Quaternary International 605-606 (2021) 349–363

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Evaluation of Plio-Quaternary uplift of the South-Eastern Caucasus based on the study of the Akchagylian marine deposits and continental molasses

Ya.I. Trikhunkov[a,b,*], T.N. Kangarli[c], D.M. Bachmanov[a], P.D. Frolov[a], E.A. Shalaeva[a], A. V. Latyshev[d,e], A.N. Simakova[a], S.V. Popov[f], M.E. Bylinskaya[a], F.A. Aliyev[c]

[a] Geological Institute, Russian Academy of Sciences, Moscow, Russia
[b] Faculty of Geography, Moscow Pedagogical State University, Moscow, Russia
[c] Geology Institute, Azerbaijan National Academy of Sciences, Baku, Azerbaijan
[d] Schmidt Institute of the Physics of the Earth, Russian Academy of Sciences, Moscow, Russia
[e] Geology Faculty, Moscow State University, Moscow, Russia
[f] Palaeontological Institute, Russian Academy of Sciences, Moscow, Russia

ARTICLE INFO

Keywords:
Neotectonics
Plio-quaternary uplift
Morphostructure
Akchagylian marine deposits
Molluscs
Greater caucasus

ABSTRACT

The highest Shahdag-Qusar segment of the South-Eastern Caucasus, located on the border of Azerbaijan and Russia, is considered. Ridges of Greater Caucasus axial zone are the closest to the Caspian Sea coast here, and the latest marine deposits cover the high-mountainous watershed surfaces. Research results of the Plio-Quaternary tectonic movements and stratigraphy are presented. Morphostructural and facies analysis of the northern macro-slope of the mountain system was performed to reconstruct the history of Plio-Quaternary orogenesis of this territory. Findings of shells of molluscs, an indicator of the Akchagylian basin, in the sediments of the homoclinal Qusar plateau at altitudes up to 2020 m asl made it possible to estimate the rate of the Quaternary uplift in the South-Eastern Caucasus and compare these data with the results of previous studies in Transcaucasia. The reconstruction of the mountain system development in the Pliocene with acceleration of the average Pliocene uplift is presented, and the probable reasons for this acceleration are discussed.

1. Introduction

The Greater Caucasus mountains stretch for 1300 km between the Black and Azov Seas in the west and the Caspian Sea in the east (Fig. 1. Inset). South-Eastern Caucasus is a high-mountainous periclinal segment of the Greater Caucasus that approaches the Caspian Sea coast.

The mountain system develops in the zone of collision between the epi-Paleozoic Scythian plate and the Transcaucasian massif. The age of primary collisional deformations leading to the formation of the Greater Caucasus is attributed to the time interval from the Eocene to Oligocene (Khain et al., 2006; Rastsvetaev et al., 2010). Lateral compression caused a collision with subsequent underthrusting of the Transcaucasian massif under the southern edge of the Scythian plate and the formation of an accretionary prism over the zone (Gamkrelidze and Gamkrelidze, 1977; Dotduev, 1986; Philip et al., 1989; Khain et al., 2006; Popkov, 2006; Kangarli et al., 2018). The underthrust is confirmed by the distribution of deep seismic sources (Mumladze et al., 2015; Kangarli et al., 2018). GPS-monitoring data of modern geodynamic activity confirm counterdirected convergence of the Transcaucasian massif and Scythian plate at a rate of 1–2 mm/year (Milyukov et al., 2015). There are also models describing vertical tectonic zoning of a folded structure and denying gentle detachment under the Greater Caucasus (Rastsvetaev et al., 2010; Rogozhin et al., 2015).

It is believed that the continental stage of tectonic development and orogenic uplift in the axial zone of the mountain structure did not begin before the Tortonian–Messinian (Khain et al., 2006; Milanovsky, 1968) and coincide with the time of indentation of the Arabian plate into the structural zones of the southern margin of Eurasia (Kangarli et al., 2018). However, does the main phase of Caucasian orogenesis coincide with the time of intense collision and is the latter the only reason of the recent uplift?

The latest development of the Greater Caucasus has been studied at the Shahdag-Qusar model zone at the junction of the Eastern Caucasus (EC) and South-Eastern Caucasus (SEC). This is the area where the mountain ranges of the Greater Caucasus come as close as possible to the Caspian Sea coast, and young marine deposits partly cover them. The

* Corresponding author. Geological Institute, Russian Academy of Sciences, Moscow, Russia.
E-mail address: jarsun@yandex.ru (Ya.I. Trikhunkov).

https://doi.org/10.1016/j.quaint.2021.04.043
Received 23 September 2020; Received in revised form 29 April 2021; Accepted 30 April 2021
Available online 20 May 2021

study of neotectonics and stratigraphy of the Plio-Quaternary (Pl-Q) deposits in this region has significantly rejuvenated the age of the active phase of the Caucasian orogenesis. Morphostructural analysis made it possible to identify structures of SEC active during the neotectonic period, study their kinematics, and identify the general type of the recent movements. Facies analysis and dating of the deposits of the Qusar-Divichi foreland made it possible to reconstruct the Neogene-Quaternary (N-Q) evolution in this part of the Greater Caucasus. In particular, the location of Akchagylian marine sediments at altitudes up to 2020 m asl made it possible to estimate the rate of the Pl-Q movements directly from the deformations of the palaeo-surface of the marine sedimentation.

2. Regional settings

2.1. Geological and tectonic settings

The studied Shahdag-Qusar segment of the SEC is located in the axial and the northern slope zones of the mountain system at the boundary with the high-mountainous Eastern Caucasus. The junction of the EC and SEC is a series of faults of the Samur transverse zone (see Fig. 1).

Several longitudinal tectonic zones are distinguished in the structure of the SEC from south-west to north-east (Fig. 1). The axial zone is formed by the structures of the Goitkh-Tfan allochthonous complex (The Main Caucasus range, Bazarduzu, 4466 m asl) and the Shahdag-Khizin nappe-folded zone which is the basis for the Side Range of the Greater Caucasus (Shahdag, 4243 m asl). The structures of the zone of the Goitkh-Tfan allochthonous complex are made of intensively folded sandy-clayey deposits of the Aalen-Bajocian, and the structures of the Shahdag-Khizin zone are made of the Upper Jurassic - Lower Cretaceous limestones (Milanovsky, 1968; Kangarli et al., 2018). According to (Kangarli et al., 2018) these structural zones are separated by the deep Main Caucasian Thrust. However, the structures of the Goitkh-Tfan zone are gently thrusted over the Chiauro-Dibrar folded zone of the southern slope of the Greater Caucasus along the Zangi thrust, which is the eastern extension of the Krasnopolyanskiy thrust of the North-Western Caucasus (NWC). However, the structures of the Shahdag-Khizin zone are thrusted onto the zone of the northern Greater Caucasus slope along the Siazan reverse fault, which is certainly lesser and younger than the above mentioned thrusts (Milanovsky, 1968; Kangarli et al., 2018).

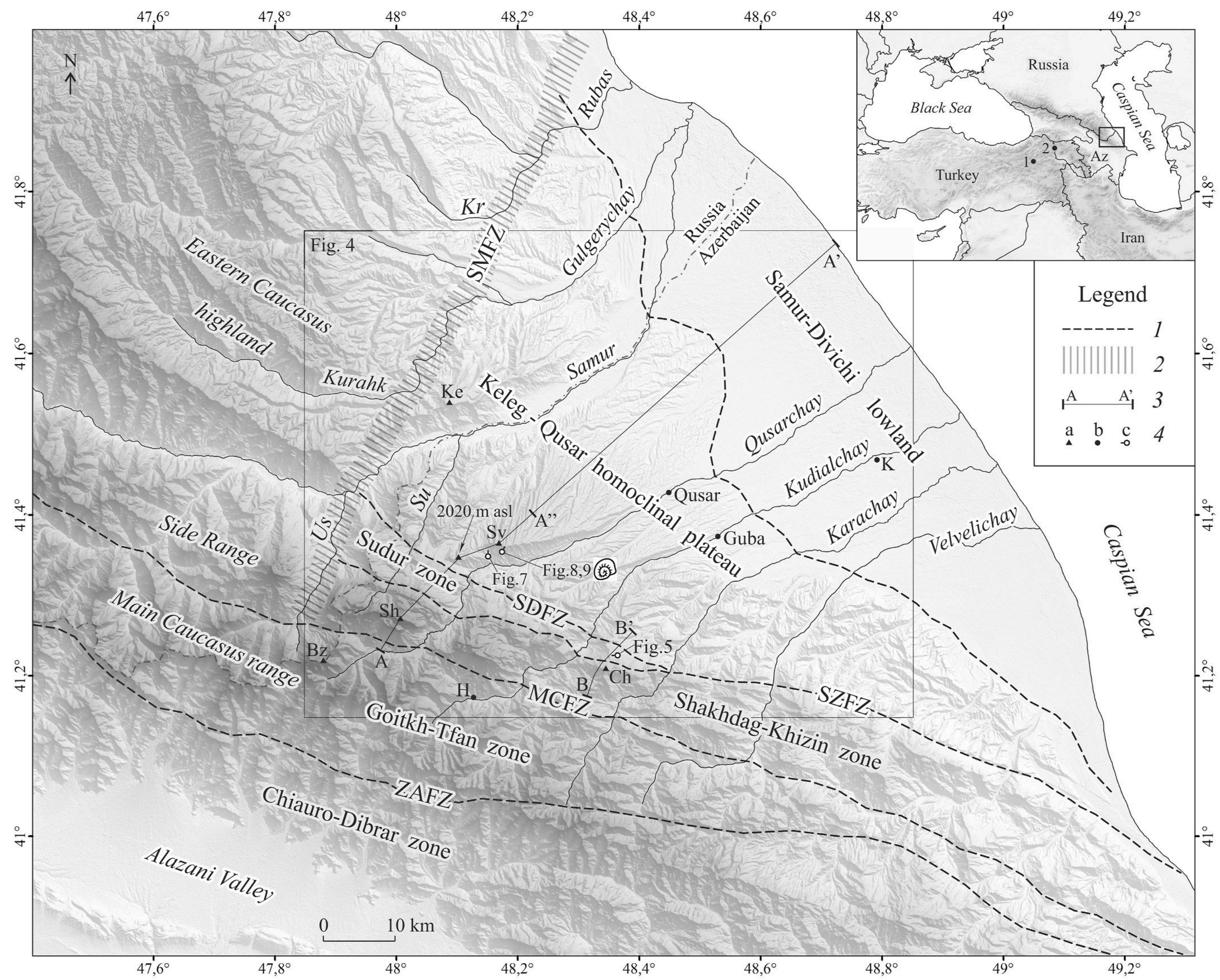

Fig. 1. The map of the structural-geomorphological zonation of the Shahdag-Qusar segment of the South-Eastern Caucasus.
1 – fault zones; 2 – Samur transverse zone; 3 – directions of cross-sections (Figs. 2 and 6); 4 – summits of mountains (a), inhabited locality (b), location of photography (c) (Figs. 5, 7–9). At the location shown in Fig. 9, the Akchagylian malacofauna was found. *fault zones:* ZAFZ – Zangi, MCFZ – Main Caucasus, SZFZ – Siazan, SDFZ – Sudur, SMFZ – Samur (transverse zone); *rivers:* Su – Sudurchay, Us – Usukhchay, Kr – Karchagsu; *summits*: Bz – Bazarduzu, Sh – Shahdag, Ch – Chereke, Sv – Big Suval, Ke – Keleg; *towns and villages*: K – Khachmaz, H – Khynalyg. A darker gray on the relief map means higher terrain levels.

Thus, the axial zone of SEC has a bilaterally symmetrical structure (Fig. 2).

The northern macro-slope of the mountains is formed by the Sudur folded zone and homocline of the Qusar plateau, separated by the Sudur flexure-fault zone. Narrow Sudur zone adjoins folding structures of axial zone from the north-east. It consists mainly of limestones, marls and sandstones of the Lower Cretaceous lying in the footwall of Siazan reverse fault and overlapping with unconformity the folded base composed of the Middle Jurassic clay shales (Fig. 2).

From the northeast, the Qusar plateau adjoins the structures of the Sudur folded zone in the form of a sharp angular wedge, which protrudes into the mountain system by nearly 50 km (Fig. 1). The plateau is composed of various N-Q sediments unconformably overlapping Middle Jurassic sandy-argillaceous folded base. Further to the north-east, the homocline is uncomformably superimposed on the structure of the Qusar-Divichi foreland, which developed intensively at the Maikop time (Oligocene - Lower Miocene), and probably earlier (Geology of the USSR, 1968; Milanovsky, 1968; Kangarli, 2007). The foreland is separated from the mountain structure by the deep Khachmaz and Guba faults. The homocline of the plateau descends gently (5–8°) to the coastal alluvial-proluvial Samur-Divichi lowland. Within the latter, the homocline is smoothed out to horizontal occurrence and is covered by the Middle - Upper Pleistocene marine sediments (Fig. 2).

2.2. Regional plio-pleistocene stratigraphy and geochronology

Because of the position of the Akchagylian Stage at the Pl-Q boundary, a full description of the lithological, stratigraphical and geochronological characteristics of the relevant sediments of the northern slope of SEC is presented. Based on the published data, a generalized stratigraphic column, with lithological-stratigraphic, bio- and magnetostratigraphic data on Plio-Quaternary sediments of the region under research was compiled (State Geological Map of USSR, 1958; Geological map of the Caucasus, 1976; Geology of the USSR, 1968; Nevesskaya et al., 2004. Fig. 3). The section starts with continental sediments of the so-called "Productive Unit" lying with unconformity on marine sediments of the Sarmatian-Pontian Stages (Tortonian-Messinian). The sediments are represented by pebble-boulder conglomerates, whose thickness varies from 200 m in the most uplifted part of the Qusar plateau to 1000 m in the Qusar-Divichi foreland. Within the studied area, the section of the Productive Unit is made mainly of pebbles of limestones and dolomites of various sizes from the Upper Jurassic and Lower Cretaceous. In general, within the Qusar plateau, these deposits are widely spread, exposing on the slopes of river valleys and, less frequently, on watersheds.

The stratigraphic position and dating allow these deposits to be attributed to the Cimmerian sequence of the Ponto-Caspian Sea with different dates of its lower boundary: 5.3–5.2 Ma (Chumakov, 2000) or 6.2–6.1 Ma according to (Semenenko, 1987). The upper boundary is definitely determined as 3.6–3.4 Ma. This is confirmed by the nanoplankton assemblages, the composition of which makes it possible to distinguish zones NN11-NN13 in the Cimmerian (Semenenko, 1987), which allows to compare it mainly with the Mediterranean Zanklian (Nevesskaya et al., 2004).

Sediments of the Akchagylian regional unit lay transgressively and with angular unconformity on pebble-boulder sediments of the Productive Unit. They are exposed on vast areas in the Southwestern part of the Qusar plateau and are usually eroded within river valleys. In the lower part of the section they are represented by gray sandy clays with scattered pebbles, and are replaced by clays with interlayers of sand, detritus sandstone and limestone upwards. The thickness of the Akchagylian deposits in the watersheds equals to nearly 300 m, and increases to 700 m when moving towards the sea.

The lower boundary of the Akchagylian coincides with the boundary of Gilbert and Gauss palaeomagnetic epochs (~3.6 Ma) (Trubikhin, 1977; Krijgsman et al., 2019), and the upper boundary is slightly higher than the Olduwai episode and, according to (Chumakov et al., 1988), has an age of 1.87 ± 0.15 My. Nanoplankton was found in the Akchagylian of the Eastern Crimea, which was attributed by S.N. Lyulieva to zones NN17 and NN18 (Semenenko, 1987). According to these data, the Akchagylian corresponds to the Mediterranean Piacenzian and Gelasian. This is a classic notion of the so-called "The Greater Akchagylian", adopted in Russian stratigraphy. In the studies by Khramov and later Van Baak (Khramov, 1963; Van Baak, 2013) the model of "The Lesser Akchagylian" was presented with by a base rejuvenated to 2.7 My, which captures only the upper part of the palaeomagnetic Gauss epoch.

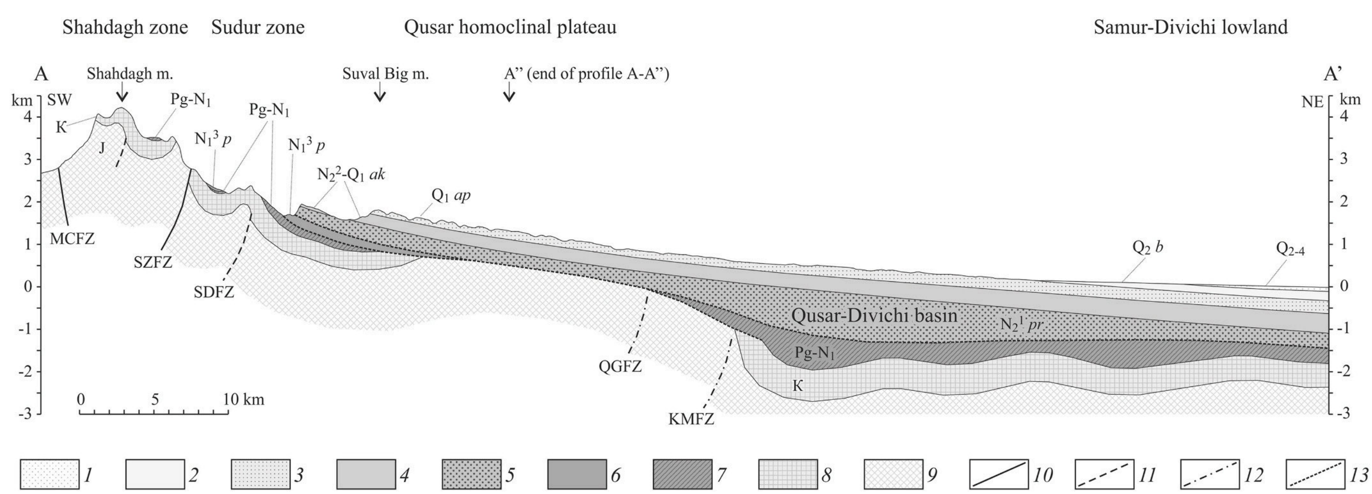

Fig. 2. Structural-geomorphological cross-section A-A′ from the Side Ridge (the Shahdag mt.) across the Qusar homoclinal plateau to the Caspian Sea. Compiled on the basis of the State Geological Map 1:200,000, 1958, sheets K39–19.25. Surface topography profile is plotted in Google Earth.

1–9 deposits: 1 – Middle, Upper Pleistocene (Khazarian and Khvalynian Stages) and Holocene, 2 – Middle Pleistocene (Bakunian Stage), 3 – Lower Pleistocene (Apsheronian Stage), 4 – Upper Pliocene and Lower Pleistocene (Akchagylian Stage), 5 – Early Pliocene (Productive Unit), 6 – Upper Miocene (Pontian Stage), 7 – Paleogene and Miocene, 8 – Cretaceous, 9 – Jurassic; 10–12 tectonic disturbances: 10 – proved faults, 11 – supposed faults and faults indicated by flexures, 12 – buried faults and not active during the Quaternary; 13 – unconformity surface.

Cenozoic sediment formation indexes: J - Jurassic, K - Cretaceous, $Pg\text{-}N_1$ – Paleogene and Miocene, $N_1^3\ s$ – Sarmatian Stage (Tortonian), $N_1^3\ p$ – Pontian Stage (Upper Messinian), $N_2^1\ pr$ – Productive Unit (Zanclean), $N_2^2\text{-}Q_1\ ak$ – Akchagylian Stage (Piacenzian and Gelasian), $Q_1\ ap$ – Apsheronian Stage (Calabrian), $Q_2\ b$ – Bakunian Stage (Lower Chibanian), $Q_{2\text{-}4}$ – Khazarian and Khvalynian Stages (Upper Chibanian and Late Pleistocene) and Holocene.

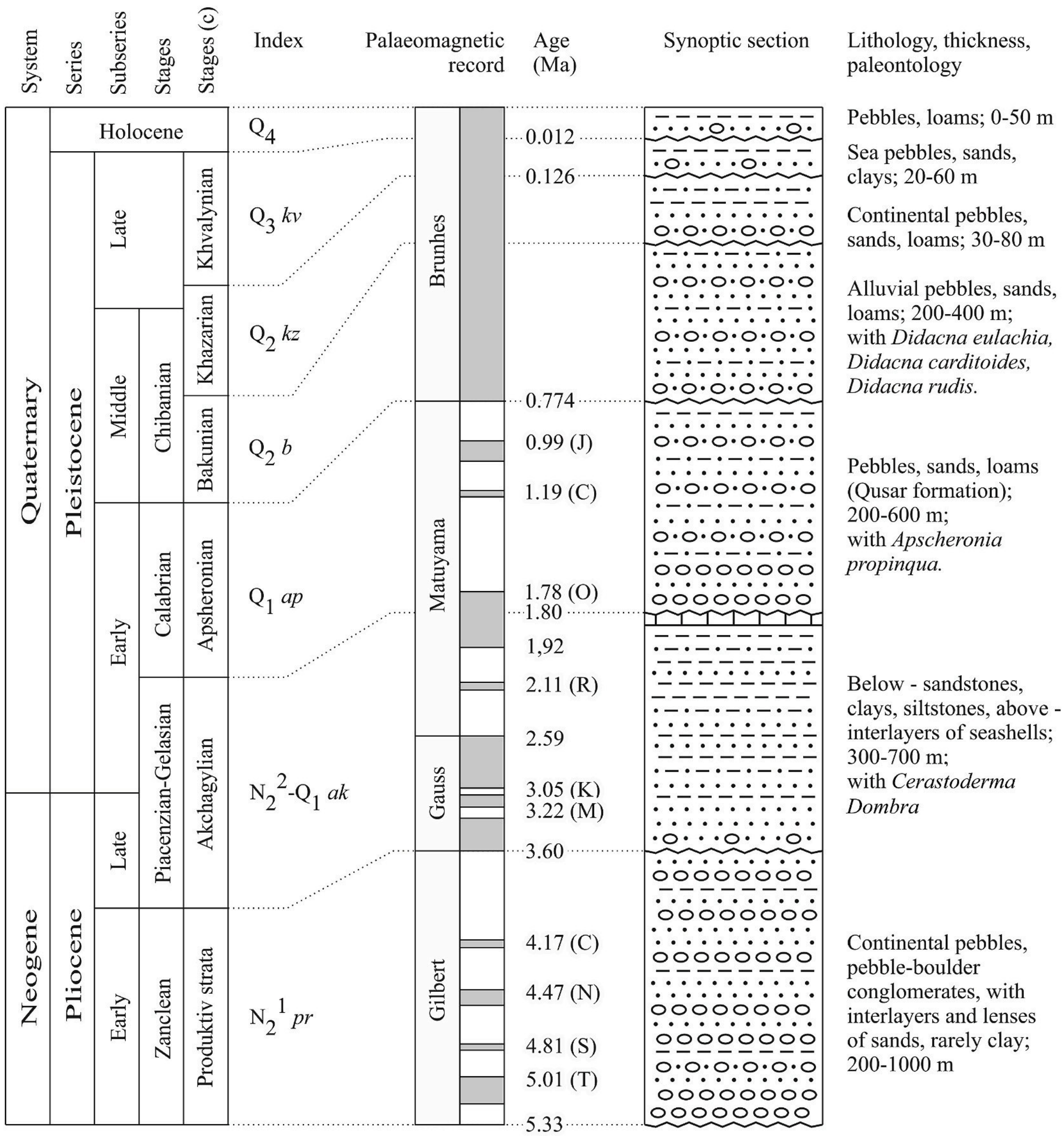

Fig. 3. Integrated stratigraphic column of Plio-Quaternary sediments of the Qusar homoclinal plateau. Subchrons, events: J – Jaramillo (0.90–1.06 m.y.), C – Cobb Mountain (1.19 m.y.), O – Olduvai (1.78–2.00 m.y.), R – Reunion (2.08–2.14 m.y.), K – Kaena (3.). 05–3.12 m.y.), M – Mammoth (3.22–3.33 m.y.), C – Cochiti (4.17–4.29 m.y.), N – Nunivak (4.47–4.64 m.y.), S – Sidufjall (4.81–4.89 m.y.), T – Thvera (5.01–5.25 m.y.).

In this article a more common model of the “Big Akchagylian” with a base of 3.6 million years is used as a basis.

The Akchagylian deposits of the Qusar plateau are covered with pebbles of the Qusar unit with sand interlayers and lenses, belonging to the upper part of the Apsheronian unit (State Geological …, 1958). These deposits, with a thickness of up to 200 m, act as the most resistant lithological complex on the vast surface areas of the Qusar plateau. In the neighboring areas of the Qusar and Keleg plateaus (in southern Dagestan, Russia), located closer to the sea, the Qusar Formation unconformably overlies on marine conglomerates, pebbles, and sandstones. These sediments contain detritus limestones and gray-brown, sometimes yellowish, in some places sandy clays with *Apsheronia brevior* Andrusov (= *Apsheronia propinqua* by Nevesskaya et al., 1997) - key species of the Apsheronian Stage, *Dreissensia polymorpha* var. *elata* Andrusov (= *Dreissena elata* by Vinarski and Kantor, 2016) and other fossils attributing the sediments to the Lower Middle Apsheronian age (Geology of the USSR, 1968).

Apsheronian sediments are confidently dated on the basis of palaeomagnetic data in combination with the above mentioned malacofauna. These sediments demonstrate the reverse magnetic polarity of the Matuyama epoch with the Jaramillo episode in the middle part of the Apsheronian (Trubikhin, 1977; Krijgsman et al., 2019). Thus, the Apsheronian sediments are confidently correlated with the Mediterranean Calabrian.

River valleys cut into the surface of the Qusar plateau are represented by a series of Neo-Pleistocene terraces: the Bakunian, the Khazarian and the Khvalynian, corresponding to the eponymous Caspian Sea transgressions. The formation of the terrace deposits began after a break in sedimentation, corresponding to the time of the Turkianian regression of the Caspian Sea. In the Turkianian sediments of Azerbaijan the Matuyama-Brunes boundary (Gurariy et al., 1976) was established as nearly 780 ka, being close to the recent dating of this boundary at 773 kyr (Channell, et al., 2010; Head and Gibbard, 2015).

The highest and most ancient terraces of the Samur, Qusarchay, Kudialchay and Karachay rivers are attributed to the Bakunian (Geology of the USSR, 1968). They are composed of pebbles with sand layers and lenses and are separated from the younger mid- and upper Quaternary terraces by a considerable scarp. Terraces with relative heights of 270–300, 220–240 and 180–200 m above chanel go deep into the river valleys. All of them with a significant inclination descend towards the

Samur-Divichi lowland, where they continue with Bakunian marine terraces of 190–210 and 220–240 m high with the Bakunian malacofauna such as *Didacna carditoides*, *Didacna eulachia*, *Didacna rudis* (Lilienberg, 1961; Yanina, 2012). The Bakunian transgression did not spread over a vast territory, but captured only a narrow strip of land within the Samur-Divichi lowland.

The Khazarian time includes terraces with relative heights of 160–170 m; 140–150 m; 120–130 m; 100–110 m; 80–85 and 55–60 m above chanel (Geology of the USSR, 1968). In the upper reaches of the Samur, Qusarchay and Kudialchay rivers the terraces are associated with moraines, and in the lower reaches - with the faunistically characterized Khazarian marine terraces of the Caspian Sea, which corresponds with the Upper Chibanian (Krijgsman et al., 2019).

The Upper Pleistocene in the Caspian region includes terraces, associated in the upper reaches of rivers with the best preserved moraines of mountain valleys and in the lower reaches - with marine deposits of Khvalynian transgression of the Caspian Sea. In the river basins of Dagestan, the Khvalynian terraces are embedded in sediments of the Late Khazarian Stage and are associated with the retreat stages of the last glaciation (Lilienberg, 1961).

Outside the Qusar plateau, the valleys of all major rivers form considerable alluvial fans that merge with each other within the flat coastal Samur-Divichi lowland (see Fig. 1).

3. Methods and materials

Morphostructural (structural-geomorphological) analysis consists of the research of the relationship between the relief and geological structure, identifying tectonogenic landforms of various orders and studying their structural-geomorphological properties. This is one of the main methods for identifying neotectonic movements and determining their qualitative and quantitative characteristics. It based on field observations, correlation of field data with data from geological maps, satellite images (Landsat TM), and digital terrain models (SRTM with a resolution of 90 m) were used to assess the structural and geomorphological position of the deposits studied (Consortium for Spatial Information CGIAR-CSI, 2017). For a detailed analysis of the distribution of recent deposits, the results of a 1:200,000 scale geological survey were used (State Geological …, 1958). Regional ARC-GIS project, created within the framework of the research data, helped to compare all the geological and geomorphological data, drawings maps and profiles with high accuracy.

Facies analysis made it possible to clarify the genesis of the deposits and the conditions of their formation. Palaeomagnetic and faunal dating methods were used to estimate the relative age of rocks. Spore-pollen and fauna samples were taken and analyzed. Fossils reviewed and described in this paper were excavated using mass screen-washing operations with hand sieves of 0.5 mm mesh size. Larger size fractions were processed during the field works, smaller fractions were sorted in the lab.

Palaeomagnetic analysis is one of the main methods we used for dating the studied deposits. Palaeomagnetic samples were collected as hand blocks from steep walls of the studied sections. Samples were taken from a deep-seated unweathered deposits that required the preparation of trenches in some places. Trenches were dug because of poor exposure of the sediments. The depth of 1.5 m was sufficient to reach non-weathered, non-deformed and non-displaced sediments. Orientation of samples was identified using the magnetic compass. The local magnetic declination was calculated using the IGRF model. The oriented samples were artificially cemented with dilute silicate glue and taken using digging tools. In the laboratory the oriented rock blocks were cut into the cubic samples. The samples were subjected to stepwise demagnetization by an alternating magnetic field with an additional device to cryogenic magnetometer 2G Enterprise in the Laboratory of the Main geomagnetic field and rock-magnetism in the Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, Moscow (IPE RAS) by A.V. Latyshev. AF-demagnetization was performed in 7 steps up to 130 mT, with a gradual increase in pitch. Remanent magnetization of samples was measured using the 2G Enterprises cryogenic magnetometer. The isolation of the natural remanent magnetization (NRM) components was carried out using the Enkin's software package (Enkin, 1994), using principal component analysis (Kirschvink, 1980).

4. Results

4.1. Morphostructural analysis

The highest Shahdag-Qusar segment of SEC is bounded by the Samur fault zone in the north-west. It serves as a regional tectonic boundary that is expressed both in morphostructure and distribution of the Cenozoic sediments. The fault zone is trans-Caucasian and within the studied area it stretches approximately from the Bazarduzu mt. (4466 m asl) to the mouth of the Rubas River (Dagestan, Russia) and consists of several branches. The main branch, the Usukhchay-Rubas, runs on the territory of the Dagestan Republic. Along the latter a straightened valley segments of the Usukhchay-Kurahk (in the upper reaches) - Karchagsu-Rubas (in the lower reaches) are built into one line of the SSE direction (Fig. 4).

In this study, for the first time, the Sudurchay branch of the Samur fault zone was identified. It stretches 10 km to the east, parallel to the main branch. It crosses the Shahdag synclinal massif: the eastern flank the massif is much more fractured and uplifted than the western flank. This fact allows to assume the presence of the right-lateral strike-slip component along the Sudurchay zone with general thrust of the massif to the south. Further north the zone is drained by the Sudurchay river and restricts the Qusar plateau from the west and further north it crosses the Keleg plateau. The Qusar and Keleg plateaus were united as a single morphostructural zone.

Folded morphostructures prevail in the uplifted western flank along the entire length of the Samur zone up to the Caspian coast. They belong to so-called "Folded Dagestan" and are composed mainly of terrigenous rocks of Lower-Middle Jurassic. Within the axial zone of the neighboring SEC in the downthrown flank the Upper Jurassic - Lower Cretaceous deposits sharply appear forming the Shahdag-Khizin nappe-folded zone. In its turn, within the northern macro-slope in the downthrown flank there appear N-Q predominantly marine sediments, overlapping with unconformity fractured rocks of the Middle Jurassic and forming homoclines of the Qusar-Keleg plateau and Samur-Divichi lowland (see Fig. 1). The average heights of these morphostructures are 1 km lower than those of the uplifted western flank. The role of the Samur zone in control of the recent sediments will be described in detail below.

The history of tectonic development of the territory is reflected in its topography. The oldest and most complicated morphostructures are developed in the axial zone of the studied mountain area. However, they simplify both when moving to the southeast towards the periclinal wedging out of the mountain structure on the Apsheron peninsula (the Baku city region) and towards the northern macro-slope of the foldbelt. Five longitudinal morphostructural zones within the studied region: Goitkh-Tfan, Shahdag-Khizin, Sudur, Qusar-Keleg and Samur-Divichi were distinguished (Fig. 1). Each of these zones corresponds to a tectonic zone of the same name and is characterized by the predominance of morphostructures of a certain type. Their type depends on the age and type of tectonic movements within the zone, and is also determined by the lithological and rheological properties of the constituent rocks.

In Goitkh-Tfan and Shahdag-Khizin zones, which form the axial zone of the mountain structure, an inverted structural relief prevails. Many summits of the Main Caucasus range are composed of the terrigenous rocks of the Middle Jurassic and have a synclinal structure. At the same time the anticlines are revealed in the topography of the upper reaches of the Qusarchay, Kudialchay, Karachay rivers etc. As well as of their subsequent tributaries. Such a topography is described in detail in the western part of the Goitkh-Tfan zone in NWC. The formation of inverted

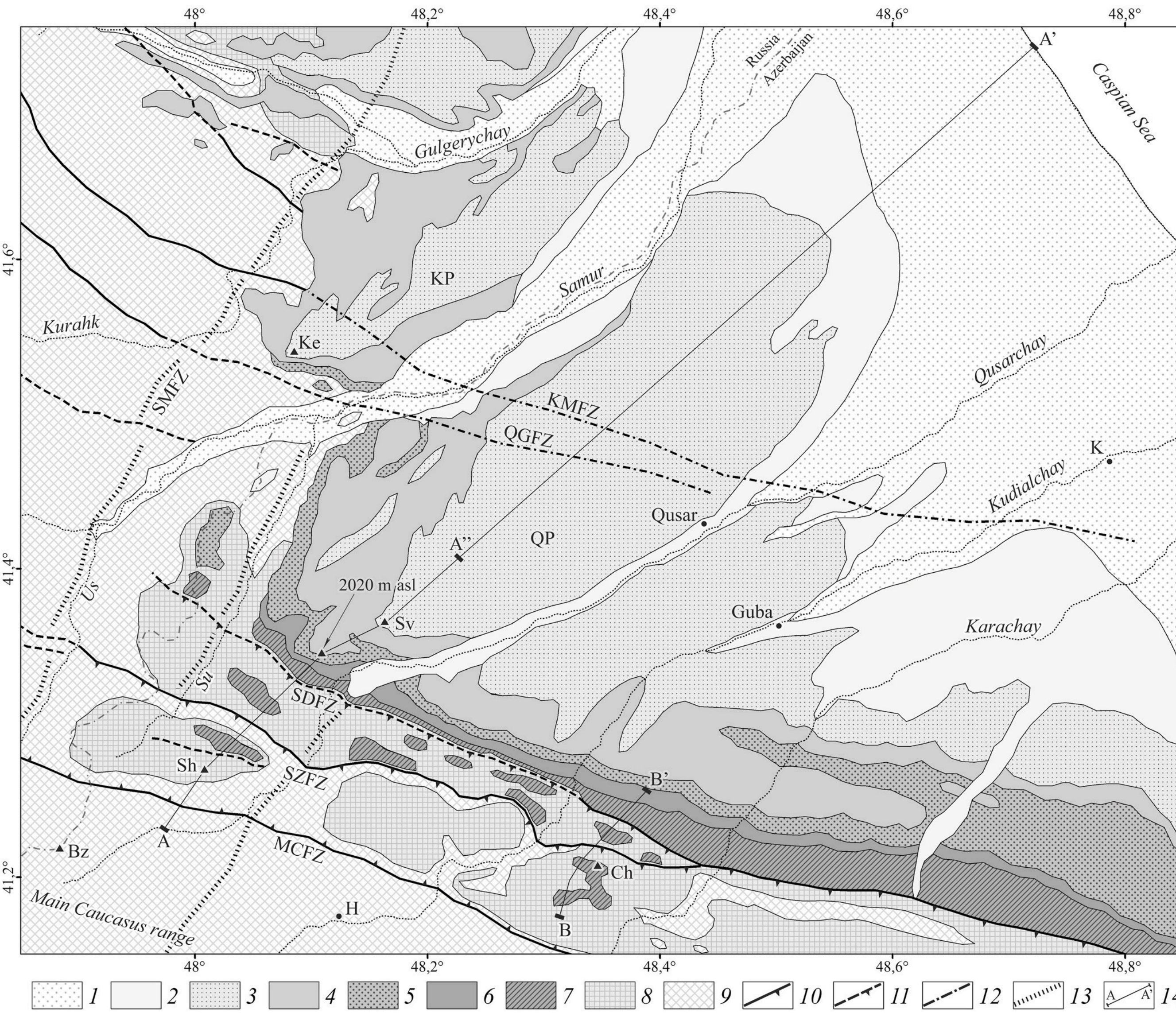

Fig. 4. The map of the distribution of Mezo-Cenozoic deposits and neotectonic disturbances of the Shahdag-Qusar segment of the SEC.
1–9 deposits: 1 – Middle, Upper Pleistocene (Khazarian, Khvalynian Stages) and Holocene, 2 – Middle Pleistocene (Bakunian Stage), 3 – Lower Pleistocene (Apsheronian Stage), 4 – Upper Pliocene and Lower Pleistocene (Akchagylian Stage), 5 – Lower Pliocene (Productive Unit), 6 – Upper Miocene (Pontian Stage), 7 – Paleogene and Miocene, 8 – Cretaceous, 9 – Jurassic; 10–14 tectonic disturbances: 10 – proved listric thrusts, 11 – supposed listric thrusts and thrusts indicated by flexures, 12 – buried faults and faults not active during the Quaternary; 13 – transverse flexure-folded zones, 14 – directions of cross-sections (Figs. 2 and 6).
Abbreviations: QP – Qusar Plateau, KP – Keleg Plateau; faults: MCFZ – Main Caucasus, SZFZ – Siazan, SDFZ – Sudur, QGFZ – Qusar-Guba (buried), KMFZ – Khachmaz (buried), SMFZ – Samur (transverse); summits: Bz – Bazarduzu, Sh – Shahdag, Ch – Chereke, Sv – Big Suval, Ke – Keleg; rivers: Su – Sudurchay, Us – Usukhchay; towns and villages: K – Khachmaz, H – Khynalyg.

folded topography was due to a combination of selective denudation with layer-by-layer thrusting and squeezing of the core of synclinal massifs under conditions of continuing formation of folds (Trikhunkov et al., 2011). The uppermost parts of the Side Range – the synclinal massifs of Yarydagh (4016 m asl), Shahdagh (4243 m asl), Kyzyl-Kaya (3757 m asl), Chereke (2383 m asl) and others have even more pronounced synclinal structure. All of them are wide synclinals composed of the Upper Jurassic and Cretaceous limestones and fractured in the south by faults of the Main Caucasian Thrust Zone (MCTZ), and in the north – by the Siazan reverse fault. These structures are thrusted on intensively folded Cretaceous limestones and in some places Middle Jurassic clay shales and sandstones (Kangarli et al., 2018). The predominance of inverted folded topography in the axial zone of the SEC indicates its long orogenic evolution. A similar dependence of the prevailing type of morphostructures on the age of the folded topography was revealed and described in detail in the NWC (Trikhunkov, 2016; Trikhunkov et al., 2019).

In the footwall of the Siazan reverse fault there are morphostructures of the Sudur folded zone. It is dominated by the medium-altitude anticlinal ridges composed of Lower Cretaceous limestones, marls and sandstones. The predominance of direct folded topography formed in rocks similar to those of Shahdag-Khizin zone, testifies to the juvenility of folded morphostructures of the Sudur zone.

Axial zones of synclinal massifs of the Shahdag-Khizin zone and bottoms of synclinal depressions of the Sudur zone are filled with littoral deposits of the Sarmatian (Tortonian). In the axial zone of the Chereke synclinal massif at the altitudes of about 2400 m asl shells of marine molluscs were found: *Obsoletiformes* cf. *beamonti* (d'Orb.); *Plicatiformes* cf. *plicata* (Eichw.) – endemic species of the upper Lower and Middle Sarmatian; *Polititapes ponderosa* (d'Orb.); *Retusa truncatula* (Brug.), *Plicatiformes* cf. *fittoni* (d'Orb.) – endemic species of the Middle Sarmatian (Identification by S.V. Popov (PIN RAS, Moscow)). Similar deposits have been noted at the northern foot of the Chereke massif already within the Sudur zone at the height of about 1560 m asl (Fig. 5).

Earlier malacofauna of the Upper Sarmatian was founded in the axial zone of the Shahdag synclinal massif at the altitude of about 3600 m asl (Budagov, 1964). At the northern foot of Shahdag in the Sudur zone the marine Sarmatian deposits lay at the altitude of about 2400 m asl. Obviously all these sequences were deposited at similar depths of the Middle Sarmatian sea shelf. The present-day difference in the altitudes of these sequences within the Shahdag-Khizin and Sudur zones can only be explained by the Pl-Q movements along the Siazan reverse fault: the uplift for the post-Sarmatian period in the Shahdag area is about 1200 m, and in the Chereke area it decreases to 840 m (Fig. 6 A, B).

Morphostructural analysis did not reveal any manifestations of the Sudur fault, separating an eponymous folded zone from the homocline of the Qusar plateau, in the topography along profile A-A. It is expressed at the surface to the east of the Kudialchay valley and to the west it is overlapped by young sediments of the Qusar plateau and forms a flexure (Fig. 6).

The homocline of the Qusar-Keleg plateau is a part of previously existed foothill plain, now involved in the orogenic uplift and forming the base of the northeastern extension of the mountain system. It was formed on the footwalls of the Sudur and Samur fault zones and is protruded as a wedge deep into the mountain system for almost 50 km (Figs. 1 and 4). The homocline is composed of different N-Q deposits, which overlap with unconformity the extension of the "Folded Dagestan" structures, and further northeast the deposits are superimposed on the Qusar-Divichi foreland. Folds or faults do not disrupt the plateau; its surface has a gentle inclination (5–8°) towards the coastal area of the Samur-Divichi lowland. Within the latter, the homocline is flattened almost to horizontal occurrence and is covered by marine sediments of the Middle-Upper Pleistocene (Fig. 2).

The Samur, Gulgerychay and Rubas river valleys start within the uplifted flank of the Samur fault zone. When crossing it, the rivers turn sharply to the northeast along the strike of this zone, and then in the footwall to the east, towards the Qusar-Keleg plateau and the Samur-Divichi lowland (see Fig. 1). The rivers of the Samur fault zone footwall - Qusarchay, Kudialchay, Karachay and Velvelichay - slightly deviate to the north-east outside the folded structure of the SEC axial zone. Within the Qusar-Keleg plateau and Samur-Divichi lowland all these rivers flow along the shortest way to the sea (Figs. 1 and 4). These data are essential for the reconstruction of the Pliocene–Quaternary history of the region and will be considered in the discussion.

4.2. Facies analysis of the Pliocene–Quaternary sediments of the Qusar-Keleg plateau homocline

Productive Unit. The base of the Pl-Q section of the Qusar-Keleg homoclinal plateau is composed of the Productive Unit deposits. Continental pebble-boulder conglomerates with a thickness of 150–200 m represent these deposits, which are not suitable for palaeomagnetic and fauna sampling (see Figs. 2–4). The deposits are alluvial pebbles and boulders characterized by strongly pronounced cross-bedding. Facies analysis allows to attribute the deposits of the Productive Unit to the first portion of the coarse continental molasses of the EC and SEC.

To the north of the Quba and Khachmaz faults within the Qusar-Divichi foreland the thickness of the Productive Unit increases sharply up to 1000 m and more. Continental molasses are replaced here by marine sandy and clayey facies (State Geological …, 1958). It testifies to continuing development of the foreland in the Early Pliocene.

Akchagylian deposits. The Akchagylian deposits lay transgressively with angular unconformity on the pebble-boulder sediments of the Productive Unit. The basal layer of the Akchagylian deposits of the Keleg plateau (Dagestan) and the entire unit itself with a total thickness of about 250 m were described and sampled on the Qusar plateau near the Big Suval mt. (1906 m asl). The deposits were subdivided into four parts (Unit 1, 2, 3, and 4) that differ both lithologically and stratigraphically. The contact between the gravels of the Productive Unit and the lower part of the Akchagylian deposits (Unit 1) is rather sharp: the deposits become finer – they change their grain size to sands and clays. The lower part of the section with a thickness of about 18 m is represented by an alternation of a dark-gray poorly cemented siltstones and sandstones. Cross-bedding typical for the Productive Unit is replaced here by a

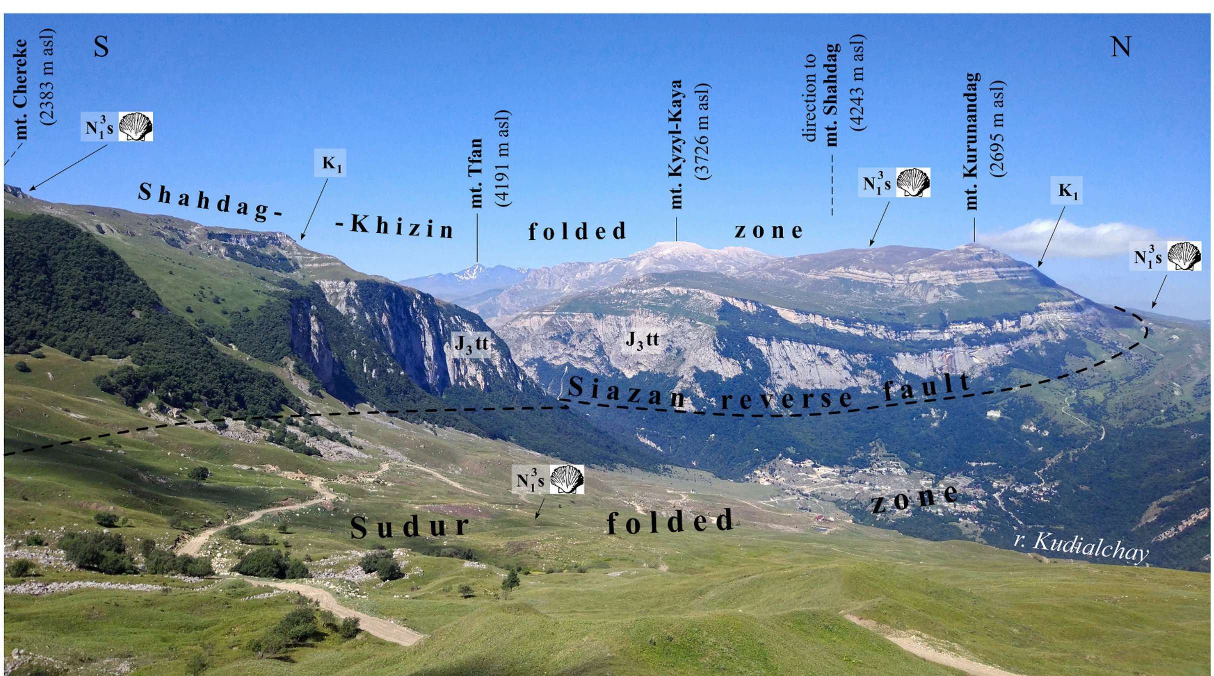

Fig. 5. The Siazan reverse fault zone between the Shahdag-Khizin (hanging wall) and Sudur (footwall) morphostructural zones (photo by P.D. Frolov). The sites of paleontological dating of Neogene deposites are marked with a "shell" icon. J_3tt - Tithonian Stage, K_1 - Lower Cretaceous, N_1^3 *s* – Sarmatian Stage (Tortonian).

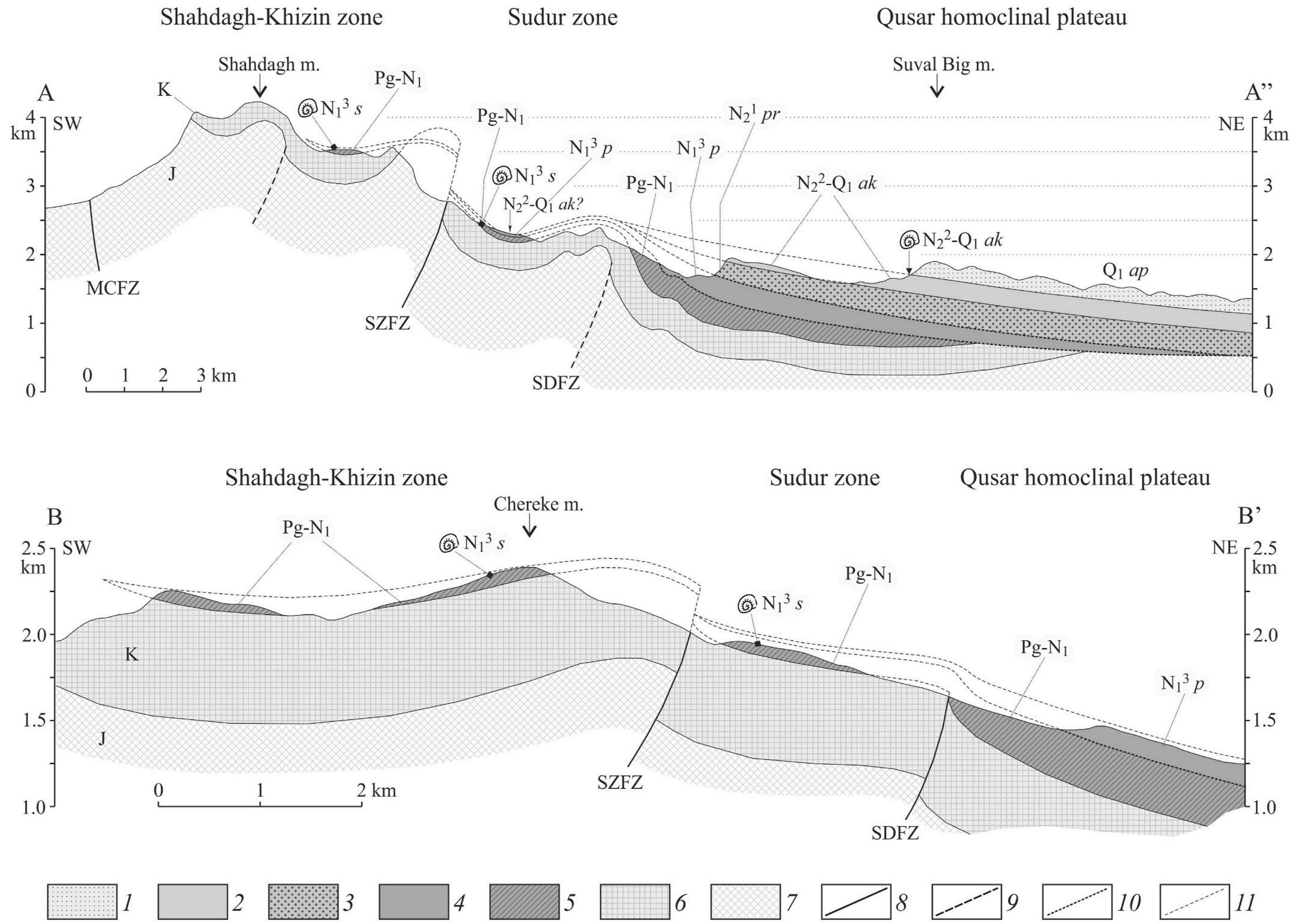

Fig. 6. Transverse structural-geomorphological cross-sections: A-A″ across the Side Range (Shahdag mt.) and the foothill of the Qusar homocline plateau (Big Suval mt.); B–B′ across the Side Range (Chereke mt.) and the foothill of the Qusar homocline plateau.

1–7 deposits: 1 – Lower Pleistocene (Apsheronian Stage), *2* – Upper Pliocene and Lower Pleistocene (Akchagylian Stage), *3* – Lower Pliocene (Productive Unit), *4* – Upper Miocene (Pontian Stage), *5* – Paleogene and Miocene, *6* – Cretaceous, *7* – Jurassic; *8–11 tectonic disturbances: 8* – proved faults, *9* – faults supposed or manifested at the surface as flexures; *10* – unconformity surfaces, *11* – supposed continuation of eroded parts of the cross-section.

Cenozoic sediment formation indexes: J - Jurassic, K - Cretaceous, Pg-N_1 – Paleogene and Miocene, N_1^3 *s* – Sarmatian Stage (Tortonian), N_1^3 *p* – Pontian Stage (Upper Messinian), N_2^1 *pr* – Productive Unit (Zanclean), N_2^2-Q_1 *ak* – Akchagylian Stage (Piacenzian and Gelasian), Q_1 *ap* – Apsheronian Stage (Calabrian), Q_2 *b* – Bakunian Stage (Lower Chibanian), $Q_{2\text{-}4}$ – Khazarian and Khvalynian Stages (Upper Chibanian and Late Pleistocene) and Holocene.

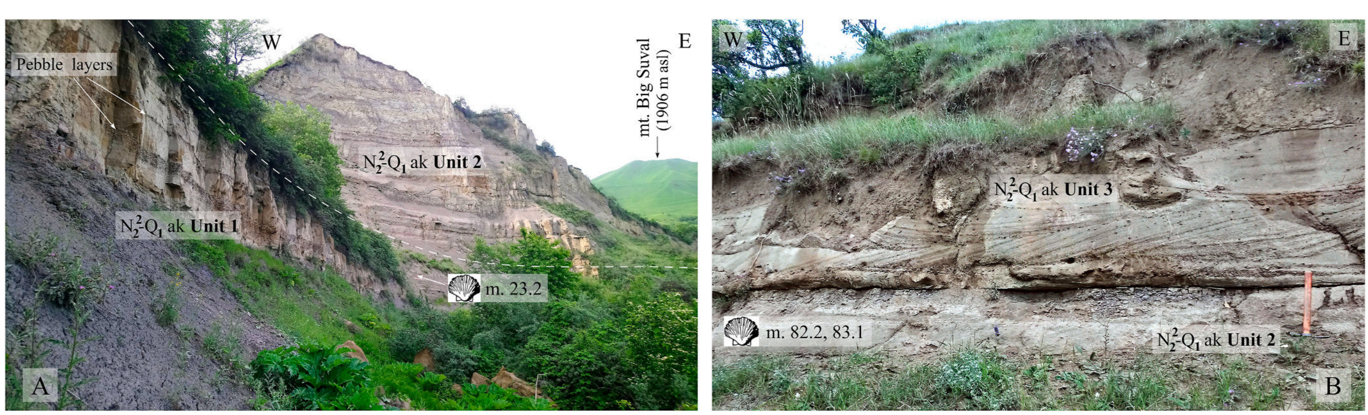

Fig. 7. A – The lower part of the section of the Akchagylian deposits of the Qusar plateau (Units 1, 2); B – The contact of the lower- (Units 1, 2) and upper-Akchagylian (Units 3, 4) deposits in the middle part of the section of the Qusar homocline. The places where paleontological specimens were founded are marked with a "shell" icon (photoes by Ya.I. Trikhunkov).
N_2^2-Q_1 *ak* – Akchagylian Stage.

chevron cross-bedding, the layers become more extended along the strike and lithologically constant, in some places there are traces of wave ripples. However, a characteristic feature of Unit 1 in comparison with the overlying parts of the section is the presence of layers and lenses of gravels (Fig. 7A). The pebbles have a marine habitus: flattened and rounded shape. These features indicate the formation of the lower layers of sediments of the Akchagylian in littoral conditions with frequent changes in the hydrodynamic regime. The nacre imprints and fragments of shells of molluscs of the Unionidae family testify to the freshwater character of the Early Akchagylian reservoir (see Chapter 4.3). The deposits of Unit 1 occur within the highest zones of the plateau, covering its highest point - 2020 m asl (Figs. 4 and 6A). The rest of the section seems to be eroded here.

Unit 2, 101 m thick, is more monotonous in terms of composition, it has massive structure, pebbles are absent; layer thickness varies from first meters to first tens of meters. There is a predominance of silts, in some places clayey and fine-grained sands, poorly cemented are found. Shells of molluscs - indicators of the Akchagylian marine basin and abundance of benthic sublittoral foraminifera shells in siltstones (see Chapter 4.3) were founded. These features together with the absence of pebbles and traces of wave ripples in the sand and the predominance of fine siltstones and clays indicate a deepening of the area to sublittoral conditions and salinization of the Early Akchagylian basin. In the upper part of Unit 2 a coarsening of the deposits to medium coarse sand and, less often, small pebbles is observed. Uncoherent layers of shells occur here as well. A layer of coarse-grained sand with chevron cross-bedding lies with unconformity upwards (Fig. 7B). These features indicate shallowing of the basin to littoral conditions and completion of the accumulation cycle, which can be associate with the Early Akchagylian transgression.

Unit 3, 138 m thick, is very similar to Unit 2. It starts with 2 m of coarse-grained sands described above and increases with 40 m of dark gray clayey silts with molluscs. Upwards the section gradually becomes coarser to medium-grained sands and sandstones with single layers of silts. In the upper part of Unit 3, like in Unit 2, sediments acquire the littoral habitus: they are composed of sands and sandstones with herringbone cross-bedding, with fragments of shells of molluscs. Sandstones alternate with tiled shell rock with carbonate-sandy cement (Fig. 8A). Thus, in the section of the Akchagylian deposits of the Qusar plateau two stages of deepening and shallowing of the sea basin, represented by Units 2 and 3 can be observed. It allows to associate it with the early and late Akchagylian transgressions.

Unit 4, the upper part of the Akchagylian sediments, was found under the Big Suval mt. At an altitude of 1620 m, but it was not preserved at the highest point of the plateau – 2020 m asl. It is represented by a layer of a very hard sandstone with carbonate cement overlapped by a layer of white calcareous clay (Fig. 8B). The deposits are strongly altered: in some places it has been preserved in the form of hard blocks, and in some places – loose to a state of powder. This unit probably formed in arid conditions with prolonged weathering and short-existing lagoon with the deposition of calcium carbonate in it which cemented the upper layer of sand of Unit 3. Subsequently, after drying out, the weathering continued. Thus, the deposits of Unit 4 mark the regression stage, a long breakup in sedimentation, active weathering, presumably during the entire Early Apsheronian.

Apsheronian deposits form the top of the section of the Qusar plateau homocline and act as an erosion-resistant rock strata. Their thickness is within 200–300 m. Deposits are represented by alluvial pebble and boulder molasses with cross-bedding and have varying thickness of single layers. They contain clay slates and sandstones of Goitkh-Tfan and limestones of Shahdagh-Khizin zones, which indicates the erosion of the latter in the Apsheronian time (Fig. 9). The pebbles began to accumulate within the low Qusar-Keleg foothill plain in the late Apsheronian time at the level of the Apsheronian Sea, which is close to a present day level (Svitoch, 2014). This indicates that the coarser molasses accumulated due to the intensification of the orogenic uplift, rather than the erosion-base drop, as it was in case of the Productive Unit.

The Akchagylian and Apsheronian deposits of the Qusar and Keleg

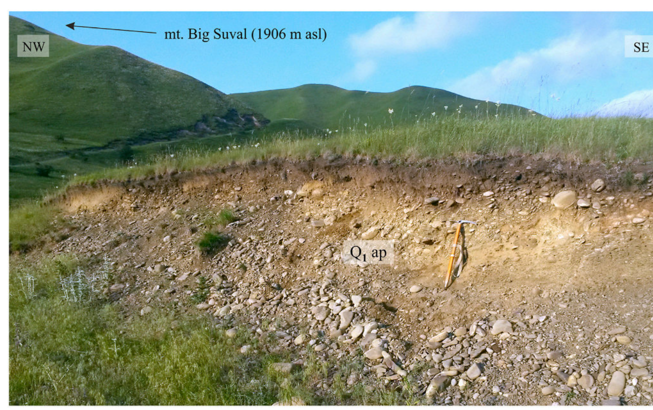

Fig. 9. Deposits of the Apsheronian Unit under the Big Suval mt., 1906 m asl (photo by D.M. Bachmanov).
Q_1 *ap* – Apsheronian Stage.

Fig. 8. The upper part of the Akchagylian deposits section of the Qusar plateau: A – Upper part of Unit 3 with fragments of the shell pavement; B - contact of the upper Akchagylian deposits between Unit 3 and Unit 4. The place where the Akchagylian malacofauna were founded is marked with a “shell” icon. (photoes by Ya.I. Trikhunkov).
N_2^2-Q_1 *ak* – Akchagylian Stage.

plateaus are of 200–300 m thick almost throughout the homoclines for each Stage. Within the Qusar-Divichi foreland, the thickness does not increase, which indicates the termination of its development during this period. Taking into account the consistency of the thickness of the Akchagylian marine sidiments and their strike angles, we have reconstructed the eroded portion of the deposits from the Big Suval cuesta towards the Sudur folded zone. The reconstruction shows that the highest position of the Akchagylian deposits is 2500 m asl (see Fig. 6A). This estimation is consistent with the data of (Milanovsky, 1968) on the existence of the beach sediments of the Akchagylian basin on the northern slope of the Shahdag mt. At an altitude of about 2500 m asl, similar to that described in Unit 4 (see Fig. 8). In this case, the maximum height of distribution of the Apsheronian deposits of the Qusar homocline is about 2600 m asl.

4.3. Biostratigraphy and magnetic stratigraphy of the deposits

Pebble-boulder deposits of the Productive Unit and Apsheronian

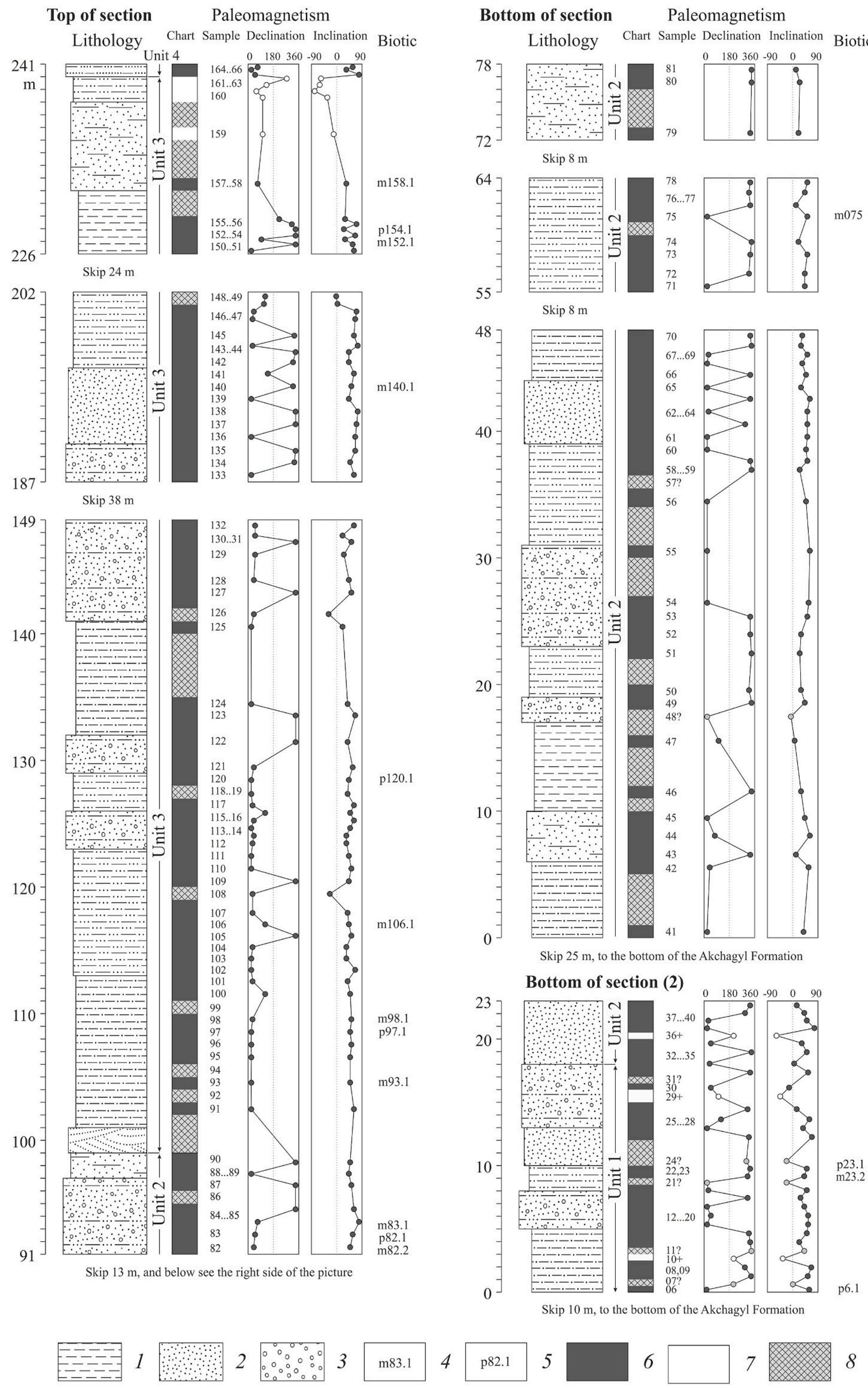

Fig. 10. Section of the Akchagylian deposits of the Qusar plateau (lithological, palaeontological and magnetostratigraphic characteristics). *1–3 sediments: 1* – clay-silt, *2* – sand, *3* – gravel-pebble; *4–5 palaeontological samples: 4* – malacofauna, *5* – spore-pollen; *6–8 palaeomagnetic polarity: 6* – normal, *7* – reverse, *8* – not identified.

within the Qusar plateau appeared to be almost unsuitable for palaeomagnetic and biostratigraphic sampling. Only a few palaeomagnetic samples were collected from the river sands at the base of the Apsheronian section near Big Suval mt.

The main part of the Qusar-Keleg homoclinal section we sampled was the Akchagylian marine deposits. 205 palaeomagnetic (PM) samples were taken from a 250-m section (Fig. 10). Some intervals of the section were not sampled because of grass cover or steep walls. The obtained results show normal polarity of the lower half of the section (Unit 1, 2). Combined with fauna data showing the Akchagylian age of the deposits and general data on the magnetization of the Akchagylian deposits (see Chapter 2.2), we present evidence that the formation of the lower half of the section took place during the Gauss Epoch. A few samples with reverse polarity at the base of the section (Unit 1) do not allow us to attribute them to any episode of this epoch.

The constant normal polarity is maintained up to the upper part of Unit 3, where it is replaced by the reverse polarity, which we refer to the lower part of the Matuyama Epoch. The appearance of normal polarity within Unit 4 gives us an opportunity to assume that a brief flooding of the late Akchagylian coastal deposits from Unit 3 occurred during the Olduvai episode which belongs to the last stages of the Akchagylian transgression (Nevesskaya, 2004). It should also be mentioned that the lithological and magnetostratigraphic characteristics of the integrated sections of the Akchagylian of the Eastern Turkey (Trifonov et al., 2020) and the Shahdag-Qusar segment of the SEC turned out to be very similar. In both cases, two stages of transgression with the reverse polarity at the top of the second half of the section are distinguished.

All the 8 spore-pollen samples contain single poorly preserved pollen

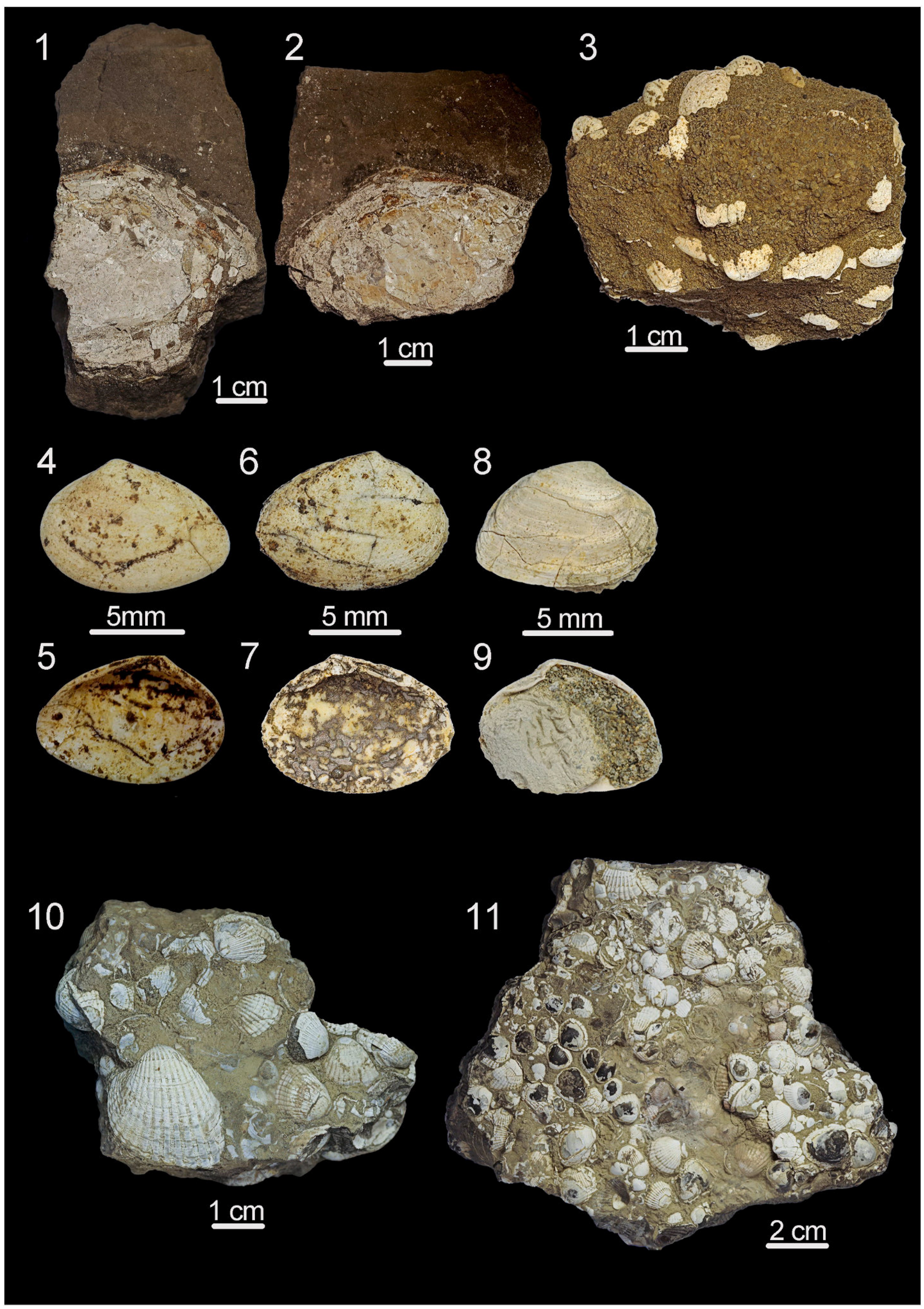

Fig. 11. Molluscs: 1–2 – Unionidae indet, sample 23.2; 3 – sample 82.2 with *Aktschagylia subcaspia* (Andrusov, 1902); 4–7 – *Aktschagylia subcaspia* (Andrusov, 1902), sample 82.2; 8–9 – *Aktschagylia subcaspia - karabugasica* (transitional form between *A. subcaspia* and *A. karabugasica*), sample 140.1; 10 – sample 158.1 with *Cerastoderma dombra dombra* (Andrusov, 1902); 11 – shell pavement, sample 158.1 with *Cerastoderma dombra dombra* (Andrusov, 1902).

grains. Reworked palynomorphs, probably of the Paleogene and Cretaceous age, are found. We did not find any true palynomorphs in the section of the Qusar-Keleg plateau.

At the bottom part of the section (Figure 7, 10 and 11) (m. 23.2) nacre imprints and fragments of internal casts of representatives of the Unionidae family were found indicating a freshwater basin. From the upper part of the section (m. 82.2), *Aktschagylia subcaspia* (Andrusov, 1902), *Aktschagylia* cf. *subcaspia* (Andrusov, 1902) and *Clessiniola* sp. Were found, from the sample (m. 83.1) - *Aktschagylia* cf. *subcaspia* and Hydrobiidae indet. In both samples, almost all valves of bivalve molluscs lie convex upwards, which most likely indicates the conditions of burial in shallow water with periodic wave activity or weak intermittent currents (Ivanova, 1973).

From the middle part of the section (Unit 3, samples m. 93.1; m. 98.1; m. 106.1) few shells of *Aktschagylia subcaspia* (Andrusov, 1902) and fragments of the representatives of the family Hydrobiidae (? *Clessiniola* sp.) were found in clay deposits, ostracods shells are also present. Sample m. 93.1, among other palaeontological remains, contains an abundance of shells of the benthic foraminifera *Ammonia tepida* (Cushman, 1926), as well as few benthic foraminifera *Miliolinella* aff. *subrotunda* (Montagu, 1803). Representatives of the genus *Ammonia* are cosmopolitan, living in the marginal parts of the oceans and seas at depths of 30–50 m and reproduce at a basin temperature of 17–32 °C and salinity of 15–40‰. The largest populations of Ammonia are found in mid-latitudes, where precipitation is higher than evaporation and salinity of coastal waters is below normal (Walton and Sloan, 1990).

In the sample m. 140.1 *Cerastoderma* cf. *dombra dombra* (Juv.), *Aktschagylia subcaspia - karabugasica*, *Clessiniola* cf. *polejaevi* (Andrusov, 1902), *Clessiniola* cf. *vexatilis* (Andrusov, 1902) were found. From m. 152.1 - *Cerastoderma* cf. *dombra dombra* and *Aktschagylia subcaspia*. These samples were also taken from clayey sediments. In both cases, *Aktschagylia* shells with both valves were found, which indicate calm hydrodynamic conditions of the environment. *Cerastoderma dombra* probably originate from some species from the *Cerastoderma glaucum* group (Nevesskaya et al., 1986; Danukalova, 1996). Modern *Cerastoderma glaucum* in the Caspian Sea live at depths up to 50 m (Kijashko, 2013). In the Black and Azov Seas, this species reaches its maximum development at depths of 1–3 m (Anistratenko et al., 2011).

In the uppermost part of the section (sample m. 158.1), *Cerastoderma dombra dombra* (Andrusov, 1902), *Aktschagylia subcaspia* (Andrusov, 1902), *Clessiniola* cf. *intermedia* (Andrusov, 1902), *Clessiniola* cf. *polejaevi* (Andrusov, 1902) were identified. The type of orictocenosis of this specimen is close to the so-called "shell pavement". It is associated with the coastal shallow water conditions and a rather high dynamics of the environment - periodic waves (Ivanova, 1973).

Based on the data above we assume that the bottom part of the section was formed under freshwater conditions (sample m. 23.2), upwards in the section marine shallow-water sediments appear, samples m. 82.2 and m. 83.1. Clay deposits (samples m. 93.1; m. 98.1; m. 106.1; m. 140.1; m. 152.1) represent deeper-water sediments, up to a depth of 50 m. To the top of the section, the basin shallows again and sediments accumulate in coastal-marine conditions (sample m. 158.1). In all samples except m. 23.2, key species were distributed throughout the entire Akchagylian Stage and occurred in almost the entire basin (Kolesnikov, 1950; Danukalova, 1996).

5. Discussion

5.1. History of Pliocene-Quaternary development of Shahdag-Qusar segment of the SEC

Marine sedimentation in SEC axial zone took place up to the Late Sarmatian and in the Meotian-Pontian and, apparently, was replaced by the initial orogenic uplift. It was concentrated in Goitkh-Tfan and Shahdag-Khizin zones, separated by faults of the MCTZ, bounded by the Siazan reverse fault in the north. Sands and clays with a few conglomerates of the Pontian sea basin covering the Sudur and Qusar-Keleg zones in the downthrown block of the Siazan reverse fault shows the absence of orogenic uplift here. Considerable thickness of coarse deposits of the Productive Unit molasses, which compose homocline of the Qusar-Keleg plateau and the Qusar-Divichi foreland, can also not be unequivocally associated with uplifts of the source area. Rather, these characteristics must be related to the drop in the base level erosion up to - 750 m (Svitoch, 2014) during the Balakhanian regression. The topography of the Sudur and Qusar-Keleg zones of the SEC was flat with numerous deeply incised river valleys that corresponded to the low water level in the Caspian basin. However, deposits of the Productive Unit are inclined to the northeast by 6–7° steeper than the Akchagylian deposits. This angular unconformity indicates the slow uplift of the Qusar-Keleg homocline in the Balakhanian time (Zanclean), which was later probably planed because of the abrasion of the Akchagylian Sea.

Fine sediments of the Early Akchagylian without traces of cross-bedding and with wave ripples, with Akchagylian type of sea molluscs, benthos and plankton testify to sublittoral conditions of sedimentation and to considerable weakening of river erosion in the Akchagylian. The latter indicates an increase of the base level of erosion by 100 m (Svitoch, 2014) under conditions of relative tectonic stability and the absence of alpine dissected topography near the source area. During the Late Akchagylian which is partly characterized by the reverse polarity the sea basin at first shallowed, then deepened, and at last finally shallowed. However, it should be noted, that it covered the present-day territory of the Qusar-Keleg plateau and the Sudur zone. Thus, the formation of the described Akchagylian deposits took place approximately at a present-day sea level. Their discovery at altitudes up to 2020 m asl and the possibility to increase their position due to theoretical reconstruction of the eroded portion of the deposits up to 2500 m asl makes them the highest Quaternary marine deposits in the Caucasus.

Analysis of the distribution of the Akchagylian deposits and the river valleys pattern shows that throughout the Akchagylian time, the entire territory of the modern Qusar-Keleg plateau and Sudur zone was a sea gulf triangular in shape, formed in the downthrown parts of the Samur transverse zone and Siazan reverse fault (see Fig. 4). The bay went 50 km deep into the mountain system and came close to Shahdag-Khizin folded zone. All the rivers of both western and southern parts of the region run into this bay and later as its coastline receded developed their channels along the shortest way to the sea (see Figs. 1 and 4).

The overlying deposits of the Late Apsheronian acquire the appearance of a coarse pebble-boulder molasses with a cross-bedding and varying thickness of layers. They accumulated on the surface of the Qusar-Keleg foothill plain at a sea level close to a present-day (Svitoch, 2014). This indicates a coarsening of the molasses precisely as a result of the intensification of orogenic uplift, rather than the drop of a base level of erosion.

A very limited distribution of the Apsheronian deposits within the uplifted part of the Samur transverse fault zone and a total coverage of flat watersheds of its downthrown Qusar-Keleg part by the upper Apsheronian pebbles was established. As well as Akchagylian sediments, the Apsheronian pebbles lay transgressively and were accumulated due to alluvial deposition at a flat coastal lowland. The thickness of pebble layer is constant both along the strike and dip lines and is of 150–230 m. However, the thickness of the marine Apsheronian deposits at the base of the Samur-Divichi lowland sharply increases (up to 1300 m) (Geology of the USSR, 1968). The valleys of Qusarchay, Kudialchay, Karachay and their tributaries are extremely narrow and incise into the homocline plateau, i.e. they were formed later than the accumulation of the Upper Apsheronian pebbles took place. Thus, at the time of their accumulation, the present Qusar-Keleg plateau was a flat, gently sloping alluvial-proluvial coastal plain up to 200–300 m asl similar to the present-day Samur-Divichi lowland (see Figs. 1 and 4). In the Upper Apsheronian time, it was a regional zone of molasses accumulation, and uplift in this period still occurred in the axial zone of the mountain system. Incision into the surface of the foothill plain and formation of modern river valleys began during the short Turkianian regression of the Caspian Sea at the beginning of the Middle Pleistocene and continued later in the Bakunian time (Chibanian), because of sharp increase in river energy due to uplifts in source areas. Abrasion terraces of the Turkianian regressive basin are found at depths of about 200 m (Yanina, 2012). The Bakunian river terraces are incised into the surface of the Qusar plateau at about the same depth in its low part and deepen relative the watersheds towards the upper reaches of the rivers.

5.2. *Recent tectonics of the region and causes of orogenic uplift*

On the basis of the data given it can be argued that the uplift of the bottom of the Akchagylian Sea to a height of low foothill plain (up to 300 m asl) took place during the Apsheronian time (~1.8–0.8 Ma). The uplift of the Akchagylian marine sediments up to the altitude of 2500 m asl occurred from the beginning of the Middle Pleistocene. The uplift estimates were obtained from the reconstruction of the eroded part of the Qusar plateau section (see Fig. 6A) and coincide with the data (Milanovsky, 1968). From these data follows that the minimal Quaternary uplift rate of the mountain system is at least of 1.4 mm/year for the last 1.8 Ma from the lower boundary of the Apsheronian with a sharp acceleration up to 2.8 mm/year in the Middle Pleistocene-Holocene. This rate is calculated only for the zone of the northern slope of the mountain system, and in the axial zone should be significantly higher.

The Akchagylian Sea deposits also discovered by (Trifonov et al., 2020; Simakova et al., 2021) at the altitudes of about 1880 m asl in the Khorasan basin and 1550 m asl in the Shirak basin (Eastern Turkey, see Fig. 1. Inset). Taking into account the beginning of the uplift 1.8 Ma ago (the end of the Akchagylian transgression and the beginning of the accumulation of coarse molasses in the Apsheronian) the average rates of uplift is 0.86 and 1.04 mm per year for the Shirak and Khorasan basins, respectively. This data allows us to state that Greater Caucasus uplift is faster than the Lesser Caucasus by 0.4–0.5 mm/year on average over the last 1.8 Ma.

The homocline of the Qusar-Keleg plateau unconformably overlaps the structures of the Qusar-Divichi foreland and it was not disturbed by any Pl-Q deformations. The foreland, as a negative morphostructure, probably still existed in the Balakhanian time (Zanclean), but was not flooded by the sea because of the extremely low level of the latter. The deposits of coarse molasses of the Productive Unit with maximum (up to 1 km) thickness in the axial zone of foreland completely filled it, and the overlying Pl-Q sediments were already subhorizontal (Fig. 2). Thus, there are no signs of the Qusar-Divichi foreland downwarping in the modern structure of the Qusar-Keleg homoclinal plateau. This indicates the cessation of the development of the foreland in the Plio-Quaternary and its pulling into the newest uplift of SEC.

Intensification in the Pl-Q of the Samur zone resulted in transverse deformations of the Qusar-Divichi foreland. In the western uplifted part the recent folding created a number of anticlinal ridges spreading over all the foreland up to the Caspian coast. In the Shahdag-Qusar transverse segment the main compression is realized in the uplifted flank of the Siazan reverse fault within the Shahdag-Khizin zone. Pl-Q folding manifested itself only in the narrow Sudur folding zone, where some anticlinal ridges were raised up to heights of over 3000 m asl. In the downthrown Qusar-Keleg flank transverse compression, apparently, is dampered by movements along the Siazan and Sudur reverse faults, which formed the conditions of "tectonic shadow". Up to the Middle Pleistocene this flank was a zone of marine sedimentation and molasses accumulation (see Fig. 4). Since the beginning of the Middle Pleistocene the Qusar-Keleg homocline has been experiencing uplift without folding and faulting. These features, along with the above described heterogeneous deformations of the Shahdag massif give us a basis to assume large-scale thrusting and right-lateral strike-slips in the Samur transverse zone (see Figs. 1 and 4), taking into account the general lateral compression and bilateral tectonic symmetry of the SEC.

Since the surface of the Qusar-Keleg plateau is not deformed by the Pl-Q folding and faulting, we have come to the conclusion that the general uplift of the Caucasian mountain region led to the uplift of the plateau by 2000–2500 m asl since the beginning of the Middle Pleistocene. This process lags behind the maximum of compression and collision, which took place in the axial zone and southern slope of the mountain system in Sarmatian (Tortonian), by about 10 Ma (Khain et al., 2006; Kangarli et al., 2018). The collisional deformations of Sarmatian epoch did not lead to the formation of high mountains. This phenomenon is vividly demonstrated in North-Western Caucasus, a zone of well-developed linear folding with inverted, not juvenile, folded topography with low altitudes (Trikhunkov, 2016; Trikhunkov et al., 2019). The reason for the uplift which is not directly related to a collisional compression could be the impact of the active asthenosphere of the subducted Tethys, which spread under the orogenic belt: the isostatic reaction to the decompaction of the upper zones of mantle as a result of partial substitution of the lithospheric mantle by the asthenosphere on the one hand and the lower portions of crust as a result of retrograde metamorphism under the influence of cooled asthenospheric fluids on the other hand (Sokolov and Trifonov, 2012).

6. Conclusion

1. The N-Q uplift of the South-Eastern Caucasus began not earlier than the Late Sarmatian. Up to the Middle Pleistocene it had concentrated in its axial zone and did not reach high rates. The entire zone of the northern flank of the mountain system was located at low altitudes and was repeatedly flooded by the sea until the Apsheronian time.
2. The Qusar-Divichi foreland ceased its development in the Pliocene-Quaternary. Initial movements of the Samur fault zone led to the transverse fracturing of the foreland by reverse fault and right-lateral strike-slip deformations. In the western uplifted flank the recent folding manifested itself over the entire zone up to the Caspian coast. In the eastern Shahdag-Qusar transverse segment, the main compression took place in the uplifted flank of Siazan reverse fault within the Shahdag-Khizin zone. Anticlinal ridges were formed and raised up to the heights of over 3000 m only in the narrow Sudur folded zone. In the downthrown Qusar-Keleg flank the transverse compression was dampered by movements along the Siazan and Sudur reverse faults due to which the "tectonic shadow" was formed and the Qusar-Keleg homocline did not experience the recent folding and faulting and was involved in the overall Quaternary SEC uplift.
3. The uplift of the Akchagylian marine sediments to the heights of the low foothill plain (up to 300 m asl) occurred during the Apsheronian time (~1.8–0.8 Ma). The rise of the bottom of the Akchagylian Sea up to an altitude of 2500 m asl has occurred since the beginning of the Middle Pleistocene. The rate of the Quaternary uplift of the northern flank of the SEC is at least 1.4 mm/year in the last 1.8 Ma from the lower boundary of the Apsheronian with a sharp acceleration up to 2.8 mm/year in the Middle Pleistocene-Holocene. Thus the Greater Caucasus uplift is faster than the Lesser Caucasus at least by 0.4–0.5 mm/year on average over the last 1.8 Ma.
4. The uplift of the Qusar-Keleg plateau at 2000–2500 m asl from the beginning of the Middle Pleistocene was caused by the general uplift of the Caucasus. This process demonstrates almost 10 million year delay relative to the Sarmatian peak compression and collision. The collisional deformations of this epoch did not lead to the formation of high mountains, and the reason for the Quaternary uplift is the impact of the active asthenosphere of the closed Tethys, which spread under the orogenic belt.

Author contributions

Trikhunkov Ya.I, Kangarli T.N. and Bachmanov D.M. performed a morphostructural and facies analysis. Shalaeva E.A. and Aliyev F.A. made outcrop descriptions and palaeomagnetic sampling. Frolov P.D.

took fauna samples, identified and analyzed Akchagylian molluscs, Popov S.V. identified and analyzed Sarmatian molluscs. Trikhunkov Ya. I. and Bachmanov D.M. conducted an initial preparation of palaeomagnetic samples and Latyshev A.V. performed palaeomagnetic analysis. Simakova A.N. studied pollen samples and Bylinskaya M.E. identified and analyzed phoraminifera.

Data availability

Akchagylian molluscs are housed in the Geological Institute of the Russian Academy of Sciences (GIN RAS), Moscow, collections GIN-1140 (molluscs). Sarmatian molluscs are in the Palaeontological Institute RAS (PIN RAS), Moscow, collections 5528.

Funding

The study corresponds to plans of scientific research and state topic of the Geological Institute of the Russian Academy of Sciences. Structural and geomorphological research was funded by RSF grant № 17-17-01073. Stratigraphical studies and palaeomagnetic data were carried under the financial support of RFBR grant № 18-00-00977. Study of paleontological data was conducted with financial support of the grant of the President of Russian Federation for young Russian PhD researchers № MK-3510.2019.5.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are very grateful to V.G. Trifonov and A.S. Tesakov (GIN RAS) for remarks and advice given while preparing the manuscript. The comments of two anonymous reviewers helped to improve the manuscript and are gratefully acknowledged.

References

Andrusov, N.I., 1902. Materials for research the caspian Neogene. Akchagylian strata. Proceedings of Geol. Com 15, 4.

Anistratenko, V.V., Khaliman, I.A., Anistratenko, O.Yu, 2011. Molluscs of the Azov Sea. Naukova Dumka Press. Kiev. 175 pp. In Russian.

Budagov, B.A., 1964. Data on the Recent Tectonic Movements in the Shahdag Massif (South-Eastern Caucasus) in Light of the Discovery of the Upper Sarmatian Fauna. DAN of the USSR. Vol. 155. №2.

Channell, J.E.T., Hodell, D.A., Singer, B.S., Xuan, C., 2010. Reconciling astrochronological and 40Ar/39Ar ages for the Matuyama-Brunhes boundary and late Matuyama Chron. G-cubed 11, Q0AA12. https://doi.org/10.1029/2010GC003203.

Chumakov, I.S., 2000. About the problem of Miocene-Pliocene boundary in Euxine. Stratigraphy. Geol. correlation. 8 (4), 84–92.

Chumakov, I.S., Byzova, S.L., Ganzey, S.S., Mamedov, A.V., Alekserov, B.D., 1988. Radiometric scale of the late Cenozoic of Azerbaijan. Azerbaijan oil indus. 2, 4–8 (in Russian).

Consortium for Spatial Information (CGIAR-CSI), 2017. SRTM 90m Digital Elevation Database, 4.1. Available from: URL. http://srtm.csi.cgiar.org/. Accessed: March 10. 2010.

Cushman, J.A., 1926. Recent Foraminifera from Porto Rico, 342. Publications of the Carnegie Institution of Washington, pp. 73–84.

Danukalova, G.A., 1996. Bivalves and Akchagylian Stratigraphy. Nauka Press, Moscow, p. 132 (In Russian).

Dotduev, S.I., 1986. The nappe structures of the Greater Caucasus. Geotektonika 5, 94–106 (In Russian).

Enkin, R.J., 1994. A Computer Program Package for Analysis and Presentation of Palaeomagnetic Data: Pacific Geoscience Centre. Geological Survey of Canada, p. 16.

Gamkrelidze, P.D., Gamkrelidze, I.P., 1977. Tectonic Nappes of the Southern Slope of the Greater Caucasus (Within Georgia). Metsniereba Publishing House, Tbilisi, p. 81 (In Russian).

Geological map of the Caucasus, 1976. In: Scale 1:500000. D.I. Nalivkin. Min. Geo. USSR.

Geology of the USSR, 1968. In: Andrushchuk, V.L., Dubinskiy, A. Ya, Khain, V. Ye (Eds.), Volume IX. Northern Caucasus. Geological Description. Nedra, Moscow, p. 760.

Gurariy, G.Z., Trubikhin, V.M., Ushko, K.A., 1976. Stratigraphic position of palaeomagnetic border Matuyama-Brunes in sections of the Western Turkmenistan and Azerbaijan. Main Geomagnetic Field and Problems of Paleomagnetism. Nauka.

Head, M.J., Gibbard, P.L., 2015. Earlye-Middle Pleistocene transitions: Linking terrestrial and marine realms. Quat. Int. 389, 7–49.

Ivanova, I.-N.V., 1973. Bivalve Molluscs and Sedimentation Conditions. Nauka Press, Moscow, p. 164. In Russian.

Kangarli, T.N., 2007. Buried mesozoic structures of the greater Caucasus within the qusar-divichi superimposed foreland. Azərbaycanda geofizika Yenilikləri 2, 31–34.

Kangarli, T.N., Kadirov, F.A., Yetirmishli, G.J., Aliyev, F.A., Kazimova, S.E., Aliyev, A.M., Safarov, R.T., Vahabov, U.G., 2018. Recent geodynamics, active faults and earthquake focal mechanisms of the zone of pseudosubduction interaction between the Northern and Southern Caucasus microplates in the southern slope of the Greater Caucasus. Geodynamics & Tectonophysics 9 (4), 1099–1126. https://doi.org/10.5800/GT-2018-9-4-0385.

Khain, V.E., Popkov, V.I., Yudin, V.V., Chekhovich, P.A., 2006. The Main Stages of Development of the Black Sea - Caspian Region. Ecological Bulletin of Research Centers of the Black Sea Economic Cooperation, pp. 98–106. In Russian.

Khramov, A.N., 1963. Paleomagnetic Sections of Pliocene and Post-Pliocene of the Absheron-Caspian Region and Their Correlation. Paleomagnetic Stratigraphic Studies. Gostoptekhizdat, pp. 220–263.

Kijashko, P.V., 2013. Chapter 5. Molluscs of the Caspian Sea. In: Bogutskaya, N.G., Kijashko, P.V., Naseka, A.M., Orlova, M.I. (Eds.), Identification Keys for Fish and Invertebrates. Volume 1. Fish and Molluscs. KMK Scientific Press Ltd (St. Petersburg. Moscow).

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of paleomagnetic data. Geophys. J. Roy. Astron. Soc. 62, 699–718.

Kolesnikov, V.P., 1950. vol. X. Paleontology of the USSR. Aktschagylian and Apscheronian molluscs. USSR Academy of Science Press, p. 259, 12, Moscow. St.-Peterburg.

Krijgsman, W., Tesakov, A., Yanina, T., Lazarev, S., Danukalova, G., Van Baak, C.G.C., Agustí, J., Alçiçek, M.C., Aliyeva, E., Bista, D., Bruch, A., Büyükmeriç, Y., Bukhsianidze, M., Flecker, R., Frolov, P., Hoyle, T.M., Jorissen, E.L., Kirscher, U., Koriche, S.A., Kroonenberg, S.B., Lordkipanidze, D., Oms, O., Rausch, L., Singarayer, J., Stoica, M., van de Velde, S., Titov, V.V., Wesselingh, F.P., 2019. Quaternary time scales for the Pontocaspian domain: interbasinal connectivity and faunal evolution. Earth Sci. Rev. 188, 1–40.

Lilienberg, D.A., 1961. North-eastern transcaucasia sea terraces. In: Geographical Reports, vol. 2. M.

Milanovsky, E.E., 1968. Noveishaya Tektonika Kavkaza. Neotectonics of the Caucasus. Nedra, Moscow (In Russian).

Milyukov, V.K., Mironov, A.P., Rogozhin, E.A., Steblov, G.M., 2015. Velocities of contemporary movements of the Northern Caucasus estimated from GPS observations. Geotectonics 49 (3), 210–218.

Montagu, G., 1803. Testacea Britannica or natural history of British shells, marine, land, and fresh-water, including the most minute: Systematically arranged and embellished with figures, 2. J. White, London, pp. 293–606.

Mumladze, T., Forte, A.M., Cowgill, E.S., Trexler, C.C., Niemi, N.A., Yıkılmaz, M.B., Kellogg, L.H., 2015. Subducted, detached, and torn slabs beneath the Greater Caucasus. GeoResJ 5, 36–46.

Nevesskaya, L.A., Goncharova, I.A., Ilyina, L.B., Paramonova, N.P., Popov, S.V., Babak, E.V., Bagdasarjan, K.G., Voronina, A.A., 1986. History of the Paratethian Neogene Molluscs. Nauka Press, Moscow, p. 208. In Russian.

Nevesskaya, L.A., Kovalenko, E.I., Beluzhenko, E.V., et al., 2004. Explanatory Note to the Unified Regional Stratigraphic Scheme of Neogene Deposits of the Southern Regions of the European Part of Russia. M. Paleontological Institute of RAS, p. 83.

Nevesskaya, L.A., Paramonova, N.P., Babak, E.V., 1997. Determinant Guide for species identification of the Pliocene bivalve molluscs of the South-Western Eurasia. Proc. Paleontol. inst. 269, 1–267 (In Russian).

Philip, H., Cicternas, A., Gvishiani, A., Gorshkov, A., 1989. The Caucasus: an actual example of the initial stages of continental collision. Tectonophysics 161 (1–2), 1–21.

Popkov, V.I., 2006. Imbricate thrust structure of the NWC. Reports Earth Sci 411 (8), 1222–1225.

Rastsvetaev, L.M., Marinin, A.V., Tveritinova, T.Yu, 2010. Late alpine dysjunctive systems and geodynamics of the western Caucasus. Earth Physics 5, 31–40.

Rogozhin, E.A., Gorbatikov, A.V., Stepanova, M.Y., Ovsyuchenko, A.N., Andreeva, N.V., Kharazova, Y.V., 2015. Structure and modern geodynamics of meganticlinoria of the greater Caucasus in the light of new data on deep structure. Geotectonics 2, 36–49.

Semenenko, V.N., 1987. Stratigraphic Correlation of the Upper Miocene and Pliocene of Eastern Paratecis and Tetis. Kiev. Naukova Dumka, p. 231.

Simakova, A.N., Tesakov, A.S., Çelik, H., Frolov, P.D., Shalaeva, E.A., Sokolov, S.A., Trikhunkov Ya, I., Trifonov, V.G., Bachmanov, D.M., Latyshev, A.V., Ranjan, P.B., Gaydalenok, O.V., Syromyatnikova, E.V., Kovaleva, G.V., Vasilieva, M.A., 2021. Caspian-type dinocysts in NE Turkey mark deep inland invasion of the Akchagylian brackish-water basin during the terminal Late Pliocene. Quat. Int. In press.

Sokolov, S.Yu., Trifonov, V.G., 2012. Role of the asthenosphere in transfer and deformation of the lithosphere: The Ethiopian–Afar superplume and the Alpine–Himalayan Belt. Geotectonics 46 (3), 171–184. https://doi.org/10.1134/S0016852112030053. https://www.researchgate.net/publication/257834175_Role_of_the_asthenosphere_in_transfer_and_deformation_of_the_lithosphere_The_Ethiopian-Afar_superplume_and_the_Alpine-Himalayan_Belt.

State Geological Map of USSR, 1958. In: Tsibovsky, N.I. (Ed.), 1:200 000. Caucasian Series. K-39-XIX, XX.Moscow. In Russian.

Svitoch, A.A., 2014. The Greater Caspian: Structures and History of Development. Moscow State University. Geographical Fact. Moscow State University, Moscow, p. 271, 2014.

Trifonov, V.G., Simakova, A.N., Çelik, H., Tesakov, A.S., Shalaeva, E.A., Frolov, P.D., Trikhunkov, YaI., Zelenin, E.A., Aleksandrova, G.N., Bachmanov, D.M., Latyshev, A. V., Ozherelyev, D.V., Sokolov, S.A., Belyaeva, E.V., 2020. The upper pliocene–quaternary geological history of the Shirak basin (NE Turkey and NW Armenia) and estimation of the quaternary uplift of lesser Caucasus. Quat. Int. 546, 229–244. https://doi.org/10.1016/j.quaint.2019.11.004.

Trikhunkov, YaI., 2016. Neotectonic transformation of Cenozoic fold structures in the NWC. Geotectonics 50 (5), 509–521.

Trikhunkov, YaI., Bachmanov, D.M., 2011. Modern structures of wringing in the axial zone of the western Caucasus (achishkho ridge). In: Second Youth Tectonophysical School-Seminar. Modern Tectonophysics. Methods and Results. T.1. M.: ULTRASOUND, pp. 270–273.

Trikhunkov, YaI., Bachmanov, D.M., Gaydalenok, O.V., Marinin, A.V., Sokolov, S.A., 2019. Recent mountain-building at the boundary juction of the north-western Caucasus and intermediate kerch-taman region. Geotectonics 4, 78–99.

Trubikhin, V.M., 1977. Paleomagnetism and stratigraphy of the akchagyl deposits of western Turkmenistan. In: Proceedings of the State Penal Institute of the USSR Academy of Sciences, vol. 301. Trubikhin V.M. M. Science, p. 79.

VanBaak, C.G.C., Vasiliev, I., Stoica, M., Kuiper, K.F., Forte, A.M., Aliyeva, E., Krijgsman, W., 2013. A magnetostratigraphic time frame for Plio-Pleistocene transgressions in the South Caspian Basin. Azerbaijan. Glob. Planet. Change 103, 119–134.

Vinarski, M.V., Kantor, Y.I., 2016. Analytical catalogue of fresh and brackish-water molluscs of Russia and adjacent countries. A.N. Severtsov Institute of Ecology and Evolution of RAS, Moscow, pp. 1–544.

Walton, W.R., Sloan, B.J., 1990. The genus *Ammonia* Brünnich, 1772, its geographic distribution and morphologic variability. J. Foraminifer. Res. 20 (2), 128–156.

Yanina, T.A., 2012. Neopleistocene Ponto-Caspian Sea: Biostratigraphy, Paleogeography, Correlation. Moscow State University. Department of Geography, p. 264 (c. In Russian).