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Late Pleistocene climatic events reflected in the Caspian Sea geological history (based on drilling data)

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A B S T R A C T

The analysis of seismic-acoustic profiles and drilling data from the Northern Caspian showed the climatic events are quite distinguishable in the Upper Pleistocene sedimentary sequence. The climatic events of the first half of Late Pleistocene (MIS 5) resulted in the onset of two warm-water transgressive basins – Late Khazarian and Hyrcanian ones. Though cooler than at the late Khazarian transgression, the climate during the Hyrcanian time was attributable to interglacial one. As the glacial stage MIS 4 approached its maximum under conditions of a dry and cold climate the Hyrcanian sea basin regressed. The Atelian regression of the Caspian Sea corresponded to MIS 4 stage and to the initial phases of the MIS 3 interstadial warming. The development of the global interstadial warming led to a considerable increase in the surface runoff from the catchment and resulted in the rising of the Atelian lake level and the onset of the first phase of the Khvalynian transgression. The sea level rising was interrupted at the time of maximum cooling and aridization at MIS 2 and resumed when the ice sheet was decaying. The conspicuous climatic events known as warm phases of Bølling and Allerød promoted the ice sheet melting along with thawing of permafrost, the latter having been widespread in the Volga drainage basin. All the above contributed to the Khvalynian transgression. The 'chocolate' clays were accumulated in the Volga estuary, as well as in depressions of the Pre-Khvalynian topography. Phases of a noticeable cooling known as the Oldest, Older and Younger Dryas marked by a decrease in the runoff volume from the Caspian drainage basin are correlated with regressive stages in the Khvalynian basin history. The Khvalynian came to its end at the time of the first sharp warming that resulted in the rise of the Caspian level and is generally taken as marking the Pleistocene/Holocene boundary. The Mangyshlakian regression is dated to the Holocene and was essentially a response of the Caspian Sea to the increase in the climate continentality during the Boreal period.

1. Introduction

The Caspian Sea is the largest isolated basin in the world, located in the depths of the Eurasian continent (Fig. 1) with an area of 380,000 km^2, a water body of 78,000 km^3 and a level of 27 m. The Sea is made of three major parts: the Northern Caspian, the Middle Caspian and the Southern Caspian that are divided by Mangyshlak and Apsheron thresholds. Although 95,000 km^2 in area, the Northern Caspian holds only 1% of the water reserve and most frequent depths are 5 m. The Middle Caspian has an area of about 140,000 km^2 and water volume of about 26 km^3; maximum depth is 788 m. The Southern Caspian (almost one third of the total Sea area) contains the bulk of Caspian water (two thirds). This is a 1025 m-deep depression. The basin receives water from river systems of the Russian Plain, the Caucasus, and Elburs, with a collection area of 3.6 million km^2. The main river is the Volga. The northern part of the sea receives 88% of the total freshwater inflow (Agapova, Kulakova, 1973; Zonn, 2004).

The Caspian water balance depends on the river drainage, atmospheric precipitation (the incoming fraction), evaporation, and outflow into the Kara-Bogaz-Gol Bay (the outgoing fraction). Within the incoming fraction, the main role is that of river drainage, 80% of which is contributed by the Volga River. The water balance directly affects the sea-level fluctuations.

The basin's physiographical conditions are varied due to large area, great meridian length, surrounding relief and climatic

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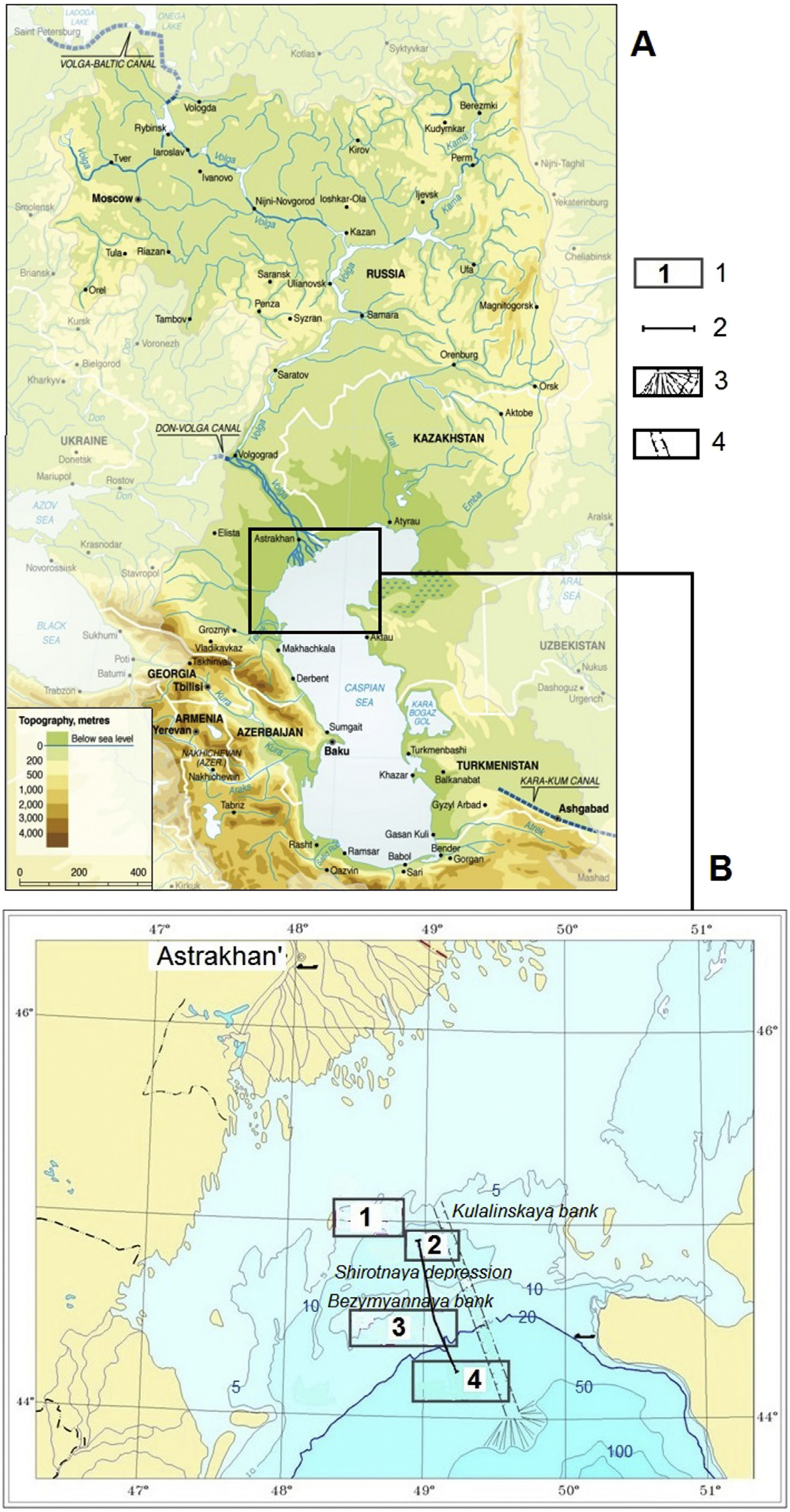

Fig. 1. Caspian Sea. Area of research. A – Caspian Sea and Caspian Sea catchment area; B – Northern Caspian Sea, research area: 1 – numbers of the studied areas; 2 –profile for correlation; 3 – paleodelta of Volga river; 4 – paleochannel of Volga river.

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zonality. The most significant natural factors, which affect the basin, appear to be the cold Arctic air, humid marine Atlantic air, arid continental Central Asian air and warm tropical Iran-Mediterranean air. The Caspian Sea covers several climatic zones: the Northern Caspian is located within temperate continental climate, the Western – within temperate warm climate, the South-Western – within subtropical climate and the East – within desert climate. As a result air temperatures vary greatly.

Temperature conditions in different parts of the Sea are determined by the latitude of the location. Maximum annual temperature amplitudes are observed on the north (25–26°) and decrease in the southward direction. The lowest temperatures occur in February (−0.1–0.5° in the Northern, 3–7° in the Middle and 8–10° in the Southern sector), maximum temperatures are located in central deep-sea parts of the Sea. In August the surface water temperature throughout the entire Sea is 24–26° and 28° on the South, an exception is the Eastern coast, where cold deep-sea waters rise to the surface (Zonn, 2004). The most intensively heated regions during summer are shallow bays. The salinity of the Caspian Sea changes from 1 to 13.5‰ from the north to the south of basin. The lowest salinity is in a zone of influence of fresh waters of the Volga River. In other areas, the average water salinity is ~12‰.

The Caspian Sea was formed in the late Pliocene, after its separation from the Black Sea. From that time, it has experienced numerous transgressions and regressions with water level fluctuations of several tens of meters (Fedorov, 1978; Chepalyga, 1980; Svitoch, 1997; Svitoch, Yanina, 1997; Yanina, 2012a, b a.o.). The evolution of the entire Caspian Sea natural system and changes in its individual constituents depended of a number of factors including global climatic changes; glacial-interglacial rhythms on the Russian Plain and in mountains; neotectonic processes; volumes of groundwater and pore water inflow; deposition within the basin; etc. (Antipov et al., 1996; Chepalyga, 2006; Fedorov, 1978; Golubov, 1984; Golubov et al., 1998; Karpytchiev, 1993; Kvasov, 1977; Lavrushin et al., 2004; Leontiev et al., 1977; Maev, 1994; Rychagov, 1997; Svitoch, 2009; Varushchenko et al., 1987; Yanina, 2012a, b; 2014; a.o.). In the course of the geological history the impact of the listed factors varied in efficiency from one stage to another. In the Late Pleistocene the leading role belonged to the global climatic changes; those were manifested as alternating cold and warm epochs and resulted from variations in insolation due to changes in the Earth orbit elements (marine isotope stages MIS 5 to MIS 2) (Fig. 2).

The Late Pleistocene beginning was marked by a considerable warming known as Riss-Würmian – Eemian – Mikulino Interglacial. Though none of specialists ever questioned the fact of that paleogeographic event, there is no general agreement as to its chronological boundaries and duration. Most of specialists think it to be correlated with MIS 5e substage (Shackleton, 1969; Litt and Gibbard, 2008; North Greenland Ice Core Project Members, 2004; Velichko (ed.), 2009; Velichko, 2012), its duration being estimated at 15 thousand years (130–115 ka BP) and thermal maximum positioned at approximately 126 ka BP (NEEM Project members, 2013; Turney and Jones, 2010). In the opinion of some others the interglacial spanned the entire MIS 5, or at least it greater part (Kukla et al., 2002; Molodkov and Bolikhovskaya, 2009; Helmens, 2014; a.o.). The discussion about the last interglacial duration is still far from being closed. Some specialists (Kukla et al., 1997; Novenko, 2016) suggested to draw a distinction between the Eemian Intergalcial *sensu stricto* (s.s.), that is, the warming recognizable in the West European sequences, and the Eemian Intergalcial *sensu lato* (s.l.) when thermophilic woods existed in the southwest and south of Europe.

The problem of the interglacial duration appeared to be closely related to interpretation of the subsequent climatic events of the Late Pleistocene. In the opinion of one group of specialists, interval MIS 5d-5a to MIS 4 corresponds to the Early Valday glaciation, MIS 3 is correlated with the Middle Valday mega-interstadial, and MIS 2 – with the Late Valday in the Russian chronostratigraphy; in West European and Central European schemes the sequence of events is as follows: the early glacial interval – MIS 5d-5a, the early Pleniglacial – MIS 4, middle Pleniglacial – MIS 3, and late Pleniglacial – MIS 2 (Velichko (ed.), 2009; Velichko, 2012). Another group of specialists attributes only MIS 4 to the Early Valday glacial stage (Molodkov and Bolikhovskaya, 2009). Within the above-named periods there have been recognized warmings and coolings, each of them being a few millennia long (Dansgaard et al.,1989, 1993; Walker et al., 1999; Sanchez-Goni et al., 2008) (Fig. 2). The Late Glacial (14 700–11 700 cal. yr BP) displayed relatively short-term climatic fluctuations known as Bølling and Allerød – 14 700–14 000 cal. yr BP (12 750–12 250 ^{14}C yr BP) and 13 600–12 900 cal. yr BP (11 800–11 000 ^{14}C yr BP) separated by a conspicuous cooling of Younger Dryas 12 900–11 700 cal. yr BP (11 000–10 300 ^{14}C yr BP) (Walker et al., 2009). During this entire interval the temperatures were changing at a considerable rate.

The generally accepted sequence of paleogeographic events having taken place in the Caspian basin in the Late Pleistocene includes the Late Khazarian and Khvalynian transgressive epochs (the latter is commonly subdivided into early Khvalynian and late Khvalynian transgressive stages), with the Atelian regression between them. Various aspects of the environmental evolution within this time interval have been fully considered in a great number of published works (Bezrodnykh et al., 2004, 2015; Chepalyga, 2006; Dolukhanov et al., 2009; Fedorov, 1978; Leroy, 2010; Leroy et al., 2013; Mamedov, 1997; Richards et al., 2017 Rychagov, 1997; Shkatova, 2010; Sorokin et al., 2017; Starkel et al., 2015; Svitoch, 2009; Tudryn et al., 2013, 2016; Yanina, 2014; Yanina et al., 2013, 2014, 2016). It is worth mentioning that the notions about the Caspian history are mostly based on the materials obtained from studies of the sea coastal sequences. Besides, practically all the issues of the Caspian basin history (except for generally recognized large regressive-transgressive stages) are still debatable. Among the most hotly debated ones there are existence of the Hyrcanian transgressive basin, the age of the Atelian regression and of the Khvalynian transgression, etc.

The recent years have been marked by the abundance of new high-quality data obtained by seismic survey and borehole drilling; those materials supplemented and made more specific our knowledge of the Caspian Sea history through the entire Late Pleistocene and provided fresh insight into the significance of global climatic changes (warmings and coolings of various amplitude) for the Caspian evolution.

2. Materials and methods

In the North Caspian region the Upper Pleistocene sedimentary series have been studied mostly within the limits of oil producing fields in the course of prospecting works. The present paper is based on the processing of high and low frequency seismic-acoustic profiles, as well as on the cone penetration tests (CPT). The results provided the basis for the sequence stratification, the identified lithological and stratigraphic units being traced all over the region and beyond it. The CPT directed by Yu. Bezrodnykh were also performed for the purpose of the lithological sequence subdivision based on physical and mechanical properties of deposits. Taking into account the above-mentioned data, the exploratory boring to a depth of 80 m has been carried out in three areas. The studied areas 1 and 2 are confined to a vast flat-bottomed depression known as Shirotnaya and bounded by Kulalinskaya and Bezymyannaya banks on the south; area 3 is located in the saddle between the banks, and

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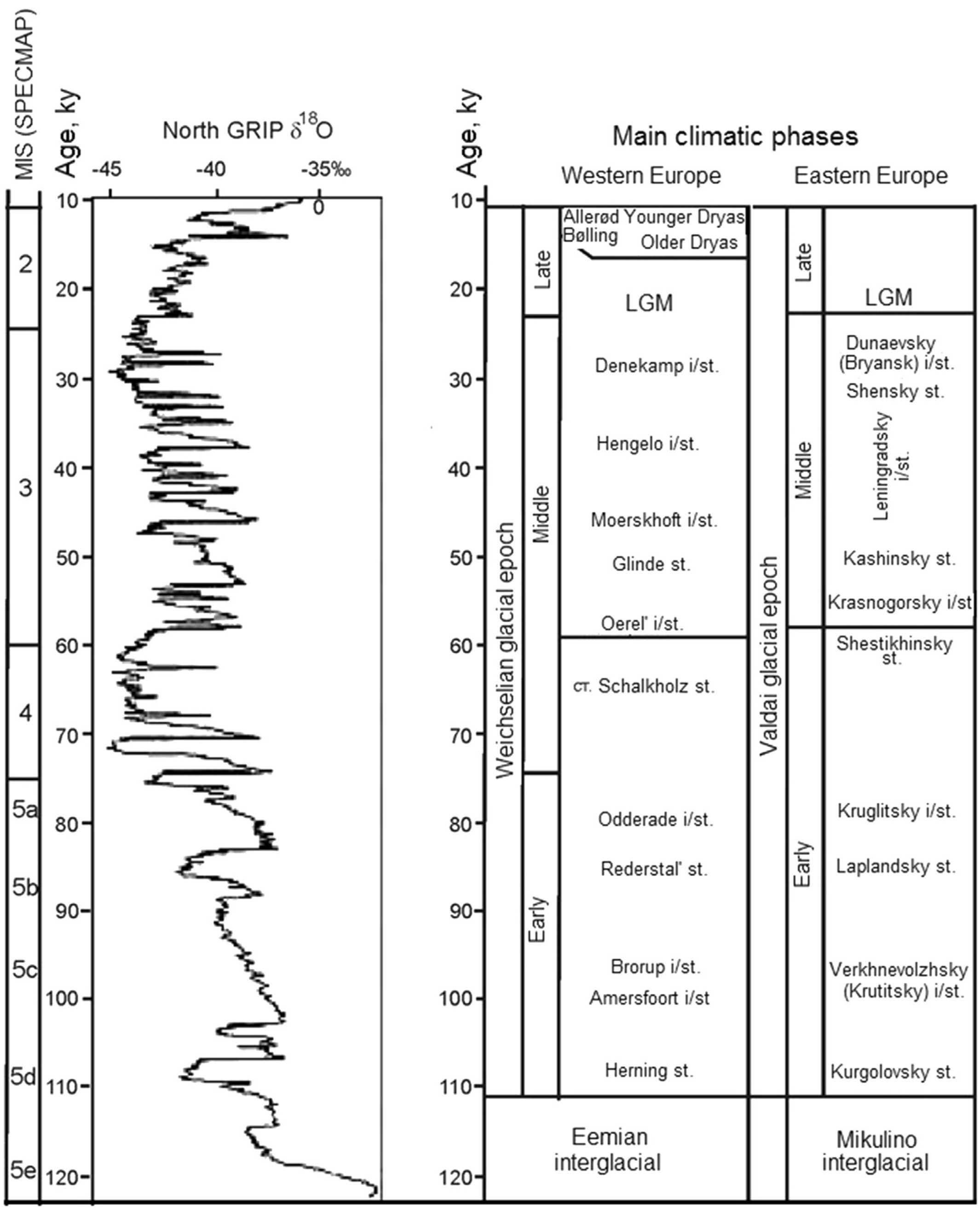

Fig. 2. Main climatic phases of the Late Pleistocene (After Novenko, 2016).

area 4 is positioned on the deepest part of the outer shelf (see Fig. 1).

The obtained core was studied using an integrated approach, with lithological, faunistic, palynological, and geochronological methods being applied. Analyses of the sediment facies and lithology have been performed by V. Sorokin at the Geological Faculty of the Moscow State University (MSU). Physical characteristics of the sediments determined by the teams of the JSC "Trust of engineering-construction survey" (Astrakhan) and of Institute of Environmental Geoscience RAS (Moscow). Biostratigraphical subdivision of the deposits and paleogeographic reconstructions of the marine basins were performed on the basis of faunal (largely of mollusk faunas) analysis that included studies of mollusk taxonomic composition, taphonomy, evolution, phylogeny, mollusk biogeography, etc. The studies were carried out at the Geographical faculty, MSU, by T. Yanina. Pollen assemblages recovered from borehole cores drilled on the Shirotnaya structure has been partly analyzed by N. Rybakova (the Geological Faculty, MSU). Organic remains in the regressive series have been studied by O. Uspenskaya (Research Institute of Horticulture, Russian Academy of Agricultural Sciences).

Mollusk shells were dated in radiocarbon laboratories of the Moscow and St.-Petersburg state universities by scintillation radiocarbon method. Radiocarbon dating of shells using AMS was performed in the Lawrence Livermore National Laboratory, the USA. Humic acids recovered from samples of organic matter were dated by ^{14}C in the Institute of Geography RAS and in the above mentioned laboratory in the USA. The calibrated age was calculated

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on the basis of the Programme "CalPal" of Cologne University (with appreciation to authors Danzeglocke et al., 2014; www.calpal.de). The reservoir effect was considered according to Kuzmin et al. (2007) calculations. The materials of the research were compared with those obtained by the authors from studies of the Caspian deposits in terrestrial sections on the coasts, as well as with earlier published data.

3. Results of the studies

As evident from the data of the seismic-acoustic survey, the Upper Pleistocene series of the Northern Caspian deposits includes several seismic-stratigraphic units separated by distinct reflecting interfaces; the inner structure of some units permits to distinguish subunits within them. The identified units and subunits, as well as reflecting horizons, are easily correlatable all over the surveyed areas, and are in good agreement with sequences penetrated by drilling (Fig. 3).

The Upper Pleistocene sequence occurs on top of a series of older Caspian sediments of complicated structure up to 28 m thick. It is separated from the Middle Pleistocene deposits by the well pronounced continental sediments (Fig. 4). In the borehole cores they are represented with sands and clays bearing traces of alteration in subaerial environments and including plant remains and freshwater mollusk shells. An erosional discontinuity surface separates it from the overlying sand layer up to 2 m thick rich in mollusk shells; among the mollusks there are *Didacna surachanica* and *D. nalivkini* typical of the Late Khazarian fauna of the Caspian. Upwards the sand gives way to sandy clays 4 m thick, which are gradually replaced by a 10 m series of fine sand with interlayers of clay. The series contains occasional shells of Cardiidae (see above), as well as various *Dreissena*. At the top of the member there is a persistent layer of sand and shell material about 1 m thick including thin cemented interbeds of sandy coquina. Among mollusks there are *Didacna surachanica*, *D. nalivkini*, *D. cristata*, quite common are *Corbicula fluminalis*. In the pollen assemblages recovered from that layer arboreal pollen makes up only 1.8% of the total, while herbaceous pollen account for 85.5% and spores – for 12.5%. A single grain of *Betula* pollen was identified in the AP group. Herbaceous plants are represented by *Artemisia* (9%), Chenopodiaceae (54.5%), Gramineae (1.8%), Compositae (1.8%), Ranunculaceae (16.3%), a.o. The spore group includes Bryales (9%) and *Sphagnum* (3.7%) mosses.

The described Upper Khazarian sequence of sediments suggests depositional environments of a shallow or moderately deep transgressive basin. Its malacofauna is dominated by *Didacna* ex gr. *crassa* noted for their relatively large shells with thick valves indicative of favorable temperatures; there is also a thermophile freshwater species *Corbicula fluminalis* which is found at present in the south of the Caspian region. The cited facts suggest the Late Khazarian basin to be rather warm-water, with salinity somewhat greater (up to 10–12‰ in the Northern Caspian) than at present. The results of the microfauna analysis (Yanko, 1989) substantiate that conclusion. The pollen assemblage suggests a wide distribution of semidesert plant communities in the region and practically complete absence of forested areas; that clearly indicates a rather arid climate of the Caspian region at that time. A poor water supply and dry climate all over the catchment area are attested to by the absence of long-range clastic material (pebbles and gravels) from the Upper Khazarian deposits. Another corroborative evidence for warm climatic conditions is the presence of a cemented calcareous

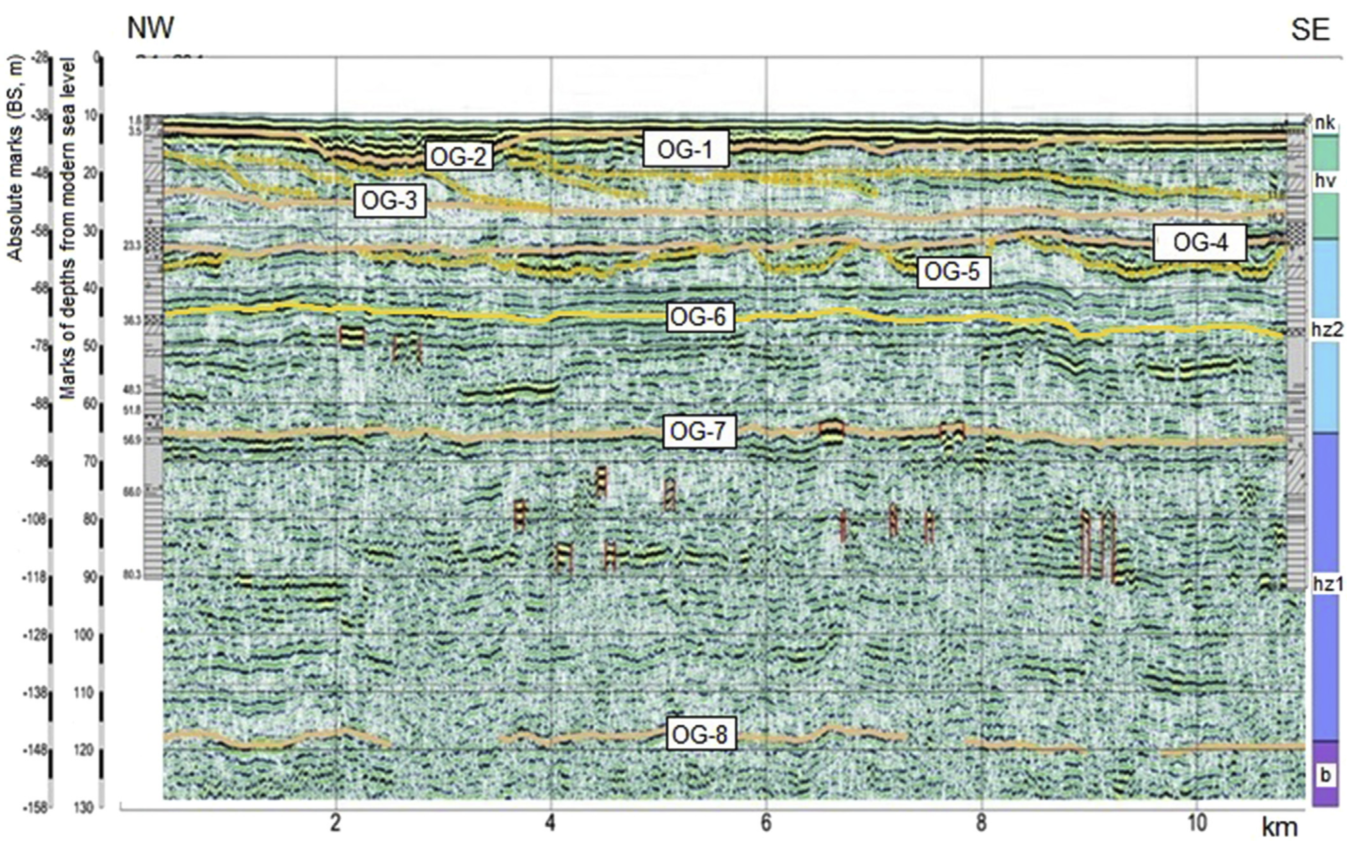

Fig. 3. The seismoacoustic profile with boreholes displaying the structure of deposits on the area No. 1. Stratigraphic horizons: b – Bakinian, hz1 – lower Khazarian, hz2 – upper Khazarian, hv – Khvalynian, nk – Novocaspian; OG – the reflecting horizons.

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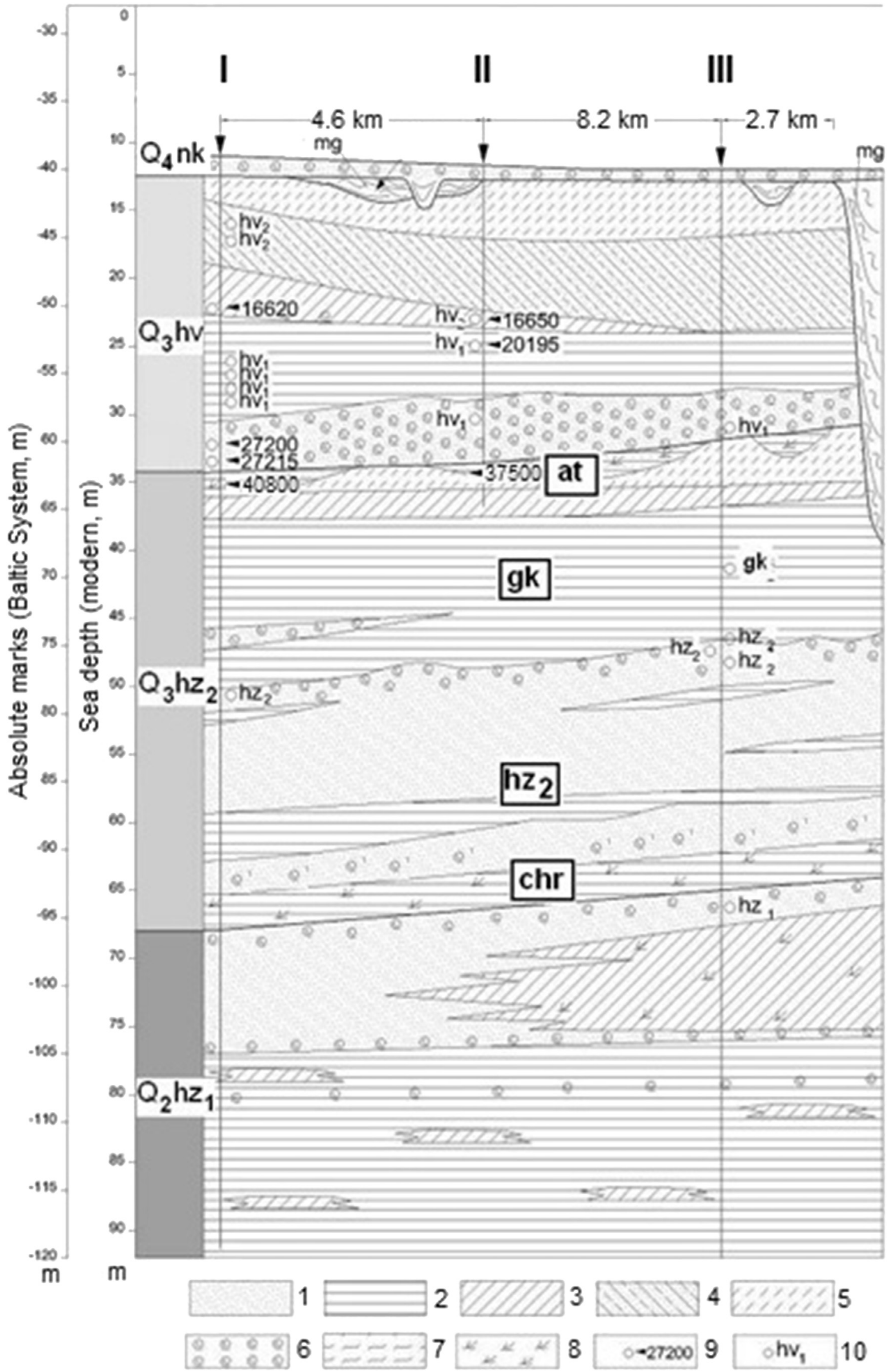

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crust on the top of shallow-water deposits dated to that epoch.

The Upper Khazarian complex is overlain with a series of relatively homogeneous compact clay more than 10 m thick with occasional interbeds and lenses of sand and shells. Dominant species is *Dreissena rostriformis distincta*, with occasional *Dr. caspia* and *Didacna umbonata*. The upper part of the complex is dominated by *D. subcatillus*, other species of that genus – *D. cristata* and small-size *D. parallella* – are less common. This faunal composition is typical of the Hyrcanian horizon first recognized in the North Caspian region by G.I. Popov (Popov, 1967; Yanina et al., 2014). Pollen assemblages of that series differ from the Late Khazarian ones: AP make up 23% of the total, NAP – 54% and spores account for another 23%. In the group of arboreal species there are *Pinus* sp. (11%), *Betula* (9%), *Alnus* (1%), and *Corylus* (2%). The bulk of herbaceous pollen is attributed to *Chenopodiaceae* (39%), *Gramineae* (5%), *Artemisia* (3%); Ranunculaceae and Compositae account for 7%. Spores belong mostly to green mosses (*Bryales*, 17%), sphagnum mosses (4%) and ferns (Polipodiaceae, 2%).

The above described deposits belong to a transgression with the sea level rise exceeding the Late Khazarian one. The presence of *Corbicula fluminalis* remains in the sediments suggests rather warm water regime in the Northern Caspian. At the same time, a somewhat increased proportion of trees in the regional vegetation, together with a notable presence of various forbs (along with xerophytes) may be considered as indicative of some cooler and wetter climate. The mollusk shells have been dated by radiocarbon using AMS in the Lawrence Livermore National Laboratory, the USA, within the range from 47 to >55 ka BP (Table 1). The estimated

Table 1
Dating of the upper Pleistocene deposits of the northern Caspian Sea.

Laboratory No.	Core interval, m	Stratigraphic unit	Analyzed material	Dating	
				^{14}C yrs BP	Cal yrs BP
Area 1					
MSU-1611	2.45–2.60	mg	humic acid	8100 ± 300	8637–9317
MSU-1601	2.00–2.15	mg	shells	8525 ± 90	9432–9561
MSU-1620	2.30–2.80	mg	humic acid	9290 ± 500	9885–11210
MSU-1600	18.00–18.40	hv	shells	29520 ± 480	32621–33767
CAMS 166531	30.80–30,90	gk	shell		>50500
CAMS 166532	33.40–33.50	gk	shell		54300 ± 3600
Area 2					
LU-6138	2.20–2.40	mg	humic acid	8870 ± 150	9762–10180
MSU-1496	2.40–2.50	mg	humic acid	9300 ± 110	10371–10598
MSU-1493	1.20–1.60	mg	humic acid	9420 ± 60	10575–10719
LU-6137	2.90–3.00	mg	humic acid	9640 ± 120	10788–10974
MSU-1494	3.40-0.3.55	mg	humic acid	9860 ± 240	11069–11768
MSU-1495	2.30–2.45	mg	humic acid	9860 ± 330	10776–11826
LU-6135	2.70–3.20	mg	humic acid	9900 ± 100	11207–11409
MSU-1562	8.20–9.10	hv	shells	16620 ± 130	19389–19762
MSU-1674	11.90–12.10	hv	shells	16650 ± 100	19346–19697
LU-6132	20.20–20.30	hv	shells	18250 ± 270	21127–21869
MSU-1673	13.60–13.70	hv	shells	20195 ± 200	23505–24012
MSU-1672	18.90–19.30	hv	shells	22230 ± 300	25731–26329
MSU-1556	21.00–22.50	hv	shells	27200 ± 340	30665–31139
MSU-1616	22.20–22.30	hv	shells	27215 ± 330	30687–31138
LU-7025	21.30–21.60	hv	shells	28550 ± 1950	30358–34151
LU-6484	20.00–20.20	hv	shells	30950 ± 1050	33539–35615
LU-6131	16.90–17.00	hv	shells	≥31570	>34057-36114
IG-4541	22.00–22.11	at	humic acid	36680 ± 850	40441–41941
IG-4542	21.75–21.85	at	humic acid	40830 ± 100	44210–44570
CAM 163762	22.00–22.11	at	humic acid	37100 ± 660	41062–42131
CAMS 159402	41.15–41.2	gk	shell		>54000
CAMS 159401	44.25–44.36a	gk	shell		55200 ± 3200
CAMS 159404	44.25–44.36b	gk	shell		51000 ± 2000
Area 3					
MSU-1508	14.70–14.90	mg	shells	9230 ± 165	9692–10162
MSU-1507	21.60–21.80	hv	shells	16900 ± 120	19644–19996
CAMS 163755	34.10–34.70	gk	shell		55200 ± 2900
CAMS 163756	35.40–35.41	gk	shell		53200 ± 2300
Area 4					
MSU-1558	7.75–7.85	mg	shells	8540 ± 70	8983–9240
MSU-1595	4.80–4.90	hv	shells	12870 ± 100	14193–14754
MSU-1651	20.30–20.50	hv	shells	14440 ± 165	16649–17223
MSU-1594	11.00–11.50	hv	shells	15710 ± 170	18310–18713
MSU-1593	15.10–15.20	hv	shells	16075 ± 120	18715–18998
MSU-1557	14.60–14.70	hv	shells	16900 ± 110	19652–19989
MSU-1592	16.90–17.20	hv	shells	19325 ± 175	22505–22920
MSU-1555	21.70–21.90	hv	shells	21090 ± 320	24418–25245
MSU-1591	29.40–29.60	hv	shells	22190 ± 400	25602–26431
MSU-1597	37.60–37.90	hv	shells	30150 ± 610	33180–34409

mg – Mangyshlakian, hv – Khvalynian, at – Atelian, gk - Hircanian.

Fig. 4. The structure of the upper Pleistocene deposits according to the engineering-geological drilling and seismoacoustic profiling on the area No. 2. I, II, III – number of the boreholes in the area; 1 – sand, 2 – clay, 3 – loam, 4 – layers of clay and sandy deposits, 5 – sandy loam, 6 – shells and debris, 7 – a complex of filling of the paleo-depressions and paleo-valley of Volga river, 8 – inclusions of the vegetable remains, 9 – radio-carbon datings, 10 – age of malacofauna complexes. Stratigraphic indexes: nk – Novocaspian, mg – Mangyshlakian, hv – Khvalynian, at – Atelian, gk– Hircanian hz2 – upper Khazarian, chr– chernoyarian, hz1-lower Khazarian.

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geological age of the Hyrcanian deposits lies beyond the ^{14}C dating limits, so further geochronological investigations are required.

Deposits of the Hyrcanian transgressive basin are overlain with the Atelian regressive horizon. The regression is pronounced in the seismic-acoustic profiles by a number of distinct erosional incisions under the base of Khvalynian sediments. The series is variable in lithology, with alternating layers of clay loams, sandy loams and clays; they contain iron monoxide in the form of hydrotroilite. The deposits include plant detritus arranged along the layers. According to O. Uspenskaya, the organic remains are dominated by fragments of higher aquatic plants, mostly of hornwort and reedmace. Palynological data obtained by N. Bolikhovskaya (Bolikhovskaya et al., 2016) lent support to the conclusion on the Atelian deposits having been deposited in channels eroded in the older layers. They contain pollen of aquatic and littoral (near-shore) plants (*Potamogeton*, *Sparganium*, *Lemna*, *Myriophyllum*); remains of freshwater and brackish-water algae, and dinocysts (*Pediastrum*, *Botryococcus*, *Spiniferites cruciformis*, etc.). Some freshwater mollusks are found occasionally (*Dreissena polymorpha polymorpha*, *Valvata piscinalis*, *Theodoxus pallasi*, *Limnea stagnalis*), as well as terrestrial gastropods.

The organic remains suggest aquatic environments – freshwater (less common – brackish-water) shallow basins deficient in biogenic elements. Palynological data on the Atelian series point to considerable changes in environments during the series deposition (Bolikhovskaya et al., 2016). The radiocarbon dating was performed in the Institute of Geography, RAS and in the Lawrence Livermore National Laboratory (the USA) on humic acids extracted from Atelian deposits infilling paleo-channels. The ages thus obtained lie in the range of 36 680 ± 850 to 40 830 ± 100 ^{14}C yr BP, or 41 191 ± 750 to 44 390 ± 180 cal. yr BP (Fig. 4, Table 1). It should be noted that the results obtained in different laboratories are close enough to each other.

The Atelian formations are overlain with Khvalynian series of complicated structure (Fig. 5). There is a layer of shell and sandy deposits 2.5–5.0 m thick at its base (Fig. 5, layer 1). The fauna is dominated by *Didacna subcatillus*, occasionally found are *Didacna zhukovi*, *D. parallella*, *Monodacna caspia*, *Micromelania caspia*, *Clessiniola variabilis*, *Theodoxus pallasi*; Dreissena shells are numerous. The shells recovered from that layer were dated by scintillation radiocarbon method and yielded the ^{14}C age within the interval of 27 200 ± 340 to 31 600 ± 420 yr BP (33 860 ± 1490 to 36 580 ± 340 cal. yr BP). The deposits suggest a shallow-water basin – the initial stage of the Khvalynian transgression. Judging from the shell appearance (medium to large size, with thick valves) the water temperature was moderately warm.

On top of the above-described shallow-water deposits attributed to Lower Khvalynian there are marine clays 8–10 m thick with

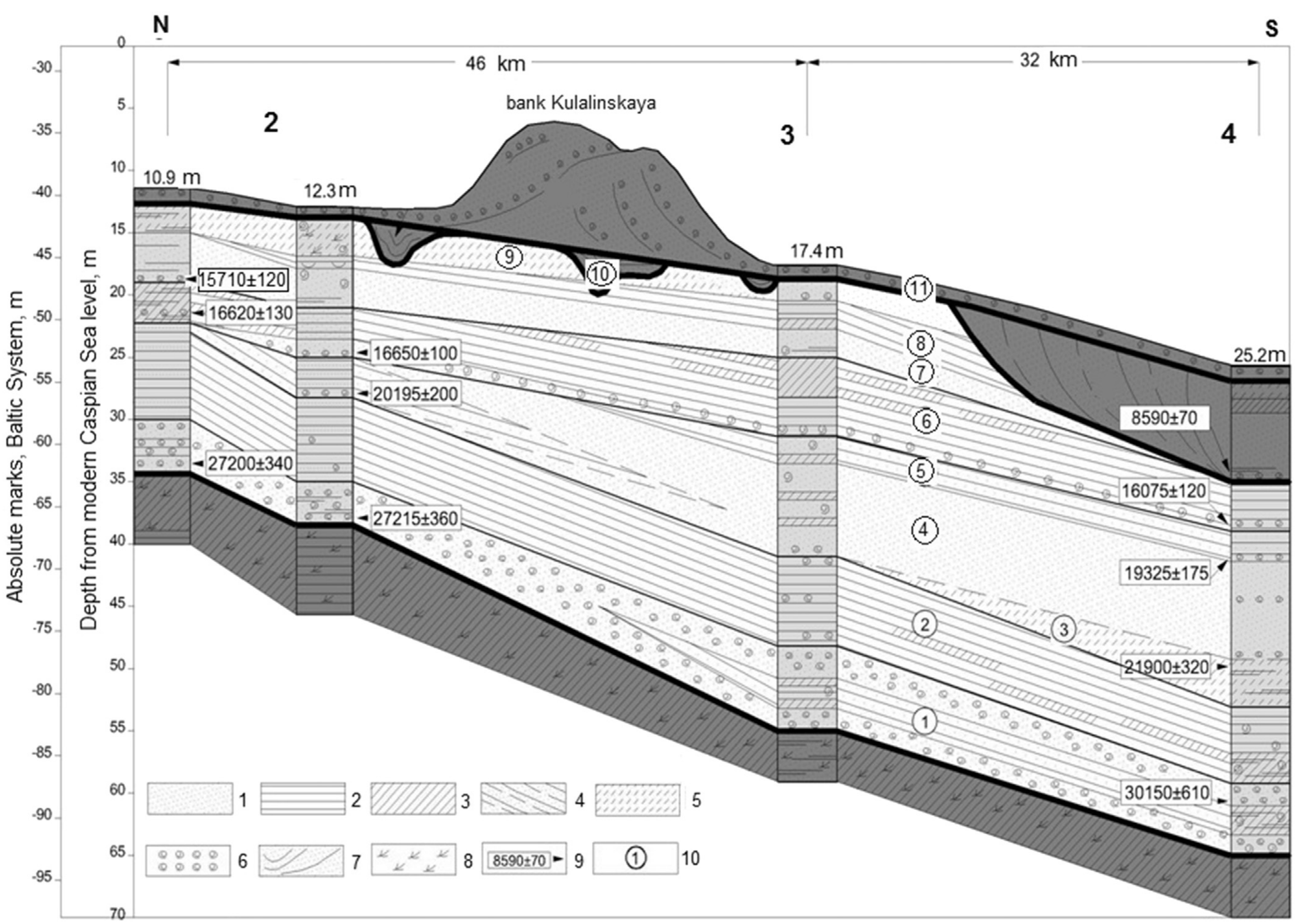

Fig. 5. Structure of the deposits along a profile (see Fig. 1), the area 2–3 – 4. Number of layers, reflecting paleogeographical events: 1, 2 –the first stage of the Khvalynian transgression; 3, 4 –the regressive stage; 5 –the short-term rise of the Khvalynian sea level; 6 – the second stage of the Khvalynian transgression; 7 – the regressive stage of the Khvalynian basin; 8 – the third stage of the Khvalynian transgression; 9 – Khvalynian sea level falling and delta progradation; 10 – Mangyshlakian regression; 11 – Novocaspian transgression. Layers 1–9 – Khvalynian series of complicated structure, pre-Khvalynian and after-Khvalynian deposits are shown by dark gray color. Another symbols see in Fig. 4.

sand interbeds varying in thickness (Fig. 5, layer 2). That part of the sequence may be interpreted as indicative of a continuing transgression. The series contains Early Khvalynian shells *Didacna protracta protracta, D. protracta submedia, D. subcatillus, Dreissena rostriformis distincta, Dreissena rostriformis compressa.* In the mollusk assemblage there are numerous subspecies known as dwellers of relatively deep water (*D. protracta submedia, Dreissena rostriformis compressa*); along with the sediment composition, their presence implies a deep-water stage of the Khvalynian transgression.

The clays are overlain with a predominantly sandy layer up to 8 m thick, which suggests a drop of the Khvalynian basin level. In the southern part of the area under study (No. 4) the faunal material includes *Didacna parallella*, *D. subcatillus*, *D. protracta*, *D. zhukovi*, *Monodacna caspia*, *Hypanis plicatus*, *Adacna laeviuscula*, *Dreissena polymorpha, Clessiniola variabilis, Micromelania caspia, Theodoxus pallasi*. The lower boundary of the series is dated by radiocarbon to the interval of 22 to 20 ka BP (Fig. 3, layers 3–4).

At area No. 4 and in its vicinity the sands are covered with a layer of sandy loam up to 2 m thick (Fig. 3, layer 5). Among shells occurring at its base there have been identified *Didacna protracta protracta, D. subcatillus, Hypanis plicatus, Dreissena rostriformis distincta*. A sample from the layer base was dated by ^{14}C at 19 325 ± 75 yr BP. The deposition of the layer was related to a short-term rise of the Khvalynian sea level.

Clays about 5 m thick (Fig. 5, layer 6) overlying the eroded surface of that layer contain some shells of Khvalynian mollusks *Didacna protracta, D. parallella, D. ebersini, Monodacna caspia*, as well as various *Dreissena*. Both lithology and composition of mollusk fauna suggest the clays to have been deposited in a deep-water basin corresponding to a transgressive stage of the Khvalynian Sea. Mollusk shells recovered from the base of the layer were ^{14}C dated to the interval of 16 650 ± 100 to 16 075 ± 120 yr BP (Table 1).

The clay member is overlain with 3–4 m layer (Fig. 5, layer 7) of predominantly sandy composition. Quite common are inclusions of small-size *Didacna parallella*, fragments of *D. praetrigonoides*, *Hypanis plicatus*, *Micromelania caspia*. There is a single radiocarbon date (15 710 ± 120 yr BP). The layer is covered with a layer of sandy loam and clay deposits (Fig. 5, layer 8) with rare Caspian gastropods and fragments of *Didacna praetrigonoides* and *Monodacna caspia.* The overlying sedimentary complex (Fig. 5, layer 9) is noted for a chaotic arrangement of discontinuous reflecting horizons. The sediments are mostly deltaic sands and clayey silts deposited in shallow water during the Caspian regression. The total thickness of the member varies from 1–2 m–10 m. The sediments include small-size shells of *Didacna parallella, D. praetrigonoides, Hypanis plicatus, Micromelania caspia,* as well as numerous fragments of indeterminable shells. The radiocarbon dates lie in the range between 12 870 ± 100 and 11 220 ± 100 yr BP.

The described complex of deltaic deposits is overlain with a series attributed to the Mangyshlakian regression of the Caspian Sea (Fig. 5, layer 10). Their occurrence is clearly seen in seismic-acoustic profiles as paleo-depressions; the drilling cores display poorly consolidated clay, peat, sapropels, silts and sands. Various organic materials are present in abundance. They are mostly mollusk shells varying in the degree of preservation, locally arranged in clusters along the layers. The malacofauna includes inhabitants of both low salinity basins (*Dreissena, Monodacna, Adacna, Hypanis*), and fresh-water ones (*Unio, Viviparus, Valvata, Lymnaea, Planorbis*). There is abundant plant detritus, either distributed in the sediments, or concentrated into thin interbeds of peat. The radiocarbon age of the sediments infilling the paleo-depressions falls in the range of 9860–6350 yr BP (Bezrodnykh et al., 2017); that makes them attributable to the initial stages of the Holocene. The mantle of the Novocaspian deposits (Fig. 5, layer 11) with Holocene mollusk fauna lies at the top of the sequence.

It seems from the above that most of transgressive and regressive events in the Caspian history have been recorded in the Upper Pleistocene sequence of the Northern Caspian basin. The records permit to perform a comprehensive reconstruction of the Caspian evolution through the Late Pleistocene against the background of the global climate changes.

4. Discussion

In the history of the Caspian Sea the beginning of the Late Pleistocene (MIS 5) is marked by the Late Khazarian transgressive epoch. According to drilling data, it proceeded in two stages known as Late Khazarian and Hyrcanian ones. The transgressive Late Khazarian basin was warm, its level standing at about −10 m asl. The malacofauna composition and characteristics, as well as palynological data obtained on the Upper Khazarian core samples, strongly suggest relatively warm temperature of its water. Pollen analysis of sediments exposed in the coastal scarps also indicates a warm (interglacial) climate of the epoch (Grichuk, 1954; Abramova, 1974). The Hyrcanian transgressive basin was also warm-water, as suggested by the presence of *Corbicula fluminalis*. As concluded palynologist N. Rybakova, the pollen assemblages point to somewhat cooler and more humid climate, similar to that of the Novocaspian transgression maximum (the latter being interglacial, as should be remembered).

Attribution of the two transgressive events in the Caspian Sea history to MIS 5 is confirmed by dating the Late Khazarian stage at 127–122 ka BP, while chronological boundaries of the entire Late Khazarian epoch are taken as 127 to 76 ka BP (Rychagov, 1997; Dolukhanov et al., 2009). That agrees well with the Upper Pleistocene stratigraphy in the Manych valley, where deposits with Late Khazarian, Karangatian, and Hyrcanian malacofauna form a kind of "layered pancake" (Popov, 1983). According to the commonly accepted view, the Karangatian transgression of the Black Sea was a consequence of the interglacial Eemian transgression of the World Ocean. The Karangatian basin level was higher than that of the present day, and the sea formed an ingression basin deeply penetrating into the Manych valley (Popov, 1983; Yanina, 2012a,b). The complicated occurrence of Karangatian deposits in combination with those of the Caspian transgressions confirms the simultaneity of those events and suggests an instability of levels of those basins. A series of Th-U dates gave grounds to estimate the Karangatian transgression age at 140 to 70 ka BP (Velichko, 2002). Radiocarbon dating of the Hyrcanian epoch has not produced any results except confirming the age is beyond the scope of the technique.

Along the entire length of the Manych depression the Karangatian-Khazarian series are overlain with Hyrcanian deposits with fauna typical of that basin and indicative of the Caspian (Hyrcanian) water outflowing into the Black Sea basin. That could happen only if the Karangatian basin level dropped along with regression of the World Ocean at the transition from warm to cold (glacial) epoch. Obviously the onset of cooling was instrumental in increasing the positive constituent of the water budget of the closed Caspian Sea: it sustained its transgressive development and promoted the discharge into the regressing Pontian basin.

Therefore, the paleographic data on the Late Pleistocene history of the Caspian provided evidence of the warm-water basins persisting within its depression throughout of the entire MIS 5 stage. This conclusion gave grounds to the opinion of other specialists (Kukla et al., 1997; Helmens, 2014) on the interglacial epoch (Eemian interglacial *sensu lato*) having been prolonged and non-uniform in structure.

As a result of research performed as a part of the European

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Science Foundation research program, that is Quaternary Environments of the Eurasian North (QUEEN) project, there have been reconstructed the overflow of the West Siberian ice-dammed lake through the Turgai Hollow, Aral Sea, and Uzboy channel into the Caspian Sea that took place about 90 ka BP (Mangerud et al., 2004 Svendsen et al., 2004). As the timing of the conjectured overflow is roughly comparable with the Hyrcanian transgression of the Caspian Sea, it seems quite pertinent to suppose it to be one of the causes of the transgression. No convincing evidence (geological or paleontological) in favor of such an assumption has been found as yet.

As the maximum cooling approached (MIS 4) and the climate became cold and dry, the Hyrcanian basin was shrinking. That is evidenced by traces of linear erosion and regressive series of the Atelian deposits clearly seen in seismic profiles and in the drilling cores. Radiocarbon dates obtained on the upper part of the Atelian deposits infilling the older erosional landforms strongly suggest them to have been deposited at the first half of the interstadial warming (MIS 3). It should be noted that those were final stages of the Atelian phase of the Caspian Sea evolution. Some corroborative data were obtained by optically stimulated luminescence dating of the upper part of the Atelian series in the Srednyaya Akhtuba section (the Volgograd Region) (Kurbanov et al., 2016; Tkach et al., 2016). At the base of the series, in the sections at the lower reaches of the Volga R., there are well pronounced cryoturbations and ice wedge pseudomorphs which penetrate deeply into the underlying series of paleosols attributed to MIS 5 (Kurbanov et al., 2016); the cryogenic structures are evidently belong to the glacial epoch (Konishchev et al., 2016). Some of the supporting evidence came from pollen assemblages of definitely periglacial character recovered from the Atelian deposits in the Northern Caspian Lowland (Grichuk, 1954; Moskvitin, 1962), and from cores of boreholes drilled within the studied area (Bolikhovskaya et al., 2016). So, the Atelian regression may be correlated with the first maximum of the Valday glaciation (MIS 4) and with the beginning of the MIS 3 interglacial warming. Judging from the data of seismic profiles and borehole cores, the Caspian Sea dropped to −100 m asl at that time.

The onset of the global warming of interstadial rank resulted in a certain increase of the positive constituent of the Caspian water balance both due to increasing runoff from the drainage basin (Panin et al., 2017), and to changes in rainfall-evaporation regime over the water area. Those changes brought about the first stage of the Khvalynian transgression recorded in the borehole sequences as deposits of a shallow and relatively warm (Fig. 5, layer 1) and those of a deeper and relatively cold (Fig. 5, layer 2) marine basin. Radiocarbon dates support the attribution of that event to MIS 3 interval.

The Last Glacial Maximum (MIS 2) was marked by exceedingly cold and dry environments even in the south of the East European Plain (Vandenberghe et al., 2014; Velichko, 2012), hardly favorable for a transgressive regime of the Caspian. Lowering of its level may be inferred from the presence of sandy layers in the Khvalynian series (Fig. 5, layers 3–4). Radiocarbon dates obtained for deposits adjoining Khvalynian ones provide support for their attribution to MIS 2 interval and fit well with results of paleoclimate modeling (Kislov and Toropov, 2006).

The ice sheet decay, together with permafrost thawing, both resulting from the global climate warming, induced the rise of the Caspian Sea level. The first phase of the transgressive changes in the sea level is evidently recorded in the predominantly clayey unit (Fig. 5, layer 5), the lower boundary of the latter being dated at about 19 ka BP. A transition to an active transgressive regime after a short-term fall of sea level was marked by erosion clearly seen at the base of the overlying clayey series. The sea level fall seemingly corresponds to a sharp cooling and increase in the climate continentality known as Oldest Dryas; according to reconstructions, the time was marked by a decrease of runoff from the Caspian catchment area (Thom, 2010).

The warmer intervals Bølling and Allerød were noted for an increased runoff (Thom, 2010; Panin and Matlakhova, 2015) and corresponded to the next transgressive stage in the Caspian Sea history (Khvalynian basin). In the sedimentary sequence the stage corresponds to the clay series (Fig. 5, layer 6), as is confirmed by numerous radiocarbon dates obtained on mollusk shells. A series of so called “chocolate” clays was accumulating in the Volga estuary and in depressions of pre-Khvalynian relief, presumably due to active thawing of permafrost and a great mass of fine material brought by rivers. A high rate of accumulation together with a considerable concentration of suspended materials account for the absence of mollusk fauna in the clays. The deposits of that transgressive stage are widely distributed in the coastal zone. The dates obtained using radiocarbon (Svitoch and Yanina, 1997; Leonov et al., 2002; Tudryn et al., 2013, 2016; Arslanov and Yanina, 2008; Arslanov et al., 2016), thorium–uranium (Arslanov et al., 2016) and optically stimulated luminescence (Kurbanov et al., 2016; Tkach et al., 2016) methods are close to each other. The chocolate clay accumulation that took place within the time interval between the LGM and 13.8 ka BP is attributed to the Scandinavian ice melting and transportation of fine particles down the Volga River (Tudryn et al., 2016).

A remarkable climatic event of the Late Pleistocene was Younger Dryas when the vegetation in Europe was dominated by periglacial formations, not unlike those of the glacial time (Grichuk, 1982). In the Caspian history it corresponds to a regressive stage, presumably due to a considerably reduced river discharge (Thom, 2010). In the Upper Pleistocene sequences in the Northern Caspian the sea level drop was marked by deposition of a sandy layer (Fig. 5, layer 7). The very first dramatic warming of climate (generally taken as indicator of the Pleistocene – Holocene boundary) resulted in a high stand of the Caspian level – the last stage of the Khvalynian transgression (Fig. 5, layer 8). The presence of mollusks in abundance, and their larger and more massive shells resulted probably from more favorable environments, in particular, higher water temperature as compared with that in the Early Khvalynian basin. Palynological data (Abramova, 1974; Vronsky, 1976) provide evidence of a general warming in the region.

The regressive trend began to develop against the background of increasingly dry climate in the region, as is apparent from the pollen assemblages (Abramova, 1974; Bolikhovskaya and Kasimov, 2010) distinctly showing the transition from diversified tree species to xerophytic grasses and herbs. In the borehole cores the climatic changes are recorded by deposition of deltaic sediments (Fig. 5, layer 9) and later by formation of depressions (Figs. 3–5) deepened into Khvalynian deposits and filled with freshwater sediments. This stage is known as the Mangyshlakian regression dated to the interval of 9860 to 6350 ^{14}C yr BP (Bezrodnykh et al., 2014). Such was the Caspian response to increasing continentality of the climate in the Boreal period of the Holocene.

5. Conclusions

The global climatic events of the Late Pleistocene (MIS 5-2) left their distinguishable imprint on the Caspian Sea history and its environment evolution. As follows from the analysis of seismic-acoustic profiles and drilling data (the boreholes were drilled in the Northern Caspian to a depth of 80 m), the climatic events are quite distinguishable in the Upper Pleistocene sedimentary sequence.

The climatic events of the first half of Late Pleistocene (MIS 5) resulted in the onset of two warm-water transgressive basins –

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Late Khazarian and Hyrcanian ones. Though cooler than at the late Khazarian transgression, the climate during the Hyrcanian time was attributable to interglacial one. Such a conclusion reached in a prolong discussion about the Eemian Interglacial permits us to agree with specialists (Kukla et al., 1997; Helmens, 2014) in their view of the Eemian as a prolonged interglacial epoch inhomogeneous in structure («Eemian *sensu lato*»).

As the glacial stage MIS 4 approached its maximum (Weichselian, Valday) under conditions of a dry and cold climate the Hyrcanian sea basin regressed. The Atelian regression of the Caspian Sea corresponded to MIS 4 stage and to the initial phases of the MIS 3 interstadial warming.

The development of the global interstadial warming led to a considerable increase in the surface runoff from the catchment and resulted in the rising of the Atelian lake level and the onset of the first phase of the Khvalynian transgression. The sea level rising was interrupted at the time of maximum cooling and aridization at MIS 2 (Late Weichselian, Late Valday glacial stage) and resumed when the ice sheet was decaying.

The conspicuous climatic events known as warm phases of Bølling and Allerød promoted the ice sheet melting along with thawing of permafrost, the latter having been widespread in the Volga drainage basin. All the above contributed to the Khvalynian transgression. The 'chocolate' clays were accumulated in the Volga estuary, as well as in depressions of the Pre-Khvalynian topography.

Phases of a noticeable cooling known as the Oldest, Older and Younger Dryas marked by a decrease in the runoff volume from the Caspian drainage basin are correlatable with regressive stages in the Khvalynian basin history. The best pronounced of them corresponded to the Younger Dryas phase. The Khvalynian came to its end at the time of the first sharp warming that resulted in the rise of the Caspian level and is generally taken as marking the Pleistocene/Holocene boundary. The Mangyshlakian regression is dated to the Holocene and was essentially a response of the Caspian Sea to the increase in the climate continentality during the Boreal period.

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