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# The timing and sedimentary facies of the early Khvalynian stage in the Lower Volga Region (Northern Caspian Lowland)

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ABSTRACT

The sedimentary record from the Lower Volga Region, located in the Northern Caspian Lowland, could provide detailed insights into the effects of global and regional changes on the world's largest endorheic basin over the last 35 ka. In this paper, we present the comparison results of sedimentological analysis and radiocarbon dating of the Khvalynian deposits obtained from key sections in the Lower Volga Region. Seven lithofacies (LF1–LF7) are recognized. According to the radiocarbon dates, the age of the Early Khvalynian stage in the Lower Volga Region ranges between 27.0 and 12.5 cal ka BP. The deposition of the chocolate clay corresponds to an interval between 20.0 and 12.5 cal ka BP. The density of radiocarbon ages peaks during the 14.1–13.4 cal ka BP period. The analysis of radiocarbon data from mollusc shells and the lithofacies characteristics of Khvalynian sediments reveal a distinct pattern corresponding to major Late Pleistocene climatic events. This information enables us to reconstruct the depositional history of the Lower Volga Region from the end of MIS 3 to the Younger Dryas.

## 1. Introduction

The history of the Caspian Sea region is inextricably linked with transgression and regression events during the Quaternary. Climatic changes during the Late Pleistocene, as well as transformations of river drainage systems, had a significant impact on coastline position, water salinity, sedimentation processes, the intensive evolution of endemic mollusc species (e.g. the genus Didacna) and other processes in the Caspian Sea (Andrusov, 1888; Pravoslavlev, 1913; Zhukov, 1945; Fedorov, 1957; Nevesskaya, 1958; Moskvitin, 1962; Obedientova, 1977 Varuschenko et al., 1987; Svitoch and Yanina, 1997; Kroonenberg et al., 1997; Yanina, 2012; Svitoch, 2014; Kislov et al., 2014; Krijgsman et al., 2019; Yanina, 2020; Kurbanov et al., 2023).

The Early Khvalynian Basin was one of the largest basins in the Late Pleistocene history of the Caspian Sea, which predetermined the development of the modern environment in this region (Svitoch, 2014). It is believed that during its maximum stage, the sea level reached 45–50 m asl (Zhukov, 1945; Kovda, 1950; Fedorov, 1957) with a total area covered up to 950,000 km$^2$ (Varuschenko et al., 1987). The evolution of the Early Khvalynian Basin went through several stages, each corresponding to marine terraces with an altitude of 45–50 and 20–22 m asl (Kovda, 1950; Fedorov, 1957; Moskvitin, 1962). Lower Khvalynian sediments, predominantly clay, were deposited in the north-west of the Early Khvalynian Basin (Northern Caspian Lowland). This sediment sequence was named "chocolate clay" (Pravoslavlev, 1908). Chocolate clay is widespread and covers the area of the Middle and Lower Volga River valley, Ural River valley, Saikhin-Botkul-Baskunchak Lakes, and the system of Sarpa Lakes (Priklonsky et al., 1956; Brytsina, 1954; Arkhipov, 1958; Moskvitin, 1958, 1962; Vasiliev, 1961; Obedientova and Gubonina, 1962; Yakhimovich et al., 1986). The chocolate clay includes sand with mollusc shells. It could be either marine brackish to freshwater species *Didacna protracta, D. ebersini, Dreissena polymorpha, Dr. rostriformis distincta, Monodacna caspia, Hypanis plicata*, etc. (Fedorov, 1957; Svitoch and Yanina, 1997; Yanina, 2012). The occurrence of chocolate clay is sporadic and depends on the bed morphology features. Their thickness varies from 1.5 m in the flat area (Raigorod and Srednyaya Akhtuba sections) to more than 12.0 m (Svetly-Yar and Kopanovka sections) in palaeodepressions (Svitoch et al., 2017). The chocolate clay in the Early Khvalynian Basin originated from Pleistocene moraines and Permian red clay found in the northwestern and eastern

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parts of the Volga Basin, respectively (Tudryn et al., 2016; Makshaev and Svitoch, 2016). The permafrost processes, such as solifluction, could also increase the supply of materials to the Early Khvalynian Basin (Chistyakova and Lavrushin, 2004; Tudryn et al., 2016).

The reasons for the sea level fluctuations during the Early Khvalynian Epoch are subject to various interpretations, yet it is clear that climate change played a critical role (Kislov and Toropov, 2007; Kislov et al., 2014; Koriche et al., 2022; Gelfan et al., 2024). The environmental shifts in the Early Khvalynian Basin during the Late Pleistocene were significantly affected by the changes and degradation of the Late Valdai (Late Weichselian) Ice Sheet alongside the vast permafrost region in the northwestern segment of the Russian Plain (Kvasov, 1975; Yanina, 2012; Tudryn et al., 2013, 2016; Yanina et al., 2018). These transformative environmental changes not only resulted in altered river drainage boundaries but also significantly impacted runoff volume and precipitation across the expansive Russian Plain (Kvasov, 1975; Panin and Matlakhova, 2015; Sidorchuk et al., 2009, 2021; Panin et al., 2020, 2021; Gelfan et al., 2024), highlighting the profound influence of climatic factors on this region's historical landscape.

The discussion regarding the time frame of the Early Khvalynian Basin comes down to the following radiocarbon and luminescence dating results, which correspond to the interval between 27 and 11 ka BP (Kaplin et al., 1972a, 1972b, 1993; Parunin et al., 1985, 1989; Arslanov et al., 1988, 2016; Leonov et al., 2002; Makshaev and Svitoch, 2016; Tudryn et al., 2016, 2022; Yanina et al., 2017; Makshaev and Tkach, 2023; Kurbanov et al., 2021, 2022, 2023), while thermoluminescence (TL) dates from the Lower Khvalynian deposits correspond to an interval between 70 and 40 ka BP (Shakhovets, 1987; Rychagov, 1997). Although numerous studies have examined the palaeogeography of the Early Khvalynian Epoch in the Northern Caspian Lowland, there is still a lack of data on the stages of the Lower Khvalynian sedimentation (especially chocolate clay) and their connection with climatic fluctuation during the Late Pleistocene. This paper provides results on radiocarbon data, the lithological structure of the Lower Khvalynian deposits, and their correlation with the main Late Pleistocene climatic events.

## 2. Regional setting

### 2.1. Geographic setting

The Caspian Sea is Earth's largest inland water basin, which occupies 378,400 km$^2$ and contains more than 78,000 km$^3$ of water (Svitoch, 2014). The catchment area is up to 3.6 million km$^2$. The present surface elevation of the Caspian Sea is −29 m asl, and the average depth is 180 m. The average salinity of the Caspian Sea is 12.7 ‰, ranging from 1 to 3‰ near the Volga River Delta to 20.3 ‰ in the Balkhan Gulf. The basin is divided into three sections: the North, the Middle, and the South. Here, we focus on the northern part of the Caspian Sea (~46.0–50.5°N, 45.0–54.0°E), which is a vast lowland with altitudes ranging between 45 m asl in the northern edge to −29 m asl in the south near the avandelta of the Volga River. The area of the North Caspian Basin is 95, 000 km$^2$ with an average depth of 4 m. It contains only 1 % of the total water volume of the basin. The rivers that discharge into the North Caspian Basin contribute about 88 % of the total inflow (Svitoch, 2014). The northern limit of the Caspian Sea Lowland is the Obshchy Syrt, with an average elevation of 150–200 m asl. In the west, the lowland boundary is marked by the Ergeni Hills (~300 km long from the north to the south), and their altitude varies between 120 and 200 m asl. In the eastern part, the limit is the Sub-Ural Plateau, with altitudes between 120 and 450 m asl. The Volga, Ural, and Emba river valleys incise the lowland. On the slopes of these uplands, a series of abrasion coasts and terrace levels of Pleistocene Caspian Sea transgressions and regressions are present (Leontiev and Fedorov, 1953).

The lowland also consists of multiple temporary streams and inland drainage rivers (e.g. the Bolshoy Uzen and Maly Uzen rivers). Large salt lakes are also distributed in the Northern Caspian Lowland. The salt lakes are usually confined to the salt-dome structures with uplifts in the periphery. One of the largest uplifts in the Northern Caspian Lowland is Mount Bolshoy Bogdo, which is 149 m asl and 170 m above the Lake Baskunchak level.

The Northern Caspian Lowland is divided into the Lower Khvalynian marine plain (within altitudes of 0–45 m asl), composed of sand, clay, and clay silt sediments, and the Upper Khvalynian marine plain, composed of sand deposits (within altitudes of 0 to −20 m asl). Several palaeovalleys, palaeodeltas, and ilmens are also present in this area.

The Lower Volga Region is a 700 km long part of the Volga River fluvial system, located on the northwest side of the Northern Caspian Lowland (Fig. 1). The elevation within the area varies from 20 m asl to −29 m bsl. In the upper part, the Volga River flows along with the Volga Upland; tectonic and geological factors predetermine the riverbed. On the south edge of the upland near Volgograd city, the Volga River turns toward the southeast, forming a 400 km long and 30–40 km wide Volga-Akhtuba floodplain. The Volga and Akhtuba rivers are incised into the Pleistocene deposits to a depth of 30 m. In many outcrops, the regional (Caspian) Middle and Late Pleistocene regional stratigraphic units — the Bakunian, Khazarian, Atelian, Khvalynian, and Novocaspian — are present (Fedorov, 1957; Svitoch and Yanina, 1997).

### 2.2. Late Pleistocene regional stratigraphy

In the Northern Caspian Lowland, Late Pleistocene regional stratigraphy is subdivided into the Upper Khazarian, Atelian, Lower Khvalynian and Upper Khvalynian stages. This research focuses on the Khvalynian horizon, which comprises Lower and Upper Khvalynian subhorizons (Fedorov, 1957, 1978) (Fig. 2).

***Atelian horizon.*** The term Atelian was introduced by P.V. Pravoslavlev (1913), derived from the ancient name (Atel River) of the Volga River. In the Lower Volga region, Atelian deposits consist of continental sediments of various origins that formed during the regressive phase of the Caspian Sea. During Atelian regression, the elevation of the coastline of the Caspian Sea dropped to −53 and −140 m asl (Leontiev and Fedorov, 1953; Lokhin and Maev, 1990).

The stratigraphy of Atelian deposits varies. The lower section is composed of alluvial sand and silt (referred to as Akhtuba sands), while the middle and upper parts consist of loess-like sediments and paleosols (Moskvitin, 1962). Atelian deposits reach thicknesses of up to 20 m. Absolute dating (TL, OSL, and radiocarbon methods) indicates that the Atelian deposits span an age of 28–130 ka. In the northern part of the Lower Volga region, the accumulation of Atelian continental sediments continued into the initial phase of the Early Khvalynian transgression. Consequently, their stratigraphic position depends on both elevation and depositional age.

The Khvalynian horizon was defined by N.I. Andrusov (Pravoslavlev, 1913), after investigation of endemic bivalve mollusc species Didacna Eichwald (1838). As a result of geomorphological and sedimentological studies of several key sections in the 1950s–1960s, the Khvalynian horizon was subdivided into the Lower and Upper Khvalynian. These stages correspond to successive transgressive phases during the Khvalynian Epoch with different sediment compositions and mollusc assemblages (Fedorov, 1957, 1978; Brotskiy and Karandeeva, 1953; Svitoch and Yanina, 1997).

***Lower Khvalynian subhorizon.*** In the Lower Volga Region, the Lower Khvalynian deposits are represented by brown to dark-brown ("chocolate") clay, sand and silt, containing brackish-water mollusc assemblages such as *Didacna protracta, D. ebersini, D. parallella, D. trigonoides, Dreissena polymorpha, Dr. grimmi distincta, Monodacna caspia, Hypanis plicata, Laevicaspia caspia,* etc. (Yanina, 2012). The Lower Khvalynian deposits correspond to the high sea-level stand of the Early Khvalynian transgression, when the coastline of the Caspian Basin reached an altitude of 45–50 m asl and covered an area of approximately 950,000 km$^2$ (Zhukov, 1945; Fedorov, 1957; Varuschenko et al., 1987). The Early Khvalynian time is marked by the appearance of endemic

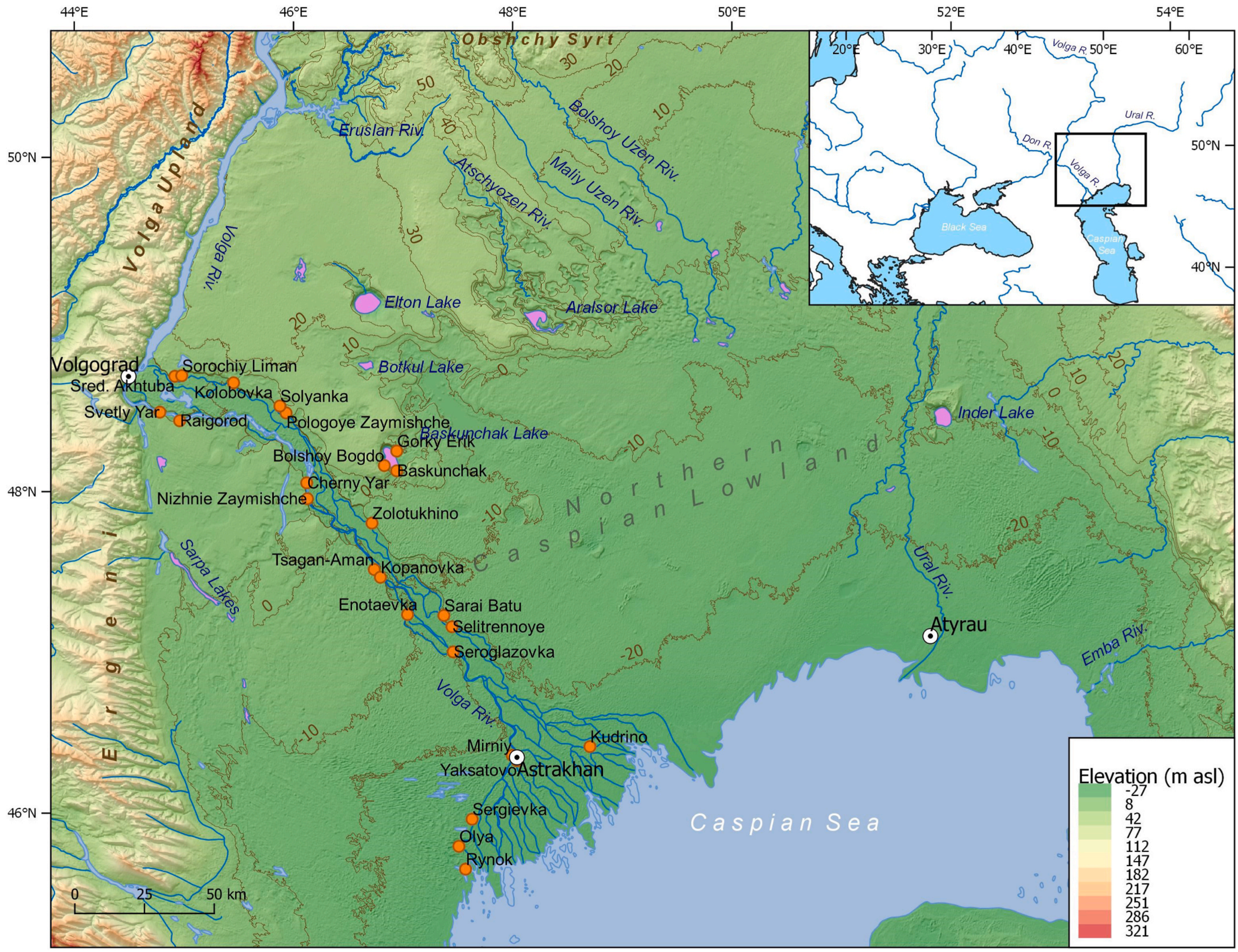


**Fig. 1.** Location of the studied key sections (orange dots) in the Northern Caspian Lowland. DEM derived from the Shuttle RADAR Topographic Mission (SRTM). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

brackish-water molluscs, such as *Didacna protracta* and *D. ebersini* (Yanina, 2012), within the sea area. During this transgression, the last connection between the Black Sea and Caspian Sea existed via the Manych Depression (Fedorov, 1978; Svitoch, 2014; Semikolennykh et al., 2022, 2025).

***Upper Khvalynian subhorizon***. The Upper Khvalynian sediments in the Northern Caspian Lowland are represented by marine light-grey sand and light-yellow silt within altitudes of 0 to −20 m asl. The Upper Khvalynian subhorizon represents the Late Khvalynian transgression event when the Caspian Sea level reached 0 m asl (Fedorov, 1978). The mollusc species diversity in Upper Khvalynian sediments is less than that in the Early Khvalynian sequence and is dominated by *Didacna praetrigonoides, Dreissena polymorpha, Monodacna caspia, Hypanis plicata*, and others (Yanina, 2012). The relative abundance of the molluscs and their large and more massive shells is attributed to warmer environmental conditions compared to those of the Early Khvalynian Basin.

A specific landform, the so-called Baer Knolls (Baer, 1856), covers areas of the Northern Caspian Lowland from the Lower Kuma, the Lower Volga and further east to the Lower Emba River regions. They are long parallel, nearly W–E trending hills mostly 10–15 m in height and 0.5–4.0 km length (Svitoch and Klyuvitkina, 2006; Badyukova, 2018; Lobacheva et al., 2021) (Fig. 3). The Baer Knolls deposits usually comprise three lithofacies: chocolate clay, cross-bedded to planar-laminated light-brown and light-grey silt and cross-bedded light yellow to yellow-grey sand. The Upper Khvalynian mollusc's age is about 14–9 ka, according to radiocarbon dating of shells. However, the reliable chronology of the Late Khvalynian phase is still under debate (Svitoch and Yanina, 1997; Rychagov, 1997; Arslanov et al., 2016).

## 3. Material and methods

### 3.1. Fieldwork

During the fieldwork in 2011–2021, the Khvalynian deposits in the Lower Volga Region sections of Svetly Yar, Srednyaya Akhtuba, Baskunchak, Raigorod, Cherny Yar, Nizhniye Zaimische, Tsagan-Aman, Kopanovka, Seroglazovka, Sarai Batu, and Selitrennoe were studied (Fig. 2). The Cherny Yar, Raigorod, Srednyaya Akhtuba, and Kopanovka sections are proposed as key sections for the Northern Caspian Lowland and have been studied for a long time (Pravoslavlev, 1908; Zhukov, 1935; Grichuk, 1954; Fedorov, 1957; Vasiliev, 1961; Moskvitin, 1962; Shkatova, 1975, 2010; Sedaikin, 1988; Svitoch and Yanina, 1997; Yanina, 2012; Tudryn et., al., 2013; Svitoch and Makshaev, 2020; Kurbanov et al., 2021, 2022, 2023; Zastrozhnov et al., 2020, 2021; Taratunina et al., 2023). We also analyzed the lithological structure of the studied sections and quarries within the Lower Volga River valley, Akhtuba River, and Volga Delta as presented earlier by Kaplin et al.

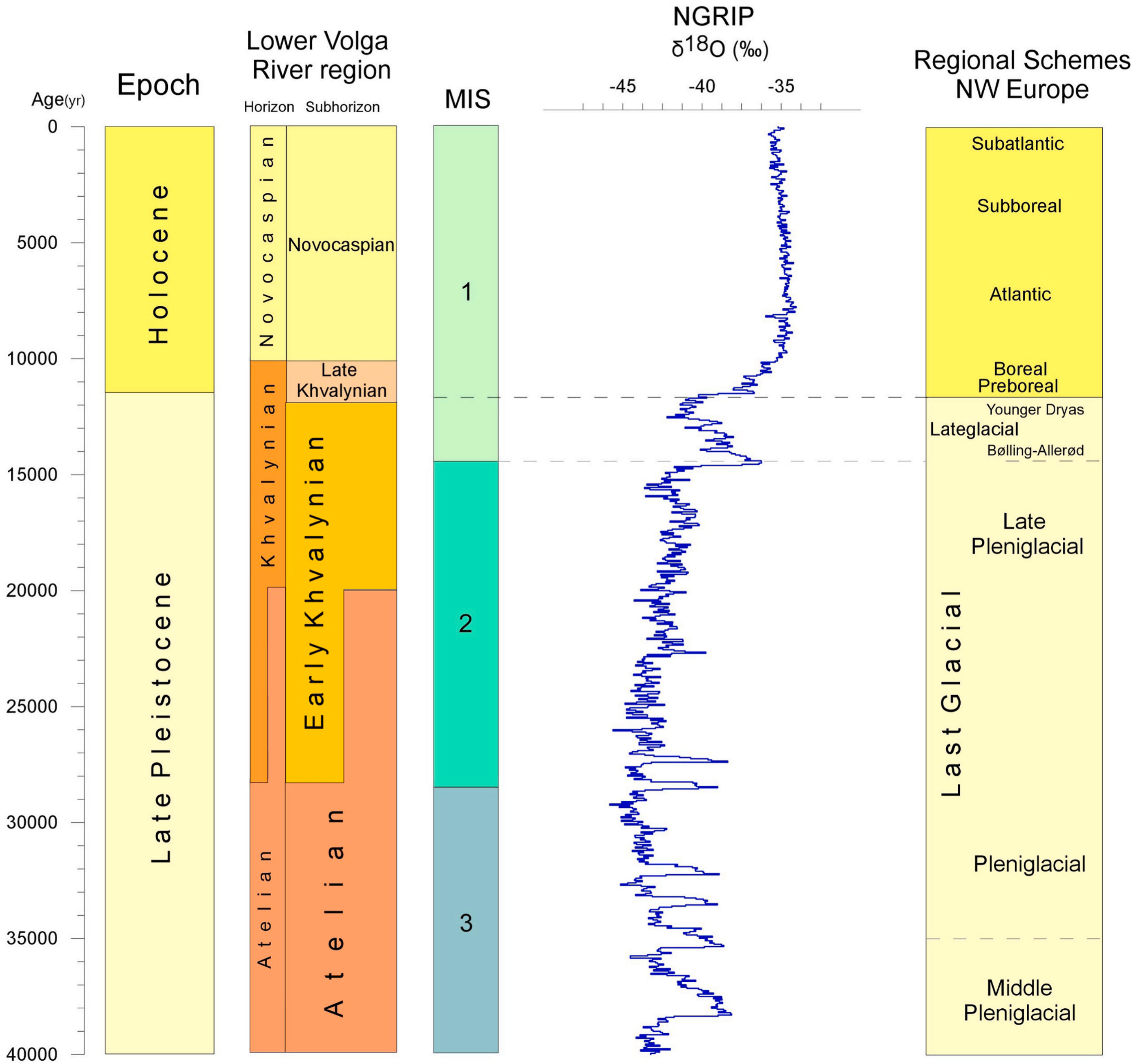


**Fig. 2.** Stratigraphic scheme for the Northern Caspian region according to this research. The Late Pleistocene-Holocene boundary was defined after Pillans and Gibbard (2012). The Marine Isotope Stages (MIS) were defined after Lisiecki and Raymo (2005). Regional schemes for northwest Europe are given according to Cohen and Gibbard (2019). The NGRIP $\delta^{18}O$ curve is taken from (Andersen et al., 2004). Regional schemes for the Lower Volga Region are given according to this research.

(1972a, 1972b), Vasiliev (1961), Svitoch and Yanina (1997), and Svitoch and Klyuvitkina (2006).

To identify lithological structures and sample the Lower Khvalynian deposits and mollusc shells, the surface of outcrops was cleaned with a mini shovel. The systematic analysis of the Khvalynian malacofauna was conducted in the Laboratory of Pleistocene Palaeogeography, Faculty of Geography, Moscow State University. For species identification, identification guides for Caspian Sea molluscs were used (Popov, 1983; Yanina, 2020; 2012; Nevesskaya, 1958), and reference collections stored at the Laboratory of Pleistocene Palaeogeography, Faculty of Geography, Moscow State University were consulted. The lithofacies analysis was implemented following the Nichols (2009) system. The sedimentary structure and lithofacies together with sampling sites of Khvalynian shells in the studied sections of the Lower Volga River valley are shown in Figs. 4 and 5.

### 3.2. Radiocarbon dating and age dataset

We compared (n = 85) radiocarbon dates from the Lower Volga Region sections to reconstruct the timing and sedimentological processes in the northwestern part of the Early Khvalynian Basin. Most radiocarbon dates were obtained from mollusc shells (*Didacna* sp., *Dreissena* sp., *Monodacna* sp. and *Hypanis* sp.). The samples for radiocarbon dating were collected from 25 natural and artificial sections and quarries (Fig. 1). For 29 radiocarbon ages obtained during the 1960s–2000s (Cherdyntsev et al., 1965; Kaplin et al., 1972a, 1972b;

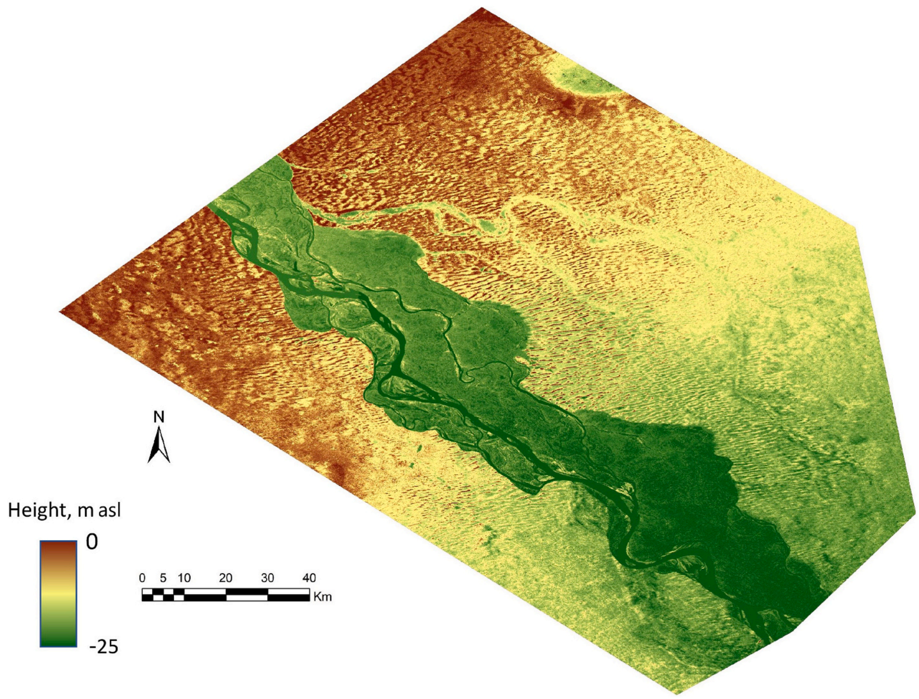


**Fig. 3.** The DEM of the Lower Volga region near Kopanovka and Selitrennoye sections, showing post-Khvalynian paleochannels incising the Baer knolls relief (SRTM data) (Lobacheva et al., 2021).

Zubakov et al., 1974; Badinova et al., 1976; Parunin et al., 1985, 1989; Svitoch and Yanina, 1997; Arslanov et al., 1988; Svitoch and Parunin, 2000; Svitoch and Klyuvitkina, 2006) the elevation of sample collection sites from outcrops was estimated according to the lithological description and then calculated using recent GPS position of the edge of the section. The location and elevation of collected mollusc samples from Cherny Yar, Enotaevka, and Seriglazovka sections were also determined from the archive field books of Dr. Sc. A.A. Svitoch. The accuracy of the sample position for previously published data was estimated to be within 0.5–2.0 m. We estimated the elevation and position within each section for 75 ages, while nine ages lack elevation data due to the absence of measurements.

The recent (collected between 2011 and 2021) radiocarbon ages (n = 41) were measured at the Radiocarbon Laboratory at the Saint Petersburg State University (Russia, lab. index LU). We also present three new ages of mollusc shells measured using accelerator mass spectrometry (AMS) at the Laboratory of Radiocarbon Dating and Electronic Microscopy, Institute of Geography of the Russian Academy of Science (Russia, lab. index IGAN$^{AMS}$).

### 3.3. Calibration curve and reservoir effect

The radiocarbon ages (n = 73) obtained by the scintillation method did not include a correction for isotope fractionation. Therefore, we relied on the concept proposed by Yu.A. Karpytchev (1993), according to which the value of $\delta^{13}C$ required for correction for the Caspian mollusc shells varies from −2.5 to 0.0 ‰, and the reservoir effect for the Caspian Sea estimated from mollusc shells and seal bones is 360–440 years. The reservoir effect of the Caspian Sea was estimated from mollusc shells as 385 ± 59 years (Olsson, 1980), 390–440 years (Kuzmin et al., 2007) and 360–410 years (Karpytchev, 1993). Based on these assumptions, we added 360–400 years to the obtained data for isotopic fractionation and subtracted approximately 400 years for the reservoir effect correction, which made it unnecessary to apply such corrections (Karpytchev, 1993). We calibrated the radiocarbon ages using CALIB 8.1 (http://calib.org/calib/) and the IntCal20 calibration curve with 2σ deviation (Reimer et al., 2020). The calibrated ages are given as cal ka Before Present (BP = 1950). For twelve AMS ages obtained from mollusc shells, a Marine20 calibration curve was used (Heaton et al., 2020). To evaluate the distribution for radiocarbon dates of Khvalynian deposits of the Lower Volga Region, the KDE_Model function in OxCal 4.4.4 (Bronk Ramsey, 2021) and the IntCal20 calibration curve (Reimer et al., 2020) were applied. All data are presented in Supplementary Table 1.

## 4. Results

### 4.1. Lithofacies

In studied sections across the Lower Volga Region, seven lithofacies (LF1–LF7) are recognized in the Khvalynian horizon, distinguished based on lithologic features, colour, and embedded fauna (Figs. 4–6).

***Lithofacies LF1 — Cross-laminated sand and silt*** (Figs. 4–6) is found in the upper part of the sections affected by Late Khvalynian transgression, lying below 0 m asl. The thickness of deposits varies depending on bed morphology. This lithofacies mainly consists of brown silt, light-brown and yellow fine-grained sand with thin (0.5–1.0 cm) shell detritus and clay conglomeratic (1–2 cm) layers. This sediment association formed the so-called Baer Knolls deposits. The bottom sediments consist of redeposited chocolate clay with thin silt, fine-to medium-grained sand layers, containing rare *in situ* bivalves and rounded shell fragments. The *in situ* bivalves and shell fragments are represented by brackish-water species *Didacna praetrigonoides, Dreissena polymorpha* and *Monodacna caspia*. The upper part consists of light brown and yellow fine to medium-grained sand with numerous thin (2–5 mm) sand layers containing rounded shell fragments to fine indeterminate shell fragments. Ichnofossils of *Nactodemasis bowni* Bird burrows (*Riparia riparia*) are typical of this lithofacies. The average thickness of the Baer Knolls sediments is 6–8 m in the central part and varies from 0.3 to 1.0 m on the flanks.

The location of lithofacies is shown as coloured squares and also presented in Fig. 4.

***Lithofacies LF2 — Laminated chocolate clay*** (Figs. 4–6) occurs in almost all Lower Volga Region sections. This lithofacies association corresponds to the Early Khvalynian stage; it is readily identified by a

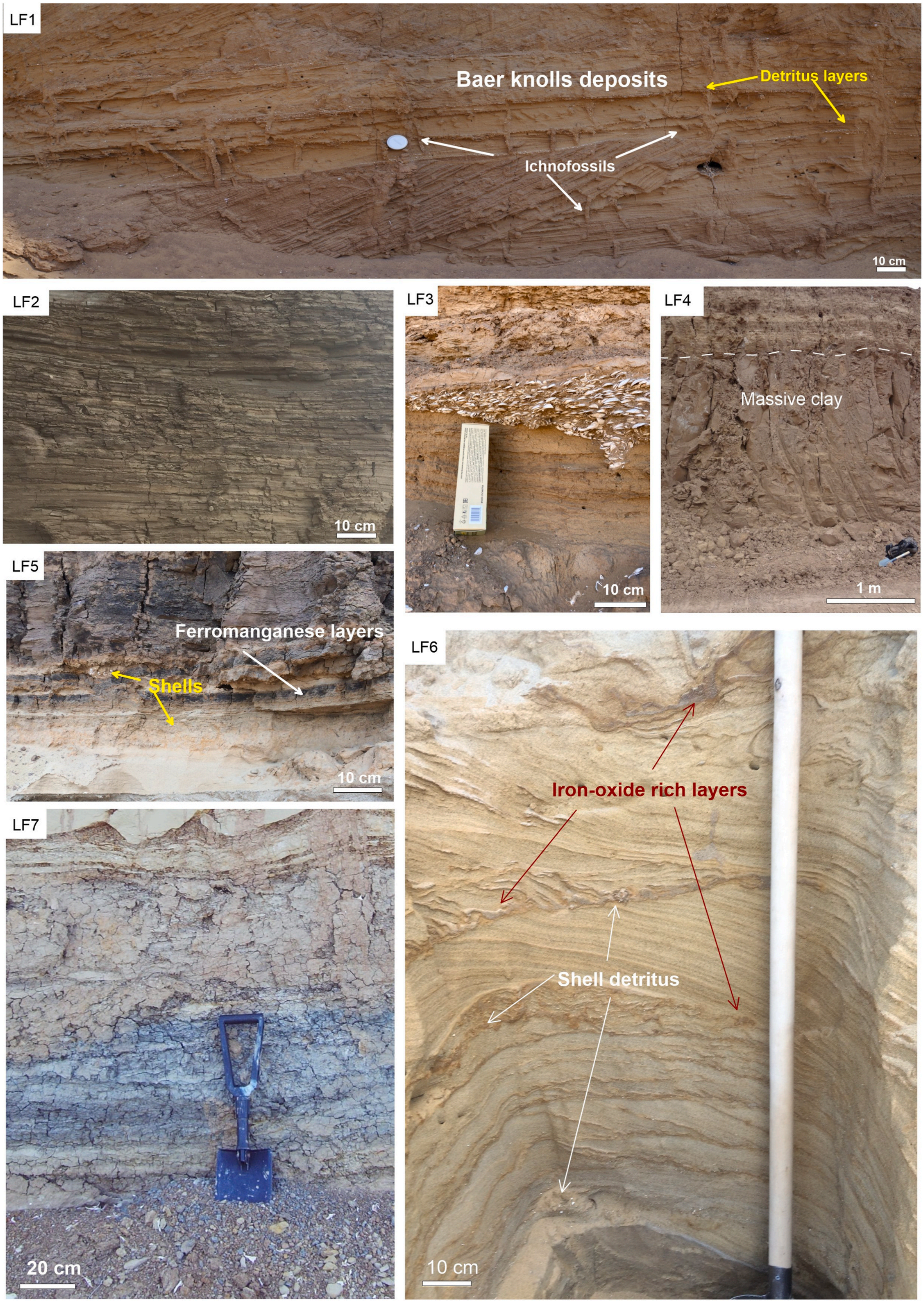


**Fig. 4.** Lithofacies of the Early Khvalynian deposits in the Lower Volga Region: Cross-laminated sand and silt, Baer knoll deposits (LF1); Laminated chocolate clay (LF2); Massive chocolate clay (LF4); Shelly sand (LF3); Well-laminated clay, silt and sand (LF5); Cross-laminated sand (LF6); Well-laminated grey and brown clay (LF7). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

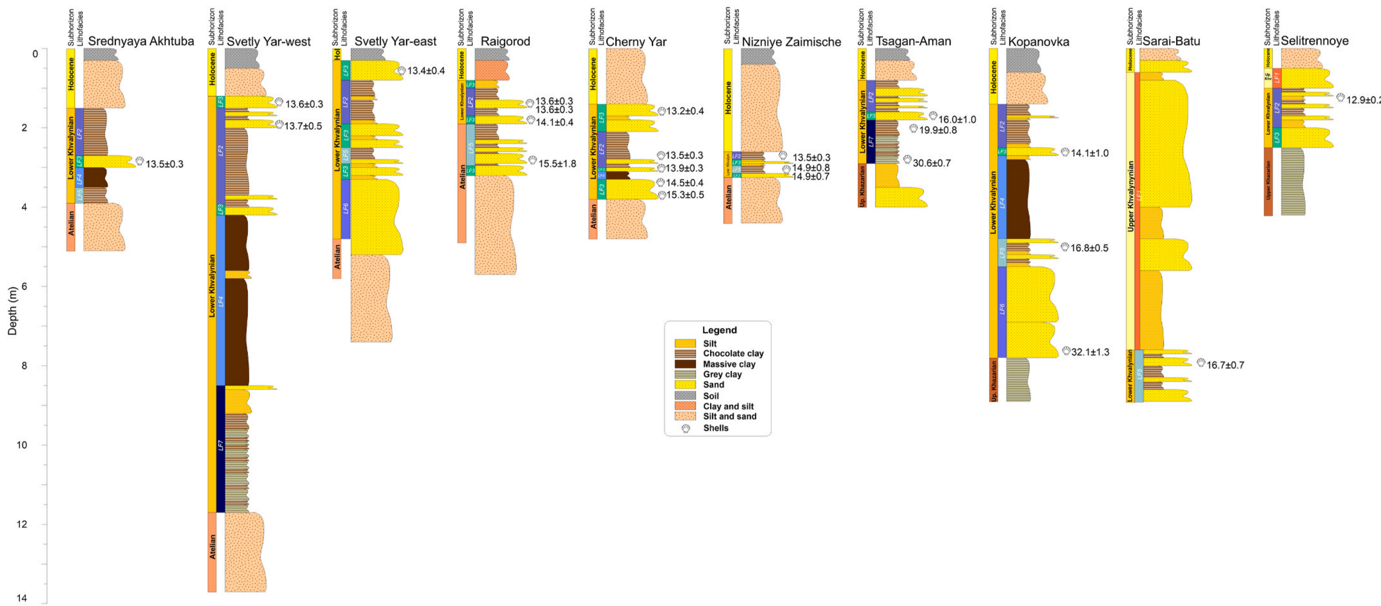


**Fig. 5.** Lithofacies columns of studied sections in the Lower Volga Region.

specific chocolate clay horizon (Pravoslavlev, 1908; Zhukov, 1945; Fedorov, 1957). The lithofacies is dominated by chocolate clay with 1–5 cm-thick light yellow-brown silt and grey-yellow fine-grained sand. The thickness of deposits varies from 20 cm to 1.5 m and depends on bed morphology. Sand layers often consist of *in situ* brackish water molluscs *Didacna protracta, D. ebersini, D. trigonoides, Dreissena polymorpha, Monodacna caspia,* and *Hypanis plicata*. In the upper part of the lithofacies, chocolate clay is often affected by reddish oxidation processes and contains single pale-grey gypsum and selenite layers, 1–4 cm thick.

***Lithofacies LF3 — Shelly sand*** (Figs. 4–6) occurs in a few sections and is characterized by a shelly light-brown, very fine to fine sand layer, 10–30 cm thick, with large (20–35 mm) *in situ* brackish-water mollusc shells *Didacna protracta, D. subcatillus, D. trigonoides, Dreissena polymorpha, Dr. grimmi.*

***Lithofacies LF4 — Massive chocolate clay*** (Figs. 4–6) is present in many sections in the Lower Volga River region and consists of homogeneous, dark-brown, faintly laminated clay, 30 cm to 8 m thick, usually with vertical fissures and isolated 1–3 cm-thick gypsum layers. Mollusc shells are rare in this lithofacies and characterized by single-piece small shells, *Didacna protracta* and *Dreissena polymorpha*. The massive chocolate clay mostly fills the pre-Khvalynian palaeodepressions (river valleys, lagoons, gullies, limans and lakes).

***Lithofacies LF5 — Well-laminated clay, silt, and sand*** (Figs. 4–6) comprises a 10 to 80 cm-thick alternation between chocolate clay, grey-yellow silt and very-fine-sand with mollusc shells and shell fragments *Didacna protracta, D. delenda, D. parallella, Dreissena grimmi.* Chocolate clay layers are often affected by ferromanganese oxidation.

***Lithofacies LF6 — Cross-laminated sand*** (Figs. 4–6) occurs in Svetly Yar-east, Cherny Yar and Kopanovka sections. This lithofacies consists of brown-yellow and grey-yellow fine-to coarse-grained sand, 0.5–3.0 m thick, with thin (0.2–1.0 cm) sand layers affected by iron oxidation. These thin layers also contain shell fragments of brackish water molluscs: *Didacna protracta, D. trigonoides, D. parallella, Dreissena polymorpha,* and *Hypanis plicata.* The lower part consists of 5–10 cm-thick combined flow ripples.

***Lithofacies LF7 — Well-laminated grey and brown clay*** (Figs. 4–6) is found only in Tsagan-Aman, Svetly Yar-west and Cherny Yar sections. This lithofacies comprises a 0.5–1.5 m-thick alternation of grey and light-brown clay and silt with rare single mollusc shells *Didacna protracta, Dreissena grimmi*. The grey clay layer is usually 20–50 cm thick and contains thin 0.5–1.0 mm thick silt laminae similar to lacustrine deposits with varves. Light-brown clay is characterized by alternation with 1–2 cm-thick silt layers.

### 4.2. Radiocarbon chronology

Compiled calibrated radiocarbon ages (n = 85) range from 35.2 to 8.3 cal ka BP (Figs. 7–8). The oldest radiocarbon ages (n = 5) correspond to 35.2–30.6 cal ka BP. However, three ages were obtained from mollusc shells *Didacna crassa naliwkini* and *D. praetrigonoides* associated with the Upper Khazarian and Khvalynian stages, and are therefore considered unreliable. There is also one age (33.4 ± 2.0 cal ka BP; MSU-21; Supplementary Table 1) obtained on freshwater mollusc *Unio* sp., which was collected from alluvium deposits (Zolotukhino section) lying under the Lower Khvalynian deposits (Kaplin et al., 1972a). Such old ages, recorded below −15 m asl, reflect the timing of fresh to low-brackish estuarine environments of the Early Khvalynian Basin in the Lower Volga Region. The oldest radiocarbon age of a typical Khvalynian species, *Didacna protracta*, is 27.1 ± 1.3 cal ka BP (MSU-1269) (Svitoch and Parunin, 2000). From this time onwards, *Didacna protracta* became the dominant species in the Lower Volga Region sections. Six ages of mollusc shells, Didacna protracta, Dreissena grimmi, range from 24.5 to 19.2 cal ka BP. The bulk of radiocarbon ages (n = 61) ranges from 16.0 to 12.5 cal ka BP. Most of these ages were obtained from mollusc shells within the elevation interval between −20 and 20 m asl (Supplementary Table 1, Fig. 8). Of these, just six ages fall between 11.2 and 8.9 cal ka BP. But only two ages, 8.3 ± 1.0 cal ka BP (MSU-796) and 8.6 ± 0.6 cal ka BP (MSU-794), were obtained from the Upper Khvalynian deposits from Enotaevka section (Abramova et al., 1983). The other three younger ages from Kopanovka, Cherny Yar and Nizhniye Zaimische sections are considered unreliable since mollusc shell samples were collected from the Lower Khvalynian deposits.

Overall, assessment of radiocarbon ages from the Lower Khvalynian deposits indicates that 71 ages, ranging from 27.1 to 12.5 cal ka BP, can be attributed to the Early Khvalynian stage in the Lower Volga Region.

## 5. Discussion

### 5.1. Correlation with Late Pleistocene paleogeographic events and Lower Khvalynian sedimentation

Comparing radiocarbon ages of mollusc shells and lithofacies

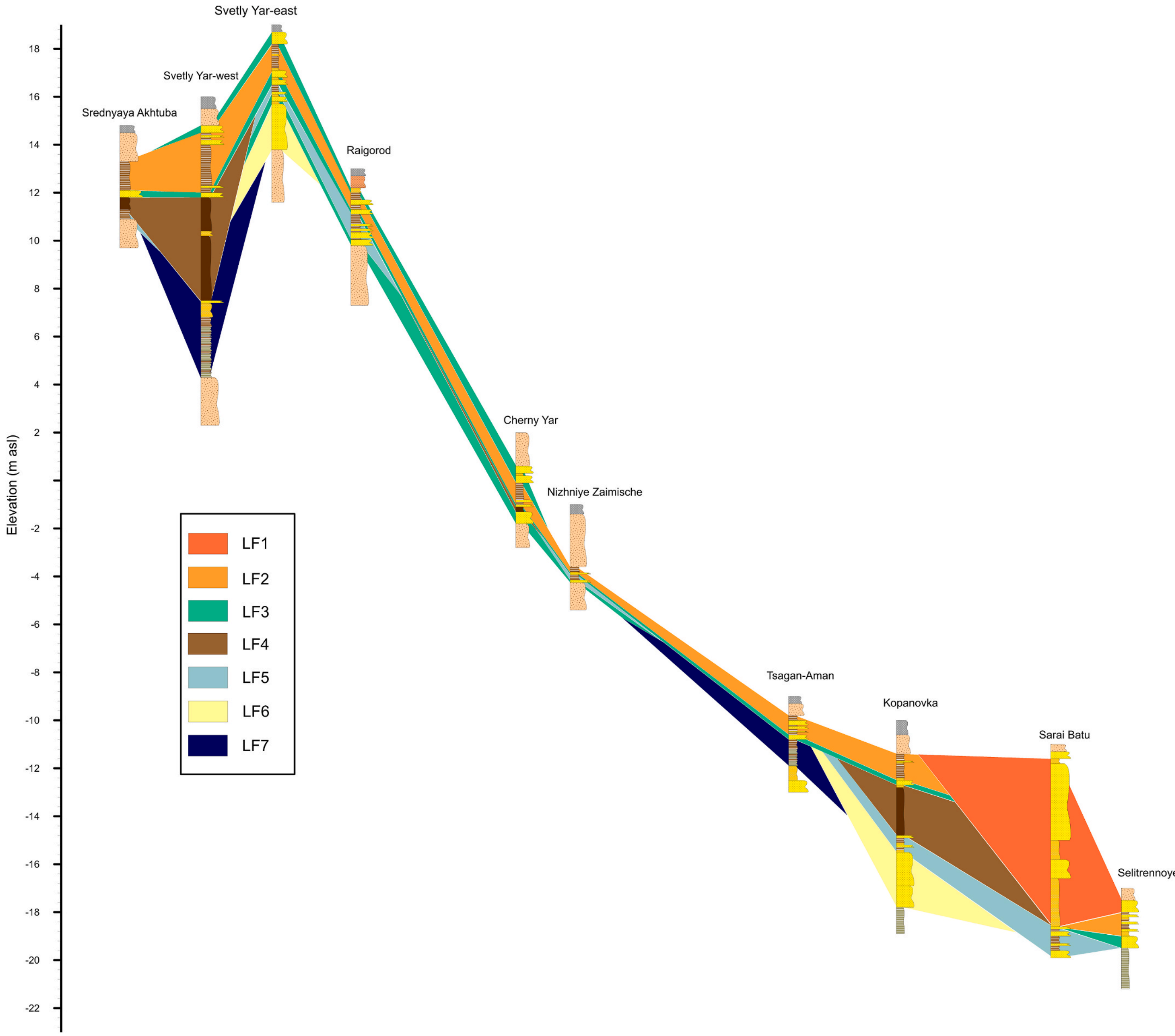


**Fig. 6.** Stratigraphic framework for the studied sections at the Lower Volga Region.

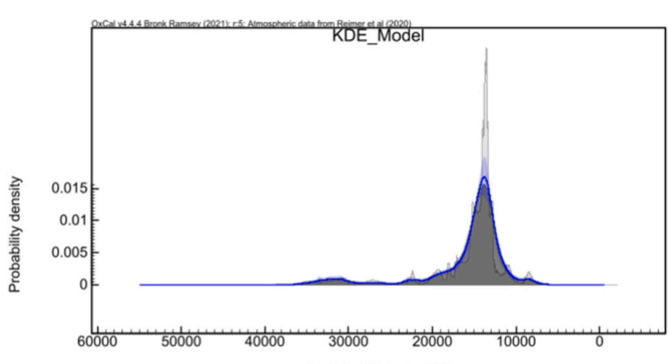


**Fig. 7.** KDE_Model distribution for radiocarbon dates of the Khvalynian deposits of the Lower Volga Region. Calibration of AMS 14C dates using OxCal v.4.4.4 (Bronk Ramsey, 2021). Atmospheric data from Reimer et al. (2020).

characteristics of the Lower Khvalynian sediments reveals a specific pattern that aligns with the main Late Pleistocene climatic events. This pattern can be used to reconstruct the depositional history during the LGM — Early Holocene period in the Lower Volga Region (Fig. 9).

### *5.1.1. End of MIS 3 — early MIS 2 (35–25 ka)*

The lower reaches of the Lower Volga River were influenced by a gradual rise of the sea level of the Early Khvalynian Basin and the first appearance of *Didacna protracta* molluscs. Nevertheless, the lithological and geochronological (TL, OSL) data indicate that most of the Northern Caspian Lowland was characterized by continental environments at that time (Shakhovets, 1987; Yanina et al., 2017; Kurbanov et al., 2021) and by deposition of the terrestrial sediments (Atelian deposits). The first thermoluminescence (TL) ages of the Atelian terrestrial deposits from the Cherny Yar, Raigorod, and Nikolskoye sections range from 28 to 80 ka (Shakhovets, 1987). The new OSL ages of the Atelian loess from Srednyaya Akhtuba, Raigorod and Leninsk sections yielded ages ranging from 19 to 32 ka (Yanina et al., 2017; Kurbanov et al., 2021, 2022, 2023; Taratunina et al., 2022, 2023, 2024). The history of the Early

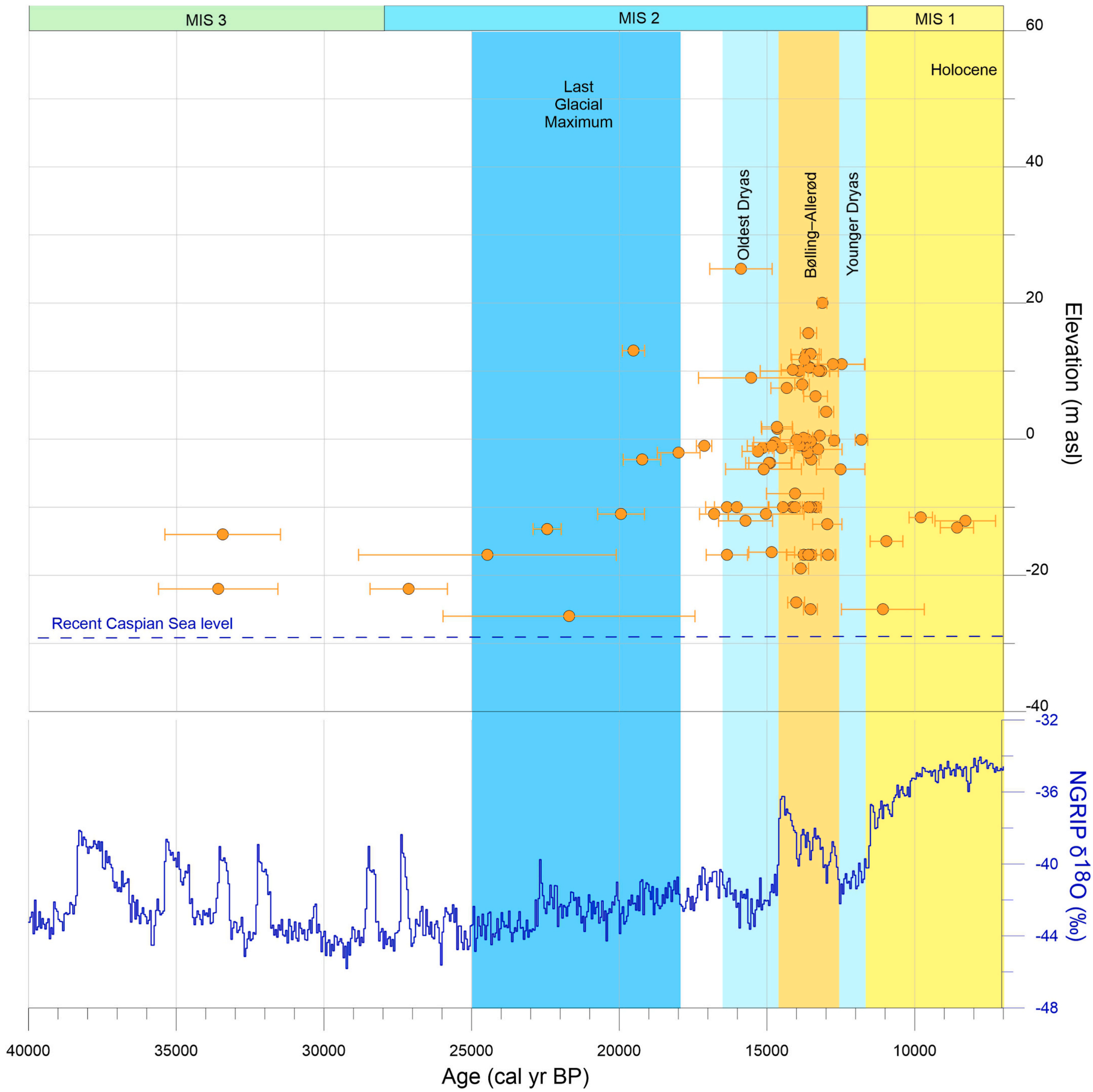


**Fig. 8.** Radiocarbon ages and elevations of dated samples from the studied sections and previously published data for the Lower Volga Region. The NGRIP isotope curve follows Andersen et al. (2004).

Khvalynian stage during that time is well represented in sediment cores from the Northern Caspian (Bezrodnyh et al., 2015; Yanina et al., 2018, 2021). The bulk of radiocarbon ages of Khvalynian mollusc shells was obtained from cores and ranges between 34.5 and 26.0 cal ka BP (Yanina et al., 2021). In this time interval, shell-rich sand is found in the lower part, while laminated clay is present in the upper part of sediment cores, indicating the initial stage of the Early Khvalynian transgression (Yanina et al., 2018, 2020).

Mollusc shells and their enclosing sediments (sand, clay) from the Lower Volga River sections may reflect the development of shallow marine, brackish to marine estuarine and lagoon regimes during this time (Fig. 10A). Radiocarbon data and geomorphological evidence for the 35–25 ka interval are not widespread within the Northern Caspian Sea Lowland. They could provide only hypothetical shoreline and sea level configurations of the Early Khvalynian Basin. In the Zolotukhino section, a single radiocarbon age of freshwater mollusc shells *Unio* sp. (33.4 ± 2.0 cal ka BP; MSU-21; Kaplin et al., 1972a) suggests a fluvial sediment deposition. This is the northernmost section for which radiocarbon data exist for this time interval. The elevation of the mollusc *Unio* sp. sample collection was estimated at around −14 m asl, according to the lithological description provided by Kaplin et al. (1972a). The elevation of the palaeoshoreline of the Early Khvalynian Basin during that time interval is observed in the bottom part of the Kopanovka section.

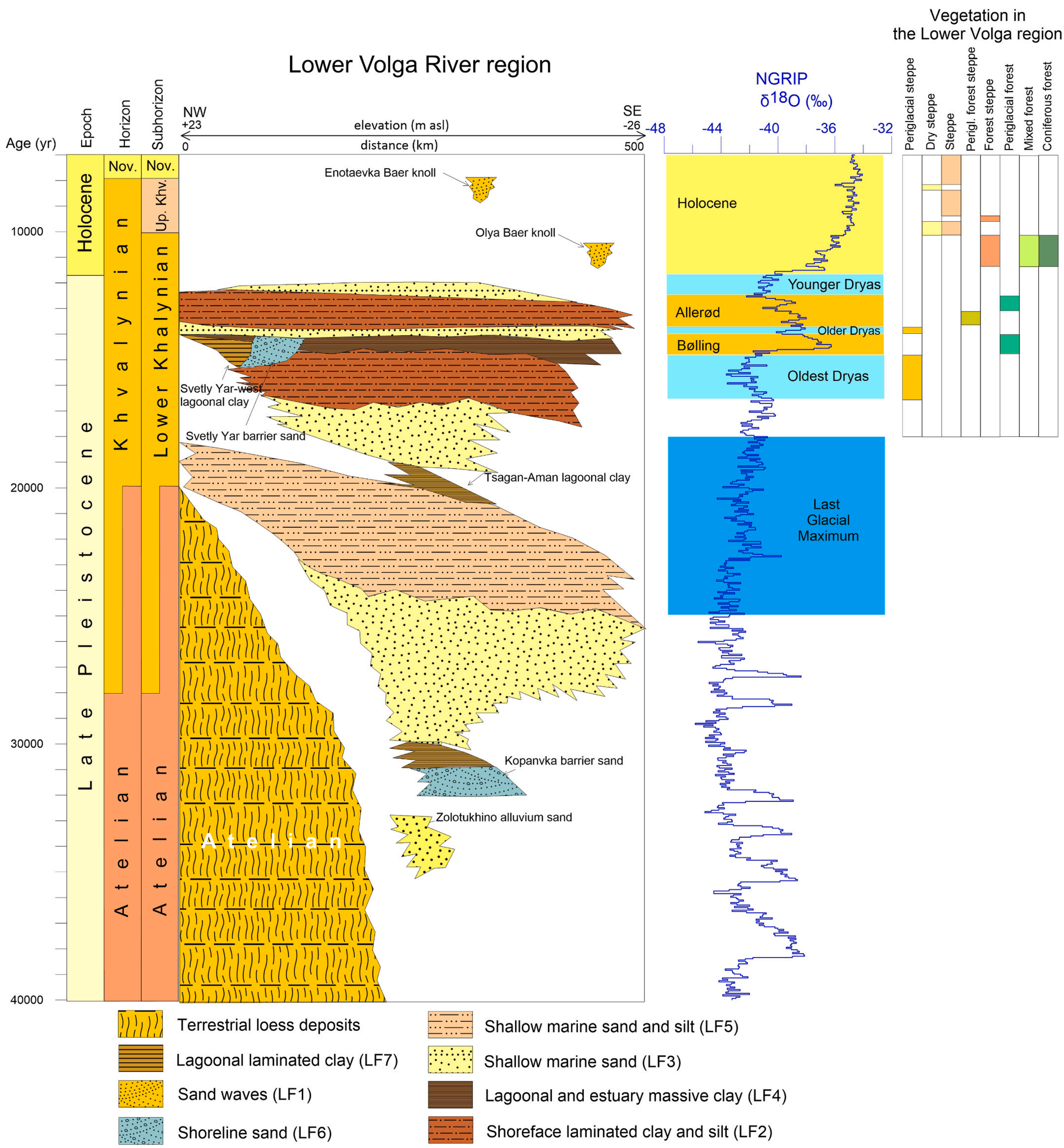


**Fig. 9.** Litho- and chronostratigraphic column for the Lower Volga Region. The Holocene and Late Pleistocene Epochs are taken from Pillans and Gibbard (2012). The NGRIP isotope curve follows Andersen et al. (2004). The Late Pleistocene and Early Holocene vegetation in the Lower Volga Region according to Bolikhovskaya and Kasimov (2010), Bolikhovskaya and Makshaev (2020).

#### 5.1.2. *Last Glacial Maximum (25–18 ka)*

Mollusc species of *Didacna protracta* and *Dreissena grimmi* in the northwestern part of the Early Khvalynian Basin dominated during this time — species that usually inhabit shallow or relatively deep (up to 50 m) brackish-water (11–12 ‰) environments (Yanina, 2012). Specifically, the shell size and morphology indicate 3–5‰ salinity in that area (Yanina, 2012). The elevations of mollusc shells sampling positions from five sections range from −26 to −2 m asl (Supplementary Table 1, Figs. 8 and 10B). At the same time, there are OSL ages between 27 and 20 ka from the Leninsk sections corresponding to elevations between 5 and 7 m asl (Kurbanov et al., 2023).

The deposition of well-laminated grey and light-brown clay and silt with sparse, thin-valved mollusc shells (LF7) indicates the influx of Caspian Sea water into the Northern Caspian Lowland. This period was characterised by extreme cold and dry environments in the East European Plain and reduced supply of freshwater by the Volga River to the

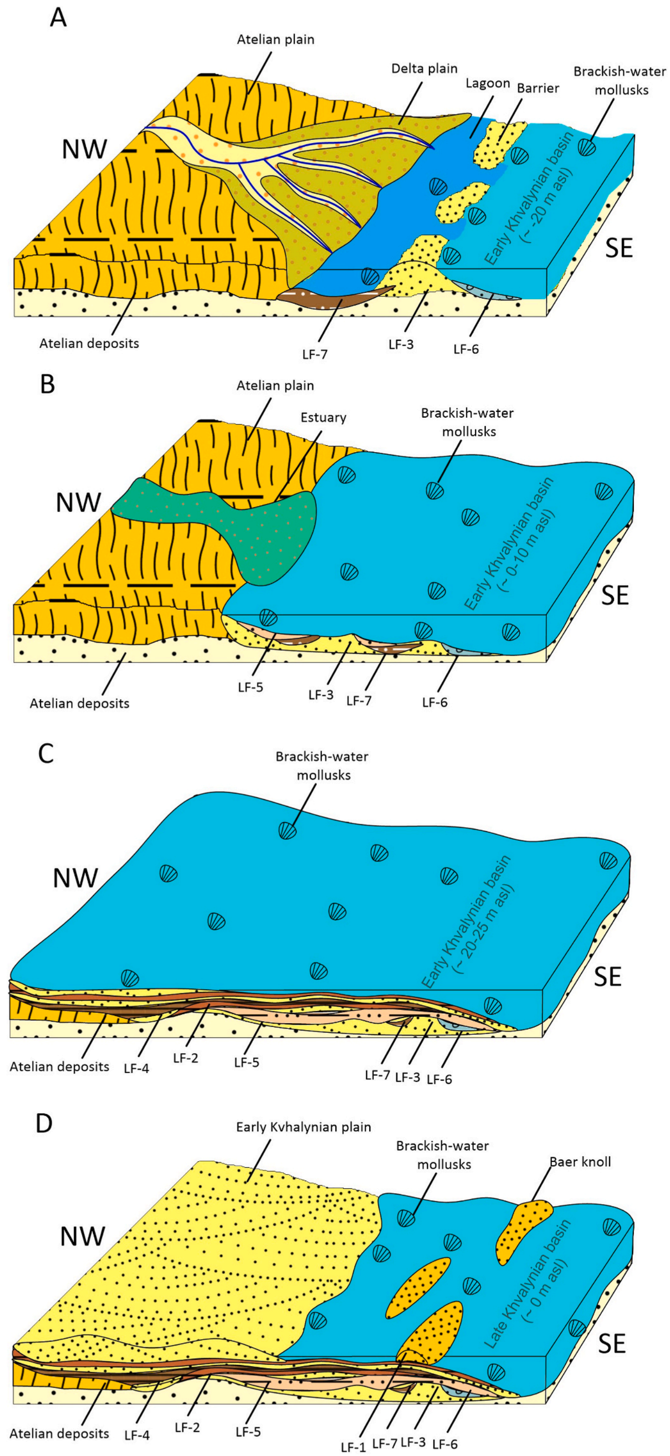


**Fig. 10.** Block diagrams of the Lower Volga Region development during the Early and Late Khvalynian stages and deposition environments. A, initial phase of the Early Khvalynian transgression (~30-25 ka cal BP), first appereance of brackishwater mollusks *Didacna protracta* in the Lower Volga Region; B, Early Khvalynian basin during the LGM (25-18 ka cal BP); C, Early Khvalynian basin sea level stabilization at +20-+25 m asl during Bølling-Allerød (14,7–12,9 ka cal BP), deposition of massive and laminated chocolate clay; D, Late Khvalynian transgression (~10 ka cal BP), sea level reach 0 m asl, development of Baer knolls.

Caspian Sea (Velichko, 1973; Velichko and Faustova, 1986; Vandenberghe et al., 2014; Panin and Matlakhova, 2015; Ukraintsev, 2022; Gelfan et al., 2024). A similar sediment composition could be found in the Lower Khvalynian deposits in the Middle Volga River valley. In the Saburovka section, the lower part (14 m asl) of the 6 m thick Lower Khvalynian deposits consists of laminated grey and brown clay and silt. One AMS radiocarbon data point indicates the age of 25.1 ± 0.3 cal ka BP (Makshaev, 2019). On the opposite side of the Middle Volga River Valley, an OSL date of the Lower Khvalynyan deposits indicates an age of 22.6 ± 1.5 (Makshaev et al., 2025). These data suggest that the Early Khvalynian transgression's water could reach the Middle Volga River valley during the LGM. Laminated grey and light brown clay and silt are also present at the bottom of the Svetly Yar, Tsagan-Aman, and Kopanovka sections. The Lower Khvalynian sediments were deposited in palaeodepressions up to 8–10 m thick in these sections. The OSL data between 27.2 and 19.9 ka from the laminated grey clay and sand loam horizon in the Leninsk section indicate the initial stages of the Early Khvalynian transgression into the Lower Volga River region (Kurbanov et al., 2023).

The sediment deposition rhythm and composition could correspond to infilling by fresh and low brackish waters into the palaeoestuary and palaeodepressions. The grey colour of clay sediments could also be interpreted as deposition in lagoonal or lacustrine complexes with preservation of organic matter, low oxygen concentration, and anoxic conditions (März et al., 2011). Light-brown clay and silt overlying grey clay sediments indicate well-mixed water with oxygen, regular tidal interchange with marine waters, or a shallow marine environment (Parham et al., 2013).

### 5.1.3. Post-LGM and the Oldest Dryas (18.0–14.8 cal ka BP)

Radiocarbon ages and lithology suggest deposition of LF6 and LF5 under the transgressive regime of the Early Khvalynian Basin. Cross-laminated sand (LF6) with mollusc shells indicates moderate to high depositional energy, associated with foreshore and backshore complexes. The appearance of small, thin-valved shells of *Didacna protracta* in sediments indicates cold, low-brackish (6–7‰) water conditions of the Early Khvalynian Basin (Yanina, 2012). These lithofacies are well represented in Kopanovka and Svetly Yar-east sections (Figs. 4 and 5) and could indicate a shoreline trajectory during the transgressive stages of the Early Khvalynian Basin. The elevations of mollusc shell sampling positions from the Cherny Yar and Kopanovka sections range from −12 to −1 m asl.

In the Raigorod, Cherny Yar, and Niznie Zaimische sections, depositional sequences in the bottom part of the Lower Khvalynian sediments indicate the marine ravinement surface between LF5 and the Atelian loess sediments (Fig. 5). In the area of these sections, the marine ravinement surface was formed by wave and tidal processes in the shallow-water environments when the supply of sediments was relatively low. Frequently, at the erosional contact between LF5 and the Atelian sediments, a thin sand layer (1–3 cm) with detritus and rounded shell fragments is present. Hence, we suggest that LF6 was formed during the transgressive stage and represents foreshore deposits and heterochronous coastlines of the Early Khvalynian Basin. According to two radiocarbon ages of LF6, deposition in the Kopanovka and Cherny Yar sections occurred around 17.1–16.8 cal ka BP. Thus, we assume that the absence of mollusc shells and radiocarbon data for that time interval may be associated with high-energy shallow-water environments that enhanced erosion processes. The process of LF6 formation was clearly described by Badyukova (2010). These concepts of depositional environments of the Early Khvalynian Basin (called the lagoonal-transgressive system) are described in detail by Badyukova (2007, 2010, 2018).

Well-laminated clay, silt and sand (LF5), found in many sections

(Fig. 5), could indicate a facies shift during the continued transgression and deposition in the shoreface environment, suitable for mollusc growth. Slight differences in the LF5 composition depended on material supply and transport distance from the coastline. Sixteen radiocarbon ages range between 16.4 and 14.8 cal ka BP, indicating deposition of LF5—the elevations of samples range from 20 to 9 m asl. Thus, we suggest that this time interval corresponds to the transgressive stage of the Early Khvalynian Basin.

The Khvalynian deposits, around 18–15 ka BP, were also found in the eastern and central parts of the Manych Depression (Semikolennykh et al., 2022, 2025). These sediments are represented by horizons, similar to those in the Northern Caspian, composed of brown and light-brown loams with signs of ferruginization at altitudes from 24 to 26 to 15–17 m in the eastern and central parts of the depression, respectively. In our opinion, these deposits correspond to the low-dynamic initial stage of the discharge of Caspian waters into the Azov-Black Sea Basin. Thus, the Caspian Sea level could have exceeded 25 m.

The time interval after the LGM (18.0–16.5 ka) is characterized by the retreat of the Late Valdai (Late Weichselian) Ice Sheet and the increasing runoff from the Volga River to the Early Khvalynian Basin (Patton et al., 2017; Panin et al., 2020). Runoff in the Volga River Basin after LGM was estimated at 563 $km^3$/yr, which is twice that of today (Sidorchuk et al., 2009). During the post-LGM retreat of the south-eastern margin of the Late Valdai Ice Sheet, a group of proglacial lakes formed (Gorlach et al., 2017). According to Patton et al. (2017), proglacial lakes in the northwest part of the Volga River Basin were predominantly small, approximately 10 $km^2$. However, huge proglacial lakes such as Sukhona, Mologa-Sheksna, Vaga, Kostroma, and Rostov existed as well (Kvasov, 1975; Svendsen et al., 2004; Panin et al., 2020). Nevertheless, the contribution of proglacial lake waters from the north-western part of the Volga River Basin to the Early Khvalynian Basin was possibly delayed until after 17 ka. According to Gorlach et al. (2017), between 19 and 16 ka, some proglacial lakes in the Valdai Upland discharged to the Caspian Sea with a maximum of 100 $km^3$ at around 16 ka ago. During the post-LGM time, the Early Khvalynian Basin experienced a gradual sea level rise, which was also confirmed by reconstructions of the high discharge of the Volga River during 17.5–14.0 ka (Gelfan et al., 2024) and core data from the Northern Caspian (Yanina et al., 2018).

The Oldest Dryas (16.5.0–14.8 cal ka BP) stage is marked by the deposition of alternating layers of chocolate clay, silt and clay with an abundance of mollusc species (LF5). Sixteen radiocarbon ages correspond to the interval between 16.4 and 14.8 cal ka BP. Similar lithological structures were obtained in cores from the North Caspian Sea, indicating a short-term period of regression during the Early Khvalynian stage (Yanina et al., 2018). These lithofacies correspond to low depositional energy, estuarine and lagoon palaeovalley complexes (Badyukova, 2018). Ferromanganese oxidation could indicate the supply of oxygen-rich waters during the deposition of chocolate clay. According to palynological data from the Srednyaya Akhtuba section, the vegetation developing during the Oldest Dryas is characterized by the wide occurrence of tundra-steppe, scattered grass-forb communities with dwarf shrub under permafrost conditions (Bolikhovskaya and Makshaev, 2020). Degradation of permafrost between 17 and 15 ka could have triggered the erosion of the active layer and solifluction processes, transporting the fine material to the Early Khvalynian Basin (Vandenberghe et al., 2014).

### 5.1.4. Bølling (14.7–14.1 cal ka BP)

This period is characterized by the deposition of a layer of massive chocolate clay (LF4) that corresponds to the Bølling stage. The thin-valved and sporadic mollusc shells of *Didacna protracta, D. delenda,* and *Dreissena polymorpha* were found only in the bottom part of the massive chocolate clay within thin sand and silt layers. These mollusc shells were dated to 14.7–14.4 cal ka BP (Supplementary Table 1). Variations in the thickness of the massive chocolate clay in the studied sections show that the sediment accumulation was predetermined by palaeomorphology. Massive chocolate clay and the absence of mollusc shells in the middle and upper part of LF4 indicate deposition from a large amount of suspended fine materials with low to moderate flows (turbidity currents) in low-brackish shoreface settings (Badyukova, 2010; Yanina et al., 2018). Such a high volume of clay was transported to the Early Khvalynian Basin by the Volga River due to increasing surface runoff (Britsyna, 1954; Sidorchuk et al., 2009; Svitoch et al., 2017) and permafrost thawing (Chistyakova and Lavrushin, 2004). The potential source of material lay in Middle (Moscovian) and Upper Pleistocene (Valday) moraine complexes in the north-west part of the Volga River Basin (Orekhov, 1955; Priklonsky et al., 1956; Arbuzova, 1970; Chistyakova and Lavrushin, 2004; Tudryn et al., 2013, 2016; Makshaev and Svitoch, 2016). The freshwater supply with high oxygen concentration oxidized clay to a dark brown (chocolate) colour (Priklonsky et al., 1956). During the Bølling interstadial in the Lower Volga Region, periglacial forest-steppes were widespread (Bolikhovskaya and Makshaev, 2020). At this time, the discharge of Khvalynian waters through the Manych Depression into the Black Sea had a most dynamic character, reflected in the accumulation of cross-layered sands in the central part of the Manych Depression at an altitude of about 18–19 m (Svitoch et al., 2008; Semikolennykh et al., 2022, 2025). Presumably, at the end of the Bølling, the sea level of the Early Khvalynian Basin decreased due to water discharge; this event could have stabilized the sea level at +20–22 m asl (Fig. 10C–11).

### 5.1.5. Older Dryas (14.1–13.9 cal ka BP)

Lithofacies LF3 lies between LF4 and LF2 and possibly represents a short regressive trend during a cold phase within the interstadial warming. Five radiocarbon dates indicate that the sedimentation process occurred between 14.1 and 13.8 cal ka BP. LF3 is commonly associated with low depositional energies and could be attributed to shallow marine or shoreline sequences (Parham et al., 2013). The absence of clay sediments could indicate reduced water discharge within the Volga River Basin due to cold and dry environmental conditions. According to palynological data, the Lower Volga Region was characterized by the broad expansion of periglacial steppe and the disappearance of broadleaf trees at that time (Fig. 8).

### 5.1.6. Allerød (13.8–12.9 cal ka BP)

During the Allerød warmer phase, deposition of chocolate clay with thin silt and sand layers and an abundance of mollusc shells, *Didacna protracta, Dreissena polymorpha,* and *Monodacna caspia* (LF2) resumed. Based on twenty-six radiocarbon dates, we assume the timing of LF2 deposition as 13.8–12.8 cal ka BP when increasing Volga River runoff due to greater precipitation predominated by snow took place (Sidorchuk et al., 2009, 2021). Potential sources of fine-grained sediments to the Early Khvalynian Basin were the Upper and Middle Pleistocene moraine complexes and Permian red clay formations from the north-western and eastern parts of the Volga River Basin, respectively (Priklonsky et al., 1956; Tudryn et al., 2016; Makshaev and Svitoch, 2016; Makshaev, 2019; Tkach, 2024). The abundance of mollusc species in LF2 at most of the sites indicates deposition in low-energy, shallow-shoreface marine conditions (Badyukova, 2010). The driving factor of material input to the Early Khvalynian Basin was the higher precipitation levels and surface runoff accompanied by the permafrost degradation that triggered the erosion of the active layer and solifluction processes. During the Allerød, the general trend of the Early Khvalynian sea level fluctuation gradually changed to a regressive one. According to palynological data, at the first stage of Allerød, periglacial forest-steppe landscapes predominated. In the second stage, the humid phase of spruce and Siberian pine periglacial forests alternating with open woodlands developed (Fig. 8).

### 5.1.7. Younger Dryas (12.8–11.7 cal ka BP)

The Younger Dryas cold stage is characterized by the sea-level fall in

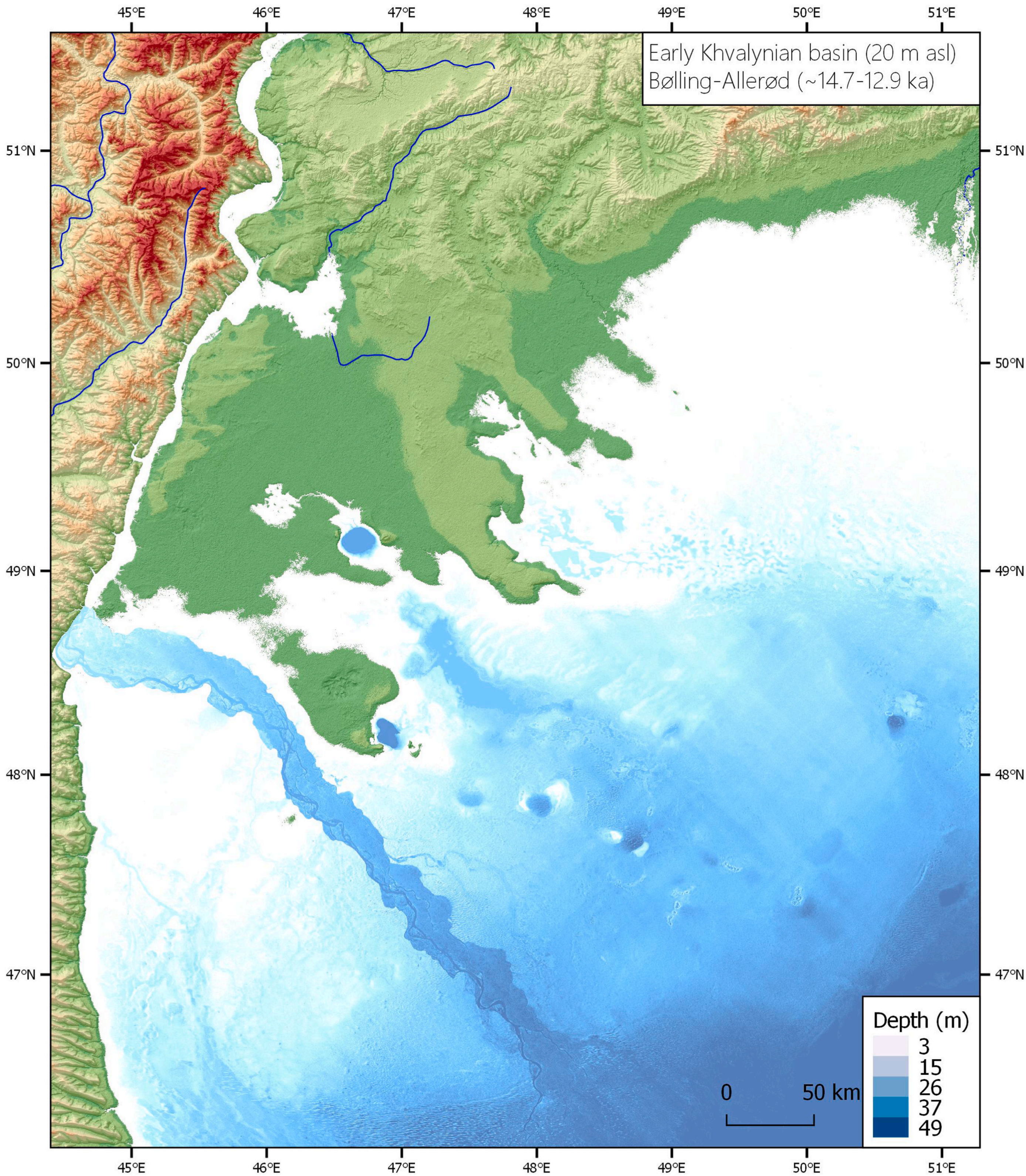


**Fig. 11.** The northern part of the Early Khvalynian Basin during the Bølling-Allerød(14.7–12.9 ka).

the Caspian region, known as the Enotaevka regression. Three radiocarbon ages, corresponding to 12.7–12.0 cal ka BP, possibly indicate the last period of malacofauna expansion into the Early Khvalynian Basin. No radiocarbon dates of mollusc shells younger than 12.0 cal ka BP may mark the end of the Early Khvalynian stage in the Lower Volga Region and the beginning of the Enotaevsk regression. Thus, the accurate timing of the Enotaevka layers' deposition is still debatable. The same problem concerns the Late Khvalynian transgression (Lobacheva et al., 2021).

The LF1 comprises brown silt, light brown, and yellow sand with thin shell detritus, forming the Baer Knolls Formation. However, geochronological data for the Baer Knolls deposits cover the interval from the Early Khvalynian to the Early Holocene (Svitoch and Klyuvitkina, 2006;

Zastrozhnov et al., 2020). We believe LF1 corresponds to the Late Khvalynian stage. This phase refers to a time of decreasing runoff from the Volga River Basin. Cryogenic structures and the coefficient of cryogenic contrast in LF2 in the Srednyaya Akhtuba section indicate intensive permafrost processes at the end of the Early Khvalynian stage (Taratunina et al., 2022).

#### 5.1.8. *Early Holocene (11.7–8.2 cal ka BP)*

The upper part of the Baer Knoll Formation contains cross-laminated yellow sand (LF1), presumably deposited during the Early Holocene (Fig. 10D). Cross-laminated sand in the upper part of LF1 represents low to moderate depositional energies of wide streams with northeast-to-southwest directions (Badyukova, 2018). Only three reliable

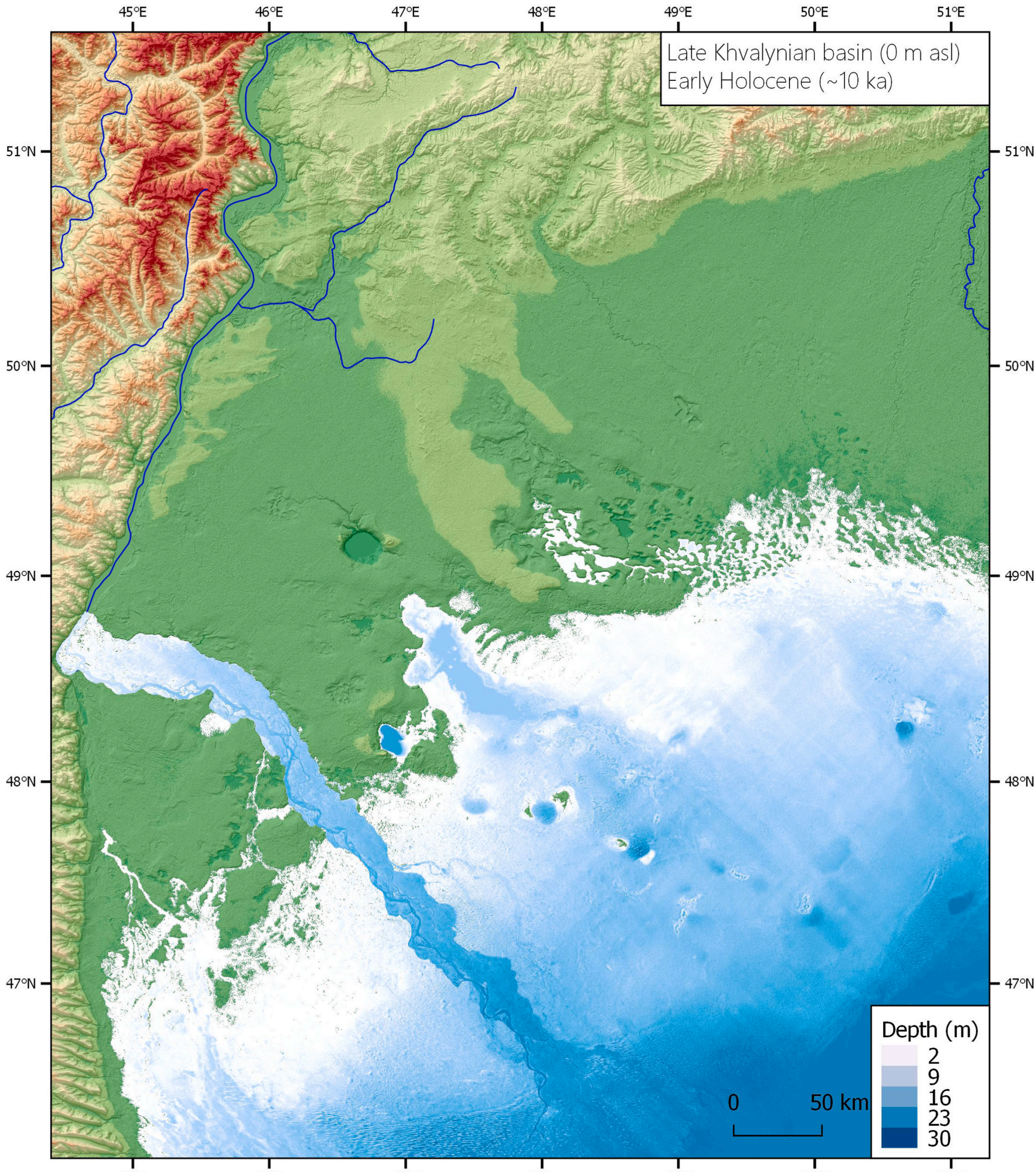


**Fig. 12.** The northern part of the Late Khvalynian Basin during the Early Holocene (~10 ka).

radiocarbon ages between 11.0 and 8.3 cal ka BP might correspond to the development of the Late Khvalynian transgression, which reached a maximum sea level of 0 m asl (Fig. 12).

## 6. Conclusion

Late Pleistocene climatic fluctuations affected sedimentological processes in the Lower Volga Region, in the north-west of the Northern Caspian Lowland. The Early Khvalynian Basin in the Lower Volga Region developed between 27.0 and 12.5 cal ka BP. The onset of the Early Khvalynian transgression in the Northern Caspian Lowland was characterized by sedimentation in pre-Khvalynian palaeodepressions and palaeovalleys, characterized by grey and light-brown clay and silt (LF7) deposits, alongside the first appearance of the mollusc *Didacna protracta*.

The initial phase of chocolate clay deposition in the Lower Volga Region corresponds to the post-LGM (Last Glacial Maximum) and Oldest Dryas. During the LGM, the sea level of the Early Khvalynian Basin fluctuated between 0 and +10 m asl. Large supplies of chocolate clay coincided with warmer intervals recorded in the NGRIP (NorthGRIP) ice-core data and pollen zones of northern Europe (Bølling and Allerød).

A significant influx of clay material during the Bølling interstadial led to the deposition of massive chocolate clay (LF4) in the north-western part of the Early Khvalynian basin. This lithofacies serves as a key stratigraphic marker in the Lower Volga Region. In contrast, sand deposition predominated during cold stages, including the LGM, post-LGM, Oldest Dryas, Older Dryas, and Younger Dryas. The expansion of mollusc species in the Lower Volga Region also occurred during cold stages.

The coastline of the Early Khvalynian basin reached elevations of +20 to +25 m asl during the Bølling stage. Despite the study area spanning approximately 300 km, the consistent presence of lithofacies LF2, LF4, LF5, and LF6 indicates uniform depositional conditions across the region. These facies suggest a predominance of estuarine, lagoon, and shallow marine environments in the north-western sector of the Early Khvalynian basin. The Late Khvalynian basin developed during the Early Holocene (~10–9 ka BP), when the Baer Knolls were formed.

## Author contributions

Conceptualisation: RM and TY. Field investigation/Laboratory analysis/sample collection: RM, TY, NB, EM, DS, NT, DL, AT. Visualisation: RM. Writing original draft: RM. Writing review and editing: RM, TY, NB, AT, DS.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2025.109601.

## Data availability

All data and/or code is contained within the submission.

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