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On the age of the Khvalynian deposits of the Caspian Sea coasts according to ^{14}C and $^{230}Th/^{234}U$ methods

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ABSTRACT

During the second half of the late Pleistocene, the Caspian experienced repeated transgressions (Early and Late Khvalynian) and regressions (Enotaevsk and Mangyshlak) with an oscillation amplitude of 120 −150 m. The question about the age of the Khvalynian deposits is controversial. The investigation presents the age chronology of the Khvalynian deposits of the Caspian coasts on the basis of marine terrace stratigraphy and ^{14}C and $^{230}Th/^{234}U$ dating conducted in the Laboratory of the Saint-Petersburg State University. Forty samples of mollusc material from Khvalynian deposits were dated. For dating, the shells of index-genus *Didacna* from the deposits of marine terraces with different elevations were sampled. Besides shells, a fragment of bone from *Equus* sp. was dated. The analysis of dating showed that during the maximum of the Late Valdai (Wurm) glaciation the Khvalynian basin was in a regressive situation. The maximum stage (+48 to +50 m) of the Early Khvalynian transgression was not dated. Transgressive stages of the Early Khvalynian basin with sea levels of +35 and +22 m occurred during the period of deglaciation approximately 16 ka cal BP and 14 ka cal BP. The transgressive stages of the Late Khvalynian basin with sea level at about 0 m and −12 m occurred 14–12 ka cal BP. Probably, the age of deposits of Makhachkala stage with level about 0 m reflected an Allerod warming, and the age of deposits of Sartassy stage with level about −12 is associated with warming at the end of Younger Dryas. Under cold climate conditions of Younger Dryas the level of the Late Khvalynian basin fell. Increasingly continental climatic conditions during the Boreal period of the Holocene resulted in the Mangyshlak regression.

1. Introduction

The Caspian Sea is the largest isolated basin in the world, located in the depths of the Eurasian continent between 47°07′ N and 36°33′ N and 46°43′ E and 54°50′ E with an area of 378,400 km^2 and a level of −27 m. The sea holds 78,000 km^3 of water, equal to 44% of the Earth's lake waters. 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. 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 total volume, 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, i.e. one third of the entire Caspian water reserve; 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 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 paleogeographical history of the basin is very dynamic. During the second half of the late Pleistocene, the Caspian

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experienced repeated transgressions (Early and Late Khvalynian) and regressions (Atelian, Enotaevsk and Mangyshlak) with amplitude of 120–150 m. The causes of sea-level changes are believed to be: the volume of river and groundwater drainage, precipitation on the basin and evaporation, sedimentation and the degree of diagenesis, tectonic and seismic activity of the basin, and coastal geomorphology. These factors are closely connected and determined by the nature of atmospheric circulation, solar activity, climatic cycles, the morphostructural position of the region, and its recent geodynamic activity. The existing material on sea-level fluctuations allows us to conclude that the main reason for Caspian instability is the climate: large-scale hydrometeorological processes that occur not only in the Sea's basin but in its proximity as well.

The Khvalynian transgression is a significant sea-level rise to 50 m asl. Well-preserved coastlines allow for reliable evaluation of the area and size of the Khvalynian basin (Figs. 1 and 2). The Khvalynian sediments are the most extensive among all

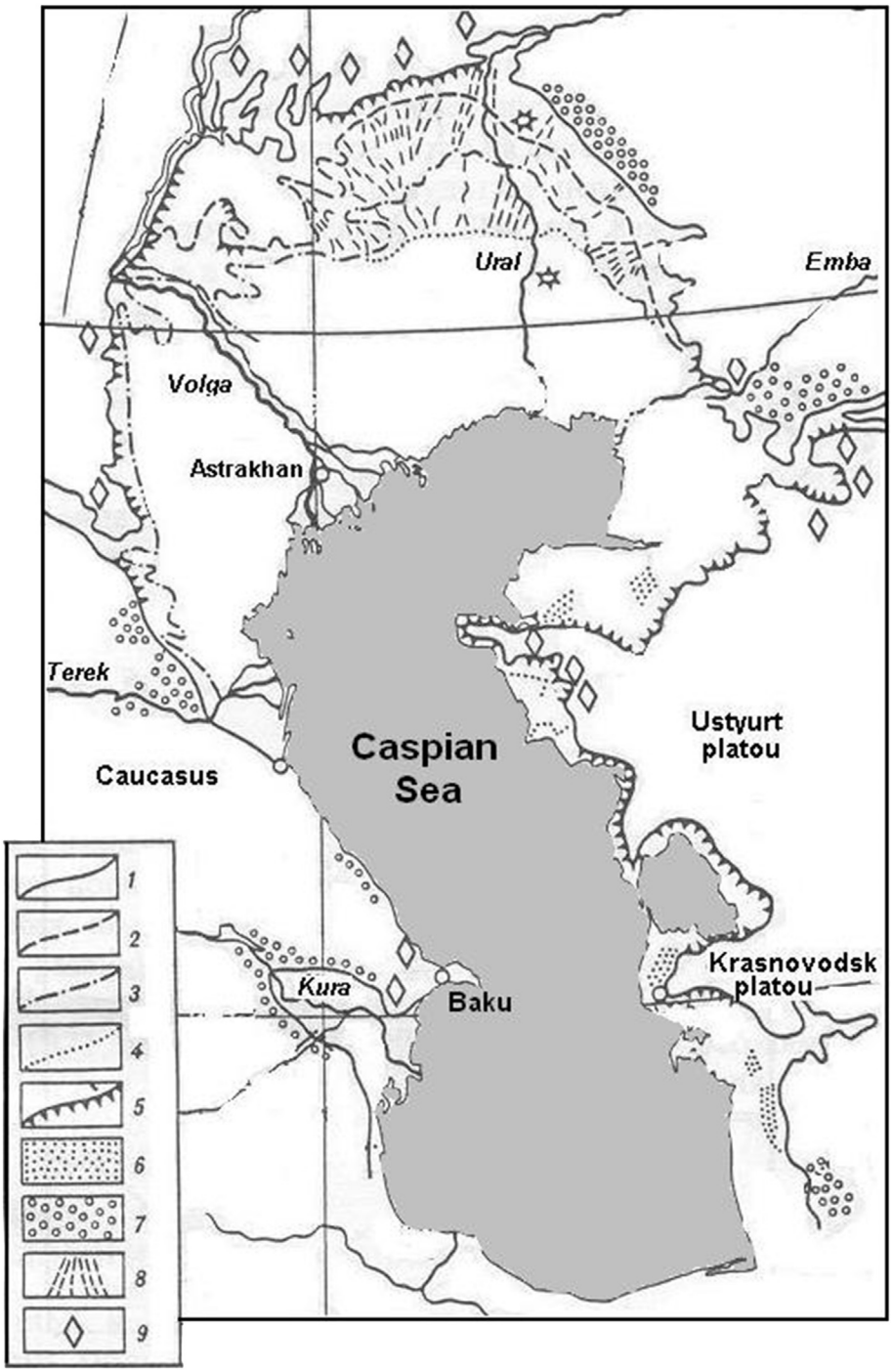

Fig. 1. Early Khvalynian basin (Leontiev et al., 1977). Coastline: 1 – maximum stage, 47–48 m, 2 – 20–22 m (Buinaksk stage), 3 – 14–15 m (Turkmenian stage), 4 – 5–6 m; 5 – abrasional shores, 6 – coastal accumulative forms, 7 – coastal alluvial plains, 8 – Early Khvalynian deltas, 9 – riass shores.

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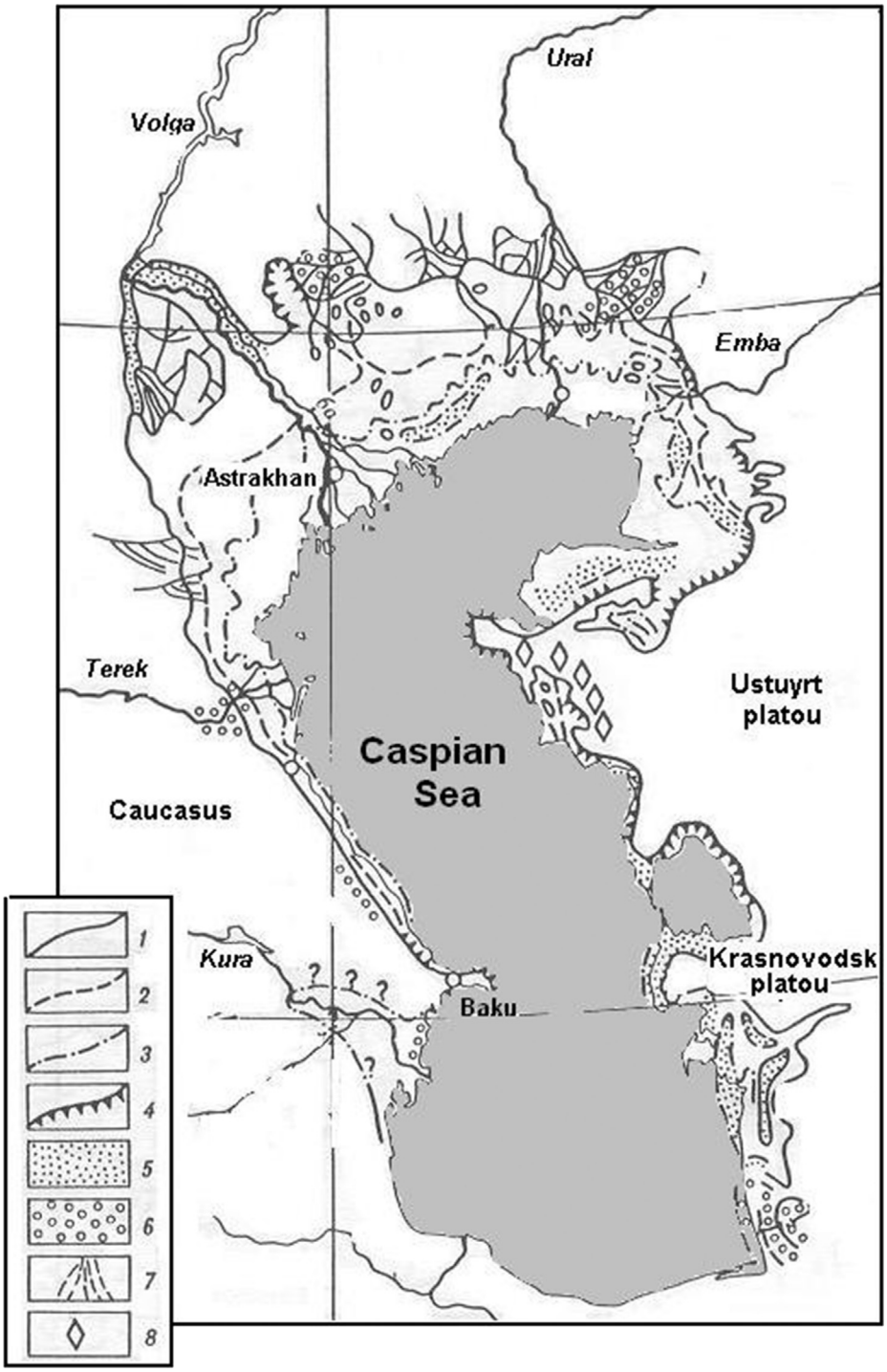

Fig. 2. Late Khvalynian basin (Leontiev et al., 1977). Coastline: 1 – maximum stage, 0 to –2 m, 2 – –10–12 m (Sartassk stage), 3 – –16, –17 m; 4 – abrasional shores, 5 – coastal accumulative forms, 6 – Late Khvalynian deltas and coastal alluvial plains, 7 – "ploughed" deltas, 8 – riass shores.

Pleistocene sediments in the Caspian Sea area. They generally form surficial sediments over extensive areas of the North Caspian, West Turkmenian, Kura and Terek-Kuma lowlands, and they form a staircase of marine terraces in the foothills of the Caucasus, Buzachi, and Mangyshlak peninsulas. They are differentiated into Lower and Upper Khvalynian on the basis of the geomorphological position of the sediments and the peculiarities of taxonomic composition of the Khvalynian molluscan fauna (*D. protracta* – *D. parallella* and *D. praetrigonoides* assemblages). Sediments within the absolute depth interval of 50 to 0 m asl are attributed to the Lower Khvalynian and lower (0 to –19 m) ones to the Upper Khvalynian deposits. The Lower Khvalynian deposits form regional levels with absolute heights of 48–50 m (maximum); 34–36 m (Talginka stage, according to Rychagov, 1997); 28–30 m; 20–22 m (Buynaksk stage, according to Fedorov, 1957); 14–15 m (Turkmenian stage, according to Fedorov, 1957); and 4–6 m. The

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Upper Khvalynian deposits form levels with absolute heights of 0 to −2 m (Makhachkala stage), −5 to −6 m (Kuma stage), and −12 m (Sartassy stage) (Fedorov, 1957). The formation of the regional levels occurred as a result of transgressive stages subdivided by regressive stages.

The question about the age of the Khvalynian deposits is controversial (Kaplin et al., 1972, 1977; Kvasov, 1975; Leontiev et al., 1975; Arslanov et al., 1978, 1988; Svitoch and Yanina, 1983, 1997; Arslanov, 1987; Svitoch et al., 1994, 1998; Rychagov, 1997; Leonov et al., 2002; Bezrodnykh et al., 2004; Chepalyga, 2005; Badyukova, 2007; Svitoch, 2007; Svitoch et al., 2008; Chepalyga et al., 2008, 2009; Arslanov et al., 2013; Tudryn et al., 2013 and others). The Khvalynian deposits have yielded numerous age estimations – radiocarbon (^{14}C), uranium–thorium (^{230}Th/^{234}U), and modified thermoluminescence (TL) dating. The estimations range from 7 ka (^{14}C) to 76 ka (TL). Leontiev and Rychagov (Leontiev et al., 1975; Rychagov, 1997) based mostly on TL dates, estimated the age of the Lower Khvalynian deposits as 70–40 ka, and the age of the Upper Khvalynian deposits as 20–10 ka. An opposite point of view based on ^{14}C and ^{230}Th/^{234}U dating was proposed by Kvasov (1975) and Svitoch and Yanina (1983, 1997); Svitoch (1991); Svitoch et al. (1994, 1998). In recent years new data on the age of the Khvalynian deposits of the Caspian Sea coasts emerged (Leonov et al., 2002; Chepalyga et al., 2008, 2009; Svitoch et al., 2008; Arslanov et al., 2013; Tudryn et al., 2013). The authors defend a "young" age of the Khvalynian transgression. The aim of our investigation is to present the age chronology of the Khvalynian deposits of the Caspian coasts on the basis of marine terrace stratigraphy and ^{14}C (traditional scintillation modification) and ^{230}Th/^{234}U dating conducted in the Laboratory of the Saint-Petersburg State University.

2. Materials and methods

Recently, we obtained a bank of ^{14}C and ^{230}Th/^{234}U dates containing new data about the age of the deposits of the Khvalynian transgression and its stages and phases. We carried out a geochronological study on the Azerbaijan and Dagestan coasts of the Caucasus, Manych Depression, Lower Volga Region, in the Ural River valley, and on the Mangyshlak Peninsula (Figs. 1 and 2). For dating, we sampled the shells of index-genus *Didacna* from the deposits of marine terraces with different elevations. Shells *in situ* with no traces of redeposition were collected. Besides shells, a fragment of bone from *Equus* sp. was dated.

The dating was conducted in the Laboratory of Geochronology and Paleogeography of the Saint-Petersburg State University by Prof. Kh. Arslanov and his colleagues. The calibrated age was calculated on the basis of the Programme "CalPal" of Cologne University (with appreciation to authors B. Weninger, O. Joris, and U. Danzeglocke, 2006; www.calpal.de).

3. Results and discussion

Forty samples of mollusc material from Khvalynian deposits of the Caspian region were dated by ^{14}C and ^{230}Th/^{234}U methods in the Laboratory of Paleogeography and Geochronology at St. Petersburg State University. Results are given in Tables 1 and 2.

Table 1
Age determinations for Khvalynian molluscs by the ^{14}C method.

No	Lab. number	Species of molluscs, sections	^{14}C age	Calibrated age
1	LU-6022	*D. protracta*, *D. trigonoides*, hv_1 deposits, +35 m, Ergeni	13,180 ± 340	16,140 ± 680
2a	LU-5853	"Total composition" of samples, hv_1 deposits, +35 m, Manych	19,330 ± 240	23,090 ± 320
2b	LU-5952	*D. trigonoides*, the same deposits	10,900 ± 200	12,870 ± 160
3a	LU-5725	*Didacna protracta*, hv_1 deposits, Zunda-Tolga, +26 m	10,670 ± 140	12,570 ± 170
3b	LU-5726	*D. ebersini* from the same layer	13,320 ± 220	16,390 ± 560
5	LU-5768	*Hypanis plicatus*, hv_1 deposits, +25 m, East Manych	11,470 ± 180	13,360 ± 180
6	LU-6021	*D. protracta*, hv_1 deposits, +25 m, Chogray, Manych	12,150 ± 900	14,180 ± 190
7	LU-6874	*D. protracta*, hv_1 deposits, +23 m, Raigorod, Lower Volga	13,030 ± 630	15,750 ± 1050
8	LU-6919	*D. protracta*, *D. subcatillus*, hv_1 deposits, +22 m, Raigorod, Lower Volga	11,630 ± 530	13,760 ± 680
9	LU-6836	*H. plicatus*, hv_1 deposits, +20 m, Cherniy Yar, Lower Volga	11,810 ± 120	13,710 ± 120
10	LU-6848	*D. protracta*, hv_1 deposits, +20 m, Cherniy Yar, Lower Volga	12,480 ± 230	14,710 ± 420
11	LU-5769	*D. protracta*, hv_1 deposits, +20 m, Lake Manych	10,930 ± 370	12,760 ± 450
12a	LU-5800A	*D. praetrigonoides*, hv_1 deposits, +18 m, Mangyshlak	12,020 ± 130	14,000 ± 210
12b	LU-5800B	Inner side of the same shells	12,550 ± 210	14,850 ± 380
13	LU-6873	*D. ebersini*, *Hypanis plicatus*, hv_1 deposits, +18 m, Raigorod, Lower Volga	11,040 ± 460	12,860 ± 550
14	LU-6847	*D. protracta*, *D. delenda*, hv_1 deposits, +15 m, Cherniy Yar	12,550 ± 280	14,920 ± 570
15	LU-5854	Debris of the shells from the archeological site in the hv_1 deposits, +13 m, San-Manych	11,210 ± 130	13,100 ± 130
16	LU-6020	*D. protracta*, hv_1 deposits, +10 m, Aral-Sor, Nothern Caspian	11,270 ± 140	13,170 ± 130
17	LU-6917	*Dreissena polymorpha*, *Dr. rostriformis*, *Monodacna caspia*, hv_1 deposits, −2 m, Kopanovka, Lower Volga	11,870 ± 370	13,960 ± 500
18	LU-6918	*Dreissena polymorpha*, hv_1 deposits, −3 m, Tsagan-Aman	12,690 ± 440	15,390 ± 930
19	LU-6846	*D. protracta*, hv_1 deposits, Tsagan-Aman, Lower Volga	13,320 ± 360	16,270 ± 680
20	LU-6019	*D. ebersini*, hv_1 deposits, −5 m, Selitrennoe, Lower Volga	11,000 ± 160	12,930 ± 140
21	LU-5954	*D. praetrigonoides*, *D. parallella*, hv_2 deposits, 0 m, «Nadezhda», Dagestan	11,420 ± 160	13,320 ± 170
22	LU-5801	*D. praetrigonoides*, hv_2 deposits, +2 m, Sangachal, Azerbaijan	12,650 ± 160	15,010 ± 300
23a	LU-5855	"Total composition", hv_2 deposits, 0–+2 m, Temirgoe	26,110 ± 470	30,790 ± 290
23b	LU-5903	*D. parallella*, the same deposits	12,650 ± 160	12,900 ± 120
24	LU-5856	*Didacna*, hv_2 deposits, −12 m, Almalo	11,960 ± 120	13,880 ± 150
25	LU-7021	*D. praetrigonoides*, hv_2 deposits, −10 to −12 m, Kalmykiya	12,270 ± 140	14,330 ± 250
26	LU-7022	*D. praetrigonoides*, hv_2 deposits, −10 to −12 m, Kalmykiya	11,730 ± 160	13,610 ± 170
27	LU-7023	*D. praetrigonoides*, hv_2 deposits, −10 to −12 m, Kalmykiya	11,670 ± 160	13,560 ± 170
28	LU-7024	*D. praetrigonoides* from hv_2 deposits, −10 m, Kalmykiya	11,480 ± 110	13,390 ± 120
29	LU-6834	*D. protracta*, hv_2 deposits, −10 m, Kalmykiya	12,130 ± 140	14,170 ± 250
30	LU-5852	The bone-fragment of *Equus* sp., Manych-Yulovskiy	19,540 ± 1470	23,480 ± 1820

Note: A – external side of a shell, B – internal side of a shell.

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Table 2
Age determinations for Khvalynian molluscs by ^{14}C and $^{230}Th/^{234}U$ methods.

Lab number	Species of mollusc, sections	^{14}C age BP	Calibrated age	$^{230}Th/^{234}U$ age BP
LU-424A LU-424B	*D. parallella*, *D. praetrigonoides*, hv_1 deposits, Turali, Dagestan	13,100 ± 490 12,720 ± 400	15,920 ± 870 15,440 ± 880	13,350 ± 440 13,800 ± 440
LU-426A LU-426B	*D. parallella*, hv_1 deposits, +25 m, Manas, Dagestan	11,600 ± 400	13,620 ± 480	12,700 ± 450 12,500 ± 300
LU-841	*D. protracta*, *D. subpyramidata*, hv_1 deposits, Inder lake, Lower Ural	11,490 ± 330	13,420 ± 330	14,100 ± 500
LU-846	*D. protracta*, hv_1, Chapaev, Lower Ural	11,830 ± 200	13,770 ± 230	15,240 ± 600
LU-423B	*D. praetrigonoides*, hv_2 deposits, −2 m, Shirvan, Azerbaijan	12,330 ± 140	14,450 ± 310	14,440 ± 400
LU-479A LU-479B	*D. praetrigonoides*, hv_2 deposits, −12 m, Azerbaijan	11,210 ± 90 11,340 ± 160	13,120 ± 90 13,250 ± 160	11,800 ± 350 12,900 ± 350

Note: A – external side of a shell, B – internal side of a shell.

The dates of the Lower Khvalynian deposits are numbers 1–20 in Table 1. For each, the specific composition of the dated molluscs is specified, the area and absolute height of location are shown also. The analysis of the table shows that datings of the maximum stage (+50 m) of Khvalynian transgression are absent. There are none in publications of other researchers. The most ancient Khvalynian deposits dated by us belong to stadial level of transgression of +35 m, with calibrated age 16,140 ± 680 (No 1) at the northwest border of the basin at the Yergeni Hills. In the Manych depression these deposits are dated 12,870 ± 160 (No 2b). The sample including all fossil molluscs (No 2a) and the same sample including only Khvalynian index fossils *Didacna* (No 2b) have different radiocarbon ages. It is methodologically correct to date samples of index or characteristic species. Dating of the bone-fragment of *Equus* sp. (23,480 ± 1820) from under Khvalynian deposits of Manych Passage shows the regressive position of the Caspian Sea at this time (LGM). Most dates belong to deposits of stadial level, 22–20 m. These sediments are very common and rich paleontologically. The dates vary from 15,750 ± 1050 (No 7) to 12,760 ± 450 (No 11). Apparently, the most reliable date (14,850 ± 380, No12b) is on the internal part of a large thick shell of *Didacna praetrigonoides* from Lower Khvalynian deposits of the Mangyshlak peninsula.

Dates of Late Khvalynian deposits (No 21–29) have close values: from 12,900 ± 120 to 15,010 ± 300. These similar values of dates from Lower Khvalynian and Upper Khvalynian deposits were a reason that researchers considered the radiocarbon method unsuitable for dating of Khvalynian deposits. It was established that thin (often small) shells from Lower Khvalynian deposits give, in most cases, a rejuvenated ^{14}C age (Arslanov et al., 1978, 1988; Arslanov and Yanina, 2008; Chepalyga et al., 2008). The rejuvenated ^{14}C age of the thin bivalves from Lower Khvalynian deposits and the more reliable ^{14}C age of the thick bivalve *Didacna praetrigonoides* from Upper Khvalynian deposits have geochemical justification: contamination of the thin shells happens very quickly by isotope exchange between the crystal structure of the $CaCO_3$ in the shells and dissolved younger carbonates in the groundwater. At the same time, diffusion of contaminating younger carbonates into the thick shells happens much more slowly. Additional confirmation of the Upper Khvalynian chronology is seen in the close values of the corrected radiocarbon age of two samples of the thick bivalve *Didacna praetrigonoides* with uranium–thorium dates (Table 2, LU-423B and LU-479B). The fall of the Late Khvalynian basin ended with the Mangyshlakian regression, the age of which is determined by the latest dates, 11–7 ka (Leroy et al., 2013; Bezrodnykh et al., 2014).

Thus, during the maximum of the Late Valdai (Wurm) glaciation, the Early Khvalynian basin was in a regressive situation. During the LGM, climatic conditions were cold and dry. Permafrost existed around the northern Caspian coasts. Average annual temperatures decreased to −10 to −5 °C in the southern areas of Europe (Paleoclimates, 2009). This resulted in a negative water balance of the Khvalynian Lake-Sea, causing a sea level drop. Climate modeling shows similar negative water balance at the time (Kislov and Toropov, 2006, 2007; Kislov, 2010).

The maximum stage (+48 to +50 m) of the Early Khvalynian transgression was not dated. Transgressive stages of the Early Khvalynian basin with sea levels of +35 and +22 m occurred during the period of deglaciation, approximately 16 ka cal BP and 14 ka cal BP. The data obtained show that the degradation of the late Valdai glaciation occurred very quickly, and it was apparently one of the main reasons for the Early Khvalynian transgression. The small thin shells of molluscs indicate low water temperatures in comparison with the present Caspian Sea. The Lower Khvalynian deposits are made up of very characteristic chocolate clays. According to Moskvitin (1962) and Goretskiy (1966), the clays were formed as a result of accumulation of fine sediments derived from the periglacial landscapes of the hinterland. Palynological data confirm a cold climate (Abramova, 1974). The Early Khvalynian transgression, having reached the level of the Manych threshold, developed an erosive valley and dumped water to the Euxinian basin. Erosion of the threshold resulted in a drop of the Early Khvalynian sea level. Ingression in the Manych valley and the final stage of overflow of waters from the Early Khvalynian Basin into the New Euxinian Basin occurred at the Caspian level about +22 m. The dates of the Khvalynian deposits in the Manych depression at similar height provide confirmation. After the final episode of overflow, the Khvalynian lake-sea underwent a series of smaller transgressive and regressive events, which reflected the pulsation of climatic conditions in the Caspian region.

The Early Khvalynian ended with the Enotayevsk regression. Terrestrial Enotayevsk deposits and numerous unconformities in the marine record are described on the coasts of the Caspian Sea. On the Caspian shelf, the Enotayevsk layers have been found in boreholes (Maev, 1994). Probably, cold dry conditions of the Older Dryas resulted in the Enotayevsk regression. According to pollen data (Sorokin, 2011), arid cool climate conditions existed.

The transgressive stages of the Late Khvalynian basin with sea level at about 0 m and −12 m occurred 14–12 ka cal BP. Probably, the age of deposits of Makhachkala stage with level about 0th m reflected an Allerod warming, and the age of deposits of Sartassy stage with level about −12 m indicated warming at the end of the Younger Dryas. Under cold Younger Dryas climate, the level of the Late Khvalynian basin fell. Relative abundance of the molluscs in the basin and their large and more massive shells are explained by favorable (warmer) conditions compared to those of the Early Khvalynian basin. Palynological data (Abramova, 1974; Yakhimovich et al., 1986) indicate general warming in the region. The regressive tendency of the Late Khvalynian sea-lake was characterized by a series of minor secondary transgressive phases. The Late Khvalynian regression coincided with increasing aridity in the Caspian region. This is shown in the change of pollen of wood vegetation (pine, alder, birch, oak, hornbeam, willow) towards xerophilous grassy pollen typical of semi-desert and steppe vegetation (Abramova, 1974). Increasingly continental climatic conditions during the Boreal period of the Holocene resulted in the Mangyshlak regression.

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4. Conclusions

Forty samples of mollusc material from Khvalynian deposits of the Caspian region were dated by ^{14}C (scintillation modification) and $^{230}Th/^{234}U$ methods in the Laboratory of Paleogeography and Geochronology at St. Petersburg State University. For dating, the shells of index-genus *Didacna* from the deposits of marine terraces with different elevations were sampled. Besides shells, a fragment of bone from *Equus* sp. was dated.

The analysis of dating showed that during the maximum of the Late Valdai (Wurm) glaciation the Khvalynian basin was in a regressive situation. The maximum stage (+48 to +50 m) of the Early Kvalynian transgression was not dated. Transgressive stages of the Early Khvalynian basin with sea levels of +35 and +22 m occurred during the period of deglaciation approximately 16 ka cal BP and 14 ka cal BP. The transgressive stages of the Late Khvalynian basin with sea level at about 0 m and −12 m occurred 14–12 ka cal BP. Probably, the age of Makhachkala stage deposits at about 0 m reflected an Allerod warming, and the age of Sartassy stage deposits about −12 m indicated warming at the end of Younger Dryas. Under the cold Younger Dryas climate, the level of the Late Khvalynian basin fell. Increasingly continental climatic conditions during the Boreal period of the Holocene resulted in the Mangyshlak regression.

In the publications devoted to the analysis of the Caspian boreholes, the radiocarbon dates of Khvalynian deposits are given (Bezrodnykh et al., 2004; Yanina, 2012a,b; Arslanov et al., 2013; Yanina et al., 2013). The data show the beginning stage of the Khvalynian transgression was associated with the period of Intra Valdai (Wurm) warming about 30 ka BP. It is impossible to reconstruct the history of the Khvalynian transgression of the Caspian Sea authentically without the analysis of boreholes.

The aims of future investigations include obtaining datable material from deposits of terraces at the maximum (+50 m) of the transgression and other terraces that are still undated. An important task is study of the marine boreholes.

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