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Gas - escape features along the Trzebiatów Fault offshore Poland: evidence for a leaking petroleum system

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Abstract: New 2D high resolution seismic and hydro-acoustic data demonstrate the presence of methane in the shallow sediments and its origin in the Pomeranian Bight, southern of the Baltic Sea area. Various shallow gas features were identified in the Gryfice block, along the inverted Trzebiatów fault zone, including chimneys, bright spots, acoustic blanking, pockmarks, and polarity reversal. Structural and stratigraphic interpretation with support of seismic attributes was carried out to show the potential of fluid migration pathways from the Upper Triassic formation reservoirs to shallow sediments below seabed and helps in explanation of how this natural gas escapes to the sea bottom. Amplitude-vs-offset (AVO) analysis verified remnants of free gas existence in the Upper Triassic potential reservoir and helped locating free gas deposits within sediments. Hydro-acoustic data illustrated the gas chimneys' anomalies and corresponding free gas accumulation in Pleistocene to Quaternary successions. Leaking of gas to sea surface was also proved by exposure of pockmarks on multibeam (bathymetry) data. We combine seismic, hydro-acoustic data and information on petroleum system from previous studies to explain signatures of free gas and its migration from lower reservoirs to shallow sediments.

Keywords: reflection seismic, hydro-acoustics, fluid escape, shallow gas, petroleum system

1. Introduction

Methane (CH_4) is the most abundant gas accumulated in shallow sediments compared to carbon dioxide, hydrogen sulfide, and higher chain hydrocarbon. Gas (hydrocarbons in general) can originate from either biological or thermogenic processes. While the biogenic gas is generated by bacterial activity mainly within few meters of sediments (Parkes et al, 1990), the thermogenic gas is derived from organic materials at high pressures and temperatures and frequently at depth of more than 1000 m (Floodgate and Judd, 1992).

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Thermogenic gas often migrates to the surface and is being trapped in shallow sediments. Presence of shallow gas impacts both the geosystem and various ecosystems: e.g., geohazards related to stability of the offshore infrastructure (Fleischer et al., 2001; Hovland et al., 1993; Naudts et al., 2009) or drilling offshore oil and gas wells (Adams and Kuhlman, 1991; Schroot and Schüttenhelm, 2003; Ren et al., 2019), as well as water chemistry and flora and fauna habitats (Idczak et al. 2020; Judd and Hovland, 2009).

Free gas presence in shallow marine sediments can be recognized in seismic and hydro-acoustic data by some distinct signal appearance. Acoustic turbidity or acoustic blanking are seismic frequency related features due to scattering and absorption of seismic energy in gas charged areas (Hovland and Judd, 1988). While acoustic turbidity appears as chaotic reflections, being mostly found in pockmark areas, acoustic blanking represents absence of reflections beneath gassy layers (Mathys et al., 2005; Tóth et al., 2014). The acoustic blanking is one of the most common gas-related features, it appears as smear zone where reflections are faint and absent in certain level (Judd and Hovland, 2009; Schroot et al., 2005). This may result of migration of free gas or reflection of acoustic energy by overlapping hard sediment (Judd and Hovland, 1992). Gas accumulation areas can also cause amplitude bright spots which usually occur at depth of more than 100 m and possibly at relatively high pressure (Hovland and Judd, 1988). Bright reflectivity zones often form reverberations or ringing in acoustic data (Davy, 1992; Tóth et al., 2014). They are similar to bright spots, but occur in shallower records. These features are frequently observed together with acoustic turbidity zones (Judd and Hovland, 1992). Decrease of seismic velocity and lower density in gas-charged sediments can also cause polarity reversal of the corresponding reflections (Garcia-Gil et al., 2002; Kim, 2020).

Presence of gas in the shallow sediments in the Baltic Sea area was investigated in many studies using either seismic or hydro-acoustic data. Blanking and turbidity evidence of gas bubbles were found in organic-rich near surface sediments in Arkona Basin (Mathys et al., 2005; Thießen et al., 2006) and in Eckernfoerde Bay (Abegg and Anderson, 1997). Shallow gas distribution in Holocene marine mud was mapped in Arhus Bay and Skagerrak (Jensen and Bennike, 2009; Laier and Jensen, 2007). Free gas in Holocene mud was also detected in the Bornholm Basin (Laier and Jensen, 2007; Tóth et al., 2014). Offshore Poland, studies on shallow gas were conducted since the early 90s (Jaśniewicz et al., 2019). Majority of the studies focused on the eastern and central part of the Polish Exclusive Economic Zone (EEZ) especially in the Gdansk Basin and the Słupsk Furrow (Jakacki et al., 2002; Tęgowski et al., 2003; Brodecka et al., 2013; Jørgensen and Fossing, 2012; Majewski and Klusek 2011, 2014; Idczak et al. 2020). Geochemical studies performed by the consortium led by the Polish Geological Institute in 2005-2008 indicated occurrence of thermogenic gas in near seabed waters (Jaworowski et al. 2010; Wagner, 2011). It was linked with the Paleozoic petroleum system, with active oil and gas production in the eastern part of the EEZ (Jaworowski et al. 2010). The area of Pomeranian Bight in the western part of the EEZ is less studied with the acoustic data collected during 1970s and 1980s (Jaśniewicz et al., 2019).

In this study, we analyze multichannel reflection seismic (MCS), high-frequency hydro-acoustic (parametric sub-bottom profiler) and bathymetric (multibeam) data acquired in the greater Pomeranian Bight area, southern Baltic Sea during RV Maria S. Merian research cruise MSM52 in 2016 (Hübscher et al., 2017). The study area is located at the offshore extension of the established Paleozoic (mostly Carboniferous) and Permian (both Zechstein and Rotliegend) petroleum play (Karnkowski et al., 2010). Our data provide evidence for gas presence in the shallow sediments, as well as its link with the deeper geological structure (Trzebiatów Fault). Amplitude-versus-offset (AVO) analysis of seismic data confirms the presence of gas at the deeper reservoir level, while seismic data portrays gas migration pathways (gas chimneys).

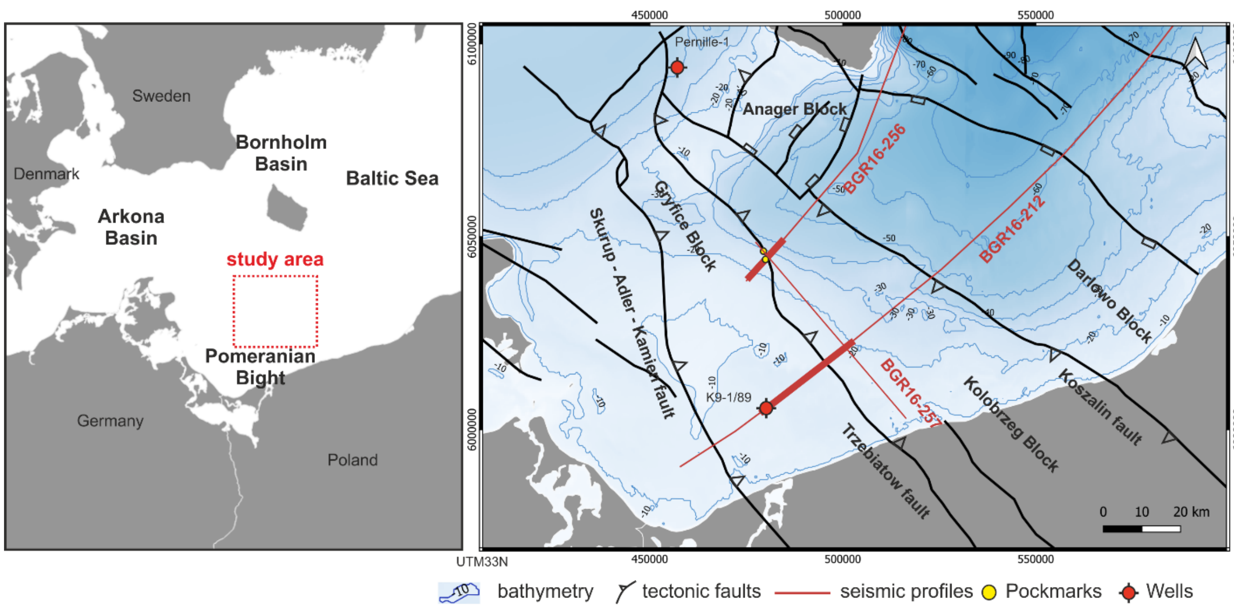

Figure 1. Location of the study area (greater Pomeranian Bight, Baltic Sea). Location of the seismic lines used in this study at bathymetry map with main tectonic structures overlayed (modified from Janik et al., 2022). Part of the seismic sections showing shallow gas features are highlighted by a thick red line. Yellow dots show two pockmarks' locations identified by multibeam data.

2. Geological background

2.1. Sub-quaternary geology

The study area is located offshore Poland within area of Gryfice block, in the inverted part of the Permian - Mesozoic Polish Basin, so called Mid - Polish Swell (Dadlez, 2003; Krzywiec, 2006). There are two main inversion-related fault zones: Adler-Kamień and Trzebiatów faults, rooted in the pre-Permian basement (Figure 1).

Development of the Permian - Mesozoic basin and its sediments distribution are consequences of two tectonic regimes: basin extension commenced in the Rotliegend through Mesozoic to Lower Cretaceous and later inversion tectonism in Late Cretaceous period (Vejbaek et al., 1994; Krzywiec, 2006, 2022). Dominant fault systems in the north western part of Mid-Polish Trough (MPT) are NW-SE trending (Scheck-Wenderoth and Lamarche, 2005). During extensional basin subsidence stage, sediments and structural features of the MPT were controlled by deep-seated and listric normal faults. These faults systems were then strongly reactivated in the basin inversion stage and extended from the basement upward into Mesozoic series (Vejbaek et al., 1994; Schlüter et al., 1997; Krzywiec, 2006), the Trzebiatów fault zone crossing our study area (Figure 1) is one of such faults. The Trzebiatów fault zone in the NE of the section (Figure 3) is a typical extension fault system inverted in a compressional tectonic regime (Schlüter et al., 1997; Krzywiec, 2002), this fault zone roots within pre-Zechstein and accompanied by asymmetric fault-propagation folds developed within the Mesozoic sedimentation.

Mesozoic sediments were studied by several authors (e.g., Dadlez, 1978, 1980, 2002, 2003; Krzywiec, 2006; Zimmermann et al., 2015). Lower Triassic deposits offshore Pomeranian Bight are represented by red-bed sediments of fine grain sandstones, silt and shale (Erlstrom et al., 1997). While carbonate-evaporites are dominant in Middle Triassic, the red-bed clastics come back in the Upper Triassic (Dadlez et al., 1995). Lithology from nearby wells data (Pernille-1 unpublished well report, 1989) also reveals a thin layer of claystones by the end of Keuper, forming a potential seal in petroleum play of the study area. Sediment deposits are consistent during Lower and Middle epoch of Jurassic. The lithology is predominantly clay with interbedded interlaminated fine grain sand. The Upper Jurassic has the same lithology as Lower and Middle Jurassic, but it is eroded in some areas due to strongly reverse faulting during inversion, similarly to the Lower Cretaceous deposits. Sedimentation of the Upper Cretaceous develops to the Maastrichtian in the southwest and until Early Paleogene in the northeast of the basin. Marginal marine limestone is dominant lithology of this formation. In this study, we consider the Upper Triassic succession as potential reservoir rocks (Figure 2, see section 2.3 below).

2.2. Quaternary geology

In the area of the Trzebiatów Fault zone offshore Poland, Tertiary sediments are almost absent due to erosion during Late Cretaceous - Paleogene inversion (Krzywiec, 2003, 2006), the Mesozoic formations are the direct substrate of the Quaternary sediments. The total thickness of the Quaternary formations in this region is estimated at about 30 - 40 m (Kramarska et al., 1999). The Quaternary profile in the south-eastern part of the Gryfice block is represented by the two levels of Pleistocene glacial tills, separated by series of fluvio-glacial sands and gravels (Kramarska, 1998). The thickness of the lower till layer is estimated to be several meters, in some places it can reach about 10 m. The layer of the upper till is thinner, often topped with lacustrine sands, silts and gyttas, locally organic silts and peat. These types of sediments can be found in many places in the Gryfice block. Numerous radiocarbon dates of organic sediments indicate that lake accumulation took place mainly in the early Holocene (e.g., Kramarska, 1998). The sea bottom surface is covered with a layer of fine-grained sands deposited in the Littorina and Post-Littorina sea, from the middle Holocene to the present day.

The Pleistocene sandy sediments are dominant in the north-western section of the Gryfice block. This sedimentary series lays directly on top of the older glacial till (the younger till is not present). The lower part of sandy layer is most probably represented by fluvio-glacial sands and gravels. The upper part is a continuation of the river and lake sediments accumulated during the warming period MIS3 (interplenivistulian). The sediments identified in cores (Kramarska, 1998) are represented by sands and silty sands with plant detritus and pieces of wood, dated with C14 at about 45-22 ka BP. The surficial part of the sand layer, with a thickness less than the resolution of the wave image, represents the marine environment of the younger Holocene.

2.3. Petroleum system of Western Pomerania

Petroleum system of Western Pomerania, encompassing both the onshore and offshore part of Poland extending to the eastern part of the Northeast German Basin, is specifically described in numerous studies (Karnkowski et al., 2010; Kotarba et al., 2004; Gawenda 2011). Lithostratigraphic chart of petroleum system offshore Poland (Figure 2) is built based on nearby well stratigraphy data (Erlstrom et al., 1997; Pernille-1 unpublished well report, 1989). Source rocks in the Western Pomerania are divided into two main units: the older Carboniferous deposits comprised of Tournaisian mudstones and claystones and the younger Zechstein Main Dolomite. Geochemical modeling of onshore Polish wells shows that both the Carboniferous source rock and Main Dolomite (Zechstein) display poor to fair source potential, and locally very good to excellent oil-source potential. The generation of hydrocarbons of both source rock types begins in the time span between the Middle Triassic and Late Jurassic (Kosakowski et al., 2006). Major recognized reservoir rocks are either Carboniferous or Rotliegend clastics, sealed by Zechstein evaporates (Karnkowski et al., 2010). Grainstones and packstones within the Main Dolomite (Zechstein) unit (Karnkowski et al., 2010) are forming the third reservoir level. Zechstein formation can be considered as a closed hydrocarbon play, where source, reservoir and seal rocks are in the same location.

Offshore West Pomerania is considered as a poor oil and gas production area even though numerous boreholes were drilled (Karnkowski et al., 2010), most of proven hydrocarbon fields locate onshore Pomerania in the North East German – Poland Basin (Kraus et al., 2018). The Lower Permian (Rotliegend) sandstones and Upper Permian (Zechstein) carbonates are dominant as main hydrocarbons reservoirs in the region, proven by numerous wells (Gawenda, 2011). Mesozoic sediments were targets of many exploration offshore wells to test hydrocarbon prospects in the surrounding area of the offshore West Pomerania such as Arkona Basin, Western of Bornholm island (Kraus et al., 2018). Reservoir rocks of Mesozoic sediments were Lower Jurassic sandstones from Roone and Hasle formation, Upper Triassic Keuper sandstone from Skagerrad formation and Lower Triassic sandstone from Buntsandstein formation. These sandstones generally consist of fine to medium grained, moderately to well sorted minerals deposited in fluvial environment. Although the Lower Jurassic and Lower Triassic sandstones (expected reservoirs) were very good to excellent in term of porosity and thickness proven by well data (e.g., Pernille-1, Stina-1 unpublished well report, 1989), however, there was no clearly show of hydrocarbon accumulation in Mesozoic strata. This may due to reservoir rocks located in the transition (oil-gas) zone of hydrocarbon generation (Karnkowski, 2010) or absence of good charge and seal condition (Bachmann et al., 2010). Apart from petroleum, the Mesozoic sandstones in the West Pomerania were analyzed as a significant potential of geothermal heating and aquifer thermal energy storage in recent years (Kilhams et al., 2018; Frick et al., 2022).

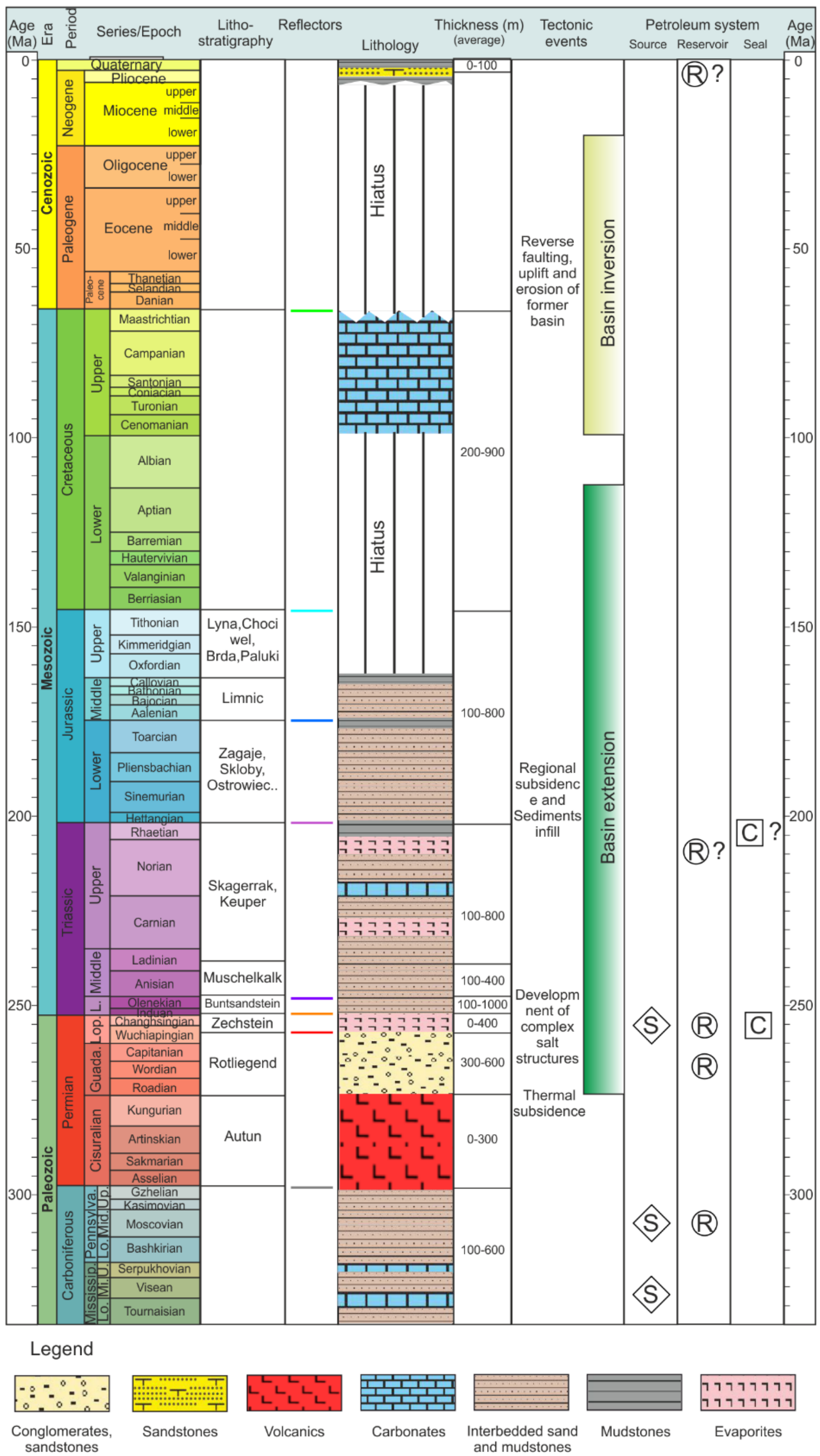

Figure 2. Simplified lithostratigraphy and petroleum system of West Pomeranian, offshore Poland. The graph is based on well stratigraphy, tectonics, and lithology from Erlstrom et al. (1997) and Pernille-1 unpublished well report (1989).

3. Data and methods

Reflection seismic, hydro-acoustic and bathymetry data were acquired in March 2016 onboard R/V Maria S. Merian (see Hübscher et al., 2017). The cruise MSM52 collected ca. 3500 km of MCS data throughout large area from Bay of Kiel to north-east of Bornholm (Hübscher et al., 2017, Hübscher, 2018). Due to some malfunction of the parametric sediment profiler and multibeam echosounder, some of the seismic lines have no coverage of these data. MCS seismic data allowed to investigate salt tectonics in North German Basin (Ahlrich et al., 2020, 2022), explain structural evolution and inversion tectonics along the Tornquist Zone (Krzywiec et al., 2022; Pan et al., 2022).

3.1. Multi-channel reflection seismic data and well data

MCS acquisition was tuned to provide high-resolution data and a gap-less image from the seafloor to deeper subsurface. Toward this end, relatively short minimum offset (37.5 m) and high-frequency air-gun array (8 GI guns) was employed. Acquisition parameters are summarized in Table 1.

Parameter	**Value**
Number of channels	216
Receiver group interval	12.5 m
Average shot interval	25 m
Minimum offset	37.5 m
Maximum offset	2710 m
Streamer tow depth	3 m
Airgun array tow depth	2 m
Airgun array	8 x GI guns (1200 inch^3 total volume)

Table 1. Acquisition parameters of MCS data acquired during MSM52 cruise (Hübscher et al., 2017)

The MCS dataset used in this study were processed in-house at Institute of Geophysics, Polish Academy of Sciences. Seismic data processing workflow included several demultiple techniques such as SRME, Tau-P deconvolution, water bottom FK filtering (see more details in Nguyen, 2020; Nguyen et al. 2022 in prep). In this study, we use 2 profiles from MSM52 cruise (line BGR16-212 and BGR16-256) (see Figure 1 for location). Final seismic sections were pre-stack time migrated. The stratigraphy horizons were correlated from nearby well K9-1/89, for which time – depth charts (check-shot data) and stratigraphy formation tops were provided (unpublished Petrobaltic report).

3.2. Hydro-acoustics data and bathymetry data

The uppermost sediment layers were surveyed using parametric sediment profiler (PARASOUND DS III-P70 system) from Atlas Hydrographic hull-mounted at R/V Maria S. Merian. By simultaneously emitting two primary frequencies between 19 and 23.5 kHz, a parametric frequency of around 4 kHz is created, allowing for a maximum penetration depth of approximately 200 m beneath the seafloor, although in the area of shallow water the image recorded was clear for interpretation up to a dozen of meters beneath the seafloor (above the multiple). The acquired hydro-acoustic data were processed using MDPS (Meridata, Finland) software.

The seafloor morphology was surveyed by a hull-mounted SIMRAD EM122 multibeam echo-sounder system. Multibeam data were processed using QINSY and QIMERA software. The raw data files have been loaded into QIMERA as Processed Point files (QPD). The processing uses a strong spline filter and CUBE processing. In addition, due to the lack of repeated water sound velocity profiles, external beams were rejected and refraction correction was added. Bathymetry grids with regular 0.75 m cell were created for the analyzed profiles.

3.3. Seismic attributes and amplitude versus offset analysis

Seismic attributes are commonly used in seismic interpretation to automate highlighting specific features, often difficult to decipher by human interpreter (Marfurt, 2018). Seismic attributes can help in tracking fluid expulsion (e.g., gas escape features) (Cartwright and Santamarina, 2015) and dissolution or collapse features (e.g., Sullivan et al., 2006; Singh et al., 2016; Meldahl et al.,1999). So-called geometrical attributes (Chopra and Marfurt, 2007), such as the coherence attribute, are commonly used in detection of faults, fractures and chaotic zones.

Amplitude versus offset (AVO) can be considered as a specific quantitative seismic interpretation attribute. It is commonly used in the oil and gas exploration industry to identify reservoir zones, fluids and lithologies. The two AVO attributes, AVO Intercept and Gradient, are calculated from pre-stack angle gathers using Aki-Richards 2 term equation (Aki and Richards, 1980), an approximation of full Zoeppritz reflectivity equations (Hilterman, 2001). Intercept is the P-wave reflection coefficient at normal incidence of an event, while gradient represents regression of amplitude variations taken at different angles of incidence (Russell, 2002). AVO technique is rarely applied in shallow gas studies because of problems in obtaining sufficient angle coverage at shallow depths, however it can be used to check where the gas distribution on the seismic section and where the gas can migrate to the surface.

4. Results

Data availability and identified shallow gas features were compiled in Table 2.

Data availability	**BGR16-212**	**BGR16-256**	**BGR16-257**
MCS	yes	yes	yes
Parametric sediment profiler	yes	yes	no
Multibeam	no	yes	yes
Shallow gas observations			
Gas chimneys	yes	yes	-
Pockmarks	-	yes	yes
Shallow geology			
Holocene mud	yes	no	no

Table 2. Data availability and shallow gas features in 3 profiles: BGR16-212, BGR16-256 and BGR16-257.

4.1. Line BGR16 – 212

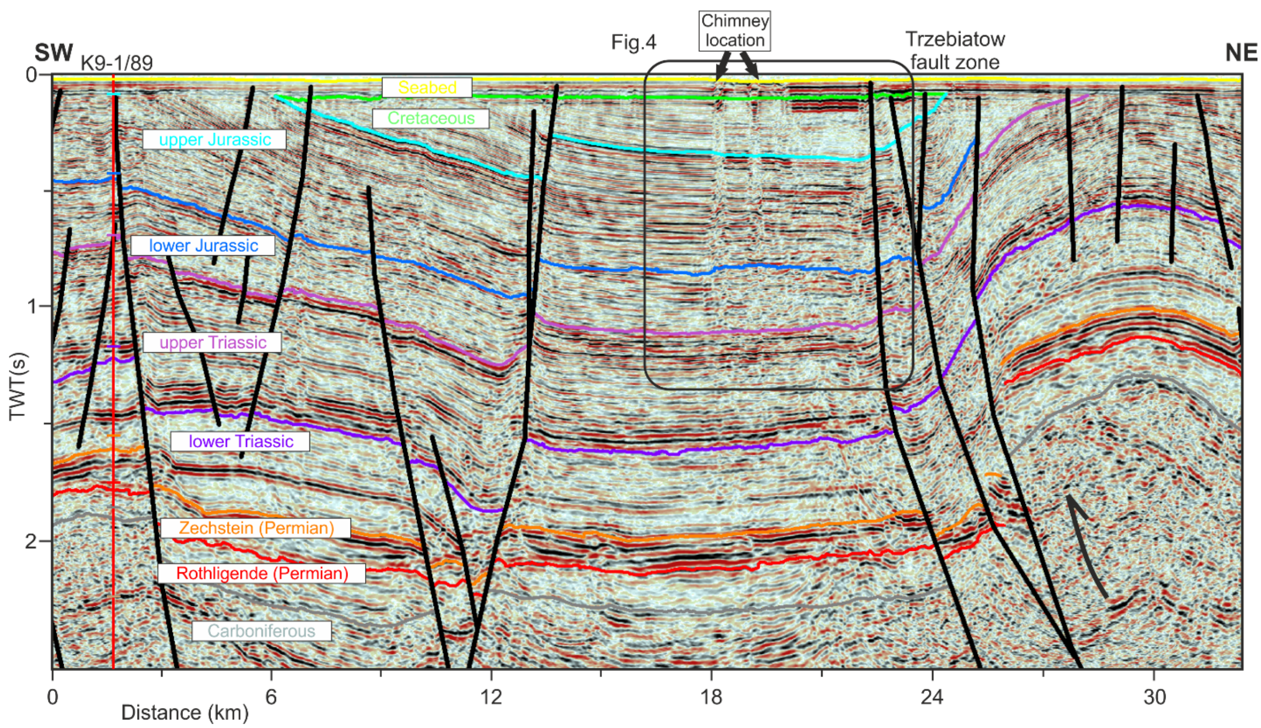

Figure 3. Part of the interpreted pre-stack time migrated seismic section along profile BGR16-212 across well K9-1/89, the Trzebiatów fault zone and the Gryfice block (see Figure 1 for the location of the seismic

profile and well). Two gas chimneys were identified near the eastern part of the Gryfice block, closed to the Trzebiatów fault zone. Rectangle marks the area displayed in Figure 4.

We start with the structural and stratigraphic interpretation of the seismic section BGR16-212 crossing important geological features such as Adler-Kamien and Trzebiatów faults zone (Figure 3). Interpretation was based on well K9-1/89 stratigraphy markers, unpublished well reports, regional cross sections and previous studies (both offshore and onshore) (Jaworowski et al., 2010; Pokorski, 2010; Krzywiec, 2006). Line BGR16-212 crosses an asymmetric fault-propagation fold and is accompanied by reverse Trzebiatów fault zone in the NE of the section (Figure 3). Due to the strong uplift of inversion anticlines, all Cretaceous and part of Late Mesozoic sediments were eroded. Toward SW of the section, there are few normal faults systems formed during syn-rift basin extensional period. Sediment thicknesses of Mesozoic remain stable in this area. Notice that the Cretaceous formation is significantly eroded due to strong uplift of inversion anticlines, only small amount of 100-300 ms of Upper Cretaceous sediment was left over in the Gryfice block (Figure 3). Two gas chimneys are identified in the section (Figure 4) together with the high amplitude reflections (bright spots) close to the Trzebiatów fault zone.

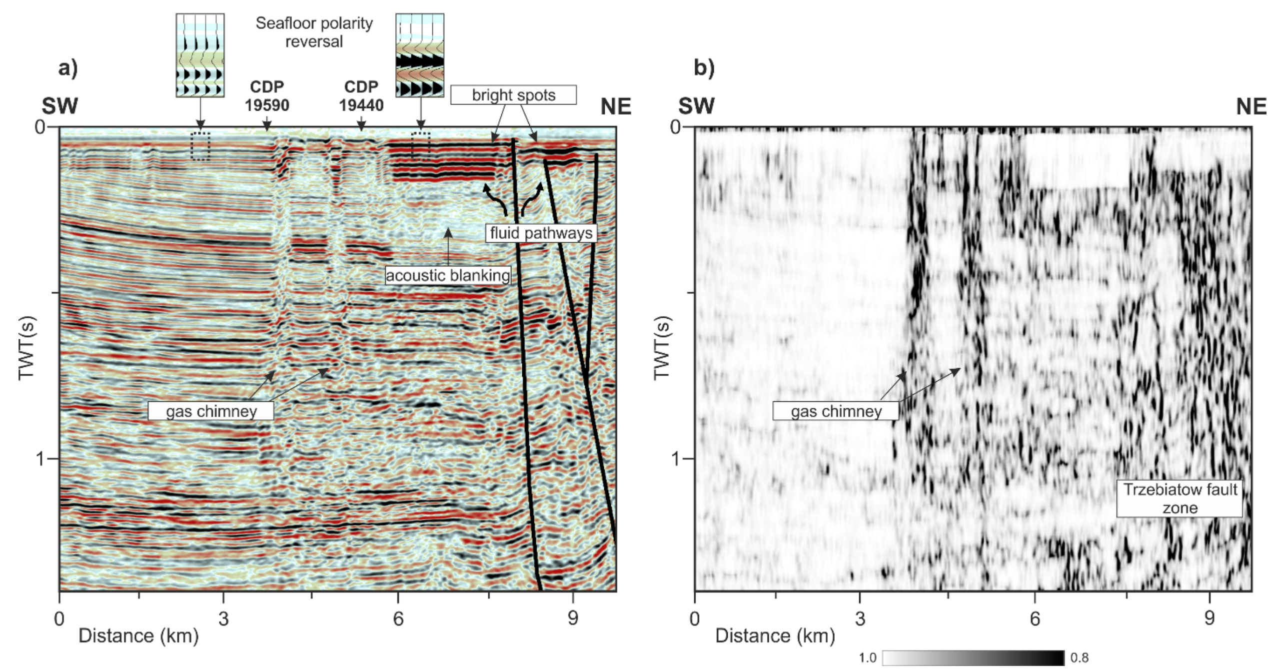

Figure 4. Part of the seismic section BGR16-212 (a) and its coherence attribute section (b). Evidence of shallow gas features is interpreted including gas chimneys, bright spots (enhanced reflection), acoustic blanking and seafloor polarity reversal.

Zoom in part of section BGR16-212 provides clearer image of the shallow gas features (Figure 4). Reflectivity of gas chimneys appears as a chaotic zone, with low trace-to-trace coherence and lower amplitudes as compared with adjacent sediments. Taking advantage of this behavior, the coherence seismic attribute was employed to help interpret free gas associated features (Figure 4b). Gas chimneys are more discriminated as high coherence values to continuous events. The Trzebiatów fault zone is also highlighted as noisy area due to discontinuous reflectivity at fault location. More importantly, low coherence zone of the gas columns is much reduced around interval of 1.1 to 1.2 s, which may suggest potential existence of a gas reservoir in the past at this interval.

Bright spots are identified on top of the Trzebiatów fault zone (Figure 4a), suggest a potential of free gas migration pathway through the faults to shallow sediments. Reflection of these bright spots shows as peak (positive amplitude), reverse of the seafloor reflection (Figure 4a). Bright spot areas are associated with the reverberations, as the consequence of strong impedance contrast between the layers of gas accumulated shallow sediments (Davy, 1992; Tóth et al., 2014). It is impossible to differentiate these reverberations with the main reflector due to very shallow water environment of the Baltic Sea (~30 ms in this area).

Apart from polarity reversal, bright spots and gas chimneys, acoustic blanking zone is identified below the bright spots and reverberations in the seismic section (Figure 4a). In this case, acoustic blanking happened below the bright spots, which indicates attenuation of seismic energy by the gas charged sediments.

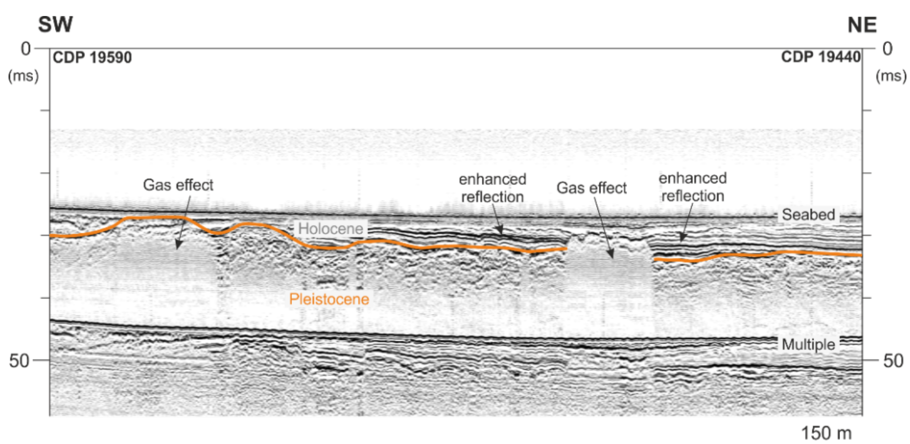

Figure 5. Hydro-acoustic data (parametric sediment profiler) from profile BGR16-212 between CDP 19440 to 19590, crossing gas chimneys identified in the MCS data. Boundary between Pleistocene and Holocene sediments (orange) is interpreted in this profile.

The gas chimneys identified in seismic data are also associated with the disturbances in amplitude pattern in the parametric sounding data (Figure 5). Gas chimneys are clearly marked within the Pleistocene sediments as non-reflective vertical zones. The width of the two zones identified along the profile is approximately 150 and 250 m, respectively. Chimneys/anomalous amplitude zones do not reach the sea bottom - the gas reaches the upper glacial till or is dispersed in the paleolakes' sediment layer. Close to the gas effect zones, some enhanced reflections are identified (Figure 5), which may prove that the gas is charged to Holocene sediments instead of leaking to the sea surface. However, such reflections may also result from the lithological variability (e.g. presence of organic layers, such as pit, gytta) or/and deposits structure (e.g., layering/stratification).

4.2. Line BGR16 – 256

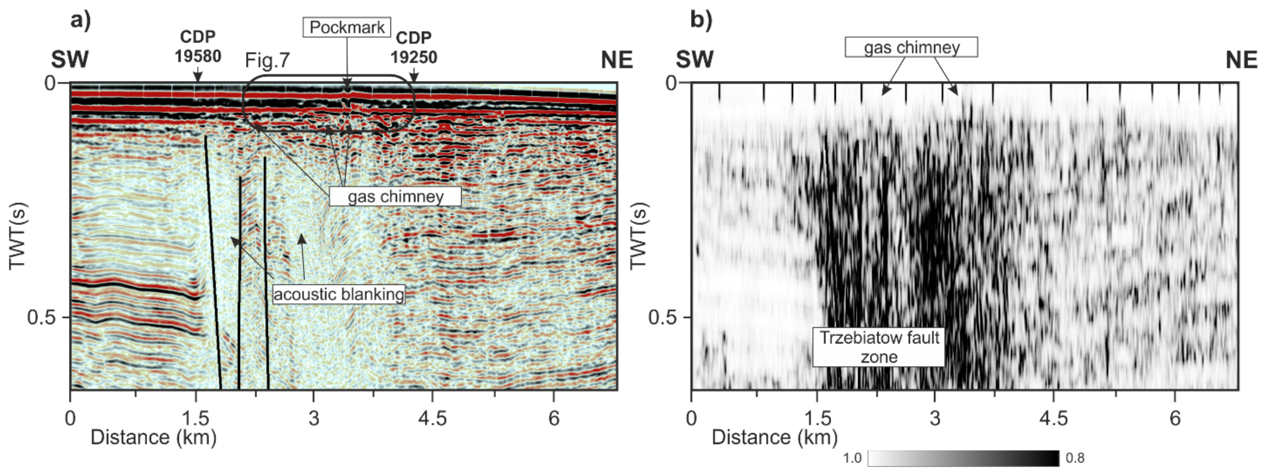

Figure 6. Part of the pre-stack time migrated seismic section along profile BGR16-256 and the corresponding coherence attribute section (see Figure 1 for the location of seismic profile). Evidence of shallow gas features is interpreted including gas chimneys, acoustic blanking and pockmarks.

Shallow gas expressions were also interpreted along profile BGR16-256 toward the northwest of the Trzebiatów fault zone. We identified gas chimneys, acoustic blanking and pockmarks in the seismic section (Figure 6). The columns of gas are much smaller than observed along line BGR16-212. They may only be recognized by little polarity changes close to the seafloor (Figure 7). The utility of the coherence attribute section is minimal in this case as locations of these gas columns are close to the complicated Trzebiatów fault zone. Acoustic blanking zones in this line appear at around 0.2 to 0.5 s joint with the fault zone (Figure 6). The coherence attribute shows a large low value zone which represents huge discontinuity zone due to faulting, fracturing and presumed free gas activities.

The analysis of the bathymetric data along lines BGR16-256 and BGR16-257 (seismic data from the latter were not interpreted as it follows the strike of the Trzebiatów fault) indicates that in some places the gas also reaches the seabed, creating small oval depressions (Figure 7). The asymmetric form recorded along line BGR16-256 is about 35 m in diameter and 60 cm deep (Figure 7a). Features identified along line BGR16-257 is smaller, approximately 25 m in diameter and only 20 cm deep (Figure 7b).

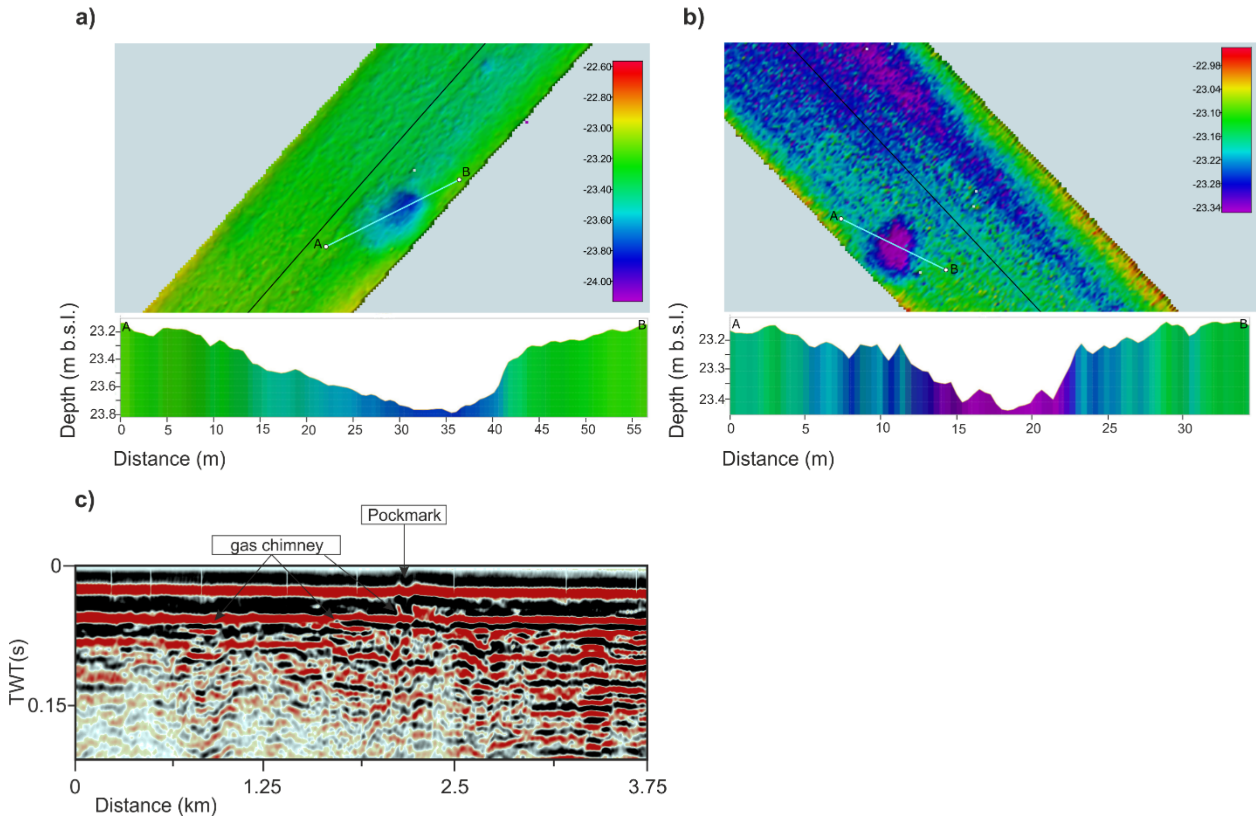

Figure 7. Seafloor topography build from multibeam data close to the pockmark identified along line BGR16-256 (a). Seafloor expressions of a pockmark identified at the strike profile (BGR16-257) (b). For position of these pockmarks, see Figure 1. (c) Part of the seismic section profile BGR16-256 at the identified pockmark location.

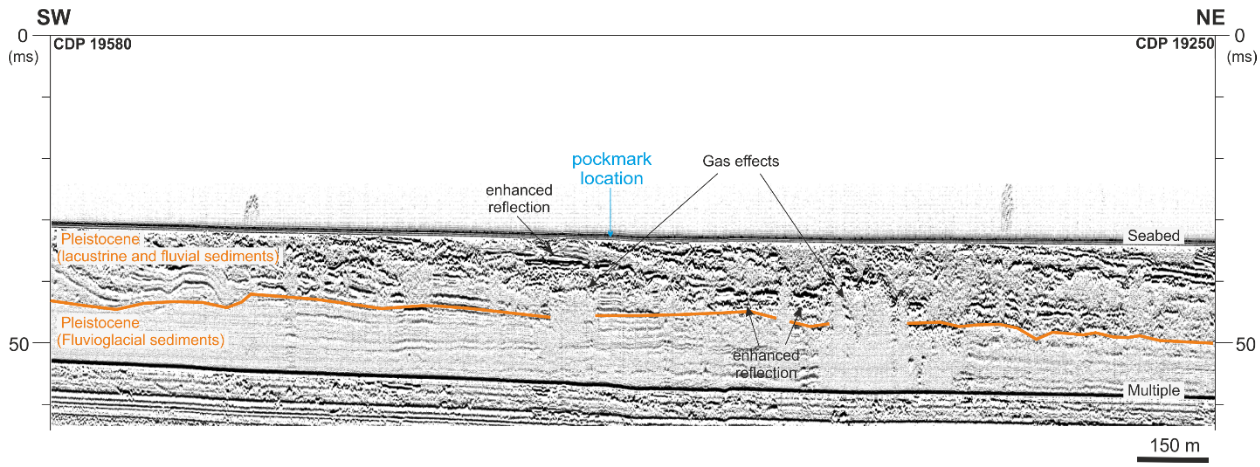

Figure 8. Hydro-acoustic data (parametric sediment profiler) from profile BGR16-256 between CDP 19250 and 19580, crossing the gas chimneys and pockmark in line BGR16-256. Boundary between 2 types of Pleistocene sediments (orange) is interpreted whereas Holocene mud sediment is absent in this profile. Note that the pockmark is not recognized in this hydro-acoustic data.

Gas chimneys are less pronounced in the parametric sediment profiler data (Figure 8) than in the line BGR16-212. It is possible that in an environment with a distinct predominance of non-cohesive deposits, represented here by river and lake sands and silty sands of MIS3, the gas is more easily dispersed inside the layers of these deposits. Anomalies caused by gas columns are still recognizable. Enhanced reflection zones, identified surrounding these anomalies probably indicate occurrence of more cohesive inter-layers, hardly permeable to gas. The structure of these layers is variable and locally the gas reaches sea surface forming small pockmarks (Figure 7). Toward SW part, the hydro-acoustic data become significantly lower quality (Figure 8). It can be also caused by shallow gas activity.

4.3. AVO analysis along line BGR16-212

In order to prove the existence of free gas remains in the potential reservoir and to discriminate fluid effect with normal background rock property, we performed AVO analysis. We followed a conventional workflow of AVO application. First, the CDP gathers are muted to remove traces beyond maximum incident angle of 45 degrees (angle mute). Signal-to-noise ratio is improved through super gather creation and residual move-out is eliminated through trim statics. AVO analysis is carried out at the presumed location of the potential gas accumulation within the Upper Triassic formation (root zone of gas chimneys identified along line BGR16-212, Figure 4). Target zone of AVO analysis is restricted at the interval of 100 ms (around 1.1 to 1.2 s TWT) and limited between the Trzebiatów Fault and a normal fault in the SW of the section. Figure 9 shows 3 angle gathers at selected locations surrounding the gas chimneys (CDP numbers 19420, 19640 and 19750) (see location of the CDP gathers in Figure 10). Notice that the three CDP gathers were chosen based on scanning through the whole NMO-corrected CDP gathers of line BGR16-212 as most representative CDP gathers exhibiting AVO effect at the interest interval.

The CDP gathers were corrected using processing velocity. Top horizon (red) is marked at ~1.11 s as a top of the reservoir. Bottom horizon (green) is marked at ~1.21 s as a presumed base of the reservoir (Figure 9). The top and base of the potential reservoir here was based on enhanced reflections visible in seismic section. They may not represent for true top and base of the gas deposit in the potential reservoir. The AVO Intercept and AVO Gradient were selected from the major trough and peak pair at 3 CDPs (19420, 19640 and 19750) (Figure 10). The amplitude variation clearly shows class 2 AVO which has small negative reflection coefficient at zero offset and amplitude increase with offset (Castagna and Swan, 1997) in 3 CDP gathers. This trend indicates presence of remnant free gas in the Upper Triassic reservoir rocks.

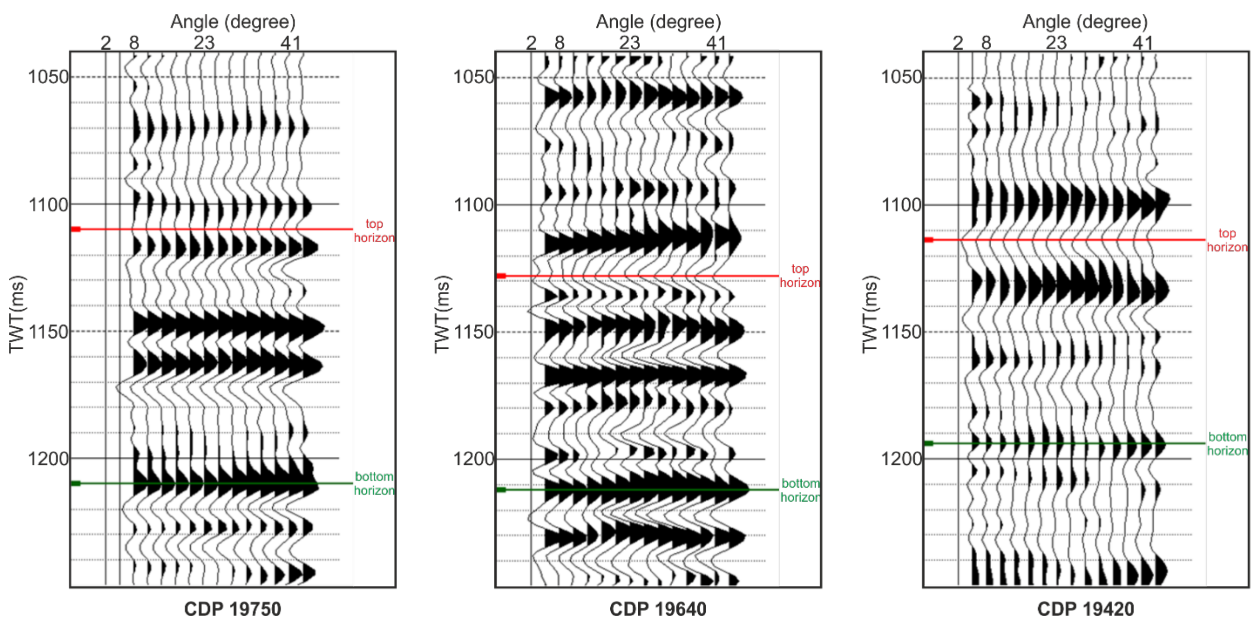

Figure 9. Angle gather extracted from profile BGR16-212, at CDP super gathers 19750, 19640 and 19420. Locations of the CDP points on stack section are shown in Figure 10. Top horizon (red) marks top of the potential reservoir, bottom horizon marks base of the potential reservoir. Normal move-out correction is applied using stacking velocity.

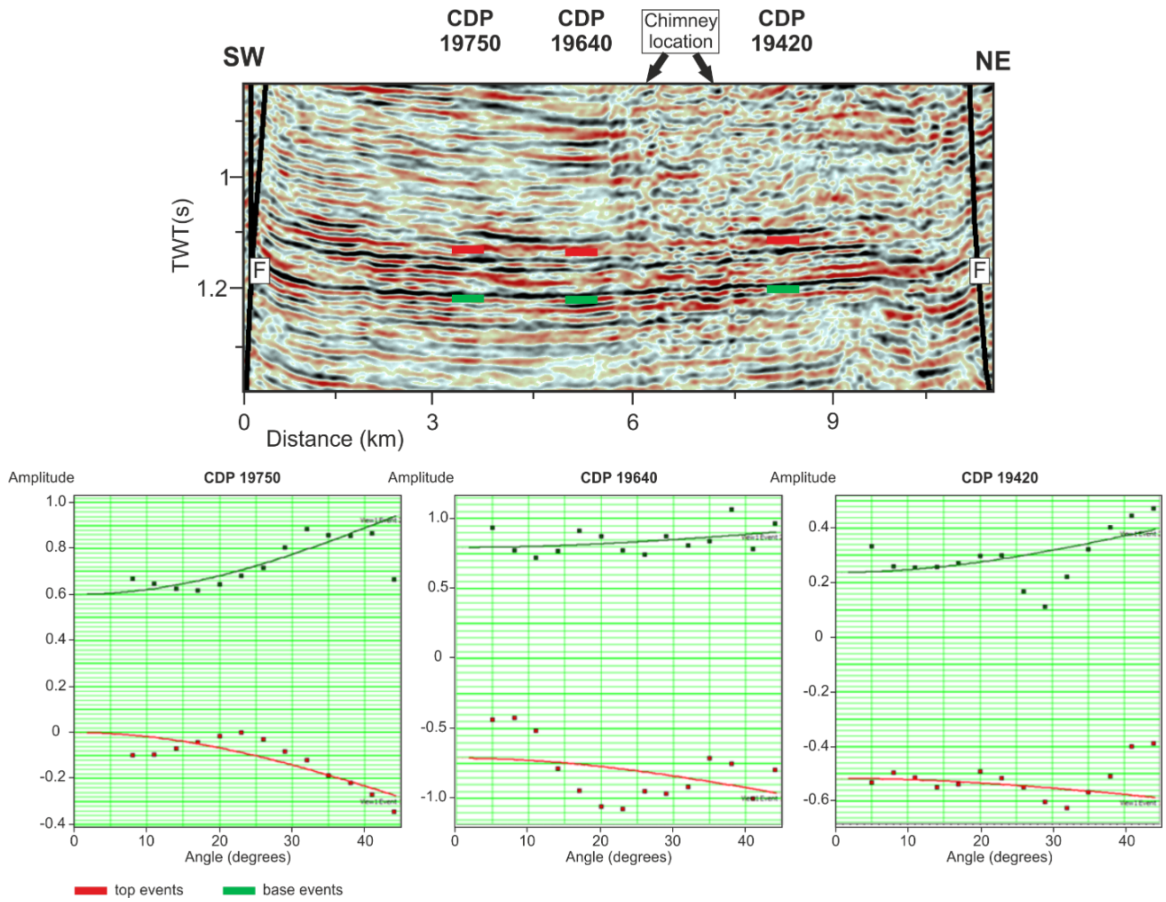

Figure 10. Gradient analysis of the angle gathers shown in Figure 9. Locations of the CDP gathers are chosen surrounding the chimneys' locations and at the potential reservoir interval (a). (b) Trough (red) and peak (green) seismic amplitudes are displayed with angle (offsets) at the depth of around 1.15 s TWT for CDP number 19420, 19640 and 19750.

Cross-plot of the derived AVO Intercept/Gradient is presented in Figure 11 to further investigate the type of AVO anomalies. The expected background trend is delineated as zone 1, while anomalous events were delineated as zone 2, consistent with class 2 AVO anomalies. Both zones were projected back onto the seismic section. AVO anomalies interpreted as free gas charged sediments (red color) are highlighted in the section (Figure 11). Majority of the free gas related anomalies are located within the predicted potential gas reservoir and along the gas chimneys' pathways.

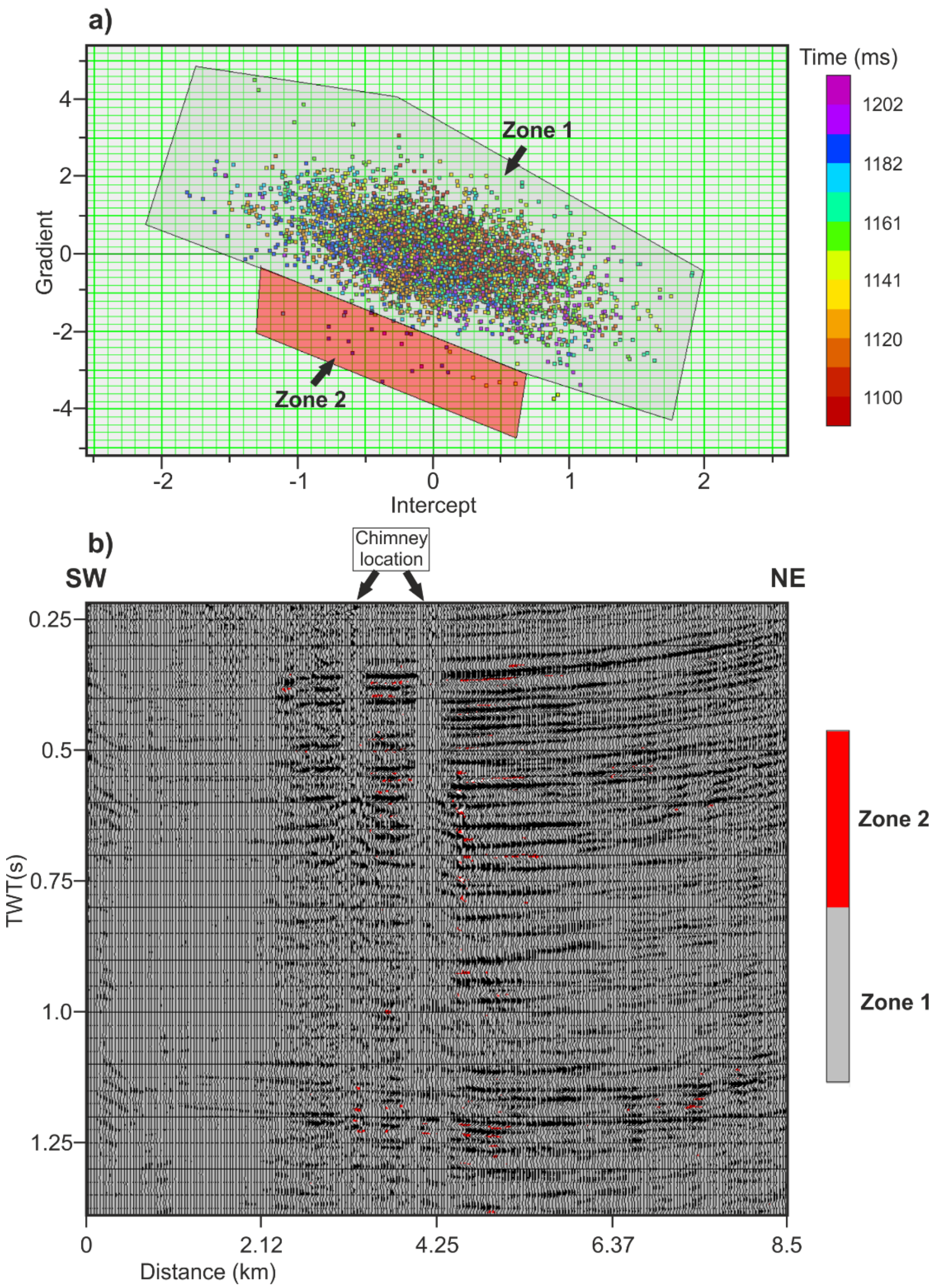

Figure 11. AVO Intercept/Gradient cross-plot and seismic amplitude and AVO anomaly section along part of line BGR16-212. (a) Cross-plot shows background trend (grey) (zone 1) and AVO anomaly (red) (zone 2). (b) Zone 1 and 2 mapped on seismic section close to the chimneys' location.

5. Discussion

5.1. Seismic and hydro-acoustic indicators of shallow gas

Evidence of the free gas in sediments of the Gryfice block are proved by indicative shallow gas features including gas chimneys, seafloor polarity reversal, bright spots, acoustic blanking and pockmarks. Two big gas chimneys interpreted along line BGR16-212 can be tracked down with support of seismic attributes to around 1.1 - 1.2 s TWT. This suggests rooting of these gas chimneys at Upper Triassic formation. The gas chimneys identified in line BGR16-256 (Figure 6) are less distinct and behave more as seepage style, which is "small and localized" (Schroot and Schuttenhelm, 2003). These small gas seepages possibly leak slowly to the surface through tiny holes or gaps caused by faults' activities. Such structures are visible closer to the Trzebiatów fault zone, indicating an escape path of the free gas from deeper successions to shallow sediments. The free gas possibly begins to migrate during the Late Cretaceous inversion period together with inverted activity of the Trzebiatów fault zone. Gas reaches also Pleistocene and Holocene deposits. Leaking of the gas associated with the pockmarks was registered close to lines BGR16-256/257 (no multibeam data available for line BGR16-212).

Apart from indicated gas features, velocity pull-down is a typical feature represented for free gas presence in sediments underneath seafloor. It happens because the compressional wave propagation velocity is decreased below the value for water saturated sediment, attenuation of acoustic waves propagating through gassy sediment and acoustic reflection and/or scattering are increased (Anderson and Bryant, 1990). Problem of imaging artifacts in form of pull-downs is contrasted with the pull-ups concept caused by high-velocity localized anomaly (e.g., till within tunnel valleys; Frahm et al., 2020). Structural image below the gas charged shallow sediments could be misinterpreted as localized syncline-like features. Some of these features are visible in the gas chimney area in line BGR16-212 (Figure 4), however the far- and near-offset stacks, as well as the general appearance of the reflectivity inside the chimney, suggest that it is not caused by dimming of the reflections due to the shallow gas anomaly only. What we observe in the seismic data is probably a combination of those two effects: shallow low-velocity anomaly and extensive fluid (gas) escape route.

Geochemical analysis also proves that the Trzebiatów fault zone is active in term of migration process and seepage of liquid and gaseous hydrocarbon (Jaworowski et al., 2010). The most liquid hydrocarbon seepage into bottom waters crosses the axial of the fault zone, while high methane concentration in water is observed in the southern part of the fault zone (Wagner, 2011). Migration of the gaseous and liquid hydrocarbons occurs despite the occurrence of sealing Zechstein salts. These geogenic substances can originate from the beneath Devonian, Carboniferous, Zechstein Main Dolomite source rock. Therefore, the Trzebiatów fault zone and western part of the Kolobrzeg Block represent a high geogenic pollution risk (Jaworowski et al., 2010).

Two anomalies at the gas chimneys' locations are clearly identified in the hydro-acoustic data along line BGR16-212 (Figure 5). They are characterized by small scattering points on top of the free gas and especially acoustic blanking behaviors below the gas charged layer. This acoustic blanking represents of low reflection and interruption image of the below sediment layer due to presence of free gas (Toth et al., 2014). It also appears that the gas columns did not reach the water bottom and stop within Holocene/Pleistocene sediments boundary. It is possible that after migrating from the below successions, the free gas did not escape through sea bed but might accumulate to very shallow sediments (Pleistocene – early Holocene). This hypothesis is further reinforced by the presence of bright spots close to the gas columns as well as polarity reversals of the seabed reflectors. Besides, in the seismic section, these high-amplitude reflectors cause heavy reverberations below the water bottom (Toth et al., 2014). Enhanced reflection in layer deposited within Holocene formation may indicate occurrence of more cohesive, hardly permeable to gas internal layers, where the gas accumulates. This parasound image is similar to gas accumulation structures in Holocene marine mud that were recorded in Bay of Aarhus (Jensen and Bennike, 2009), Bornholm Basin (Laier and Jensen, 2007; Toth et al., 2014) and other sedimentation basins of the Southern Baltic Sea (e.g., Jaśniewicz et al., 2019; Idczak, et al., 2020).

Gas effects are more obscure along line BGR16-256 (Figure 8), what most probably result from different lithological formations of Quaternary deposits in this area (Kramarska, 1998). 2 types of Pleistocene sediments can be differentiated by high amplitude, chaos reflection of lacustrine and fluvial origins sediments, compared to dim and flat reflection of fluvio-glacial origin sediments. Anomalies caused by gas activities can be identified by scattering points and blanking zones within the fluvio-glacial related sands and river and lake related fine-grained sands. These sands could possibly be potential deposits of the free gas in Pleistocene sediments. The pockmarks identified by multibeam data (Figure 7) and enhanced reflection features identified surrounding the gas effects illustrates simultaneous free gas accumulation and sea surface leakage.

The coherence seismic attribute, commonly used to detect discontinuities (faults, fractures), seems to be an effective tool to detect and differentiate free gas associated features from other seismic events in the section (Figure 4 and 6). Due to absorption and scattering of the seismic energy, chaotic behavior of seismic signal of the gas chimneys and acoustic blanking can be differentiated compared to continuous seismic events of adjacent areas within the section. Attribute section enabled to delineate the rooting point of the gas chimneys along line BGR16-212 (Figure 4). The attribute anomalies of the columns start from around 1.2 s TWT. It suggests an upward pathway for the free gas to migrate from Upper Triassic formation to shallow formations. The Trzebiatów fault zone appears as a mixture of coherence anomalies due to discontinuity of seismic events within a complex faults zone. For profile BGR16-256 (Figure 6), the anomalies caused by gas or faulting are difficult to be differentiated as location of small gas chimneys are too close to the Trzebiatów fault zone. However, this may prove that the gas migrates from much deeper to shallow sediments and then to surface through the faults system.

5.2. AVO attribute analysis

After interpreting the indicators of shallow gas in seismic section, a starting point of the gas chimneys in line BGR16-212 is recognized by the coherence seismic attributes. It reveals a possibility of a potential gas reservoir existence at around 1.1 to 1.2 s TWT, in the Upper Triassic formation, so there is a high chance there are still free gas remains in this interval. Due to limited of lithology information and lack of well data, to verify this hypothesis, AVO analysis was only used to detect the remnant of free gas in the potential reservoir.

Accumulation of gas in rocks causes decrease in velocity and density, as the results there will be decrease in acoustic impedance (AI) of the formation (Simm and Bacon, 2014). The angle gathers of line BGR16-212 shows the increase of amplitudes in far offsets which represents for the decrease of AI due to free gas presence (Figure 9). AVO class 2 anomalies from the angle gathers were identified by gradient analysis plots as near zero impedance contrast between charged gas sand and surrounding non-gas sand and shale (mudstones). The class 2 AVO illustrates the similar properties of mudstones and gas sands at the presumed reservoirs interval and nature of the sand is compacted and consolidated. This matches with lithology of the Triassic and Jurassic formations in the Gryfice block dominantly composing of interbedded sands and mudstones with very thin carbonate and evaporates layers (Figure 2). It might be concluded that the free gas could not be trapped permanently at the potential reservoirs due to homogenous of lithology between Mesozoic sediments and absence of good overlying seal.

Using the scatter plot of intercept against gradient (Figure 11a), the low negative gradient represents for contained gas rock (zone 2, red) was discriminated from the background trend of surrounding normal rock property (zone 1, grey). Therefore, samples with no AVO behavior in grey polygon (zone 1) could imply for this dominant interbedded sand and mudstones, while it is not possible to conclude precisely the type of sand that contains the free gas in red zone (zone 2) due to lack of nearby well data information. So in this study, we just call it contained gas sand. The free gas was exactly highlighted in the section, not only at the potential reservoir interval (1.1 – 1.2 s TWT) but also in whole Upper Triassic – Jurassic formation. Deposition of the free gas proves the hypothesis of origin of the gas chimneys and free gas “crept” to sediment layers throughout the gas chimneys migration pathways.

AVO technique was rarely applied in other fields than petroleum exploration, especially for shallow gas study. Kim et al., (2020) was possibly the only study that included AVO analysis for identifying free gas, helping to discriminate water contacts and bright events among the chaotic signals on the MCS data. Our study is probably the first one in which shallow gas can be linked with a potential deeper gas reservoir via AVO analysis.

5.3. Petroleum system and shallow gas expressions

Linking of shallow gas to near surface sediments was carried out in several investigations in nearby areas of the offshore West Pomerania, Southern Baltic Sea. Connections of geological settings of near surface sediments with distribution of methane were showed in Eckernförde Bay (Abegg and Anderson, 1997) and in Aarhus Bay (Jensen and Bennike, 2009). In Arkona Basin, characterization of acoustic turbidity caused by gas presence in near surface sediments were investigated by geochemical, core analysis and very high-resolution seismic profiles (Mathys et al. 2005, Thieben et al. 2006). In Bornholm Basin, Tóth et al. (2014) linked free shallow gas with organic-rich Holocene marine mud by velocity field analysis in MCS data. Further north and east of Gotland Basin, Schäfer et al. (2021) interpreted phase reversed seismic reflections beneath the Quaternary Klints Bank drumlin as evidence for hydrocarbon gas accumulation of thermogenic origin.

In this study, the shallow gas expressions from seismic and hydroacoustic data illustrate a leaking hydrocarbon play offshore West Pomerania. The free gas probably generates initially from the source rocks in Palaeozoic and Permian (Carboniferous mudstones and Main Dolomite Zechstein) (Kotarba et al., 2008; Karnkowski et al., 2010). The free gas then escapes to upper sediments through either the Trzebiatów fault zone or directly in areas where the Zechstein evaporates are thin or absent. This is more likely to happen when dominant sediments of Lower to Middle Triassic compose of just interbedded sand and mudstones layers. The Keuper (Middle - Upper Triassic) formation comprises of various types of potential reservoir rocks: fine grain sandstone and carbonate evaporates. In addition, the oil and gas prone window of the West Pomeranian falls into this period (Kosakowski et al., 2006; Karnkowski et al., 2010). Therefore, there are favorable conditions that the free gas can charge these rocks. Moreover, AVO analysis at the potential reservoir interval also proves the presence of remnant free gas in the Upper Triassic formation.

Based on the seismic interpretation, seismic attributes and lithology of the study area, there are two possible migration pathways of the free gas from the potential reservoir in the Upper Triassic sediments to seabed: through gas columns and through reactivated (during Late Cretaceous inversion) Trzebiatów fault zone. The first pathway can be explained that there is no good seal layer on top of the Upper Triassic, and free gas could creep through unconsolidated successions above to near surface. The second pathway can be due to strong reactivation of the existing listric faults, which created spaces for free gas to escape to the shallow sediments.

6. Conclusions

Shallow gas-escape related features were for the first time identified in the seismic and hydro-acoustic data in Pomeranian Bight, offshore western Poland. Various indicators of gas features including seismic chimneys, bright spots, acoustic blanking were interpreted on seismic sections with support of seismic attributes. In the area of dominance of near-bottom Quaternary sandy sediments the gas can leak to the seabed, forming small (25-35 m diameter) pockmarks. Those shallow gas features were linked with the activity of the Trzebiatów fault zone. We hypothesize that this fault zone is providing potential fluid pathways of the free gas from Carboniferous or Zechstein formation "kitchen" below to migrate to Upper Triassic sediments or directly to Quaternary shallow sediments. This hypothesis was also supported from geochemical data from some previous studies. Some evidences from the parametric sediment profiler data suggest that after migration, the free gas either accumulates in near surface Quaternary sediments or is leaking to the seafloor.

The use of AVO analysis technique in shallow gas investigation is highlighted in this study. AVO attributes analysis proves the presence of remnant free gas in the potential Upper Triassic reservoir (at ~1.15-1.2 s), which supports hypothesis of gas reservoir existence in the past and origin of free gas escape to shallow sediments.

Our study also proves the potential of hydrocarbon existence in the offshore West Pomerania, which is still considered as poor hydrocarbon exploration area in the Polish territorial waters.

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Data availability

Data are uploaded to PANGAEA database and will be released after acceptance of the manuscript. Web link and DOI will be updated during the revision process.

Author contribution statement

Quang Nguyen: Conceptualization, Methodology, Data Curation, Writing – Original Draft preparation, Software, Visualization. **Michal Malinowski**: Supervision, Project administration, Writing – Review & Editing. **Regina Kramarska** and **Dorota Kaulbarsz**: Data Curation, Writing – Original Draft preparation. **Leslaw Mil**: Data Curation. **Christian Hübscher**: Project administration, Funding acquisition, Writing – Review.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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