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SPECIAL TOPIC

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cover: Aerial view of a winding river in North Dakota. This month we feature the giant, continuous Three Forks Play in the US state.

UNCONVENTIONALS AND PASSIVE SEISMIC

Large-scale exploration of shale oil and gas in America has driven innovation in the unconventionals sector in the past few years and some of the latest developments will be showcased here. Meanwhile, interest in passive seismic techniques, such as microseismic monitoring has continued to grow, driven by the success of such techniques in providing insights into subsurface geomechanical processes.

Vasilii Ryzhov et al demonstrate the offshore deployment, acquisition and applicability of LFS to delineate hydrocarbon deposits in the North Sea. They show how low-frequency seismic sounding (LFS) technology has the potential to delineate oil and gas reservoirs to derisk drilling decisions and shorten the appraisal and development timeframe.

Joshua Richard Williams et al discuss the development of an artificial neural network for classifying seismic triggers as events or blasts using source parameters estimated in real-time.

Thomas L. Davis answers the question as to what natural fractures tell us about the origins of faulting in the Wattenberg Field in the Denver Basin.

D Kühn et al present recent work on reservoir-triggered seismicity (RTS) from Koyna, western India, a prominent site where a large artificial water reservoir-triggered earthquake of magnitude 6.3 occurred on 10 December 1967.

Majid Nasehi demonstrates potential for enhanced oil recovery in the Western Canada Sedimentary Basin (WCSB).

Stephen A. Sonnenberg demonstrates how unconventional-style completions have unlocked resources in the Three Forks play comprising the Bakken petroleum system, a giant, continuous accumulation in the Williston Basin. They demonstrate the effective deployment of horizontal drilling and multi-stage hydraulic fracture stimulation.

Submit an article

First Break Special Topics are covered by a mix of original articles dealing with case studies and the latest technology. Contributions to a Special Topic in *First Break* can be sent directly to the editorial office (firstbreak@eage.org). Submissions will be considered for publication by the editor.

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Special Topic overview

March	Land Seismic
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November	Marine Seismic & EM
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More Special Topics may be added during the course of the year.

Offshore field trial application of low-frequency passive microseismic technology in the North Sea for exploration, appraisal and development of hydrocarbon deposits

Vasilii Ryzhov[1], Dmitrii Ryzhov[1], Ilshat Sharapov[1], Sergey Feofilov[1], Evgeny Smirnov[1], Ivan Starostin[1], Roy P. Bitrus[1]* and Ben Chichester[1] demonstrate the offshore deployment, acquisition and applicability of LFS to delineate hydrocarbon deposits in the North Sea.

Abstract

The recent downturn in the industry has led to a focus on maximizing economic recovery and low-frequency seismic sounding (LFS) technology has the potential to delineate oil and gas reservoirs to derisk drilling decisions and shorten the appraisal and development timeframe. The change in the low-frequency range of natural microseismic background noise is due to the mechanics of fluid saturated, fractured and porous media, with oil and gas reservoirs having a high-velocity dispersion and attenuation at low frequencies.

Here, we demonstrate the offshore deployment, acquisition and applicability of LFS to delineate hydrocarbon deposits in the North Sea. The spectra of the dry and oil-bearing sections of the surveyed area is observed in the frequency range of 0.6-1.9 Hz, while noise interference in the form of Scholte waves is also observed in the low-frequency range of 2Hz. We developed new filtering procedures to remove interference and exclusively select vertically directed P waves from the recorded signal. The result is a map of correlation coefficients which characterize the absence and presence of hydrocarbons as a probability map of hydrocarbon. The offshore trial has confirmed the application of the LFS technology highlighting areas that can be improved to deliver optimal results.

Introduction

Passive microseismic studies are commonplace in engineering geology and seismology but are a relatively new geophysical trend in the oil and gas industry. The downturn in the global market and decline in new discoveries of hydrocarbon deposits, have resulted in a focus on maximizing economic recovery at both government and operational levels. This has opened a window of opportunity for advanced, disruptive technologies, which help to avoid the drilling of dry holes and shorten the appraisal and development timeframe. Low-frequency seismic sounding (LFS) is such a technology and here we describe its offshore application.

Several global studies carried out by academic teams and companies have shown that long-term observations of the natural microseismic background noise by a large number of highly sensitive sensors can provide information about geological media characteristics, specifically:

1. Variations in the low-frequency range of the spectrum of natural microseisms provide information about the presence or absence of hydrocarbon deposits at the observation point (Arutyunov S. et al. [1], Birialtsev E. et al. [2-4], Beatriz Quintal et al [5]).
2. The cross-correlation function of a passive microseismic field recorded at two observation points, over a prolonged observation period, tends to simulate the response of the media to an active impulse. In other words, theoretically, information on the geological structure of the media can be extracted from the passive microseismic field (Wapenaar et al [6]). This is similar to the results of active seismic exploration techniques.

The change in the low-frequency range of the natural microseismic background noise directly above hydrocarbon deposits has been observed in various oil and gas provinces since the 1990s [1-3]. Due to the mechanics of fluid-saturated, fractured, and porous media, oil and gas reservoirs have high-velocity dispersion and high attenuation at low frequencies. A thin (>2m) layer of an oil/gas reservoir with high absorption amply reflects the low-frequency P-waves to transform the amplitude-frequency characteristics of the media under the observation point on the ground surface. Using highly sensitive low-frequency equipment, comprehensive processing and interpretation software, it is possible to detect and quantify this phenomenon, leading to the identification of oil and gas deposits in a fast and environmentally friendly way without the need for specialised vessels, airguns or explosions.

Various passive microseismic technologies are based on the study of this effect, and are successfully applied onshore [5]. Its use offshore and in transit zones is subject to reliable field data being obtained from the seabed, and interpretation taking into

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account the specifics of marine noise interference. One of these passive microseismic methods is low-frequency seismic sounding (LFS) technology, which filters the low-frequency (0.5-10 Hz) natural background noise and assesses the spectral characteristics of vertically oriented waves to determine the presence or absence of hydrocarbon reservoirs. The LFS technology identifies anomalies on the seabed above hydrocarbon deposits and defines the geometry of hydrocarbon-bearing reservoirs in mature or exploratory areas.

TenzorGEO Ltd was established in February 2018. Its aim was to confirm the practical applicability of LFS technology offshore, which required a full-scale offshore field trial (including preparation, data acquisition and interpretation stages). The Aberdeen-based Oil and Gas Technology Centre's TechX accelerator programme recognized the potential of LFS technology for the industry and accepted TenzorGEO onto the TechX programme. This enabled TenzorGEO to develop its business proposition and secure market interest for the offshore trial of its LFS technology.

Offshore field trial

In Q4 2018, TenzorGEO secured a field trial with an unnamed operator in the North Sea. The trial aimed to demonstrate a) the ability of TenzorGEO to perform an offshore data acquisition campaign (including validation of equipment performance, deployment and recovery methods, timeframes); b) to test the ability of LFS technology to locate hydrocarbons in offshore conditions, and c) to delineate the boundary of the hydrocarbon reservoir in the investigation area.

The offshore campaign was conducted over a week in February 2019, using the diving support vessel (DSV) 'Rever Sapphire' provided by Rever Offshore, and 25 ocean bottom seismometers (OBS) provided by by K.U.M. Umwelt- und Meerestechnik Kiel GmbH. The OBS's used in the trial are designed to autonomously operate for up to 18 months in water depths of up to 6000 m and had previously been successfully deployed in global academic research. The average water depth at the trial area was 90 m. In each OBS instrument, the broadband seismometer has a frequency range of 120 seconds and 200Hz. The hydrophone has a frequency range from 100 seconds up to 100 Hz, and the data logger has four channels and a sampling rate of up to 4000 samples per second.

It was agreed with the operator that it was a blind field trial of an area with oil-water contact line and conventional seismic data of a known accumulation was not provided. The field trial investigation area was rectangular, stretched north-east to south-west with the OBS's deployed in a four by ten grid (350 m x 350 m). An additional four OBS's were deployed outside the survey area next to nearby wells for calibration purposes. The survey area was 3.3 km^2 and there was a total of 44 observation points. The deployment was split into two stages:

Deployment of four calibration instruments next to existing wells outside of the survey area, and deployment of 21 instruments within the survey area (two of which are calibration instruments),

Relocation of 19 instruments to new positions within the survey area.

Before the OBS deployment, final tests and GPS clock synchronization were performed on deck. Recording was initialized on deck and the OBS's were deployed by freefall descent to the seabed. Each deployed instrument recorded continuously for at least 14 hours. After the recording was completed, OBS instruments were recovered from the seabed and the raw data was downloaded.

During the trial, all the OBS instruments were safely deployed and recovered with no loss or damage. Data acquisition for the trial was completed successfully. Areas of hardware and software improvement were identified and subsequently addressed to complete the field trial.

Data processing and interpretation

During this stage of the field trial, the following main steps were completed:

1. Data analysis of the wells (oil depths, net pay).
2. Preparation of the layered depth-velocity model for the LFS survey area.
3. Numerical simulation of the vertical component of media responses (dry and saturated).
4. Filtering of the strong Scholte's wave noise from non-moving surface sources.
5. Filtering of the ambient background surface noise (omnidirectional Scholte's waves).
6. Design and application to optimize the filtering parameters by maximizing correlation coefficients between real and simulated spectra (dry and oil).
7. Construction of correlation maps.
8. Construction of hydrocarbon presence probability maps.

The synthetic model was constructed using velocity seismic profiles (VSP) from two wells. The velocity intervals in the velocity model of the section are determined by the boundaries of geological formations or stratigraphic boundaries with similar lithological characteristics. Considering that the presence of oil-saturated sand was identified in two wells drilled in the surveyed area, the exploration area with the highest potential of hydrocarbons was associated with Lista Formation, Montrose Group. Therefore, the model oil layer was placed at a 3100-3150 m interval.

During the modelling process, various approaches were reviewed to identify the best location for the force application (i.e. sea level or seabed), as the difference between the sea level and seabed in the survey area was around 90 m. The model closest to the field data results was where the force was applied from the seabed level. The control was carried out based on a comparison of model spectra, with real spectra obtained from six calibration instruments next to existing wells used for the field trial. The similarity was determined by the comparative position in frequency space of spectral peaks between the observed spectrum and the simulated spectrum, which is associated with the presence of hydrocarbons (Figure 1, green curve) for the indicated wells in the target frequency range. The similarity metric was the correlation coefficient. The resulting spectra before and after detrending are presented in Figure 1. Analysing the final synthetic model, it can be noted that the main difference in the spectra of the dry and oil-bearing sections of the surveyed area is observed in the frequency range of 0.6-1.9 Hz, which was adopted as the target range for further processing and interpretation in this field trial.

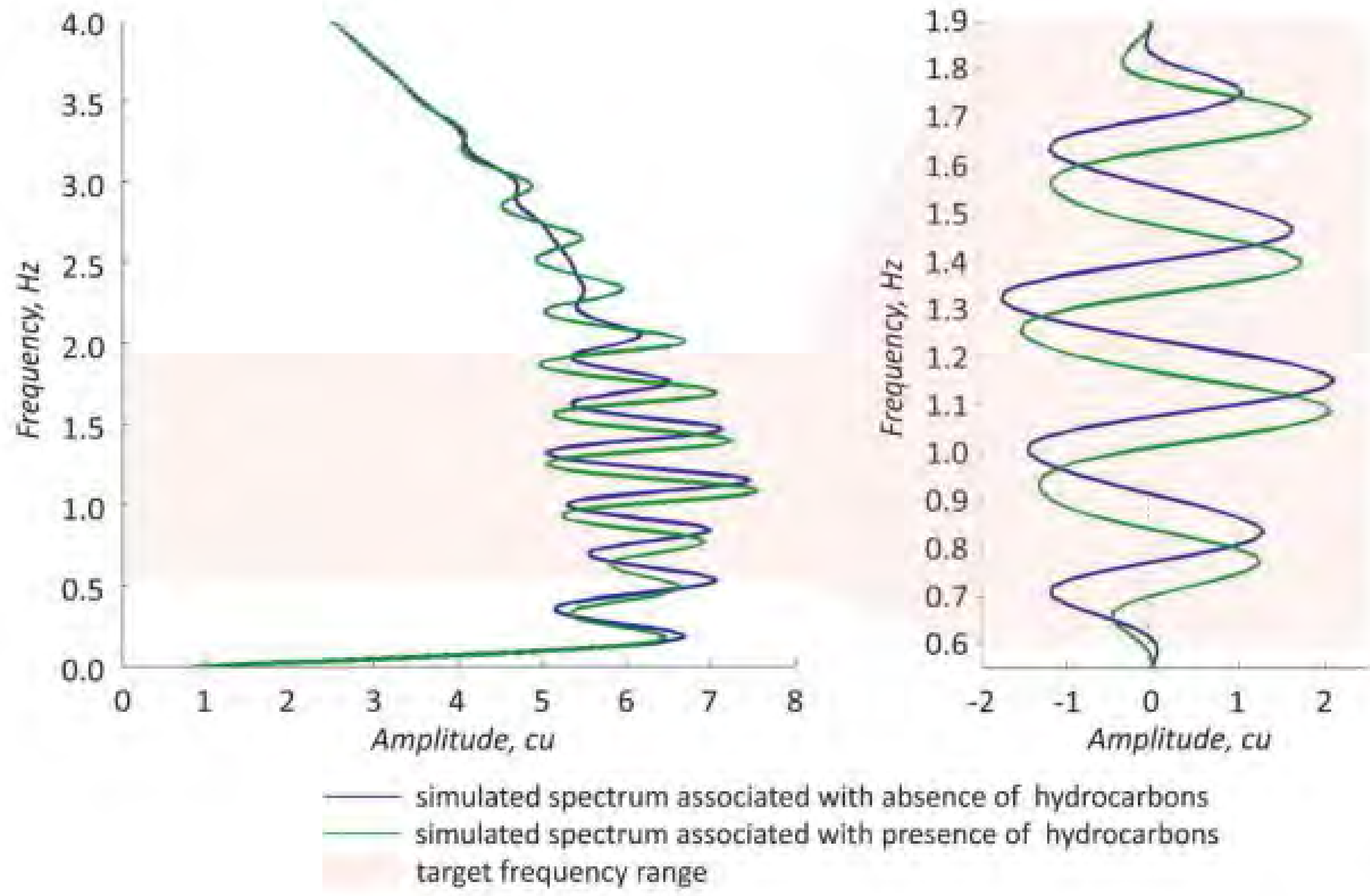

Figure 1 Final simulated spectra. *Left:* Before detrending. *Right:* Detrended and zoomed to the frequency range 0.6-1.9 Hz.

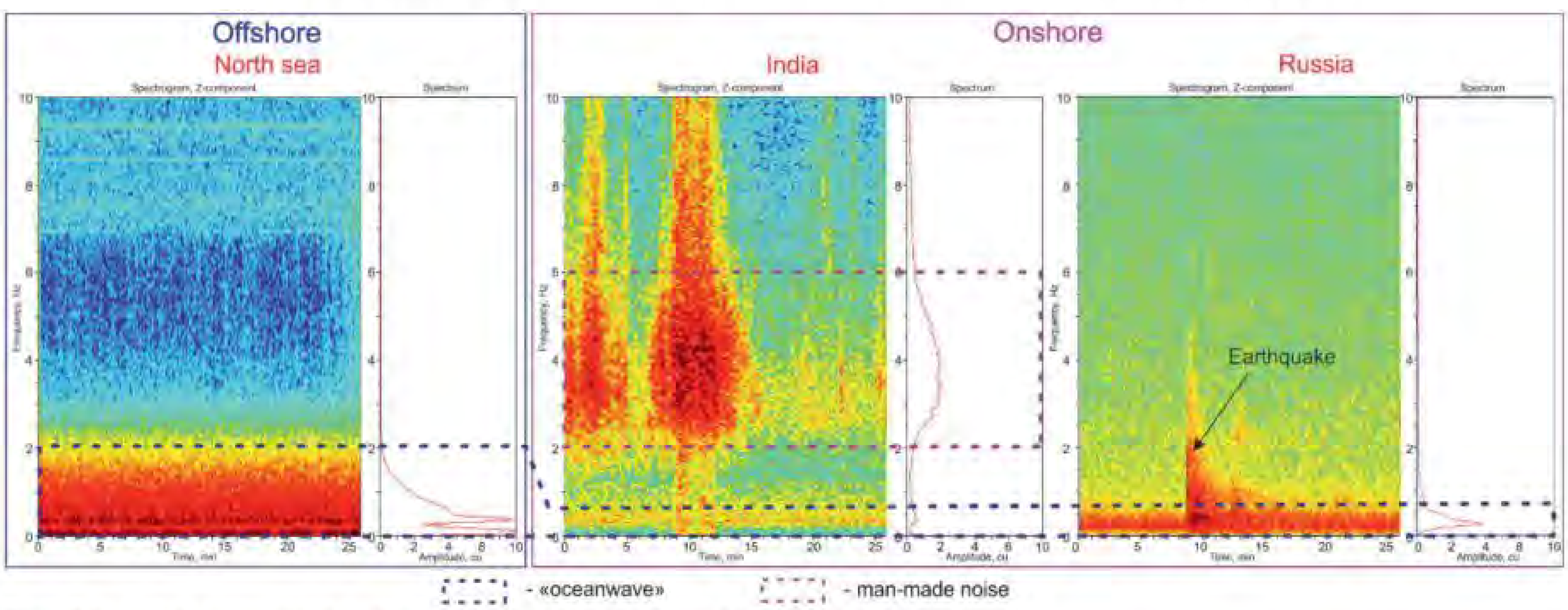

Figure 2 An example comparison of spectrograms and spectra of raw offshore data and onshore data.

During processing and interpretation, a comparison was made between the raw offshore field data and onshore low-frequency microseismic records. This was done in order to identify the offshore special features in the recorded material, and the subsequent selection of the appropriate filtering and processing procedures in order to remove the effect of the natural and technogenic acoustic noise of the sea. The microseismic records obtained on the North Sea seabed and onshore in India and Russia are shown graphically in Figure 2. The figure clearly shows how the distribution of interference associated with surface Rayleigh and Scholte's waves changes. On the North Sea shelf, the formation of interference in the form of Scholte's waves is associated with sea waves and sea surf, and their main influence is constant and can be traced in the low-frequency range below 2 Hz (Figure 2, Offshore). According to the results of numerical modelling, this frequency range is a target range for LFS interpretation and the presence of noise associated with the Scholte's waves (i.e. 'ocean waves') required the development and application of additional filtering procedures in order to remove interference, and exclusively select vertically directed waves from the recorded signal. On land, the effect of these 'ocean waves' is significantly weakened with a decrease in the upper frequency to 0.5-0.8 Hz. Onshore, most of the noise comprises surface waves concentrated in the higher frequency range from 2 to 6 Hz (Figure 2, Onshore) and is caused by moving (motor vehicles, trains, etc.) or stationary (factories, pumping stations, downhole equipment etc.) technogenic sources at the surface.

When processing offshore field data, two methods of filtering the surface waves associated with the omnidirectional noise of sea waves were tested. They were based on the use of the cross-correlation function between the two simultaneously observed Z-components from two records (along the line) and three records (triangle). Adaptive filtering, a process to select optimal values for filtering parameters, was applied to further improve the quality of the interpretation. The process has been automated by maximizing the correlation coefficients between the actual spectra and the simulated spectra (both dry and saturated) for each virtual point. This was realized by simple enumeration in a confidence interval.

The trial identified three distinct stages. Results of Step 1 were presented to the operator for review and comparison with the operator's own data. Although areas of presence and absence of hydrocarbons were correctly identified, oil-water contact line fell outside the 600 m lateral tolerance agreed for the trial with the operator providing an oil-water contact line drawn according to their own studies. Subsequently Steps 2 and 3 were performed to improve the quality of the oil-water contact line prediction.

- Step 1 – Modelling with the application of force and recording responses at sea level and 'ocean wave' filtering using simultaneously observed Z-components of two (along the line) records.
- Step 2 – Modelling with the application of force and recording responses at seabed and 'ocean wave' filtering using the simultaneously observed Z-components from three (triangle) records.
- Step 3 – Adaptive filtering to select optimal filtering parameters.

To assess the quality of the obtained processing and filtering results at all stages, before performing Steps 2 and 3, a map of maximum values of correlation coefficients (*Cmax*) between the actual spectra and the simulated spectra was constructed (Figure 3), based on which, the correlation coefficient *mean (Cmax)* for the study area was determined. These maps clearly show an increase in the similarity of actual spectra with model spectra after applying the above filtering approaches (Steps 1, 2, and 3). The average correlation coefficient increased significantly over the course of modification of filtering algorithms: 0.25 to 0.56 from Step 1 to Step 2, and 0.56 to 0.75 from Step 2 to Step 3. The highest mean correlation coefficient *(mean(Cmax))* for the study area was obtained in Step 3 and this processing and filtering approach has formed the basis for the final interpretation and production of the map of hydrocarbon presence probability according to LFS processing of the field trial data (Figure 4).

Evaluation of the similarity, using Pearson's linear correlation, between the processed spectra at observation points and the simulated spectra, results in the following maps of correlation coefficients:

1. The map that characterizes the absence of hydrocarbons.
2. The map that characterizes the presence of hydrocarbons.
3. The map of normalized correlation coefficients (Figure 4).

Obtained values of correlation coefficients are only the similarity measure of the studied spectra with the reference spectrum and do not directly reflect the oil-bearing capacity in the section. Zones with the highest values of the correlation coefficients indicate the highest similarity of the spectra of the observation point with the reference spectrum.

The map of hydrocarbon presence probability is constructed from the map of normalized coefficients of morphological similarity (Figure 4). Normalized coefficients are transformed to probability of hydrocarbon presence. The map of hydrocarbon presence probability (Figure 4) was the final deliverable of the processing and interpretation of LFS data from the field. According to this map, the hydrocarbon deposit within the study area is located in the north-eastern part of the survey with an estimated hydrocarbon boundary, defined by a probability of 50%, along

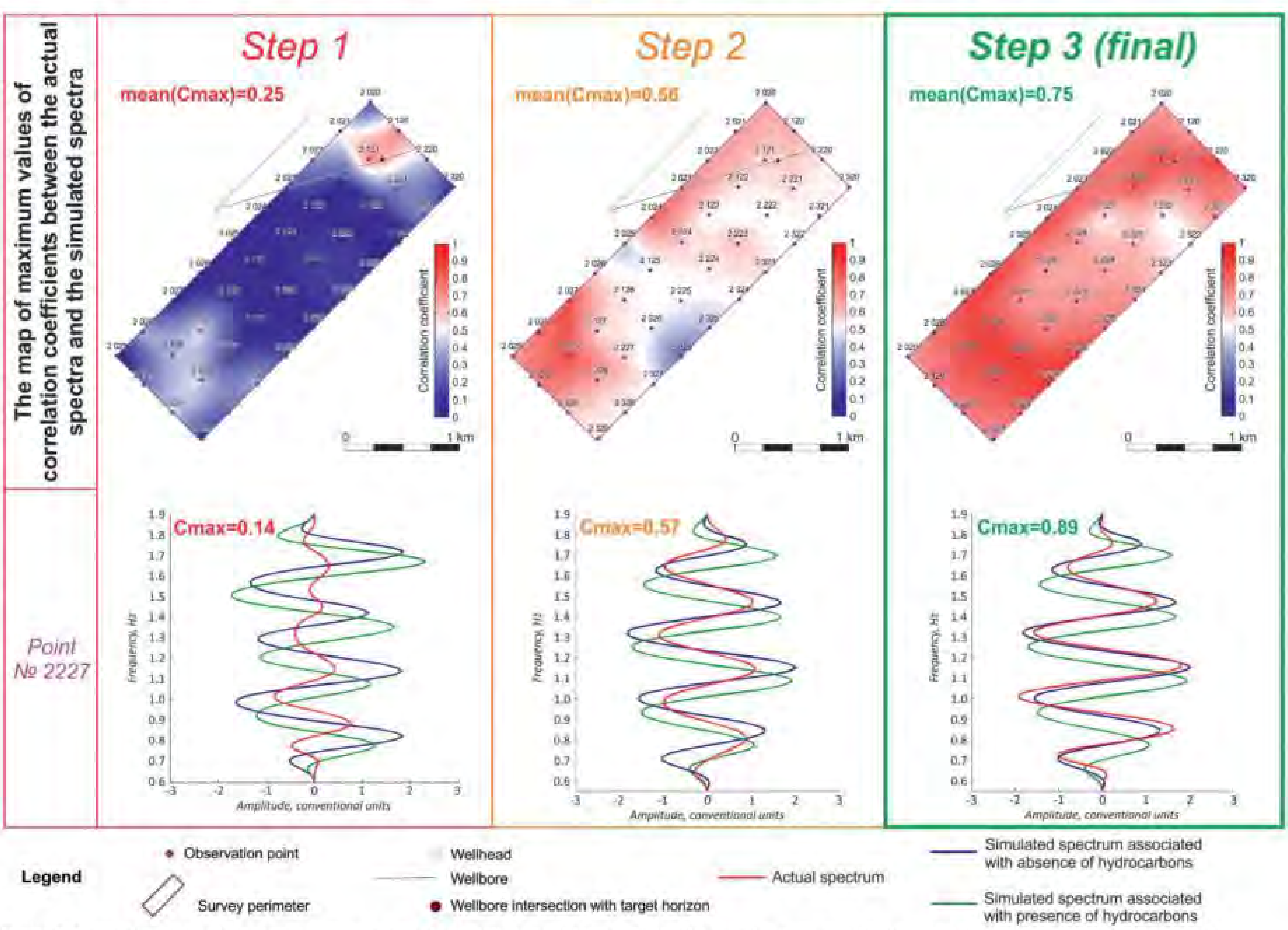

Figure 3 Comparison table of maps of maximum values of correlation coefficients between the actual spectra and the simulated spectra (top panels), and spectra for observation point 2227 (bottom panels), over three processing approaches (Steps 1, 2, and 3).

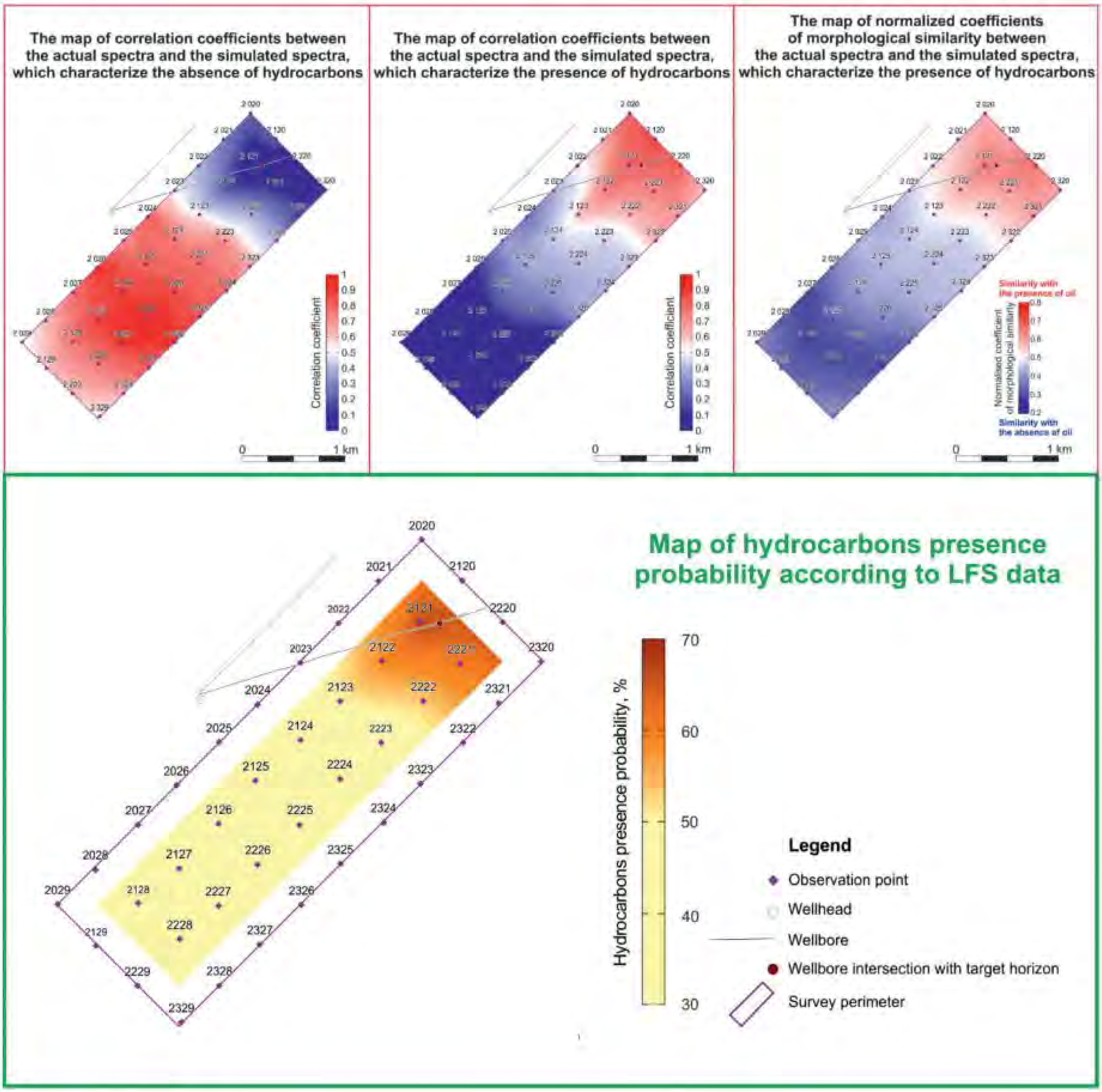

Figure 4 North Sea offshore LFS results.

the observation points 2123 and 2222. Comparison of the new position forecast of the hydrocarbon deposit boundary, according to LFS research after performing all three stages, to the actual position of the boundary provided by the operator showed better convergence and indicated potential viability of LFS technology in offshore conditions.

Conclusion

The North Sea field trial has demonstrated that TenzorGEO is able to safely and efficiently acquire low-frequency seismic data in offshore conditions.

Field trial data analysis demonstrated the possibility of exposing differences in spectral characteristics of low-frequency seismic data, recorded within the boundaries of the hydrocarbon deposit and outside it. Under initial blind test conditions of the trial, areas of the high and low probability of the hydrocarbons presence were correctly identified. However, the predicted oil-water contact did not agree with the operator-provided contact location and fell outside the 600 m lateral tolerance quoted for the method at that depth.

After the initial results were reviewed and additional well control data and the oil-water contact location provided by the operator, more complex filtering techniques and further model calibration incorporating the additional well data were introduced (Step 2 and 3). The quality of filtering significantly increased which enabled the data interpretation process to achieve a reasonable match between LFS predicted line of 50% probability of hydrocarbon presence and the oil-water contact location provided by the operator. The zone of 40-50% probability of hydrocarbons presence suggested by the LFS extends over 800 m laterally below the oil-water contact, which suggests that further validation is required for application in similar conditions.

LFS technology has been used onshore for more than 15 years and the North Sea field trial results show its potential for continental shelf exploration, appraisal and development purposes. A further field trial will help to reconfirm updated processing and interpretation methods, test optimized OBS deployment grids, further validate the use of LFS to identify hydrocarbons in an offshore reservoir and lastly to improve and fine-tune the oil-water contact prediction accuracy in an offshore environment.

Going forward, in order to achieve reliable results when applying LFS technology to offshore surveys, the following processing and interpretation guidelines should be used:

1. The application of force and the registration of responses during full-wave numerical simulation should be performed at the seabed.
2. The filtering of the surface waves associated with the omnidirectional noise of the sea waves should be based on multiple cross-correlation functions between the Z-components of several simultaneous observation records.
3. Automated mechanisms for selecting optimal filtering parameters (adaptive filtering) should be used to achieve reliable results.

Higher efficiency of LFS application should be expected at study areas with the following characteristics:

1. Data logs from wells in the study area (with or without hydrocarbon presence).
2. Completed vertical seismic profiling (VSP).
3. A completed seismic survey and availability of structural maps (isochrons) of the main reflecting stratigraphic horizons, especially in regions with complex geology (for example, significant differences in depth).

Employing LFS technology within the scope of offshore geological surveys could be used for:

- Prospecting for oil and gas.
- Delineation of hydrocarbon deposits.
- Identification of unstructured hydrocarbon deposits.
- Identification of hydrocarbon deposits beneath salt and other seal systems.

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