Factors controlling the formation and oil-generating potential of the Middle Eocene organic-rich shales of Eastern Azerbaijan

Factores que controlan la formación y el potencial generador de petróleo de las lutitas ricas en materia orgánica del Eoceno Medio en el Este de Azerbaiyán

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How to cite this article:
Abbasov, O.R., Baloglanov E.E., Yolchuyeva U.J., Khuduzade A.I., Akhundov R.V., 2025, Factors controlling the formation and oil-generating potential of the Middle Eocene organic-rich shales of Eastern Azerbaijan: Boletín de la Sociedad Geológica Mexicana, 77(1), A020724. http://dx.doi.org/10.18268/BSGM2025v77n1a020724

Manuscript received: May 27, 2024
Corrected manuscript received: June 25, 2024
Manuscript accepted: June 30, 2024

Peer Reviewing under the responsibility of Universidad Nacional Autónoma de México.

ABSTRACT

The Maikop (Oligocene-Miocene) formation is considered the main and the deepest stratigraphic unit generating oil and gas in the South Caspian Basin. This study identifies factors that control the oil-generating potential of deeper sediments, Middle Eocene organic-rich oil shales. First of all, the patterns of distribution of Middle Eocene oil shale formation across geodynamic and tectonic zones were analyzed. Based on mineralogical and geochemical proxies, the parent rocks of samples taken from outcrop sections and mud volcanic ejecta have been studied, and the obtained results were correlated with Jurassic-Middle Eocene volcanism, established in the southeast of the Greater Caucasus and adjacent regions. The presence of organic-richer shales in the coastal areas of the Caspian Sea is explained by the relatively saline and deep conditions of the oligotrophic paleobasin, indicating a closer connection with the marine environment (influence of the Peri-Tethys). Referring to the results of extraction, ^{1}H NMR, FTIR, thermogravimetric and pyrolytic analyses, the organic composition of oil shales was studied and their high oil productivity was revealed. Although most of the samples show immature thermal characteristics, the active oil-generating potential of some samples taken from mud volcanoes located near the coastal zones of the Caspian Sea was determined based on geological, mineralogical and organo-geochemical proxies. Besides the Caspian Sea, the samples from mud volcanoes of the Lower Kura basin also show satisfactory thermal maturity. We believe that the Middle Eocene shale source rocks made a greater contribution to the formation of the rich oil fields being developed in Azerbaijan than the Maikop deposits. Immature Middle Eocene oil shales occurring at depths of up to 4000 m onshore in East Azerbaijan are considered hybrid systems able to generate and accumulate shale oil.

Keywords: Eastern Azerbaijan, organic-rich shale, mineralogy, geochemistry, genesis, oil potential.

RESUMEN

La formación Maikop (Oligoceno-Mioceno) se considera la unidad principal y más profunda estratigráfica generadora de petróleo y gas en la Cuenca del Caspio Sur. Este estudio identifica los factores que controlan el potencial generador de petróleo de los sedimentos más profundos, lutitas ricas en materia orgánica del Eoceno Medio. Para esto, en primer lugar, se analizaron los patrones de distribución de la formación de lutitas del Eoceno Medio a través de zonas geodinámicas y tectónicas. Basándose en proxies mineralógicos y geoquímicos, se estudiaron las rocas madre de muestras tomadas de secciones aflorantes y de eyecciones de volcanes de lodo, y los resultados obtenidos se correlacionaron con el vulcanismo del Jurásico-Eoceno Medio, establecido en el sureste del Gran Cáucaso y regiones adyacentes. La presencia de lutitas más ricas en materia orgánica en las áreas costeras del Mar Caspio se explica por las condiciones relativamente salinas y profundas del paleocuenca oligotrófico, lo que indica una conexión más cercana con el entorno marino (influencia del Peri-Tetis). Refiriéndose a los resultados de análisis de extracción, ^{1}H, RMN, FTIR, termogravimétricos y pirolíticos, se estudió la composición orgánica de las lutitas y se reveló su alta productividad petrolera. Aunque la mayoría de las muestras presentan características térmicas de inmadurez, se determinó el potencial generador de petróleo activo de algunas muestras tomadas de volcanes de lodo ubicados cerca de las zonas costeras del Mar Caspio, basado en proxies geológicos, mineralógicos y organo-geoquímicos. Además del Mar Caspio, las muestras de volcanes de lodo de la cuenca del Bajo Kura también muestran una madurez térmica satisfactoria. Creemos que las rocas origen de lutitas del Eoceno Medio hicieron una mayor contribución a la formación de los ricos campos petrolíferos que se están desarrollando en Azerbaiyán que los depósitos de Maikop. Las lutitas inmaduras del Eoceno Medio que se encuentran a profundidades de hasta 4000 m onshore al Este de Azerbaiyán se consideran sistemas híbridos capaces de generar y acumular petróleo de lutitas.

Palabras clave: Este de Azerbaiyán, lutitas ricas en materia orgánica, mineralogía, geoquímica, génesis, potencial petrolero.

http://dx.doi.org/10.18268/BSGM2025v77n1a020724

1. Introduction and research status

The history of the oil industry of Azerbaijan is very ancient. Thus, the first commercial oil well at the Bibiheybat field in the capital Baku was drilled 13 years earlier than the famous well of Edwin Laurentine "Colonel" Drake in Pennsylvania in 1859. In East Azerbaijan, including the adjacent Caspian Sea, the richest hydrocarbon sedimentary complexes belong to the stratigraphic units between the Maikop (Oligocene-Miocene) and the Productive Series (Lower Pliocene). Many studies highlight the role of Maikop as a source rock in the generation of rich oil and gas deposits, especially associated with reservoirs of the Productive Series. For example, according to Abrams and Narimanov (1997), oil from the Miocene and older reservoirs is most likely associated with the Lower Maikop (Oligocene) Formation. This study suggest that the main contribution belongs to the Upper Maikop (Lower Miocene) sediments, without excluding the role of Diatom (Middle-Upper Miocene) in the formation of oil-rich reservoirs of the Productive Series. Guliyev *et al.* (2001) highlighted that the Lower Maikop Formation, which contains relatively little organic matter, has a better oil yield potential than the Upper Maikop Formation. They conclude that the onshore Maikop Group has not undergone the necessary thermal maturity to generate hydrocarbons. Feyzullayev *et al.* (2001) suggested that favorable thermal conditions for the realization of Oligocene-Miocene source rocks are expected in the most subsided central part of the South Caspian basin. Although Katz *et al.* (2000) suggest that the Oligocene-Miocene Maikop Group may exceed 1000 m in thickness, the net oil-prone source interval represents significantly less. Additionally, this work supports the idea of Inan *et al.*, (1997) that vertical migration plays an important role in charging of young reservoirs, but does not confirm the significant oil-generating capacity of the Diatom Formation. The organic richness of the Maikop shales of Central Gobustan was also estimated from many samples by Aghayeva *et al.* (2021), but their low HI values have not been presented as a clear indication of a South Caspian Basin oil source.

Our analyses demonstrate that the role of the Maikop Formation, recognized as the most efficient source rock for East Azerbaijan in frequently cited research, in replenishing long-exploited oil reservoirs remains subject to ambiguous substantiation. Furthermore, contemporary studies (Abbasov, 2022; Abbasov et al., 2024) evaluate the oil generation potential of this formation, with an average TOC of at most 5%, as significantly weak compared to gas hydro-carbons. Concurrently, despite the Diatom sedi-ments' higher organic matter content, their burial depth in East Azerbaijan raises questions regard-ing their thermal maturity. From this point of view, the issue of evaluating the potential of deep sediments of the Cenozoic succession, especially the Eocene Koun Formation, becomes relevant.

However, some published literature presents inconsistent views on the Eocene's source rock potential in East Azerbaijan. For example, Inan et al. (1997) highlight that Eocene and older sediments in the Lower Kura oil-gas region may have reached maturity for oil formation, and emphasize the possible role of vetical migration in charging younger sediments . In the Feyzullayev *et al.* (2001), as a result of studying Eocene samples from the coastal regions of Eastern Azerbaijan, a very low value of TOC (0.02-0.9%) and HI (13-29 mg HC/g TOC) was established. Johnson *et al.* (2010) emphasized only the weak gas potential of Eocene Formation. Goodwin *et al.* (2020) concluded that Eocene formations may also have contributed to hydrocarbon accumulation. In Aghayeva *et al.* (2021), referring to several samples from one outcrop section (Pirekeshkul), based on the fact of the low net thickness, the Middle Eocene sediments were evaluated as an insignificant source rock in onshore Eastern Azerbaijan as a whole. In Isaksen *et al.* (2007), although Maikop was presented as the main source of rock oil and gas production for the South Caspian Basin, the Eocene sample of the Otmanbozdagh mud volcano, located closer to the Caspian Sea, is also assessed as a source rock capable of generating sweet crudes and gases.

It becomes clear from Eocene studies that the potential of this formation as a source rock has not been satisfactorily assessed in comparison with the Maikop and Diatom sediments. On the other hand, the question of which lithostratigraphic unit may be promising in the thick Eocene section, consisting of three parts, has not been clearly stated. In addition, an interesting fact is that the oil hydrocarbons are produced from Eocene foraminiferous sediments in the Kura-Gabirri, Ganja, and Muradkhanli oil-gas regions of Western Azerbaijan (Babayev *et al.*, 2015; Salmanov *et al.*, 2015), which stimulates their research in the eastern part of the country as well. In particular, it is necessary to take into account that there are favorable conditions for the vertical migration of hydrocarbons in the studied region (Inan *et al.*, 1997; Abrams and Narimanov, 1997; Feyzullayev, 2013), where it seems possible that the younger reservoirs were filled with hydrocarbons generated from deeper, more heated Eocene sediments.

Our long-term studies have established the significant thickness and effective layers of Middle Eocene organic-rich oil shales in the Eocene section of Eastern Azerbaijan (Aliyev *et al.*, 2018; Aliyev *et al.*, 2019; Abbasov, 2022). Notably, analysis of multiple source rock studies in this region (*e.g.*, Aghayeva *et al.*, 2021; Isaksen *et al.*, 2007) reveals that poositive assessments of the Eocene, Maikop and Diatom formations are primarily associated with oil shale rocks. In this regard, the main issue of interest is the lack of special attention to the oil shales recorded in numerous sections. In addition to outcrops in the study region, oil shale rocks are frequently found in mud volcano ejecta (Aliyev and Abbasov, 2019a; Aliyev and Abbasov, 2019b; Aliyev *et al.*, 2022), which represents a favorable opportunity to study the entire section of Middle Eocene oil shale-bearing deposits and the continuity of effective layers at depth. In this respect, this research is devoted to an integrated study of the patterns of distribution, features of genesis, and hydrocarbon potential of Middle Eocene oil shale based on geological, mineralogical, and geochemical proxies of samples taken from surface outcrops and ejecta of mud volcanoes in East Azerbaijan.

2. Geology and tectonics: a general overview

Global oil and gas resources, generated from source rocks of various stratigraphic units, are associated with four realms (Klemme and Ulmishek, 1991). Among these realms, the Tethyan stands out for its high effectiveness in generating oil from Type II kerogen, which is rich in marine organic matter and was deposited in low-altitude environments (Baudin, 1995).

Bounded by the Hercynian collision zone to the north, the Tethyan realm is associated with an east-west equatorial seaway that opened and closed during several orogenic events as microplates were rifted from northern Gondwana and collided on the southern accretionary margin of Laurasia (Klemme, 1994).

Approximately 70% of the global petroleum resources (mainly oil) are associated with the opening and closing of the Tethys during Hercynian, Cimmerian, and Alpine orogenic events, resulting in clastic and carbonate deposits in rift/sag structural basins formed over less than one one-fifth of the world's land and continental shelves (Yang *et al.*, 2014; Klemme and Ulmishek, 1991).

In the Eocene within the Peri-Tethys realm, the territory of Azerbaijan occupied part of the northern margin of the Tethys Ocean. Gradually losing contact with the World Ocean, starting from the Oligocene, the present-day territory of the country occupied the southeastern parts of the Paratethys - a large inland sea separated from the Mediterranean Sea and the Indian Ocean by the Alpine-Himalayan ridge.

Eocene sections of the southeastern part of the Greater Caucasus are characterized predominantly by clayey lithofacies. In contrast to the white-clayey-sandy Lower Koun and the green-clayey Upper Koun, the Middle Koun consists of brown-shale lithofacies (Babayev *et al.*, 2015).

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Their thickness varies depending on tectonic zones (Abbasov, 2022). For instance, the thickness of the Middle Koun section reaches 250 m in the center of Gobustan and 400 m in the north and south of it (Aliyev *et al.*, 2019; Abbasov, 2022).

Outcrops of Middle Eocene (Lutetian-Bartonian) oil shale extend from the west of East Azerbaijan, Diyalli area (Ismayilli region), to the east, Goytepe area (Absheron Peninsula), a distance of 120 km, and they were traced in a strip of northwest-southeast direction (Abbasov, 2022).

In the east of the Caucasian segment of the Mediterranean (Alpine-Himalayan) belt, including in East Azerbaijan, the occurrence of extensive sedimentation, hydrocarbon formation and mud volcanism on a large scale is associated with the specific geodynamic conditions of the region located in the marginal influence zone of the African-Arabian and Eurasian plates (Baldermann *et al.*, 2020; Odonne *et al.*, 2020; 2021; Bayramova *et al.*, 2023). The accretionary prism of the ancient Tethys Sea basin, located between the North Caucasian continental microplate of the Scythian-Turanian Epi-Hercynian platform (southern edge of the Eurasian continent) and the South Caucasian microplate (passive margin of Gondwana), is characterized by numerous outcrops of Middle Eocene oil shale and several mud volcanoes (Figure 1). Here, surface outcrops of the oil shale facies are established in the southeast of the Zagatala-Govdagh zone of the Southern Slope Megazone, which belongs to the Greater Caucasus Fold-and-Thrust Belt.

The Absheron is another local zone, also located in the South Slope Megazone, where some Middle Eocene oil shale outcrops have been recorded (Aliyev and Abbasov, 2019a). Here, the outcrops were registered only in areas located on the border with the Shamakhi-Gobustan zone of the Kakheti-Vendam-Gobustan Megazone, which has a significant distribution of oil shale. The Shamakhi-Gobustan basin is located on the subsiding limb of the Girdimanchay-Velvelechay flexure. This structural zone contains the densest concentration of terrestrial mud volcanoes in East Azerbaijan (Figure 1).

On the other hand, from a tectonic point of view, the distribution features of the Eocene oil shales of Eastern Azerbaijan can be considered within the Jeyrankechmez-South Caspian Megabasin (Figure 1). The north and northwest of the oceanic Megabasin is Gobustan, the northeast is Absheron Peninsula and Abşeron archipelago (Caspian Sea), the west is Southeast Shirvan Lower Kura, and the east is the Baku archipelago (Caspian Sea) oil and gas regions. This Megabasin consists of a thick sedimentary cover of the Meso-Cenozoic characterized by a thickness of up to 25-30 km. The tectonic units such as allochthonous, parautochthonous, and autochthonous have been established within its boundaries (Aliyev and Bayramov, 2000). Along with the distribution of oil shale, differences in the number, morphological type, and activity of mud volcanoes are particularly noticeable in these tectonic units.

In the geological literature, the northern boundary of the Jeyrankechmez-South Caspian Megabasin is limited by the Goredil-Masazyr Convergence Zone (Figure 1). However, in the north of this tectonic zone, under the Upper Cretaceous carbonate flyschoids, drilling revealed the Upper Maikopian shale facies. In addition, rock fragments bearing Miocene fauna were found in the ejecta of Demirchi and Gizmeydan mud volcanoes (Aliyev and Bayramov, 2000; Aliyev *et al.*, 2015). The listed facts indicate the existence of a tectonic cover in the Jeyrankechmez-South Caspian, consisting of the territories of the Gizmeydan-Sumgait synclinal zone. The northern border of that allochthonous called North Gobustan is limited by the Altiaghaj-Kurkechidagh fault, so the Miocene sediments lying beneath it also belong to the molasses of the Jeyrankechmez-South Caspian Megabasin. The Upper Cretaceous carbonate sediments of the allochthonous, defined between the Altiaghaj-Kurkechidagh and the Goredil-Masazyr faults, belong to the nappe sliding from the southern slope of the Greater Caucasus Fold-and-Thrust Belt. We assume that in the Cenozoic section under this nappe, there may also be the

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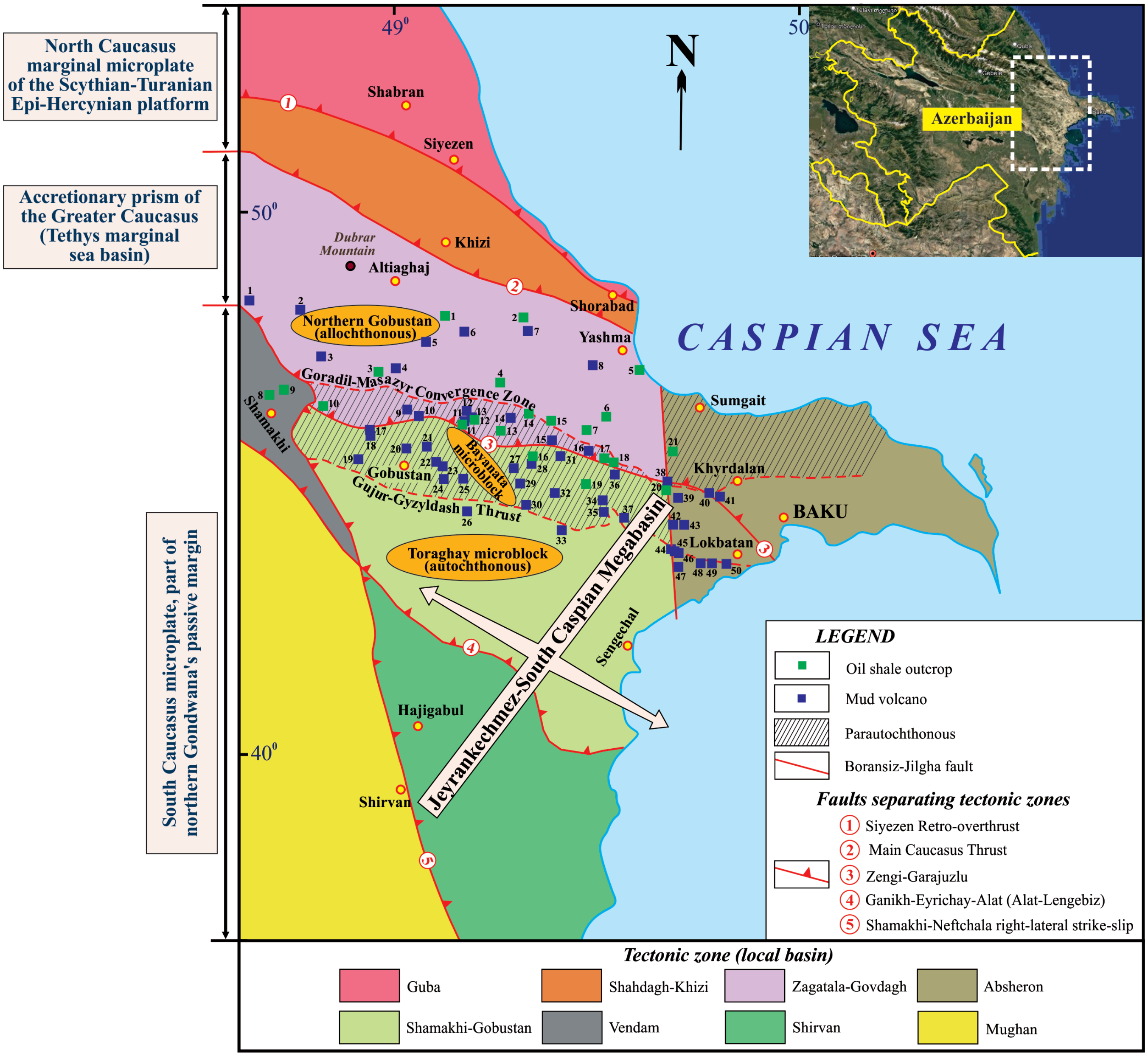

Figure 1 Tectonic map of the distribution of the Middle Eocene oil shale outcrops and mud volcanoes of Eastern Azerbaijan (based on Aliyev and Bayramov, 2000; Kengerli et al., 2012). Oil shale outcrop: 1. Embizler, 2. Chargishlag, 3. Khilmilli, 4. Shikhandagh, 5. Shorabad-Yashma, 6. Aghburun, 7. Mayash, 8. Khinisli-Pirdireyi, 9. Engekharan, 10. Erebshalbash, 11. Garajuzlu, 12. Tuva, 13. Kichik Siyeki, 14. Boyuk Siyeki, 15. Gibledagh, 16. Jengichay, 17. Kecheller, 18. Pirekeshkul, 19. Bayanata, 20. Uchtepe, 21. Nasosni-Goytepe. Mud volcano: 1. Demirchi, 2. Gizmeydan, 3. Hajili, 4. Khilmilli, 5. Yaylag-Tudar, 6. Gasimkend, 7. Kohnegedi, 8. Kurkechidagh, 9. Nabur, 10. Chaygurbanchi, 11. Garajuzlu, 12. Yelderesi, 13. Tuva, 14. Siyeki, 15. Veys, 16. Neftik, 17. Jeyirli, 18. Chalov, 19. Akharbakhar, 20. Mereze, 21. Shimshedi, 22. Bozaakhtarma, 23. Kichik Mereze, 24. Shikhzerli, 25. Gayiblar, 26. Sheytanud, 27. İyimish, 28. Jengi, 29. Birgut, 30. Donguzlug, 31. Sungur, 32. Baygushlu, 33. Charani, 34. Girdagh, 35. Girgishlag, 36. Pirekeshkul, 37. Boransız-Jilgha, 38. Uchtepe, 39. Damlamaja, 40. Aghzikhezri, 41. Bozdagh-Gobu, 42. Deveboynu, 43. Bozdagh-Guzdek, 44. Gulbakht, 45. Sarinja, 46. Shongar, 47. Giziltepe, 48. Gushkhana, 49. Akhtarma-Puta, 50. Lokbatan.

presence of oil shales of the Eocene, as evidenced by the ejecta of the Demirchi mud volcano.

The areas corresponding to the parautochthonous are the Bayanata microblock (Central Gobustan) and the northern part of the Absheron Peninsula (see Figure 1). The Bayanata microblock can also be considered a characteristic tectonic zone of distribution of the Eocene oil shales of East Azerbaijan. By the way, it is worth noting that in the parautochthonous zones of Central Gobustan and Absheron, numerous outcrops of oil shales of the Upper Maikop and Diatom formations have been established. The Bayanata microblock, defined between the Goredil-Masazyr and the Gujur-Gyzyldash tectonic structures, is separated from the Absheron oil and gas region from the east by the Boransiz-Chilgha fault.

The autochthonous areas of the Jeyrankechmez-South Caspian Megabasin, located south of the Gujur-Gyzyldash Trust, are the Toraghay microblock, the southern parts of the Absheron Peninsula, the South-Eastern Shirvan and the Baku archipelago (Figure 1).

Compared to Bayanata, the top of the Upper Cretaceous strata in the Toraghay microblock and south of the Absheron Peninsula lies much deeper (Figure 2B). From this point of view, outcrops of Eocene oil shale have not been recorded due to the appearance of younger sediments on the surfaces of these intensely subsiding zones (Figure 2A). Here, mud volcanoes are distinguished by their large sizes (Figure 2A) and conical morphology, due to the participation of all stratigraphic units in the thick Cenozoic section (Figure 2B). Since the geological structure of Bayanata, a highly elevated microblock in the southeastern plunge of the Greater Caucasus, is characterized by Paleogene-Miocene deposits (Figure 2A), numerous areas of Eocene oil shale outcrops are established here (see Figure 1).

The Shamakhi-Neftchala right-lateral strike-slip fault, recorded in the west of South-Eastern Shirvan, separates the Transcaucasian paleo-island-arc system (consisting of Mesozoic volcanogenic derivatives) from the Jeyrankechmez-South Caspian Megabasin, in which oil shale outcrops and mud volcanoes have not been identified (Figure 1).

The typical eruption depth of the mud volcanoes of Eastern Azerbaijan is considered to be 2-6 km. In Gobustan, Eocene oil shale ejecta is more typical for eruptions of mud volcanoes of the Bayanata microblock (Aliyev *et al.*, 2019), where Paleogene-Miocene deposits occur at shallower depths (2-4 km). Since the depth of Eocene deposits is significantly increased along the southern and southeastern autochthonous zones of the Absheron Peninsula and Toraghay microblock, respectively (Figure 2B), Eocene oil shale ejecta can be brought to the Earth's surface only due to eruptions of mud volcanoes associated with deep mud chambers.

In the coastal zones of the Caspian Sea of Lower Kura, Middle Eocene oil shales are found neither in outcrops nor in eruptions of mud volcanoes. However, oil shale ejecta is characteristic of the Akhtarmaardi and Akhtarma-Pashali mud volcanoes, located in the steep northwestern part of this basin. This is explained by the fact that the thickness of the sedimentary cover in the coastal subsiding zones of this basin reaches 20-25 km, more than half of which consists of deposits of the Upper Neogene and Quaternary. Eruptions of mud volcanoes here cannot penetrate the deep intervals where the Eocene unit is located (Abbasov, 2022).

2.1. PATTERNS OF DISTRIBUTION ACROSS TECTONIC ZONES, FOLDS AND OUTCROP SECTIONS

The distribution of Middle Eocene shale outcrops in East Azerbaijan is mainly characterized by zones located north of the Zangi-Garajuzlu Thrust, including the territory belonging to the accretionary prism of the Tethys Sea basin (see Figure 1). If we also take into account oil shale rocks in the ejecta of mud volcanoes, then the role of the Jeyrankechmez-South Caspian Megabasin as a whole comes to the fore.

When assessed within this Megabasin, the dis-

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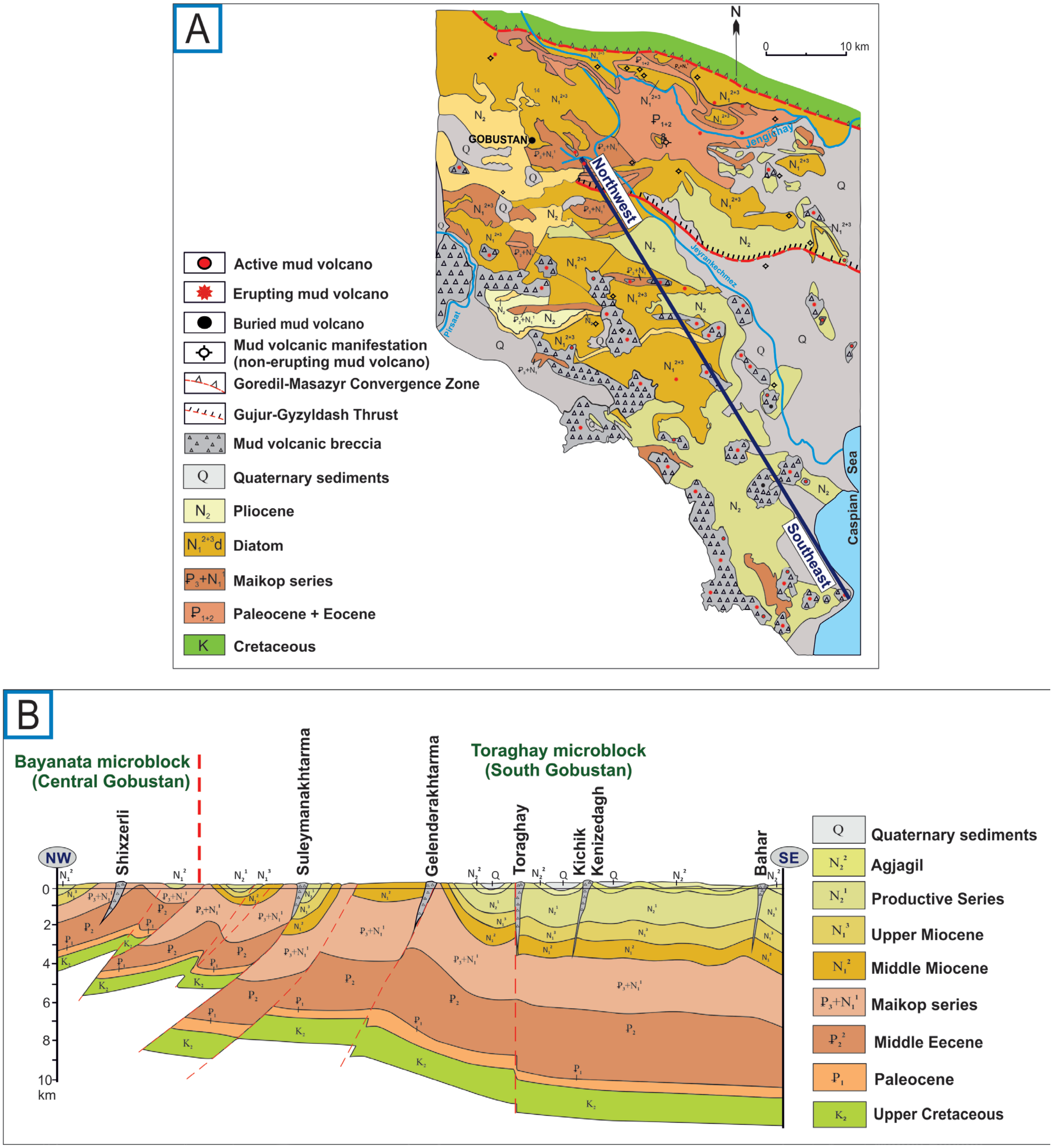

Figure 2 Geological map (A) and geological profile (B) of Central and Southern Gobustan (based on Aliyev and Bayramov, 2000; Aliyev and Abbasov, 2019a).

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tribution of Middle Eocene oil shales in the northern zones of Eastern Azerbaijan can be limited by the Altiagaj-Kurkechidagh fault. However, if we evaluate it in terms of the areas that correspond to the accretionary prism, then this border can be extended a little to the north, to the Main Caucasian Thrust. There is no doubt that the areas corresponding to the accretionary prism played a certain role in the distribution of Middle Eocene oil shales in Eastern Azerbaijan. However, in our opinion, the hydrocarbon systems of the region as a whole, including mud volcanism, oil and gas deposits, as well as organic-rich Eocene, Maikop, and Diatom shale formations, correlate very well with the boundaries of the Jeyrankechmez-South Caspian Megabasin, especially its continuation in the Caspian Sea (see Figure 1).

In the northern parts of the Shamakhi-Gobustan oil and gas region, the cores of synclines (Shikhandag, Chargishlag, Embizler, Boyuk Siyeki, Kichik Siyeki, etc.) are characteristic of the Middle Koun oil shales (Abbasov, 2022). These synclines are characterized by an abundance of thin oil shale layers in their upper horizons. Con-versely, Central Gobustan's outcrop sections ex-hibit thick shale layers in their lower horizons. Notably, anticlines such as Diyalli and Jangichay in this region display substantial oil shale layers.

The increase in the thickness of oil shale layers with depth is also confirmed by large oil shale fragments (Figure 3) belonging to ejecta of mud volcanoes, recorded in Central and Southern Gobustan, as well as in the south of the Absheron Peninsula. This idea is also confirmed by shallow drilling data in the Diyalli area. Thus, three of the five wells drilled here were able to identify up to five layers of oil shale at depths of more than 100 meters (Aghjayev, 2004). The largest oil shale layers were thicker than those identified in the outcrop sections.

3. Samples and analyses

In the study, 23 samples were taken from 20 areas of outcrop sections, and mud volcanoes identified in Shamakhi-Gobustan, Absheron, and Lower

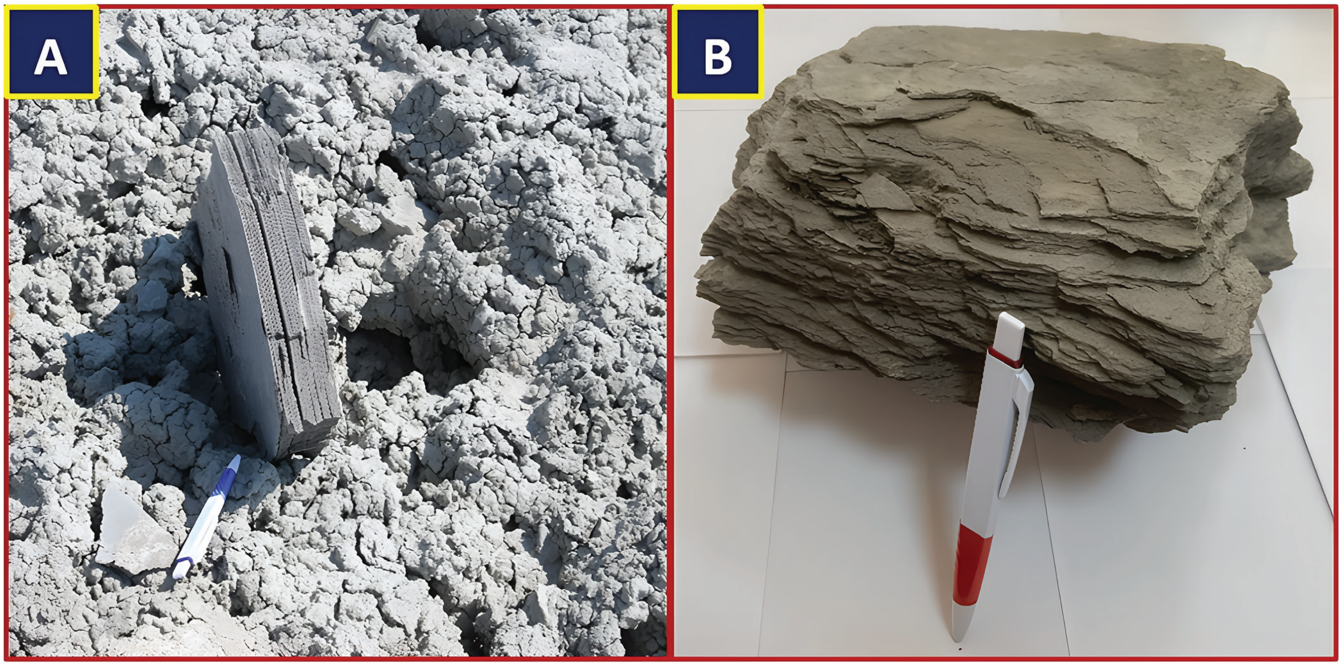

Figure 3 Middle Eocene oil shale rocks belonging to the ejecta of Otmanbozdagh (A) and Bozdagh-Guzdek (B) mud volcanoes.

Kura oil-gas regions of Eastern Azerbaijan (Figure 4) were analyzed.
Descriptions of some of the samples are shown in Table 1.

The ages of the samples were determined at the Integrated Engineering, Exploration, and Production Division, Department of Geophysics and Geology, SOCAR. Microfaunas were studied at magnification x200-300, using the Loupe Zoom Paralux XTL 745 and МБС-10 microscopes. Microscope images were transferred to a computer using a digital camera OptixCam.

The bulk rock mineralogical composition of samples was determined by XRD "MiniFlex 600". The major elements were determined by X-ray fluorescence spectrometry with wavelength energy dispersion on the "S8 TIGER Series 2". The trace elements were analyzed using an "Agilent 7700 Series ICP-MS".

Petrographic studies were carried out using a Carl Zeiss Microcracy GmbH device. Mineralogical, chemical, and petrographic analysis was carried out at the Institute of Geology and Geophysics of the Ministry of Science and Education of the Republic of Azerbaijan.

Rock-Eval pyrolysis was performed using a Rock-Eval 6 Standart device from Vinci Technologies at the Gubkin Russian State University of Oil and Gas.

^{1}H NMR spectra were recorded on TOP SPIN and FTIR spectra on ALPHA FT-IR (Bruker) spectrometers at the Institute of Petrochemical Processes of the Ministry of Science and Education of the Republic of Azerbaijan.

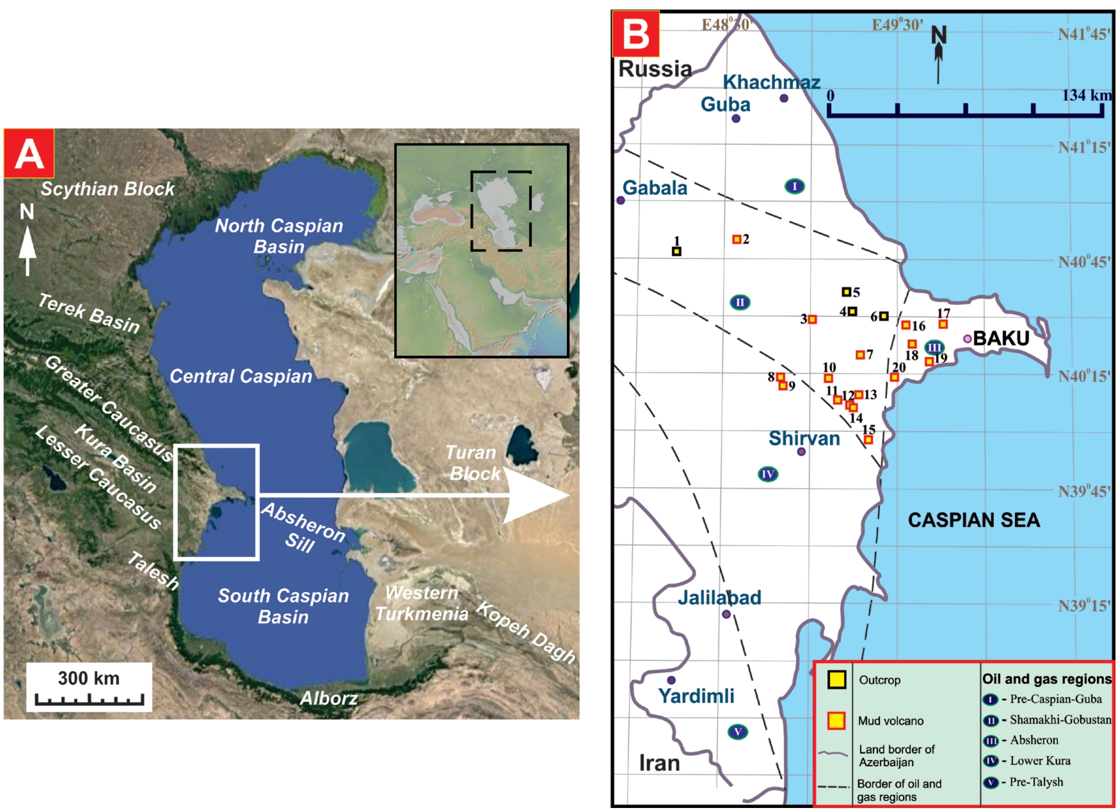

Figure 4 Location map of sampled outcrops and mud volcanoes in oil and gas regions. (A) Satellite maps of the Caspian Sea and surrounding geological features. Inset places the enlargement within the wider West and Central Asia. (B) Map of sampled outcrops and mud volcanoes in eastern Azerbaijan (Aliyev *et al.*, 2015; Liu *et al.*, 2024). Sampled areas: 1. Diyalli, 2. Demirchi, 3. Shikhzerli, 4. Boyuk Siyeki, 5. Jengichay, 6. Pirekeshkul, 7. Chapylmysh, 8. Akhtarmaardi, 9. Akhtarma-Pashali, 10. Shekikhan, 11. Durandagh, 12. Go-tur, 13. Toraghay, 14. Aghtirme, 15. Goturdagh, 16. Uchtepe, 17. Keyreki, 18. Bozdagh-Guzdek, 19. Lokbatan, 20. Otmanbozdagh.

http://dx.doi.org/10.18268/BSGM2025v77n1a020724

Table 1. Descriptions of Middle Eocene oil shale samples collected from outcrops and mud volcano areas.

Area	Sample	Description
Diyalli (outcrop)		Oil shale consists of a mixture of dark grey-brown colors and three separate layers.
Chapylmysh (volcano)		Dark black color oil shale. The paper-shaped layers can be easily separated from each other.
Shikhzerli (volcano)		Dark gray and denser oil shale. Although looks massive, the laminated texture is clearly visible around the edges.
Lokbatan (volcano)		Oil shale consists of dark grey and paper-shaped layers. Volcanic mud is observed above the upper layer of hard-to-break rock.
Keyreki (volcano)		Dark black in color and its paper-shaped layers are clearly visible. Mud volcanic breccia penetrated between the layers of rock.

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4. Mineralogy

17 minerals representing 6 classes were identified in the samples. Most minerals are silicates. They consist of quartz, feldspar, augite and clinoptilolite, as well as clay minerals such as montmorillonite, illite, chlorite, kaolinite and clinochlore. Carbonates, sulfides, sulfates, and oxides were also identified in the samples (Table 2).

Clay minerals are dominated by montmorillonite and illite. Samples taken from volcanic ejecta contain more chlorite. From this point of view, the samples belonging to the south of the Absheron peninsula and the Lower Kura oil and gas region differ more. These samples are also richer in calcite (>9%). The outcrop samples are richer in quartz than mud volcanoes. The concentration of jarosite in the oil shales of Absheron is relatively high, reaching up to 10% (Table 2).

4.1. MINERALOGICAL CLASSIFICATION

The Eocene oil shales of Eastern Azerbaijan are clayey-siliceous. The result of Figure 5 shows that some samples of the Shamakhi-Gobustan oil and gas region contain more brittle minerals, such as the Barnett shale, which is exploited for the extraction of shale hydrocarbons.

5. Major oxides and trace elements

The subsiding order distribution of major oxides in the samples: SiO_2 > Al_2O_3 > Fe_2O_3 > CaO > SO_3 > K_2O > MgO > Na_2O > TiO_2 > P_2O_5 > MnO. Compared to the Shamakhi-Gobustan and Absheron oil and gas regions, samples of the Lower Kura contain less Si. The Shamakhi-Gobustan samples differ from others in their lower content

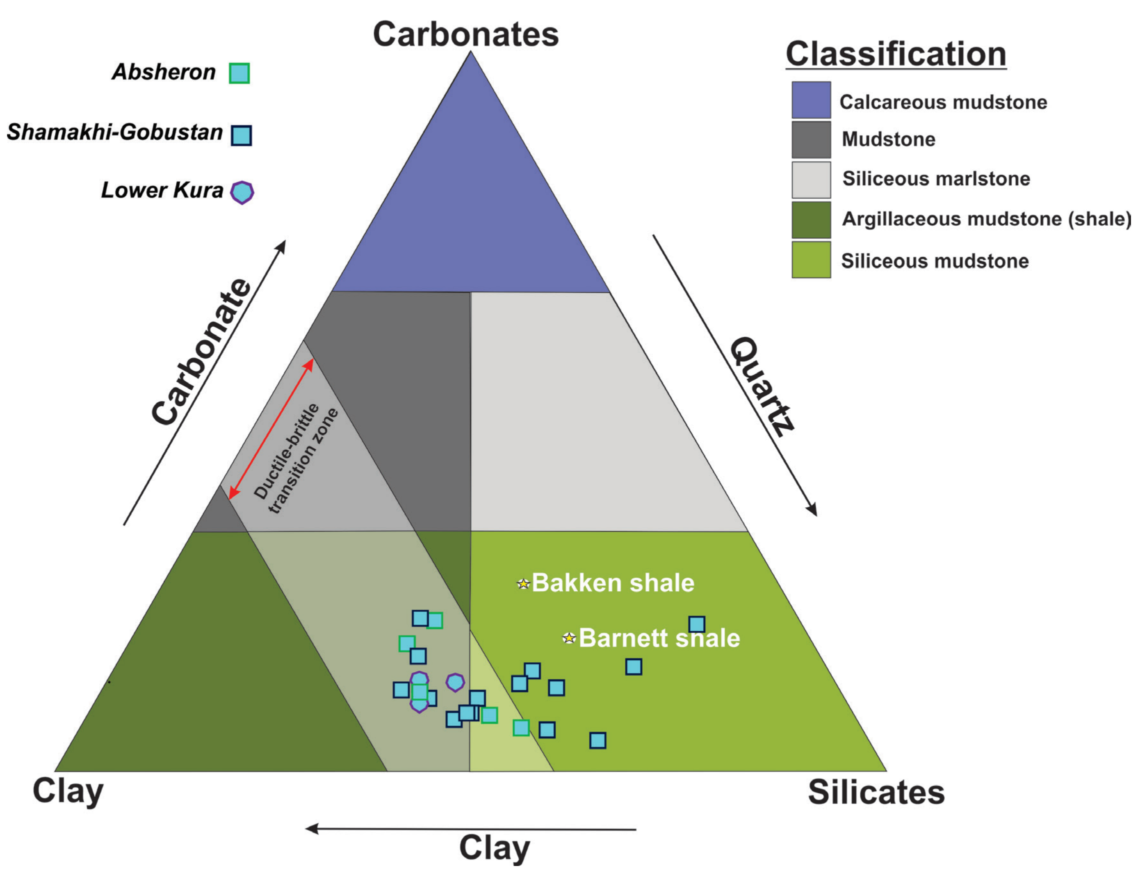

Figure 5 Distribution of samples in a three-dimensional mineralogical classification diagram (Hennissen *et al.*, 2017).

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Table 2. Comparison of the distribution of minerals in samples.

	Quartz	Feldspar	Augite	Clinoptilolite	İllite	Montmorillonite	Kaolinite	Chlorite	Clinochlor	Calcite	Mg-calcite	Pyrite	Yarosite	Gypsum	Bassanite	Hematite	Tridymite
Average value for 23 samples, %																	
Samples	27	9.9	0.4	0.5	14	15	5.3	5.9	1.1	8.2	0.6	1.8	4.8	0.4	0.7	2.4	0.9
Average value of samples taken from outcrop sections and ejecta of mud volcanoes in oil-gas regions, %																	
Shamakhi-Gobustan (outcrop)	28	10	1.3	1.5	14	16	6.4	2.5	-	7.4	1.5	2.2	1.9	-	1.3	3.4	2.5
Absheron (volcano)	26	11	-	-	12	15	0.6	12	-	10	0	0	10	-	0.4	2.2	0
Shamakhi-Gobustan (volcano)	27	9.1	-	-	16	15	7	4.3	3.1	7.4	0.2	2.5	3.8	1.3	0.6	2	0
Lower Kura (volcano)	26	8.7	-	-	16	16	7.3	6. 7	0	9.7	0	2	5	0	0	2	0

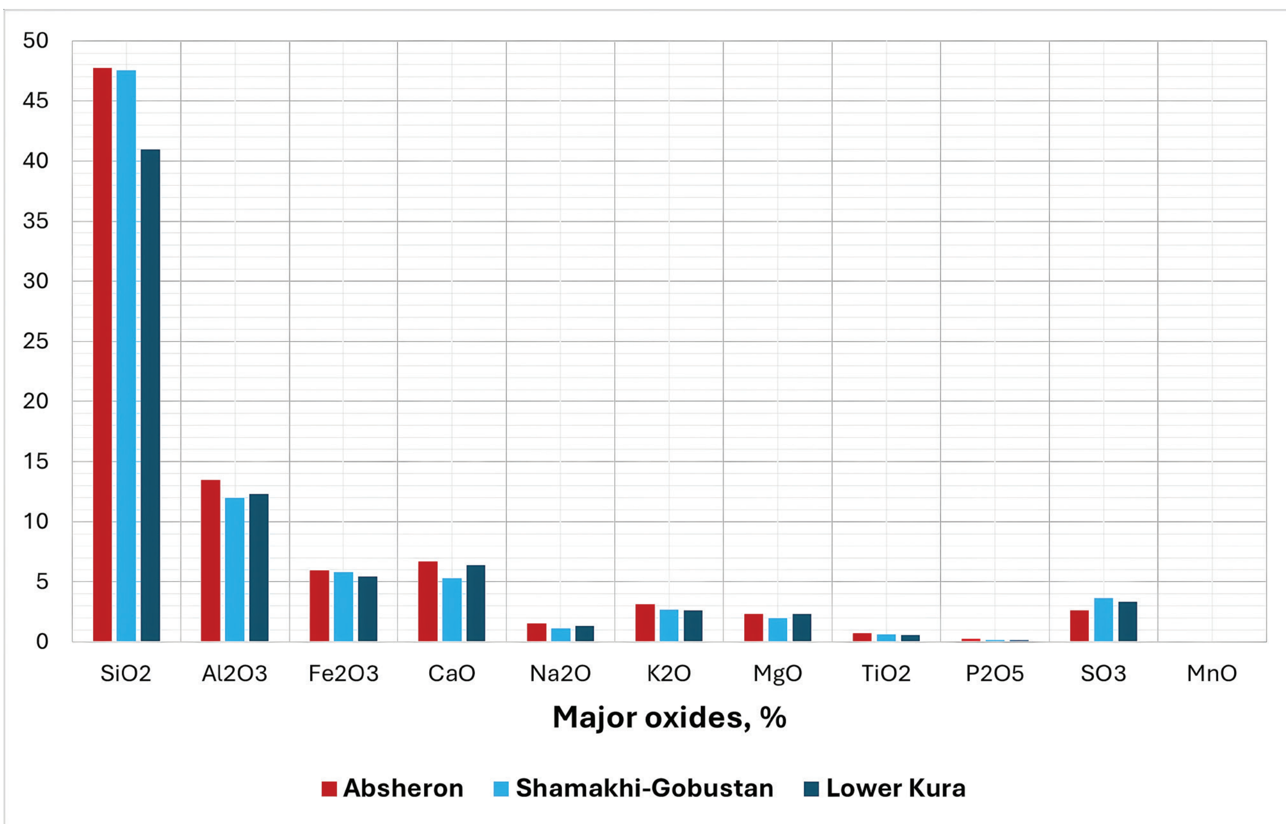

Figure 6 Comparative diagram of average values of the major oxides for samples of the studied oil and gas regions.

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of Al, Ca, and Mg. In terms of average S content, the Shamakhi-Gobustan and Lower Kura samples are superior to the Absheron samples (Figure 6).

As for trace elements, a significant preference is recorded for V, Cu, Mo, and As for Shamakhi-Gobustan samples, and for Ni, Rb, and Sr for Absheron samples. According to the content of Ba, Rb, Sr, and Ni, a decreasing trend is observed in the oil and gas regions: Absheron < Shamakhi-Gobustan < Lower Kura (Figure 7).

6. The origin and formation

6.1. CHEMICAL WEATHERING, NATURE OF THE PROVENANCE, AND TECTONIC SETTING AND PALEOCLIMATE

The Middle Eocene oil shales exhibit weak to moderate chemical weathering (Figure 8). A group of samples better endowed with calcite shows significantly lower chemical weathering and contains the lowest Rb/Sr values. This is an indicator of wind-blown volcanic ash deposits (Selvaraj and Chen, 2006). In addition, some samples contain minerals such as tridymite and clinoptilolite (Table 2), the genesis of which is associated with volcaniclastics. Our calculations related to the contribution of terrigenous material to the formation of samples (based on Cr in the samples and PAAS, Peters *et al.*, 2000) showed lower chemical weathering and Rb/Sr values, as well as analyses based on Zr/TiO_2 and transition metals such as Cr, V, and Ni, also support the idea that the genesis of Middle Eocene oil shale is also associated with volcanic ash (Figure 9).

In terms of evolution in geodynamic space, although the protoliths of several samples are correlated with arc volcanism (Figure 10A and Figure 10D), in general, the Middle Eocene oil shales of East Azerbaijan demonstrate proximity to magmatism associated with intraplate settings (Figure

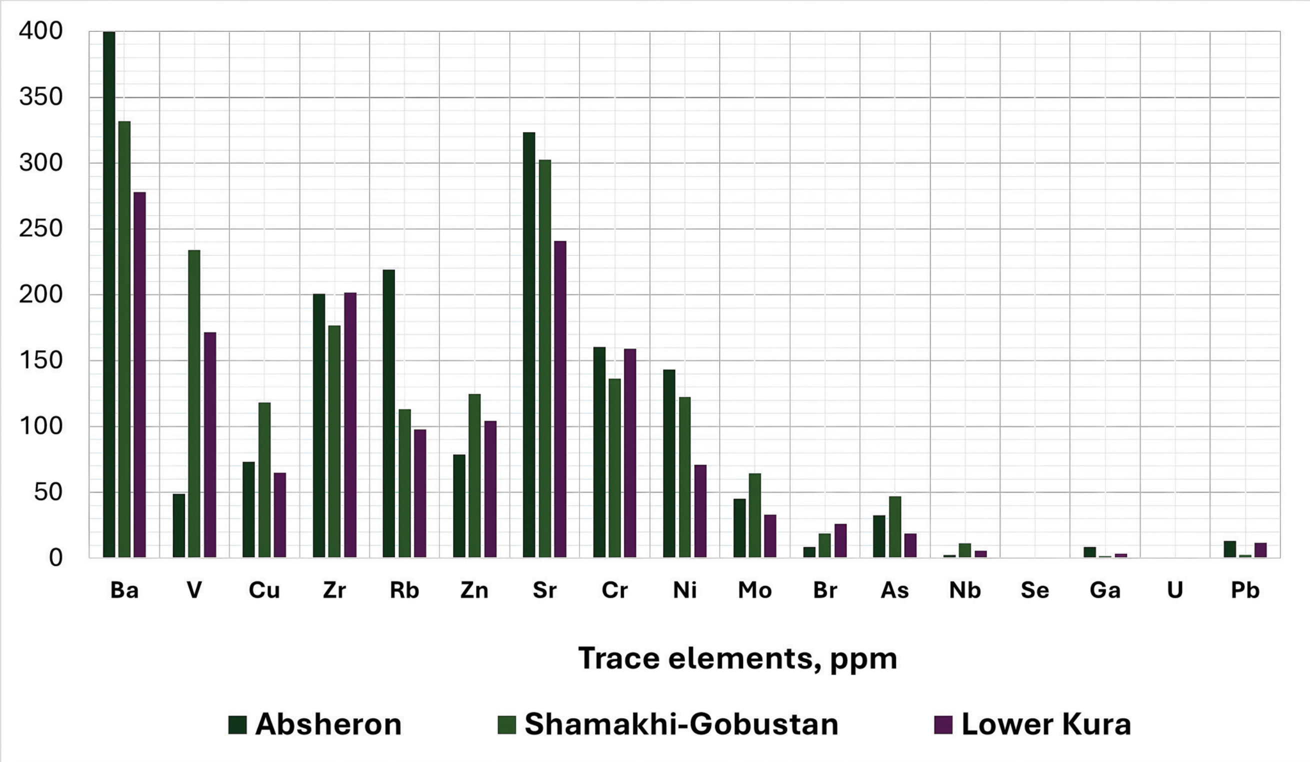

Figure 7 Distribution of the average values of trace elements in samples for oil and gas regions.

10A). Protoliths of samples correlate mainly with basalts and partly with andesites (Figure 10B). Figure 10C points to the role of tholeiitic volcanism and Figure 10E to the processes that occurred under rift-collisional geodynamic conditions.

The results of the reconstructions related to the protolith and the paleotectonic setting show that the evolution of the Middle Eocene shales, which are widespread in the accretionary prism zone of East Azerbaijan (Figure 1), is in good agreement with the geodynamic processes established (Rustamov, 2019) for the Caucasus and the Caspian region. These processes are associated with a rift located between the South Caucasus and the North Caucasus (Transcaucasian) microplates. The rift was active in the Lower Jurassic-Upper Eocene time, known as a suboceanic basin, consisting of the North Crimean-Greater Caucasus-Kopet Dag trough. The subduction of the Tufan basin under the Scythian platform in the Jurassic and the Dubrar trough under the Kakheti-Vendam zone in the Cretaceous led to the occurrence of Jurassic and Cretaceous island and Andean rift volcanism in the region.

In the Upper Eocene, the closure of this rift basin led to the cessation of volcanic processes in the Greater Caucasus and, as a consequence, to the beginning of collision in the region (Rustamov, 2019). Such geodynamic evolution, determined for the Jurassic-Upper Eocene periods of the region, agrees well with our reconstruction results of the tectonic setting, showing the transition from a rift to a collision setting in Figure 10E.

On the other hand, the correlation of samples with tholeiitic basalts in Figure 10C shows the major role of Tufan tholeiitic volcanism in the Middle Eocene shale formation. The proximity of the samples to partially andesitic sources in Figure 10B and Figure 10C suggests the role of Cretaceous volcanism in the Vendam zone with the activation of the continental margin and intraplate meridional faults. In addition, the identification of strong explosive volcanism during the Lutetian-Bartonian in Talysh, Nakhchivan, and the

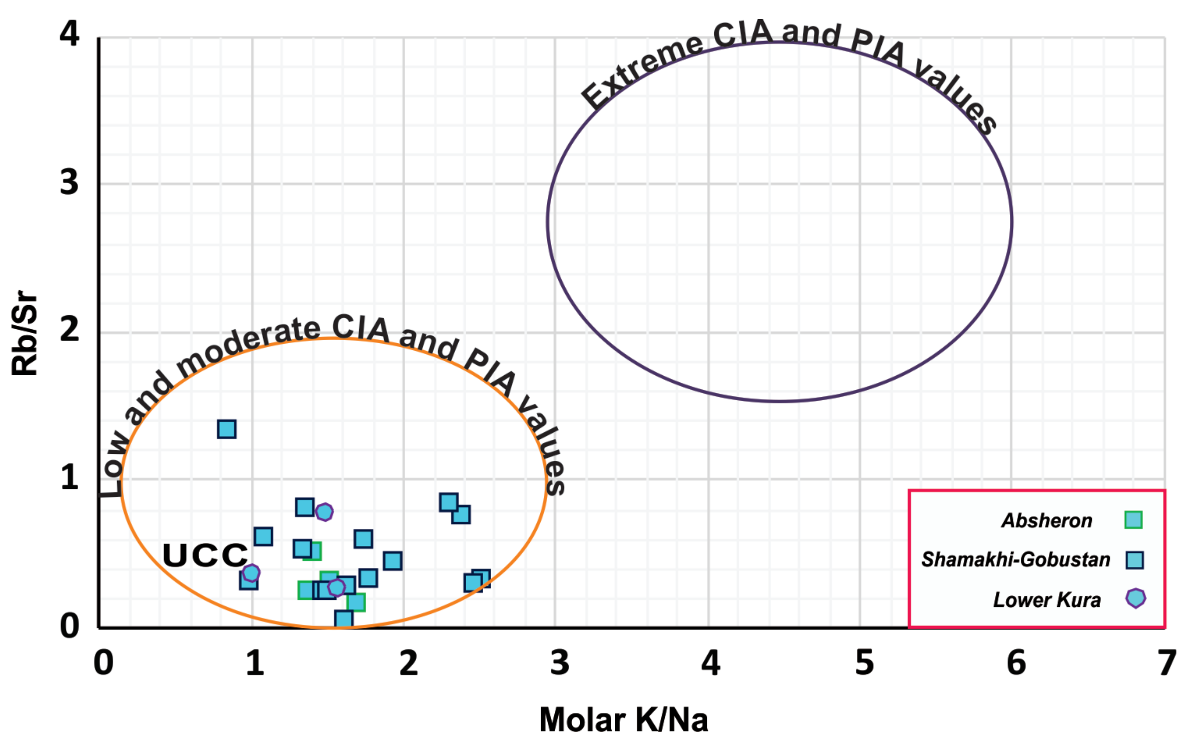

Figure 8 Diagram showing the degree of paleoweathering of samples (the areas in the diagram that belong to low and extreme values of CIA and PIA were determined based on Selvaraj and Chen (2006)).

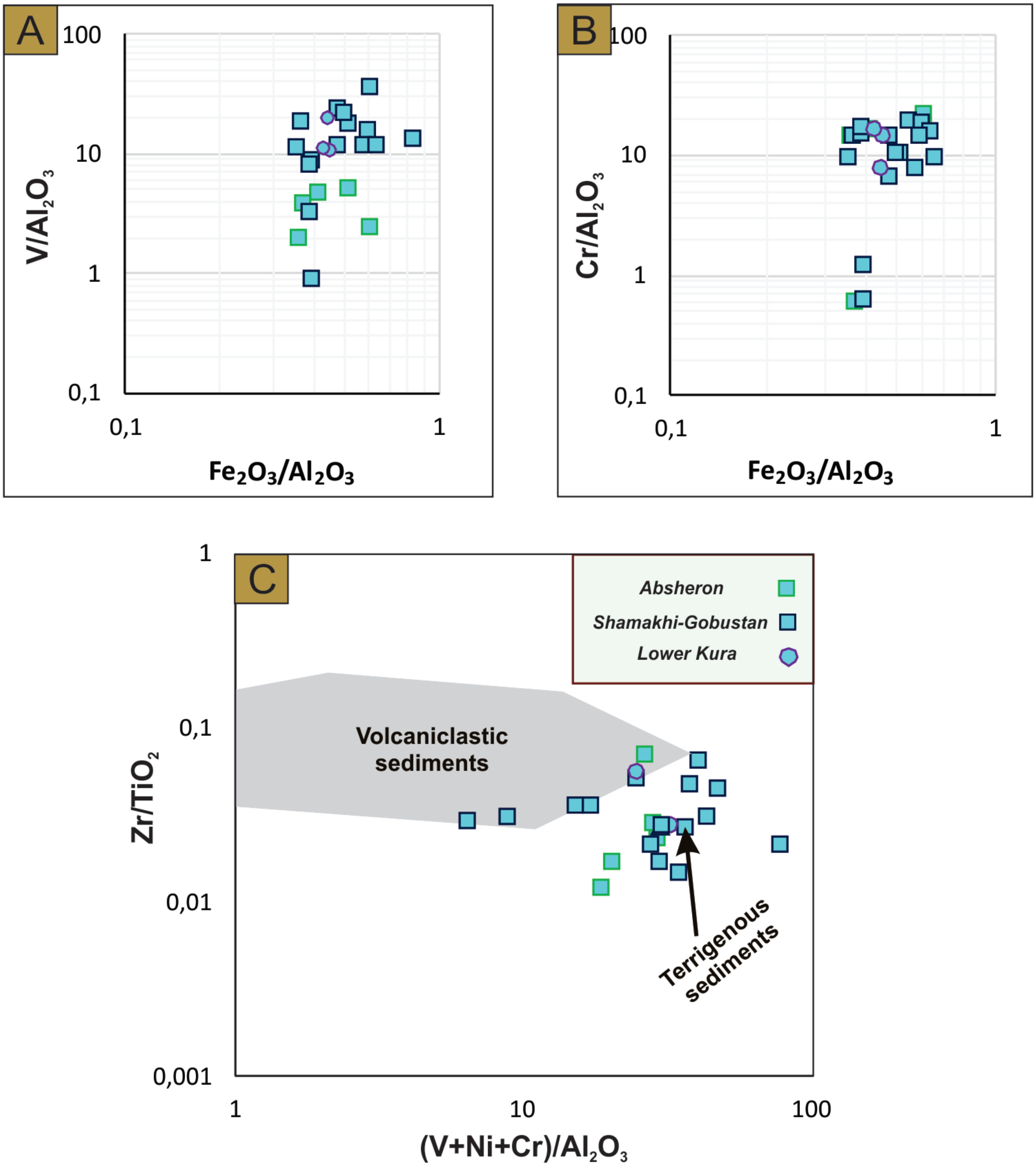

Figure 9 Diagrams showing the association of some samples with volcaniclastics (Andreozzi *et al*., 1996).

Lesser Caucasus (Rustamov, 2019) also confirms the role of pyroclastics in the formation of Middle Eocene shales, since in our studies some samples show contact with volcanic ash in Figure 9. The correlation of these samples with arc volcanism (Figure 10A and Figure 10D) also strengthens our conclusion.

The mineralogical composition of Middle Eocene shales is dominated by montmorillonite and illite (Table 2), which are considered an indicator of sedimentation occurring under dry and cold paleoclimate conditions, respectively. This paleoenvironment is accompanied by weak-moderate chemical weathering, which is also confirmed by geochemical proxies (Figure 11). Calculation of paleotemperature on the earth's surface using CIA indicators (Xu *et al.*, 2020) showed that the temperature in the Middle Eocene was higher than the minimum temperature value (4 °C) determined for Upper Maikop. The fact that the Middle Eocene had higher temperature conditions than Maikop is in good agreement with the paleotemperature indicator reflecting global climate change, determined based on isotope data for deep-sea foraminifera (Zachos *et al.* 2001).

6.2. DEPOSITIONAL ENVIRONMENTS

A calcite concentration of about >5% indicates a mixture of fresh and seawater, and a high concentration shows a strong influence of seawater. The results of Figures 12A and Figure 12C show that the samples exhibit an average calcite concentration of 8.2% (Table 2), formed under low-salinity

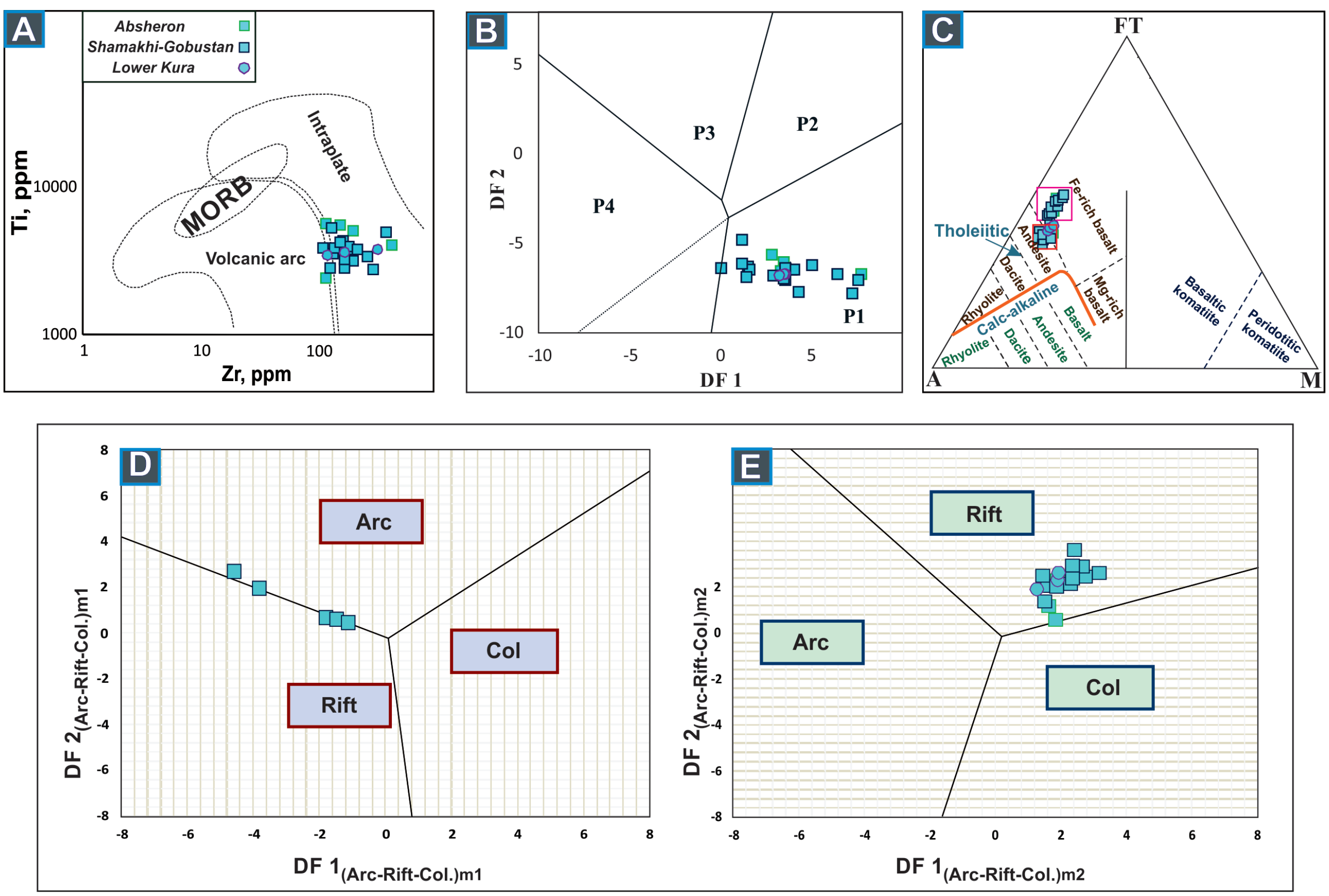

Figure 10 Diagrams showing protoliths and tectonic settings of samples (after Zou, 2013 (A); Roser and Korsch, 1988 (B); Jensen 1976 (C); Verma and Armstrong-Altrin, 2013 (D - high-silica $(SiO_2)_{adj}$ = 63-95% and E - low-silica $(SiO_2)_{adj}$ = 35-63%)).

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paleobasin conditions. The association of volcanic ash-related samples (*e.g.*, Gotur and Aghtirme) with low-salinity paleobasin in Figure 12C is evidence of the weak transport of volcanic ash into the Middle-Eocene basin and the major role of seawater in its salinization. This idea is well supported by the Otmanbozdagh sample, which correlates well with the pyroclastics in Figure 9. Thus, in Figure 12C this sample shows almost the same paleosaline environment as other samples around the Caspian Sea that show no correlation with pyroclastics.

According to our estimates, the samples from mud volcanoes located closer to the Caspian Sea correlate better with paleomarine conditions. Our comparative analysis shows their association with relatively higher salinity (Figure 12C) and deeper (Figure 12D) paleobasin environments. The evolution of Middle Eocene oil shales is in good agreement with sedimentation occurring in an oligotrophic basin (Figure 12B). The transfer of new freshwater flows into the oligotrophic basin, which is a relatively open type of lake, leads to the formation of a low-salinity and oxygen-rich aquatic environment (Figure 12E).

6.2.1. BIOGENIC SEDIMENTATION

The formation of montmorillonite, Si-rich clinoptilolite, and tridymite from water-deposited rhyolite or dacite ash mainly depends on the ability of the ash to provide at low temperatures and pressure abundant silica in solution together with alkalis (Brown *et al.*, 1969). Clinoptilolite, which is considered to be of authigenic origin, appears in the form of automorphic crystals, and organic remains (foraminifera, etc.) are often found in its crystal cavities. Biogenic opal forms the dominant

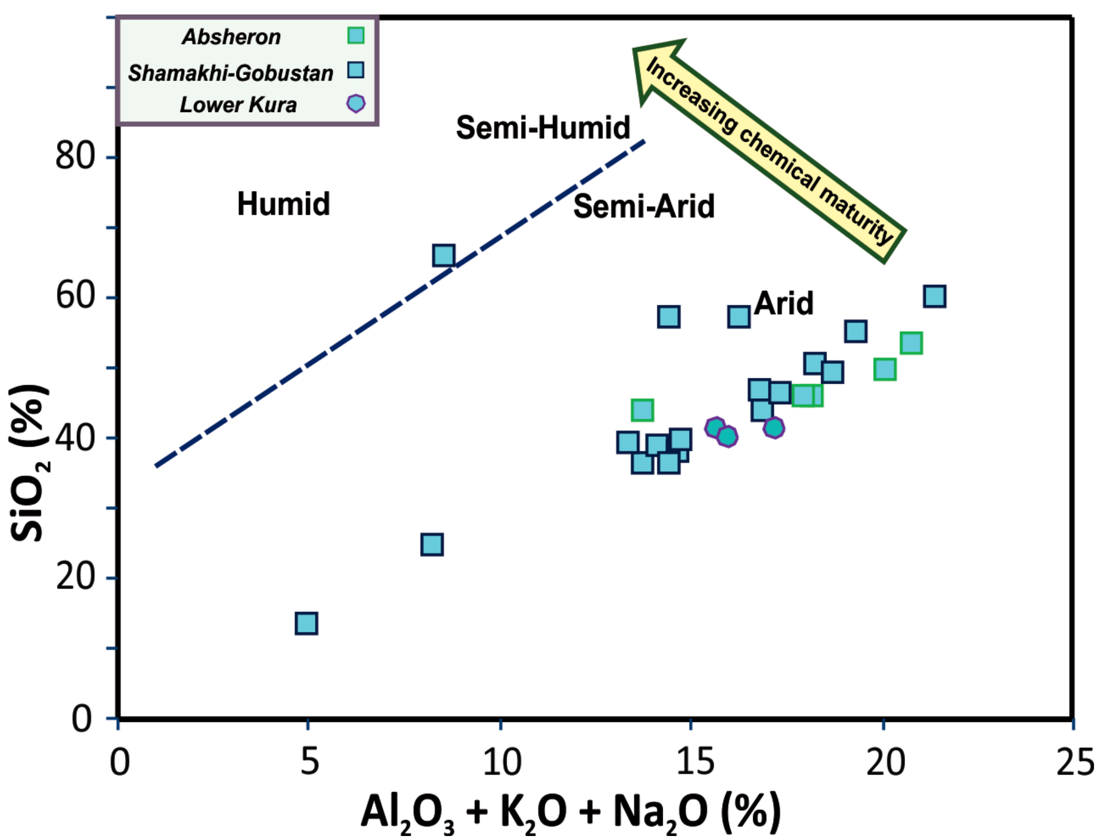

Figure 11 Bivariate plot to discriminate paleoclimatic conditions during the deposition of Middle Eocene sediments (after Lee and Prodip, 1986).

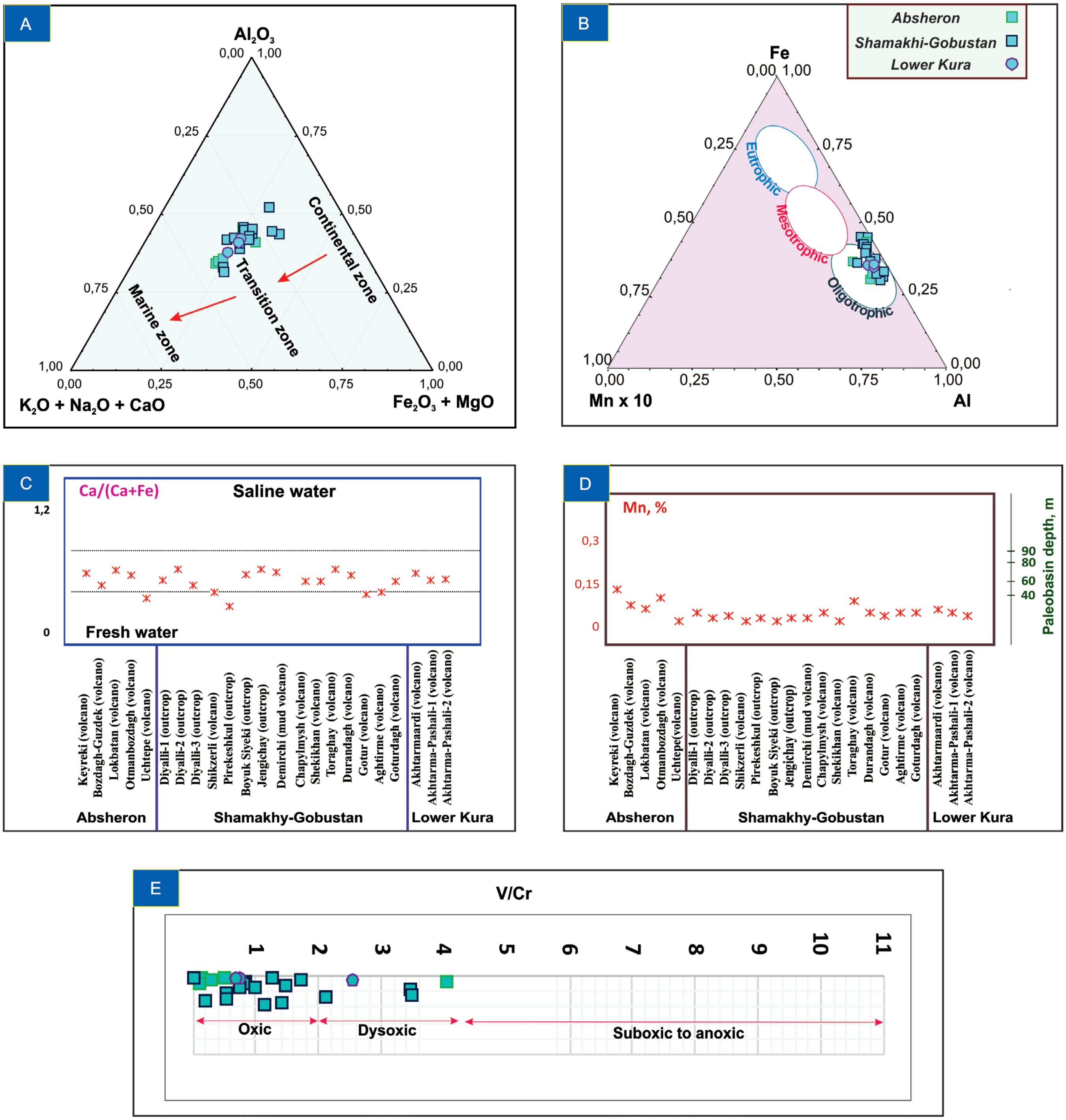

Figure 12 Diagrams showing the paleobasin conditions of samples (After Englund and Jørgensen, 2010 (A); Toyoda, 1993 (B); Matsumoto and Iijima, 1981 (C); Koyama *et al.*, 1985 (D); Arora *et al.*, 2015 (E))

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composition of the rock containing clinoptilolite. The presence of montmorillonite, clinoptilolite, and tridymite in the samples (Table 2), minerals that evolved from volcanic ash (Figure 9), indicates a certain role of biogenic sedimentation in the formation of oil shale in East Azerbaijan.

In addition to the above, in connection with the distribution and diagenetic inactivity of Zr and Al in the continental crust, their correlation with Si in the sedimentary rock allows us to form an idea about its origin. Thus, a positive correlation between Zr or Al and Si indicates a detrital quartz trend, while a negative correlation demonstrates the presence of biogenic quartz. Consistent with mineralogical indicators, the results of Figure 13A and Figure 13B also confirm the role of biogenic Si in the formation of Middle Eocene oil shales.

The index [Si/(Si + Fe + Al + Ca)] indicates the role of biogenic silica in sedimentary rock in relation to aluminosilicate, Fe- and Ca-containing minerals. The value of this index for the studied samples is 0.18-2.86. Comparing this result with the literature data on biogenic sediments (0.58-0.75, Liang *et al.*, 2020; 0.70-0.93, Bo *et al.*, 2015; 0.63-0.76, Niu *et al.*, 2018), it becomes clear that, in addition to terrigenous, biogenic sediments also played a certain role in the formation of the studied oil shale.

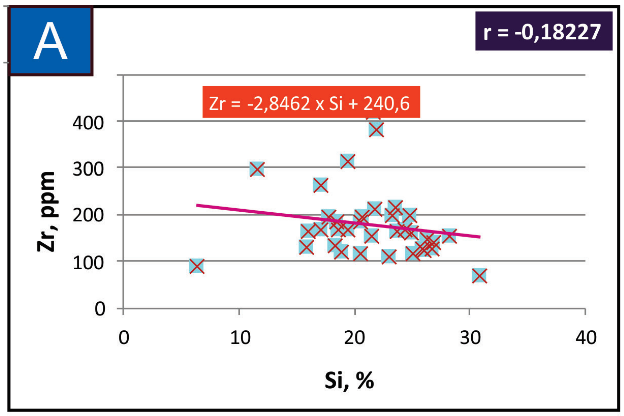
7. Organo-geochemical characteristics and petroleum potential

7.1. ORGANIC MATTER RICHNESS, KEROGEN TYPE AND OIL-GENERATING CAPACITY

The connection of the Middle Eocene shales with the sedimentation of an oxygen environment in Figure 12E may also be due to paleobioproductivity, including the enrichment of the basin with oxygen as a result of planktonic photosynthesis.

The distribution of organic matter in a structureless form (amorphous) along the interlayer joints of clay minerals in Figure 14A is an indicator of a composition consisting of organic molecules with high lipid content. The genetic association of several samples with volcanic ash in Figure 9 can be characterized as the influence of such nutrient-rich acidic igneous derivatives on the increase of planktons in the paleobasin. In addition to telalginite, the determination of inertinite in the petrographic study (Figure 14B and Figure 14C) indicates the association of organic matter with mixed sources consisting of autochthonous and allochthonous. From this perspective, it is interesting to determine which type of organic matter contributes

Our estimates indicate that increasing Al con-



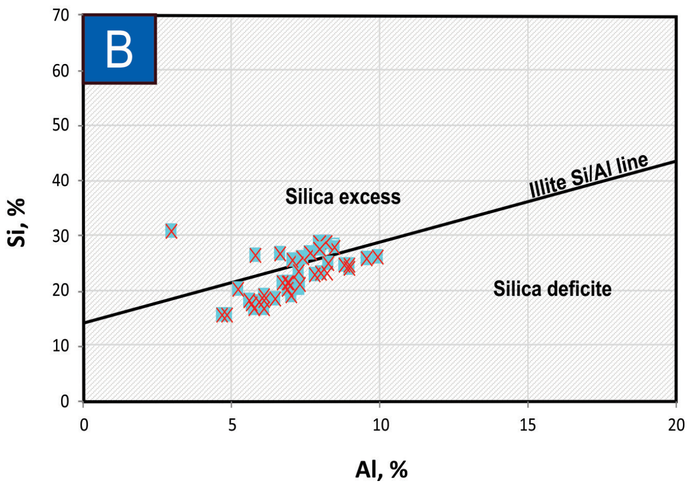


Figure 13 Diagrams showing the role of biogenic Si in the evolution of samples (After Liang *et al.*, 2020 (A); Skobe *et al.*, 2013 (B)).

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centrations in shale samples did not significantly affect organic matter enrichment (Figure 15). More specifically, only an Al concentration of 6-7% corresponds to enrichment with organic matter. This is an indication of the major role of primary paleobioproductivity, which is in good agreement with organic matter of autochthonous origin, compared to terrigenous inputs directly related to Al activity in the paleobasin.

The TOC values of the analyzed samples of Middle Eocene oil shales were 6.4-27.7%, which is many times higher than Maikop sediments, considered the best source rock in Azerbaijan (Feyzullayev *et al.*, 2001; Guliyev *et al.*, 2001; Aghayeva *et al.*, 2021). The enrichment in the organic composition of Middle Eocene oil shale was established in samples taken from the areas of mud volcanoes located around the Caspian Sea (Figure 16).

This can be explained by the closer connection with the marine environment, as well as the higher salinity and greater depth of the paleobasin in these zones (see Figure 12A, Figure 12C, and Figure 12D). On the other hand, the richness of organic matter in the oil shales belonging to the ejecta of the Lower Kura mud volcanoes is also noteworthy (Figure 16). Sedimentation conditions

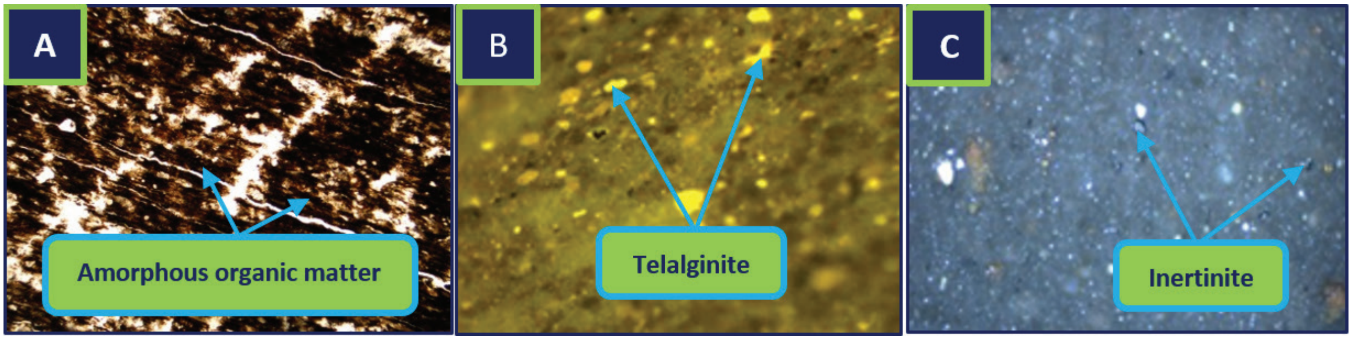

Figure 14 Petrographic images of Middle Eocene oil shale samples (Aghayeva *et al.*, 2021).

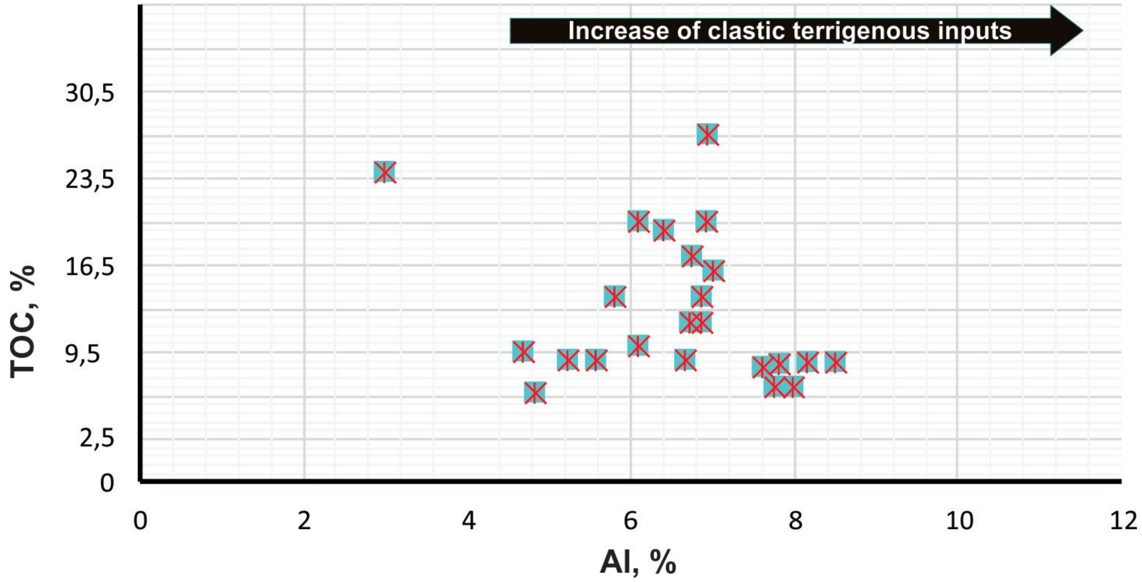

Figure 15 Diagram showing the degree of influence of terrigenous inputs on the concentration of TOC in oil shale samples.

Table 3. Average indicators (%) of structural groups calculated from [1]H NMR spectra of bitumen fractions isolated from oil shal samples.

Bitumen fractions	H_{ar}	H_{α}	H_{naften}	$H_{paraffin}$	H_{γ}	Aromaticity (fa)	Isoparaffin index (J)
Hexane	12	13.9	16.2	35.3	22.6	0.39	0.43
Benzene	10.5	14.3	11.3	41.7	22.2	0.35	0.36
Alcohol-benzene	11.7	17.3	17.3	42.1	18.0	0.38	0.29

Note: H_{ar} – hydrogen atoms belonging to aromatic nuclei, H_{α} – CH_3 and CH_2 groups that are in the α position relative to aromatic nuclei, $H_{naphthen}$ – protons belonging to naphthenic structures, $H_{paraffin}$ – CH_2 groups belonging to the alkyl chain, H_{γ} – terminal methyl (CH_3) groups.

in the Paleo-Kura delta zone are considered favorable for the formation of source rocks in this oil and gas region.

A study of the parameters of the [1]H NMR spectra of benzene and alcohol-benzene bitumens of Middle Eocene oil shales shows that the degree of aromaticity is significantly lower. On the contrary, high values of paraffin compounds were recorded in both fractions (Table 3). FTIR spectra (some of which are shown in Figure 17) identified components consisting of aromatics and oxygen-containing functional groups, as well as a high predominance of aliphatic hydrocarbons in the bitumen and kerogen compositions of the samples. In addition to cycloalkanes, the structure of aliphatics is mainly dominated by long-chain methyl and methylene.

The overlapping results of [1]H NMR and FTIR analyses confirm that Middle Eocene oil shales contain rich aliphatic organic matter derived from plankton. In thermogravimetric studies, the occurrence of maximum loss of organic matter in the temperature range up to 400°C (Figure 18) indicates the high oil potential of kerogens of autochthonous origin. In contrast to other samples corresponding to type II oil-bearing kerogens, Diyally samples with fairly high TOC content (average = 19.08%) and high HI show a correlation with type I kerogens (see Figure 19). The rich oil content of Type I kerogen-bearing source rocks associated with lacustrine algal material (*e.g.*, botryococcal algae) is observed in the thermogravimetric curve of a sample from the Sadiyan section of the Diyalli area (Figure 18 A).

Referring to our analysis based on mineralogical, chemical, petrographic, and organo-geochemical studies, we present in Figure 20 a schematic illustration that vividly reflects the main evolutionary features of Middle Eocene organic-rich source rocks. This figure alsopresents a comparison with the Upper Maikop Formation, which is considered to play a crucial role in generating Azerbaijan's abundant oil reserves.

Taking an integrated approach to the results of comprehensive studies, we conclude that in contrast to the Upper Maikop which is composed mainly of gas-bearing kerogen of type III, the richness of the Middle Eocene in type II kerogen-bearing oil source rocks is due to the influence of several factors: 1) Relatively less terrigenous input into the Middle Eocene basin; 2) Significant increases in mineral nutrients in the basin due to wind-blown volcanic ash deposits resulting from the region's intense explosive volcanoes during the Middle Eocene; 3) The Peri-Tethys transgression led to closer contact with the marine, including salinity and deep-water conditions, of the Middle Eocene basin; 4) Significant enrichment of the Middle Eocene basin with planktonic organisms due to the intense influence of the marine environment along with volcanic ash deposits; 5) The limitation of biodegradation of rich organic matter under the influence of the oxygenated environment was probably due to rapid sedimentation.

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7.2. THERMAL MATURATION

It is known that the temperature corresponding to the illitization of smectite correlates well with the vitrinite reflectance (R_o) value determined for the oil window, meaning that the provision of the heat of approximately 60°C coincides with the initial stage of kerogen decomposition into petroleum hydrocarbons (Pollastro, 1993). An increase in temperature with depth corresponds to an increase in illite content in the I/S mixture. The illite concentration in this mixture of 25-50% corresponds to vitrinite reflectance values of 0.5-1.0%, which characterizes the oil window zone (Jiang, 2012). If analyzed from the listed patterns' perspective, then the average illite concentration determined for the samples (14%) suggests that the samples will not exhibit satisfactory vitrinite reflectivity. In addition, according to the results of ^{1}H NMR and FTIR, along with the C − O and C = O functional groups, the predominance of long-chain methyl and methylene aliphatic hydrocarbons in bitumens isolated from shale samples is also an additional indicator of the insufficiency of the temperature required for thermal maturation. However, the establishment of higher illite values, T_{max} (Figure 19), and medium-high bitumen concentrations in several samples of mud volcanoes located in the coastal zones of the Caspian Sea and Lower Kura demonstrates satisfactory thermal maturity. From a spatial point of view, the oil shale ejects belonging to the high-mountain conical mud volcanoes (*e.g.*, Otmanozdagh and Lokbatan) of the southern zones of Absheron are characterized by the highest thermal maturity. The temperature gradient (>20°C/km, Abdullayev *et al.*, 2022) of these autochthonous coastal zones allows us to establish a good correlation between the depths of the Middle Eocene organic-rich shales (>4 km, Figure 2B) and the oil window in the South Caspian Basin (~ 4-5 km, Feyzullayev and Learch,

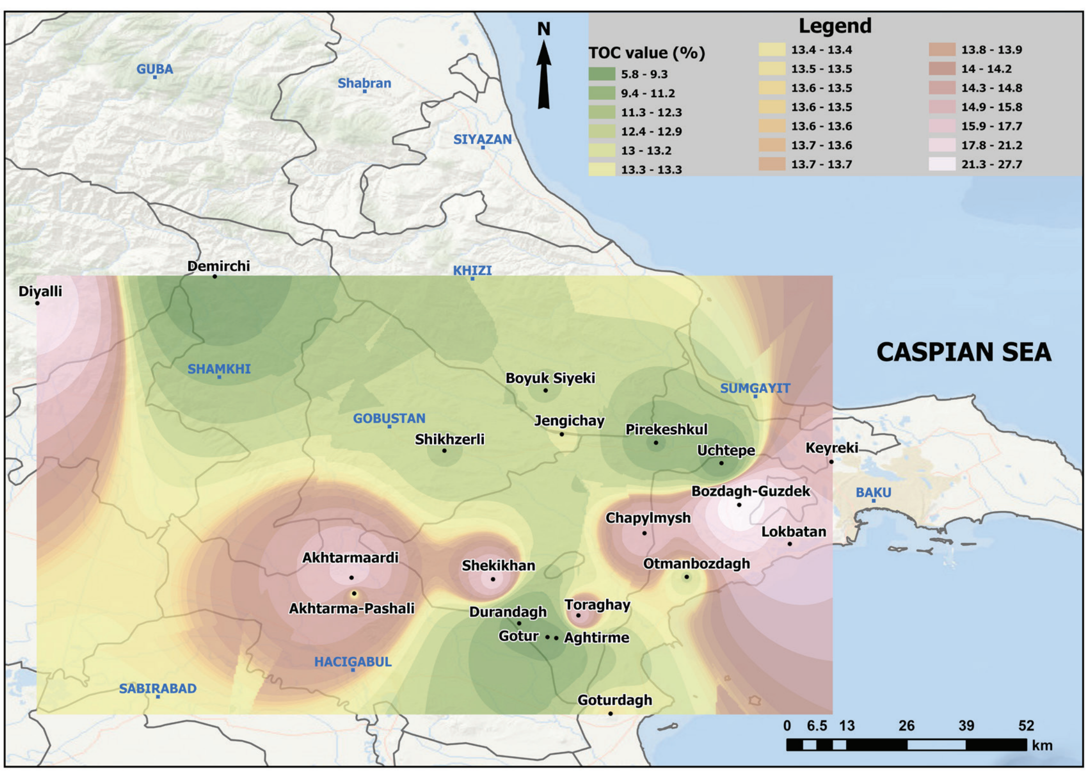

Figure 16 Map showing the distribution of TOC in Middle Eocene oil shale across East Azerbaijan.

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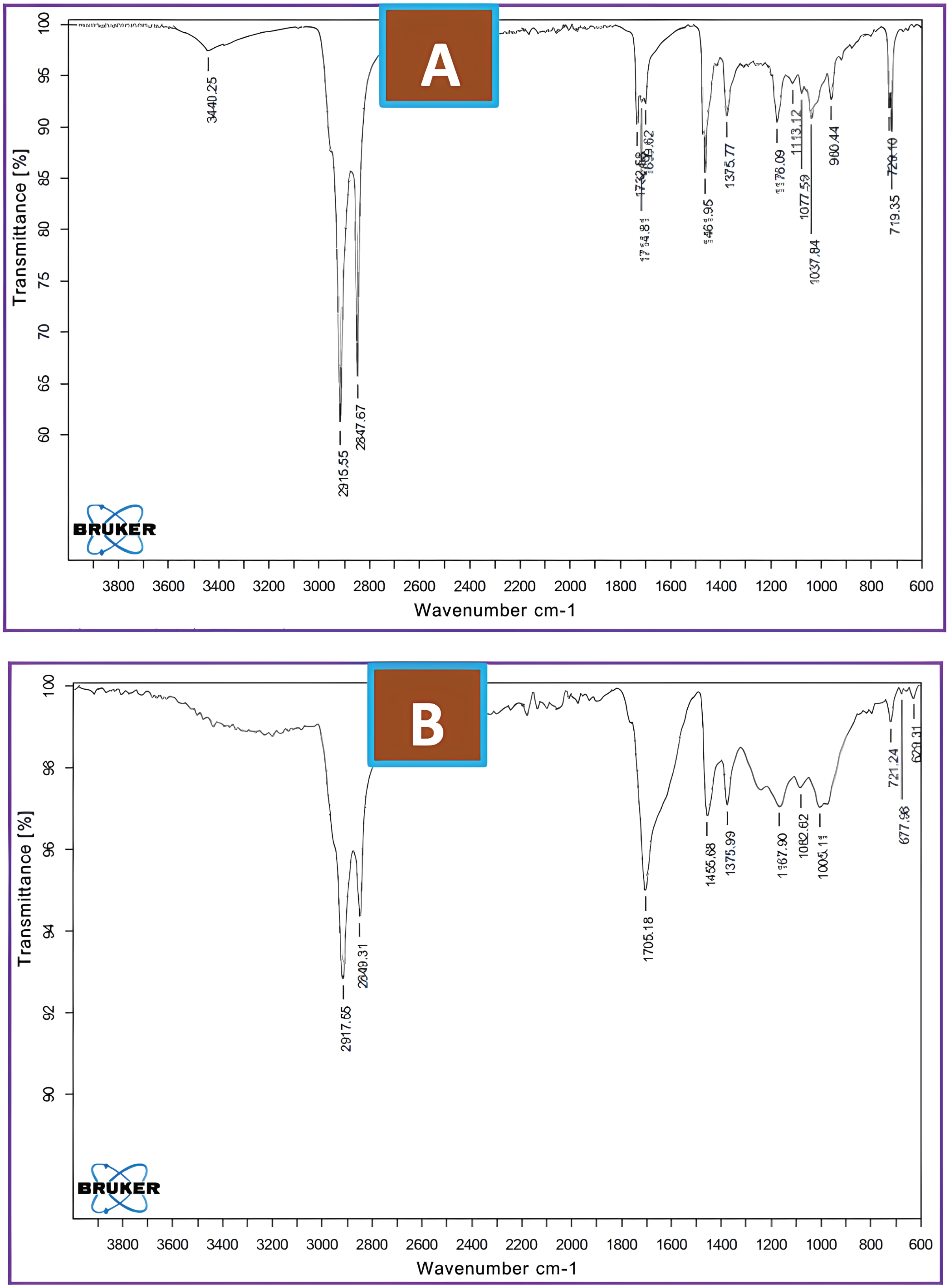

Figure 17 FTIR spectra of benzene (A) and alcohol-benzene (B) fractions isolated from the Keyreki (mud volcano) sample.

2020). Thus, given the burial depth of the Eocene layers, located at a depth of >10 km in the Caspian Sea (Goodwin *et al.*, 2020), and the temperature conditions to which they were exposed (geothermal gradient >14°C/km, Abdullayev *et al.*, 2022), we confidently assume that the Middle Eocene oil shales here were subjected to an active oil-generating process.

On the other hand, an interesting aspect of the oil shales from the Demirchi mud volcano, located in the allochthonous zone of North Gobustan, is their relatively higher thermal maturity (Abbasov, 2022). We believe that the high internal heat source of this tectonic zone, characterized by a small thickness of the sedimentary layer, is associated with internal magmatic intrusions (Aliyev *et al.*, 2005) and the occurrence of large thrust-type tectonic structures (Kengerli *et al.*, 2012). The establishment of a higher temperature gradient here in some published publications (Abdullayev *et al.*, 2022; Mukhtarov, 2012) also supports our opinion.

Given the occurrence depth (up to 4 km, Figure 2B) and mineralogical nature (see Figure 5) of the immature Middle Eocene oil shales of Central Gobustan, which are organic-rich and exhibit a thickness of 250 m, their viability as a hybrid system for future synthetic oil production is evident. The presence of alternating thick layers of laminated shale (2-3% organic matter, Abbasov, 2022) with oil shale layers (total effective thickness 10-20 m or more) within the same sections provides a significant advantage for shale oil production.

8. Conclusions

Although the entire Jeyrankechmez-South Caspian Megabasin is characterized by the distribution of oil shales of East Azerbaijan, the zone of the southern slope, corresponding to the accretionary prism of the Greater Caucasus, is distinguished by a denser manifestation of surface exposures of Middle Eocene bedrock.

The parent compositions of the Middle Eocene oil shales correlate mainly with the Jurassic high-Fe basalts of Tufan zone, and also partially with the Cretaceous andesites of Vendam zone, which are recorded in the southeast of the Greater Caucasus. The wind-blown volcanic ash has also played a certain role in the formation of oil shale samples, showing weak chemical weathering, the lowest

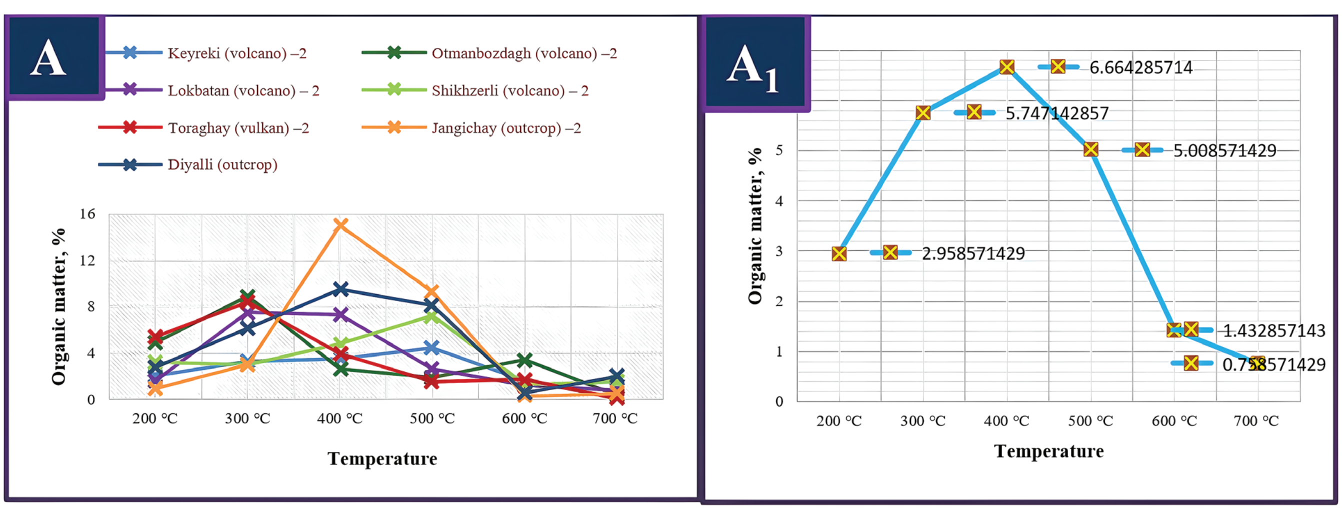

Figure 18 Diagrams showing the thermogravimetric properties of samples at temperatures of 200-700 °C (A – for individual samples, A1 – for average indicator).

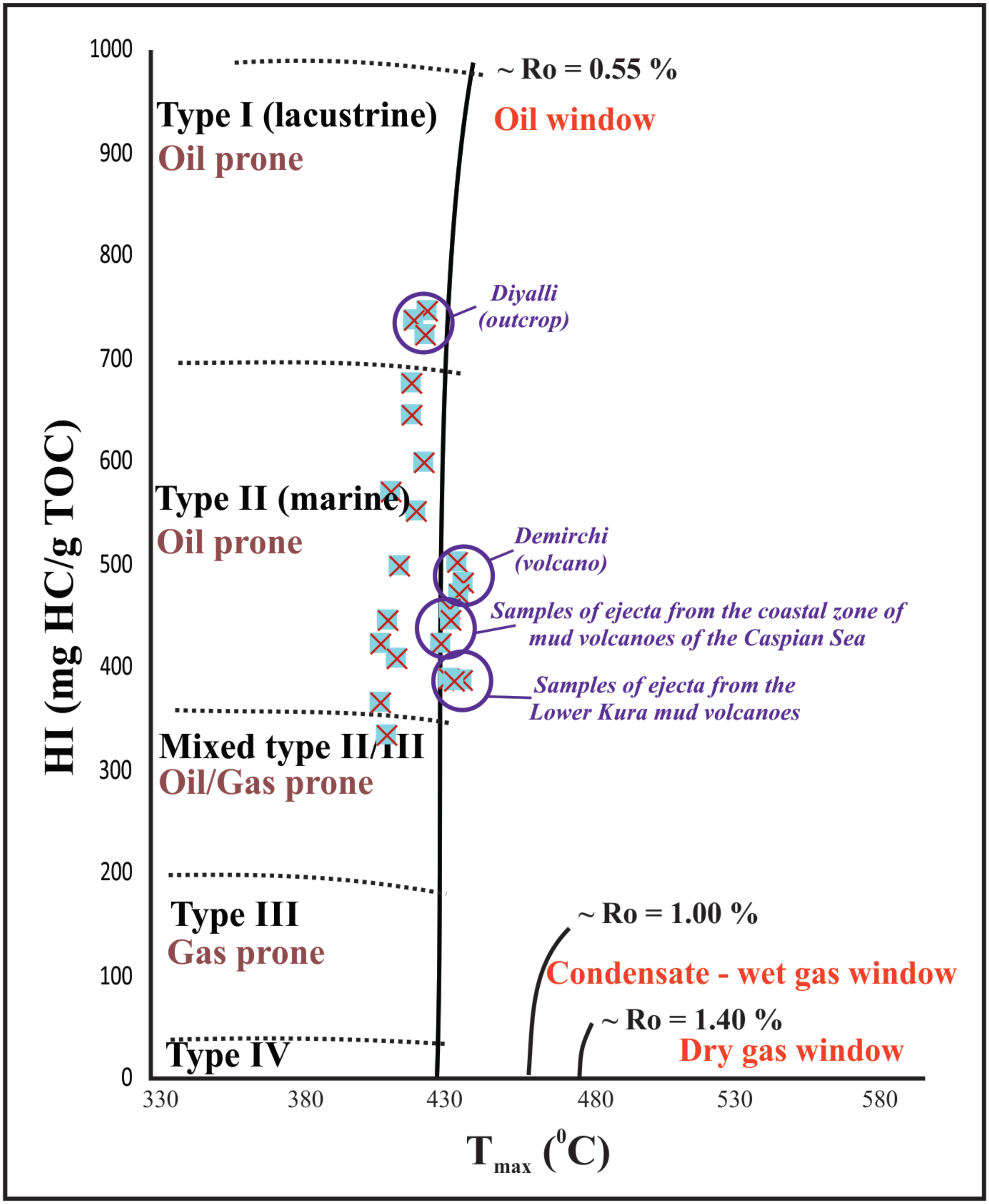

Figure 19 Hydrocarbon generation and kerogen type of source rocks of the Middle Eocene oil shale formation based on pyrolysis data of samples plotted on Van Krevelen diagram (Hudson *et al.*, 2008).

Rb/Sr, and andesitic protolith features. These pyroclastic deposits likely originated from intense explosive volcanism during the Lutetian-Bartonian in Talysh, Nakhchivan, and the Lesser Caucasus.

Our study shows that Middle Eocene shales have a significantly higher TOC (12%) than Maikop Group sediments, which are considered Eastern Azerbaijan's primary source rock. We link this to the initial paleobioproductivity of the paleobasin influenced by the Peri-Tethys transgression. Middle Eocene ejecta samples from large cone-shaped mud volcanoes located near the Caspian Sea in southern Absheron and Gobustan demonstrate the highest TOC values and show a stronger association with salinity and deep paleobasin conditions. The analogous features observed in the coeval samples from the Lower Kura are explained by biogenic sedimentation in the Paleo-Kura delta.

1H NMR, FTIR, thermogravimetric and pyrolytic analyses reveal Middle Eocene shales, rich in aliphatic compounds, as source rocks with high oil generation potential.

Ejecta samples from mud volcanoes near the-Caspian Sea showed higher thermal maturity, indicating active oil generation potential in Middle Eocene oil shales within subsiding zones, including the Caspian Sea.

Thermally immature onshore oil shales in East Azerbaijan, especially in Central Gobustan, have high prospects for synthetic oil production.

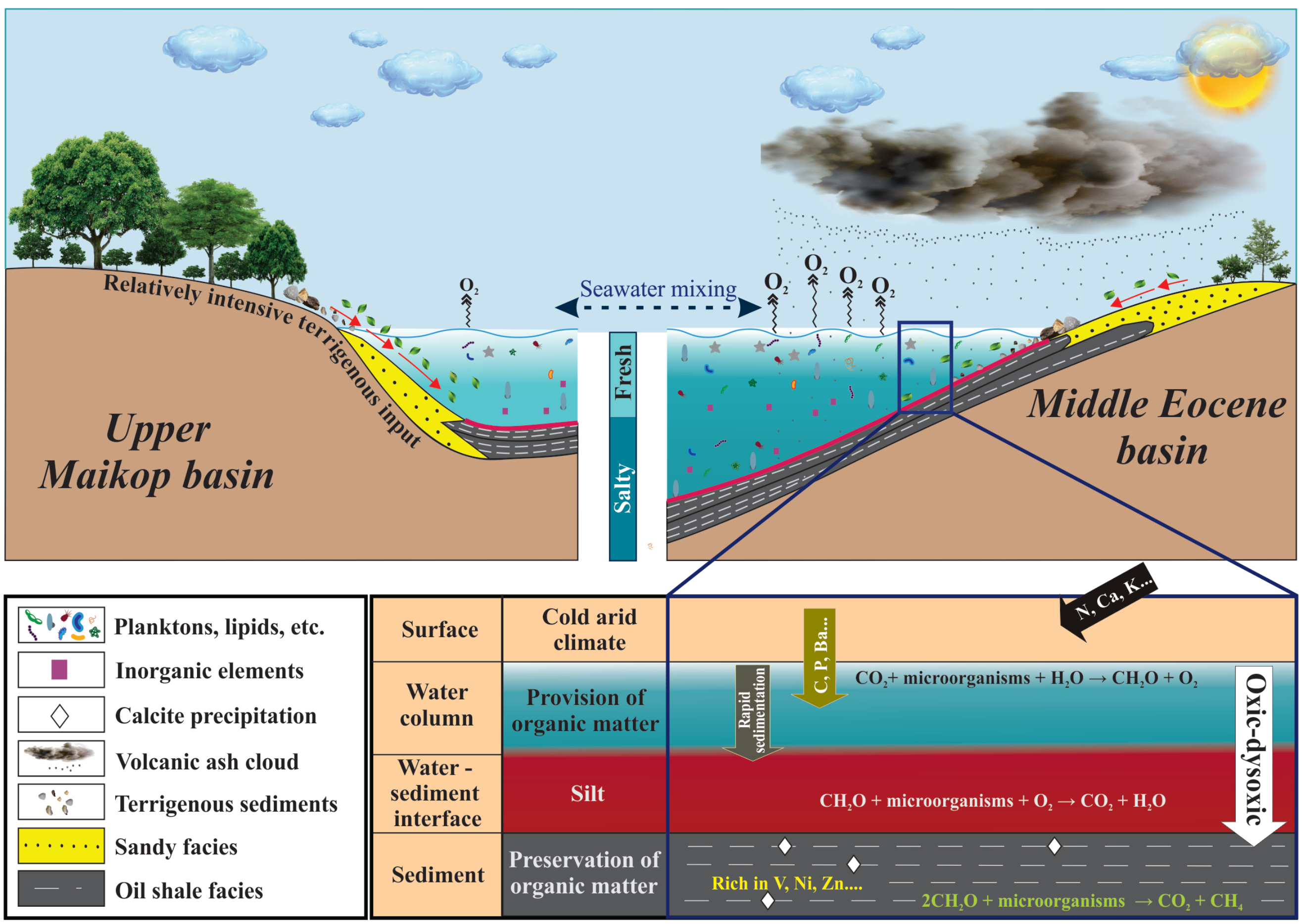

Figure 20 Schematic illustration showing the evolutionary features of the Middle Eocene and the Upper Maikop oil shale basins (Abbasov, 2022).

Contributions of authors

ORA and EEB: fieldwork and sampling, conceptualization, research, original manuscript writing: UJY: physical and chemical analyses and interpretation of results; AIK: conceptualization and research; RVA: fieldwork and sampling, graphic materials preparation.

Financing

This research was developed with the resources of the authors.

Acknowledgments

We express our sincere gratitude to Nazim Sadigov, head of the laboratory of the "Center for Collective Use of Analytical Instruments and Equipment" of the Institute of Geology and Geophysics of the Ministry of Education and Science of the Azerbaijan Republic, and Prof. Rena Jafarova, head of the department of "Physical and physical-chemical research" of the Institute of Petrochemical Processes of the Ministry of Education and Science of the Azerbaijan Republic for their contribution to the mineralogical, physical-chemical analysis of samples.

Conflicts of interest

We declare no conflicts of interest.

Handling editor

Liliana López

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