Hydrocarbon seeps and mud volcanoes in the Caspian Sea characterized with use of the Envisat ASAR images

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A numerous oil slicks of natural origin were revealed in the southwest (SW) part of Caspian Sea by the synthetic aperture radar (SAR) images acquired by Envisat satellite in 2003-2004. On the basis of computer processing, visual analysis of SAR images and comparisons with bathymetry, geophysical and seismic data in geographic information system (GIS), a link between these slicks and unloading of liquid hydrocarbons in the SW Caspian is established. Oil slicks are basically concentrated above domes of local geological formations of the sedimentary cover. In total more than 90 seeps and mud volcanoes having a repeating regime and representing an active type were identified; they are distributed across the SW Azerbaijan and West Iranian sectors. Periodical occurrence of slicks can reflect alternation of mud volcanism pulses forced by intensive seismicity with the quiet periods. Seepage rate of oil in the SW part of the Caspian Sea according to SAR images is estimated to be up to 16,000 metric tons per year. The importance of unloading of oils on hydrochemistry and ecological conditions of the Caspian Sea is demonstrated. Conclusion is done that the Envisat SAR to be an excellent tool for studying oil seeps through observation oil slicks floating on the sea surface.

Introduction. It is well-known that natural oil seeps (a common name of leaking structures located on the seafloor, such as salt, mud volcanoes, gas-hydrate mounds, gryphons, etc.) can indicate the accumulations of seabed hydrocarbon rocks. Most seepage worldwide is located along linear trends above faults or fractured anticlines on the seafloor. In the offshore conditions leaking oil are often can be detected due to the fact that oil is transported from the seafloor to the surface as gas bubbles coated by oil or oil drops. Oil on the surface forms thin oil films, which in calm sea conditions are often visible as slicks.

Spaceborne synthetic aperture radar (SAR) systems, such as ASAR aboard the Envisat satellite, are an ideal tool for these applications, since they have day-and night capability and are not affected by cloud conditions. Detection of oil slicks related to seepages using SAR aboard the ERS-1/ERS-2, Almaz-1 and Radarsat satellites, has been successful worldwide [1-5].

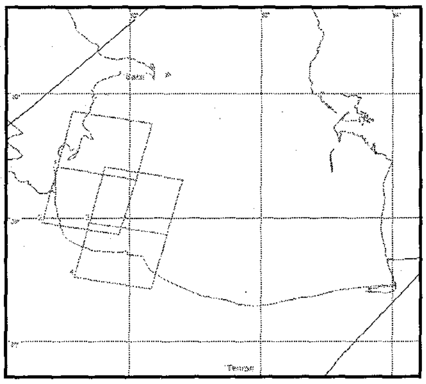

Figure 1 Coverage of the SW part of the Caspian Sea by Envisat ASAR images.

Combination SAR imagery with geophysical, seismic and bathymetry data enables to detect and map natural oil seep-related slicks on the sea surface and link them with seafloor structures. For example, InfoTerra and NPA (Nigel Press Associates Ltd.) are providing oil seep detection service to oil and gas companies through Offshore Basin Screening (OBS) technique [6]. The OBS combines seepage detection using ERS, Envisat and Radarsat SAR imagery with collection geophysical data to investigate basin structure and to map regional seep distribution. The InfoTerra's Global Seeps Database (GS) and NPA's Global Offshore Seeps Database (GOSD) covered more than 75% of the world's seepage phenomena.

One of the largest and intense seepage occurs in the southwest (SW) part of the Caspian Sea. The hydrocarbon seeps in the sea have a long history. In the middle 1900s seepages were used by the explorers to identify petroleum deposits and develop oil production. Nowadays the Caspian Sea is one of the most important production areas in Middle Asia. Slick mapping technology developed in [7] is applied to study an impact of seepage on the marine environment of the Caspian Sea. Based on combination Envisat ASAR images with essential supplemental information including geographical, geophysical and seismic data in geographical information system (GIS), this technology can significantly improve the characterization of natural seeps through observations of slicks floating on the sea surface.

Envisat ASAR images and their processing. Seven pairs of Envisat ASAR scenes acquired in the framework of this AO Envisat project 226 in Image Mode (100 m swath width and 25 m resolution) provide 200 km strips of data covering the SW Caspian (Fig. 1). They have been used to characterize hydrocarbon upflow in the Caspian Sea and restore parameters of leaking underwater sources in coordination with collection additional geophysical and seismological data. SAR images showing multiple seepage slicks from the deepwater Caspian are shown on Fig. 2; their parameters are summarized in Tab. 1. All SAR images were acquired under appropriate wind and sea-state conditions, when wind speed did not exceed 6-7 m/s.

The technology applied includes: (1) SAR image processing including antenna pattern correction, SAR image filtering and speckle noise reduction, (2) detection of dark features, (3) interactive classification on the basis of geometrical/textural properties and contextual information, and (4) discrimination among other look-alikes. When the oil slicks in each SAR image have been identified, the images were georeferenced and mosaic layer created. Then all identified oil slicks were contoured; these contoured areas on the SAR images were separated, removed from image background and put on the map projection. By such way the slick distribution map has been created; finally it has been integrated with GIS.

Fig. 3 shows the map of seepage slicks that have been imaged by the Envisat satellite in period from July, 2003 to October 2004. About 90 potential oil sources were identified in the SW Caspian, which, as shown in [3], in most cases have repeating point sources and represent active underwater mud volcanoes. Widely distributed across the SW Caspian Sea, in deep-water Azerbaijan and Iranian sectors, they remake enormous masses of sediments and often serve as an indicator of hydrocarbon accumulations.

Table 1. Parameters and conditions of collected ASAR images and oil slick/pollution characteristics

Orbit	Frame	Date	Wind speed, m/s	Number of slicks	Average area of a slick, km^2	Total area, km^2
7031	2817 2835	5.07.03	3-6	30	3.4	101.6
7532	2817 2835	9.08.03	2-7	78	1.5	113.9
8534	2799 2817	18.10.03	2-4	52	1.3	66.7
10767	2817 2835	22.03.04	2-6	64	0.5	31.4
11540	2817 2835	15.05.04	3-7	69	1.2	84.3
11769	2817	31.05.04	2-4	98	1.3	127.2
13544	2817 2835	2.10.04	2-5	32	0.6	19.3

Extracting seepage characteristics. A number of key parameters characterizing detected oil slicks and their distribution such as locations, total number and total area (as a sum of areas of all detected slicks) for each day were calculated using the standard procedures available in GIS. For estimation of pollution produced by these seeps two methods, based on measurements of amount of oil in a film of known thickness were applied. Results of these calculations are presented in Tab. 1,2. Other seepage characteristics have been extracted on a basis of results of previous studies and modeling.

Table 2. Estimated rate of natural seepage of oil into the marine environment of the Caspian Sea

Min and max total area of slicks, km^2	metric tons/day		metric tons/ year	Remarks
19.3	6.8		2,500	Estimates based on Russian Hydrometeorological Service's method [8]; film thickness ~ $0.5*10^{-3}$ mm
127.2	44.5		16,200	
	min silvery	max rainbow		
19.3	0.4	5.8	1,700	Estimates based on Bonn Agreement Counter Pollution Manual [9]
127.2	2.5	38.2	11,100	

Results and Discussion

1 Oil bearing of the seafloor structures. In total 423 slicks were mapped, all of them were interpreted as seepage slicks with high level of confidence. The average area of oil slicks varies from 0.6 to 3.4 km^2, while total area does from 19.3 to 127.2 km^2 (Tab. 1). The relatively large number of seepage slicks on the sea surface can reflect a high density of hydrocarbon accumulations. There is a firm link between locations of leaking structures and those of geological formations discovered by conventional methods in this region. This causal relationship was known long ago before the launch the first SAR-equipped satellite. Oil slicks were detected floating near the oil fields in the SW Caspian Sea in seven Envisat SAR images collected over 15 month time interval. Evidently oil slicks detected on SAR images are signs of upflow of the liquid hydrocarbons from the interior of the Earth and local geological formations (deltaic and marine source rocks) beneath are oil-bearing. Clusters of oil slicks were observed on the sea surface above the following local structures (Fig.4 a, b): Shirvan-Deniz, Inam, Kurgan-Deniz, Salavan, Irs, D-7, D-20, D-35, D-45, D-52, D-54 and D-55, but only three of them, i.e. Inam, Kurgan-Deniz and Salavan, are marked as perspective ones (Fig. 4). Several clusters of oil slicks occur on the Azerbaijan shelf, in water depths of less than 150 m, over well-known underwater mud volcanoes (Fig. 3). There are also perspective fields in Iranian sector of the Caspian Sea, but additional exploration is needed (Fig. 4).

2 Shape of oil slicks. On the sea surface, the oil forms slicks and drifts under the effects of wind and currents. Shape of detected oil slicks is changing from small spots to semicircles or even circles and loops (Fig. 2). The current first and wind second are those factors, which affect the slick size and shape on the SAR images. Sometimes the hook or loop shape of oil slicks highlights the effect of vorticity of the surface currents. In particular, involved into cyclonic eddies, generated at the periphery of main current, slicks followed anticlockwise circulation. In turn, the local current field in a great extent can reflects the wind forcing. One of interesting seep's characteristics is double/triple signatures that clearly seen on the SAR images (Fig. 2). By analyzing slicks in GIS, evidence that they have nested behavior and emission points (circles on Fig. 3) can be obtained.

According to the NPA classification [6] these slicks can be categorized as Rank 1 seepage slicks because they have a characteristic shape, emission points, repeating and nested behavior (Fig. 2 and 3). Such slicks are resulting from multi-emission points and associated with prolific seepage.

3 Seepage rate. Estimates of seepages rate directly depend on the film thickness and area covered by oil. Seepage film thickness and lifetime of oil slick on the sea surface are estimated to be 10^{-3} до 10^{-4} mm and 8-24 hrs (12 hrs in average) correspondingly [1]. These parameters strongly affect estimations of seepage rate. According to many observations a color of oil films floating on the sea surface above seeps, and mud volcanoes ranging from silvery to rainbow [8,9].

Two methods have been applied to estimate seepage rate. One of them was developed by Russian Hydrometeorological Service [8] and based on experimental observations, another one is known as Bonn Agreement' method [9] and based on color coding of oil films. In the first one is assumed that one km^2 of oil film to contain ~0.5 metric ton (t) of oil in average. The second one uses color of oil films to calculate oil concentration: oil concentration in silvery films (film thickness of $2*10^{-4}$ mm) is 0.02 t/km^2, in grey films ($1*10^{-3}$ mm) – 0.1 t/km^2 and in rainbow films ($3*10^{-3}$ mm) – 0.3 t/km^2. Min and max estimates of seepage rate associated with seepages are presented in Tab. 2.

4 Frequency of seeps. SAR images showed that action of underwater seeps can be of two kinds [11]. On the one hand clusters of slicks can be produced by the same source acting periodically. On the other hand the slick clusters can be the results of action of group of different sources. Undoubtedly multiple slicks above the Shirvan-Deniz, Inam, D-35, Kurgan-Deniz, D-7 and Irs local structures (Fig. 3, 4 a,b) mark the locations of mud volcanoes.

Double/triple signatures sometimes visible on the SAR images (Fig. 2) are suggested to be a result of either acting of one source in periodic regime or manifestation of a group of close located underwater sources acting occasionally and simultaneously. In first case, taking into account the velocity of local surface current over the range of 10-30 cm/s, an estimate of acting period in 6-10 hrs can be obtained. It is concluded, therefore, the frequency of slick appearance on the sea surface is rather periodic than episodic.

5 Displacement of slick origin. The surface manifestations are displaced from the seafloor sources by a distance of several hundred meters. This displacement is a function of rise speed (as estimated to be 15-20 cm/s [1]) and movement due to currents in the water column; its magnitude is determined by time oil requires for transit to the surface. Under the assumption that gas bubbles coated by oil rise at speed of 20 cm/s [1] and undergo by permanent with depth current of 10-30 cm/s; this displacement can reach 800-900 m. Our estimate shows the deeper a source the farther a slick from origin. The multiple slicks marks more closely the seep's location on the seafloor in shallow water (100-200 м) than at depths of 500-700 m (Fig. 3).

6 Seepage rate and oil pollution. Evidently that seeps and mud volcanoes bring in the significant contribution to the marine environment of the Caspian Sea. Oil pollution due to seepage can be mistakenly attached to human activity or offshore oil production, although in reality that is one of most characteristic features of the Caspian Sea. Natural oil emission according to Caspian Ecological Program (CEP) is 17,2 % of the total oil pollution, which estimated in 120,000 tons per year [10]. Our max estimate for the SW Caspian Sea gives 16,000 tons per year or 13 % of the total oil pollution of the sea.

For offshore California, an estimate of annual rate of oil seepage is 8,000÷20,000 tons. The annual rate of oil seepage for offshore Alaska is estimated to be about 20,000 tons. Compared with the estimates obtained for the Cantarella seep in the Gulf of Mexico (Venezuela) of 46.4 to 62 tons per day [5] based on the same methodology, our values are 5.8÷38.2 tons per day.

7 A link with regional seismicity. There is a link between activity of seepage and mud volcanoes and seismicity of the region. It was established [11] that activity of mud volcanoes can correlate with seismic activity of the interior. Fig. 6 shows a "first look" correlation between intensity of earthquakes and number of detected oil slicks. It is seen that against a background seismic quiet period from 01.01.2003 to 31.12.2004, there is short-term 'disturbing' period (March-May 2004), which is characterized by an increase of number and magnitude of earthquakes in the Northern Iran (ellipse on Fig.5). Moreover, there is evidence that intensive drilling the sedimentary source rocks and extensive oil production can produce a ground for both man-made eruptions of mud volcanoes and man-made earthquakes. In this connection ability of the Envisat ASAR to get data with low revisit time and wide swath can significantly contribute to this problem.

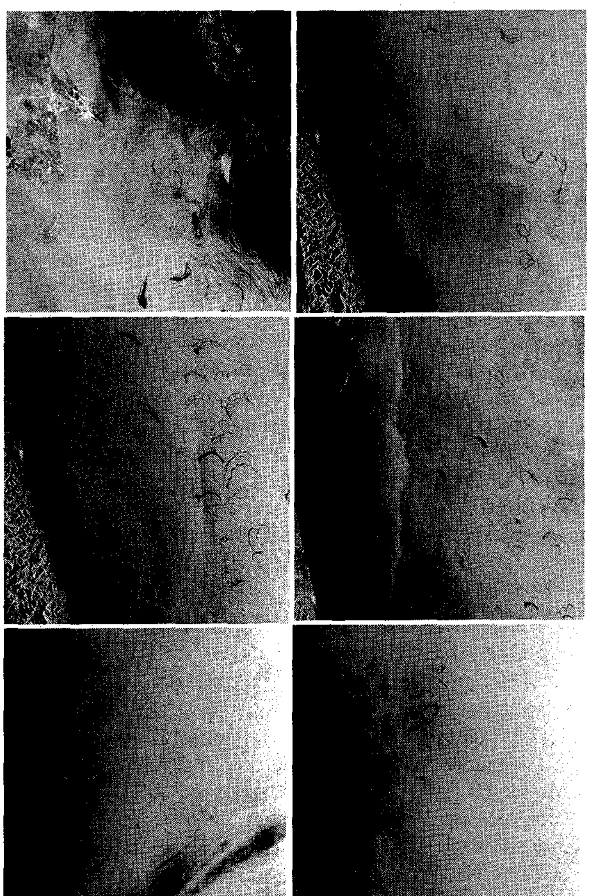

Figure 2. Envisat ASAR images acquired 5.07, 9.08 and 18.10.2003, 22.03, 15.05 and 31.05.2004 over the SW part of the Caspian Sea. © ESA

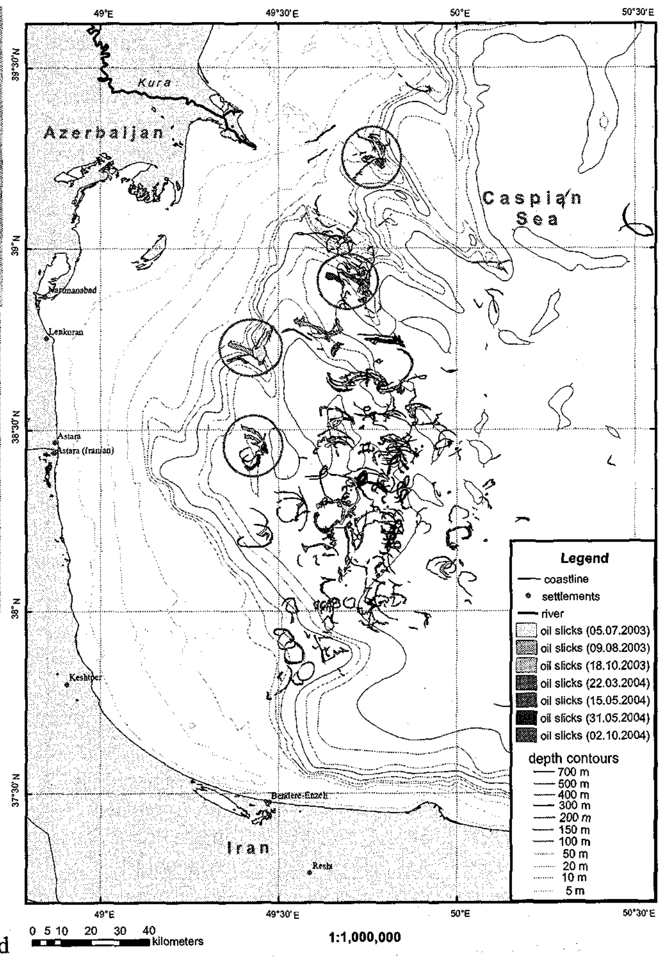

Figure 3. GIS-based integral map showing distribution oil slicks relaed to oil seeps and mud volcanoes on the sea bottom.

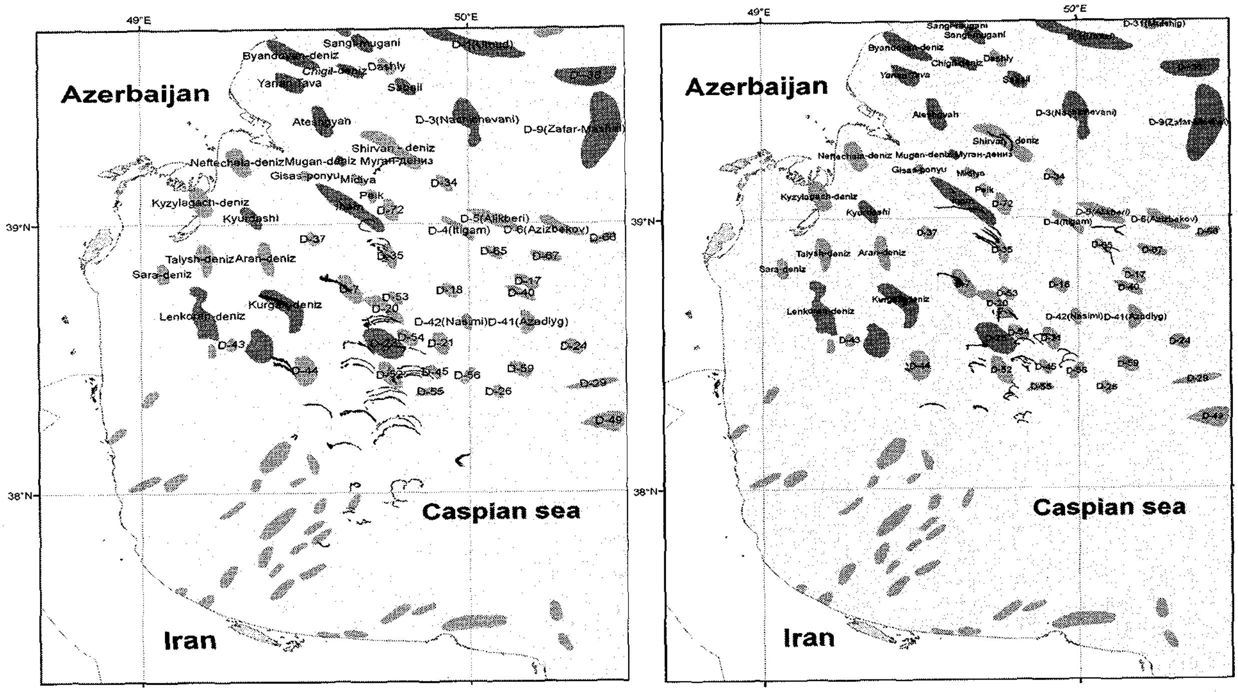

Figure 4. Location of oil fields known as local structures (formations) in the SW Caspian Sea. (Light-gray colour: revealled structures, dark-gray: perspective structures.). Correspondence between seep slicks floating on the sea surface and local structures (oil fields); a – 9.08.2003, b – 18.10.2003

Acknowledgements. Envisat ASAR images for this study have been received from ESA (AO Envisat project #226). We are very grateful for financial support provided by Agency on Science and Innovation of Russian Federation and Russian Foundation for Basic Research (grant #06-05-64468).

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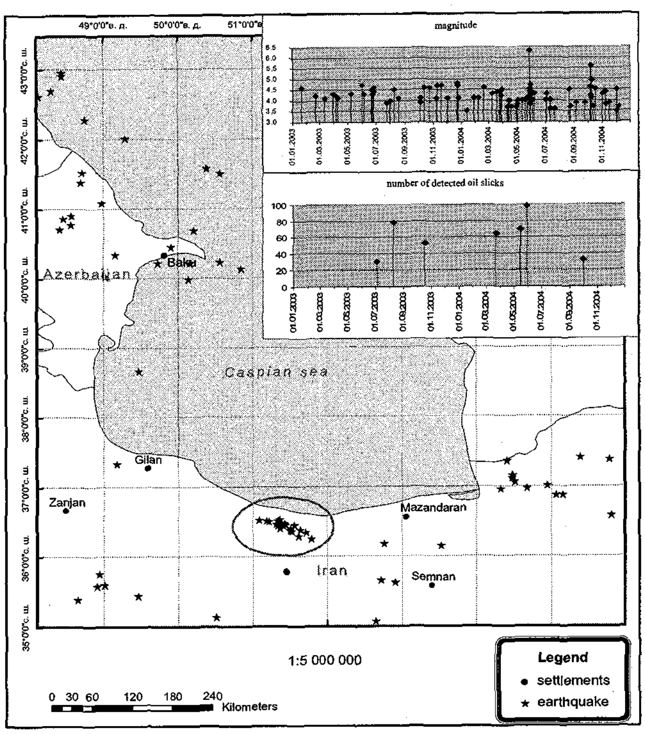

Figure 5. Map of earthquakes taken place in 2003-2004 in the Caspian Region and correlation of their intensity (magnitude) to number of detected oil slicks. © U.S. Geological Survey Earthquake Data.