The Ponto-Caspian region: Environmental consequences of climate change during the Late Pleistocene

Tamara A. Yanina

Lomonosov Moscow State University, Faculty of Geography, Leninskie Gory 1, Moscow 119991, Russia

Article info

Article history:
Available online 24 February 2014

Keywords:
Late Pleistocene
Climate change
Caspian Sea
Black Sea
Sea level fluctuations
Environment

Abstract

Evolution of the Caspian and Black Sea (Pont) Basins environments was analyzed in comparison, and both general and specific features of their development under multi-scale and multi-directional changes of climate during the Late Pleistocene were identified. The cold extensive transgressions of the Caspian Sea and the transgressions of the Caspian type of the Pontian Basin, not exceeding the present sea level, developed synchronously in the cold (glacial) climatic epochs. The maximum height of level of the Caspian transgressions was limited by the height of the Manych threshold, and the transgressions of the Caspian type in the Pontian Basin by the height of the Bosporus threshold. The warm small transgressions of the Caspian Sea and the marine (Mediterranean type) transgressions of the Pont with maximum level developed during the warm interglacial epochs. In the Caspian these occurred mainly during the interglacial endothermal (cool and moist) phases, while marine transgressions of the Pont correlated with the interglacial transgressions of the World Ocean. The cold transgressions of the Caspian and the Caspian type transgressions of the Pontian Basin developed asynchronously with the transgressions of the World Ocean.

© 2014 Elsevier Ltd and INQUA. All rights reserved.

1. Introduction

The Ponto-Caspian region (Black Sea, Sea of Azov and Caspian Sea) contains a system of basins (Fig. 1), relics of the East Paratethys that have their own unique environmental features and paleogeographical history. In the evolution the Ponto-Caspian basins global climatic changes are reflected, including glacial — interglacial rhythms of the East European Plain and mountain territories as well as transgressive — regressive events in the World Ocean. The study of the Late Pleistocene development of the Ponto-Caspian basins, initiated at the end of the nineteenth century by the works of Andrusov (1888, etc.), was continued by many researchers (Arkhangelskiy and Strakhov, 1938; Zhukov, 1945; Fedorov, 1957, 1978; Vasiliev, 1961; Moskvitin, 1962; Nevesskaya, 1965; Goretskiy, 1966; Vronskiy, 1974; Kvasov, 1975; Ostrovskiy et al., 1977; Popov, 1983; Balabanov and Izmailov, 1988, 1989; Yanko, 1989; Svitoch, 1991, 2007; Maev, 1994; Chepalyga, 1997; Rychagov, 1997; Bezrodnykh et al., 2004; Yanina, 2005, 2012; Aksu et al., 2006; Badyukova, 2007; Yanko-Hombach et al., 2007; Sorokin, 2011; Tudryn et al., 2013 and many others).

Despite abundant data and insights, major questions about the paleogeographic development of the region are still being debated. Major phases of basin development during the Late Pleistocene in the various basins were identified by the various authors: the Karangat and New Euxinian transgressions and intervening regression in the Black Sea area; the Late Khazar and Khvalynian transgressions, and the intervening Atelian regression in the Caspian area. Disagreements developed over the small-scale events in the history of both seas, their timing, magnitude, hydrological, and ecological characteristics. Today, no broad agreement exists over the interrelation of events in the Ponto-Caspian, their response to global and regional climatic changes, and correlations with paleogeographical events in adjacent territories (Moskvitin, 1962; Markov et al., 1965; Goretskiy, 1966; Fedorov, 1978; Vasiliev, 1982; Zubakov, 1986; Rychagov, 1997; Svitoch et al., 1998; Mangerud et al., 2004; Kislov and Toropov, 2006, 2007; Chepalyga, 2007; Dolukhanov et al., 2009, 2010; Kislov, 2010; Shkatova, 2010; Sorokin, 2011; Yanina, 2012ab, 2013b).

Global climatic events of the Late Pleistocene (130—11 ka) were presented by the warm interglacial (Eemian, Mikulino) epoch and the successive cold glacial (Weichsel, Valdai) epoch. The Ponto-Caspian environment directly depends on climate change and the sea-level fluctuations caused by them. In the Caspian Basin, the inflow from its basin and the balance between regional...
precipitation and evaporation is a main driver, whereas in the Azov/Black Sea the global oceanic sea levels also play an important role. The aim of this paper is to make a comparative analysis of the environmental evolution of the Caspian and Pont Seas during the Late Pleistocene, and to establish general rules and features of the development of these different basins under the conditions of multidirectional climate changes of different scales.

2. Materials and methods

Reliable paleogeographical reconstructions depend on well-constrained age estimates of events and episodes that allow correlation between the different basins. The bases for reconstruction of events in the Ponto-Caspian Seas and their correlation are the biostratigraphical (ecocratigraphical) schemes of the Caspian Sea, the Manych depression and the Black Sea, executed by the author as a result of analyses of all main sections of the Late Pleistocene mollusks in the region (Yanina, 2005, 2012a, 2013a).

In this study, the Late Pleistocene development of the Caspian and Pontian Basins is documented using the malacofaunistic method. The method includes the analyses of taxonomical structure, taphonomy, phylogeny, biostratigraphical distribution, historical development, and biogeography of mollusks. The study focuses on the bivalve genus Didacna Eichwald, an index–fossil genus for the modern Caspian Sea and an endemic fossil for the Quaternary Ponto-Caspian basins. The genus is known for its high evolutionary rates at the species and subspecies levels. The use of Didacna species for the stratigraphical subdivision of the Pleistocene, not only of the Caspian Sea but also of the Black Sea, plays an important role at the correlation of deposits and events of the region. For paleogeographical reconstructions, the interface method was used, complementing and supervising results of geomorphological, lithological, facial, palynological, diatom, isotope, geochronological and other analyses of the recent deposits. Materials about global and regional climatic events of the Late Pleistocene are taken from references.

3. Results and discussion

3.1. Caspian Sea

During the Late Pleistocene, several transgressive and regressive episodes developed, including the Late Khazar (Late Khazar and Girkan transgressive stages) and the Khvalynian (Early Khvalynian and Late Khvalynian transgressive stages) transgressive epochs, separated by the Atel regression (Fig. 2).

The Late Khazar transgression developed in two successive stages that are separated by a regression. Lake levels in the earlier Late Khazar basin, according to spatial distribution of the deposits, did not exceed 
-10 m, and its surface area was not much bigger than the modern Caspian Sea. The mollusc fauna contained crassoidal-type Didacna and was characterized by the occurrence of Didacna nalivkini and Didacna surachanica (Fedorov, 1978; Yanina, 2005). The fauna is characterized by the large size and massive nature of shells, especially in the southern parts of the Caspian Basin. Abundant trigonoidal and catilloidal Didacna-dominated faunas occurred in the freshened areas of the northern Caspian, influenced by the Volga River during Late Khazar times. Common gigantism of shells, high carbonate content in the sediment, and the presence of oolites represent warm climate conditions during Late Khazar times. Salinities reached from 10 to 12‰ in the northern up to 14–15‰ in the southern part of the Caspian Basin, higher than today’s salinities. Data on foraminifera (Yanko, 1989) support this conclusion. The warm climatic phase is also shown in palynological analyses (Abramova, 1974; Yakhimovich et al., 1986). During early Late Khazar times, the Caspian Basin was occupied by an isolated lake-sea that lacked any connection with the Black Sea Basin.

After the Early Late Khazar stage, a regression followed that is seen in hiatuses in the depositional sequences of Dagestan and erosion and soil formation in the Volga River valley (Yanina and Svitoch, 1990; Svitoch et al., 1993, 1997; Yanina, 2005). Stratigraphic hiatuses from this regressive stage were recorded by Fedorov (1957), Rychagov (1997), and Popov (1983). At present, there is no direct evidence to estimate the extent of the Late Khazar regressive phase. As the composition of the mollusc fauna was not much altered, this probably was a minor regression.

Traces of the second transgressive Late Khazar stage are not preserved along the Caspian coasts. Based on borehole material from the northwestern part of the Caspian region, Goreskii (1957) and Popov (1953, 1967) indicated the presence of a brackish water basin which existed after the Late Khazar transgression and before the Khvalynian transgression, the Girkan transgression. The Girkan basin was inhabited by “Khvalynian-like” fauna, traces of which have not been recorded elsewhere. A number of researchers strongly objected to the Girkan transgression concept (Shkatova, ...
The stratigraphic succession in cores from the northern Caspian Sea (Yanina et al., 2013) shows that between the Chernoyarsk and Atel regressive phases, two intervals of brackish deposits exist. The lower interval is assigned to Late Khazar transgressive interval. These deposits contain an admixture of warm species with a Pontocaspian nature (D. nalivkini and also rare D. surachanica, Didacna vulgaris and Didacna pallasi) as well as the fluvial Corbicula fluminalis. During late Khazar times, the Caspian Basin was a brackish water shallow warm-water basin with inflow of fresh waters. The overlying marine sandy-clay sediments contain abundant Didacna subcatillus, the occurrence of Didacna cristata and species of Khazar type D. pallasi, Didacna shuraosenica and Didacna subcrassa. According to Popov (1983), D. subcatillus in combination with D. cristata characterized the Girkan fauna. Thus, the interval identified in the boreholes can be attributed to the Girkan transgression. The widespread fresh-water C. fluminalis is indicative of the warm-water character of the basin.

Very crude and partially overlapping age estimates exist for the Late Khazar epoch. U-14C techniques give age estimates of 114–76 ka (Leontiev et al., 1975; Rychagov, 1997); 115–81 ka (Arslanov et al., 1978), and 122–91 ka (Shkatova et al., 1991). Based on thermoluminescence (TL) analysis, age estimates are 144–90 ka (Geochronology, 1974), 130–91 ka (Leontiev et al., 1975), and 122–106 ka (Shakhovets, 1987; Shkatova et al., 1991). Results of electronic paramagnetic (spin) resonance (ESR) show ages between 140 and 85 ka (Bolikhovskaya and Molodkov, 1999, 2008; Molodkov and Bolikhovskaya, 2008). The wide range of age estimates as well as the improved understanding of the paleogeographic successions implies a longer duration for this period than is generally accepted (Fedorov, 1978).

The Khazar epoch ended with the deep Atel regression. During this time, vast areas of the Caspian shelf were exposed and river incision was very deep (Fedorov, 1978; Rychagov, 1997). Atel epoch deposits are found in many parts of the Caspian Region (Svitoch, 1991; Svitoch and Yanina, 1997). In the Lower Volga region, the base of the Atel regressive unit is formed by the Akhtuba deposits,
referred to by Goretskiy (1958) as periglacial. These deposits represent a perfect marker horizon in the Lower Volga sections, often with sharp wedges penetrating the underlying sediments. These wedges and the co-occurring winter fractures in the base of Akhtubas sands form evidence of very cold climate conditions at the time of deposition that included the development of permafrost. Vegetation was represented by tundra—steppe associations (Grihuk, 1954). Formation of juxblinite crystals in the Akhtubas sands indicate cold dry climate (Moskvitin, 1962).

The Akhtubas deposits are conformably overlain by Atel sandy loam and loam sediments (up to 20 m thick) of various origins, formed in continental environments in the Caspian region. Some shells of stunted freshwater and continental mollusks are found in these sediments. The deposits contain mammal remains of the upper Paleolithic faunal complex, including mammoth, horse, reindeer and other species that show the cold nature of the Atel epoch. Palynological assemblages typical of taiga were found (Grihuk, 1954; Chiguryaeva and Khvalina, 1961; Moskvitin, 1962).

The Atel layer has up to four palaeosol horizons with different degrees of development, which implies a multiple change of climatic conditions in the region, with increasing warming and humidity. Towards the end of the Atel epoch, the climate became warmer. In the vegetational, a share of arboreal pollen increased, along with birch, pine and spruce, newly introduced elm, oak and linden appeared. In the herbaceous associations the importance of xerophytes decreased, while Gramineae and herbaceous vegetation were introduced. Steppe and forest-steppe environments became dominant.

Based on seismic-acoustic profiling (Lokhin and Maev, 1990; Maev, 1994), during the maximum regression the water level of the basin was 120 to 140 m. The Caspian basin retreated into the middle and southern parts of the lake. There is no data on the shell fauna of this basin. A drastic faunal shift occurred, and the formerly abundant Khazar Didacna of the crass group and closely related taxa became almost completely extinct. The main components of the Khvalynian fauna with preference for lower salinity habitats were inherited from the Girkan fauna. Based on the thickness of the Akhtubas—Atel deposits, and the presence of at least three paleosol horizons within them, the continental hiatus on the territory of the Northern Caspian Depression was long-term and multi-phase. It started with the water retreat from the Girkan basin, which, most likely, happened after 76 ka.

The Atel regression was followed by the “Great” Khvalynian transgression with the most extensive sea-level rise in the Late Pleistocene history of the Caspian Sea. During the Early Khvalynian transgressive stage, levels reached as high as 48–50 m a.s.l. The basin was occupied by a low diversity fauna dominated by catiloid and trigonoid Didacna species, all characterized by thin and small shells. The structure of mollusc fauna is indicative of relatively low salinities for the basin as a whole, but regional variations existed. Salinities in the main water body of the northern Khvalynian Sea were slightly higher than modern salinities (3–4‰) whereas salinity of the middle and southern parts of the basin (about 11‰) was slightly lower than today (Yanina, 2012a).

The small thin shells of mollusks indicate low water temperatures in comparison with ancient basins and the present Caspian Sea. The lower Khvalynian deposits are made up of very characteristic chocolate clays. According to Moskvitin (1962) and Goretskiy (1968), the clays were formed as a result of accumulation of fine sediments that derived from the periglacial landscapes of the hinterland. Palynological data confirm a cold climate. In the Ural River basin, the early Khvalynian epoch was characterized by maximum development of forests for the entire Late Pleistocene (Yakhimovich et al., 1986), with dominant conifer forests at the onset. The forests retreated during the second half of the epoch. On the western Caspian coast at the beginning of the Early Khvalynian epoch, tree species (oak, elm, alder, birch, maple, pine, fir-tree) dominated. The forests gave way to grassland and shrub vegetation by the end of this epoch when climate conditions improved (Abramova, 1974).

Caspian Sea researchers have shown stadial coastlines during an epoch of the Early Khvalynian basin: maximum, 34–36 m (Talinsk), 28–30 m, 20–22 m (Buinaksk), 14–15 m (Turkmnenian), and 4–6 m (Fedorov, 1957; Rychagov, 1970, 1974). The author supports the point of view about their origin in the transgressive phases divided by regressions as proposed by Vasilev (1961) and Rychagov (1974, 1997); Vasilev (1961) drew a conclusion on the existence of two Early Khvalynian transgressions divided by the “Elton” regression, a point of view further developed by Chepalyga (2006, 2007; Dolukhanov et al., 2009, 2010). In the Caspian core studied by Svitoch et al. (2008a), five transgressive and regressive phases are recorded, confirming the complexity of the Early Khvalynian transgression stage. In some of the cores, two units with different Early Khvalynian fauna assemblages were found (Yanina et al., 2013). These indicate the complexity of transgressive-regressive evolution of the Caspian Sea during the Early Khvalynian epoch. Chepalyga (2006, 2007) offered the “fantastic” concept according to which Early Khvalynian transgression was a catastrophic Great (Bible) Flood, and its transgressive phases were the “waves” of this flood developed at high speed. He even executed a Noah’s Ark reconstruction on waves of the Khvalynian Sea. His conclusions were contested by others, including Badyukova (2007), Svitoch (2007), Sorokin (2011) and Yanina (2012a), According to their reconstruction, development of the Khvalynian transgression was gradual and had no catastrophic character.

The Early Khvalynian ended with the Enotayevsk regression, with a maximum level estimated at −105 m (Maev, 1994). Terrestrial Enotayevsk deposits and numerous unconformities in the marine record are described on the coasts of the Caspian Sea (Leontiev and Fedorov, 1953; Vasilev, 1961; Rychagov, 1974; Fedorov, 1978; Svitoch, 1991; Svitoch and Yanina, 1997). On the Caspian shelf, the Enotayevsk layers have been found in boreholes (Maev, 1994; Svitoch et al., 2008a). According to pollen data (Sorokin et al., 1983), arid cool climate conditions existed.

During the succeeding Late Khvalynian transgressive stage, sea levels reached about 0 m. Didacna praetrigonoides, a rare species in the early Khvalynian, became dominant. Salinity of the main water body of Late Khvalynian basin was very similar to that of the Early Khvalynian, 11–12‰, although foraminifera faunas suggest salinities up to 12–14‰ (Yanko, 1989). In the northern Caspian coastal zone, salinities were as low as 3–4‰ (Yanina, 2012a). Relative abundance of the mollusks 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 (Grihuk, 1954; Abramova, 1974; Sorokin et al., 1983) indicate general warming in the region.

The regressive tendency of the Late Khvalynian Sea was characterized by a series of minor secondary transgressive phases (Leontiev and Fedorov, 1953; Leontiev and Foteeva, 1965; Rychagov, 1997). 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).

The age of the Khvalynian epoch remains a subject of discussion (Kaplin et al., 1972, 1977a,b; Leontiev et al., 1975; Kvasov, 1975; Arslanov et al., 1978; Rychagov, 1997; Bezrodnykh et al., 2004; Badyukova, 2007, and others). Leontiev and Rychagov (Leontiev et al., 1975; Rychagov, 1997) based mostly on TL dates, estimated the age of the Early Khvalynian transgression as 70–40 ka, and the
age of the Late Khvalynian transgression as 20–10 ka. An opposite point of view based on $^{14}$C and U–Th dating was proposed by Kvasov (1975) and Svitcho (1991). The author also participated in this discussion, defending a “young” age of the Khvalynian transgression (Svitcho and Yanina, 1983, 1997; Svitcho et al., 1994, 1998).

In recent years, new data on the age of the Khvalynian transgression of the Caspian Sea emerged (Leonov et al., 2002; Bezrodnikhy et al., 2004; Svitcho, 2007; Arslanov and Yanina, 2008; Chepalyga et al., 2008, 2009; Svitcho et al., 2008a,b; Arslanov et al., 2013; Tudryn et al., 2013). Analyses on molluscs from boreholes show 30 to >30 ka for the lower part of the Khvalynian deposits (Bezrodnikhy et al., 2004); $^{14}$C age 28.5–31.5 ka, calibrated age from 33.5 to 36.5 ka (Arslanov et al., 2013; Yanina et al., 2013). According to these data, the Khvalynian transgression began about 35 ka. Unfortunately, no radiocarbon age estimates exist for the maximum level of the Khvalynian transgression, and all existing estimates (Chepalyga, 2007; Svitcho, 2007; Dolukhanov et al., 2009, 2010) are based on indirect correlations and assumptions. Most are associated with the stadial level about 22–24 m, defining its age (calibrated) as 15–14 ka. During the Holocene Boreal period, in times when climate became more continental, the Late Khvalynian was succeeded by the Mangyshlak regression.

3.2. Pontian Basin

The scheme of the Late Pleistocene events of the Pontian Basin includes the Karangat (Karangat and Tarkhankut stages), Surozh and New Euxinian transgressions, and intervening regressions (Fig. 2).

The paleogeography of the Karangat transgression is well studied (Andrusov, 1903; Arkhangelskiy and Strakhov, 1938; Nevesskaya, 1965; Ostrovsky et al., 1977; Fedorov, 1978; Yanko et al., 1990; Chepalyga, 1997; Dynamics, 2002; etc.). According to these researchers, the Karangat transgression is the largest Pleistocene interglacial transgression with the highest salinities during the Pleistocene. The analysis of the Karangat fauna showed that transgression developed with two stages, Karangat and Tarkhankut. They were characterized by faunal complexes that contained stenohaline as well as euryhaline mollusc taxa.

The Karangat transgression developed in two phases. During the early Tobechik phase (Nevesskaya, 1965), a mollusc fauna similar to the modern Black Sea fauna was established. Sea levels did not exceed the modern levels. Age estimates for this phase range from 121 to 127 ka (Dynamics, 2002). With further development of the interglacial Mediterranean transgression, the penetration of marine waters in the Black Sea led to the second phase of the Karangat transgression. Stenohaline species (Acanthocardi, tuberculatum, etc.), which are absent in the Black Sea today, flourished in the Karangat basin. They indicate salinities of about 30‰ in the open part of the sea. High salinity was characteristic for the southern part of the Sea of Azov, and the Manych and the Don estuary. The Karangat transgression was characterized by warm waters, as shown by the composition of the mollusc fauna, as well as the presence of warm-water subtropical types of diatoms (Zhuze et al., 1980). Spores and pollen ranges also indicate warm conditions in the region (Sherbakov et al., 1977; Koreneva, 1982; History of geological development, 1988).

In the second phase of the transgression, the Karangat Sea exceeded the limits of the present Black Sea and Sea of Azov. The sea ingressed into river valleys tens of kilometers upstream and even 70–80 km upstream in the Danube River system (Mikhaylesku, 1990). According to Popov (1983), the maximum extension of the Karangat Sea extended as far east as the Manych watershed. The age of the maximum transgressive stage is not well constrained: a series of thorium — uranium dates show a range between 140 and 70 ka (Arslanov et al., 1975; Balabanov and Izmailov, 1989; Dynamics, 2002).

After the maximum transgression, the Karangat Sea lowered. During this Tarkhankut stage, the Karangat Sea had a similar outline as the modern Black Sea. It was the residual basin of the Karangat Sea, a final stage of its existence. The Mediterranean connection had ceased to exist at the time. Salinities did not exceed 14–15‰. The mollusc faunas were dominated by Mediterranean taxa but lacked stenohaline species. During the Tarkhankut stage, Girkan waters entered through the Manych passage, and Didacna species (D. cristata, D. subculatus) invaded the basin margins on the northeast from the Caspian Basin.

The Post-Karangat regression lake level dropped to –110 m (Ostrovskiy et al., 1977; Balabanov and Izmailov, 1989). The marine environment was replaced by brackish-water, and then almost fresh-water conditions (History of geological development, 1988). Diatom species indicate cold water conditions. Palynological analyses also show very cold conditions at the time (Sherbakov et al., 1977).

According to Popov (1983), during the Post-Karangat epoch a single transgression occurred, the Surozh transgression. Remains of this transgression were observed from the western Manych river valley and the Sea of Azov coast. A Surozh coastal terrace is furthermore documented by Ostrovskiy et al. (1977) and Popov (1983) on the Caucasian coast of the Black Sea. However, other researchers doubted the assignment of these terraces to the Surozh period (Nevesskaya, 1965; Fedorov, 1978; Yanina, 2012a). Surozh deposits have been identified on the shelf and in the deep-water conditions (History of geological development, 1988). During the Surozh transgression, sea levels reached –25 m. There was no connection with the Mediterranean Sea at the time. The mollusc fauna of the Surozh stage is not known. Palynological analyses indicate warming climate (Sherbakov et al., 1977). The epoch of the existence of this basin is estimated as 40–25 ka (Sherbakov, 1982).

After the Surozh epoch, a deep regression developed in the Pontian Basin. Lake levels dropped to –80 m (Sherbakov et al., 1977; Fedorov, 1978) and possibly even to –140 to –150 m (Ryan et al., 1997). Deposits and faunas dominated by Dreissena found in depressions, on the lower part of the shelf, and on the continental slope show that the basin was occupied by an almost fresh-water lake. The diatom flora indicated very cold conditions (Zabelina and Sherbakov, 1975; Zhuze et al., 1980). The Sea of Azov was a coastal plain crossed by the Don River whose mouth was located 50 km south of the Kerch Strait. The lower courses of the Dnepr, Dnestr, and Danube rivers merged, resulting in a formation of the “grand canyon” and a single delta (Kaplin and Sherbakov, 1986). Periglacial landscapes surrounded the northern coasts with cold and arid climate conditions as shown by palynological data (Vronsksiy, 1974; History of geological development, 1988). An arctic fauna, including arctic foxes, white partridges, and reindeer roamed the coasts (Khristov and Sherbakov, 1974). The most severe cold conditions existed around 22–23 ka, coinciding with the onset of the New Euxinian regressive basin (23–16 ka: Balabanov and Izmailov, 1989; Sherbakov et al., 1977).

The New Euxinian transgressive stage was initiated ca 16 ka. Around 12.5 ka, its level reached –45 m. The New Euxinian basin was populated by a slightly brackish Pontocaspian fauna dominated by Monodacna, Adacna, and Dreissena, and lacked Mediterranean taxa. Rare occurrences of Khvalynian species such as Didacna ebersini and Didacna mortbunda in the New Euxinian deposits indicate the overflow of Caspian waters during the Khvalynian transgression. Khvalynian ostracod and foraminifera species are also found in New Euxinian sediments (Popov, 1983; Yanko, 1989). Around 9.8 ka, New Euxinian lake levels reached about –30 m
3. Manych

The Manych area experienced ingressions from the Black Sea Basin in the west and from the Caspian Sea Basin in the east. During the maximum extent of the Karangat transgression, marine waters reached the Manych watershed from the west, but did not cross the threshold, as indicated by the extent of the marine fauna. Popov (1983) defined the two stages of the ingestion of the Karangat Sea in the Manych region, and the maximum ingestion was reached in the second stage. In the valley of East Manych, two ingresses (Late Khazar and Girkan) occurred. During the Karangat regression, overflow of Girkan waters from Caspian Sea occurred, with the establishment of Caspian species such as D. cristata and D. subcatillus. The overflow coincided with the early phases of a cold interval as shown by palynological analyses (Goretskiy, 1953). At the end of the Girkan epoch, a large lake in the Manych depression, Lake Burtass (Goretskiy, 1966), was formed. Immersion of the Manych-Gudilo deflection was limited to the slopes of Salsk and Zunda-Tolga horsts (Popov, 1983). Fresh-water mollusks and ostracods lived in the lake. In its deposits, pollen of coniferous trees were found (Goretskiy, 1966). With a 40–45 m thick depositional record, the lake must have existed for a considerable time. In the upper part of the Burtass deposits, fossil soils of meadow and marsh type are developed, showing lake level fluctuations. At the same time, the Caspian Basin experienced the deep Atel regression, and the Black Sea Basin, the Post-Karangat regression.

The Manych passage overflowed during the Early Khvalynian transgression, when lake levels in the Caspian Basin reached about +50 m. Both the geomorphology of the depression and the faunal content of the deposits imply a two-stage overflow. During the Early Khvalynian sea level maximum (+48–+50 m), strong erosion occurred in the valley (first erosive stage). During the Buinaksk stage (+22–+24 m) of the Early Khvalynian transgression, terraces formed in the Manych depression about 22 m (the second accumulative stage). The second stage is dated at about 12.5–12.7 ka (14C) or about 14.3–14.8 cal ka (Arslanov and Yanina, 2008; Svitoch et al., 2008a,b). Fossil assemblages of the Khvalynian mollusks indicate unidirectional migration of the fauna from the Caspian Sea to the New Euxinian basin (Svitoch and Yanina, 2001; Yanina, 2006). This was the last time the Manych served as a spillway between the Caspian and Black Sea Basins.

3.4. Features of the environmental evolution of the Caspian Sea and Pontian Basin

During the Late Pleistocene, the Caspian Sea Basin and Pontian Basin represented basins of different types. Timing and extent of sea level changes, hydrological parameters, palaeogeographical evolution, and features of fauna were mostly independent.

During most of the Late Pleistocene, the Caspian Basin was an enclosed basin. During the Girkan transgression stage and twice in the Early Khvalynian transgression, overflow developed from the Caspian basin towards the Pontian Basin across the Manych Passage. In the Pontian basin endorheic conditions existed in the maximum stages of regressions. When the lake rose above the Bosporus sill, lake waters drained into the Marmara Sea. The basins were overflowing at times when the Caspian Sea overflow and the Black Sea Basin overflowed and connected to the Sea of Marmara through the Bosporus. Development of marine transgressions in Pont Basin was caused by inflow of the Mediterranean waters. There was no bilaterial exchange with the Caspian Sea.

During maximum transgressions, the surface area of the Caspian Sea increased as much as 250% compared to the current sea, and water levels reached +50 m. The maximum level of the transgression was controlled by the height of the Manych threshold. Caspian Sea levels were as low as −140 m during maximum regressions, resulting in lake level variations of 190 m in the Late Pleistocene. During the maximum transgression of the Pontian basin, sea level was at most 7 m higher than today. The maximum level of the transgression was controlled by the level of the Mediterranean Sea. The lowest levels were 100 m below the current sea level of the Black Sea, resulting in sea level variations of 100–110 m in the Late Pleistocene.

Despite the large changes in sea level and water volumes, salinity fluctuations in the Caspian Sea were relatively small, no more than 6–7‰. During extensive transgression, the basin as a whole became slightly fresher, but during small transgressions salinities were notably high. Salinity maxima in the Pontian were much higher as a result of the marine ingursions during the Karangat, and the basin experienced marine, semi-marine, as well as endorheic conditions. Late Pleistocene salinity fluctuations were possibly as high as 30‰.

The successive Caspian lake stages were inhabited by species and genera of the Caspian autochthonous brackish complex. Didacna species in the Caspian basin underwent very rapid speciation and high turnover rates. Species diversity increased with a diversification of habitat types in the Caspian subbasins. Different faunal types (Mediterranean as well impoverished Pontocaspian faunas) inhabited the Pontian Basin in successive stages. Faunal turnover was as profound as in the Caspian Sea, but the diversity and turnover in the Pontocaspian fauna of the Pontian basin was less dramatic owing to the more uniform character of the entire basin, that did not stimulate speciation.

The biodiversity of Caspian faunas was defined by variability of conditions in the basin. The shallow nature of the Northern Caspian and variation of Volga input created dynamic and very variable habitats. Biodiversity in the Pontian basin depended on either invasions of Caspian taxa or of Mediterranean marine taxa. The highest species richness occurred during the Karangat stage.

Within the Caspian Basin, transgressions occurred in cold climate conditions (such as the extensive Early Khvalynian transgression) and in warm climate conditions (such as the relatively small Late Khazar transgression). In their late stages, climate of the cold transgressions became warmer and that of warm transgression became colder. Transgressions in warm episodes correspond to high salinities, whereas transgression in colder episodes produced lowered salinities. The marine transgressions in the Pontian Basin (Karangat in the Late Pleistocene and Black Sea in the Holocene) occurred in warm interglacial times. Caspian type of lake-seas in the Pontian Basin developed during cold climate intervals. The most severe regressions occurred during the coldest episodes.

The episodic Manych Passage between the Caspian and Pontian basins is a unique passageway influencing the palaeogeography of the region. The elevation of this passageway set the upper boundary of transgressions in the Caspian Basin, especially in cold intervals. Intermittent overflow must have deprived the Caspian Sea of salt and depressed salinities and at the same time contributed to the salt balance in the Pontian lakes. The Manych area acted as a threshold for marine ingressions from the Pontian Basin during interglacial periods. The intake of the Caspian waters increased water volume in the Pontian Basin, modifying hydrological, hydrochemical, and ecological conditions.
The paleogeographical conditions of the Caspian and Pontian basins were in many respects defined by the degree of their isolation. The influence of global climate change on their development is very different in both basins.

3.5. Global climate change and evolution of the Ponto-Caspian basins

The global climatic events of the Late Pleistocene, caused by cyclic changes of the Earth orbital elements, in turn caused variations of insolation resulting in the warm interglacial epoch (MIS 5 or MIS 5e, according to representations of different researchers) and the complex cold glacial epoch (MIS 4-2 or MIS 5d-2). In different latitudes and regions, glacial and interglacial intervals were expressed differently. In the Ponto-Caspian region, they were reflected by an alternation of the transgressions and regressions. On the East-European plains and in adjacent mountain areas, they were expressed in the advance and retreat of glaciers that also impacted the evolution of the Ponto-Caspian basins.

The beginning of the Late Pleistocene was characterized by the warm epoch (MIS 5: Eemian or Mikulino interglacial in Eastern Europe). Debatable is the age limits and duration of interglacial conditions. The age of the Mikulino interglacial is estimated at 100–70 ka (Zarrina and Krasnov, 1983), 128–116 ka (Spiridonova, 1991; Arslanov, 1992), 140–100 ka (Paleoclimates, 2009); and 140–70 ka (Bolikhovskaya and Molodkov, 1999). For the territory of Belarus it is 130–90 ka (Yelovicheva and Sanko, 1999), for Ukraine 130–107 ka (Gerasimenko, 2001). According to some researchers (Mangerud et al., 2004; Svendsen et al., 2004; Brauer et al., 2007; Brewer et al., 2008; Orombelli et al., 2010) truly interglacial conditions existed only briefly during isotope stage 5e with the warmest period about 125 ka. The Mikulino interglacial consists of three thermal maxima. The oldest corresponds to isotope stage 5e (Bolikhovskaya and Molodkov, 1999, 2008; Molodkov and Bolikhovskaya, 2009). The younger two correspond to substages MIS 5c and MIS 5a. The warm episodes were intervened by two cold periods (endothermals).

Reconstructions of the paleogeographical events in the Ponto-Caspian region (Fig. 3) shows that during the warm interglacial epoch at the beginning of the Late Pleistocene (cf MIS 5e) the Caspian Sea experienced regressive conditions. During the early endothermal (cf MIS 5d) the early stage of the Late Khazar transgression developed when climate conditions became somewhat colder and humid. The Late Khazar lake was relatively warm and lake levels reached ~10 m. In the Pontian Basin, MIS 5e corresponds to Karangat transgression when full marine conditions developed and sea levels were highest as a result of connection with the Mediterranean and world oceans. The transgression reached the Manych threshold.

Regression of the Early Late Khazar lake developed under warm and dry conditions that possibly correspond to MIS 5c. During the second endothermal and climate cold interval (cf MIS 5b), the second Late Khazar transgressive stage (Girkan) developed. During that time the Girkan lake penetrated deeply into the Manych area from the east, forming an extensive estuary in the Pre-Manych area. In the Pontian Basin, the Karangat transgression continued its development. The succession of Late Pleistocene deposits of the Manych depression with alternating deposits containing Karangat and Late Khazar mollusc faunas indicates the synchronous existence but asynchronous development of both systems. The warm-water Late Khazar lake-sea and Karangat sea co-existed in the Ponto-Caspian region during the entire MIS 5 interglacial, showing that the Mikulino interglacial was a relatively long epoch with a complex structure.

At the beginning of MIS 4, the Karangat sea level dropped, coinciding with the global ocean level drops. The Caspian waters of the Girkan transgression ingressed in the Manych valley and at the same time Karangat waters withdrew into the Pontian basin. The regressive trend of the Karangat Sea was complicated by overflow of Girkan waters through the Tarkhankut basin.

The nature, extent, and regional variability of the cold Weichselian or Valdai epoch (MIS 4-2 or MIS 5d-2) on the East European plains are debated. The epoch was predominantly characterized by cold continental climate and complex succession of climate conditions and regional variability. The number of glaciations and their extents are still not completely understood (Velichko, 1991; Velichko et al., 1999; Mangerud et al., 2004; Svendsen et al., 2004; Sudakova, 2005; Paleoclimates, 2009; Shik, 2010; Rychagov et al., 2012). Palynological data indicate the presence of two early Valdai and three middle Valdai interstadial intervals and five cold stadial intervals (Bolikhovskaya and Molodkov, 2008).

During the cold maximum of the interval MIS 4 when regional climate was cold and arid, a regression developed in lake Girkan in the Caspian Basin, the Akhtuba-Atel regression. The development of periglacial continental conditions is shown by deep ice wedges in the lake sediments of the Akhtuba basin and periglacial spores and pollen in these deposits. A succession of colder and warmer periods (a stadial-interstadial alternation) is shown by successive podzol horizons in the Atel deposits. Synchronously with the Akhtuba-Atel deposits in the Caspian Basin, thick lake deposits developed in the freshwater lake-Burtass in the Manych depression. These lake deposits contain pollen of cold plant taxa, and four paleosol horizons are found. At the same time in the Pontian Basin, the very deep Post-Karangat regression developed and connection with the Mediterranean was completely lost.

The slightly warmer conditions of MIS 3 resulted in increasing precipitation and river activity in the East-European plain and simultaneous reduction of evaporation over the lake basins. The water balance became positive, resulting in transgressions in the Caspian Basin (the first phase of the Early Khvalynian transgression), and in the Pontian Basin (the Surozh moderately warm-water basin). The upper part of the terrestrial Atel deposits also corresponds to this time interval.

During the ultimate glacial interval (MIS 2), the Late Valdai glaciation developed. During the Late Glacial Maximum (LGM), the deep New Euxinian regression developed. An almost freshwater lake occupied the Black Sea Basin. In the isolated Caspian Basin under cold conditions, the Early Khvalynian transgression further developed. The general transgressive trend was interrupted though during the LGM. Permafrost existed around the northern Caspian coasts. Average annual temperatures decreased to −10 to −5°C in the southern areas of Europe (Paleoclimates, 2009). The climate conditions resulted into a negative water balance of the Khvalynian Lake-Sea, causing sea level drop. Climate modeling shows similar negative water balance at the time (Kislov and Toropov, 2006, 2007; Kislov, 2010).

The Early Khvalynian transgression resumed during deglaciation after the LGM. Transgression of the Caspian type began in the New Euxinian basin: however, its levels remained low because of dumping of waters through the Bosphorus passage towards the Marmara Sea and beyond. The Early Khvalynian transgression, having reached the level of the Manych threshold, developed an erosive valley and discharged into the New Euxinian basin. Erosion of the threshold resulted in a drop of the Early Khvalynian sea levels. 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 Caspian inflow raised sea levels of the New Euxinian lake-sea. Its
Fig. 3. Scheme of development of the Ponto-Caspian basins during the Late Pleistocene under global climate change: A — Interglacial epoch (MIS 5, Mikulino interglacial on the East-European Plain): the Karangat transgression of the Pont (with ingression in the Manych valley) and the Late Khazar transgressive stage of the Caspian (isolated basin). B — Transitional epoch from interglacial (MIS 5) to glacial (MIS 4) epochs: beginning of the Karangat regression of the Pont and Girkan transgressive stage of the Caspian; Girkan passage of the Manych. C — Early stage of the glacial epoch (MIS 4, Early Valdai glaciations on the East-European Plain), glacial maximum: Post-Karangat regression of the Pont and Atel regression of the Caspian Sea. D — Interstadial warming (MIS 3, Bryansk interstadial on the East-European Plain), glacial degradation: Surozh basin of the Pont and beginning of the Early Khvalynian transgression of the Caspian Sea. E — Late stage of the glacial epoch (MIS 2, Late Valdai glaciations on the East-European Plain), glacial maximum: the New Euxinian regression of the Pont and regressive stage (Elton?) of the Early Khvalynian basin. F — Degradation of glaciations (MIS 2): the New Euxinian transgression of the Pont and maximal stage of the Early Khvalynian transgression of the Caspian Sea. G — Glacial degradation (MIS 2) — beginning of post-glacial epoch (MIS 1): the New Euxinian transgression of the Pont and Late Khvalynian transgression of the Caspian Sea. H — Beginning of the Interglacial epoch of the Holocene (MIS 1): beginning of the Black Sea transgression of the Pont and the Mangышлак regression of the Caspian Sea.
maximum coincided with the onset of the Mediterranean transgression (Yanko-Hombach et al., 2007).

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 catchment. Cold dry conditions of the Middle Dryas resulted in the Enotayevsk regression. Increasingly continental climatic conditions during the Boreal period of the Holocene resulted in the Mangyshlak regression. In the Pontian Basin at the onset of the Holocene, the final transgression from the Mediterranean developed.

Global climate change in the late Pleistocene was driving transgressive-regressive cycles in the Ponto-Caspian basins as well as in their catchments through glacier development and retreat (Yanina, 2012a,b). In the Caspian Basin, two types of transgressions occurred: those under relatively warm and those under cold conditions, with different amplitudes. Grichuk (1969) distinguished warm and cold phases within glacial cycles on the East-European Plain, and in each phase, based on degree of humidity, he distinguished stages: in the warm — xerothermic and gygrothermic; and in the cold — cryogygroctic and cryoxerotic. Moisture and heat supply curves on the East-European Plain shifted in relation to each other by half-phase, although in the Caspian region they shifted by three-quarters (Alisov and Poltoraus, 1962; Grichuk, 1969; Filippova, 1997). Southward, correlation between lowered temperatures decrease and increased humidity is more apparent (Yanina, 2012a,b). Analysis of temporal humidity changes in the studied region (the key factor for transgression development), indicates that “cold” transgressions occurred during cryogygroctic phases, with favorable conditions for glacial development on the East-European Plain. However, the moisture peak in the Caspian reached its maximum earlier than the glacial maximum (approximately by the middle of the preceding cryogygroctic phase). By the time of the glacial maximum on the East-European Plain (the end of the cryogygroctic phase) sea-level drop occurred, corresponding to the “cold” regression.

Existence of a “pluvial belt” during global climate cooling is shown for the entire arid zone in Asia (Devyatkin, 1989, 1993). Reconstructions show increased humidity on the Caucasus coast with simultaneous temperature decrease (pluvial intervals) during glacial epochs and humidity decrease and temperature rise during interglacial cycles (Markov et al., 1965; Abramova, 1974; Markov, 2005 and others).

An “idealized” scheme of transgressive-regressive Caspian cyclicity correlation with global climatic events is complicated by regional factors, such as glaciations on the East-European Plain (magnitude, outline, dynamics, reorganization of hydrographic system), introducing regional changes in climatic parameters and in the magnitude of water inflow. Retreating glaciers and increased melt water inflow caused several rises on small temporal scales. According to the scheme, regression maxima corresponded to xerothermic interglacial phases. Such “warm” transgressions apparently developed at the onset of cooling at the end of interglacial cycles with increasing moisture. Geological factors (neotectonic movements, sedimentation in the basin) also played a role in the dynamics of basins. Reorganization of hydrographic system impacted development of the Caspian basins. The height of the Manych threshold provided the upper limit of the maximum sea-level rise of the cold Caspian transgressions. Further sea level rise resulted in overflow of the Caspian waters to the Pontian Basin.

In the Pontian Basin, two types of transgressions occurred: marine transgressions (those driven by the ingress of marine Mediterranean waters) and transgressions of the Caspian type (when the Pontian basin was in the lake phase, and those driven by the overflow of brackish waters from the Caspian Basin). The marine high stands are unambiguously correlated with interglacial episodes when transgressions of the World Ocean occurred, and are correlated with the interglacial epochs of the East-European Plain as well. Transgressions of the Caspian type developed synchronously with the cold transgressions in the Caspian Sea, but with different results. If lake or sea levels in the isolated Caspian Basin rose above the Manych threshold, its waters would overflow, driving transgressions in the Pontian Basin and eventually resulted into an overflow over the Bosporus towards the Sea of Marmara and the Mediterranean that experienced low stands at the time.

4. Conclusions

The Caspian Basin and Pontian Basin behaved differently during the Late Pleistocene: the nature, magnitude and driving forces behind sea/lake level change and the environmental evolution were in general not synchronous.

The event scheme of the Late Pleistocene of the Caspian Sea includes the small Late Khazar transgression that developed during the Mikulino interglacial epoch (MIS 5), and extensive Khvalynian transgression with the highest level in the Late Pleistocene that developed during the second part of the Valdai glacial epoch (MIS 3-2). The Late Khazar transgression occurred in two phases: both corresponded to endothermal phases of a cold interval when regional humidity increased during the Mikulino interglacial epoch. In the xerothermic conditions of the interglacial epoch, the Caspian Sea was in the regressive situation. The transgressive development of the Girkan Lake phase and its overflow across the Manych were supported by the first cooling phases of the Valdai glacial epoch at the transition period from interglacial to glacial climatic conditions.

Between the Khazar and Khvalynian transgressions, the very deep Atel regression resulted from a severe continental climate of the cold maximum in the Valdai stage (MIS 4) of the glacial epoch. The transgression initiated when the regional water balance shifted positively with increasing riverine input and precipitation and reduced evaporation rates at the MIS 3 interstadial. The Khvalynian transgression was interrupted during the LGM of the Late Valdai glaciations (MIS 2). The transgression resumed during the deglaciation phase after the LGM. A return to cold and dry conditions of the Younger Dryas caused the short-term level fall of the Khvalynian basin, so-called Enotayevsk regression. The continentalization of the Boreal period of the Holocene led to the Mangyshlak regression of the Caspian Sea. During the Khvalynian epoch, the Manych threshold was breached twice resulting in overflow into the Pontian Basin during the maximum (48–50 m) and Burtass (20–22 m) phases of the transgression.

The Late Pleistocene succession of the Pontian Basin is marked by large interglacial (MIS 5) Karangat transgression of the Mediterranean type, extending deep into the Manych valley, and the Post-Karangat development of the Caspian type basins (maximum sea-lake levels below present-day levels: Surozh and the New Euxinian stages), corresponding to the Valdai glacial epoch (MIS 4–2). The Karangat transgression developed in two phases. During the second stage (Tarkhankut) a residual marine basin of the Black Sea type received waters from the Girkan transgression of the Caspian Basin. The Post-Karangat regression of the Pontian Basin corresponded to the cold maximum of the Valdai glacial stage (MIS 4). An intra-Valdai interstadial epoch (MIS 3) caused small sea level rise (because of increase in a positive component of the water balance) and warming of waters, the Surozh transgression. At that time, no connection with the Mediterranean existed. During the Late Valdai glacial stage (MIS 2) in the Black Sea Basin, the New Euxinian sea-lake developed, a low salinity basin that during the LGM was
isolated and became a transgressive basin of the Caspian type during the glacial retreat. Khvalyinian waters flowed in from the Caspian Basin twice. The Holocene transgression of the Mediterranean type marked the end of the New Euxinian stage and the establishment of the modern Black Sea.

Development of transgressive and regressive rhythms of the Caspian Sea and Pont Basin during the Late Pleistocene was caused by many factors driven by global climate change. Glacial and interglacial events of the East-European Plain and mountain areas of the region, which development also was defined by global climate changes, in turn, had regional impact (sizes of glaciers, their dynamics, by changes of a hydrographic network, shift of climatic zones and so forth) on the environmental evolution of the Ponto-Caspian region.

The cold extensive transgressions of the Caspian Sea and the transgressions of the Caspian type of the Pontian Basin, not exceeding its modern level, developed synchronously in the cold (glacial) climatic epochs. The maximum height of level of this transgression was limited by the height of the Manych threshold, and the transgressions of the Caspian type in the Pontian Basin by the height of the Bospors threshold. The warm small transgressions of the Caspian Sea and the marine (Mediterranean type) transgressions of the Pont with maximum level developed during the warm interglacial epochs. However, if the existence of the interglacial endothermals was the main factor for the warm Caspian transgressions, for development of the Pontian Basin it was the interglacial marine transgressions of the World Ocean. The cold transgressions of the Caspian Sea and the Caspian type transgressions of the Pontian Basin developed asynchronously with the transgressions of the World Ocean.

The cold transgressions of the Caspian Sea occurred during cryogenic phases of climatic cycle of the East-European Plain with favorable conditions for glaciation. However, the moisture peak in the Caspian reached its maximum earlier than the glacial maximum (approximately by the middle of the cryogenic phase). By the time of the glacial maximum on the East-European Plain (the end of the cryogenic phase), a sea-level drop occurred simultaneous with the coldest conditions. Deglaciation and increase river discharge caused a new transgression. Sea-level drops in the Caspian were due to transgressive-regressive pulses. Warmer regressions corresponded to the thermoxic interglacial phase of the East-European Plain. Warm transgressions happened during cold intervals and moistening phases in the interglacial epochs.

The Pontian transgressions of the Caspian type developed synchronously with cold transgressions of the Caspian Sea, but their sea/lake levels were low due to dumping of waters in the regressing Mediterranean Sea. The Pontian marine transgressions of the Mediterranean type unambiguously are correlated with the interglacial phases of the East-European Plain.

Acknowledgements
I am thankful to all colleagues for the collaborative investigations in the Ponto-Caspian region, and to Dr. Frank Wesselingh for text editing in English. I am thankful to the Russian Foundation for Basic Research for financial support of the research (Projects 12-05-01052, 13-05-00086, 13-05-00242, 14-05-00227).

References


Dynamics of landscape components and internal marine basins of Northern Eurasia over 130000 years, 2002. GEOS, Moscow, pp. 1–212 (in Russian).


Caspian and Aral Seas in the Cenozoic, vol. I. Moscow State University, Moscow, pp. 42–52 (in Russian).


