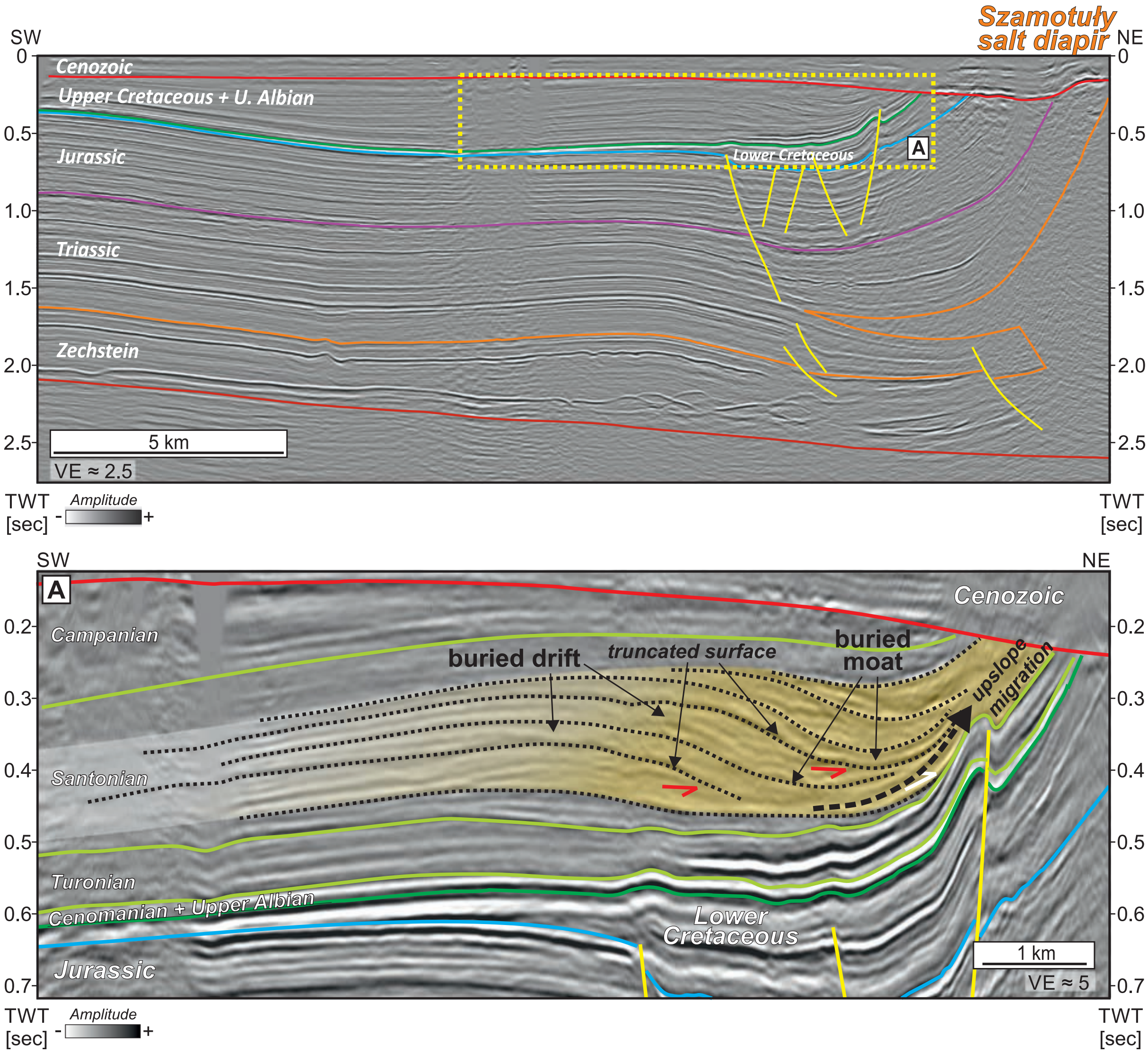


Text-fig. 7. Szamotuły diapir and surrounding Mesozoic sedimentary cover, including Upper Cretaceous contourites developed on both flanks. For location, see Text-fig. 4; AGH28511 seismic profile; yellow line indicates fault; VE: vertical exaggeration.



Text-fig. 8. Santonian contourites developed along the southwestern edge of the Szamotuły diapir (cf. Text-fig. 7). They are characterized by asymmetric moat and mound geometry (drift), closely resembling the model from Text-fig. 1; reflection terminations: onlap (white arrow), truncated reflectors (red arrow); dashed black line: inner reflector; dashed black arrow indicates 'upslope migration', also highlights stratigraphic-climbing unconformity; VE: vertical exaggeration.

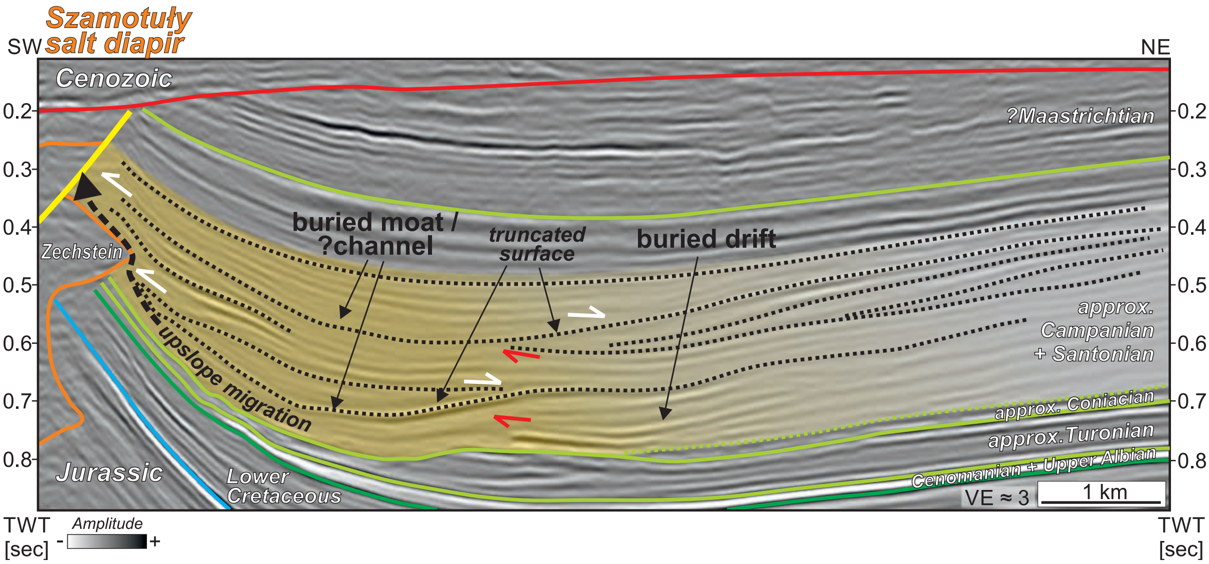
shaped packages are characterized by laterally-continuous medium-amplitude internal reflectors with locally wavy characters. Concave seismic horizons are visible in the immediate vicinity of the diapir. Reflectors of these distinct channel-like features exhibit relatively high amplitudes compared to adjacent basinal deposits. Additionally, seismic profiles reveal that reflections associated with mound-shaped packages either descend toward the depressions/incisions or are truncated by them. Concave seismic reflections usually onlap onto the slope associated with the Szamotuły salt diapir. In the lowest Santonian, the mound-shaped package is less convex and channel-like features are flatter than in younger strata (Text-fig. 9). These seismic features form a system composed of channel- and mound-shaped packages and closely



Text-fig. 9. Szamotuły diapir and surrounding Mesozoic sedimentary cover, including Santonian contourites developed on its southwestern sides. For location see Text-fig. 4; T0074207 seismic profile (cf. Krzywiec *et al.* 2022a). A – Interpreted Santonian contourites on the seismic profile (cf. Krzywiec *et al.* 2022a) characterized by asymmetric moat and mound geometry, closely resembling the model from Text-fig. 1; reflection terminations: onlap (white arrow), truncated reflectors (red arrows), dashed black line: inner reflector; dashed black arrow indicates 'upslope migration', also highlights stratigraphic-climbing unconformity; VE: vertical exaggeration.

resemble a moat-drift system formed by contour currents. Moreover, aggrading and prograding (Text-fig. 8) or – upslope – only aggrading (Text-fig. 9) stacking patterns are associated with this system.

To the northwest of the Szamotuły salt diapir, the seismic profile revealed numerous unconformities, erosion incisions, and changes in thickness, highlighted by seismic reflection terminations such as onlap and erosional truncation (Text-fig. 10). Due to the absence of appropriate wells to calibrate seismic data in this area, our stratigraphic interpretations should be treated as approximate. Nevertheless, it is clear that these seismic features are developed in the Upper Cretaceous succession, probably in Santonian–Campanian strata (Text-fig. 10). To the northeast of the diapir, erosional incisions are usually highlighted by high-amplitude reflections. The filling of these channels is quite simple, layered, and characterized by continuous reflections of medium amplitude and frequency.



Text-fig. 10. Santonian–Campanian contourites developed along the northeastern edge of the Szamotuły diapir (cf. Text-fig. 7). They are characterized by asymmetric moat/?channel and mound geometry, closely resembling the model from Text-fig. 1; reflection terminations: onlap (white arrows), truncated reflectors (red arrows); dashed black line: inner reflector; dashed black arrow indicates 'upslope migration', also highlights stratigraphic-climbing unconformity; VE: vertical exaggeration.

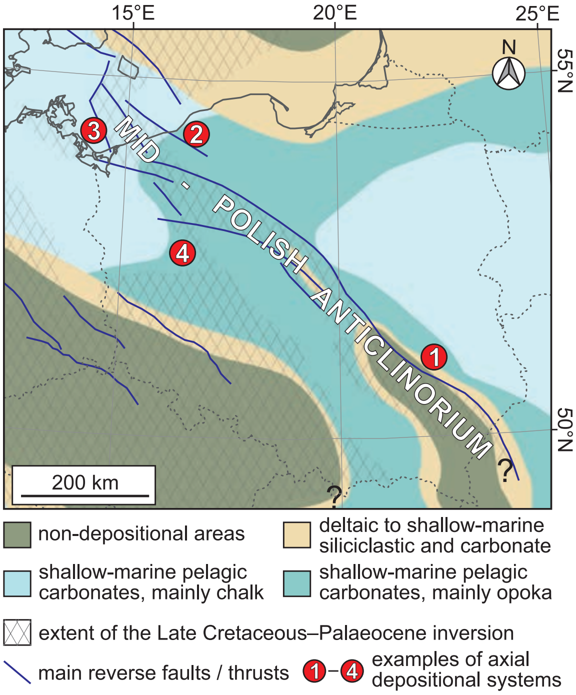
Seismic-stratigraphic interpretations reveal a clear thinning and/or total disappearance of Coniacian strata, as well as a significant reduction in the thickness in Turonian strata, towards the Szamotuły salt diapir (Text-figs 8–10). The Coniacian and uppermost Turonian are cut-terminated by Santonian concave reflections associated with the base of erosional incisions (i.e., moats). Seismic data clearly illustrate onlapping concave reflections that form a diachronous, stratigraphically-climbing unconformity. Therefore, Upper Santonian seismic horizons uncomfortably overlie the Lower Turonian succession in the immediate vicinity of the diapir.

DISCUSSION

It has long been recognized that the progressive growth of salt diapirs triggered by regional compressions exerts a direct control on local deposition (e.g., Hudec and Jackson 2007; Jackson and Hudec 2017; Pichel *et al.* 2017). Growth strata associated with rising salt structures are characterized by (i) thinning towards the diapir and (ii) the presence of local unconformities caused by localized sea-floor erosion above the crests of salt-related anticlines (e.g., Krzywiec 2006b, 2012; Hudec and Jackson 2007; Krzywiec and Stachowska 2016; Pichel *et al.* 2017). In most cases, proposed conceptual models for syn-tectonic sedimentation during salt diapir growth do not account for sediment supply along diapir edges. This is primarily due to the fact that such models are either based on 2D seismic profiles or sliced analogue models, which lack characteristic features indicative of active processes along the salt structures.

In the vicinity of the Szamotuły salt diapir, seismic data reveal numerous changes in thickness, unconformities, erosional incisions, and pinch-outs within the Upper Cretaceous succession. This complex pattern of seismic horizons is interpreted as resulting from contour currents flowing along salt diapir-associated slopes. In the Santonian succession, the seismic features on the southwestern side of the diapir resemble a typical moat-drift system migrating laterally and/or upslope over time (i.e., an elongated mounded shape, and an adjacent moat filled by younger contour current deposits; Text-figs 8 and 9; cf. Faugères *et al.* 1999; Rebesco *et al.* 2014). On the northeastern side of the diapir, Santonian–Campanian channel-like features have also been tentatively associated with contour current activity (Text-fig. 10).

The Santonian–Campanian contourites described presently are yet another example of Upper Cretaceous contourites formed along the edges of local bathymetric highs that, in turn, formed due to regional Late Cretaceous inversion tectonics. These

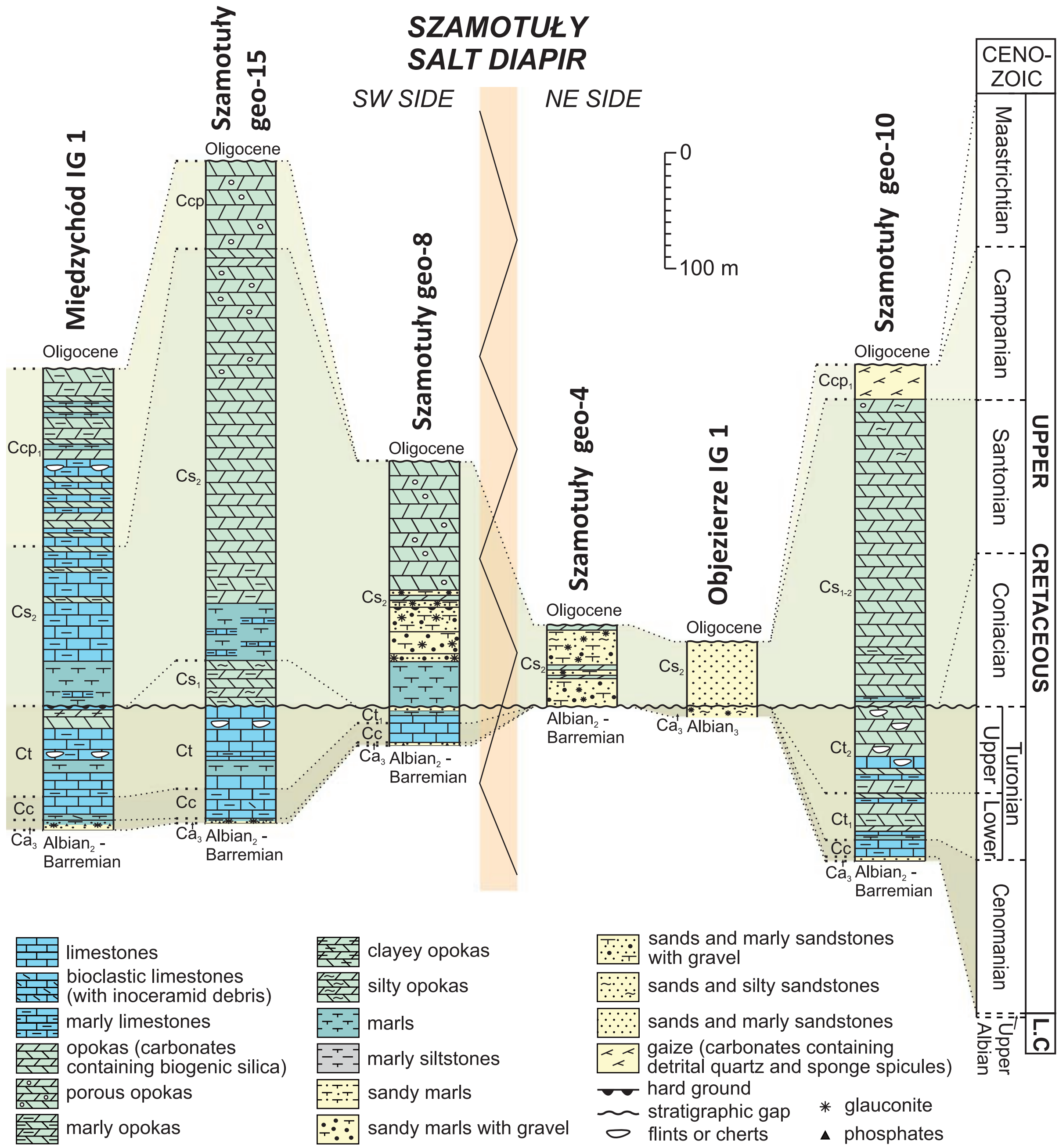


Text-fig. 11. Late Cretaceous axial depositional systems in the Polish Basin and its surroundings: contourites formed on the northeastern side of the Mid-Polish Anticlinorium – 1 (Krzywiec *et al.* 2009, 2018) and 2 (Stachowska and Krzywiec 2023); contourites formed on the southwestern side of the Mid-Polish Anticlinorium – 3 (Hübscher *et al.* 2019) and 4 (Krzywiec *et al.* 2022a and this study). Late Cretaceous (approx. Campanian) palaeogeography after Vejbæk *et al.* (2010), Bojanowski *et al.* (2017), Jurkowska *et al.* (2019), Machalski and Malchyk (2019), and Remin *et al.* (2022a); extent of Late Cretaceous inversion and main reverse faults/thrusts based on Ziegler (1990), Ziegler *et al.* (2002), Krzywiec (2006b), Krzywiec *et al.* (2006, 2022b), Kley (2018), and Voigt *et al.* (2021).

highs and related contourites may be associated with uplifted basement blocks during thick-skinned inversion (Surlyk and Lykke-Andersen 2007; Krzywiec *et al.* 2009, 2018; Hübscher *et al.* 2019), blocks mobilized above Zechstein evaporites during thin-skinned inversion (Stachowska and Krzywiec 2023), and compresionally-reactivated salt diapirs (Krzywiec 2006b, 2012; Krzywiec *et al.* 2022a, and this paper). Collectively, these examples support the existence of an active Late Cretaceous contour current system along the Mid-Polish Anticlinorium (Text-fig. 11; cf. also Remin *et al.* 2022b).

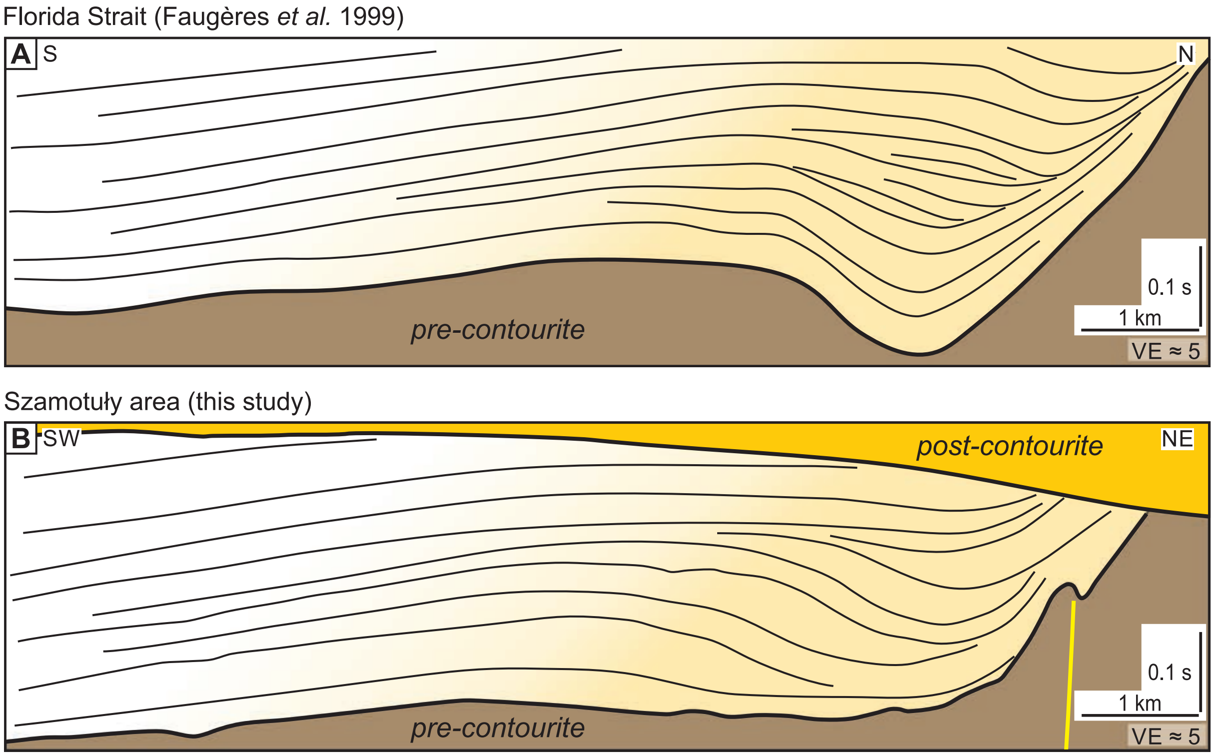
To date, Upper Cretaceous facies and internal geometry variations in the study area have been almost exclusively associated directly with salt structure movement in the Late Cretaceous (Jaskowiak-Schoeneichowa 1979, 1981; Leszczyński 2002). For example, the significant local admixtures of terrigenous quartz within the carbonate successions, as well as thick sand, sandstone and gravel layers in the Szamotuły geo-8 (Popówko geo-8 in the Central Geological Database of the Polish Geological Institute, CBDG, http://baza.pgi.gov.pl), Szamotuły geo-4 (Wargowo geo-4 in CBDG) and Objezierze IG 1 wells (Text-fig. 12; Jaskowiak-Schoeneichowa 1979, 1981) – all in close vicinity to the Szamotuły salt diapir – were commonly associated with a transverse depositional system (i.e., erosion of the diapir overburden). At greater distances from the Szamotuły structure, the Santonian succession is characterized by a lesser sand component and a greater contribution of opokas (see Szamotuły geo-15 and Szamotuły geo-10 wells) and limestones (e.g., Międzychód IG 1; Text-fig. 12; Jaskowiak-Schoeneichowa 1979, 1981), probably due to the less significant impact of diapir growth on sedimentation. We suggest that bottom current activity had a significant impact on the depositional architecture and redistribution of Upper Cretaceous facies on both sides of the Szamotuły diapir. Redistribution of siliciclastic sediments could have occurred not only transversely to the diapir, but also along it – that is, along moat and channel axes. Additional evidence for such processes, beyond seismic data, is provided by hardgrounds and abundant glauconite in the Santonian succession (in Szamotuły geo-8 – Popówko geo-8 in CBDG; Text-fig. 12, see Jaskowiak-Schoeneichowa 1979, 1981; Leszczyński 2017). These sedimentary features may indicate a slowdown or even cessation of sedimentation, which are common phenomena during sediment bypass (i.e., when bottom currents are active but no deposition took place). The fine-grained sediment that contributed to opoka mineralogy was probably deposited as a contour drift.

As shown by previous studies by Jaskowiak-Schoeneichowa (1979, 1981) and Leszczyński (2002), the Turonian is capped by a discontinuity surface, representing a well-documented stratigraphic gap that spans either the Upper Turonian (e.g., Obrzycko 1; Text-fig. 5), the Upper Turonian and Coniacian (e.g., Szamouły geo-15), or up to the lowermost Santonian (e.g., Szamotuły geo-8 – Popówko geo-8 in CBDG, Szamotuły geo-4 – Wargowo geo-4 in CBDG; Text-fig. 12]. The existence of Coniacian strata in Obrzycko 1 was not demonstrated biostratigraphically due to the absence of suitable core material. Jaskowiak-Schoeneichowa (1979, 1981) proposed that the Coniacian was present based on long-distance correlations of geophysical logs with boreholes from northeastern Poland in which the Coniacian was recognized; as such, previous recognitions of the



Text-fig. 12. Stratigraphy and facies of selected boreholes from the study area (stratigraphic correlations and lithological descriptions after Jaskowiak-Schoeneichowa 1979, 1981; http://baza.pgi.gov.pl/). Ccp – Campanian, Ccp_1 – Lower Campanian, Cs_2 – Upper Santonian, Cs_1 – Lower Santonian, Ct – Turonian, Ct_2 – Upper Turonian, Ct_1 – Lower Turonian, Cc – Cenomanian, Ca_3 – Upper Albian, L.C – Lower Cretaceous.

Coniacian should be treated with considerable caution. Instead, we suggest that the Coniacian is probably absent on both flanks of the Szamotuły structure, where Santonian strata – sometimes even Upper Santonian strata – directly overlie Turonian or older deposits (Text-fig. 12; Jaskowiak-Schoeneichowa 1979, 1981). These findings are consistent with the analyzed seismic data. Moreover, the development of the stratigraphic gap in the vicinity of the Szamotuły diapir can be directly related to both (i) the progressive uplift of the salt-cored anticline and associated local erosion and (ii) the development of a moat-drift



Text-fig. 13. Comparison of vertical sizes, horizontal sizes, and internal geometries of (A) Neogene contourites from the Florida Strait (Faugères *et al.* 1999) and (B) Santonian–Campanian contourites from the Szamotuły salt diapir (this study).

system – more precisely, to the erosional nature of moat and contourite channels. Specifically, this gap is related to the diachronous unconformity described above.

During compressional reactivation of the Szamotuły salt diapir, substantial buckling of its overburden must have taken place, leading to the formation of a local morphological high on the sea-floor, associated with localized thinning of syn-inversion strata, and/or localized erosion, as in other salt diapirs from this part of the Polish Basin (cf. Krzywiec 2006b, 2012; Krzywiec and Stachowska 2016). In this particular diapir, post-inversion erosion was rather deep (Text-figs 3, 4 and 7) so inversion-related growth strata were not preserved. However, an almost complete Cenomanian to Maastrichtian succession was preserved within two synclines along the southwestern and northeastern edges of the Szamotuły diapir (Text-fig. 7). The Upper Cretaceous depositional architecture suggests progressive inversion-related growth of the diapir began in the Coniacian, which is compatible with estimates of the onset of inversion tectonics from elsewhere in the Polish Basin (Krzywiec 2006b, 2012; Krzywiec *et al.* 2009; Krzywiec and Stachowska 2016). The preserved Upper Cretaceous succession includes Santonian–Campanian contourites on both flanks of the Szamotuły diapir (Text-figs 7–10). Their formation was driven by the locally uplifted sea-floor above the Szamotuły diapir during its inversion-related growth, forming a slope along which contourite currents developed (Krzywiec *et al.* 2022a).

The Upper Cretaceous contourites in the vicinity of the Szamotuły salt diapir can be directly compared to seismic images of other contourites – for example, the Florida drift in the Florida Strait (Faugères *et al.* 1999 and their fig. 10). In both cases, the overall internal contourite geometries are comparable, as illustrated by Text-fig. 13. Additionally, their lateral (few kilometers) and vertical (0.5–1 sec TWT) dimensions are very similar. Contourites with similar internal geometries and sizes have also been seismically detected on the upper slope of the north margin of the Gulf of Cádiz (i.e., the Faro drift, cf. Faugères *et al.* 1999 and their fig. 8; Rebesco *et al.* 2014 and their fig. 10). Of course, the contourites from the Gulf of Cádiz and the Florida Strait formed in different geodynamic settings. However, they exhibit many similarities to contourites from the Polish Basin, in both the present study area and elsewhere in the basin

(Krzywiec *et al.* 2009; Stachowska and Krzywiec 2023), strongly suggesting that similar processes responsible for their formation.

Seismic data from the Santos Basin (offshore Brazil) document how extruded salt diapirs form obstacles for contour current flow and eventually lead to contourite formation (Schattner *et al.* 2018). While the Szamotuły diapir probably did not extrude onto the basin floor – although this cannot be completely excluded – inversion-related overburden buckling created a local morphological high on the sea-floor that was apparently large enough to focus contourite current flow and promote contourite deposition, as in the Santos Basin.

Finally, the presented results illustrate how contourites can be used as palaeomorphologic indicators in ancient sedimentary basins. A slope along which contour currents can flow is required for contourite formation. The majority of existing seismic examples come from modern continental margins, where the existence of a slope along which contour currents can flow is obvious. However, the identification of contourites in other settings, such as epicontinental basins, implies that some sort of slope/morphological barrier at the basin seafloor must have existed during their formation – related, for example, to uplifted basement blocks during inversion (cf. Krzywiec *et al.* 2009) or compressionally reactivated salt diapirs (this study). This illustrates how contourites can be indicative of varied palaeomorphologic features that might have been overprinted by later geological processes, such as tectonic deformation or erosion.

CONCLUSIONS

This study provides a comprehensive seismostratigraphic analysis of the Upper Cretaceous sedimentary succession in the vicinity of the Szamotuły salt diapir in northwestern Poland, based on seismic data supported by wells. In particular, we focus on the complex internal geometry of Santonian–Campanian deposits, and reveal the presence of contourite drifts and moats, interpreted as the result of contour currents that flowed along the flanks of the salt diapir and its folded overburden. The formation of Santonian–Campanian contourites was linked to the growth of the Szamotuły salt diapir during regional compression and Polish Basin inversion; seismic data suggest progressive inversion-related growth of the diapir initiated in the Coniacian, consistent with estimates from other parts of the Polish Basin. Observed stratigraphic gaps were related to the erosional activity of contour currents. Contour currents in the Szamotuły region, and the associated contourites, were integral components of a regional axial depositional system that evolved within the flanks of the Mid-Polish Anticlinorium. These findings suggest that contour currents played a significant role in shaping Upper Cretaceous depositional architecture in the study area, highlighting their association with the tectonic evolution of the broader region.

Comparisons of the Szamotuły contourites with other contourites, such as the Faro drift in the Gulf of Cádiz and the Florida Strait, revealed similarities in contourite internal geometries and sizes. These similarities suggest that similar processes might have led to their formation, despite their varied geodynamic settings. Furthermore, this study highlights the potential of contourites as palaeomorphologic indicators in ancient sedimentary basins. Contourite identification necessarily implies the existence of sea-floor slopes or morphological barriers, providing valuable insights into the associated geological history and tectonic activities, such as tectonic inversions or compressionally reactivated salt diapirs that shaped these ancient sedimentary basins.

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