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RESEARCH ARTICLE

Radiocarbon dating of the end of the latest Caspian Sea overflow through the Manych Depression (southeastern European Plain)

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Abstract

The Manych Depression is a relatively narrow elongated depression of tectonic origin, connecting the Caspian and Azov-Black Sea basins. The Caspian Sea repeatedly discharged its waters through this depression into the Black Sea and further into the Mediterranean Sea during the Quaternary period. The last discharge occurred in MIS 2 when the Khvalynian transgression waters exceeded the drainage divide between those two basins. The geochronology of the last flow of Caspian waters into the Black Sea was established recently based on ^{14}C dating of Khvalynian shells, carried out mainly by liquid scintillation counting, and the end of this event was dated to 12.5–12.8 ka cal BP. Recently obtained OSL dates for one of the most complete sections of the Khvalynian deposits of the Manych Depression indicate an older time for the end of the flow. This study aimed to clarify the timing of the Khvalynian transgression discharge by examining two sections containing the Khvalynian mollusk fauna in layers that, according to their stratigraphic and geomorphological position, belong to the final phase of the flow of the Caspian waters. Four ^{14}C AMS dates were obtained from single shells of *Didacna ebersini* and *Hypanis plicata*, which agree with the OSL dating results. The results indicate that the last overflow of Caspian waters through the Manych Depression had ceased at around 14.5 ka cal BP.

Introduction

The Caspian Sea is the largest lake on Earth by square kilometers (sq km). Currently, the Caspian Sea is an enclosed basin with no exit flow. However, during the Quaternary, it repeatedly discharged its waters into the Azov-Black Sea basin. The Caspian waters flowed through the Manych Depression—an elongated tectonic depression separating the Caucasus Mountains and the East European Plain (Figure 1a). The history and causes for the occurrence of this flow are still debated by Caspian researchers (see review in Semikolennykh et al. 2022). Most researchers associate the most recent discharge of Caspian waters into the Black Sea with the Khvalynian transgression—the highest rise in level over the past 700 ka years (Yanina 2020). Two phases of the Khvalynian transgression are traditionally distinguished: the early, highest, when the sea level rose to +48 – +50 m, and the late with a maximum level of 0 m asl (e.g., Fedorov 1957; Rychagov 1997; Svitoch 2008; Yanina 2012). According to the preserved terrace levels, the Early Khvalynian transgression flooded the entire area of the Caspian lowland and penetrated the Volga valley, north of 52°N. For a long time, there were two dominant opinions regarding the age of the Early Khvalynian transgression: one group of researchers, based on the results of TL dating, attributed this transgression to MIS 4—the Early Valdai (Kalinin)

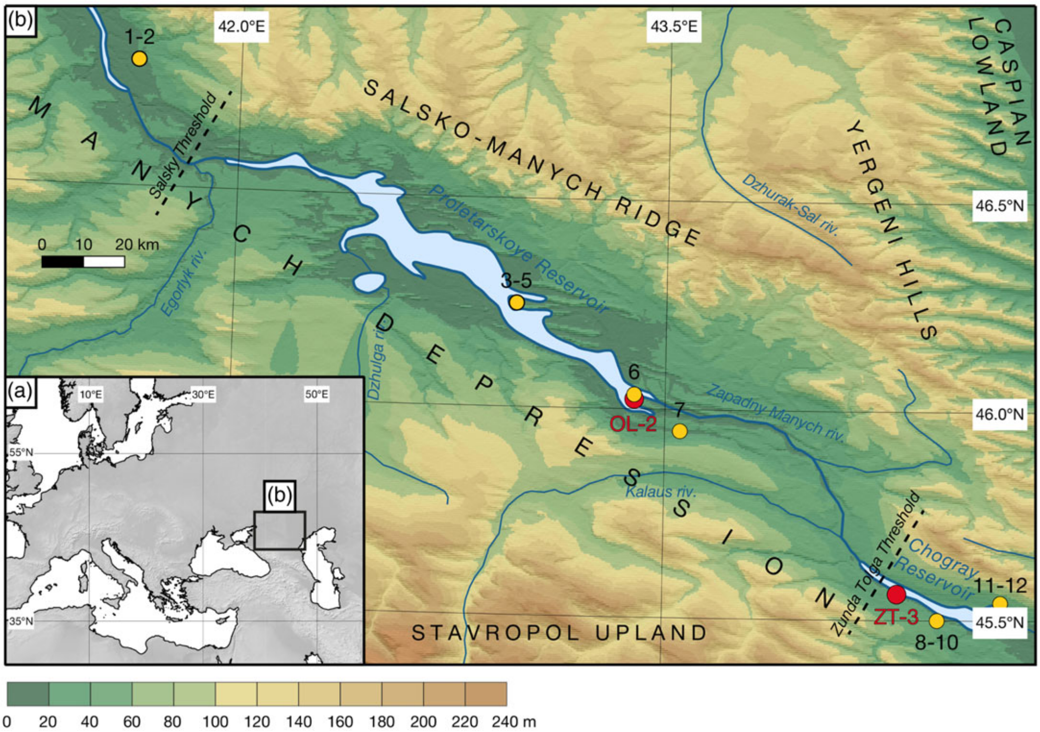

Figure 1. *Location map: (a) the Manych Depression; (b) study sites. Red dots indicate sections we studied in this paper; yellow dots indicate published radiocarbon dates on shells of Khvalynian mollusks listed in Table 1. Elevation data taken from GEBCO (www.gebco.net).*

glaciation on the East European Plain (e.g., Moskvitin 1962; Fedorov 1978; Rychagov 1997, 2014), the other group based on the results of ^{14}C and ^{230}Th/^{234}U dating—to the second half of MIS 2 (e.g., Kvasov 1975; Leonov et al. 2002; Svitoch and Yanina 1997). However, at present, most researchers refer to the younger age—the second half of MIS 2 (e.g., Arslanov et al. 2016; Kurbanov et al. 2021, 2023; Makshaev and Tkach 2023; Svitoch 2008; Tudryn et al. 2013; Yanina 2020; Yanina et al. 2018). Most researchers associate the last event of Caspian water flow through the Manych Depression with the Early Khvalynian transgression. However, some argue it continued into the Early Holocene (Badyukova 2006, 2011).

As there is still no consensus regarding the absolute chronology of this event, we present new radiocarbon dating results, which resolve the timing of the end of the Caspian Sea's last discharge through the Manych Depression.

Regional settings and study history

The Manych Depression is located south of the European part of Russia. It is a vast, weakly dissected, low-lying plain, stretching from the northwest from the mouth of the Don River southeast to the northern Caspian Sea for more than 400 km (Figure 1b). Its width spans 30–50 km, narrowing to 15–20 km near the Salsky uplift and the Zunda Tolga structure. The central part of the depression is a combination of elongated ridges with steep slopes and peaks reaching a height of 40 m abs.

The ridges are separated by hollows, partially closed and occupied by lakes. This ridge topography is considered to have been created by a cataclysmic flood due to the overflow from the Caspian Sea at the maximum stage of the Khvalynian transgression (Chepalyga 2007; Grosswald 1998; Komatsu and

Baker 1996). The western and eastern parts of the depression have a relatively flat bottom, into which is cut a valley about 2 km wide and up to 10 m deep, currently occupied by the Zapadny and Vostochny Manych rivers, mostly swamped or turned into reservoirs.

The runoff threshold has a height of approximately +27 m (Badyukova 2011). However, Svitoch and Makshaev (2012) suggest that it had a height of 45–50 m during the Khvalynian time and was eroded during the formation of the Manych overflow. To the east of this threshold, the current bottom of the depression belongs to the Caspian basin, while to the west, it belongs to the Black Sea basin. The sediments containing the Caspian mollusk fauna indicate the penetration of the Caspian waters into the Manych Depression. The Early Khvalynian mollusk assemblage contains index species such as *Didacna ebersini*, *D. parallela* and *D. protracta*, accompanied by *D. subcatillus*, and numerous species of the genera Dreissena, Monodacna and Hypanis broad stratigraphic range, which live in slightly brackish water (Yanina 2012). Until recently, only radiocarbon dating of Early Khvalynian shells allowed for determining the timing of the Caspian water discharge through the Manych Depression.

The first radiocarbon dates for the fauna of the Early Khvalynian mollusks of Manych Depression were obtained in 2000 at the Laboratory of Pleistocene Paleogeography of Lomonosov Moscow State University (lab. index MGU) (Svitoch and Parunin 2000; Svitoch and Yanina 2001). Kh. A. Arslanov (St. Petersburg State University, LU) obtained a series of ^{14}C dates for several natural sections in 2008–2009 (Arslanov and Yanina 2008; Chepalyga et al. 2009). All these dates were obtained using liquid scintillation counting (LSC). The first data using accelerator mass spectrometry (AMS) were obtained at the University of Groningen (GrA) (Svitoch and Yanina 1997; Svitoch et al. 2008, 2009). Based on an analysis of the available geochronological data, Svitoch and Makshaev (2017) suggested that the last discharge in the Manych Depression occurred about 15 ka BP, and the flow of the Caspian waters along the Manych continued for about 3–4 ka. The latest synthesis of geochronological data for the Caspian region (Makshaev and Tkach 2023) suggests two phases of the Caspian flow along the Manych—short-term flow between 17.5–17.0 ka BP at the rise of the Early Khvalynian transgression and renewed flow between 14.5–13.5 ka BP with its complete cessation no later than 12.8 ka BP, when, according to the authors, a rapid drop in the level of the Early Khvalynian basin occurred. Some researchers believe that the flow of Caspian waters along the Manych continued during the Early Holocene. The current drainage divide near the Zunda Tolga village was raised later due to accumulation in the internal deltas of local rivers (Badyukova 2011).

The geochronology of the Khvalynian stage of the Manych Depression has been based on scattered dating of interlayers with the Khvalynian fauna of various coastal outcrops. (Table 1, Figure 1b).

Previously published dates vary significantly, and the position of samples in the sections is inadequately described, with a lack of detailed geomorphological characteristics of the sites. As a result, it is impossible to determine which relief surfaces the obtained dates belong to. Consequently, it becomes challenging to analyse whether these dates correspond to different stages of the discharge event and verify them using geomorphological criteria.

Our study aims to determine the timeline of the last overflow of Early Khvalynian waters through the Manych Depression. We analysed two sections containing the Early Khvalynian fauna to achieve this and obtained new AMS dates. In addition, we summarised and critically analysed the literature data with previously obtained ^{14}C dates.

Materials and methods

We studied the two most representative sections (Figure 1b) of the Khvalynian discharge sediments in the Manych Depression. The height of terraces where outcrops were found was measured by the GNSS rover EFT M4 in RTK.

*Table 1. Published radiocarbon dates of the Lower Khvalynian deposits of the Manych Depression**

No.	Site	Material	Lab no.	^{14}C age, yr BP	^{14}C age, cal yr	Dating reference
1	Manych-Balabino	Shells of Khvalynian *Didacna*	MGU-1491	14300±680	17390±880	Svitoch et al. 2009
2	Manych-Balabino	Mollusk shells of different compositions	MGU-1489	25690±300	29940±360	Svitoch et al. 2009
3	Sanmanych	Shell detritus	LU-5854	11210±130	13100±130	Arslanov et al. 2016
4	Lake Manych	Mollusk shells of different compositions	LU-5853	19330±240	23340±270	Arslanov et al. 2016
5	Lake Manych	*D. trigonoides*	LU-5852	10900±200	12860±200	Arslanov et al. 2016
6	Levyi Island-3	Shells of *D. protracta*	LU-5769	10930±370	12800±450	Svitoch et al. 2009
7	Podmanok-2	Shells of *Didacna*	MGU-1553	8070±120	8960±190	Svitoch et al. 2009
8	Zunda Tolga	Shells of *Didacna protracta*	LU-5725	10670±140	12590±190	Svitoch et al. 2009
9	Zunda Tolga	Shells of *D. ebersini*	LU-5726	11420±220	13320±210	Svitoch et al. 2009
10	Zunda Tolga	Shells of *D. ebersini*	GrA-33717	12740±50	15190±80	Svitoch et al. 2009
11	Chogray	Shells of *Hypanis plicatus*	LU-5768	11470±180	13360±170	Svitoch et al. 2009
12	Chogray	Shells of *D. protracta*	LU-6021	12150±900	14670±1240	Arslanov et al. 2016

*Calibration was performed in OxCal 4.4 software (Bronk Ramsey and Lee 2013) using the IntCal20 terrestrial calibration curve (Reimer et al. 2020).

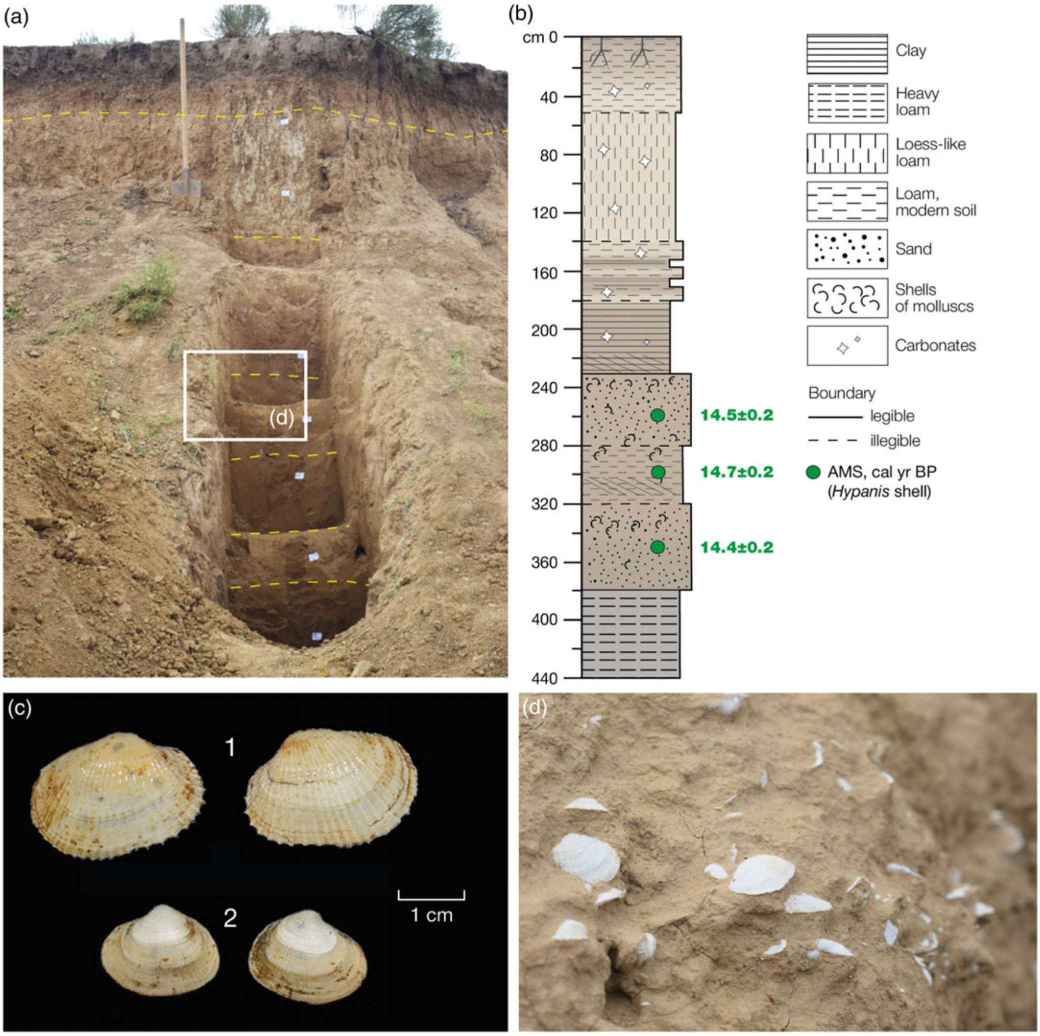

Figure 2. *ZT-2 section (Zunda Tolga, Chogray Reservoir); (a) general view; (b) lithological plot; (c) mollusk finds: 1 – Hypanis plicata; 2 – Monodacna caspia. (a), (b) and (c) modified after Semikolennykh and Panin (2023).*

ZT-3 section

ZT-3 section (45°35′53′′N, 44°12′28′′E; H = 28.2 m) is located in a natural outcrop of the Khvalynian terrace on the southwestern shore of the Chogray reservoir. The terrace's surface has a gentle slope towards the reservoir, complicated by aeolian landforms (a cluster of small, up to 3x1 m, dunes). Plumes, bars, and aeolian forms are observed near the sandy outcrops on the former reservoir's dry bottom.

In the ZT-3 section, we selected three samples of Caspian mollusk shells *Hypanis plicata* and *Monodacna caspia* (Figure 2b) from the strata of poorly sorted brown sands and brown loams with a total thickness of 1.5 m. *Hypanis plicata* and *Monodacna caspia* shells were found throughout the entire depth of the strata (Figure 2c, Table 2). The shells are predominantly small, thin-walled, located randomly or enriched in thin layers within the sediments (Figure 2d), including in two valves, which indicates the *in situ* formation. The basin's salinity could range from 4–8‰, significantly lower than the Early Khvalynian Caspian basin's reconstructed salinity of 10–12‰, though waters closer to the coasts

Table 2. *Species composition of the lower Khvalynian deposits of the OL-2 and ZT-3 sections**

No.	Species	Family	Sediments	Basin	Salinity, ‰	Depth, m
1	[a]*Didacna ebersini* (Fedorov 1953)	Cardiidae	Lower Khvalynian	Caspian	5–7	—
2	[a,c]*Didacna protracta protracta* (Eichwald 1841)	Cardiidae	Khvalynian, Novocaspian	Caspian	11–13	25–85
3	[a]*Didacna subcatillus* (Andrussov 1910)	Cardiidae	Bakinian, Khazarian, Hyrcanian, Khvalynian	Caspian	—	—
4	[b]*Dreissena polymorpha* (Pallas 1771)	Dreissenidae	Upper Quaternary sediments	Ponto-Caspian	≤2	≤10
5	[b]*Hypanis plicata* (Eichwald 1829)	Cardiidae	Old Euxinian and Neoeuxinian, Lower Khvalynian	Ponto-Caspian	4–8	0–30
6	[b]*Monodacna caspia* (Eichwald 1829)	Cardiidae	Neoeuxinian, Lower Khvalynian	Ponto-Caspian	2–14	2–15

**References:*
[a]*Nevesskaya (2007);*
[b]*Kijashko (2013);*
[c]*Logvinenko and Starobogatov (1969).*

were much less saline and hosted *Hypanis plicata* and *Monodacna caspia* as typical species (Yanina 2012, Fig. 47D), and it was the coastal waters that fed the Manych strait.

Also, the studied section of the Manych discharge of Caspian waters could have been under the desalination influence of the waters of local rivers.

Hypanis plicata and *Monodacna caspia* shells do not strictly indicate the Early Khvalynian age of sediments. However, the height of the host layers (22–25 m above the present sea level) leaves no room for any other interpretation of stratigraphic attribution other than Early Khvalynian. Also, on the northern shore of the Chogray reservoir, typical Early Khvalynian mollusk assemblage with indicator species *Didacna ebersini* and *D. protracta* were found as part of deposits of the same terrace at similar heights (Svitoch et al. 2010).

The section's structure reflects fairly dynamic marine sedimentation conditions, which were later replaced by calm lagoon-estuary conditions and subaerial conditions. According to high-precision satellite positioning data, the layer of sandy deposits with the Early Khvalynian fauna is 25.9–24.4 m above modern sea level.

OL-2 section

OL-2 section (46°01′38.0′′N; 43°23′05.9′′E; H = 20.5 m) is located at the western tip of the Island Levyi of Lake Manych (Figure 3). This is one of the most complete sections of Lower Khvalynian deposits (Svitoch and Khomenko 2009).

Island Levyi is a ridge with a gently sloping or slightly undulating surface, extending up to 16 km long and with an average width of 250 m (maximum 1 km). It is a sub-latitudinal landform situated above the edge of Lake Manych, with a relative height of 6–7 m. The ridge is composed of clayey sediments of the ancient lake (Svitoch and Khomenko 2009), overlain by a deluvial and eluvial cover with adjacent sediments of the Khvalynian runoff.

We found the well-preserved skull of a northern mole vole *Ellobius talpinus* (Pallas 1770) (Figure 3c) at a depth of 1.45 m in the Island Levyi section (Figure 3a). A.K. Markova identified the skull. It was discovered in light beige, wavy, cross-layered, well-sorted, medium-grained quartz sand. We also collected a mollusk shell sample of *Didacna ebersini* (Figure 3d) from the same layer but at a depth of 1.60 m.

In this section, we found small, rare shells of *Didacna protracta protracta, D. ebersini, D. subcatillus subcatillus, Dreissena polymorpha,* and *Hypanis plicata* (Table 2) in well-sorted, medium-grained sands at a 1.4–1.7 m depth. They were found in a thin layer of sediment. This mollusk's fauna indicates the Early Khvalynian malacofaunal assemblage. The composition of malacofauna suggests that the water has a salinity of about 11–13‰, which is similar to the salinity of the modern Middle Caspian Sea. However, the shells' depressed appearance suggests that the discharge water area was somewhat desalinated, possibly due to the freshwater introduced by local rivers.

The section's structure reflects a gradual change in sedimentation conditions from a calm estuary (ingression of the Caspian waters) to dynamic flowing ones (development and activation of the flow). The upper section of the Lower Khvalynian sediments consists of cross-bedded, well-sorted, medium-grained sands containing Caspian mollusk fauna. This sedimentary layer indicates a rise in the discharge water level, up to 19 m above the current sea level, and an increase in water flow velocity.

The malacofaunal composition of the sediments indicates a slightly lower (compared to the Early Khvalynian basin) salinity of the strait (about 10–11‰), which is explained by the desalinating influence of local watercourses.

Outcrop deposits have been studied previously (Svitoch and Khomenko 2009; Svitoch et al. 2009, 2010). A radiocarbon date of 10930±370 BP, 12800±450 cal BP (Svitoch et al. 2009) was obtained from the shells of the Khvalynian mollusk fauna (*Didacna protracta*) from the section (Figure 3f). The idea of the time of the Manych discharge closure—the cessation of the flow of water from the Khvalynian Caspian Sea—is primarily based on this date (Svitoch and Makshaev 2012, 2017;

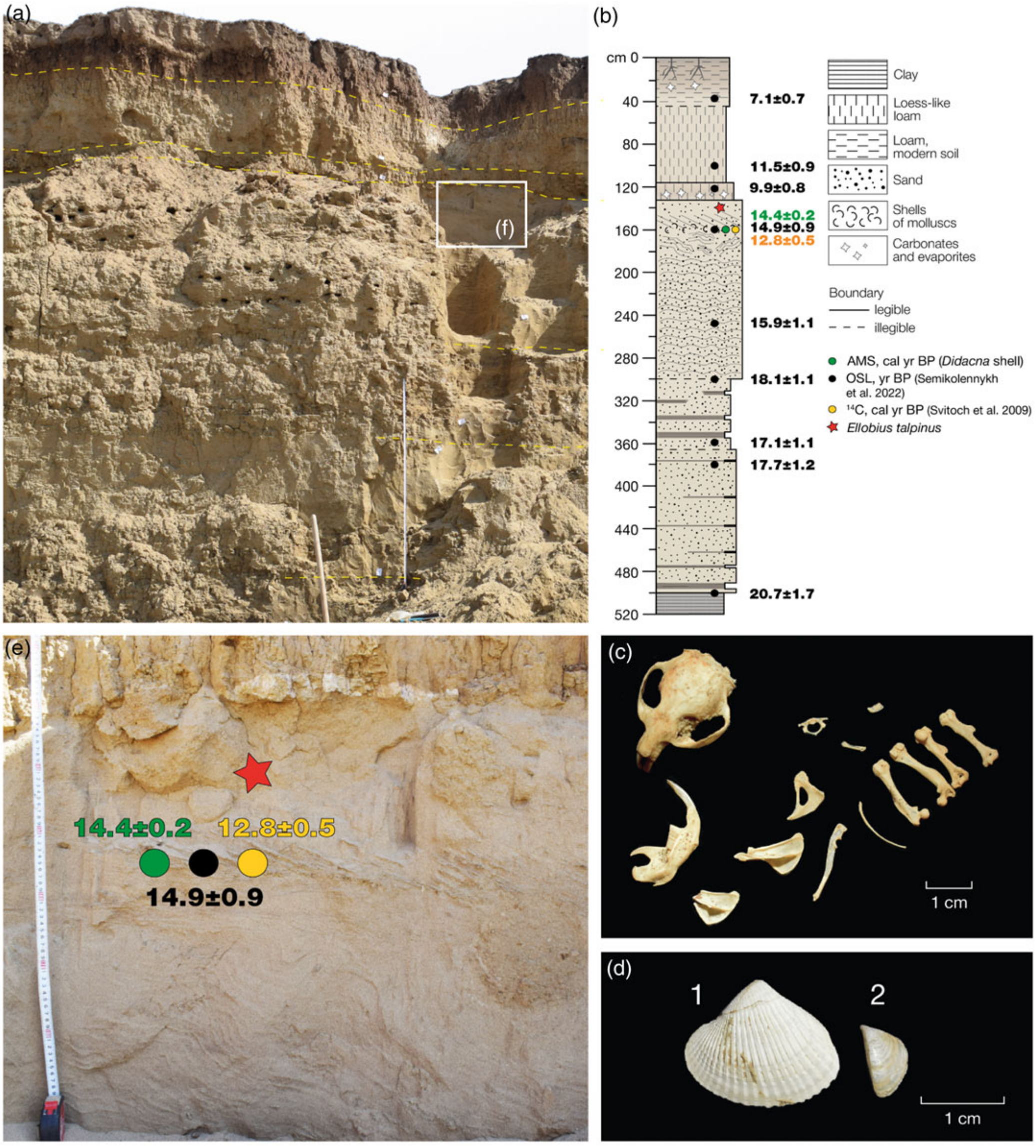

Figure 3. *OL-2 section (Ostrov Levyi, Lake Manych); (a) general view; (b) lithological plot; (c) skull of a northern mole vole Ellobius talpinus found in the section; (d) mollusk finds 1 – Didacna ebersini, 2 – Dreissena polymorpha; (f) the top part of the Khvalynian sands with mollusk fauna and the skull of the Ellobius talpinus for which three dates (AMS, ^{14}C, OSL) have been obtained.*

Makshaev and Tkach 2023). Semikolennykh et al. (2022) recently obtained the first OSL dates for this section and, respectively, the first OSL dates for all Khvalynian deposits within the Manych Depression, which made it possible to determine the age of the Khvalynian discharge in the range of 17.7–14.9 ka BP (Figure 3b). Upon discovering that the OSL dates were considerably older than the previously obtained radiocarbon date, it is necessary to conduct further investigation of this section.

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AMS dating

Four shells were selected for radiocarbon dating: three from section ZT-3 (layers 5, 6, 7; depths from the earth's surface 2.6, 3.0, and 3.5 m, respectively) and one from section OL-2 (layer 4, depth 1.6 m). All shells from ZT-3 belonged to the species *Hypanis plicata*, which had two valves preserved, confirming they were formed *in situ*. The sample from the OL-2 section is an intact, well-preserved valve of *Didacna ebersini*. Additionally, the skull of *Ellobius talpinus* was collected in the OL-2 section at a depth of 1.45 m and was used for dating. The good preservation of the skull indicates its *in situ* position. The discovery of the remains of a digging animal at the very top of the Khvalynian sands suggested that they would help constrain the timing of the establishment of land conditions after the cessation of flow through the strait.

Radiocarbon dating was conducted in the Centre for Applied Isotope Studies at the University of Georgia. The shells were manually cleaned and placed in an ultrasonic bath for 40 min to remove superficial contaminants, sonicated with diluted HCl for 15 min to leach surface contamination, and then rinsed and dried at 105°C (Hadden and Schwadron 2019).

The carbonate samples were reacted under vacuum with 100% H_3PO_4 to recover CO_2. The resulting CO_2 was cryogenically purified from the other reaction products and catalytically converted to graphite (Cherkinsky et al. 2010). Graphite $^{14}C/^{13}C$ ratios were measured using the NEC 500 kV Tandem Pelletron accelerator mass spectrometer (AMS). The sample ratios were compared to those measured from Oxalic Acid I (NBS SRM 4990). Carrara marble (IAEA C1) was used as the background, and travertine (IAEA C2) was used as a secondary standard. The sample $^{13}C/^{12}C$ ratios were measured separately using a Thermo GasBench II-IRMS and expressed as $\delta^{13}C$ with respect to PDB, with an error of less than 0.1‰. All ^{14}C dates have been corrected for natural isotope fractionation. The error is quoted as one standard deviation and reflects statistical and experimental errors.

Calibration of radiocarbon data was carried out in the OxCal program using the IntCal20 calibration curve (Reimer et al. 2020). The event's timing was determined using the R_Combine module of the OxCal program (v.4.4).

Results and discussion

Analysis of previously published dates

In recent years, there has been a significant increase in geochronological data obtained for the Caspian region, including both ^{14}C and OSL dating results. Several reviews have been published to reconstruct the historical level of the Caspian Sea and the palaeogeographical events that caused changes in its level (Leroy et al. 2022; Makshaev and Tkach 2023; Tudryn et al. 2022). These reviews are based on the summary of previously obtained radiocarbon data.

The difficulty of choosing between the marine and atmospheric calibration curves and the progress made in recent years in the radiocarbon method leads to many conflicting interpretations of existing radiocarbon data. Most previously published works used a marine calibration curve with an ΔR value to calibrate radiocarbon ages obtained from shells and bottom sediments.

Some researchers, such as Tudryn et al. (2022), use the calibration curve for terrestrial materials for their data and the generalisation of previously obtained results. They base this choice on the classification of the Caspian Sea as an inland water body (Leroy et al. 2022; Tudryn et al. 2022). In contrast, other researchers employ both marine and atmospheric calibration curves, as seen in the work of Makshaev and Tkach (2023).

There is also no consensus on whether, in such generalisations, one should consider the reservoir effect and which values to utilise. It should be noted that all available data for the Caspian region allowing an assessment of the reservoir effect are derived from radiocarbon ages not exceeding 1000 years, primarily based on contemporary samples. According to these data, the reservoir effect is estimated to be around 400 years on average (Arslanov and Tertychnaya 1983; Kuzmin et al. 2007;

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Leroy et al. 2022; Olsson 1983). However, it is well-established that the reservoir effect is not a constant value for a particular water body; it can vary over time. Given significant changes in the geochemistry of the carbon cycle in the region and shifts in the sources of incoming material, we cannot be certain that the reservoir effect was approximately 400 radiocarbon years throughout the entire reconstructed history of the Caspian Sea. Considering that the Caspian Sea is not part of the global ocean, we also take the stand that, when applicable, it is reasonable to use the atmospheric calibration curve with an adjustment for a "freshwater" reservoir offset for calibrating radiocarbon ages. Estimating the reservoir effect for the Caspian Sea poses some challenges. Firstly, due to its vast size and depth, and secondly, due to a lack of paired dates (aquatic and terrestrial origin) or, for example, shells from museum collections of known age (collected before 1850). Comparing dates obtained from a shell with the atmospheric age taken from the calibration curve allows for calculating the offset (ΔR).

Based on the above, we decided to use the INTCAL20 curve to calibrate the obtained data for this study. Two additional arguments for this choice were:

- The objects of our study are in the shallow part of the Caspian Sea (Manych Strait), which ensures good gas exchange of water masses with the atmosphere, and, accordingly, the predominance of atmospheric carbon;
- The morphological features of the dated shells (whole, with preserved two valves) indicate their "in situ" origin, and accordingly, we can assume they formed with the predominance of atmospheric carbon.

Dates obtained through the LSC method, currently outnumbering those obtained using AMS, primarily exhibit a larger standard deviation, leading to wider calibrated age intervals. Typically, these data lack corrections for isotopic fractionation. Often, we cannot be certain of the "cleanliness" of the dated material. Even if, for instance, clusters of shells of the same species were selected for dating, biological fractionation can lead to different radiocarbon ages on the inner and outer sides of an individual shell (with a difference of approximately 500 years). This variability can impact dates derived from large assemblages, especially when using the LSC method.

The analysis of the dates previously obtained by the LSC method (Table 1) indicates that most of the dates obtained from one species of Khvalynian shells are rejuvenated. This may be due to incomplete removal of organic carbon (of soil origin) from the shell material during dating. When dating carbonate material using the LSC method, the treatment of the carbonate material to obtain CO_2 for benzene synthesis (the counting substance) occurs under the influence of hydrochloric acid. This acid also dissolves stable forms of soil humic substances that are challenging to remove by other means. Considering the complex paleogeographic history of deposits in the studied sections, it is plausible to acknowledge the possibility of shell impregnation with percolating soil organic matter, which may carry younger carbon. The sole AMS date obtained earlier aligns well with the dates presented in this study.

It must be acknowledged that methodological approaches to dating carbonate material using AMS are generally more advanced. They enable the extraction of pure CO_2 when dating very small samples, assuring that no sample rejuvenation occurs during sample preparation. All the described challenges contribute to the dispersion of dates obtained for the Lower Khvalynian deposits of the Manych Depression earlier.

Geomorphological and stratigraphic position of dated samples

New AMS dates were obtained from samples of Early Khvalynian shells taken from sandy deposits, the formation of which suggests the presence of a directional current. In the Zunda Tolga village area, the sands stretch as a strip at the bottom of the depression and are cut by a younger incision about 2.0 km wide (Figure 1b). This incision from east to west crosses the local watershed (the drainage threshold of the depression near the Zunda Tolga village), i.e., could not have been created by local rivers. We assume the incision was formed by early Khvalynian waters and later inherited by local rivers. In the central part of the depression, the incision is lost in a complex ridge-hollow topography, which is older than the runoff event under consideration. The central part of the depression is composed of lacustrine loams, which most researchers date to the first half of the Late Pleistocene (e.g., Badyukova 2011; Kurbanov et al. 2018; Popov 1983; Svitoch and Makshaev 2017; Yanina 2020). There are no local sources of sand here. The sandy deposits found at the bottom of the depression were transported from the east through the drainage from the Caspian Sea. This is supported by mollusk shells from the Khvalynian Epoch, which are present only in these sands and no other deposits.

The species identity of the dated shells allows them to be attributed to the Early Khvalynian Epoch. In section OL-2, shells were sampled from the upper part of the sands near their top, i.e., refer to the end of Khvalynian sedimentation in this section. Both studied sections are coastal outcrops located near the incision marking the end of the flow through the Manych Depression. Currently, layers of sand with dated shells lie 5–8 m above the bottom of the depression, while both studied sections form terraces higher than 10 m. The geomorphological position of the sections indicates that soon after the accumulation of sands with shells, the bottom of the former stream was cut by erosion, and Khvalynian sedimentation in both sections ended—subsequently, subaerial deposits—loess-like sandy loams and loams—accumulated on the Khvalynian sands. Based on the totality of data, it can be considered that the layers of Khvalynian sands dated by shells belong to the final stage of runoff through the Manych Depression.

New radiocarbon dates and their interpretation

The results of radiocarbon dating are presented in Table 3. The dates for marine shells in both sections were very compact, although the date UGAMS 61397 is somewhat out of line with the other three (Figure 4). The ^{14}C dating results correlate well with OSL ages obtained for the top marine sands in the OL-2 section (Figure 3b). Considering the excellent condition of the shells, including two preserved valves, and their stratigraphic and geomorphological position, it can be confidently stated that the obtained dates refer to a single event. This provides the basis for determining the time of this event by combining dates. For this purpose, the R_Combine module of the OxCal (v.4.4) program was used. All four dates give a combined date of 12391±16 BP or 14520±170 cal BP, but the chi-squared test for internal consistency fails at 5% (Figure 4b). If we exclude the date UGAMS 61397, the test is passed successfully, and the combined data is generated at 12360±18 BP, or 14470±200 cal BP (Figure 4c). We take the last date to be the age of the dated event.

The combined data was obtained from the same localities of the Khvalynian malacofauna for section OL-2 and from the same lithological layer as the dates published earlier (Table 1, No. 6, 8–12). Most LSC dates are in the range of 12.6–13.4 cal ka BP, and the opinion about the relatively late, after 13 ka BP, cessation of the flow of Caspian waters through the Manych Depression is based on these dates (Makshaev and Tkach 2023; Svitoch and Makshaev 2017). The new AMS dates we obtained, which align with the results of OSL dating, suggest that most of the previously published LSC dates underestimate the age of the Khvalynian deposits in the Manych Depression. The reasons for this seem to be methodological (see *Analysis of previously published dates* in the *Results and discussion* section). The only AMS date (Table 1, No. 1) matches our dates well.

The marine Khvalynian deposits found in both sections are covered by subaerial strata, which suggests that there were no later instances of seawater penetrating the central part of the Manych Depression. This leads us to believe that the dated event was the final overflow of Caspian waters into the Black Sea basin. Marine sand containing the Caspian mollusks suggests the presence of runoff instead of a sea bay. These sediments could not accumulate in stagnant water but imply a relatively high flow speed, measured in several decimeters per second. Thus, the water flow from the Early Khvalynian transgression along the Manych stopped soon after 14.5±0.2 ka BP. Taking into account the previously obtained OSL dates for the OL-2 section, the time interval for the functioning of the strait can be

Table 3. *Radiocarbon dating results*

UGAMS	Sample ID	Depth, m	Material	$\delta^{13}C$, ‰	^{14}C age, years BP	±σ	Calibrated age, years BP	±σ	pMC	±σ
61396	ZT-3-1	2.6	Shell: *Didacna ebersini*	0.33	12360	30	14460	200	21.47	0.08
61397	ZT-3-2	3.0	3 shells: *Hypanis plicata*	1.09	12480	30	14700	160	21.14	0.08
61398	ZT-3-3	3.5	3 shells: *Hypanis plicata*	0.51	12370	30	14480	190	21.43	0.08
61399	OL-2-2	1.6	6 shells: *Hypanis plicata*	0.57	12350	30	14440	210	21.48	0.09
62542	OL-2-2	1.45	*Ellobius talpinus,* Cranial bones (collagen)	−17.14	160	20	150	90	97.99	0.25

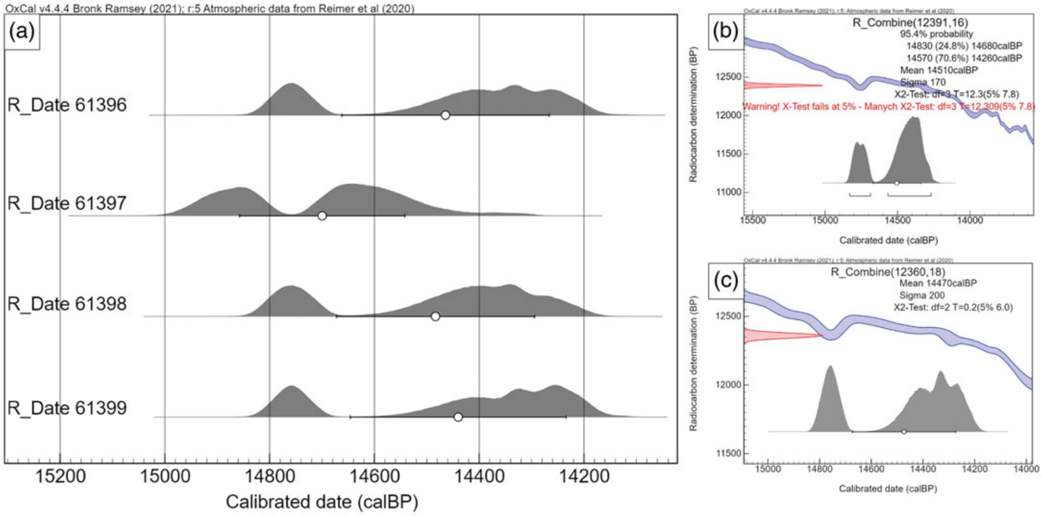

Figure 4. *Determination of the time of the final runoff event through the Manych Depression. (a) calibrated dates from shells in the Lower Khvalynian marine sands (Table 3). Combined dates: (b) on all four dates; (c) on three dates excluding the UGAMS 61397.*

determined at ~18.0–14.5 ka BP, which is in good agreement with the age of the Early Khvalynian deposits of the Lower Volga (Kurbanov et al. 2021, 2023). Our results also corroborate the results of ^{14}C dating of the Early Khvalynian deposits in the northern Caspian Lowland by Arslanov et al. (2016) that proposed the high stands at +35 and +22 m to have occurred between 16 and 14 ka cal BP. The Late Khvalynian basin with 0 m and 12 m sea level stages were dated to 14–12 ka cal BP. In this or any other study, the highest stage of the Early Khvalynian transgression (+48 to +50 m) was not dated.

A 5–6 ka gap exists between the OSL dates for the lower subaerial strata and the upper sea sands in section OL-2 (Figure 3b). To clarify, when subaerial sediments began accumulating, the cranial bones of a northern mole vole (*Ellobius talpinus*) skeleton found in section OL-2 at the border of subaerial and marine sediments, were dated (Figure 3c). The skeleton was in an anatomical position, i.e., no signs of redeposition or traces of a burrow were found in the overlying sediments. Unfortunately, the date turned out to be too young—only 100–200 years ago. Probably, traces of excavation activity remained in the already destroyed part of the section. At the same time, the AMS and OSL ages of the tops of marine sands correspond well to each other.

Loess-like sediments did not accumulate immediately on the former bottom of the Early Khvalynian discharge after the flow ceased. It is possible that the Manych Depression remained damp for several thousand years after the flow stopped. Analysis of the rodent fauna revealed that the climate of the Manych Depression was cold and dry during the discharge (Chepalyga and Markova 2019). Therefore, recent humidification cannot be attributed to climatic factors. Most likely, residual reservoirs existed, and only after they dried up were conditions created for wind activity and loess accumulation. The arid conditions that accompanied the beginning of the accumulation of loess-like deposits in section OL-2 are evidenced by a relatively thick layer of evaporites at the base of subaerial sediments (Figure 3f).

Conclusions

The published array of ^{14}C dates for the Khvalynian deposits of the Manych Depression, obtained mainly by the scintillation method, gave previous researchers the basis for the conclusion that the last flow of Caspian waters into the Black Sea ended after 13.0 ka BP. However, recently obtained OSL dates indicate an older age for this event. These new dates were obtained from single shells using AMS,

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with a clear paleogeographic reference, and correlate well with the results of OSL dating. The obtained ^{14}C dates make it possible to estimate with greater accuracy the time of the last phase of runoff at about 14.5 cal ka BP.

Despite the wealth of geochronological data available, we still need to obtain well-documented ^{14}C AMS ages with a small confidence interval tied to the paleogeographic context and study the reservoir effect across different chronological sections. Furthermore, it is essential to correlate the obtained data with the OSL data. These steps are necessary to determine high-resolution reconstructions for the Caspian region and to accurately estimate the time of the beginning of the last flow of Caspian waters.

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