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STATE-OF-THE-ART 3D ACQUISITION AND IMAGING IN ULTRA-SHALLOW WATER IN THE NORTHWESTERN PART OF THE BLACK SEA

(Представлено членом редакційної колегії д-ром геол. наук, доц. О. В. Шабатурою)

Background. *The paper discusses the acquisition and imaging (PSDM+FWI) of 3D seismic data in the ultra-shallow waters of the Black Sea's northwestern shelf, focusing on the Dolfin Inner shelf license areas. Despite depths ranging from 14m to 40m, an efficient acquisition setup has been chosen to navigate seafloor obstacles.*

Methods. *GeoStreamer data has allowed more advanced imaging options. Access to separated wavefield components has permitted us to include advanced processing technologies. The data underwent advanced processing, including 3D wavefield separation, deghosting, demultiple, and machine learning-guided denoising.*

Results. *Results demonstrate the final migration velocity model's (with FWI) ability to capture high and low velocity contrasts critical for depth imaging. Separated wavefield imaging (SWIM) enhances imaging of the seafloor providing a very good match with bathymetry data. SWIM also allows acquiring high-resolution images of the shallow water area, which opens up the possibility of using this data for wind farm siting and hydrogen exploration.*

Conclusions. *Comparing 2D and 3D seismic data emphasizes the latter's superior quality, crucial for evaluating the Dolfin Inner shelf area's hydrocarbon potential. Next study will focus on the exploration in the Outer Shelf and adjacent deepwater domains, highlighting the Black Sea's Ukrainian waters as a promising frontier for oil and gas exploration. The acquired 3D seismic data plays a pivotal role in advancing this exploration, contributing valuable insights in a cost-effective manner.*

Keywords: *acquisition, depth imaging, ultra-shallow water, FWI, SWIM, PSDM, Black Sea, Machine learning.*

Background

The northwestern shelf of the Black Sea mega-basin is a gas producer no. 1 within the Southern petroleum province of Ukraine and still offers great exploration opportunities in largely unexplored acreage. Many large structural and potential stratigraphic hydrocarbon trapping features were identified by a regional 2D survey. The area depicts a promising frontier for 3D seismic exploration, holding the potential to significantly contribute to the country's future energy security. In 2021, Naftogaz of Ukraine contracted PGS to acquire 5000 km^2 of high-quality multi-sensor seismic data (Fig. 1) in the inner shelf area of the Dolfin license.

Despite the area's ultra-shallow water depth which varies from 14 m to 40 m, an efficient acquisition set-up with 8 km long streamers towed 112.5 m apart utilizing triple sources had been selected. In addition to the already shallow water depth, a high-resolution bathymetry study conducted prior to the streamer operations uncovered various obstacles on the seafloor. To mitigate the risk of hitting the ground or one of those obstacles, the streamers had to be towed at a depth between 8 m and 10 m which is significantly shallower than the usual 25 m.

As the first depth imaging project in the area, the data was processed using a state-of-the-art broadband flow, comprising of techniques such as 3D wavefield separation, 3D deghosting, 3D demultiple, 4D regularization, velocity model building incorporating full waveform inversion and reflection tomography followed by VTI Kirchhoff depth migration and post-processing. Separated wavefield imaging (Whitmore et al., 2010) provided an accurate image the water bottom while a machine learning guided denoise (Klochikhina et al., 2020) was applied to the migrated image to further enhance the final product.

The results show how an efficient 3D acquisition and state-of-the-art imaging can provide cost-effective and high-quality data to accelerate exploration in a frontier basin.

Geological Setting. The geology of the NW Black Sea was revealed thanks to more than 100 deep wells and a rather dense 2D seismic lines grid (Stovba et al., 2023). The depth of the wells varies from 2000 to 4600 m (Tauvers et al., 2022). The sediments covering the NW Black Sea are represented by terrigenous and carbonate formations of Triassic to Neogene sequences with thickness up to 9 km in total. The productive horizons are located in Upper Cretaceous and Tertiary reservoir rocks. A major feature is the Karkinit Trough, an extensive Early Cretaceous rift basin filled with Cretaceous to Quaternary post rift sediments. The newly acquired 3D dataset plays an important role to understand the integral geological image of the region and to identify new hydrocarbon prospects.

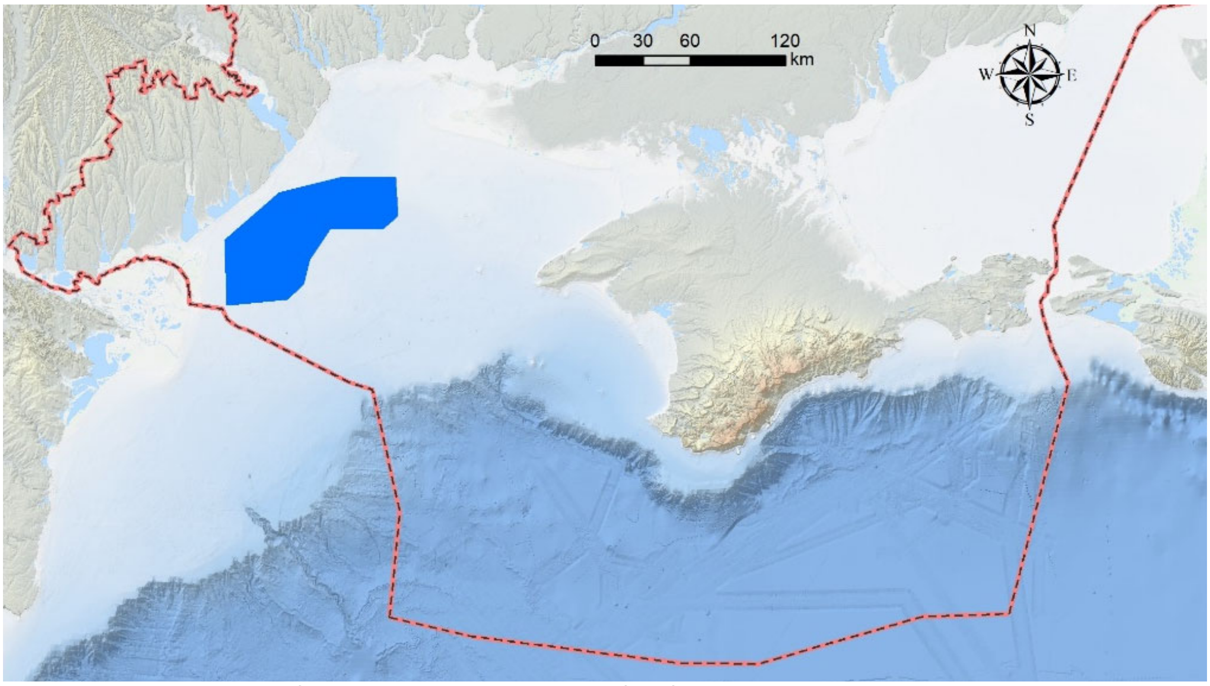

Fig. 1. Location of the survey area. The Inner shelf Dolfin license sits in the northwestern corner of the Black Sea, offshore Ukraine

The area of interest covered with newly acquired 3D seismic data is represented by two thrusted slabs (pre-Cenomanian inverted normal faults with strike-slip component) located north to the front of the Golitsyn-Sassyk main thrust developed during the main Maikop inversion and further series of the Styrian tectonic phases. Two types of the basement occur there – first one with the AR-PR_2 true basement of the East European Craton with Lower-Middle PZ acoustically transparent metasedimentary cover and the Vilkovo composite mini-basin surrounded by horsts made by the Cadomian basement. The AOI is well correlated with the Dobrogea foredeep with producing oil fields onshore.

Methods

Multisensor GeoStreamer data (Carlson et al., 2007; Lu et al., 2015) has allowed more advanced imaging options. The multisensor data, with full-frequency coverage, provides clearer reservoir details. Access to separated wavefield components has permitted us to include advanced processing technologies, such as Separated Wavefield Imaging (SWIM), Full Waveform Inversion (FWI).

GeoStreamer mitigates the effect of the receiver ghost reflections from the highly reflective sea surface. Higher-signal-to-noise ratio (SNR) than hydrophone-only streamers for all survey conditions are achieved by towing the streamers at a safe operational depth in ultra-shallow waters, without compromising the bandwidth. Another benefit is the longer operating weather windows due to low-noise deep towing. Collocated pressure and particle velocity sensor provide direct complementary measurements and therefore yield separated wavefields which are free of artifacts associated with local variations in sea-surface height or receiver depth. Shallow seismic images have substantially fewer artifacts, and shallow geohazards can be detected with far greater confidence and resolution with SWIM. High-fidelity AVO / AVA pre-stack gathers are optimal for quantitative interpretation and subsurface characterization.

Collocated groups of hydrophone pressure sensors and vertical velocity sensors record the continuous interference between the wavefield scattered upwards from the geology in the subsurface and the downgoing wavefield that carries the imprint of the reflecting sea surface, which is different for every shot. This downgoing wavefield is called the receiver ghost wavefield (Fig. 2**)**.

Wavefield separation is a critical step in broadband seismic imaging workflows applied to multisensor streamer and node seismic data. The pressure and velocity sensors record each upgoing seismic event with equal polarity, while the time-delayed downgoing seismic event is measured with opposite polarity (Fig. 3).

All events associated with sea-surface ghost reflections can be isolated and removed for traditional high-resolution imaging and subsurface characterization. Alternatively, separated data can be used for SWIM imaging to improve the resolution of the shallow subsurface where traditional imaging solutions fail, in particular in shallow waters due to limitation in near angle illumination.

Operationally, multisensor streamers are less noisy as they permit deep towing with a shallower front end to reduce tension and enable very wide streamer spreads. The upgoing wavefield has a rich low-frequency signal, courtesy of the deep towing, and also a rich high-frequency signal; Primary reflection signal is not affected by sea-surface variations.

The acquired data was processed using a state-of-the-art depth imaging flow (Fig. 4). 3D wavefield separation (Carlson et al., 2007), which outputs the upgoing pressure wavefield, was followed by 3D deghosting to compensate for the amplitude and phase effects of the source ghost, therefore enhancing the bandwidth of the data. 3D shot-to-shot designature was designed to convert the far-field signatures into a zero-phase wavelet, honouring the varying conditions in which each shot was fired and correcting for the directivity of the source.

The ultra-shallow water depths found in the Inner Dolfin area requires modern demultiple techniques to successfully enhance the signal-to-noise ratio of the data. The demultiple sequence comprised of adaptive subtraction of a 3D wavefield extrapolation multiple model to target free-surface short-period multiples followed by adaptive subtraction of a muted convolutional 3D SRME model to target long-period multiples. The sequence was complemented with parabolic Radon demultiple to further clean the data discriminating primaries and multiples based on velocity.

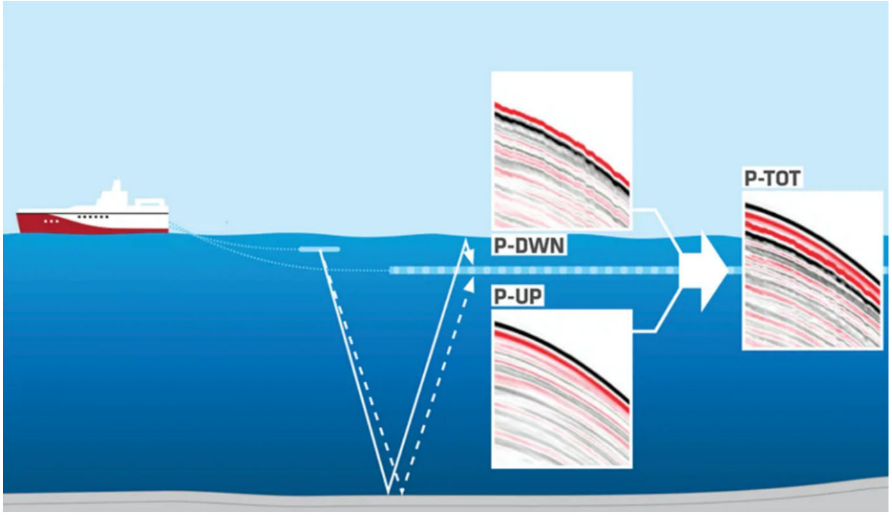

Fig. 2. Schematic illustration of the continuous interference between the up-going and time-delayed down-going wavefields recorded by hydrophone-only streamers. Wavefield separation of multisensor streamer (GeoStreamer) data accurately recovers the P-UP and P-DWN wavefields

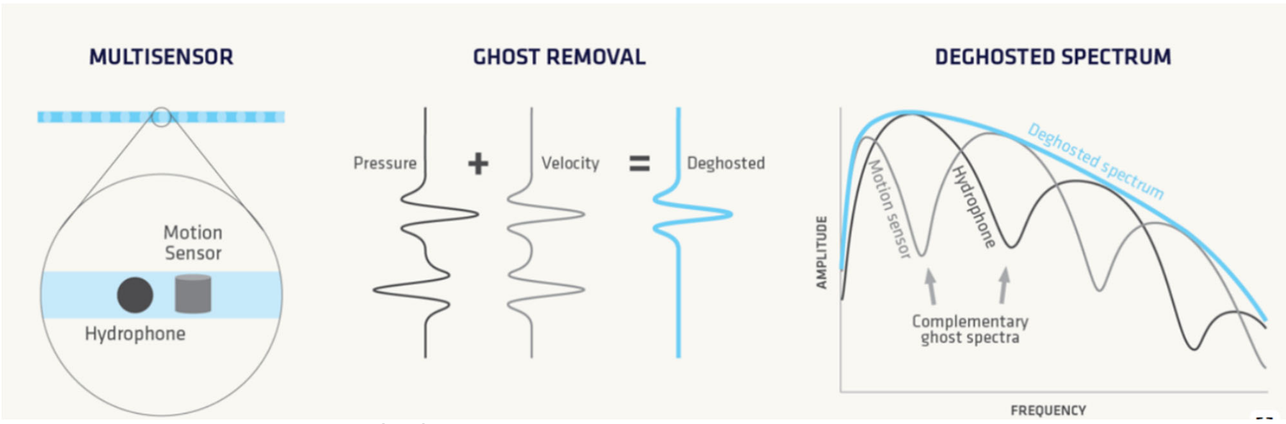

Fig. 3. Multisensor GeoStreamer has both pressure and particle velocity sensors collocated in the streamer body. Two signals are recorded and using a processing step called wavefield separation two complementary data volumes are created: an up-going pressure wavefield and a down-going pressure wavefield. These wavefields are used in complementary ways for various subsurface imaging and characterization pursuits

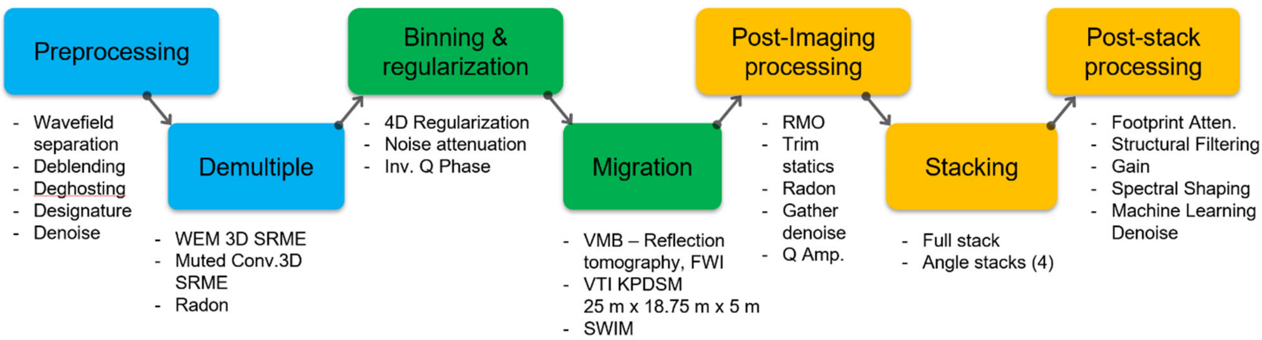

Fig. 4. High-level state-of-the-art broadband depth imaging flow

The velocity model building flow consisted of building an initial velocity model from a smooth manually picked time velocity field which was updated by a 12 Hz Full Waveform Inversion (FWI) interleaved with several reflection tomography passes. FWI provided complex velocity updates in the overburden while tomography handled the target section and below. FWI (Yang et al., 2020, 2021) delivers high-resolution models of subsurface properties by iteratively reducing the misfit between recorded and synthetic shot gathers.

The FWI solution uses both diving waves (wavefronts continuously refracted upwards through the earth) and reflected waves to update the velocity model. The use of reflection information relaxes the traditional dependence of FWI upon very long offset acquisition for deeper velocity updates. Thanks to advanced inversion kernels, the background velocity model can be separated from the reflectivity information, thereby avoiding crosstalk artifacts in the output velocity model.

The final velocity model was used in Kirchhoff pre-stack depth migration (KPSDM) and Separated Wavefield Imaging (SWIM) to obtain a high-quality image of the subsurface with a correctly positioned water bottom that tied well to the high-resolution bathymetry. After post-processing of migrated gathers and stacks, machine learning imaging denoise (Klochikhina et al., 2020) was utilized to further enhance the final product, which targets migration swings and general residual random noise. The process improves event continuity and signal-to-noise ratio which leads to a cleaner and better interpretable product.

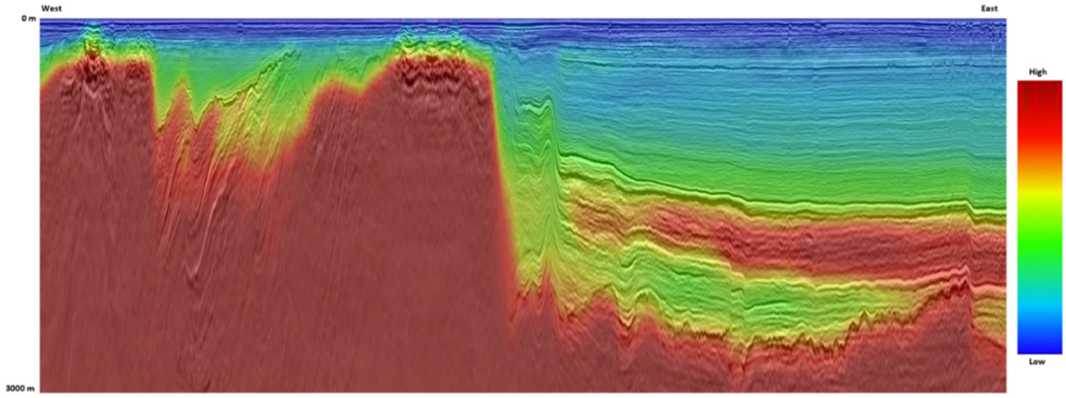

Fig. 5. Migration velocity model overlaid onto final stack. Large velocity contrasts are present over the seismic section, from the uplifted basement of high velocity in the west to the low-velocity shallow channel systems and gas pockets in the east. The velocity model is overall very conformable with the geology

Results

The geology consists of both low and high velocity contrasts, from channel systems and gas pockets, but also uplifted basement close to the sea floor. An accurate velocity field capturing these velocity contrasts is essential for successful depth imaging. Figure 5 shows the final migration velocity model overlaid onto a stack. To the west, velocities up to 3000 m/s can be observed as shallow as 200 m below the sea floor. To the east, on the contrary, low-velocity features can be observed, some very locally, most likely from shallow gas and channel systems. In overall, the final velocity model is capturing the velocity variations of the subsurface, critical for a good final image.

In ultra-shallow waters, near surface imaging with primaries can suffer from the lack of near-offsets when using efficient acquisition configurations. This is evident from the final stack in Fig. 6a, where the water bottom cannot be successfully interpreted and shows a significant timing difference with the overlaid water bottom from the high-resolution bathymetry study. Imaging with multiples, achievable with separated wavefield imaging (SWIM) can overcome the challenges from lack of near-offsets as each receiver is used as a virtual source, reducing the effective near-offset gap to the distance between each receiver. Fig. 6b shows the final stack after merging images from primaries and multiples. The overlaid water bottom from the high-resolution bathymetry study shows how the SWIM image accurately represents the water bottom, also capturing small scale details that can be observed from the bathymetry data.

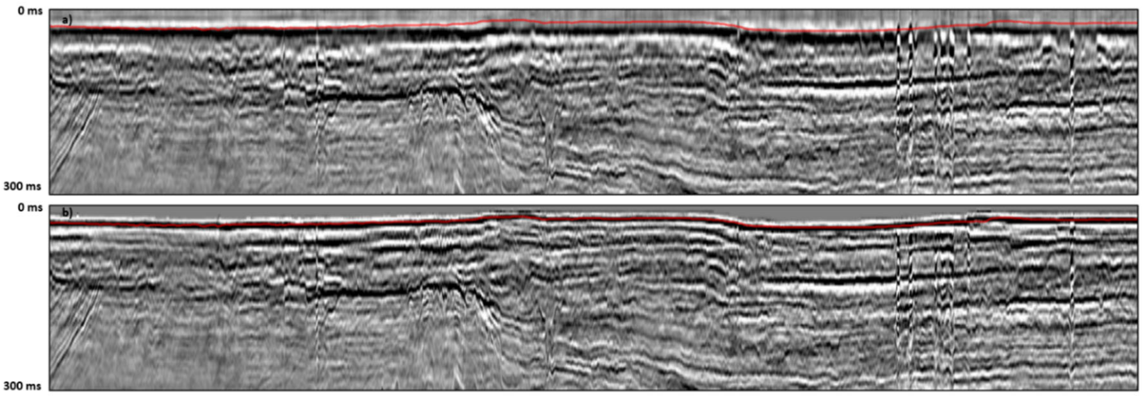

Fig. 6. Final KPSDM stack (a) and final KPSDM stack with SWIM imaging in shallow section (b). The SWIM imaging helps to improve the shallow imaging, especially evident from the good match with the bathymetry data (red line overlaid). An increase in acoustic impedance is shown as a black event (peak)

Several seismic 2D lines have been acquired in the past over the Dolfin area. Although 2D seismic serves as a good foundation to develop understanding of the geology, the limitations are well known. The final 3D data is compared to a 2D line in Fig. 7. Although there are significant processing differences between the two data sets, the major geological boundaries can be tracked in both. The 3D data set shows overall superior data quality, especially evident in the deeper section, where there are large differences in imaging and multiple attenuation.

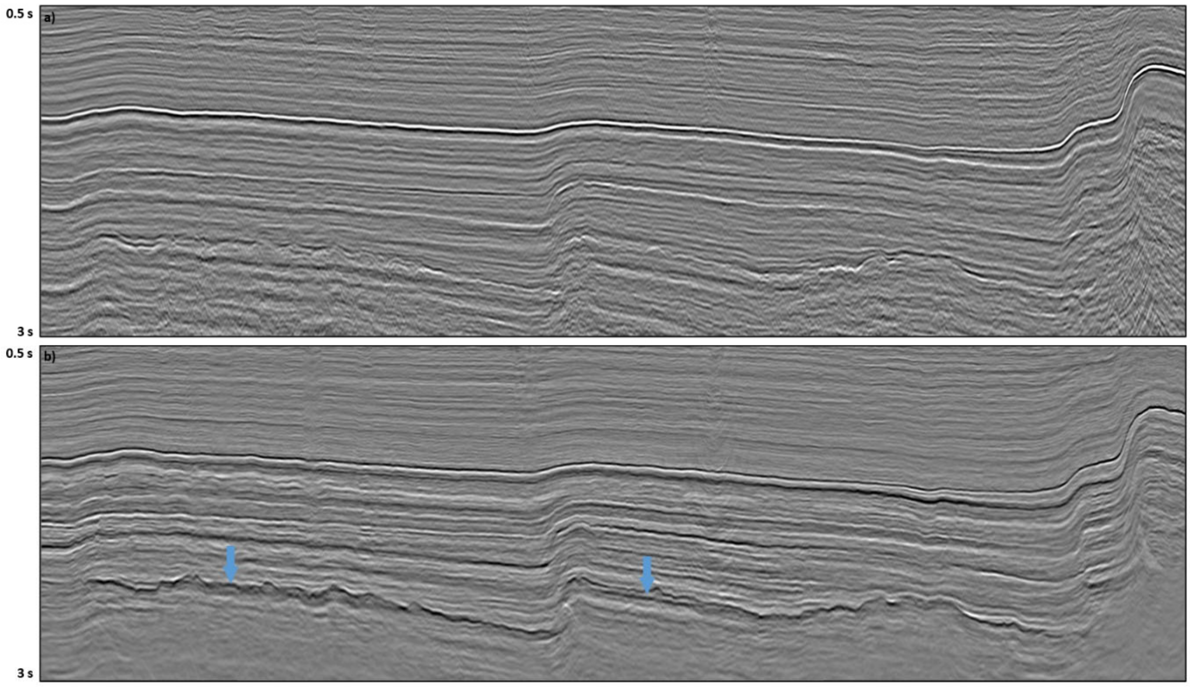

Fig. 7. Comparison between 2D (a) and 3D seismic data (b) of the target section over the Inner Dolfin area. The two are comparable when considering at the main geological boundaries, but the 3D data shows overall better imaging. An increase in acoustic impedance is shown as a black event (peak)

Discussion and conclusions

The Black Sea's Ukrainian waters stand as a promising frontier for future oil and gas exploration. The efficient acquisition and imaging of 3D seismic data over the Inner Dolfin area has provided a new data set to further develop and evaluate the prospectivity in the area. Utilizing SWIM, we were able to provide a high-resolution image of the shallow section which opens the option to also use the data set for wind farm site evaluation (Oukili et al., 2022) and hydrogen exploration. The next exploration stage is to acquire the same quality 3D seismic data over the Outer Shelf and adjacent deepwater domain bordering with Domino and Sakarya gas discoveries in Romanian and Turkish waters respectively.

Authors' contribution: Andrii Tyshchenko – writing, investigation, methodology, formal analysis, conceptualization, data curation, supervision; Andrii Vyzhva – investigation, visualization, data curation, formal analysis, supervision; Leonid Melnyk – supervision, validation, conceptualization, formal analysis; Jonas Fagerli Tegnander – investigation, writing, visualization, data curation; Lars-Erik Kittell – investigation, methodology, data curation; Kristian Svarva Helgebostad – investigation, visualization, data curation.

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СУЧАСНА СЕЙСМІЧНА 3D-ЗЙОМКА Й ОБРОБЛЕННЯ ДАНИХ НА НАДМАЛИХ ГЛИБИНАХ У ПІВНІЧНО-ЗАХІДНІЙ ЧАСТИНІ ЧОРНОГО МОРЯ

В с т у п . ***Розглянуто проведення сучасної 3D-сейсморозвідки та її оброблення (PSDM+FWI) на надмалих глибинах на ділянках внутрішнього шельфу Дельфін північно-західної частини Чорного моря. Незважаючи на глибини від 14 м до 40 м, було обрано ефективну систему збирання даних, що дало змогу оминати перешкоди на морському дні.***

М е т о д и . ***Технологія GeoStreamer допомогла отримати більше можливостей для оброблення сейсмічних даних. Відокремлені компоненти хвильового поля дали змогу застосувати передові технології оброблення даних. Одержані дані було опрацьовано сучасними алгоритмами часового та глибинного оброблення, включно із 3D-розділенням хвильових полів, дехостингом, послабленням кратних хвиль і шумів за допомогою машинного навчання.***

Р е з у л ь т а т и . ***Продемонстровано здатність фінальної глибинної швидкісної моделі міграції (FWI) фіксувати високошвидкісні та низькошвидкісні контрасти, що критично важливо для глибинної міграції. Зображення розділеного хвильового поля (SWIM) поліпшило візуалізацію морського дна, забезпечуючи відповідність батиметричним даним. Використовуючи SWIM, стало можливим отримати зображення мілководної ділянки з високою роздільною здатністю, що відкриває можливість використання цих даних для оцінювання місця розташування вітроелектростанцій і розвідки водню.***

В и с н о в к и . ***Порівняння сейсмічних 2D- і 3D-даних вказує на вищу якість останніх, що має вирішальне значення для оцінювання вуглеводневого потенціалу ділянки внутрішнього шельфу Дельфін. Наступне дослідження буде зосереджене на розвідці зовнішнього шельфу та прилеглих глибоководних ділянок, виділяючи українські води Чорного моря як перспективний район для розвідки вуглеводнів. Отримані сейсмічні 3D-дані відіграють ключову роль для подальшого розвитку й оцінювання перспективності цієї ділянки, надаючи цінну інформацію в економічно ефективний спосіб.***

К л ю ч о в і   с л о в а : ***сейсморозвідка, глибинна візуалізація, мілководдя, FWI, SWIM, PSDM, Чорне море, машинне навчання.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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