

---

USING SPACE-BASED INFORMATION ABOUT THE EARTH  
STUDYING SEAS AND OCEANS FROM SPACE

---

## Search and Detection of Natural Oil Seeps in the Seas Surrounding the Russian Federation Using Spaseborne SAR Imagery

A. Yu. Ivanov<sup>a, b, \*</sup>, E. R. Matrosova<sup>b</sup>, A. Yu. Kucheiko<sup>c</sup>, N. A. Filimonova<sup>d</sup>,  
N. V. Evtushenko<sup>a</sup>, N. V. Terleeva<sup>a</sup>, and N. V. Libina<sup>a</sup>

<sup>a</sup>*Shirshov Institute of Oceanography, Russian Academy of Sciences, Moscow, 117218 Russia*

<sup>b</sup>*AEROCOSMOS Institute for Scientific Research of Aerospace Monitoring, Moscow, 105064 Russia*

<sup>c</sup>*Marine Hydrophysical Institute, Russian Academy of Sciences, Sevastopol, 299011 Russia*

<sup>d</sup>*SCANEX Group, Moscow, 108811 Russia*

\*e-mail: [ivanoff@ocean.ru](mailto:ivanoff@ocean.ru)

Received March 23, 2020; revised June 1, 2020; accepted July 3, 2020

**Abstract**—Results are presented from research aimed at detecting natural seepage and oil seeps in the seas of Russia using synthetic aperture radar (SAR) imaging. Real-time and archived data from such modern SAR-equipped satellites as Envisat, Radarsat-1/2, Sentinel-1A/1B, are indispensable material in searching, detecting, and studying natural oil seepage by observing oil slicks floating on the sea surface. They are used to detect oil seeps and natural petroleum hydrocarbon flows in the Black Sea, the Sea of Azov, the Barents Sea, the Caspian Sea and the Sea of Okhotsk. Using SAR imagery and the geoinformation (GIS) approach as well as bathymetric data and additional geological and geophysical information, oil seeps can be detected from space, their real position on the sea bottom determined, and additional information about the activity, frequency and volume of oil emissions obtained. As a result, regional oil and gas potential can be confirmed. This methodical approach can be used to search and detect similar phenomena in the seas worldwide, and the detection of new hydrocarbon sources using satellite images once again confirms its efficiency.

**Keywords:** seas of the Russian Federation, oil slicks, oil seeps, SAR images, searching and detection from space

**DOI:** 10.1134/S0001433820120439

### INTRODUCTION

The history of the development of the offshore oil and gas industry in Russia dates back to the end of the 19th century, when attempts were made to extract oil in the shallow part of the Caspian Sea. It was the natural release of oil to the surface that in turn served as the basis for drilling wells, which led to the discovery of the well-known Oil Rocks field in Azerbaijan and gave a strong impetus to the development of the offshore oil industry (Serikova, 2015).

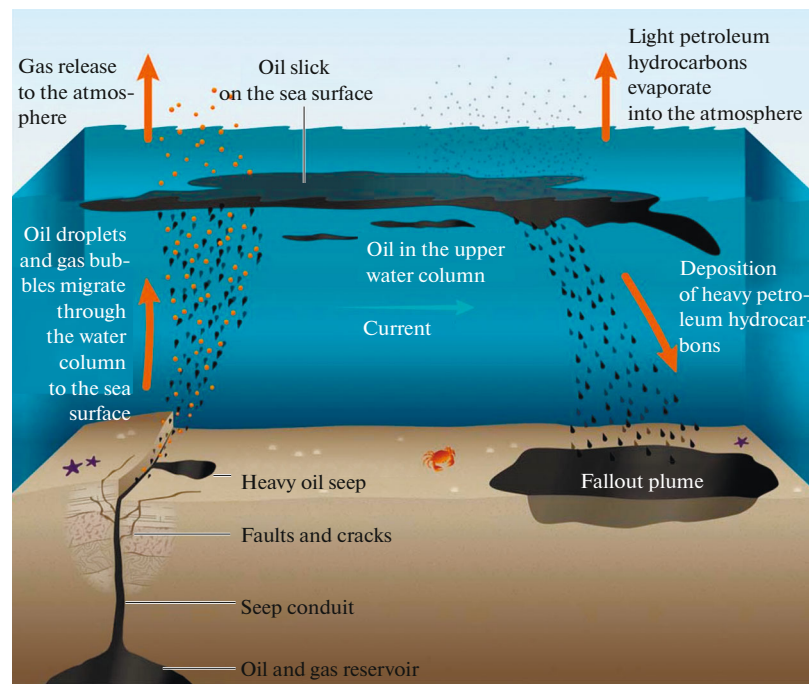
A number of oil and gas fields have been discovered as a result of detecting natural oil seeps in the Caspian Sea, the Gulf of Mexico, and other regions of the World Ocean. They are now important sources of oil and gas hydrocarbons.

Depending on the geological structure of the sea floor, underwater sources can become active, temporarily cease their activity, or completely disappear and then reappear. At the same time, such phenomena can result from either natural factors associated with, e.g., the seismicity of the subsoil (Aliiev, 2010; Ivanov et al., 2007), or such antropogenic activity as gas and oil pro-

duction from offshore wells, as was observed in the Black Sea in 2018 (Ivanov and Matrosova, 2019). One way or another, natural oil seepage indicates underwater accumulations of gas, gas condensate or oil, located at considerable geological depths and activated in an appropriate geodynamic setting (Gubkin, 1975).

The importance of the surface as an indicator of the oil and gas content of a particular area of the sea floor cannot overestimated, since such signs only (sometimes even very bright ones) are not enough to judge the oil and gas content of the field associated with them (Gubkin, 1975). In addition to indicating oil fields, detecting natural oil seeps and their outcrops on the sea floor is vital for ensuring the safety of engineering structures of the offshore oil and gas complex (Bondur, 2005; Bondur, 2010; Bondur et al., 2014; Bondur and Zamshin, 2012, 2018; Bukharitsin et al., 2016) (e.g., oil platforms and subsea pipelines), that is of extreme importance to the active development of offshore mineral resources.

These circumstances determine the prospects of searching for and detecting natural oil seeps on the



**Fig. 1.** Schematic representation of a natural source of oil seepage (© Woods Hole Oceanographic Institution).

vast shelves and continental slopes of the marginal and inland seas of Russia. It is believed that petroleum hydrocarbons form there in the sediments of the lower complex of these seas, where conditions for the formation of oil and gas are favorable. It is obvious that oil can be discharged into the water column of the sea through permeable zones of various geological structures and their faults. Oil and gas formed in productive sediments first enter the bottom area and then travel to the sea surface. There are often eruptive structures at the bottom in such places. These include mud volcanoes and such secondary and single forms as seeps or gryphons, from which oil is released with varying frequency in the form of oil drops or gas bubbles coated in oil (MacDonald et al., 2002). When it reaches the sea surface, gas escapes into the atmosphere and oil is left behind, accumulating and spreading on the surface, forming many kilometers of slicks that are clearly visible from space (Fig. 1). Oil films dampen small gravity–capillary waves, resulting in oil slicks being displayed on synthetic aperture radar (SAR) images in the form of dark signatures.

Remote sensing methods is of great interest for detecting natural oil seepage in seas and oceans. Modern SAR systems ensure regular all-weather data acquisition over vast water areas, regardless of lighting conditions and cloudiness, and with spatial resolutions of 5–20 m. Satellite data are now actively used to study processes and phenomena in the upper layers of seas and oceans, including natural oil seepage (Bondur, 2005, 2011a, 2011b; Bondur and Starchenkov,

2005; Ivanov, 2007; Bondur and Zamshin, 2012; Bondur and Kuznetsova, 2012, 2015; Bondur et al., 2014).

Methodics developed in the works of Williams and Lawrence (2002) and Ivanov et al. (2007) is used to analyze and study natural oil seeps detected at one location on multi-temporal SAR images, along with the geographic information (GIS) approach (Ivanov and Zatyagalova, 2007; Ivanov et al., 2014) used in the majority of similar projects under way in the Russian Federation. Natural sources of oil have also been discovered and studied using spaceborne SARs and the GIS approach in the Gulf of Mexico (MacDonald et al., 1993; De Miranda et al., 2004), in the Caspian Sea (Williams and Huntley, 2002; Ivanov et al., 2007, 2015, 2020; Ivanov, 2019), in the Black Sea (Evtushenko and Ivanov, 2012; Zatyagalova, 2012), in the Adriatic Sea (Ivanov and Morović, 2020), in the Persian Gulf (Ivanov and Gerivani, 2020), on the shelves of Sakhalin (Ivanov and Zatyagalova, 2008; Ivanov, 2010), Africa (Jatiaux et al., 2017) and Australia (Struckmeyer et al., 2002), and in many other marine basins. Some aspects of oil seepage in the Black and Caspian Seas were described by Lavrova et al. (2016).

Aside from pure scientific research, the importance of studying natural oil seepage is that along with indicating oil and gas content, it is also a source of constant natural pollution of the sea. This must be known and considered in industrial and environmental assessments (Kvenvolden and Cooper, 2003) in order to distinguish natural pollution from anthropogenic. Studies in the field of gas and oil releases and their sources also allow us to obtain global estimates of

methane and other hydrocarbon emissions into the atmosphere and hydrosphere (Judd and Hovland, 2007; Etiope, 2015; Bondur, Kuznetsova, 2015).

In this work, we summarize the results from detecting and studying oil seepage in the seas of Russia (the Black Sea, the Sea of Azov, the Barents Sea, the Caspian Sea, and the Sea of Okhotsk) using SAR imagery. The efficiency of this approach is demonstrated by specific examples. The focus is on little-known sources of liquid hydrocarbons or those discovered in 2018–2020.

### UNDERWATER SOURCES OF PETROLEUM HYDROCARBONS

Underwater sources of petroleum hydrocarbons are oil and gas effluent (eruptive) structures on the sea or ocean bottom, through which oil enters or seeps into water column (Shnyukov et al., 1986; Etiope, 2015; Leifer, 2019).

Natural oil seeps usually occur over accumulations of petroleum hydrocarbons. Their distribution in different seas and oceans is known, and they are of biogenic (microbial metabolic origin), thermogenic (from deep-lying parent rocks or oil accumulations) or mixed origin. Oil and gas content is generally considered the main reason for this phenomenon. Hydrocarbons can seep along or across oil- and gas-bearing layers through faults and cracks in sedimentary rocks, directly from oil-bearing layers, and be released from different bottom morphological formations due to increased reservoir pressure (e.g., during sedimentation or expansion of the fluid-bearing environment) and similar reasons. Note also that oil seepage is a complex and not fully understood phenomenon, and the literature on this topic is vast.

There is still no unified terminology for bottom morphological formations that result in oil seepage (Shnyukov et al., 1986). One of the main reasons for this is the problem of geologically interpreting underwater sources of hydrocarbons. The most common sources include cold seeps, which are often understood to be a variety of bottom formations (Leifer, 2019) or even small areas of the discharge of liquid and gaseous hydrocarbons on the sea floor. Seeps can therefore be considered all possible forms of underwater sources of hydrocarbons that are of an eruptive nature: mud volcanoes, salses, gryphons, pockmarks, and a number of others.

According to Etiope (2015), mud volcanoes are geological formations in the form of cone-shaped formations (mud salses), from which mud masses and hydrocarbon gases (usually methane) erupt constantly or on occasion, often accompanied by water and oil. Salses are underdeveloped mud volcanoes that also emit gas, water and sometimes oil (their craters can be 0.5 to 30 m or more in diameter). Gryphons are responsible for separate gas, water, and oil discharges.

Their outlets are from 1 cm to 0.5 m in diameter, and their cones can be as high as 1–3 m. Pockmarks are rounded cone-shaped depressions on the sea floor that usually form in loose fine-grained sediments due to gas being released into the water column. They range from meters to tens of meters in size at depths of 5–10 m. Sources at the bottom are sometimes positioned separately, but more often in groups with a common eruptive focus.

### DATA AND MATERIALS

Our research was based on results from the SAR monitoring of Russian seas, many of which have been published and presented in the literature. We used high and medium-resolution SAR data from the Envisat, Radarsat-1/2 and Sentinel-1A/1B satellites.

SAR data have a number of advantages over ones obtained in other bands of the electromagnetic spectrum (e.g., optical). Most important, they do not depend on natural light or cloud cover, which allows all-weather monitoring and regular data collection. Due to their sensitivity to the roughness of the sea surface and the dielectric properties of the underlying surface, SAR systems are able to detect natural oil seepage in the sea. Under cloudless conditions and with appropriate lighting, oil seeps are nevertheless clearly displayed on optical images.

For example, data from the European and Canadian satellites ERS-2, Envisat, Radarsat-1/2 have been used to monitor the Russian seas since 2009, but their data were difficult to access. The European satellites Sentinel-1A/1B, the daily data of which are freely available, were launched in 2014 and 2016. Since 2015, it is mainly these that have been used for SAR monitoring of the Black Sea, the Sea of Azov, the Barents Sea, the Caspian Sea, and the Sea of Okhotsk. Optical survey data from the Landsat-8 and Sentinel-2A/2B satellites, which are also in the public domain, have also been used.

Other data and information resources should be used in addition to satellite data to conduct a comprehensive analysis of natural oil seeps in Russian seas. These include geological, geophysical and hydrometeorological materials, geospatial databases, and bathymetric and navigation data from various sources (e.g., the GEBCO and GMRT databases, and the C-MAP map service), along with available geological and geophysical data from oil companies whenever possible. The position and activity of one underwater oil source or another at the sea bottom can be characterized more accurately using such data.

### METHODICS

A procedure for recognizing seep activity via GIS approach was used to detect natural oil seepage in the seas of Russia from SAR images (Ivanov, Zatyagalova, 2007; Ivanov et al., 2014). It contains a sequence of

actions performed in the GeoMixer web-based GIS cartographic application (geomixer.ru):

- visually interpreting oil slicks, identifying possible natural oil seeps, and analyzing them interactively with specialized computer programs;
- spatio-temporal analysis of all available SAR surveys for the detected location(s);
- selecting and vectorizing individual and groups of slicks at different times, and creating vector layers suitable for entering into the GIS software;
- comparison of slick detection results with the available ground-based data and other materials;
- assessing the nature of a slick and determining the position (coordinates) of its underwater source.

Visual interpretation (extracting useful information about oil seeps using the human eye, with its great ability to recognize images) requires expert selection of areas in SAR images that correspond in their characteristics to natural oil seepage. Such signs are due to variations in the formation and dynamics of oil slicks on the sea surface, and thus to features of their display on SAR images (Ivanov, 2007). These include shape, size, contrast, thickness (based on optical satellite images), and lifetime. The main features in visual interpretations of oil seep signatures are tone (brightness), image texture, and contrast. An important factor in recognizing natural oil seepage is allowing for hydrometeorological conditions, especially wind direction and speed.

Interactive (automated) SAR data processing is normally done as well, and in stages using intermediate or additional results/data to obtain more reliable information and confirm the results from visual interpretation (Garcia-Pineda et al. (2009)). However, interactive analysis with visual interpretation remains the main means of analysis (Jatiaux et al., 2017).

The main characteristics of slicks that should be noted when searching for signs of natural oil seepage in optical and SAR images for anomalies of the sea surface are:

- size, shape (simple or complex) and length; aspect ratio;
- edge of the spot (e.g., sharp, feathery, blurred, or gradient);
- radar contrast between a slick and clean water;
- color of the oil film on optical images (metallic, rainbow, silver-gray);
- position relative to the expected location of a seep on the bottom;
- direction of the drift from the oil seep origin under the influence of wind and currents;
- period of repeatability in consecutive images;
- spatial grouping and its structure (groups of slicks);
- orientation and connection with phenomena in the ocean and atmosphere (e.g., manifestations of

internal waves, current shears, eddies, frontal zones, river outflows, zones of upwelling, temperature and chlorophyll anomalies, shallow topography, biogenic films, calm zones, rain cells);

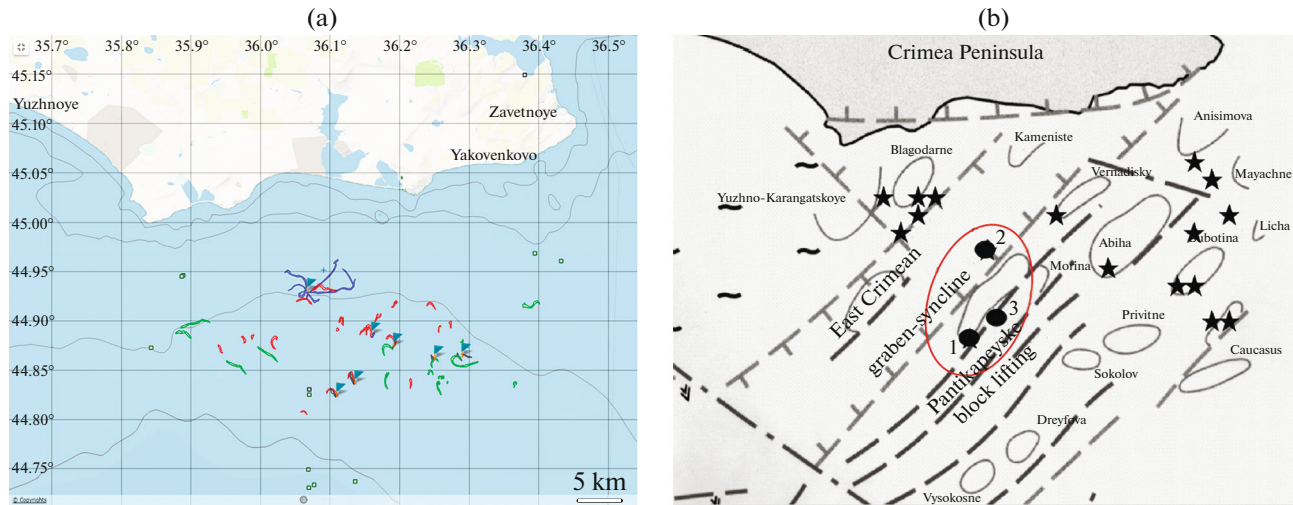
- contextual environment or spatial reference of oil slicks to offshore oil and gas facilities (rigs, platforms, terminals, etc.), anchorages, roadsteads, ports and ships (bright spots and traces), shipping routes, and places where sewage water is discharged.

Oil discharges from the seabed are often accompanied by outflows of natural gas, gas condensate, and light oils. The latter form slicks on the sea surface; in SAR images they have negative contrast relative to the surrounding surface, and oil seepage on the sea surface forms dark spots (Ivanov, 2007). Thin oil slicks (film thickness,  $\sim 10^{-6}$ – $10^{-8}$  m) that are round and small form as a result of oil floating on the sea surface. Drifting on the sea surface, they trace the current field and form a line over time. In a complex vortex field, they sometimes take the shape of hooks, zigzags, loops, and even ovals (Ivanov, 2007). Under the influence of environmental factors natural oil films can be transported tens of kilometers from the source (Ivanov, 2007). The form of natural oil seepage can thus differ in space-based SAR images, depending on the lifetime of the slick. According to MacDonald et al., (1993) they can exist on the surface from 4 to 24 hours (on average, 6–12 hours) at wind speeds of 2–3 to 7 m/s. It is worth noting that the thickness of the oil films is important for recognizing of oil seepage in optical images, since it correlates with their color.

Since oil slicks are confined to specific stationary bottom sources (e.g., mud volcanoes and gryphons) that can be activated in constant, quasi-periodic, or episodic modes. Slicks in a sequence of SAR images group near certain points (their places of surfacing). They are distinguished by the pattern of their distribution and form clusters of characteristic, so-called fan-shaped structures (Ivanov et al., 2007). As a result, the surfacing point, periodicity and other characteristics of seep slicks can be determined using the GIS approach, especially when wind conditions and subsatellite information are available.

Problems of interactive processing are now being solved using the GeoMixer web-GIS application developed by SCANEX Group. The use of this application allows spatial analysis of current and archived SAR images at different times, allowing the nature of a slick to ultimately be established, and the coordinates of one possible natural oil seep or another to be identified as the geometric center of a group of detected slicks. The search and detection of natural oil seepage in the seas of the Russian Federation are done exclusively on the basis of the use of this technique.

To determine the volume of emitted oil using SAR data, we use a procedure in which the area of slick is measured on SAR images and the film thickness is estimated from general physical considerations by



**Fig. 2.** (a) Oil seeps detected using SAR images on the Prikerchensky area of the Crimean shelf and continental slope; (b) Distribution of mud volcanoes on the tectonic scheme (shown are volcanoes named after: (1) Mitin, (2) OMGOR, and (3) Naumenko. Asterisks denote minor mud volcanoes identified by geophysical means (after Shnyukov et al. (2010)).

associating the color of films with their thickness. Based on the Bonn Agreement Oil Appearance Code manual (BAOAC, 2016), estimates of the thickness of natural oil seep films can be obtained using the color of the films captured on high and medium resolution optical images. On the one hand, the color of oil films in the sea generally varies over a wide range: from dark brown to silvery gray in the thinnest examples. On the other hand, the films formed by oil seeps are characterized by light fractions of oil, the real colors of which change from metallic gray (thickness,  $5.0\text{--}50 \times 10^{-3}$  mm) at the oil seep origin, to rainbow ( $0.3\text{--}5.0 \times 10^{-3}$  mm) and silvery gray ( $0.04\text{--}0.3 \times 10^{-3}$  mm) at their peripheries. Note that this technique is constantly being improved. More accurate estimates of oil emissions can be obtained in particular if the lifetime of films on the sea surface and the dynamics of their spreading are considered (Daneshgar Asl et al., 2017).

## NATURAL OIL SEEPAGE IN SEAS OF THE RUSSIAN FEDERATION

### *Black Sea*

Emissions of gas as a product of oil and gas content are well known in the Black Sea. According to available data, they play an important role in this sea basin (Shnyukov et al., 1986, 2010, 2013). The conditions for the formation of gas sources are faults, favorable tectonic environment, the development of diapirism, the thicknesses of underlying plastic clay rocks, large accumulations of gas, and abnormally high pressure in them. Thousands of gas flares have been identified so far, and gas releases are observed in the sea everywhere along the shelf, the boundaries of the shelf dump, and the continental slope. They are now being systematized and mapped (Pasyukov, 2017). Less known,

however, are the natural oil seeps that have been detected and studied in the Russian, Georgian, and Turkish sectors of the Black Sea during monitoring with SAR.

### *1. Russian Sector*

In the Russian sector of the Black Sea, natural oil seeps have been found on the Prikerchensky area of the Crimean shelf, on the Sevastopol shelf, and on the continental slope of the Crimean Peninsula, along with the vast northwestern shelf (Ivanov et al., 2017a, 2017b; Ivanov and Matrosova, 2019).

On the Prikerchensky section of the Crimean Shelf, natural oil seeps were discovered 13 km from Cape Karangat and 16.5 km from Cape Opusk (Ivanov et al., 2017a) (Fig. 2a). (Note that hereinafter Figs. 2–8 show slicks (their colored outlines) detected over underwater sources on successive SAR images of different days.) Analysis of the results from monitoring in 2015–2017 and data from geology and geophysics allowed us to establish a connection between these oil seeps and local mud volcanism (Fig. 2b).

On the Sevastopol shelf and over the continental slope of the Black Sea, including the waters of the Kalamitsky Gulf, irregular oil emissions in the form of single or groups of oil slicks were recorded sporadically in 2015–2017, in both SAR and optical satellite images (Ivanov et al., 2017b).

From time to time, natural oil slicks have been observed virtually everywhere on the vast northwestern shelf of the Black Sea (Ivanov et al., 2017a). In mid-spring 2018, however, numerous oil slicks were detected in the Sentinel-1A/1B SAR images over depths of 40–50 m near production platforms at the Golitsynskoye, Arkhangelskoye, and Shtormovoye gas

and gas condensate fields, and at some distance from them (Ivanov and Matrosova, 2019). According to the monitoring data, there was no such activity in this area in earlier years (2011–2017). Therefore one of the main reasons for the increase in seeping there could be the technogenic impact on the bottom sediment layer during the redevelopment of these fields (Ivanov and Matrosova, 2019).

### 2. Georgian Sector

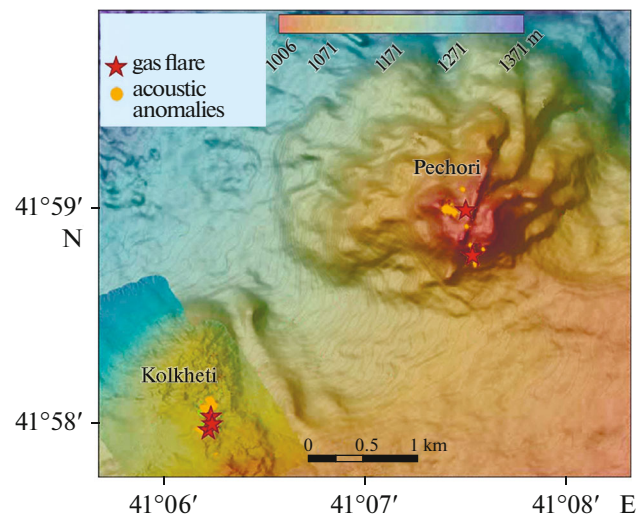
Oil seeps within the Georgian sector offshore of Poti (about 48 km) have long been known (Judd and Hovland (2007). We shall not dwell on them here, but we do refer the reader to the works of MacDonald and Naehr (2011), Evtushenko and Ivanov (2012) and Zatyagalova (2012), in which they were given considerable attention. Note that detailed bathymetric and geophysical surveys performed by experts have confirmed the presence of two powerful underwater sources of oil at the bottom of the sea (Pechori mount and Kolkheti seep) and revealed a number of secondary seeps in this area that are periodically active and emit slightly smaller volumes of oil onto the sea surface (MacDonald and Naehr, 2011). Using SAR data, the positions of two powerful sources on the seabed at points with coordinates  $41^{\circ}59' \text{ N}$  and  $41^{\circ}07'30'' \text{ E}$ ,  $41^{\circ}58' \text{ N}$  and  $41^{\circ}06'15'' \text{ E}$ , and depths of 1000–1050 m were determined independently (Fig. 3), and even estimates of the seep rates were obtained. The volumes of oil emissions from regular activity were estimated at 1 to 8 tons of oil per day (or 400 to 3000 tons per year). Analysis of the entire data set allowed a connection to be established between oil slicks on the sea surface and processes of hydrocarbons accumulation and migration in the sedimentary complex of this part of the sea.

### 3. Turkish Sector

In the Turkish sector, space-based SARs has also detected natural oil seepage 19.6 km northeast of the city of Rize and 43 km off the shores of the city of Ünye (Ivanov et al., 2017b). Two places with a grouping of slicks on the sea surface were identified by analyzing SAR images obtained at different times as a result of a SAR survey, and thus the locations of sources of oil on the sea floor.

Oil seepage off Rize has been long known. Its slicks have been observed on SAR images of the Envisat, Radarsat-1, Sentinel-1A/1B and Landsat-8 satellites. Analysis reveals that the source of oil is located in the deep-water part of the sea at a depth of about 1050 m at the base of the continental slope and at  $41^{\circ}09'10'' \text{ N}$  and  $40^{\circ}41'06'' \text{ E}$  (Fig. 4a). Considering its constant flow, it is estimated that the oil discharged from this source may provide an average supply of 0.3 to 2.5 tons of oil per day, or 140 to 1000 tons per year.

The second source of natural oil, discovered off the city of Ünye, is located in the deep-water part of the sea



**Fig. 3.** Pechori mount and the Kolkheti seep, the main sources of oil seepage in the Georgian sector of the Black Sea (original figure from MacDonald and Naehr (2011)).

at a depth of about 1020 m, in the middle part of the continental slope at  $41^{\circ}31'09'' \text{ N}$  and  $37^{\circ}20'23'' \text{ E}$  (Fig. 4b). It was also discovered in 2016 as a result of radar monitoring.

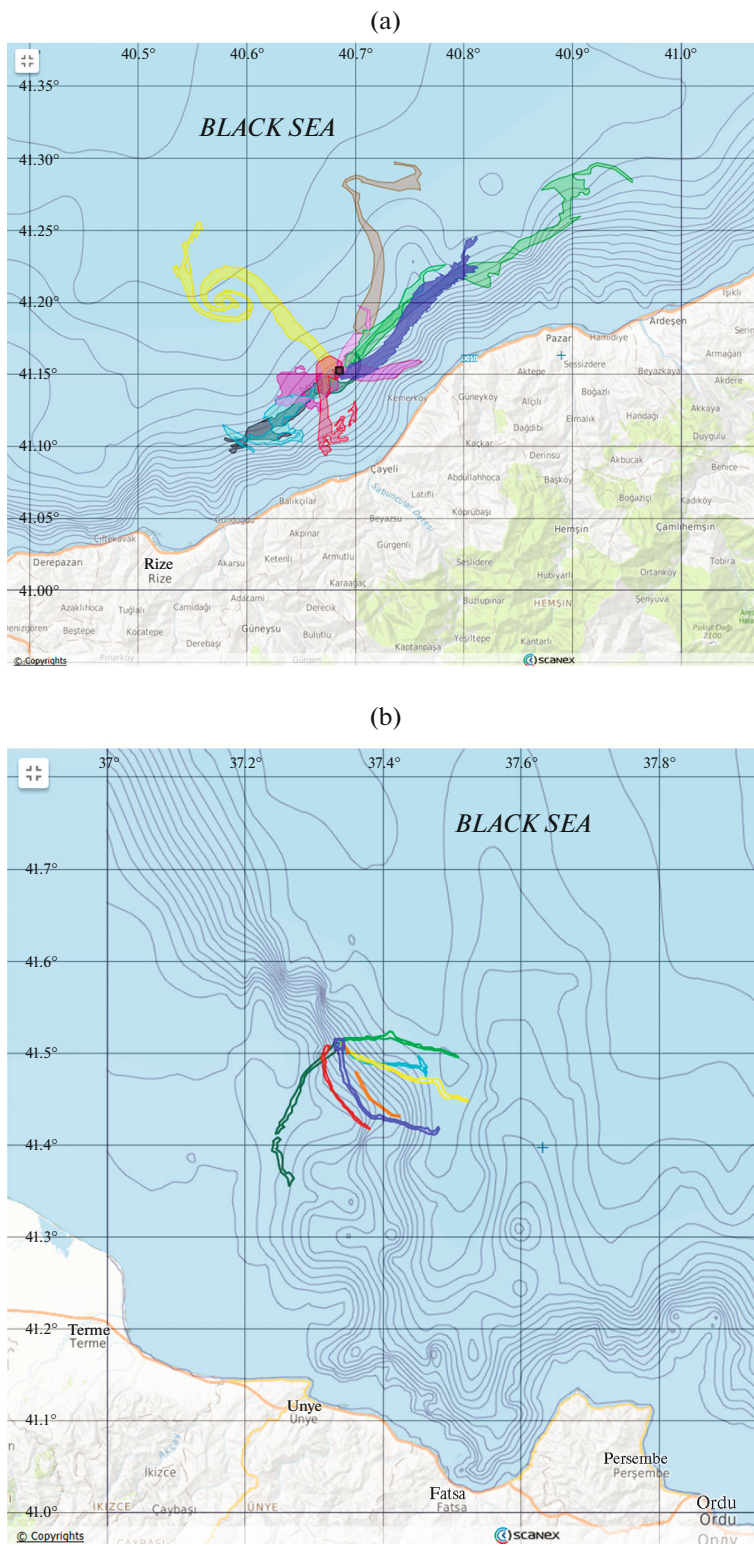
As in other areas of the sea, natural oil seeps in the southeastern part of the Black Sea are generally caused by the accumulation and migration of liquid hydrocarbons in the sediments of the continental slope (Judd and Hovland, 2007; Kruglyakova et al., 2009).

### Sea of Azov

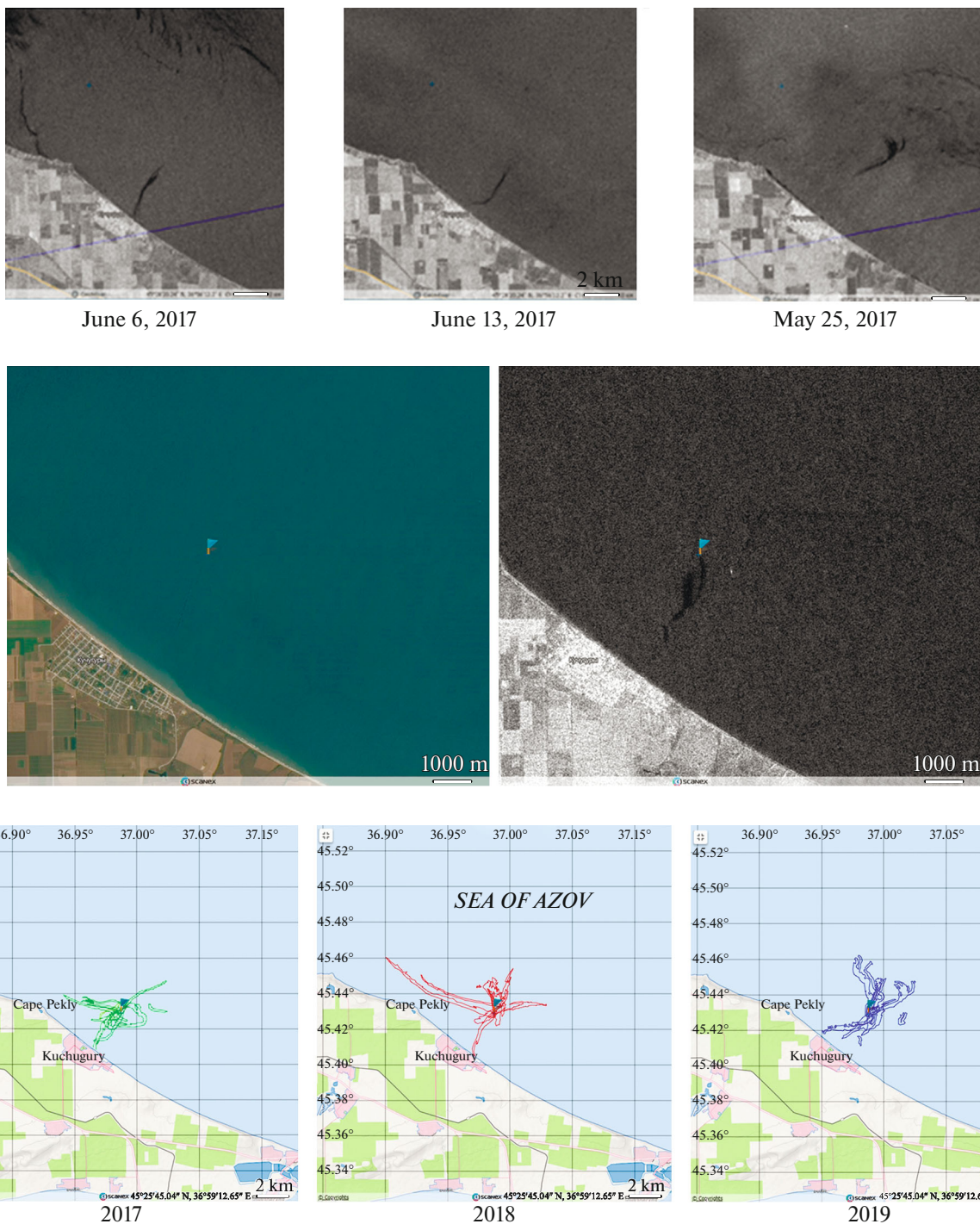
Even though single and episodic oil seep manifestations have often been recorded in different parts of the Sea of Azov, constant oil seepage has been detected only in the southern part of the sea, 3.5 km from the village of Kuchugury. It was discovered in 2019 by analyzing SAR images obtained by the Sentinel-1A/1B satellites in 2017, 2018 and 2019 (Fig. 5a).

Analysis of the monitoring results showed this oil seepage was recorded in 49 SAR images (11 in 2017, 18 in 2018, and 20 in 2019) and in eight optical images of Sentinel-2 and Landsat-8, from which it was found that the slicks on the sea surface were formed by thin oil films (Figs. 5a, 5b).

The slicks found here were mostly linear and 0.5 to 17 km long. The area of the sea covered by oil films ranged from 0.1 to 2.4 km<sup>2</sup>, depending on the wind speed. The fan character of the grouping of slicks at the same place in the sea was detected by spatio-temporal analysis of SAR images for 2017–2019 using the GeoMixer application (Fig. 5c). This indicated there is an underwater source at the bottom, and allowed us to determine its position at a depth of about 10 m and at  $45^{\circ}25'45'' \text{ N}$  and  $36^{\circ}59'13'' \text{ E}$ .



**Fig. 4.** (a) Spatio-temporal grouping of oil slicks in the area of the oil seepage (continental slope of the Black Sea; depth ~1050 m) northeast of the Turkish city of Rize. (b) Spatio-temporal grouping of oil slicks in the area of oil seepage opposite the Turkish city of Ünye (continental slope of the Black Sea; depth ~1020 m). They were detected on SAR images.



**Fig. 5.** (a) Oil seepage in the southern part of the Sea of Azov offshore the village of Kuchugury in sub-scenes of SAR images from the Sentinel-1A/1B satellites. © ESA. (b) Oil seepage in the Sea of Azov on quasi-synchronous images on July 19, 2019: optical Landsat-8 (08:19 UTC) and SAR Sentinel-1A (15:28 UTC). © USGS, ESA. (c) Spatio-temporal grouping of the largest slicks at the place of detecting an underwater source of hydrocarbons in the sea. (d) Detected oil seep (shown by flag) in the system of mud volcanoes of the Taman-Azov Region.

Judging from the participation of geological and geophysical material, there could be a connection between the observed oil seepage and the processes of mud volcanism, along with the release of small volumes of hydrocarbons from the sedimentary complex

of the Sea of Azov, as on the Taman Peninsula. According to the Taman Mud Volcanoes database, the Peklo Azovskoye mud volcanoes and their underwater counterpart lie on the coast and in the coastal waters of the Sea of Azov, in the immediate vicinity of the





Fig. 5. (Contd.)

identified source (5.5 and 4.5 km away, respectively). They are joined by the Kuchugurskiy and Tizdar mud volcanoes (on land and sea) (at 4.6 and 10.5 km away, respectively) (Fig. 5d).

According to Shnyukov et al., (1986), there could be a number of reasons for oil seepage in this area of mud volcanoes, so the explanation of the activity of underwater sources according to the area's oil and gas content is contradictory and should be an object of further research.

### *Barents Sea*

Radar monitoring of the Barents Sea has been under way since 2015 (Ivanov, 2019). Thanks to the possibility of using daily space data from the Sentinel-1A/1B satellites and the GIS approach, a group of natural oil slicks was observed for the first time in the Norwegian sector of the sea. They were visible on 29 SAR images of Sentinel-1A/1B satellites (in 2016, 2017, and 2018), and firstly in the SAR image of May 2, 2016.

The area of seep activity was established from the spatio-temporal grouping of slicks in SAR images of the sea surface (fan structures). This grouping was located in the central part of the sea, 232 km southeast of Hopen Island and 370 km northeast of Bear Island (Fig. 6a). Based on an analysis of the aggregate of slicks using the GeoMixer, it was concluded that a group of three underwater sources lie at the bottom in the deepwater part of the sea at a depth of about 345 m at 75°13' N and 31°45' E. The detected oil slicks formed

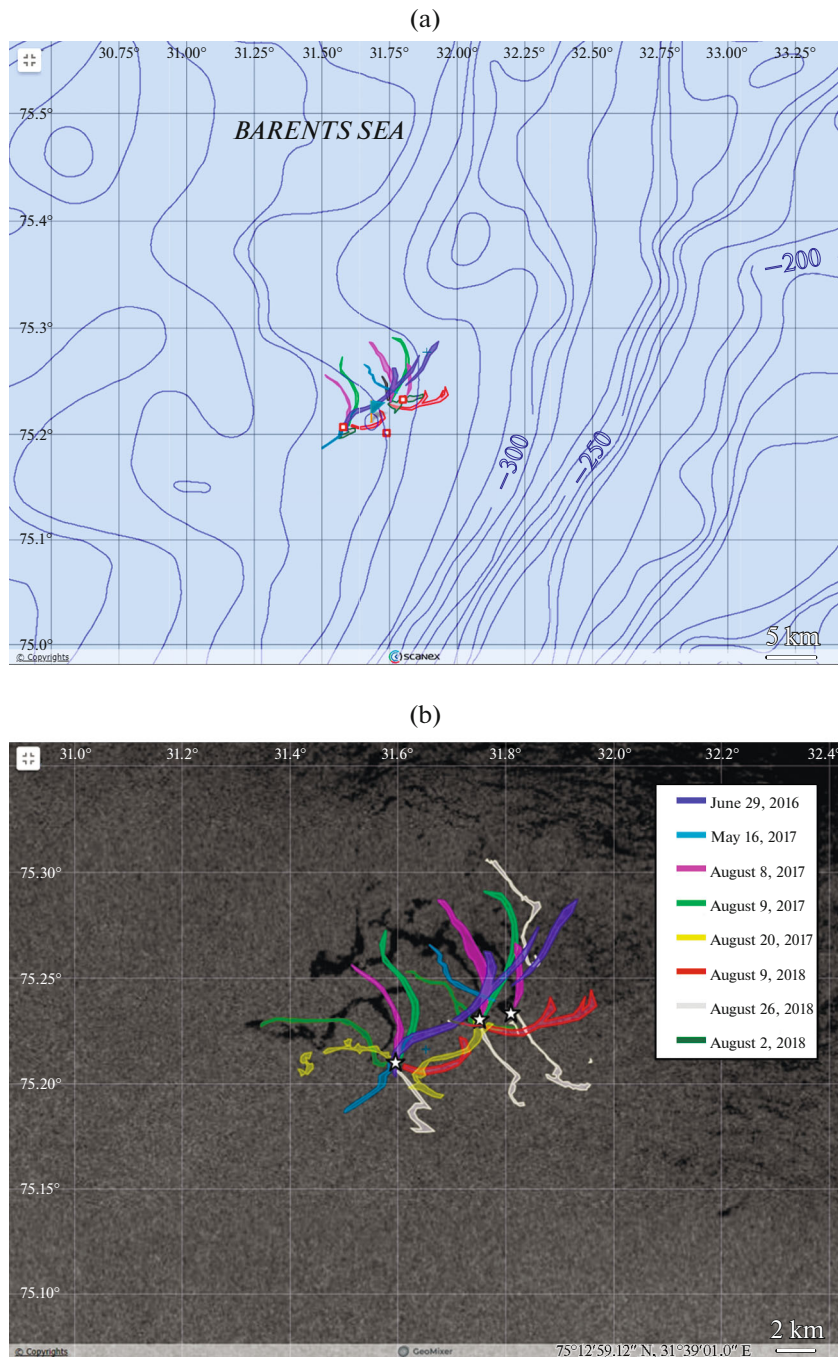
lines up to 23 km long. The area of individual slick ranged from 0.1 to 20 km<sup>2</sup>, mainly depending on the wind speed. Another oil seep is presumably located on the slope of the seamount (at 79°15' N and 46°04' E) to the south-southwest of the Franz Josef Land Archipelago.

Based on an analysis of SAR images and ground-based data on bathymetry and shipwrecks, we may assume the cause of seepage in this region of the Barents Sea could be due to processes of oil migration in the sedimentary complex of the central part of the sea, as in other regions of the World Ocean.

### *Caspian Sea*

One of the best known places of seep activity and oil seepage is the southwestern part of the Caspian Sea (Williams and Lawrence, 2002; Aliev, 2014). In the literature its oil seepage was analyzed in detail by Ivanov et al. (2007, 2015).

SAR imagery allows a new approach to assessing the fluid dynamics in the sediments of the Caspian Sea. The widespread availability of SAR data has also allowed us to detect and study the micro-seep activity of the northern Caspian Sea for the first time (Fig. 7). This activity takes the form of a great many small repeating slicks on the sea surface (Golubov and Ivanov, 2014), which were first recorded on SAR images in 2011. The spacial extent of the slicks indicates that these slicks have been fed from below for some time, and transport on the surface occurs under the influ-

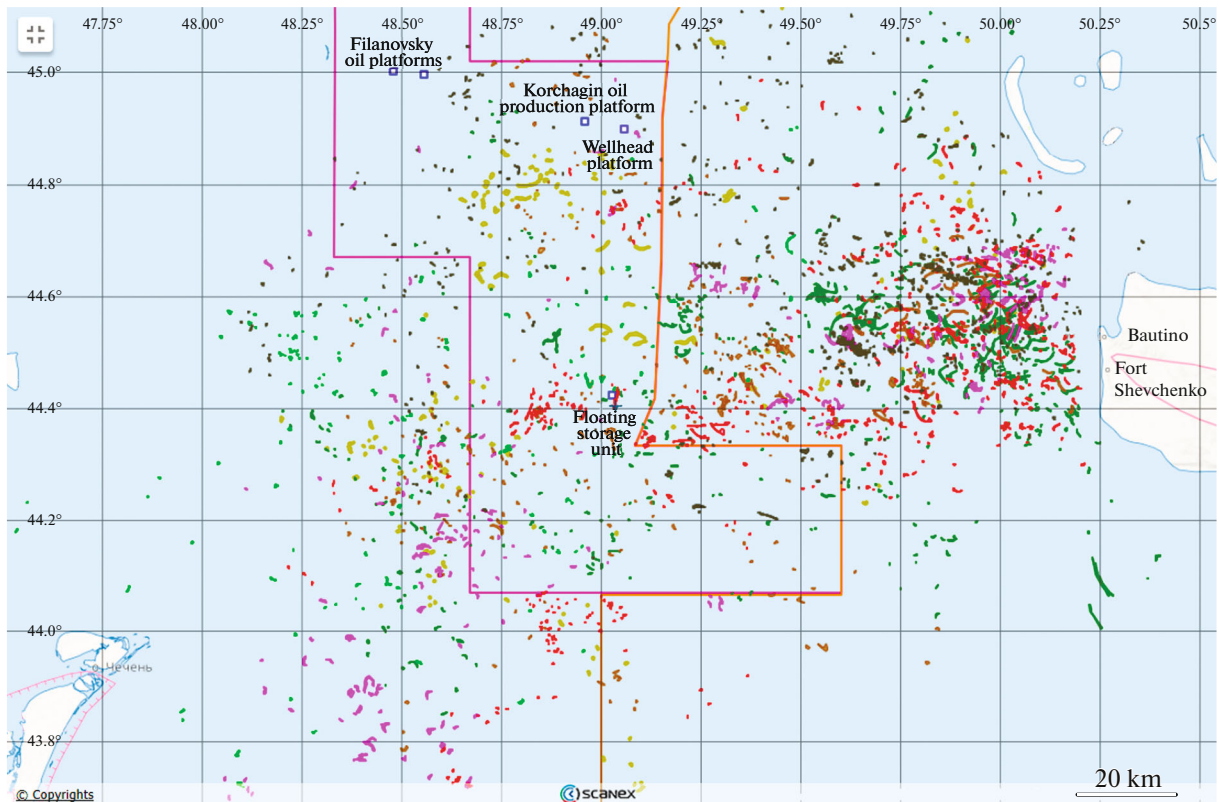


**Fig. 6.** (a) Oil slicks detected in the central part of the Barents Sea (Norwegian sector) in 2018 as a result of monitoring with SAR; (b) Spatio-temporal grouping of slicks caused by the activity of the detected seeps (asterisks) in a sub-scene of the SAR image of Sentinel-1A on August 4, 2017.

ence of currents. Based on the area of an individual slick on the sea surface, it is possible to estimate the volumes of oil coming from the sea floor at weak winds. Estimates of the areas of slicks in several  $\text{km}^2$  indicate that units of  $\text{m}^3$  are required for their formation (Ivanov et al., 2014b).

It is interesting that micro-seep activity has been observed and recorded on SAR images annually, but

only in the spring–summer period (from late March to early June). There are a number of hypotheses about this. One of hypothesis is that such a short period of activity is explained by the influence of the underground hydrosphere, which raises the pressure of underground water after snow melts on land, and the effect it has on the oil and gas bearing strata of sediments. Note also that micro-seep activity with a sim-



**Fig. 7.** Micro-seep activity in the northern Caspian Sea based on satellite monitoring with SAR in 2011–2018 (the boundaries of the sectors of the sea and the license block are shown in light-brown and violet).

ilar regime has started to be observed on the shelf of the Black Sea and in the coastal zone of the Crimean Peninsula.

The results from analyzing ground-based measurements and SAR images obtained over the north and middle of the Caspian Sea also show that a great many small slicks have seepage nature. They are observed on the surface annually, some in approximately the same place, favoring the hypothesis of the periodic release of gas- and oil-saturated fluids from the upper horizons of sedimentary rocks. The results from combining the distribution of slicks observed on the surface in the northern Caspian Sea in 2011–2019 and side-scan sonar data obtained during expeditions by Institute of Oceanology are extremely interesting. In several cases, there is coincidence between objects on the bottom (pockmarks) found using the sonar data and the positions of seep slicks on the sea surface (Putans et al., 2019).

#### *Sea of Okhotsk*

Natural oil seepage in the Sea of Okhotsk was detected for the first time in 2007 on SAR images from the Envisat satellite. The seepage was detected on the northeastern shelf of Sakhalin Island over the promising East Odoptinskaya structure (Ivanov and Zatyaga-

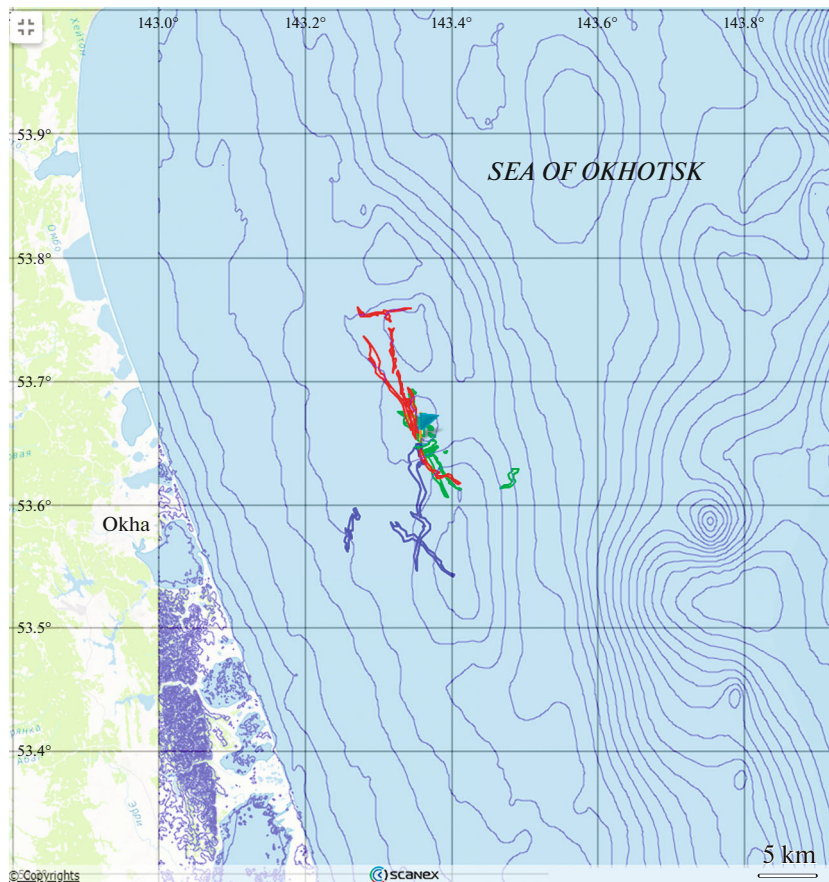
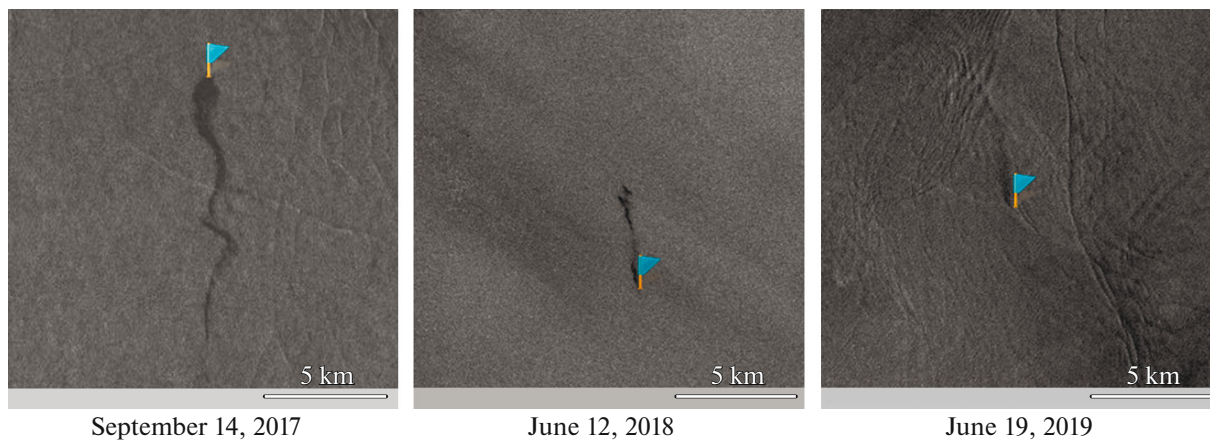
lova (2008) and Ivanov (2010)) and is now well known. It was investigated in more detail by Sizov et al. (2020) using archive SAR imagery.

Near the end of 2019, a spatial grouping of smaller slicks was discovered 21.5 km from the coast and 28 km offshore the town of Okha, to the north of the oil seepage detected earlier. Slicks were recorded on 11 SAR images acquired in 2017, 2018, and 2019 by the Sentinel-1A/1B satellites. They were obviously of natural origin, since they were linear and created a characteristic structure (Figs. 8a, 8b).

Based on the analysis of SAR images obtained at different times in 2017–2019, it was established that this oil seep is due to an underwater source on the sea floor (presumably a cold seep) located at a depth of 67 m at 53°39' N and 143°21' E. Joint analysis using available oil and gas maps showed that this seep is located on one of the structures of the Kaigan field (Sakhalin-5 project). Estimates of emission using the BAOAC (2016) method yield average values of 0.16 m<sup>3</sup> of oil per day and up to 58 m<sup>3</sup> per year.

#### CONCLUSION

An analysis was performed of results from studies aimed at searching and detecting natural oil seepage in the seas washing Russia using spaceborne SAR imag-



**Fig. 8.** (a) Examples of oil slicks on the northeastern shelf of Sakhalin Island in sub-scenes of SAR images of Sentinel-1A/1B satellites. © ESA. (b) Spatio-temporal grouping of slicks at the place of an oil seepage discovered on the shelf.

ery. Specific examples were given of the possibilities for detecting oil seepage using spaceborne SARs, which is now one of the most effective ways of searching and detecting such phenomena. The availability of remote sensing data and the simplicity of their processing and interpretation ensure the reliability and high probability of identifying oil seep signatures. The use of SAR images and the accompanying geological, geophysical, and bathymetric information ultimately

provides a complete picture of the sources of hydrocarbons in different seas.

It is obvious that satellite information on the state of the sea surface complements the set of traditional geological and geophysical observations and greatly improves ways of searching and detecting underwater sources of oil and gas on the shelves of Russian seas. This became possible only after the launch of the Euro-

pean satellites Sentinel-1A/1B (the Sentinel-1C/1D are planned), which provide daily SAR surveys of a number of important water basins, and the Arctic seas as often as twice a day. In addition, in conditions when surface manifestations are often inexpressive, only GIS approach allows us to obtain positive results.

The procedure for recognizing areas of seep activity in the sea was improved, allowing us to determine the position of sources on the bottom. We can now obtain information about their activity and volumes of oil emissions, and in some cases to establish the causes of natural oil seepage in the context of the regional oil and gas potential. Accumulations of oil, gas, and gas condensate formed in different periods of the Earth's geological history can be found in areas where oil seepage is widespread and should be confirmed in detail.

The detection of new oil seeps using satellite imagery once again confirms the effectiveness of such approaches. This is illustrated by the discoveries of new sources of oil in the Sea of Azov, the Barents Sea, the Caspian Sea, the Sea of Okhotsk, the Adriatic Sea (Ivanov and Morovič, 2020) and the Persian Gulf (Ivanov and Gerivani, 2020).

Finally, satellite observations are an effective and important source of information about different processes and phenomena in the seas and oceans. The growing constellation of remote sensing satellites and improvement in ways of analyzing satellite information allow us to steadily expand the practical application of satellite data for detecting and studying natural oil seepage in the ocean.

#### ACKNOWLEDGMENTS

The authors are grateful to the SCANEX Group for allowing us to use resource geoportals created on the basis of the GeoMixer application.

#### FUNDING

The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme no. 0149-2019-0003). It was also partially supported by the Russian Foundation for Basic Research, project no. 18-55-20010.

#### REFERENCES

- Aliev, A.A., Mud volcanoes of the Caspian Sea, *Geol. Polezn. Iskop. Mirovogo Okeana*, 2014, no. 1, pp. 33–44 [in Russian].
- BAOAC (Bonn Agreement Oil Appearance Code), 2016. [https://www.bonntagreement.org/site/assets/files/1081/special\\_on\\_volume\\_calculation\\_20160607.docx](https://www.bonntagreement.org/site/assets/files/1081/special_on_volume_calculation_20160607.docx).
- Bondur, V., Complex satellite monitoring of coastal water areas, in *Proc. 31st Int. Symp. Remote Sens. Environment (ISRSE-2005)*, St. Petersburg, 2005.
- Bondur, V.G., Aerospace methods and technologies for monitoring oil and gas areas and facilities, *Izv., Atmos. Ocean. Phys.*, 2011a, vol. 47, no. 9, pp. 1007–1018.
- Bondur, V.G., Satellite monitoring and mathematical modelling of deep runoff turbulent jets in coastal water areas, in *Waste Water—Evaluation and Management*, F.S.G. Einschlag, Ed., Rijeka, Croatia: InTech, 2011b, pp. 155–180.
- Bondur, V.G. and Kuznetsova, T.V., Study of natural oil and gas seeps on the sea surface using space imagery, in *Aerokosmicheskii monitoring ob'ektov neftegazovogo kompleksa* (Aerospace Monitoring of Oil and Gas Industrial Units), Bondur, V.G., Ed., Moscow: Nauchnyi Mir, 2012, pp. 272–287 [in Russian].
- Bondur, V.G. and Kuznetsova, T.V., Detecting gas seeps in Arctic water areas using remote sensing data, *Izv., Atmos. Ocean. Phys.*, 2015, vol. 51, no. 9, pp. 1060–1072.
- Bondur, V. and Starchenkov, S., Monitoring of anthropogenic influence on water areas of Hawaiian islands using Radarsat and Envisat radar imagery, in *Proc. 31st Int. Symp. Remote Sens. Environment (ISRSE-2005)*, St. Petersburg, 2005, pp. 184–187.
- Bondur, V.G. and Zamshin, V.V., Space radar monitoring of offshore regions in hydrocarbon production and transportation areas, in *Aerokosmicheskii monitoring ob'ektov neftegazovogo kompleksa* (Aerokosmicheskii monitoring ob'ektov neftegazovogo kompleksa), Bondur, V.G., Ed., Moscow: Nauchnyi Mir, 2012, pp. 255–271 [in Russian].
- Bondur, V.G. and Zamshin, V.V., Comprehensive ground-space monitoring of anthropogenic impact on Russian Black Sea coastal water areas, in *Proc. 3rd Scientific-Practical Conf. "Research and Development-2016"*, SpringerOpen, 2018, pp. 625–637.
- Bondur, V.G., Kuznetsova, T.V., Vorob'ev, V.E., and Zamshin, V.V., Detection of gas seeps on the Russian shelf from satellite imagery, *Georesur. Geoenerg. Geopolit.*, 2014, no. 1, pp. 1–23 [in Russian].
- Bukharitsin, P.I., Golubov, B.N., and Ivanov, A.Yu., *Metodika prognoza avariinykh vybrosov plastovykh flyuidov iz nedr morskikh mestorozhdenii nefii i gaza* (Methodology for Predicting Emergency Fluid Emissions from Offshore Oil and Gas Fields), Saarbrücken: Palmarium Academic Publishing, 2016 [in Russian].
- Daneshgar Asl, S., Dukhovskoy, D., Bourassa, M., and Macdonald, I.R., Hindcast modeling of oil slick persistence from natural seeps, *Remote Sens. Environ.*, 2017, vol. 189, pp. 96–107.
- De Miranda, F.P., Marmol, A.M.Q., Pedroso, E.C., et al., Analysis of Radarsat-1 data for offshore monitoring activities in the Cantarell Complex, Gulf of Mexico, using the unsupervised semivariogram textural classifier (USTC), *Can. J. Remote Sens.*, 2004, no. 3, pp. 424–436.
- Etiopie, G., *Natural Gas Seepage*, Springer, 2015.
- Evtushenko, N.V. and Ivanov, A.Yu., Oil seeps in the southeastern Black Sea according to satellite SAR images, *Issled. Zemli Kosmosa*, 2012, no. 3, pp. 24–30 [in Russian].
- Garcia-Pineda, O., Zimmer, B., Howard, M., et al., Using SAR images to delineate ocean oil slicks with a texture-

- classifying neural network algorithm (TCNNA), *Can. J. Remote Sens.*, 2009, pp. 411–421.
- Golubov, B.N. and Ivanov, A.Yu., Activation of oil seeping in the northern and middle Caspian sea in April–June 2012 according to satellite and geological and geophysical data, *Issled. Zemli Kosmosa*, 2014, no. 2, pp. 67–81 [in Russian].
- Gubkin, I.M., *Ucheniye o nefi* (The Theory of Oil), Moscow: Nauka, 1975 [in Russian].
- Ivanov, A.Yu., Slicks and film signatures on synthetic aperture radar images, *Issled. Zemli Kosmosa*, 2007, no. 3, pp. 73–96 [in Russian].
- Ivanov, A.Yu., On the retrieval of environmental parameters from satellite SAR data, *Issled. Zemli Kosmosa*, 2010, no. 3, pp. 77–92 [in Russian].
- Ivanov, A.Yu., Natural oil seepage in the Caspian and Barents seas: Detection and analysis from remote sensing data, *Okeanol. Issled.*, 2019, vol. 47, no. 5, pp. 52–64 [in Russian].
- Ivanov, A.Yu. and Gerivani, H., Oil leaking and seeping site in the Persian Gulf detected and studied by satellite observations, *Mar. Georesour. Geotechnol.*, 2020. <https://doi.org/10.1080/1064119X.2020.1853286>
- Ivanov, A.Yu. and Matrosova, E.R., Man-made seepage activity in the northwestern Black Sea according to satellite imagery, *Ekol. Prom-st. Ross.*, 2019, vol. 23, no. 8, pp. 57–63 [in Russian].
- Ivanov, A.Yu. and Morović, M., Detection and mapping oil seeps in the Adriatic Sea using SAR imagery, *Acta Adriat.*, 2020, no. 1, pp. 13–26.
- Ivanov, A.Yu. and Zatyagalova, V.V., Mapping oil spills in the marine environment using satellite SAR imagery and geographic information systems, *Issled. Zemli Kosmosa*, 2007, no. 6, pp. 46–63 [in Russian].
- Ivanov, A.Yu. and Zatyagalova, V.V., Radar monitoring of offshore platform installation and transportation sites, *Oil Gas J. Russia*, 2008, no. 16, pp. 61–70 [in Russian].
- Ivanov, A.Yu., Golubov, B.N., and Zatyagalova, V.V., On oil-gas-bearing and unloading of underground fluids in the southern part of the Caspian Sea using synthetic aperture SAR images, *Issled. Zemli Kosmosa*, 2007, no. 2, pp. 62–81 [in Russian].
- Ivanov, A.Yu., Kolmykov, E.V., Bobkov, A.A., et al., On the nature and reasons of the occurrence of small-scale film slicks in the Northern Caspian Sea detected by satellite radar monitoring, *Zashch. Okruzh. Sredy Neftgazov. Komplekse*, 2014a, no. 12, pp. 17–22 [in Russian].
- Ivanov, A.Yu., Potanin, M.Yu., Filimonova, N.A., et al., Operational monitoring of marine water areas: New GIS solutions and internet technologies, *Zemlya Kosmosa – Naibolee Eff. Resheniya*, 2014b, no. 18, pp. 37–42. [zikj.ru/images/archive/no18\\_en/no18-4-ivanov-en.pdf](http://zikj.ru/images/archive/no18_en/no18-4-ivanov-en.pdf).
- Ivanov, A.Yu., Golubov, B.N., and Terleeva, N.V., Comparative analysis of oil seep distribution in the southern Caspian Sea with estimation of oil and gas bearing using satellite SAR images, *Issled. Zemli Kosmosa*, 2015, no. 6, pp. 47–61 [in Russian].
- Ivanov, A.Yu., Kucheiko, A.Yu., Evtushenko, N.V., et al., Natural oil seepage in Crimean waters of the Black Sea according to SAR data, in *Vseross. otkr. konferentsiya “Sovrem. Probl. Distantzionnogo Zondirovaniya Zemli iz Kosmosa”* (All-Russian Open Conference “Current Problems of Remote Sensing of the Earth from Space”), Moscow: SRI RAS, 2017a [in Russian].
- Ivanov, A.Yu., Kucheiko, A.A., Filimonova, N.A., et al., Spatial and temporal distribution of oil spills in the Black Sea and the Caspian Sea based on SAR images: Comparative analysis, *Issled. Zemli Kosmosa*, 2017b, no. 2, pp. 13–25 [in Russian].
- Ivanov, A.Yu., Gerivani, H., and Evtushenko, N.V., Characterization of natural hydrocarbon seepage in the South Caspian Sea off Iran using satellite SAR and geological data, *Mar. Georesour. Geotechnol.*, 2020, no. 5, pp. 527–538.
- Jatiault, R., Dhont, D., Loncke, L., and Dubuc, D., Monitoring of natural oil seepage in the Lower Congo Basin using SAR observations, *Remote Sens. Environ.*, 2017, pp. 258–272.
- Judd, A. and Hovland, M., *Seabed Fluid Flow: The Impact on Geology, Biology and the Marine Environment*, Cambridge University Press, 2007.
- Kruglyakova, R.P., Kruglyakova, M.V., and Shchevtsova, N.T., Geological and geochemical characterization of natural hydrocarbon occurrences in the Black Sea, *Geol. Polezn. Iskop. Mirovogo Okeana*, 2009, no. 1, pp. 37–51 [in Russian].
- Kvenvolden, K.A. and Cooper, C.K., Natural seepage of crude oil into the marine environment, *Geo-Mar. Lett.*, 2003, nos. 3–4, pp. 140–146.
- Lavrova, O.Yu., Mityagina, M.I., and Kostyanoi, A.G., *Sputnikovye metody vyyavleniya i monitoringa zon ekologicheskogo riska morskikh akvatoriy* (Satellite Methods for Detecting and Monitoring of Marine Ecological Risk Zones), Moscow: SRI RAS, 2016 [in Russian].
- Leifer, I., A synthesis review of emissions and fates for the Coal Oil Point marine hydrocarbon seep field and California marine seepage, *Geofluids*, 2019, no. 4724587, pp. 1–48. <http://downloads.hindawi.com/journals/geofluids/2019/4724587.pdf>.
- MacDonald, I. and Naehr, T., Remote sensing and sea truth measurements of methane flux to the atmosphere (HYFLUX project), Quart. Rep. Oct.–Dec. 2010, National Energy Technology Laboratory, Texas A&M University, USA, 2011. [https://netl.doe.gov/sites/default/files/netl-file/NT0005638\\_QPROct-Dec 2010.pdf](https://netl.doe.gov/sites/default/files/netl-file/NT0005638_QPROct-Dec 2010.pdf).
- MacDonald, I., Guinasso, N.L., Ackleson, S.G., et al., Natural oil slicks in the Gulf of Mexico visible from space, *J. Geophys. Res.*, 1993, vol. 98, no. C9, pp. 16351–16364.
- MacDonald, I., Leifer, I., Sassen, R., et al., Transfer of hydrocarbons from natural seeps to the water column and atmosphere, *Geofluids*, 2002, vol. 2, no. 2, pp. 95–107.
- Pasynkov, A.A., The hydrocarbon gas components of the Azov–Black Sea basin, *Geopolit. Ekogeodin. Reg.*, 2017, vol. 3, no. 2, pp. 16–20 [in Russian].
- Putans, V.A., Merklin, L.R., Ivanov, A.Yu., and Ambrosimov, A.K., Manifestations of modern fluid dynamic activity in the northern Caspian Sea (geophysical data), *Okeanol. Issled.*, 2019, vol. 47, no. 5, pp. 98–115 [in Russian].
- Serikova, U.S., The beginning of the development of offshore oil and gas industry in Russia and abroad, *Istor.*

- Pedagog. Estestvozn.*, 2015, no. 3, pp. 12–15 [in Russian].
- Shnyukov, E.F., Sobolevskii, Yu.V., Gnatenko, G.I., et al., *Gryazeveye vulkany Kerchensko-Tamanskoi oblasti. Atlas (Mud Volcanoes of the Kerch–Taman Region)*, Kiev: Naukova Dumka, 1986 [in Russian].
- Shnyukov, E.F., Pasyukov, A.A., Lyubitskii, A.A., et al., Mud volcanoes on the Kerch shelf and the continental slope of the Black Sea, *Geol. Polezn. Iskop. Mirovogo Okeana*, 2010, no. 3, pp. 28–36 [in Russian].
- Shnyukov, E.F., Kobolev, V.P., and Pasyukov, A.A., *Gazovyi vulkanizm Azovo–Chernomorskogo regiona (Gas Volcanism of the Azov–Black Sea Region)*, Kiev: LOGOS, 2013 [in Russian].
- Sizov, O.S., Chudakova, M.A., and Lobzhanidze, N.E., Monitoring of natural oil seeping along the northeastern coast of Sakhalin Island based on radar and optical remote sensing data, *Zashch. Okruzh. Sredy Neftegazov. Komplekse*, 2020, no. 2, pp. 63–69 [in Russian].
- Struckmeyer, H.I.M., Williams, A.K., Cowley, R., et al., Evaluation of hydrocarbon seepage in the Great Australian Bight, *J. Aust. Pet. Prod. Explor. Assoc.*, 2002, vol. 42, no. 1, pp. 371–385.
- Williams, A. and Huntley, A., Oil from space: Detecting the sleeping giants of the deep-water Caspian by satellite, in *Petroleum Exploration Society Conf. (Petex-98)*, London, 1998, pp. 1–3.
- Williams, A. and Lawrence, G., The role of satellite seep detection in exploring the South Atlantic’s ultra deep water. Surface exploration case histories: Applications of geochemistry, magnetics, and remote sensing, *AAPG Stud. Geol.*, 2002, vol. 48, pp. 327–344.
- Zatyagalova, V.V., On some specific features of natural hydrocarbon seeps in the eastern part of the Azov–Black Sea basin, *Sovrem. Probl. Distantionnogo Zondirovaniya Zemli Kosmosa*, 2012, vol. 9, no. 4, pp. 194–201 [in Russian].

*Translated by V. Selikhanovich*