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Micropaleontological Approaches to South Caspian Oil and Gas Development

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Abstract

The South Caspian Basin is among the most structurally complex and geodynamically active regions globally, characterized by rapid sedimentation, high subsidence rates, extensive overpressure zones, and frequent mud volcanism. Together with strong seismicity, these factors pose substantial engineering challenges for offshore oil and gas development. Quaternary deposits, which underpin most offshore facilities, are critical to the safe and economical design of platforms, drilling rigs, and subsea infrastructure. Yet despite extensive studies of Caspian Sea sediments, engineering–geological data on the physical and mechanical properties of Quaternary deposits in hydrocarbon-bearing areas remain insufficient.

This study integrates micropaleontological, lithological, and stratigraphic analyses of 300 core samples from 70 boreholes across 45 offshore structures to characterize the composition, distribution, and engineering relevance of Quaternary deposits. For the first time, a detailed stratigraphic subdivision based on ostracod fauna is presented, comprising five supra-horizons, ten horizons, and seven biozones defined by index species. Eleven characteristic ostracod assemblages were identified, enabling correlation of deposits across the Apsheron and Baku archipelagos and the Turkmenian sector.

Results show pronounced lateral and vertical lithologic variability, strongly controlled by depositional environment, structural setting, and post-depositional processes. Quaternary sequences include Bakuvian, Khazarian, Khvalynian, Novo Caspian, and modern sediments, with facies ranging from fine-grained clays in deep-water settings to loams and sands in nearshore and eastern shelf areas. Integrating micropaleontological data with lithostratigraphy improves geotechnical mapping and zonation, supports the prediction of overpressure zones, and reduces development risk.

These findings establish a new stratigraphic framework for the Quaternary in the South Caspian Basin and provide essential baseline data for offshore engineering, supporting safer infrastructure design, optimized field development, and risk mitigation in one of the world's most challenging petroleum provinces.

Keywords: South Caspian Basin; Quaternary deposits; Micropaleontology; Engineering geology; Offshore oil and gas; Ostracoda

1. Introduction

Questions of engineering geology are among the most urgent in modern geological science. This urgency stems from the rapid development and exploitation of offshore oil and gas fields, as well as the increasing construction of large-scale engineering structures on continental shelves. At the same time, the study of marine geological environments contributes to solving broader theoretical problems of lithogenesis (Javadova, 2025).

The Caspian Sea shelf occupies an area of about 250,000 km², which represents over 60% of its total surface area. The shelf is generally defined by the 100-meter isobath, though its boundary varies locally (Lebedev et al., 1987). The expansion of industrial activity across the Caspian continental shelf has marked the emergence of a new branch of engineering geology—marine engineering geology. Offshore exploration has already identified promising oil and gas accumulations, but the development of these resources demands the construction of costly and technically challenging hydraulic engineering structures. The safety and efficiency of these facilities depend directly on accurate knowledge of the engineering–geological conditions of the seabed, particularly the properties of foundation soils.

The South Caspian Basin is a region of special importance in this context. It is structurally complex, tectonically active, and characterized by rapid sedimentation, subsidence, high seismicity, and widespread mud volcanism. The sedimentary cover varies from 1.8 km in platform areas to 20–25 km in folded zones (Shikhalibeyli and Grigoryan, 1983). Offshore facilities in this basin must withstand both extreme geodynamic conditions and environmental challenges. Understanding the strength, compressibility, and bearing capacity of seabed deposits is therefore a prerequisite for safe and cost-effective offshore operations.

The geotechnical investigation gives a first broad impression of the design and topographical parts of the proposed site and determines whether further investigation of the site is warranted. The information obtained from the site investigation would be utilized to arrange the type, area, and size of the outlined structure. This information can likewise be utilized for laboratory testing required as part of future research for more definitive investigation (Rahman et al., 2016).

However, knowledge gaps persist despite previous geological and geophysical studies (Akhmedov et al., 1998) that have integrated seismic, lithological, geochemical, and paleontological data to establish the regional framework. The detailed stratigraphic and engineering–geological characterization of Quaternary deposits remains inadequate. The chronostratigraphic resolution of Quaternary sediments is still limited because of fragmentary core material and the inherent difficulties in correlating marine strata. Moreover, the potential of micropaleontological data—particularly ostracods and mollusks—in refining stratigraphy and reconstructing paleoenvironmental conditions has not been fully realized. Similarly, the relationships between microfaunal assemblages, lithological characteristics, and the geotechnical behavior of seabed deposits remain underexplored, which diminishes the accuracy of engineering–geological zoning.

This research aims to address these deficiencies by integrating lithological, micropaleontological, and geotechnical datasets from the Quaternary deposits of the South Caspian Basin. The study focuses on characterizing the stratigraphy and depositional environments of Quaternary sediments through the analysis of ostracod and mollusk assemblages in conjunction with lithological markers. It also seeks to evaluate the physical and mechanical properties of seabed soils to determine their suitability as foundations for offshore structures. Ultimately, the research will develop a comprehensive engineering–geological framework that combines micropaleontological, sedimentological, and geotechnical evidence for direct application in offshore oil and gas development.

By connecting detailed scientific analyses with practical engineering requirements, this study contributes to a deeper understanding of Caspian Sea stratigraphy while providing applied solutions to support safe and sustainable offshore petroleum operations in one of the world’s most strategically important basins.

2. Materials and Methods

This work is based on research materials of soil samples from geotechnical boreholes drilled in the Southern Caspian, carried out by the author during the period 1984–1996, and additionally in 2019–2022. A total of 300 core samples from 70 boreholes over 45 offshore structures have been studied. These boreholes were drilled in the Baku Archipelago, the Absheron–Pre-Caspian zone, the Iranian and Turkmenia sectors of the Southern Caspian Basin (Fig. 1).

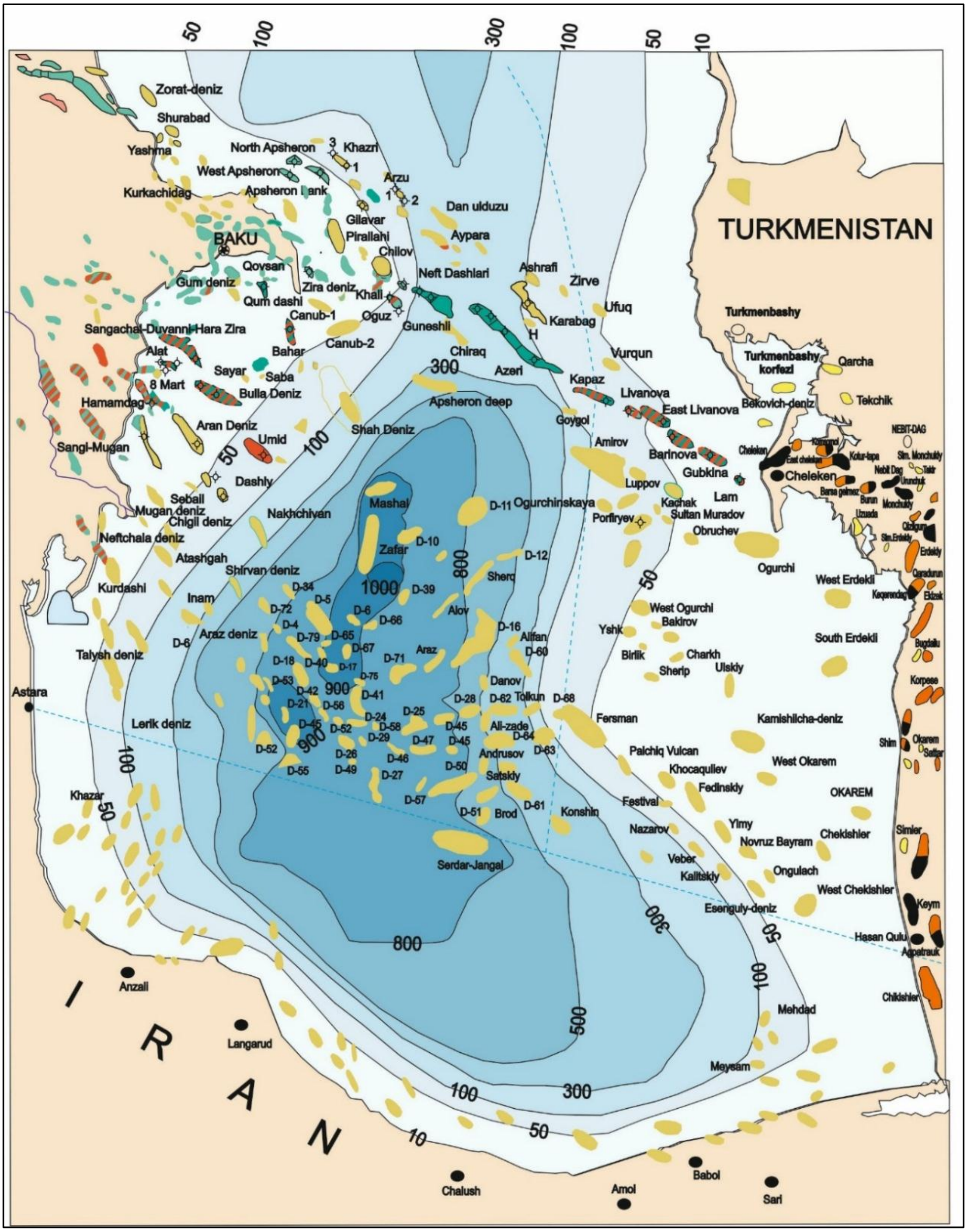


Fig. 1. A schematic map of the South Caspian Basin (modified after Azerbaijan Petroleum Industry Review, 2007).

Drilling of exploration and engineering–geological boreholes were drilled by the State Oil Company of Azerbaijan (shortly SOCAR) across key structural highs, depressions, and transitional zones of the Caspian shelf. In addition to the current results, data from published studies were also used to address the research objectives. The study of the mineral composition of silt and clay fractions of Quaternary deposits, as well as data on the engineering–mechanical properties of Quaternary clay soils, was processed by the company MicroPro GmbH.

Between 1982 and 1997, I was in charge of sampling and analysing core materials taken from Turkmenistan. Azerbaijani and a few wells of the Iranian sectors of the South Caspian basin.

Core samples were recovered at regular depth intervals, with particular attention to horizons rich in microfaunal remains (mainly ostracods). In areas without coring, drill cuttings collected at 9 m (30 ft) intervals were used for supplementary micropaleontological analysis. Microfossils were extracted from sediment samples using standard washing, sieving, and picking procedures. Both calcareous and siliceous microfaunal groups were studied under stereoscopic and binocular microscopes (Rahman et al., 2023) as well as transmitted light microscopy (i.e., Nikon SMZ-25) (Ali et al., 2023). Species identification followed established taxonomic literature, with nomenclature standardized according to international conventions. SEM photographs of micro- and macrofauna were carried out at the Institute of Geology of the Azerbaijan Academy of Sciences and the University of Jena in Germany

It was recognized that a well-preserved fauna spanning from the Miocene to the Recent time is present. These fossils tell a story of both immigration and local evolutionary change. The rocks have been subdivided into biostratigraphic horizons (biozones), based on fossil content (Raynolds et al., 2022).

Lithostratigraphic interpretations were based on species assemblages, diversity indices, ecological tolerances, and comparison with modern analogues. Chronostratigraphic frameworks were established by correlating microfaunal zones with regional biostratigraphic schemes (Fig. 2).

3. Results and Discussion

Geotechnical maps and profiles of the Quaternary deposits for the explored oil- and gas-bearing areas of the Caspian, which would characterize the changes in their engineering and geological properties both laterally and with depth, have also not been compiled.

Issues of bottom tectonics on a regional scale for the Southern Caspian, the study of the formation of engineering and geological properties of bottom sediments, and the influence of various factors on the development of these properties remain insufficiently covered. All of the above determine the need for studies of Quaternary deposits. The role of micropaleontology in identifying Quaternary deposits is one of the key aspects of the present work. In order to carry out research on all of the above-mentioned problems, it is first necessary to determine the distribution of Quaternary deposits and their constituent horizons in different sectors of the Southern Caspian, where their thickness varies from zero to 2000 meters.

This work is part of a comprehensive study of the engineering and geological properties of soils that make up the seabed. Our goal is to highlight the key aspects of this comprehensive study of the engineering and geological properties of soils, omitting detailed descriptions and focusing primarily on the role of micropaleontology.

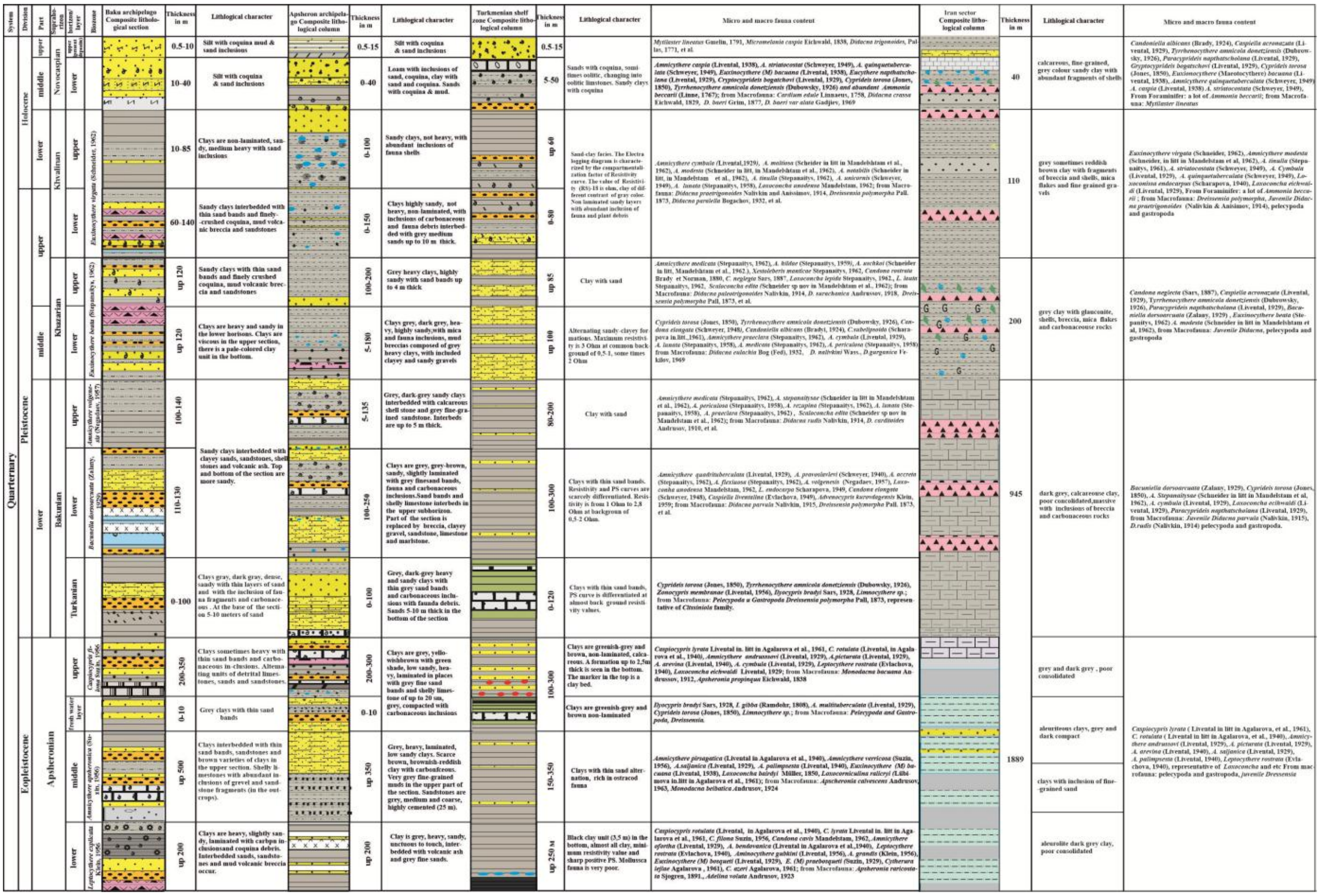


Fig. 2. Lithostratigraphy of the Quaternary deposits of the Baku and Apsheron archipelagos, Turkmenia, and Iranian sectors of the South Caspian basin (Javadova, 2023).

3.1 Stratigraphic Framework of Quaternary Deposits

Quaternary sediments are widespread throughout the South Caspian shelf, overlying Tertiary strata that crop out locally on structural highs. Based on microfaunal assemblages and lithological characteristics, the Quaternary succession is divided into the Bakuvian, Khazarian, and Khvalynian horizons, and modern Holocene sediments (Javadova et al., 1995).

- Baku Horizon: Dominated by massive grey clays with interbeds of sands, marls, and shell limestones. Thickness reaches 200–250 m, increasing toward the south and east.
- Khazarian Horizon: Grey clays with sandy-silty layers, rich in fauna; includes occasional volcanic breccia; thickness ~140–150 m.
- Khvalynian Horizon: Structureless grey to brown clays underlain by sands and breccias; thickness variable due to post-depositional erosion, generally ≤ 100 m.
- Modern Holocene sediments: Range from sandy-shell material in coastal and shallow areas to fine silty clays in deeper basins; thickness varies from a few cm to over 25 m depending on location.

Micropaleontological zonation improves correlation between these units and supports age assignments where lithology alone is ambiguous.

3.2 Micropaleontological Insights for Engineering and Reservoir Geology

Microfossil assemblages serve as powerful tools for high-resolution chronostratigraphy, enabling accurate correlation of engineering and reservoir sections even within structurally complex terrains. Paleoenvironmental reconstructions derived from microfaunal records clarify lithological and geotechnical variability.

When integrated with seismic stratigraphy, micropaleontological data significantly enhance predictions of overpressured zones, reservoir geometries, and facies distributions. Such insights reduce drilling risks and guide the safe placement of offshore infrastructure, particularly in seismically active regions and areas affected by mud volcanism.

Quaternary and Upper Pliocene (Akchagylian) deposits show notably richer microfaunal assemblages compared to Middle and Lower Pliocene strata. These seabeds also host abundant macrofauna, especially pelecypods and gastropods, accompanied by diverse ostracod populations. In addition to their applications in geotechnical studies, ostracods serve an important stratigraphic function in the identification of hydrocarbon-bearing reservoirs, thereby significantly reducing the cost of drilling exploration wells once the target reservoir horizon is encountered. Ostracoda fauna is also useful. Figures 3–5 illustrate these applications.

3.3 Key Aspects of Modern Geological Processes and Phenomena

By the end of the Post-Pliocene, numerous submarine and surface mud volcanoes in the South Caspian Basin became active, while others remained buried within Apsheron deposits. The study of Quaternary sediments in this region is of considerable practical importance, given their close relationship to oil and gas accumulation.

Tectonic and sedimentary activity during the Post-Pliocene was highly uneven. On the northern part of the western shelf, approximately half of the structural growth occurred during this time, whereas in the southern shelf, tectonic processes were weaker than during the Upper Pliocene.

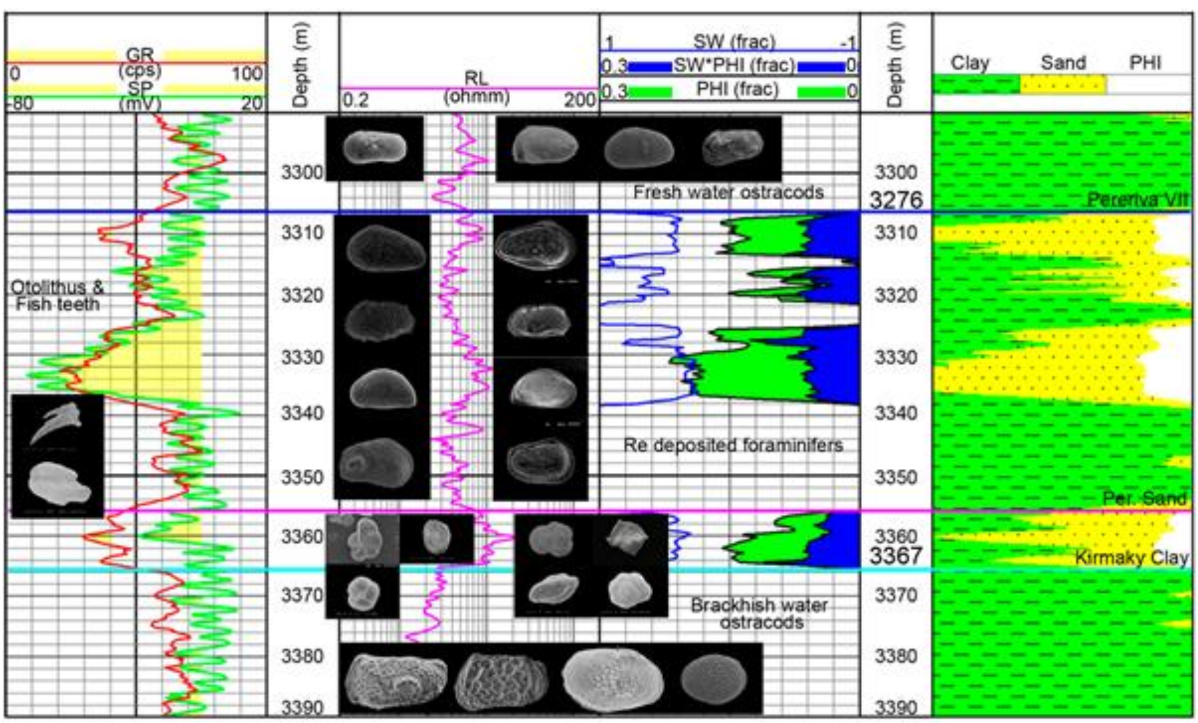


Fig. 3. Micropaleontological and Core-Log Data Integration Showing Lithostratigraphy and Biostratigraphy of the Key Reservoir Section, Offshore Alyat-17 Well (Baku Archipelago, Azerbaijan, South Caspian Basin).

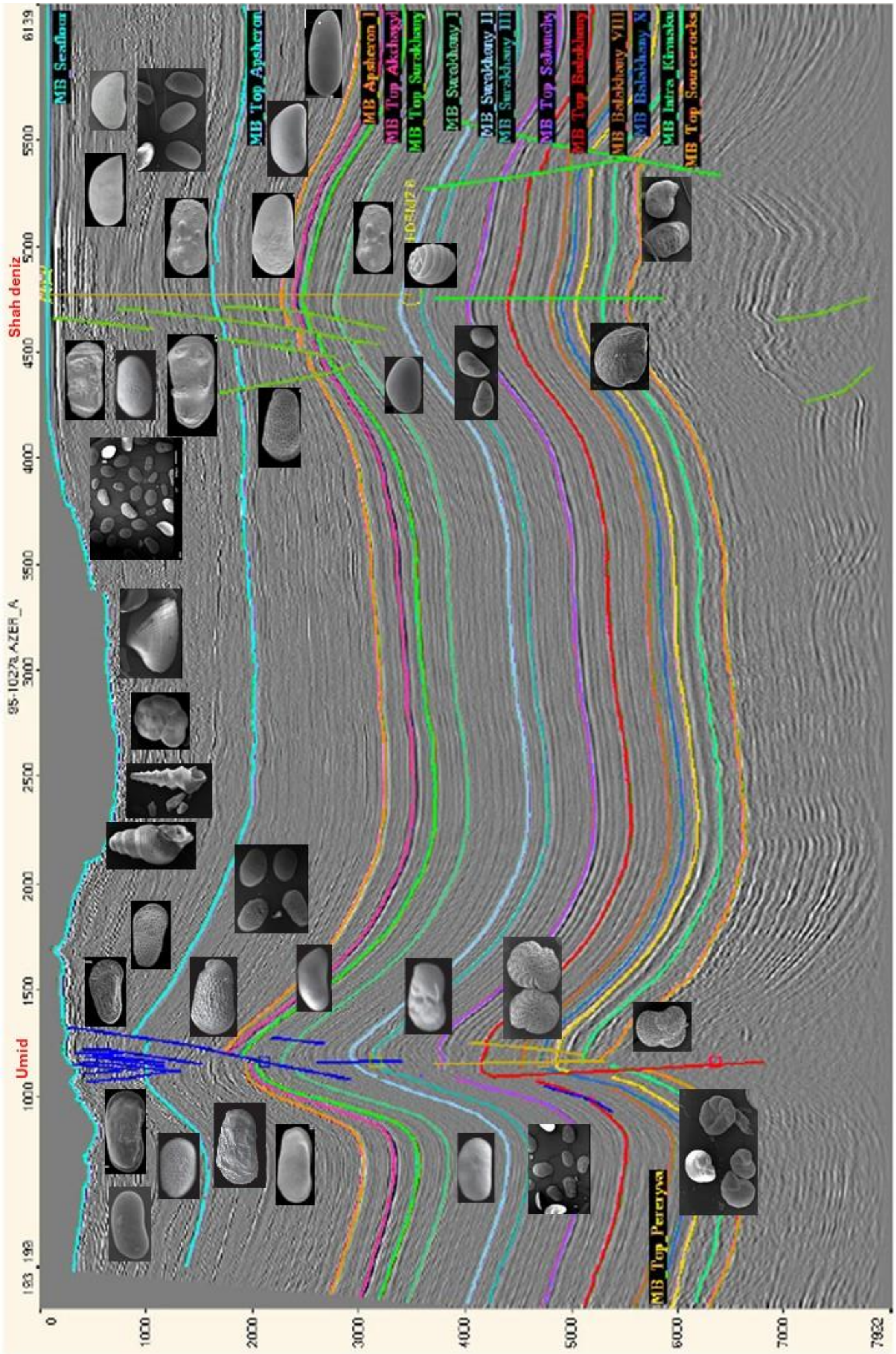


Fig. 4. Seismic line over the Umid and Shah Deniz fields (Baku archipelago of the Azerbaijan part of the South Caspian basin) with integration of micro and macro paleontological data

The thickness of Quaternary deposits indicates irregular subsidence across the basin: in the northern and eastern sectors, sediment influx from land almost entirely compensated for sea-floor subsidence.

These processes were critical for hydrocarbon generation, as the onset of the Quaternary (Apsheron age) marked a fundamental reorganization of the basin, including fold formation, trough development, and faulting. Such structural changes facilitated migration flows that contributed to the accumulation of oil and gas.

Vertical movements at the Pliocene–Quaternary transition were significant; in the Lower Kura region, displacements reached up to 1000 meters. Alongside active neotectonics, extensive redistribution of sedimentary material occurred. Submarine landslides filled neotectonic depressions, producing dome-like structures composed of weakly consolidated silty deposits (e.g., Umid). These features underscore the geotechnical significance of Quaternary deposits, particularly in the context of safe hydrocarbon field development (Rzaeva, 2005).

Mud volcanism in the Southern Caspian is concentrated within the Absheron–Pribalakhan uplift zone and the Turkmen structural terrace, where activity remains intense.

For the planning of offshore wells, platforms, and related infrastructure, marine engineering geology plays a key role. Investigations focus on the genesis of rock properties, the classification of bottom sediments, and the assessment of their engineering behavior, beginning with microfaunal analysis to establish deposit age.

Mud volcanism is typically associated with major oil and gas fields and correlates with zones of abnormally high formation pressure, which present significant geohazards. The highest seismicity (up to magnitude 8) is recorded along the shelf near the northern and eastern Absheron Peninsula.

Here, tectonic activity has produced sharply differentiated vertical movements. The northern shelf slope, linked to the Absheron–Pribalakhan zone, is undergoing uplift, while the southern slope is subsiding. Rates of vertical movement vary considerably: 1.3–1.4 mm per year on Chilov and Artyom islands, and up to 57 mm per year along the coastal zone of Baku Bay (Dzhandzhgava et al., 1990; Zaionchek, 1980).

According to geoacoustic and seismic data, the mud volcanoes of the South Caspian shelf are associated with fault zones within brachyanticlinal and diapiric uplifts. In most cases, their eruptive conduits break through diapiric folds and form cones at the summit composed of volcanic breccia (Figs. 4 and 5).

Particularly difficult conditions for drilling wells are characteristic of mud volcano areas, as the presence of mud-volcanic breccia reduces the physical and mechanical properties of the soil. In addition, in recent times, drilling operations in these areas have increasingly encountered oil and gas shows followed by the Gryphon formation, which, in some cases, have led to accidents.

It should be particularly noted that the experience of geotechnical development of the shelf and coastal zone of the Caspian Sea demonstrates the need for comprehensive geotechnical studies, which would make it possible to provide industry with scientifically grounded recommendations for the most rational use of its resources, taking into account the protection of the geological environment. Micropaleontological analysis, integrated with lithological, granulometric, mineralogical, and geotechnical data, significantly improves the resolution of stratigraphic correlations and the interpretation of paleoenvironmental conditions.

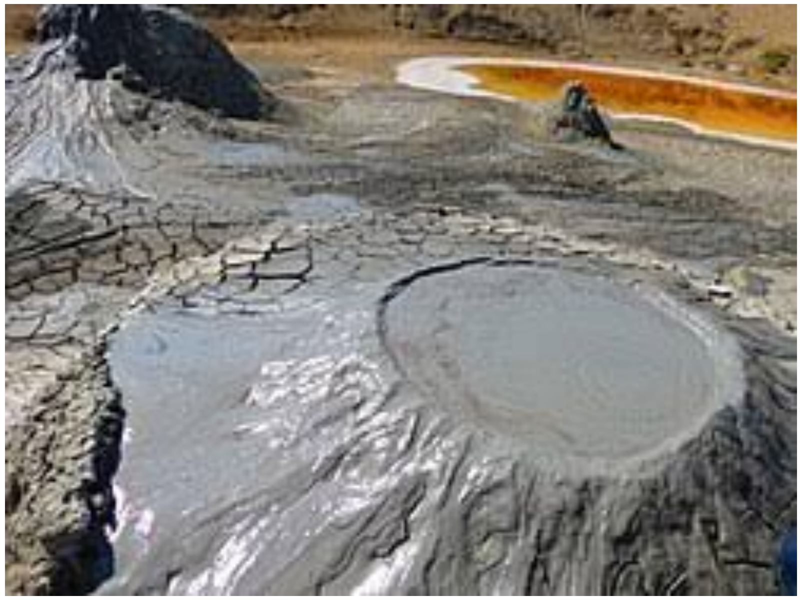


Fig. 5. Mud volcano from the Kobustan (Azerbaijan) area near the coastal area of the South Caspian basin (Photo taken in 2004).

Akhmedov et al. (1997) emphasized the geological specificity of the South Caspian, characterized by the region's complex structure and such features as mud volcanoes and active lithodynamic processes.

4. Conclusions

599 core samples from 68 exploration and shallow engineering boreholes over 43 offshore structures have been studied. For the first time detailed stratigraphic breakdown was given for the Quaternary deposits on ostracod fauna in the South Caspian basin, along with specified 5 supra-horizons and 10 horizons, and 7 biozonas/ index species. We attempted to correlate Quaternary deposits of the South Caspian with different facies (Apsheron and Baku archipelagos and Turkmenian sector), based on ostracod fauna. The faunal list contains 19 genera, including *Aminocythere, Euxinocythere, Leptocythere, Loxoconcha, Loxocaspia, Caspiocypris, Paracyprideis*, and *Ilyocypris*.

Eleven characteristic ostracod assemblages were identified within seven biozones of Quaternary sediments of the South Caspian basin (Figs. 2 and 6). Key findings include:

1. Stratigraphic variability: Quaternary sequences across the South Caspian shelf comprise Bakuvian, Khazarian, Khvalynian horizons, as well as Novo Caspian and modern sediments, with thicknesses and facies distribution strongly influenced by structural setting (Fig. 6).
2. Lithological patterns: Fine-grained, highly silty clays dominate deep-water areas, while loams and sands prevail in higher-energy nearshore and eastern shelf zones (Fig. 2).
3. Micropaleontological value: Microfossil-based correlations and lithostratigraphy interpretations enhance engineering, geological zonation, support overpressure prediction, and reduce development risk in this seismically active basin (Javadova, 2025).

These integrated results provide a solid basis for engineering–geological mapping of the South Caspian shelf, guiding the safe and efficient design of offshore oil and gas infrastructure in one of the world's most challenging marine environments.

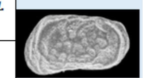
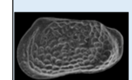
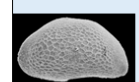
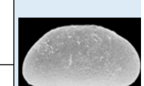
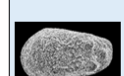
System	Division	Part	suprahorizon	horizon/layer	biozone	Offshore South Caspian basin Biostratigraphy: Ostracoda	Offshore South Caspian basin Biostratigraphy: *Mollusk*	
Quarternary	Holocene	upper	Novocaspian	upper (present deposits)		*Amnicythere caspia (Livental, 1938), A. striatocostata (Schweyer, 1949), A. quinquetuberculata (Schweyer, 1949), Euxinocythere (M) bacuana (Livental, 1938), Paracyprideis napthatscholana (Livental, 1929), Cryptocyprideis bogatchovi (Livental, 1929), Cyprideis torosa (Jones, 1850), Tyrrhenocythere amnicola donetziensis (Dubowsky, 1926) and a lot of Ammonia beccarii (Linne,1767)*	*Mytilaster lineatus Gmelin, 1791, Micromelania caspia Eichwald , 1838, Didacna trigonoides, Pallas, 1771, et al.*	
		middle		lower			*Cardium edule Linnaeus, 1758, Didacna crassa Eichwald, 1829, D. baeri Grim, 1877, D. baeri var alata Gadjiev, 1969*	
		lower	Khvalinan	upper	*Euxinocythere virgata (Schneider, 1962)*	*Amnicythere cymbula (Livental,1929), A. maltiosa (Scheider in litt in Mandelshtam et al., 1962), A. modesta (Schneider in litt, in Mandelshtam et al., 1962), A. notabilis (Schneider in litt, in Mandelstam et al., 1962), A. tinulla (Stepanaitys, 1962), A. unicornis (Schweyer, 1949), A. lunata (Stepanaitys, 1958), Loxoconcha unodensa Mandelstam, 1962*	*Didacna praetrigonoides Nalivkin and Anissimov, 1914, Dreissensia polymorpha Pall. 1873*	
	Pleistocene	upper		lower			*Didacna paralella Bogachov, 1932, et al.*	
			Khazarian	upper	*Euxinocythere beata (Stepanaitys, 1962)*	*Amnicythere medicata (Stepanaitys, 1962), A. hildae (Stepanaitys, 1959), A. uschkoi (Schneider in litt, Mandelshtam et al., 1962.), Xestoleberis manticae Stepanaitys, 1962, Candona rostrata Brady et Norman, 1880, C. neglegta Sars, 1887, Loxoconcha lepida Stepanaitys, 1962., L. lauta Stepanaitys, 1962, Scaloconcha edita (Schneider sp nov in Mandelshtam et al, 1962)*	*Didacna paleotrigonoides Nalivkin, 1914, D. surachanica Andrussov, 1918, Dreissensia polymorpha Pall, 1873, et al.*	
		middle		lower		*Cyprideis torosa (Jones, 1850), Tyrrhenocythere amnicola donetziensis (Dubowsky, 1926), Candona elongata (Schweyer, 1948), Candoniella albicans (Bradyi, 1924), C.subelipsoida (Scharapova in.litt.,1961), Amnicythere praeclara (Stepanaitys, 1962), A. cymbula (Livental, 1929), A. lunata (Stepanaitys, 1958), A. medicata (Stepanaitys, 1962), A. periculosa (Stepanaitys, 1958)*	*Didacna eulachia Bog (Fed), 1932, D. nalivkini Wass., D.gurganica Vekilov, 1969*	
		lower	Bakuvian	upper	*Amnicythere volgenesis (Negadaev, 1957)*	*Amnicythere medicata (Stepanaitys, 1962), A. stepanaitysae (Schneider in litt in Mandelshtam et al., 1962), A. periculosa (Stepanaitys, 1958), A. rezupina (Stepanaitys, 1962), A. lunata (Stepanaitys, 1958), A. praeclara (Stepanaitys, 1962) , Scaloconcha edita (Schneider sp nov in Mandelstam et al, 1962)*	*Didacna rudis Nalivkin, 1914, D. carditoides Andrusov, 1910, et al.*	
				lower	*Bacunella dorsoarcuata (Zalany, 1929)*	*Amnicythere quadrituberculata (Livental, 1929), A. pravoslavlevi (Schweyer, 1940), A. accreta (Stepanaitys, 1962), A. flexiuosa (Stepanaitys, 1962), A. volgenesis (Negadaev, 1957), Loxoconha unodensa Mandelstam, 1962, L. endocarpa Scharapova, 1949, Candona elongata (Schweyer, 1948), Caspiella liventalina (Evlachova, 1949), Advenocypris kurovdagensis Klein, 1959.*	*Didacna parvula Nalivkin, 1915, Dreissensia polymorpha Pall. 1873, et al.*	
				Turkanian		*Cyprideis torosa (Jones, 1850), Tyrrhenocythere amnicola donetziensis (Dubowsky, 1926), Zonocypris membranae (Livental, 1956), Ilyocypris bradyi Sars, 1928, Limnocythere sp.*	*Pelecypoda and Gastropoda Dreissensia polymorpha Pall, 1873, representative of Cltssiniola family.*	
	Eopleistocene		Apsheronian	upper	*Caspiocypris filona Suzin, 1956*	*Caspiocypris lyrata Livental in. litt in Agalarova et al., 1961 , C. rotulata (Livental, in Agalarova et al., 1940) , Amnicythere andrusssovi (Livental, 1929) , A.picturata (Livental, 1929) , A. arevina (Livental, 1940) , A. cymbula (Livental, 1929) , Leptocytere rostrata (Evlachova, 1940) , Loxoconcha eichwaldi Livental, 1929*	*Monodacna bacuana Andrussov, 1912, Apsheronia propinqua Eichwald, 1838*	
				fresh water layer		*Ilyocypris bradyi Sars, 1928, I. gibba (Ramdohr, 1808), A. multituberculata (Livental, 1929), Cyprideis torosa (Jones, 1850), Limnocythere sp.*	*Pelecypoda and Gastropoda, Dreissensia.*	
				middle	*Amnicythere apsheronica (Suzin, 1956)*	*Amnicythere pirsagatica (Livental in Agalarova et.al., 1940), Amnicythere verricosa (Suzin, 1956), A.saljanica (Livental, 1926), A. palimpsesta (Livental, 1940), Euxinocythere (M) bacuana (Livental, 1938), Loxoconcha bairdyi Müller, 1850, Loxocorniculina ralicryi (Lübimova in.litt in Agalarova et al., 1961).*	*Apscheronia calvescens Andrusov, 1963, Monodacna beibatica Andrusov, 1924*	
				lower	*Leptocythere explicata Klein, 1956*	*Caspiocypris rotulata (Livental, in Agalarova et al., 1940), C. lyrata Livental in. litt in Agalarova et al., 1961, C. filona Suzin, 1956, Candona cavis Mandelstam, 1962, Amnicythere ofortha (Livental, 1929), A. bendovanica (Livental in Agalarova et al.,1940), Leptocythere rostrata (Evlachova, 1940), Aminocythere gubkini (Livental, 1956), A. grandis (Klein, 1956), Euxinocythere (M) bosqueti (Livental, 1929), E. (M) praebosqueti (Suzin, 1929), Cytherura lejlae Agalarova , 1961), C. azeri Agalarova, 1961*	*Apsheronia raricostata Sjogren, 1891., Adelina voluta Andrusov, 1923*	

Fig. 6. Biostratigraphy scheme of South Caspian Quaternary deposits (Javadova, 2023).

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Author Contributions

A. Javadova conceived and designed the study, conducted micropaleontological and lithological analyses, interpreted results, and prepared the manuscript.

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Conflict of Interest

The author declares no conflict of interest.

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