GAS ESCAPE FEATURES ON THE ROMANIAN BLACK SEA SHELF – EXAMPLES FROM 2D SEISMIC INTERPRETATION

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Abstract. Gas escape features are a common presence on any young sedimentary basins where large amounts of organic-rich sediments are deposited within a short time. The fast burial process conducts to maturation and carbonization of the sedimentary organic matter by bacterial and, later, by temperature transformations. The Black Sea is one such basin, where numerous shallow gas accumulation and gas escape features were observed and analyzed, ranging from gas hydrates, gas chimneys, flares, and mud volcanos. The study of such geological phenomena is important for identifying present seabed geohazards, and nonetheless for hydrocarbon exploration. Our study integrates newly acquired 2D high-resolution seismic lines, further used to correlate the gas escape features and their relationship with deep-seated faults, such as Peceneaga-Camena, and petroleum system of the Romanian Black Sea Shelf area. Our results show that in the studied area the gas escape features are confined into the Pliocene-Quaternary sequence, hence not related to Peceneaga-Camena Fault or to a deeper thermogenic petroleum system, and most probably, the gas is sourced from the shallower biogenic system.

Key words: gas, seismics, faults, geohazard, chaotic zone, petroleum system, Histria Basin

1. INTRODUCTION

Gas escape features are widespread in the present-day sedimentary basins, where thick and relatively recent sediments with a high content of organic matter are deposited (*e.g.*, Cartwright *et al.*, 2007; Cathles *et al.*, 2010). When fast burial rates are involved, this significant amount of organic matter becomes subject to bacteria decomposition and carbonization, that will conduct to gas (methane) generation until temperature-driven processes are taking over (*e.g.*, Tissot and Welte, 1984). The rise in temperature with depth, coeval with the sediments/organic matter burial can conduct to a thermogenic petroleum system. This will produce higher liquid and gaseous hydrocarbons, that will further migrate and accumulate at depth, or find their way to the seafloor (*e.g.*, Tissot and Welte, 1984).

The Western part of Black Sea Basin (the Romanian continental shelf and slope) is one of the world's best examples, where numerous shallow gas accumulations, gas escape features and even gas hydrates have been noticed and studied, from shelf to slope and to deepwater (see Dinu *et al.*, 2018 and references therein). Nowadays, in the Western Black Sea basin, significant volumes of both deep-thermogenic and shallow-biogenic gases are escaping continuously from the seabed into the water column (*e.g.*, Dinu *et al.*, 2018; Hillman *et al.*, 2018 Popescu *et al.*, 2007; Riboulot *et al.*, 2017). These processes are not peculiar to present times and they seem to occur over the geological times (*e.g.*,Popescu *et al.*, 2006, 2007; Zander *et al.*, 2017).

The seismic datasets, 2D or 3D, stand for a long time as a principal method to identify most of the shallow seabed fluid escape features. This type of subsurface imaging (usually, combined with other hydroacoustic methods), can identify in less compacted sediments from intermediate depths (200-1000 m below seabed) so-called "gas chimneys" and mud diapirs (Zander *et al.*, 2017), while, at the seabed level, can distinguish pockmarks, seepages/vents and mud volcanoes (Egorov *et al.*, 2011; Kruglyakova *et al.*, 2004).

Using this method, the best are identified gas hydrates, that form, in general, a "Bottom Simulating Reflector" or BSR, which represents a thermodynamic limit between solid and free gases that simulates the seafloor shape (*e.g.*, Popescu *et al.*, 2007, Dinu *et al.*, 2018).

The study of gas escape processes is important for delineating present geohazards and for geological hydrocarbon exploration. In terms of geohazards, seabed gas flow can translate into seabed instability - submarine landslides, sudden and high volume gas discharges into the water column, and even tsunamis, that can damage marine ecosystems, transportation, sub-sea installations and anthropic areas (*e.g.*, Camargo *et al.*, 2019, Oaie *et al.*, 2016 and others). In terms of hydrocarbon exploration, these phenomena can prove the existence of a hydrocarbon system when they are related to deep processes, but also can present real geohazards for exploration drilling when such processes are present in the seabed (*e.g.*, Wegner *et al.*, 2014 and references therein).

This short paper aims to illustrate some of the gas escape features identified on 2D high-resolution seismic lines, on the Romanian Black Sea shelf. The lines have been recorded in the area where no gas escape features have been previously described (Fig. 1). The area corresponds with the southern edge of Oligocene-Lower Miocene Histria Basin (Fig. 1) and, partly, overlaps the deep-seated Peceneaga-Camena Fault (PCF in Figs. 1 and 2) (Munteanu *et al.*, 2011), suggesting that this fault system might represent a migration pathway for deeper hydrocarbons (see also Popescu *et al.*, 2004).

These newly acquired high-resolution 2D seismic data, integrated within a regional database, will allow us to understand the correlation between distribution and depth of the gas escape features and their relationship with deep-seated faults like Peceneaga-Camena (Figs. 1 and 2), and existing petroleum system in the Romanian Black Sea shelf area (*e.g.*, Ionescu *et al.*, 2002; Moroșanu, 2012; Olaru *et al.*, 2018).

2. GEOLOGICAL SETTINGS

The Black Sea back-arc basin is one of the last active major depositional domains from the Neogene Paratethys Basin (Rögl, 1999), currently draining most of Europe's largest rivers: Danube, Dnieper, and Dniester (Popov *et al.*, 2006). The formation of the Black Sea Basin is related to the Early Cretaceous (Barremian-Aptian) extension, that occurred behind the Pontides magmatic arc, during the N-ward subduction of

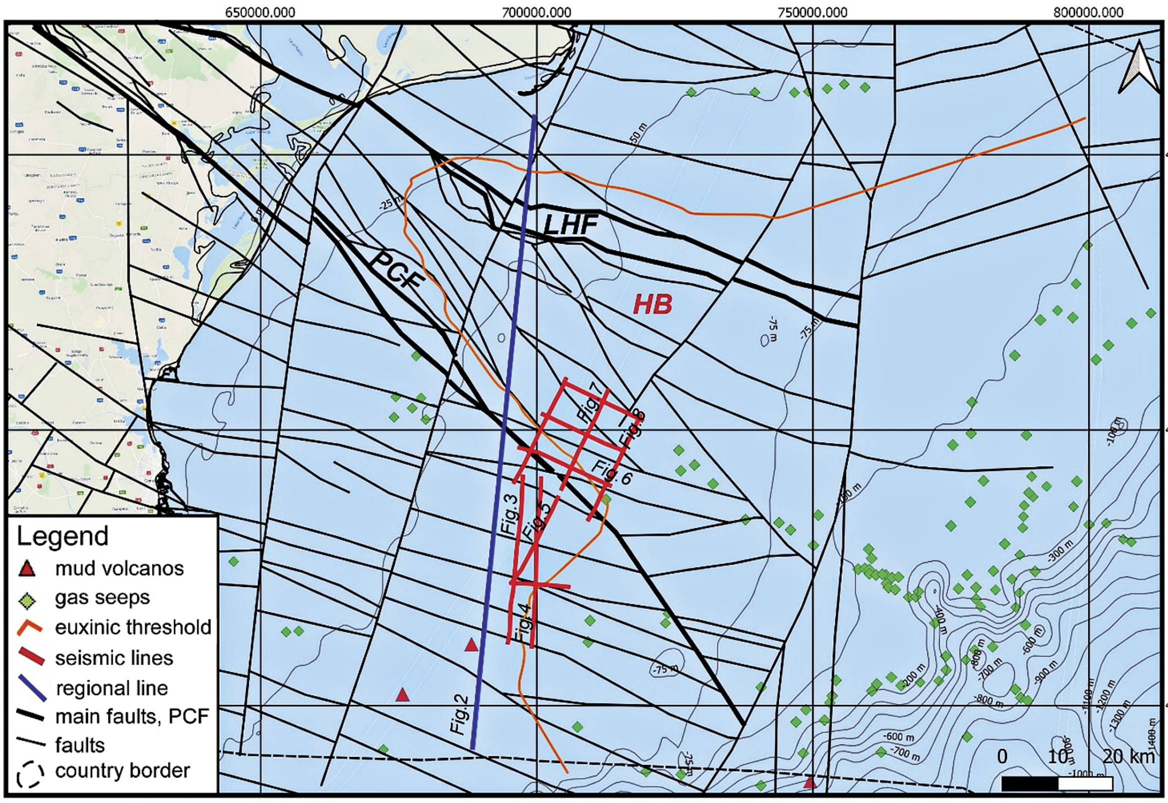

Fig. 1. Tectonic map of the Romanian Black Sea shelf compiled from the data of Dinu *et al.*, 2005; Moroșanu, 2012 and Munteanu *et al.*, 2011. Red lines - 2D seismic lines included in this paper. Blue line – localization of the regional cross-section, illustrating the Romanian Black Sea shelf architecture in Fig. 2 (after Dimitriu, 2019). Orange line – the Euxinic Edge illustrating the border of Histria Depression - HB (after Pătruț *et al.*, 1984 and Anton *et al.*, 2019). Green dots and red triangles - gas seeps and mud volcanoes as identified by Egorov *et al.*, 2011, Popescu *et al.*, 2007 and Kruglyakova *et al.*, 2004. PCF – Peceneaga-Camena Fault. LHF - Lebăda-Heracleea Fault.

Neo-Tethys Ocean (Görür,1988, Finetti *et al.*, 1988, Robinson *et al.*, 1996). The Western Black Sea (WBS) rifting and expansion continued during Late Cretaceous and ended in Middle Eocene. It is accepted that crustal spreading continued in the basin center, while former rift-shoulders evolved to passive margins (*e.g.*, Belousov *et al.*, 1988; Munteanu *et al.*,2011; Nikishin *et al.*, 2015). The extensional deformation conducted also to reactivation of former Cretaceous basins, such as Histria Basin (Tambrea *et al.,* 2002; Munteanu *et al.*, 2011). During the post-Middle Eocene, the collision of Taurides and Pontides blocks (*Okay et al., 1994*) reactivates former structures in a compressional style. The positive inversion created a coherent fold-and-trust belt, involving the Lebăda-Heracleea and Peceneaga-Camena Faults, which constituted the limits of the Histria Basin (Figs. 1 and 2, see also Munteanu *et al.*, 2011). The compression stage affected the WBS until the Middle Miocene times (Sarmatian *s.l.* - regional stage of Eastern Paratethyan domain), followed by a rapid sinking of the central part of the basin which triggered a large-scale shelf deposition (Dinu *et al.*, 2005).

3. MATERIAL AND METHODS

A number of ten 2D high-resolution profiles have been acquired by GeoEcoMar during the 2016 cruise on the Romanian Black Sea shelf. The seismic acquisition system is a modern Sercel Seal 428, towed by the R/V Mare Nigrum. Seismic source was provided by 2 Sercel GI-355 air guns of 5917 cm^3. The data QC was performed using the eSQC-Pro Marine software, in order to certify good data quality acquisition. The profiles are between 10 and 20 km long, with 2s TWT recorded signal, sufficient to cover most of the Miocene-Quaternary sequence and, locally, the Paleogene ones (see next chapter).

Standard processing sequence has been applied for all the lines, and with a few isolated artifacts, the data quality is good. The procedure consisted of correction of the navigation data, resample to 2 ms, band pass filter, despike, predictive deconvolution, swell noise attenuation, NMO + Sort to CMP, Mute + Full offset stack, Migration, K filter, amplitude Q compensation and AGC.

The interpretation of resulted 2D seismic lines was realized in an integrated manner with previously published seismic data sets. Main horizons were identified and calibrated by using nearby hydrocarbon exploration wells (see Fig.2 - Munteanu *et al.*, 2011) The data integration and subsequent interpretation were realized using IHS Kingdom Suite seismic interpretation software.

4. SEISMIC INTERPRETATION

4.1. GEOLOGY

A number of four main horizons have been identified, correlated, and interpreted on the acquired seismic data sets: Base Oligocene, Base Middle Miocene, Top Intra-Miocene and Top Pontian. The age of these horizons was defined by correlation with the main stratigraphic markers from Delfin and Tândală exploration wells (Munteanu *et al.*, 2011). Most of the interpreted horizons, excepting Top Pontian, represent basin-wide unconformities with clear erosional origin as evidenced on the seismic lines.

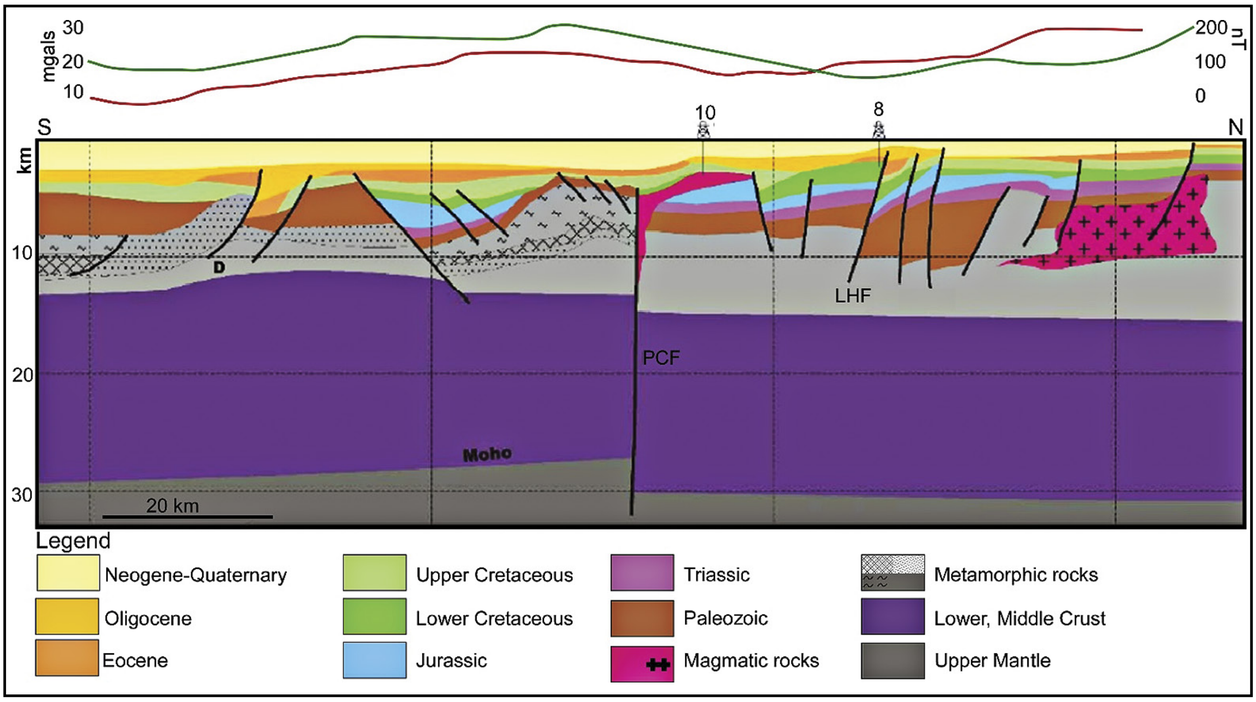

Fig. 2. Regional geological cross-section illustrating the crustal architecture of the Romanian shelf (redrawn after Dimitriu, 2019). Free Air Gravity anomaly - green line; Magnetic anomaly - red line; PCF - Peceneaga-Camena Fault.

The Pre-Oligocene horizon could be interpreted only in three sections (Figs. 3-5) located south of PCF and outside of Euxinic Edge, which represents the Histria Basin – HB border (Fig.1). In the HB, the Quaternary-Pliocene deposits are getting thicker and bury deeper than the Oligocene or older deposits (compare Figs. 5 with 6). The geometry of this surface is marked by large-scale erosional canyons, which cut down into the older sediments, removing more than 500 m in thickness (0.5s TWT in Figs. 3-5). On the Z1P1A line, the entire Eocene and, partially, Upper Cretaceous deposits were removed by erosion (left part of Fig. 3).

Base Middle Miocene represents another unconformity with large erosional features - canyons and channels that create a paleorelief of almost 0.4s TWT in height (Fig. 4) and erode most of the Oligocene-Lower Miocene deposits. This newer unconformity reworks the previous one formed at the Base Oligocene (Fig. 3), therefore its age is debatable, most of the previous publications considering it as Lower Miocene in age, since Oligocene sediments are covered directly by Middle Miocene (Badenian and Sarmatian) series (Dinu *et al.*, 2005 and references therein). Several newer publications consider the age of this surface as of late Lower Miocene-early Middle Miocene (Olaru *et al., 2018*). Other interpretations infer that the surface was created during late Lower Miocene times, and re-worked during Lower Badenian and Sarmatian times (e.g., Munteanu *et al., 2018*).

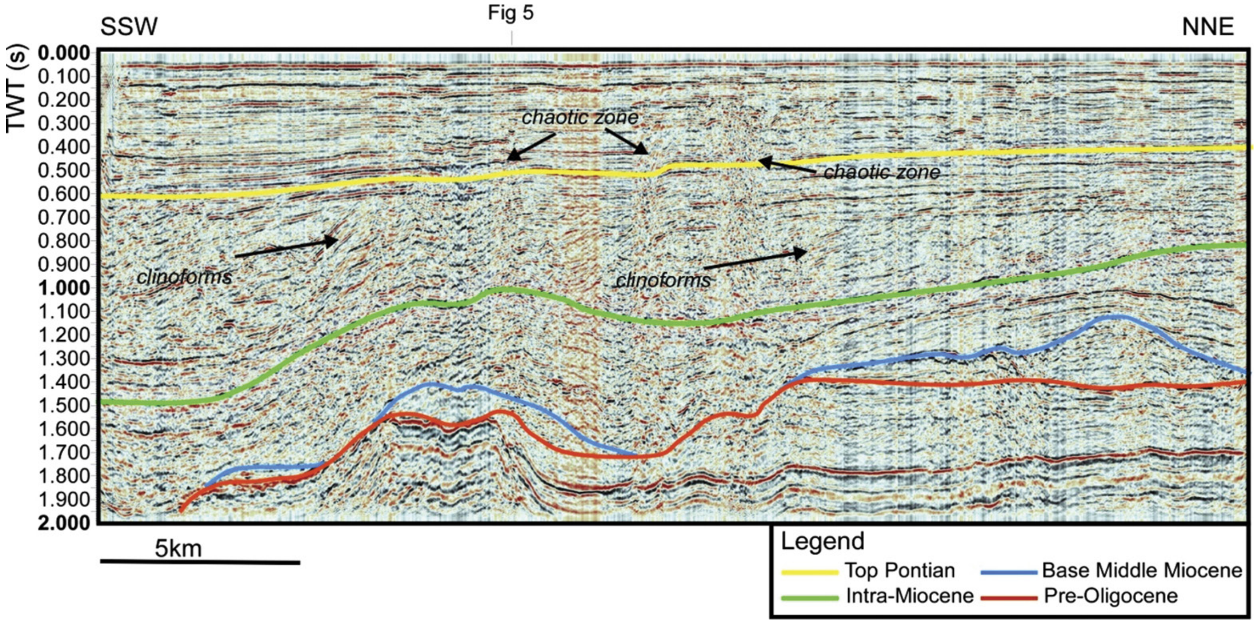

Fig. 3. Interpreted seismic line **Z1P1A**. For localization see Fig. 1. The legend is similar for all the other interpreted lines.

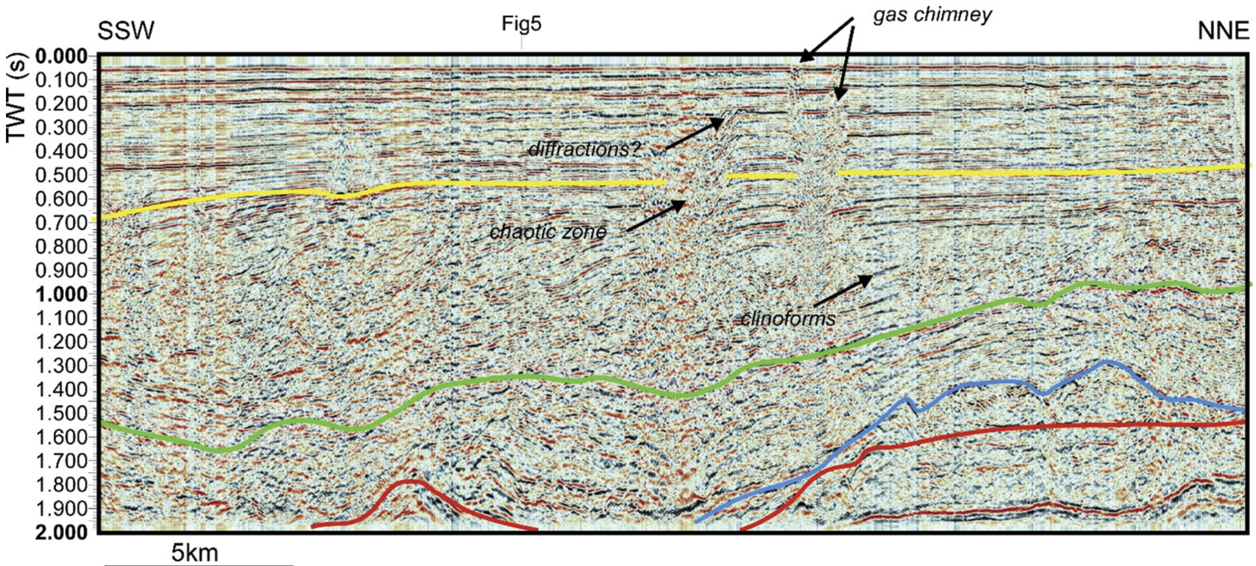

Fig. 4. Interpreted seismic line **Z1P1B**. For localization see Fig. 1. Note the presence of gas chimneys.

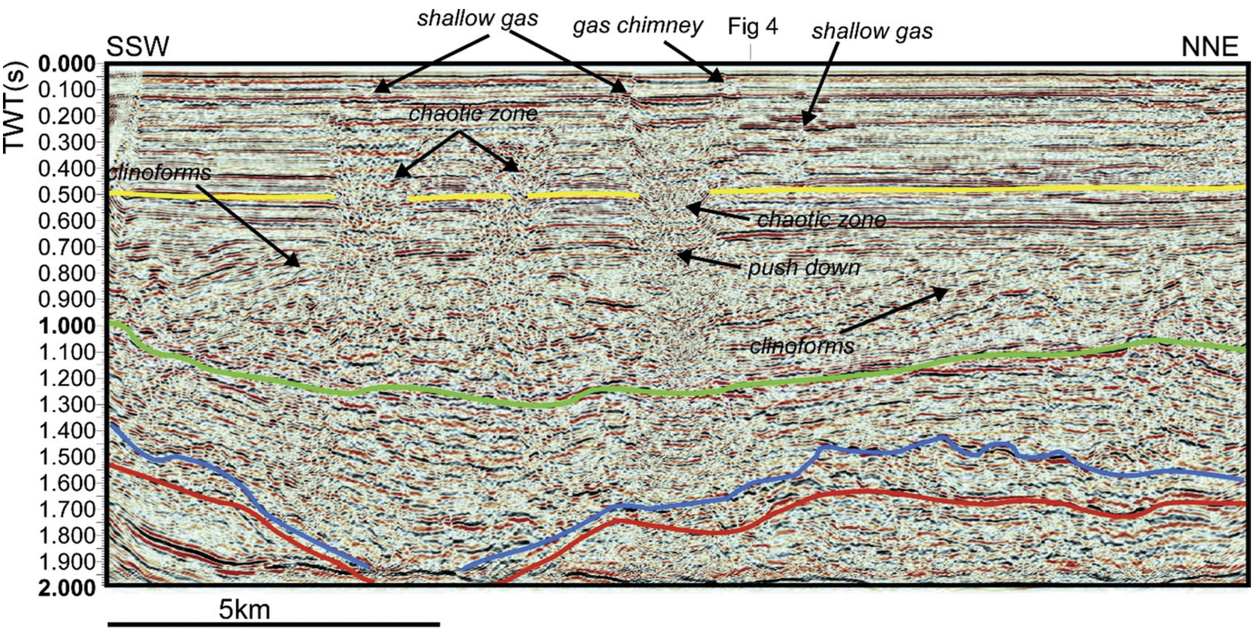

Fig. 5. Interpreted seismic line **Z1P7**. For localization see Fig. 1. Note the presence of the chaotic zones and push down effects related to gas presence/escape.

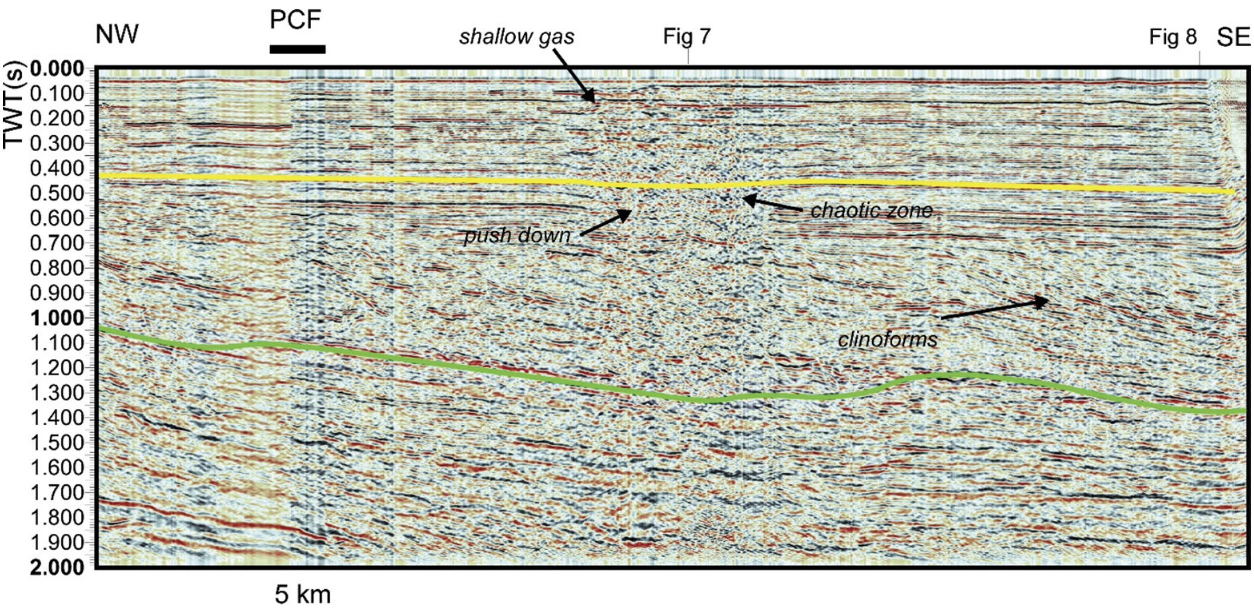

Fig. 6. Interpreted seismic line **X2P2**, over the southern border of Histria Basin. For localization see Fig. 1. We illustrate the zone where PCF should be located at deeper levels.

Intra-Miocene unconformity is the first reflector (surface) that can be traced across all seismic lines. This surface corresponds with a sequence boundary 3 (SB3 in Munteanu *et al.*, 2012), as evidenced by reflector configurations - truncations below this surface and downlaps on top of it. Also, this surface marks a clear change in seismic character with large-scale Upper Miocene-Pliocene clinoforms recognized in all the lines (Figs. 3-8).

Top Pontian represents a large conformable reflector and can be correlated across all lines. The surface is cut by several canyons (Figs. 7 and 8) of most probably Dacian age and is coeval with a large sea-level drop that affected the Romanian Black Sea shelf (Konerding *et al.*, 2010). In some cases, the surface is affected by several chaotic zones (Figs. 4 and 5), however, this does not hamper the interpretation, since the surface is conformable and most of the time flat with a gentle S-ward dipping (Fig. 3).

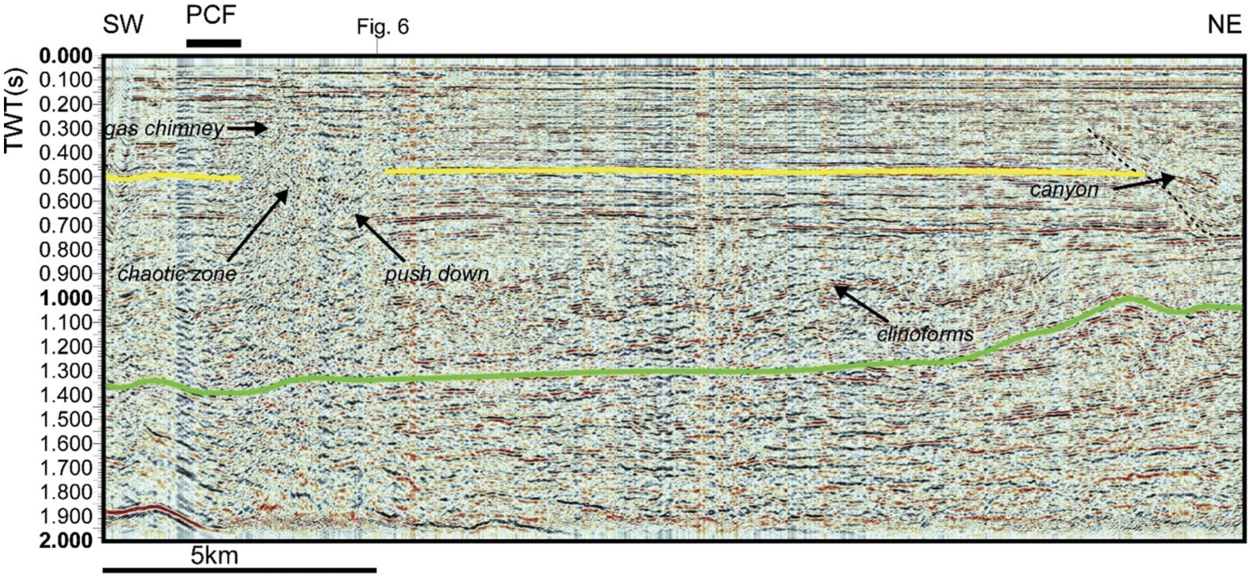

Fig. 7. Interpreted seismic line **Z2P5**. For location see Fig. 3. The line crosses the southern border of Histria Basin. The southern part of the line crosses the inferred deep-seated PCF. Note that there is no evidence of the fault crossing young sediments.

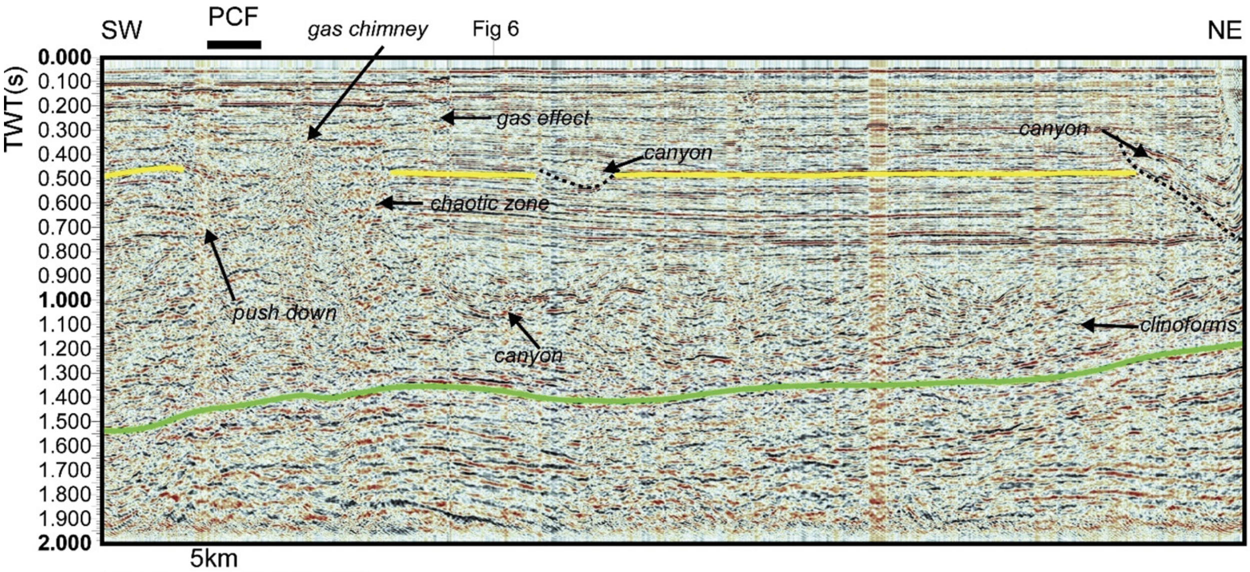

Fig. 8. Interpreted seismic line **Z2P4**. For localization see Fig. 1. Note the large canyon on the NE of the line, which cuts deep into Pontian and Dacian strata.

4.2. GAS ESCAPE FEATURES

The interpretation revealed across all seismic lines, narrow, vertical zones of chaotic reflectors, that usually affects an interval below the seabed of approx. 1s (~1km) in thickness (Fig. 7). Most of the affected deposits are the Quaternary-Pliocene sediments, while those older than Miocene seem to be intact (Figs. 3-8).

Associated with these chaotic zones one can notice push-down effects, generated by low velocity due to gas presence. In most cases, these effects can be noticed below the Top Pontian surface, with the exception of lines from Figs. 4 and 5, where the push-down effects start above this surface, at approx. 0.3-0.4s TWT (Figs. 3 and 4).

Since all these chaotic vertical zones are combined with push-down seismic anomalies, it becomes clear that they represent gas escape features or gas chimneys. In the vicinity of these zones can be interpreted several reflectors with very high amplitudes and reverse polarity, which usually indicates gas accumulations (Fig. 5).

5. DISCUSSIONS AND CONCLUSIONS

On the shelf, the highest concentration of gas seeps has been encountered as pockmarks above the margins of filled channels, as was previously noticed by Popescu *et al.*, 2007. Our data indicate that the gas escape features are also concentrated at the SW edge of the Histria Basin, the so-called Euxinic threshold (Fig. 9). Most of the gas escape features develop within Quaternary-Pliocene deposits, with only one gas chimney that seems to affect Lower Miocene deposits, although one can interpret this as an artifact due to shallow gas presence. Except for this particular chimney, it can be assumed that there is no evidence for deeper gas sources. Moreover, deposits older than Miocene are not affected by any gas escape features, while current data do not favour the assumption that the possible deeper one can be linked to Peceneaga-Camena Fault system. In addition, as demonstrated by Hippolyte, 2002 and Munteanu *et al.*, 2011 the last deformation recorded on this fault is Late Eocene in age, the fault being sealed by pre-Oligocene series (see Fig. 2).

The existing petroleum system, either the shallow-biogenic or deep-thermogenic, are assumed as the source for gases. The biogenic gas from the Quaternary-Pliocene series was proved by the existence of the biogenic gas fields like Ana and Doina on the Romanian Black Sea shelf (Duley and Fogg, 2009). The large Pliocene progradation related to rapid basin subsidence and filling might have trapped a large amount of biogenic gas, which, due to some subsequent geological processes, has been released. A second possible source for the gas might have come from Oligocene-Miocene petroleum system which charged oil and gas fields from the northern edge of Histria Basin, such as Lebăda, Sinoe, *etc*. (Figs. 1 and 9). However, in order to discriminate between these three possible sources, a geochemical analysis or petroleum biomarker analysis of the gas seeps is required. The thermogenic origin of the gases might be a possible explanation for the lack of oil and gas accumulations at the southern edge of Histria Basin and the presence of a large number of gas seeps in this area. Nevertheless, our study shows that the gas escape features are constrained within the Pliocene-Quaternary deposits, without influence from deeper, Miocene, and older strata, hence a shallow, Pliocene gas source is the most probable.

6. ACKOWLEDGEMENTS

We are obliged for the useful pieces of advice and suggestions of the reviewers: Prof. Corneliu Dinu, Dr. Dorina Țambrea, Dr. Marius Tiliță and Dr. Silviu Rădan. The research was financially supported within the PN 16 45 03 01 (EUXINUS) project, funded by the Romanian Ministry of Education and Research.

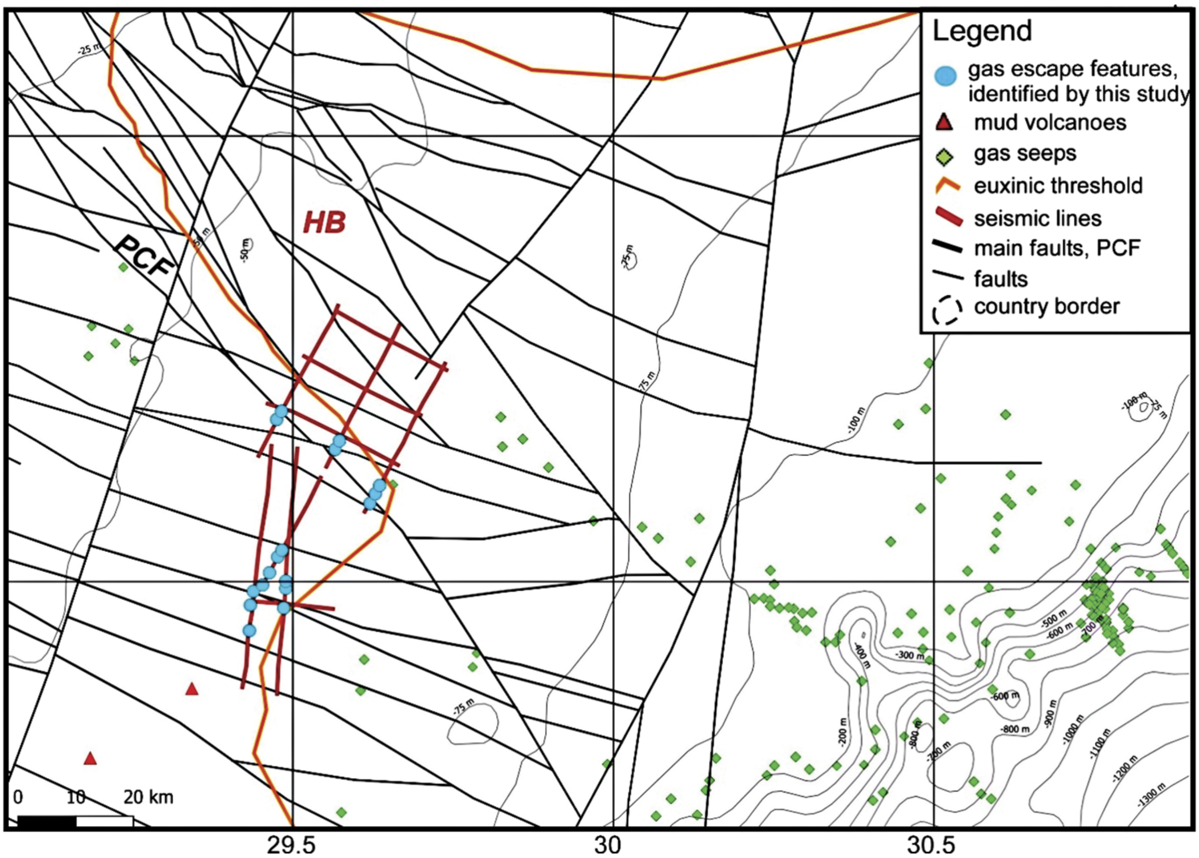

Fig. 9. Detailed map illustrating the gas escape features identified on the Romanian Black Sea Shelf, including those identified in this study and highlighted by blue dots. The rest of the legend is similar to that used for Fig. 1.

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