Natural Resources Research, Vol. 9, No. 4, 2000

Importance of Remote-Sensing Data in Structural Geologic Analysis of Oil- and Gas-Bearing Regions of Azerbaijan

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Received and accepted 10 September 2000

In addition to surface geologic and geophysical investigations, Panchromatic SPOT and Landsat Thematic Mapper (TM) data were merged using an IHS approach to produce a satellite composite image to use as a basis for structural geologic analysis of the oil- and gas-bearing regions of Azerbaijan, including the South Caspian and Kura Basins. With the development of new exploration technology, various nonseismic reconnaissance methods, such as remote sensing, gravity, and magnetics for oil exploration have been substantiated and improved. The Azerbaijan and surrounding mountain ranges are favorable for studying natural hydrocarbon seepages. Most of the seepage occurs in faulted and mud volcano areas onshore of the Caspian Sea in Azerbaijan. Determining the geometry of the fault system from analysis of remote-sensing data allows prediction of (1) vertical oil migration from source rocks into tectonic traps in overlying formations and (2) quantitative volume of oil reservoirs.

KEY WORDS: Mud volcano; petroleum seepage; oil exploration.

INTRODUCTION

Mud volcano is a unique geologic phenomenon localized within the boundaries of mobil belts. It is an important information source on age, composition of rocks (not yet drilled), as well as on fluids saturating them. In spite of a long history of study of this interesting phenomenon, there is much debate on problems of mud volcanism. They are the stratigraphic location of the "roots" of mud volcanoes, and their relation with folded complex of different age, deep faults, diapir folds, and seismic activity; formation and eruption mechanism; the place and role of mud volcanism in the system of geotectonical, gashydro-, and thermodynamic processes; and the formation and destruction of oil and gas accumulations.

Azerbaijan is considered a classical region for development of mud volcanoes because the largest collection of those features is concentrated there (Fig. 1). The majority of these mud volcanoes are connected with petroleum seepage. Tectonic conditions of this area are characterized by stratigraphic breaks with large dislocations, compression, thrusting, and other features. At the same time geologically, high rates of sedimentation occurred in Azerbaijan. These processes produced sizable thickness (about 15 km) and accumulation of plastic clays of Paleogene–Miocene and Pliocene–Quaternary deposits accompanied by widespread development of diapirism and mud volcanism. Accumulation of oil and gas coincided with strong tectonic dislocations and complicated faulting of structures. Practically all known types of oil and gas pools were developed in the area of Azerbaijan.

The main oil resources of Azerbaijan are concentrated in Lower Pliocene deposits (locally termed the "Productive Series"), with the hydrocarbons having migrated from underlying source deposits. The main reason for generation of oil and gas in this region is the high organic content and sufficient temperature conditions for transformation of carbonaceous material to oil in Miocene and Paleogene sediments at depth. With respect to formation of oil accumulations in Lower Pliocene deposits, faults have played a significant role as routes for vertical migration from Paleogene–Miocene deposits to Lower Pliocene

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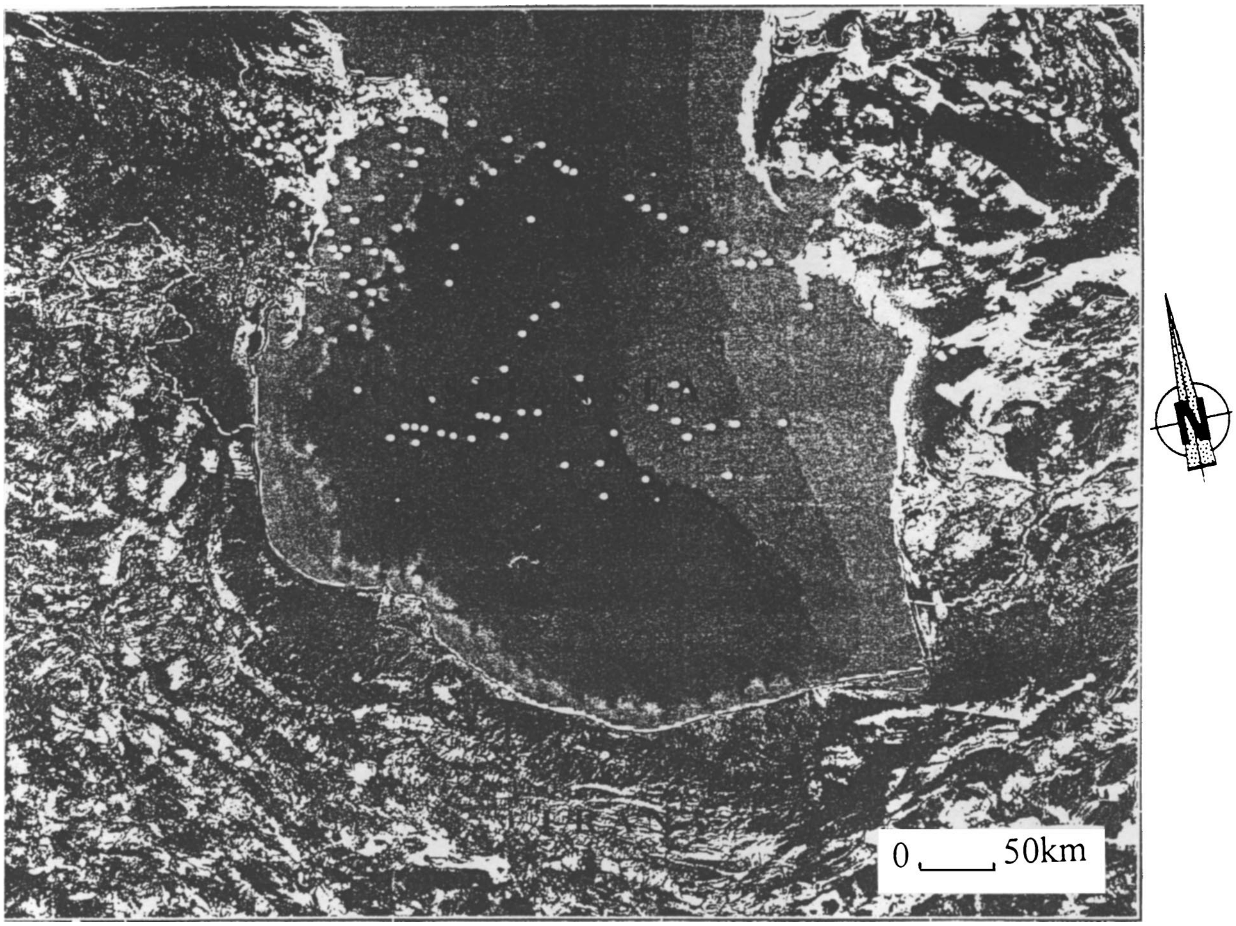

Figure 1. SPOT/Landsat TM data over test area in regional frame. ○, Mud volcanoes.

sandstone traps (Zeinalov and Feizullayev, 1999). In other selection, faults may have destroyed traps, and as a result, part or possibly all of the hydrocarbons migrated to the surface. Therefore, estimation of the roles of faults in migration, formation, and preservation (or destruction) of oil and gas accumulations and their distribution in Azerbaijan has great significance in exploration programs.

Remote-sensing research methods have assisted considerably in these fault analysis considerations. Interpretation of the Landsat MultiSpectral Scanner (MSS) and Thematic Mapper (TM) images was performed in order to map exposures and identify fault genesis. Image interpretation drew upon knowledge of structural geology and geomorphology and detected hydrocarbon seeps related to fault and mud volcano geomorphology. The main objectives are to determine the role of faults and mud volcanoes within the geologic structure of the study regions and to guide future oil exploration.

Remote sensing to detect hydrocarbon seepage onshore allows recognition of marginal and submarginal low-relief structural prospects and stratigraphic traps that are overlooked by reflection seismic surveys. Continuous progress in remote-sensing technology has been of considerable significance to petroleum geology in this area in particular. Remote-sensing data and images are integrated in hydrocarbon exploration programs with other exploration data, such as seismic surveys, well logs, gravity surveys, and other geologic–geophysical investigations. Surface geologic–geophysical studies were performed for separate local areas. As a regional studying methodology, remote-sensing data were made more precise by aforementioned investigations. Many researchers also have attempted to use remote-sensing imagery to detect distinct spectral characteristics of surface manifestations of hydrocarbon seepages originating from oil and gas reservoirs at depth. The occurrences of surface hydrocarbon seeps indicate that oil or gas reservoirs are leaking, although they act as traps for hydrocarbons (Halbouty, 1980; Moore and Anderson, 1985; Zeinalov, 1998; Yang, 1999; Zeinalov, 2000a, 2000b, 2000c).

Oil and gas are mobile fluids, and rocks generally are permeable. Surface oil and gas seeps primarily reflect avenues of migration (or escape) from deeper and distant locations. Moreover, because avenues of migration (or escape) from deeper accumulations after considerably in the degree to which the pathways are sealed, the quantitative size of a seep has little relationship to the size of the source accumulation. Therefore, the value of hydrocarbon seepages largely depends on the accuracy with which they can be interpreted geologically (Tharsher and others, 1996; Zeinalov, 1999).

This study used SPOT and Landsat data to study the tectonic position and habitat of natural oil seeps in onshore Azerbaijan (Fig. 1). The combination of these data types allowed us to confirm the remote-sensing characteristics of onshore oil seeps in Azerbaijan.

METHODOLOGY

Methods to analyze Panchromatic SPOT and Landsat MSS and TM imagery have been developed for petroleum exploration purposes. These methods have been assessed for a part of Azerbaijan, a region already associated with past and present petroleum exploration and production activity. It was attempted to map steeply dipping active faults, which correspond in the field to abrupt scarps, in order to obtain information about the fault throws. Landsat scenes were selected because they have high ground resolution, which image covers a large areas.

On remotely sensed images, geologic structures do not have a characteristic pattern of reflectance. Therefore, methods of classification using multispectral data are of little use since visual perception is not sufficient to systematially detect all significant landforms as geomorphologic indicators of strike-slip faulting. In contrast, computerized methods are able to process systematically and small details are enhanced everywhere in the same way (Callot, Mering, and Simonin, 1994).

The methodology of filtering detailed here has been tested on Landsat MSS and TM composite scene located in oil- and gas-bearing regions of Azerbaijan, which will serve as an example to explain the image processing. Structural interpretation, which consists of selecting continuous dark lines corresponding to fault scarps from features, is easy by visual observation. However, in other part of same scene, the pattern is more complex and needs some suitable filtering to extract at least the relevant lines which are underlined by shadow. Filtering techniques generally are used to assist visual interpretation, which in this example, was morphologic and geodesic transformations. After such standard processing of MSS and TM data, an overall analysis at a scale of 1:200,000 was performed on a mosaic of different images. This was followed by a detailed analysis at the same scale. A more detailed analysis at a scale of 1:100,000, which also takes into account all of the existing interpretation data that were compiled from the imagery, results in a combined geologic map.

Systematic exploitation of Landsat stereoscopy, good ground resolution, and more specialized processing techniques permitted the discovery of large and detailed structures that previously were unknown in the study area. Many important results and interpretations concerning subsurface structures and petroleum exploration problems were obtained, including the fracturing pattern, basin faulting and fault inversion, evaluation of the thrusting as a cover detachment, and amount and direction of strike-slip movements. These results were part of the assessment of the efficiency of our methodology (Zeinalov, 1999).

Interpretation of these satellite images was controlled by 1:100,000 topographic maps. We identified linear, bundle-shaped, and circular geomorphologic elements, which have been substantiated as real features by the combined results of surface geologic structural and subsurface geophysical studies.

Figure 2 is an illustration of the association between hydrocarbon accumulations in the Kura Basin and regional faults. Based upon this information and additional geologic–geophysical and remote-sensing research, a tectonic map was can constructed. The map shows many faults with different orientations and styles of movement (sublatitudunal, causcasusian, anticaucasusian, submeridional, etc.) and depth of occurrence (from pre-Mesozoic through younger Cenozoic ages). These interpretation results were used for estimation of faults systems and oil and gas content in eastern Azerbaijan.

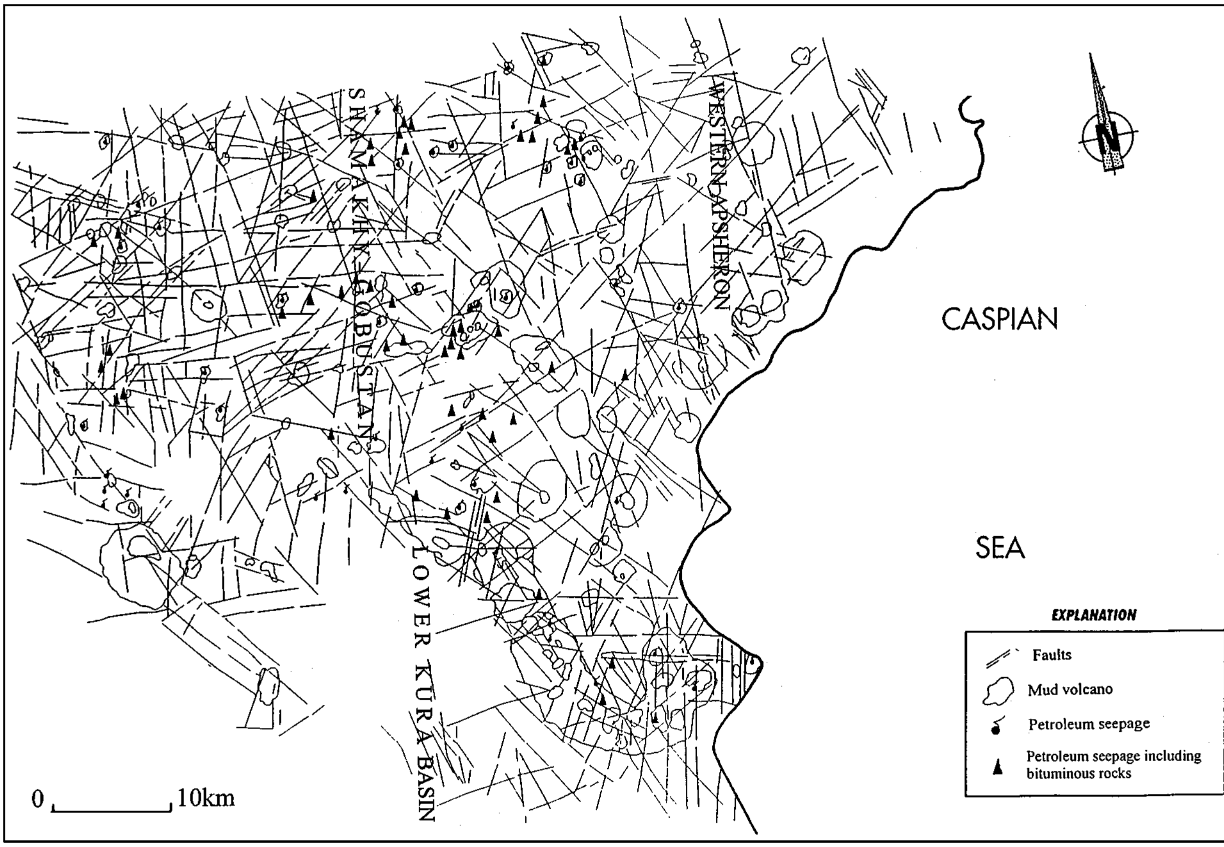

Figure 2. Map of faults from analysis of Landsat data of central–eastern part of Azerbaijan.

RESULTS AND DISCUSSION

Geological factors driving both mud volcanism and petroleum seepage in Azerbaijan are coeval with compressional tectonic stress, rapid Paleogene through Quaternary sedimentation (more than 6 km of sediment), and resulting abnormal pore pressures in both reservoir and nonreservoir rocks. Under these conditions, petroleum accumulations and preservation in the subsurface are relatively remarkable.

Analysis of field surveys and results of drilling on structures affected by mud volcanoes revealed interesting regularity, which served as an important criterion for estimating oil-bearing structures. It was determined that the structures where mud volcanism is accompanied by intensive oil seepages at the surface, as a rule, are not oil-bearing in commercial quantities (Table 1).

Hence, the conclusion is that absence of commercial oil accumulations in the Productive Series deposits (Lower Pliocene), on structures with intensive oil seepages in connection with mud volcanoes, indicates the destruction of oil accumulations as a result of there not being enough thickness, or complete absence, of overlying Upper Pliocene–Quaternary deposits, or even parts of the Productive Series deposits, to preserve potential accumulations. Note that where Productive Series deposits are exposed at the surface, without oil seepages, are not contradictory to the conclusion.

Most seepage occurs in faulted areas in the onshore part of Azerbaijan. From satellite-image analysis, the fault system geometry was determined, which allowed a prediction of likely vertical oil migration from source rocks to tectonic traps and volumes of oil reservoirs in the overlying formations. Surface oil and gas seeps primarily reflect avenues of migration (or escape) from deeper and, sometimes, distant locations.

For onshore Azerbaijan, visible seepages have been recorded. The nature of the relationship of seepages to subsurface petroleum accumulations has been studied, if not always successfully determined.

Table 1. Information about Oil Content of Some Structures Affected by Mud Volcanoes

Structure name	Availability of intensive oil seepages	Availability of oil accumulations	Thickness of sediments covering the Productive Series (in m)	Mud volcano position on structure
Kalamadyn	—	+	1700	Northwest part of structure
Kalamadyn	+	—	0	Southeast part of structure
B. Kharami	+	—	0	
M. Kharami	—	—	0	
Kurovdag	—	+	2000–2600	
Babazanan	+	—	0	
Durovdag	—	—	1600	
Khilli	—	+	900–1200	
Neftchala	—	+	600–800	
Kursangi	—	+	3000	
Mishovdag	—	+	1500	West part of structure
Mishovdag	+	—	0	Central part of structure
Kirkishlag	+	—	0	
Kalmas	—	+	1600	
Khidirli	—	—	500	
Bandovan	—	—	500–1200	
Ayrantekan	+	—	0	
Shorbulag	+	—	0	
Dashgil	—	+	0	
Solakhay	—	—	0	
Kanizadag	—	+	0	
Kirkishlag	+	—	0	
Shorbulag	+	—	0	

Azerbaijan and the surrounding mountain ranges are favorable for studying natural hydrocarbon seepages. Numerous gas and oil seeps of differing chemical composition, maturity, and type occur within a relatively small region. This variety is related to the structural contrasts between depressions of the western flank of the South Caspian Basin. This area is characterized by high sedimentation rate and enormous thickness of sedimentary cover (up to 30 km). The Pliocene–Quaternary complex (up to 10 km thick) consists predominantly of shaly terrigenous rocks. A low heat flow (25-50 m W/m^2) and abnormally high pressures (with anormaly factors, ratio between pore and hydrostatic pressures up to 1.8) also characterize this basin. Finally, there is considerable tectonic activity and faulting and fracturing of the sedimentary cover (Guliev and Feizullayev, 1996). All of these factors create favorable conditions for migration of hydrocarbons and seepage at the surface, especially in areas associated with mud volcanoes, active groundwater flow, and faults and fractures.

In Azerbaijan (onshore), surface light hydrocarbon anomalies exist directly above two seismic-defined oil-producing traps, defined by seismic surveys, at depths of 6000 m–9000 m. These anomalies do not extend substantially beyond the limits of field. The occurrence of hydrocarbon seepage directly above reservoirs points to vertical migration of hydrocarbons, despite the fact that groundwater movement might be expected to retard or redirect the migration, depending upon pressure.

In this region, vertical subsurface petroleum migration occurs for tens of kilometers between source rock and trap and between accumulations and the surface. Thus, seepage only can provide information for identifying petroleum accumulation potential at basin scales and, second, that there may be no direct spatial relationships between subsurface accumulations and surface seepages. Knowledge of the geology and petroleum dynamics of the South Caspian Basin and the Kura Basin and adjoining territory (Azerbaijan) is key to understanding and using seepage information in exploration. Related controls on fluid flow and seepage range from active mud volcanoes, through high fluid-potential gradients resulting from rapid deposition of fine sediment, to faults and mud diapirism.

A case study of onshore oil seepage from the Shamakhy-Gobustan, Absheron, and Lower Kura Basin is used to illustrate analysis of SPOT and TM images. Characterization of seepage in terms of basin geology and petroleum dynamics not only in necessary for interpreting seepage for exploration purposes, but also is critical for planning sample collection from seep.

The locations of probable oil slicks were compiled from interpretation of the TM scene, collection of floating oil, and observations of onshore seeps. Monitoring individual seeps through time contributes to understanding the natural loading of hydrocarbons in the coastal environment. Most seepage occurs along good migration pathways, such as active faults. However, in the absence of such focused migration pathways, some vertical migration through sediments probably occurs.

The western flank of South Caspian Basin and adjoining territory of Azerbaijan is an emerging exploration area, with some large petroleum discoveries in fairly tectonically complex regions. Main features of the geologic environment are thick Pliocene–Miocene sediments and the presence of mud volcano activity.

The high sedimentation rate during Pliocene–Miocene time resulted from the large volumes of sediment delivered to the South Caspian by the ancestral Volga and Kura Rivers. The main petroleum plays are turbidite sand reservoirs structurally bounded by mud volcanoes or faults with, in some cases, a stratigraphic component.

Petroleum accumulations indicate the presence of deep Mesozoic source rocks (Ali-Zadeh, Salayev, and Aliyev, 1985). These source rocks have not been ecountered by drilling, but their predicted existence implies extensive vertical migration of hydrocarbons.

This region is characterized by thick accumulations of plastic clayey sediments of Paleogene–Miocene age and by the densely developed structures with strong dislocations, with the vast majority of these features complicated by the mud volcanism. These factors have been confirmed through the quantitative fault analyses performed during estimation of oil and gas potential of the region.

As a result of this analysis, we have established that the majority of oil and gas fields are located in regions of fault development. Based upon the density of the fault network, it seems that oil- and gas-bearing fields preferentially are formed in areas with lower fracture density. Therefore, regional faults contribute not only to the destruction preservation-existing oil and gas deposits, but they also play a positive role in the formation of the oil and gas accumulations, their presrvation, and prevention of groundwater flooding of oil strata. Main oil reserves were determined in the Lower Kura Basin and western–central part of Absheron region, in areas that were dislocated by faults (100 m/km–280 m/km). Reduction of oil resources also corresponds to the next increase of dislocation in the region on a whole as the separated structures (Shamakhy–Gobustan region). This regularity is connected with pool formation, migration, and accumulation in oil and gas traps.

These correlations can be explained by noting that important surface oil and gas shows such features as mud volcanoes, oil seepages, and other surface features occurring in the zones with increased number and density of faults. According to available statics, subsurface oil reserves are smaller in these regions.

Abundant bitumen-bearing rocks occur in other structures where the density of structures is high. For these structures, the commercial oil accumulations have not yet been determined.

Large, sublatitudinal, regional faults are the proposed pathways for vertical hydrocarbon migration from Mesozoic and Paleogene–Miocene deposits to the surface. Therefore, these faults destroyed any accumulations formed prior to this faulting. Thereby these faults played a negative role in petroleum geology of the region. These ruptures, located in the mobile tectonic zones in the Mesozoic age, contributed to the formation of the regional tectonic belts that contained traps for oil and gas. In this way, these regional faults also contributed overall to conditions necessary for the formation of oil and gas accumulations. Thus, the faults also played a positive role in petroleum geology of the region. During vertical migration, some part of the hydrocarbons from deep-seated horizons along the faults entered higher trapping units and participated in the formation of hydrocarbon accumulations.

On the flanks of northern fold structures, local faults along the longitudinal axis, and the lateral and diagonal axes mainly serve as tectonic screens, forming traps for the oil and gas. These faults may play a negative role because they can separate earlier deposits into different areas. However, this dismemberment factor is insignificant in comparison with the tectonic screen factor because the total hydrocarbon deposit size does not reduce as the result of the dismemberment.

The role of the local faults, developed in the tectonic compression zones formed by sublongitudinal regional faults, mainly is negative because these fractures are the pathways for hydrocarbon migration to the surface. Intensive oil and gas shows on the surface, which indicate fault disruption of sediments in tectonic compression zones, correlate with an absence of the oil and gas inflows of commercial importance in the test wells drilled in these zones.

Where tectonic zones of Paleogene–Miocene deposits are buried under the massive Pliocene cover, these sublongitudinal faults can play a positive role for petroleum geology. Because the faults contribute to vertical hydrocarbon migration into overlying horizons reservoirs, oil and gas accumulations from near these tectonic zones, are exceeded only by the Pliocene types of reservoirs.

Thermal modeling shows that oil expulsion from source rocks began during the Miocene and, in some areas, continues to the present day. Thus, oil seepage may be coming directly from the source rocks as well as from leaking accumulations. As noted before, in the onshore part of Azerbaijan, light hydrocarbon surface anomalies have been observed above two seismic-defined oil-producing traps, which are at a depth of 6000 m–9000 m. These anomalies do not extend substantially beyond the known field limits. The occurrence of hydrocarbon seepage directly above reservoirs points to vertical migration of hydrocarbons, despite the fact that groundwater movement might be expected to impact vertical migration.

CONCLUSIONS

Faults related to mud volcanoes are more likely to be continually active, at least on a small scale. The distribution of detected oil and gas seeps in connection with mud volcano structures is good evidence that the mud volcanoes are related to faults. Growth faults resulting from slumping during high sedimentation rates are less likely to be continually active than mud volcano-associated faults and are not expected to be as effective as migration conduits to the surface.

Seepage favors good migration pathways. Mud volcano activity and seepage along active faults can be detected and sampled at many stages along the migration and seepage pathways.

Mainly, oil and gas seeps in Azerbaijan are associated with mud volcanoes, outcrops of oil-bearing strata, and mineral water springs. Most of the seepage occurs in faulted areas along the eastern part of onshore Azerbaijan. Analysis of satellite images allowed a determination of the geometry of the fault system and prediction vertical of oil migration from source rocks to tectonic traps in overlying formations and the quantitative volumes of potential oil reservoirs.

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