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# **Chronology of the Late Pleistocene Caspian Sea hydrologic changes: a review of dates and proposed climate-induced driving mechanisms**

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## **Abstract**

This paper provides a review of the dates used to define major hydrologic changes in the Caspian Sea during the Late Pleistocene that includes the Early Khvalynian and Hyrcanian highstands and the Atelian lowstand, and it discusses their driving mechanisms. Dates obtained by <sup>14</sup>C (that are the most numerous), by OSL and by U/Th for samples that are well identified in the literature through their geographic location and their laboratory number, are considered. Samples derive from sediments both in the current Caspian Sea coast and in its Middle and Northern basins. Most of dates concern the Early Khvalynian highstand while less abundant ones correspond to the Hyrcanian highstand and Atelian lowstand that preceded the Early Khvalynian. The review of these Late Pleistocene dates provides an overall revision of the hydrologic changes that the Caspian Sea experienced. Accordingly, the Early Khvalynian highstand presents two major phases. The first Early Khvalynian phase (hv1-1) took place between 36.0 and 22.0 cal kyr, and water level reached ca 0 m a.s.l. Its second phase (hv1-2) is characterised by the deposition of the so-called Chocolate Clays especially

in the Northern Peri-Caspian and took place between ca 22.0 and 12.5 cal kyr BP with a water level rise until at least 40 m a.s.l. between ca 17 and 13 cal kyr BP. Before the Early Khvalynian highstand, the Caspian water level underwent a lowstand between at least 70.0 and 36.0 kyr, *i.e.* the Atelian lowstand, which was interrupted by the Hyrcanian highstand. During the late stage of the Atelian lowstand, between 43.5-42.9 and 36.0 cal kyr BP, the water level decreased between more than -60 m a.s.l. and less than -90 m a.s.l. at 42.0 cal kyr BP. The importance of the water level drop in the early stage of the Atelian regression between ca 70 and 55.2 kyr could not be estimated but according to seismic profiles, it was much less pronounced than later. The dates for the Hyrcanian highstand range from 55.2 (or even before) to 43.5-42.9 cal kyr BP and the water level reached at least 0 m a.s.l. in its late phase. Through this synthesis, the origins of water inflows into the Caspian Sea could be suggested for the upper part of the Early Khvalynian transgression: it matches with a very large inflow of meltwater from the southern front of the Scandinavian Ice Sheet; the fluvio-glacial waters from the ice cap discharging to the Caspian Sea via the Volga River. Concerning the Hyrcanian transgression, meltwater inputs from the glaciers of western High Asia can be proposed, the fluvio-glacial waters being transported into the Aral Sea and later into the Caspian Sea by the Syr Darya and Amu Darya.

### **Keywords**

Caspian Sea water level change, Quaternary, Last Glaciation, Atelian regression, Hyrcanian transgression, Early Khvalynian transgression, Chocolate Clays, <sup>14</sup>C, OSL and U/Th dates.

## 1. Introduction

During the late Quaternary history of the Caspian Sea, several stratigraphic evidences of transgression and regression indicate major hydrological changes, producing phases of highstand and lowstand of various durations and magnitudes. The Early Khvalynian that occurred during the Late Pleistocene was the largest major transgression believed related to lake highstand and its deposits are known from the Caspian coast and from its Northern and Middle basins (*e.g.* Varushchenko et al., 1987). A great number of dates for the Early Khvalynian highstand have already been published for a long time. However, the age of the Early Khvalynian highstand and its development steps are still considered by many authors as ambiguous due to discrepancies between results from different sites and from different dating methods, *i.e.*  $^{14}\text{C}$  ages: 56.0-7.0 kyr BP,  $^{230}\text{Th}/^{234}\text{U}$  (U/Th) ages: 24.2-9.6 kyr, thermoluminescence ages (TL) : 77.0-13.0 kyr (Varushchenko et al., 1987; Mamedov, 1997; Arslanov et al., 2002, 2015; Leonov et al., 2002; Bezrodnykh et al., 2004, 2015; Badyukova, 2007; Svitoch et al., 2009; Shkatova, 2010; Sorokin et al., 2014; Makshaev and Svitoch, 2016; Yanina et al., 2018; Kurbanov et al., 2020; Svitoch and Makshaev, 2020; and references therein). Dolukhanov (2009, 2010) reviewed 47 formerly published  $^{14}\text{C}$  dates of the Early Khvalynian deposits from Dagestan and from the lower Volga area (Fig. 1b) obtaining ages that range from ca 30.7 to 8.7 kyr BP. Later on, in 2016, Arslanov and collaborators investigated the Early Khvalynian chronology on the basis of 22  $^{14}\text{C}$  dates and a few U/Th dates from Northern Peri-Caspian, Manych, Dagestan, Azerbaijan and Mangyshlak areas (Fig. 1b) and obtained a narrower age range displaying values between 19.3 and 10.7 kyr BP. Furthermore, recently published dates for Early Khvalynian transgression from river terraces of the lower Volga, show values from Last Glacial Maximum (LGM) to ca 13.0 cal kyr BP, by both  $^{14}\text{C}$  (Leonov et al., 2002; Tudryn et al., 2013; Makshaev and Svitoch, 2016) and optically stimulated luminescence (OSL; Kurbanov et al., 2020). Moreover, in sediment cores taken from the Northern Caspian Sea basin, the beginning of the Early Khvalynian is

recorded at ca 34.0 cal kyr BP (Bezrodnykh et al., 2015), or even possibly ca 50.0 cal kyr BP (Sorokin et al., 2014). Such a high number of dates provides younger ages from the current Caspian Sea coast and older ones in its Northern basin. Arslanov and Yanina (2008) suggested a rejuvenation of the most recent ages determined on the coast), while Bezrodnykh et al. (2004, 2015) have highlighted the early onset of this transgression. Below the Early Khvalynian succession, sediments indicate a regressive phase called Atelian and interpreted as a lake lowstand (Varushchenko et al., 1987).. This lowstand is estimated to display water level at ca -140 m a.s.l. (Lokhin and Maev, 1990), and the related ages range between ca 80 and 19 kyr in the Northern Peri-Caspian while in the Northern Caspian Sea basin, they are all centered on ca 40 cal kyr BP (*e.g.* Varushchenko et al., 1987; Sorokin et al., 2018; Kurbanov et al., 2020; Yanina 2014; Yanina et al., 2020). This lowstand separates the Early Khvalynian highstand from the previous Late Khazarian highstand that took place probably between 130 and 76 kyr (*e.g.* Varushchenko et al., 1987; Kroonenberg et al., 1997; Mamedov, 1997; Shkatova, 2010; Yanina, 2012). Nevertheless, transgressive Hyrcanian deposits (named also Girkanian) are known from the Northern Peri-Caspian and Manych areas (Fig. 1b) below the Atelian lowstand, and they were recently identified in seismic-acoustic profiles and sediment cores from the Northern Caspian Sea basin (Sorokin et al., 2018; Yanina et al., 2020). The age and stratigraphic position of this highstand are not well defined. Its age is estimated to be ca 120-90 kyr (Zubakov 1992; Kurbanov et al., 2018), ca 80 kyr (Sorokin et al., 2018; Yanina et al., 2018, 2020) or even ca 43 cal kyr BP (Lavrushin et al., 2014) and stratigraphically it is not clear whether it constitutes an independent transgression, a part of the Late Khazarian or a part of the Early Khvalynian transgression. Major hydrological periods have been recognized for a long time especially in Russian literature; nevertheless, the associated sedimentary sequences are often incomplete or missing as it was highlighted by Svitoch and Makshaev (2020), and consequently their stratotypes are not established yet.

In the context of such ambiguities and regarding the high number of available data that are however still intensely discussed, a detailed review of the chronology is proposed based on dates identified in the literature as belonging to the Early Khvalynian, Atelian and Hyrcanian deposits from the modern Caspian Sea coast and from its Northern and Middle basins. The following dates are considered: by  $^{14}\text{C}$  (representing the bulk of the data), by OSL and by U/Th that are well identified in the literature through their geographical location and laboratory number. The dates gathered both from marine and terrestrial sites of the Caspian Sea basin represent the largest database available in one single paper for the considered timescale.

The identification of the precise sequence of hydrological changes in the Caspian Sea during the late Quaternary and establishing the chronology of these changes is crucial for the debate on the correlation between Caspian Sea level change and global climate, and in identifying its causal mechanisms contributing to a better understanding of its possible future evolution.

## **2. Study area**

### *2.1. The Caspian Sea*

The Caspian Sea (Fig. 1) belongs to the Ponto-Caspian region; it is a relic of the East Paratethys that became separated during the Pliocene (Varushchenko et al., 1987; Forte and Cowgill, 2013; Yanina, 2014; Van Baak, 2015). Today the Caspian Sea is the world's largest inland, closed water body (390,000 km<sup>2</sup>; 66,100 km<sup>3</sup>). It lies at -28 m a.s.l., has a catchment area of 3.5 million km<sup>2</sup> and extends northwards over 15° of latitude to the East European Plain (Fig. 1a; Chalié et al., 1997). Although from a strictly hydrological point of view, it is a lake, it is commonly called the Caspian Sea. It is divided into three basins, each of about the same area, but of different depths and volumes, *i.e.* the South (water depth < 1020 m), Middle (< 900

m) and North (< 15 m) basins that represent ca two-thirds, one-third and 1 % of the total volume of water, respectively (Chalié et al., 1997). The salinity of the Caspian Sea varies from the North to the South within the range of 1 to 13.5 psu, the lower values being due to the large freshwater supply by the Volga River to the North. The average water salinity of the whole Caspian Sea is of ca 12.5 psu (Dumont, 1998). The Volga River that contributes between 80 and 90 % of the sea's total inflow ( $237 \text{ km}^3 \text{ yr}^{-1}$  on average) drains the eastern part of the East European Plain and has a catchment area of 1.4 million  $\text{km}^2$  (Kroonenberg et al., 1997; Dumont, 1998; Leroy et al., 2020). The relief around the Caspian Sea is contrasted with the high mountains of the Alborz and Caucasus to the south and southwest respectively and mainly low-altitude plains in its northern and eastern parts. Due to the diversity of the relief, the great meridional extension of its catchment as well as the varying influence of air masses from the North Atlantic, Polar region and Central Asia, the Caspian Sea area includes several climatic zones. According to Leroy et al. (2013), the northern and largest part of the drainage basin lies in a zone of temperate continental climate with the Volga catchment extending into the humid mid-latitudes. The west coast has a moderately warm climate while the southwestern and the southern regions fall into a subtropical humid climatic zone and the east coast has a cold desert climate.

During the Quaternary, the Caspian Sea experienced several water-level fluctuations of large amplitude (well above 100 m) implying important modifications of its size and catchment area (*e.g.* Serebryanny, 1982; Varushchenko et al., 1987; Hoyle et al., 2021). From about 130 kyr and before the Holocene, according to many authors (*e.g.* Varushchenko et al., 1987; Kroonenberg et al., 1997; Dumont, 1998; Svitoch 1997; Dolukhanov et al., 2009; 2010), Late Khazarian and Khvalynian highstands were recognised, as well as the two major lowstands: the Atelian one (-120 ÷ -140 m a.s.l.) that occurred between the Late Khazarian (-10 ÷ -5 m a.s.l.) and Khvalynian ones, and the Enotayevian one (-80 ÷ -100 m a.s.l.) that separated the early (maximum +50 m a.s.l.) and late stages (maximum 0 m a.s.l.) of the Khvalynian highstands, *i.e.* Early

Khvalynian and Late Khvalynian transgressive stages. During the Holocene, the Mangyshlak lowstand (ca -90 - 75 m a.s.l.) and the Neocaspian highstand were identified (*e.g.* Varushchenko et al., 1987; Svitoch 1997). Some authors have proposed the subdivision of the Khvalynian transgression into three parts (*e.g.* Lavrushin et al., 2014; Yanina, 2020). However our paper focuses on dates that are identified in the literature as belonging to the Early Khvalynian highstand.

## 2.2. Early Khvalynian highstand

The Khvalynian highstand was identified by Andrusov in 1900. Its lower part, *i.e.* the Early Khvalynian transgression is the largest one recorded for the late Quaternary in the Caspian Sea basin. During this highstand, the water level fluctuated and displayed heights of +10 m a.s.l., +20 m a.s.l. and even rose up to +50 m a.s.l. implying important modifications of the hydrography of the catchment (*e.g.* Varushchenko et al., 1987; Volozh et al., 2004; Fig. 1). The area to the north of the Caspian Sea, *i.e.* the Northern Peri-Caspian including the lower reaches of the Volga and Ural Rivers and that is not currently submerged, formed an additional shallow water basin. In addition, the Caspian Sea water overflowed into the Black Sea through the Manych Pass (threshold at ca 25 m a.s.l.; Fig. 1b). The Early Khvalynian sediments transgressively overlie the Atelian and Khazarian deposits, are separated from the following transgression, *i.e.* Late Khvalynian, by the Enotayevian lowstand and present taxonomic peculiarities in the molluscan fauna (Dolukhanov et al., 2009; Arslanov et al., 2016; Krijgsman et al., 2019 and references therein). Early Khvalynian mollusc assemblage includes *Didacna cristata*, *D. ebersini*, *D. zhukovi*, *D. parallella* and *D. protracta* (Fiodorov, 1957 in Dolukhanov et al., 2009). These molluscs are distinctive from the less varied but massively abundant Late Khvalynian ones (*Didacna praetrigonoides*, *D. parallella*, *D. protracta*, *D. subcatillus*) by their small sizes and thin walls. The palaeo-coastlines and Khvalynian deposits situated from 0 m a.s.l. to +50 m a.s.l. are classified as the Early Khvalynian while those between 0



and -17 m a.s.l. are viewed as the Late Khvalynian (Dolukhanov et al., 2009 and references therein). The Early Khvalynian sediments generally form surficial deposits over extensive areas of the North Caspian, West Turkmenistan, Kura and Terek-Kuma lowlands, while they appear as a staircase of Caspian terraces on the foothills of the Caucasus, Buzachi, and Mangyshlak peninsulas (Arslanov et al., 2016). Lately, they also have been identified in core sediments collected from both the Iranian coast (Kakroodi et al., 2015) and mainly from the Northern (Bezrodnykh 2004, 2015; Svitoch et al., 2008b; Yanina et al., 2018; Richards et al., 2017) and Middle (Sorokin et al., 2014; Tudryn et al., 2016) basins of the Caspian Sea. According to Krijgsman et al. (2019), the thickness of Early Khvalynian deposits is generally only a few metres, but can reach more than 100 m in the Kura and West Turkmen basins. The deposits include a wide range of sandy, silty and clayey sediments, among which brown coloured clays, *i.e.* the so-called “Chocolate Clays” are specific for this transgression.

In the northernmost shallow water basin (present-day Northern Peri-Caspian area), Chocolate Clays, more or less regularly interbedded by thin, sandy or silty laminae were deposited during the Early Khvalynian highstand. These Chocolate Clays of a few metres thick on average are well known (*e.g.* Leonov et al., 2002; Badyukova, 2007, 2010; Chepalyga, 2007; Svitoch, 2009; Shkatova, 2010; Tudryn et al., 2013; Makshaev and Svitoch 2016): their detailed description and distribution are given by Makshaev and Svitoch (2016), Svitoch and Makshaev (2020) and references therein. The oldest publication in Russian dates back to 1856. Chocolate Clays were also identified in the Manych area (Svitoch et al., 2009) and in sediment core collected from the Middle Caspian basin (Tudryn et al., 2016). Chocolate Clays from the lower reaches of the Volga River and from the Middle Caspian basin are characterized by high contents of illite (Tudryn et al., 2013, 2016; Makshaev and Svitoch, 2016) as well as by specific, *i.e.* very low, values of Neodymium isotope ratios,  $\epsilon_{Nd}$  (Tudryn et al., 2016). These clays are similar to the so called “Red Clays” known in the Black Sea sediments, which are also illite-rich and which also display low  $\epsilon_{Nd}$  values (Soulet et al., 2013; Tudryn et al., 2016).

A detailed description of the Early Khvalynian sediments in the Manych area, the overflow pass from the Caspian to the Black Sea (Fig. 1b), is given by Svitoch and collaborators (2008a, 2009). They indicate that the lithological facies of the Khvalynian sediments are variable due to the hydrodynamics in the strait and the geomorphological situation on its shores and that among different facies, Chocolate Clays of entire thickness of approximately 3 m have been identified. Early Khvalynian sediments in western Turkmenistan (Fig. 1b) crop out in the upper part of cliff at altitudes of –24.5 to –20 m a.s.l., forming a poorly defined Caspian terrace: they are composed of grey to brown–grey clays and silty loam while above the erosional surface, they consist in both grey sands and brownish grey, horizontally and crossbedded sands (Kurbanov et al., 2014). Recently published data from sediment cores collected from the Northern basin of the Caspian Sea indicate that Early Khvalynian sediment there consists of two lithologically different sections (Bezrodnykh et al., 2015; Yanina et al., 2018; Yanina, 2020): (i) the lower part (2.5-5.0 m thick) made of alternation of shelly detritus of variable size with a sandy or clayey matrix, and clays with inclusions of shells and shelly detritus, and (ii) the upper part (8-10 m thick) composed of clays with variably thick sand intercalations.

### *2.3. Atelian lowstand and Hyrcanian highstand*

The Atelian lowstand that is considered as separating the Late Khazarian highstand from the Early Khvalynian one is known from the Northern Peri-Caspian, Azerbaijan, Dagestan, eastern Caspian coast and from the Northern Caspian Sea basin (*e.g.* Varushchenko et al., 1987; Svitoch and Makshaev, 2020; Yanina et al., 2020 and references therein) (Fig. 1b). In 1918, Pravoslavlev introduced the term « Atelian » in reference to the old name of the Volga River, Atel. Yanina et al. (2020) presented a very complete review of discussions on its duration and on the related Caspian Sea water level drop and climatic conditions. These authors indicated that most of studies have been

made on the coastal Atelian outcrops that are up to 15-20 m thick. The onland Atelian sediments are mostly composed of sandy and silty loam, loess, alluvial-deltaic deposits and palaeosols. It is expected that purely lacustrine Atelian deposits would form only in the deep basins. The deformations observed in the coastal deposits are attributed to either cryogenic deformations (Yanina et al., 2020) or gravitational sediment displacements (Lavrushin et al., 2014, 2019). The Caspian Sea water level maximal drop estimates during this lowstand vary from ca -140 – -120 m a.s.l. (Lokhin and Maev, 1990) to -15 m a.s.l. (Badyukova, 2021). The former, based on seismic-acoustic profiling, indicates the Caspian Sea retreated into its Middle and South basins. Dating of subaerial sediments outcropping in the Lower Volga and assigned to the Atelian, provided ages between 80.0 and 28.0 kyr using TL method (Shahovets, 1987 in Svitoch et Makshaev, 2020 ), while by OSL they are between ca 70.0 and 19.0 kyr (Kurbanov et al., 2020; Költringer et al., 2020). Calibrated radiocarbon dates from Northern Caspian Sea basin where Atelian sediments have been identified in seismic-acoustic profiles and sediment cores, ranged from ca 44.4 to 39.3 cal kyr BP (Svitoch et al., 2008b; Bezrodnykh et al., 2017; Yanina et al., 2018, 2020). Yanina (2020) proposed the Atelian lowstand occurred between ca 75.0 and 40.0 cal kyr BP and considered younger sediments from the Lower Volga as no more representing the Atelian period, while Lavrushin and colleagues (2014) have recognised two stages: (i) an old and long-lasting palaeoAtelian between ca 130.0 and 60.0 kyr, and (ii) a short-term event at ca 20.0 cal kyr BP. According to Lavrushin et al. (2014), most of the researchers studying the Quaternary deposits of the Northern Peri-Caspian attributed the subaerial loams below Chocolate Clays to the Atelian without any further justification and considered that they represent the same deposits in different sections. However, Lavrushin et al. (2014) highlighted that there may be several such strata of subaerial loam in the sections, that they may be of different ages, and that they can be separated by Caspian sediments even within a single site (e.g. Tsagan Aman site).

The first reports on the Hyrcanian highstand from the northwest of the Caspian region and Manych valley have been made by Goretskiy in 1957 and Popov in 1957 and 1961. Lavrushin et al. (2014) and Sorokin et al. (2018) present very complete discussions on this highstand with nevertheless, different points of view. Indeed, the stratigraphic positioning of the Hyrcanian highstand remains unclear since time-discrepancies exist due to both geochronological and biostratigraphic data, and unknown relationships between Hyrcanian, overlying Early Khvalynian and underlying Late Khazarian deposits. Neveeskaja (2007) classified Hyrcanian molluscs as belonging to the Early Khvalynian and other authors as «Khvalynian - like» (Yanina, 2014). Lavrushin et al. (2014) did not consider the Hyrcanian phase as an independent highstand but identified it as palaeoKhvalynian step in the whole Khvalynian highstand. Other researchers did not take into account the Hyrcanian highstand at all (Svitoch, 1997; Svitoch and Makshaev, 2020) or consider other hypotheses such as: (i) it is part of the Khazaro-Khvalynian basin (Varushchenko et al., 1987), (ii) the Hyrcanian and Upper Khazarian horizons represent the same horizon of the Pleistocene stratigraphic sequence (Zubakov, 1992), or even (iii) the Late Khazarian and Hyrcanian sediments are the two different parts of the Late Khazarian highstand, considering Hyrcanian as the younger step since it is characterized by the freshened environment of the second half of the Late Khazarian highstand that corresponds to the Eemian interglacial (Yanina, 2012, 2014; Yanina et al., 2018; Sorokin et al., 2018). Age estimates for the Hyrcanian transgression vary widely: 120-90 kyr (Zubakov, 1992), 119-107 kyr (Kurbanov et al., 2018) and 43 or even 25 cal kyr BP (Lavrushin et al., 2014). Lately, in addition to this discussion concerning the northwest of the Caspian region and the Manych valley, sediments representing the Hyrcanian highstand have been identified in the Northern Caspian Sea basin (Sorokin et al., 2018). AMS  $^{14}\text{C}$  dates display values of 48.5- 55.2 cal kyr BP. Sorokin et al. (2018) noted that these dates are close to or even beyond the limits of the AMS  $^{14}\text{C}$  method and they considered that radiocarbon ages are rejuvenated and that the real age of the Hyrcanian deposits should be about 80 kyr.

Four selected sedimentary sequences that follow North-South transect of the Caspian catchment (Fig. 2) reflect major transgressive and regressive phases of the sea. These sequences are composed of subaerial and marine sedimentary units and discontinuities at altitudes from +15 m a.s.l. at Srednaya Akhtuba in the Northern Peri-Caspian area to -39 m a.s.l. in the Northern Caspian Sea basin (Fig. 2b-d), and of marine sediments in its Middle basin at -507 m a.s.l. (Fig. 2e). For Srednaya Akhtuba that is very well known and studied coastal site (*e.g.* Leonov et al., 2002; Tudryn et al., 2013; Makshaev and Svitoch, 2016; Kurbanov et al., 2020), two stratigraphic interpretations of the sequence are represented (Fig. 2b: *b1* and *b2*) to highlight the differences in the identification of regressive and transgressive periods by various authors of even very recent publications (Kurbanov et al., 2020; Költinger et al., 2020; Yanina et al., 2017; Makeev et al., 2021).

### **3. Material and methods**

173  $^{14}\text{C}$  dates, 12 U/Th dates and 28 dates either by TL and OSL methods were gathered, all obtained on sediment samples from the Caspian Sea and from its current coast. The dates that were considered are those available in the literature with metadata such as the indication of the laboratory number, the location and the nature of the material used for each method. The review of 47  $^{14}\text{C}$  dates with laboratory number by Dolukhanov and collaborators (2009, 2010) from the Dagestani coast and the Lower Volga area (Fig. 1b) did not however indicate the precise location of the samples, nor the nature of the dated material. Part of these dates could be identified owing to the availability of the original paper (*e.g.* Leonov et al., 2002) or have been cited later on again (*e.g.* Svitoch and Makshaev, 2020). Nevertheless, the precise location for 15 remaining samples could not be found. Since these 15 dates could certainly be better identified in the future, they are presented to be referenced in the database, but they are not included in the discussion. Most of the dates relate to the Early Khvalynian (187), a few of them have been identified as belonging to the Early or to Late

Khvalynian highstand and the rest relate to the Atelian lowstand and the Hyrcanian highstand. For statistical treatment of the gathered dates, frequency distribution diagrams, box plots and Student's t-test (e.g. Davis, 1973) were used.

Metadata including dates, the laboratory number, the location and the nature of the material used for each dating method are presented in Table 1. Since several ages have been published and then re-published in other articles, the laboratory numbers in such references were thus checked in order to avoid duplication of data, and the multiple references were listed. According to their geographical location, the dated sites are presented in clusters as follows: (1) Northern Peri-Caspian area, including the lower Volga and Ural Rivers area, (2) Manych area, (3) Azerbaijan/Dagestan, (4) Mangyshlak, (5) Turkmenistan and Northern Iran, as well as the modern Caspian Sea itself from: (6) Northern and (7) Middle basins (Fig. 1b).

The dates used in our investigation were collected from different scientific articles, although some of them, published several times, are slightly different in one or the other of these publications. OSL dating were made on quartz and feldspar grains from relevant sediments (Tkach et al., 2016; Yanina et al., 2017; Kurbanov et al., 2020), while U/Th dating was performed on bivalve shells (Rychagov, 1977; Arslanov et al., 1978, 2002; Mamedov, 1997), as well as most of  $^{14}\text{C}$  ages (see Table 1), all following the state-of-the-art methodologies.

All the  $^{14}\text{C}$  ages were mostly published as uncalibrated radiocarbon dates (BP) and much more rarely, as already calibrated ones (cal BP). Some  $^{14}\text{C}$  activities have been measured on “composite shell” samples (different materials or debris), really questioning their accuracy and validity (for example in Table 1, line 57). These samples were thus not taken into account. In order to compare all the available and reliable dates, all  $^{14}\text{C}$  dates were calibrated in the same way, *i.e.* Program CALIB REV. 8.2 using IntCal20 (Reimer et al., 2020; Stuiver et al., 2021), taking into account the continental reference curves since (i) the Caspian Sea is considered an inland water body (see also Leroy et al., 2022 for the late Holocene), and (ii) the calibration of samples at sea and on land

required a common reference. The differences between already published dates and those calibrated in this paper fall into the age uncertainties and are only due to the calibration program used. The few samples that did not have BP ages, were considered as such in the table, without modifications.

Finally, as reservoir and hard water effects will be small in comparison to the large time scale of the ages discussed in this paper and as it will most likely have changed across time due to large changes both in the geochemistry of the carbon cycle and sources of sediment and water inputs in the period covered by our investigation, no correction to  $^{14}\text{C}$  ages was applied before calibration.

## **4. Results**

All data identified in the literature as representing Early Khvalynian highstand, Atelian lowstand and Hyrcanian highstand are presented both on Fig. 3a and Table 1, and all the 36 scientific papers from which these data are extracted, are listed on Table 1. Moreover, each age is linked to its reference publication or publications.

### *4.1 Early Khvalynian highstand*

Dates attributed to the Early Khvalynian range between ca 52.0 and 10.0 cal kyr BP. However, their distribution is not continuous (Fig. 3a). The distribution diagram (Fig. 4a) clearly shows a separation without any values between 42.0 and 38.0 cal kyr BP, indicating that the two groups of values, above and below this separation are different. Additionally, only two samples present younger values than 12.5 cal kyr BP (11.7 and 11.9 cal kyr BP), and only one sample of 36.0 cal kyr BP represents the interval 36-38 cal kyr BP (Fig. 4a). Most dates derive from sediments from the Northern Peri-Caspian and the Northern Caspian Sea basin, respectively, areas 1 and 6 (Fig. 1b).

On Fig. 3b, dates are only plotted for sites in the Northern Peri-Caspian (area 1), where Chocolate Clays are present. Thus, the ages range between 22.4 and 12.5 cal kyr BP and only one age is much older, at 35.1 cal kyr BP. Most of these dates display values from ca 18.0 to 13.0 cal kyr BP. Additional OSL and U/Th values are in very good agreement with  $^{14}\text{C}$  dates, although one U/Th age is slightly younger. When looking to all the dates for coastal sediments with respect to their geographical position presented on Fig. 3c (area 1 to 5), a similar cluster of ages is observed between ca 22.4 and 12.5 cal kyr BP with especially an increased density of dates between ca 18.0 and 13.0 cal kyr BP clearly shown on the distribution diagram (Fig. 4b; the distribution of coastal samples between 52 and 10 cal kyr BP and the focus on the interval between 20 – 10 cal kyr BP). For older sediment, even if fewer dates exist, their number is still quite high with the oldest ones being at 36.0 cal kyr BP (Figs. 3c and 4b). In addition, two exceptionally old ages of 47.1 and 42.9 cal kyr BP are recorded (Kura River delta in area 3, Fig. 3c, Table 1, lines 72 and 73).

In the Northern Caspian basin where several sedimentary sequences were cored under ca 2 to 25 m water depth (area 6, Fig. 1b, Fig. 3c), dates mostly display values from 36.0 to 20.1 cal kyr BP, and there are no younger ages in this area as it is the case of the coast. Additionally, ages as old as 52.0 - 42.0 cal kyr BP are recorded (Fig. 3c, Fig. 4b) and some others are close to or at the limit of the dating method (see grey square on Fig. 5a). In the Middle Caspian basin (area 7 on Fig. 1b, Fig. 3c-7), the dates from a sediment core collected to its western side at water depth of ca 45 m display values of 28.9 and of 46.9 cal kyr BP. In another sediment core collected to the east at -507 m a.s.l. (479 m water depth), the Chocolate Clays as those from the Northern Peri-Caspian area have been identified in the lowest part of the core and they exhibit ages from 15.2 to 14.1 cal kyr BP.

#### *4.2. Atelian lowstand and Hyrcanian highstand*



Samples related to the Atelian lowstand cover time from 68.3 to 27.2 kyr in the Northern Peri-Caspian area; additionally, one younger age of 18.6 kyr is recorded too (Kurbanov et al., 2020; Költringer et al., 2020) (Fig. 3a). Older subaerial sediments are also known in this area, but they are indicated in the literature as not belonging to the Atelian lowstand (Költringer et al., 2020). In the Northern Caspian Sea basin, the Atelian is recorded between 43.9 and 39.5 cal kyr BP, and some authors consider that ages younger than ca 40 kyr obtained on subaerial samples in the Northern Peri-Caspian area do not belong any more to the Atelian lowstand but to the Early Khvalynian highstand (Yanina, 2020).

The Hyrcanian highstand presents ages of 55.2-48.5 cal kyr BP in the sediment from the Northern Caspian Sea basin and of 42.6 cal kyr BP in the Northern Peri-Caspian Sea area (Fig. 3a, Fig. 4a), two additional ages being close to the limit of the  $^{14}\text{C}$  method (see green square on Fig. 5a). Further, from Fig. 3a, 4a and 5a, it may be seen that the groups of (i) oldest Early Khvalynian ages, between ca 42 and 52 cal kyr BP, and (ii) Hyrcanian dates are overlapping. It is particularly true when considering uncalibrated ages at the limit of the method for both groups (Fig. 5a). This may be tested using the Student's t-test (*e.g.* Davis, 1973). The null hypothesis  $H_0$  that the population means from which the samples are coming,  $\mu_1$  and  $\mu_2$ , are equal, was verified:

$$H_0: \mu_1 = \mu_2$$

against the alternative:

$$H_1: \mu_1 \neq \mu_2$$

the t statistics is

$$t = (X_1 - X_2) / S_p((1/n_1) + (1/n_2))^{1/2}$$

The  $S_p$  quantity is the pooled estimate of population standard deviation found from the pooled estimation of the variance for the two groups: 1 – oldest part of Early Khvalynian, and 2 – Hyrcanian samples

$$S_p^2 = ((n_1-1)S_1^2 + (n_2-1)S_2^2) / (n_1 + n_2 - 2)$$

The values are listed in Fig. 4c. Then  $S_p^2$  and  $S_p$  are equal to 19.695 and 4.438 respectively. The t statistics is 1.150 that does not permit to conclude, at 10% level of significance, that the two groups came from populations having different means. The same conclusion is valid for a F test checking the variance.

## 5. Discussion

The heterogeneous distribution of ages between the coast and the Northern Caspian Sea basin, the large range of the older Early Khvalynian dates between ca 52 and 42 cal kyr BP that cover the period similar to Hyrcanian, the Atelian lowstand recorded along a very wide range of ages between 68.3 and 27.2 kyr and the occurrence of the Hyrcanian highstand at 55.2 – 42.6 cal kyr BP, altogether show a complex pattern for the Caspian Sea hydrological evolution and, without any complementary information, the difficulties in defining chronological limits for the periods under consideration (Fig. 3a).

### 5.1. *Early Khvalynian highstand*

Data for the Early Khvalynian highstand display values that suggest its evolution in two main steps that are discussed below as the first, older phase, Early Khvalynian 1 (hv1-1), and the second, younger phase, as Early Khvalynian 2 (hv1-2).

The oldest ages of ca 52.0 – 42.0 cal kyr BP recorded for the Early Khvalynian highstand will be discussed with the Hyrcanian highstand (see section 5.2.2.).

#### 5.1.1. Early Khvalynian 2 (hv1-2)

The radiocarbon ages recorded for the younger part of the Early Khvalynian highstand in coastal sediments range from 22.0 to 12.5 cal kyr BP and are very clearly concentrated between ca 18.0 and 13.0 cal kyr BP (Fig. 4b, Fig. 5a). This transgressive phase is marked by the deposition of the Chocolate Clays, especially in the Northern Peri-Caspian, in the Manych areas, and in the Middle Caspian Sea basin. However, Arslanov and Yanina (2008) have obtained a similar radiocarbon date ( $15.01 \pm 0.30$  cal kyr BP) on shells from Azerbaijan but they associated it to the next period, the Late Khvalynian highstand. Such puzzling data for both transgressions also appear in some other publications (Dolukhanov et al., 2009, 2010) and some authors consider the Late Khvalynian setting between ca 16.0 and 13.0 kyr BP (e.g. Badyukova, 2021). Arslanov and co-authors (2002, 2013, 2016; Arslanov and Yanina, 2008) proposed that the thin, often small shells from Early Khvalynian deposits give in most cases rejuvenated  $^{14}\text{C}$  age. Indeed, these authors demonstrated that a difference in  $^{14}\text{C}$  age exists when the dating is performed either on the inner or the external side of the same shell, the former one taking into account biological fractionation and displaying a 500-yr older age and being considered as the most realistic one. Moreover, for cores collected from the Northern basin of the Caspian Sea, the  $^{14}\text{C}$  ages exhibit generally older values than those from the coast (Fig. 3c and Fig. 4b) and Bezrodnykh and collaborators (2015) indicated that the lower boundary of the next transgression, *i.e.* the Late Khvalynian, is already reached at approximately 17.0 – 16.0 kyr BP. The age difference between coastal and core sediments as well as the confusing limit between Early and Late Khvalynian are surprising. This could be considered as being the result of rejuvenated ages for Early Khvalynian coastal shells or as a quite tricky discrimination between samples that are close to the limit for these two highstands, as indicated by the somewhat fragmented, unreliable matching of ages to one or other of the highstands in the literature (see references in Table 1). Indeed, some samples both on the coast and in sediment cores from the Northern Caspian Sea basin are considered, on the base of sedimentological data, as belonging to the first or to the second highstand in different publications and not always by considering the absolute ages (see in Table 1, line 49, 115, 119).

In our opinion, the sharp termination of calibrated ages at ca 13.0 cal kyr BP observed for coastal samples (Figs. 3c, 4b and 5a) indicates their very good consistency. Moreover, these ages are in perfect agreement with OSL and U/Th dates obtained on coastal sediments too (Arslanov et al., 2002, 2008, 20013, 2016; Kurbanov et al., 2020). Additionally, the end of Early Khvalynian deposits has been identified at the very base of a sediment core collected in the Middle Caspian Sea basin at 479 m water depth (Boomer et al., 2005; Tudryn et al., 2014). The concerned sediment that was characterised by high occurrence of pollen grains indicative of a stronger contribution from river sources to the sediment than later on, consisted in Chocolate Clays similar to those found in river terraces in the modern lower Volga (Tudryn et al., 2013, 2016; Fig. 2b, c and e). These Chocolate Clays presented the same colour, grain size, clay mineralogy and Neodymium isotopic composition. In contrast to the sediment cores from the shallow Northern basin, the material collected from the Middle basin has been deposited largely below the water level, even during the Enotayevian and Mangyshlakian lowstands that occurred after the Early Khvalynian highstand, with water levels decreasing down to ca -100 m a.s.l. and ca -75 m a.s.l. respectively (Svitoch 1997). The sediment core from the Middle basin presents a continuous sedimentation and the calibrated ages on ostracod shells display values from ca 15.2 cal kyr BP at the core bottom to ca 14.1 cal kyr BP for Chocolate Clays of the Early Khvalynian (Tudryn et al., 2016; Table 1 line 157, 158). This matches perfectly with data from the coast and indicates that from ca 14.1 cal kyr BP, Chocolate Clays were no longer deposited in the Middle Caspian Sea basin. Such a concordance of ages for the end of the Early Khvalynian, which is observed despite different dating methods, different geographical positions of the dated samples and different nature of these samples, would be very difficult to explain by exactly the same pollution and rejuvenation of the shells used for  $^{14}\text{C}$  dating. Thus, according to the reviewed dates and arguments above, the end of the highstand is proposed at ca 13.0-12.5 cal kyr BP. It may seem strange to find no ages corresponding to Chocolate Clays in the Northern

Caspian Sea sediments while they are present in the Middle basin as well as on the coast, especially in the Northern Peri-Caspian and in Manych areas. This open question could highlight the difficulty in identifying and comparing chronologically the same sediments on the coast and offshore, the difficulty to avoid the possible confusion between Early and Late Khvalynian as well as the possibility of discontinuities in the sedimentary sequence from the Northern Caspian Sea shallow basin. The study of sediments from the Northern Caspian Sea basin through parameters such as those that allowed the identification of Chocolate Clays in the Middle one, would probably allow to better understand the specificity of the Early Khvalynian end.

#### 5.1.2. Early Khvalynian 1 (hv1-1)

Sediments from the Northern Caspian Sea basin present older ages than those discussed above: few range from 52.0 to 42.0 cal kyr BP while many, quite homogeneously distributed through time, span between ca 36.0 and 22.0 cal kyr BP (Fig. 3c and 4b). On the coast, sediments also fall into this time-scale, even if they are rare. Nevertheless, if samples from Dagestan and the lower Volga areas that have been compiled by Dolukhanov et al. (2009, 2010) but unfortunately without any location precision are taken into account (Table 1, line 88-102; Fig. 3c - area 8), this number increases considerably. Thus, such a coherence of ages between ca 36.0 and 20.0 cal kyr BP from both the coast and the Northern Caspian Sea basin likely indicates a stage of the Early Khvalynian transgression during that time and makes a clear onset at ca 36.0 cal kyr BP. Since the exact altitudes for three coastal samples that display ages between ca 36 and 28 cal kyr BP were not indicated in the reference papers, they were thus roughly estimated according to the sample location. It can be noticed that samples are distributed at altitudes of ca -10 and 0 m a.s.l. during this phase of the Early Khvalynian (Fig. 5a).

The data indicate that during the Early Khvalynian 1 (from ca 36 to 22 cal kyr BP), the

Caspian Sea reached an altitude comprised between ca -10 and 0 m a.s.l. while during the Early Khvalynian 2 (between 22 and 12.5 cal kyr BP) it rose and reached at least ca 40 m a.s.l between 17 and 13 cal kyr BP (Fig. 5a).

## 5.2. *Atelian lowstand and Hyrcanian highstand*

### 5.2.1. Atelian lowstand

According to many authors, sediments from the Atelian regression in the Northern Peri-Caspian coast are recorded between ca 70.0 and 27.0 kyr (Fig. 2a). Only one date was obtained at 18.6 kyr (*e.g.* Kurbanov et al., 2020; Svitoch and Makshaev, 2020; Költringer et al., 2020; Table 1). In the Northern Caspian Sea basin, ages range between 43.9 and 39.5 cal kyr BP (Bezrodnykh et al., 2017; Yanina et al., 2018), and some authors proposed that the younger ages obtained on the coastal samples, no more represent the Atelian lowstand but a Khvalynian highstand (Yanina, 2020; Makeev et al., 2021). The different consideration of subaerial coastal samples by the authors is expressed in Fig. 2b which concerns the sedimentary sequence of Srednaya Akhtuba in the Northern Peri-Caspian area. When looking at ages attributed to the Atelian lowstand as being between ca 70.0 and 27.0 kyr and with respect to the altitude of the corresponding dated samples (Fig. 5a), they can be divided into three groups as follows.

1 - The youngest ages are concentrated between 39.5 and 27.2 kyr in the Northern Peri-Caspian at altitudes of ca 10 to 5 m a.s.l. The timing from ca 36.0 cal kyr BP is the same as that for the first step of the Early Khvalynian highstand, hv1-1 (Fig. 5a). The corresponding altitudes for the sediments from both Atelian lowstand and the lower part of the Early Khvalynian highstand allow the Caspian water level to be specified as fluctuating between ca -5 and +10 m a.s.l. (Fig. 5a). So, according to these data, it is possible to confirm that this period does not correspond to a lowstand but to a highstand with subaerial sediments deposited above the water level, those sediments having been

inaccurately considered as being part of the Atelian sequence by some authors (*e.g.* Költringer et al., 2020; Kurbanov et al., 2020) but accurately interpreted by others (Yanina, 2020; Makeev et al., 2021). The proximity of the shoreline with certainly a hardly changing water level, explains the existence of several subaerial deposits with various ages that are sometimes separated by Caspian Sea sediments in the Northern Peri-Caspian area. During the late phase of the transgression, *i.e.* the Early Khvalynian 2 phase, the water reached higher levels. The associated sediments mostly consisting in Chocolate Clays have been deposited directly on top of these subaerial ones. A distinct age on subaerial sample at around 19 kyr obtained by Kurbanov and coauthors (2020) may reflect a small, short-lived drop in the water level of the Caspian Sea below about 10 m a.s.l. before it rises during the Early Khvalynian 2 transgressive phase.

2 - The middle age group attributed to the Atelian regression is linked to sediments from the Northern Caspian Sea basin and displays values between 43.9 and 39.5 cal kyr BP (Yanina et al., 2018, 2020). These sediments have been identified through seismic-acoustic profiles and they are clearly sandwiched by deep-water sediment, the upper part being related to the transgressive stage we defined as starting at ca 36.0 cal kyr BP (Fig. 5a).

According to these data, the water level at the beginning of the regression decreased between ca -60 m and -90 m a.s.l. and possibly beyond in its phase of maximal extension (Fig. 5a). This clearly represents a very important lowstand confining the waterbody to its Middle and South basins. On the coast, no dates are available for this phase, probably due to increased erosional processes rather than depositional ones as it is indicated by erosional surfaces on the corresponding lithological profiles (Kurbanov et al., 2020; Költringer et al., 2020).

3 - The oldest group of Atelian ages, between 68.3 and 43.9 cal kyr BP, has only been recognized in the Northern Peri-Caspian coast at altitudes around 0 to 5 m a.s.l. and thus the precise water level during this time cannot be estimated (Fig. 5a). Dates of Caspian Sea sediments between 55.2 and 43.9 cal kyr BP allow proposing a water level somewhere between ca 0 and -50 m a.s.l. for this

timespan. Between 68.3 and 55.2 kyr, no clear deduction of the water level elevation is possible.

Thus, given the data, the question on the scale and amplitude of this regression remains open.

Moreover, (i) the absence of evidence for regressive sequences in seismic-acoustic profiles in the shallow Northern Caspian basin for the considered part of sediments and (ii) the presence of transgressive ones (Sorokin et al., 2018; Yanina et al., 2018), both suggest that this older Atelian lowstand is much less important than that defined between ca 43.9 and 36.0 cal kyr BP.

The results clearly indicate a two-step Atelian regression with its upper, maximal regressive stage between ca 43.9 and 36.0 cal kyr BP and its lower stage with much less water-level lowering (remaining to be clearly defined). Such an evolution of the Atelian lowstand composed of two separate steps was proposed by Lavrushin et al. (2014) who however, suggested older ages for the lower Atelian step, and younger ages for the upper Atelian one (respectively palaeoAtelian and Atelian on Fig. 5c).

### 5.2.2. Hyrcanian highstand

The oldest ages recorded for the Early Khvalynian highstand in the Northern Caspian Sea basin display values of 50.0 – 42.1 cal yr BP, and even older (55.7 kyr BP), close to the limits of the  $^{14}\text{C}$  method (Sorokin et al., 2014, 2018)(Fig. 5a). Ages of 47.1 and 42.9 cal yr BP have also been obtained on two samples from sediments of the Lower Kura River delta (Kroonenberg et al., 2010). These old Early Khvalynian ages fall just below the ages obtained for the deep, upper Atelian lowstand (Fig. 5a) and are very close to those published for the Hyrcanian highstand recorded in the Northern Caspian Sea basin too, *i.e.* partly between ca 55.2 and 48.5 cal kyr BP and partly beyond the limits of the  $^{14}\text{C}$  method (Sorokin et al., 2018; Table 1). In the same paper, Sorokin and collaborators separated the Hyrcanian samples from those of the Early Khvalynian. However, one of the ages at 48.5 cal kyr is considered as belonging to the Early Khvalynian highstand or to the Hyrcanian one depending on the authors (Sorokin et al., 2014; Bezrodnykh et al., 2017), and all ages



together form a cluster from at least ca 55.2 to 42.1 cal kyr BP (Fig. 5a) as shown by Student t statistics discussed above (chapter 4.2. Atelian lowstand and Hyrcanian highstand). Based on studies of these sediments from the Northern Caspian Sea basin, Bezrodnykh et al. (2017) have described below the Atelian horizon, a moderate water body approximately 80 m deep with a malacofaunistic assemblage corresponding to the Hyrcanian basin that they attributed to the second step of the Late Khazarian highstand.

In the Northern Peri-Caspian, an age of 42.6 cal kyr BP was obtained from sediments attributed at first to the Late Khazarian but discussed afterwards as being Hyrcanian (Tudryn et al., 2013, Lavrushin et al., 2014). This age belongs to the Hyrcanian highstand cluster from the Northern Caspian Sea basin at 55.2 - 42.1 cal kyr BP (Fig. 4a). Such consistency of data from the coast and from the Northern Caspian basin suggests the highstand starting at ca 55.2 or 58.4 when taking into account the age uncertainty, and finishing at 42.1 cal kyr BP. However, the very close ages obtained for the end of Hyrcanian highstand (43.0, 42.6 and 42.1 cal kyr BP) and the beginning of the Atelian regression (43.9 cal kyr BP), make the transition poorly defined but indicate it as very fast with water drop below -60 m a.s.l.. If the age uncertainty ( $2\sigma$ ) is taken into account, the Atelian age (from 44.4 to 43.5 cal kyr BP) is consistent with the two first Hyrcanian ages (from 43.7 to 41.7 and from 43.6 to 41.2 cal kyr BP respectively), but falls into a range that is slightly older than the Hyrcanian age at 42.1 cal kyr BP (42.9 to 41.4 cal kyr BP). Consequently, the transition from Hyrcanian to Atelian can be rather precisely considered as being between 43.5 and 42.9 cal kyr BP.

Nevertheless, authors who obtained  $^{14}\text{C}$  ages for Hyrcanian highstand in the Northern Caspian Sea basin (Sorokin et al., 2018; Yanina, 2020), acknowledged that the ages are close to the limit of  $^{14}\text{C}$  method. They estimated these ages as being too young due to possible recrystallisation of shells, and thus positioning this highstand at about 80 kyr. Indeed, these authors have all considered Hyrcanian as a second stage of the Late Khazarian highstand that is known for the Eemian interglacial – Mikulin interglacial in Russian stratigraphy –, and that terminated at the beginning of the last glacial.

The dating of the end of this Late Khazarian highstand is between 90 and 75 kyr (Svitoch and Makshaev, 2020 and references therein). According to some authors (Kurbanov et al., 2018; Sorokin et al., 2018; Yanina, 2020), the deposits in the Manych area indicate that the Karangatian highstand known in the Black Sea between 115 and 95 kyr and the Hyrcanian one were partly coeval and that after the fall of the Karangatian sea level, the “Hyrcanian water” flowed to the Black Sea.

Independent dating such as by OSL would help clarify whether  $^{14}\text{C}$  ages of Hyrcanian sediments from the Northern Caspian Sea basin considered as rejuvenated, really are or not. This is quite important since other ages belonging to the cluster (*i.e.* between 55.2 and 42.1 cal kyr BP) have not been considered as rejuvenated (Tudryn et al. 2013, Sorokin et al., 2014, 2018; Bezrodnykh et al., 2017; Richards et al., 2017). Moreover, Tudryn and her collaborators (2013) highlighted that the X-ray diffraction (XRD) analyses of well-preserved, in-situ shells including juvenile forms, show aragonite as the only component of these shells, therefore indicating the absence of calcite recrystallisation. XRD tests were carried out to precisely define the detection limit of calcite in samples composed of different amounts of aragonite and calcite. At 99.5% of aragonite and 0.5% calcite in the mixture, calcite cannot be detected with certainty. Therefore, in order to simulate what will be the effects of a 0.4% of recrystallised calcite in sample published in Tudryn et al. (2013),  $^{14}\text{C}$  ages were calculated with extreme assumptions of a recrystallised calcite of 0 and 100 pMC respectively. The results showed that the impact of old carbon (0 pMC) on the age obtained is clearly in the error bar (42.63 cal kyr BP with  $2\sigma$ : +1.48/-0.98) while an impact of a 100 pMC  $^{14}\text{C}$ -activity calcite gives an age of 46.74 cal kyr BP ( $2\sigma$ : +1.82, -1.74), which belongs to the obtained cluster of ages for Hyrcanian highstand.

Thus, according to the data, the Hyrcanian phase can be identified as a transgression that started at 55.2 cal kyr BP or even before and finished between 43.5 and 42.9 cal kyr BP. Apart from dating, the freshening of Hyrcanian water, a “Khvalynian-like” fauna (Popov, 1961, 1967; Yanina 2020) and a climate colder than during the Eemian (Shkatova 2010; Tudryn et al., 2013) plead for the late

occurrence of the Hyrcanian highstand, even if Shkatova (2010) associated it with the Eemian climate fluctuations. In that case, the highstand known at ca 80 kyr is not Hyrcanian as claimed by some authors (Sorokin et al., 2018; Yanina, 2020) but represents the Late Khazarian one. Between both highstands, an early stage of Atelian lowstand could take place with, however, limited water level decrease as discussed above.

### 5.3. *Synthesis of the hydrologic evolution of the Caspian Sea*

#### 5.3.1. Chronology of the main hydrological changes

The ages compiled and reviewed locate the Early Khvalynian highstand in a time period between ca 36 and 13 cal kyr BP, with two phases, *i.e.* older - Early Khvalynian 1, hv1-1 and younger - Early Khvalynian 2, hv1-2 phases (Fig. 5b). These phases clearly correspond (i) to the upper part of the Hyrcanian-palaeoKhvalynian and to the Early Khvalynian defined by Lavrushin and co-authors (2014; Fig. 5c) and (ii) to the Khvalynian stages I and II defined by Yanina (2020) (Fig. 5d).

Considering these different names, it seems important to stress the need to determine a unique nomenclature for this highstand which is considered here as Early Khvalynian based on the literature and divided into two parts due to clear lithological, chronological and bathymetric differences between the two.

As the time frame and limits for this Early Khvalynian highstand are now determined, the reliable and calibrated ages between ca 36 and 13 cal kyr BP which have been or will be published without being linked to any specific period, can now be formally attributed to it. For example, ages between 25.4 and 13.7 cal kyr BP obtained from sediment cores from Gorgan Bay in the SE Caspian Sea (Leroy et al., 2019) can be attributed to the Early Khvalynian transgression and even to its older or younger parts.

The data concerning the Atelian lowstand indicate that it is composed of two distinct periods separated from each other by the Hyrcanian highstand. Its pattern thus appears different from what is described in the literature (Lavrushin et al., 2014; Yanina, 2020) (Fig. 5b, c, d). Indeed, the first Atelian phase from ca 68.3 kyr to the beginning of the Hyrcanian highstand at ca 55.2 cal kyr BP remains poorly determined. During the second Atelian phase, between ca 43.5-42.9 and 36.0 cal kyr BP, the water level decreased until -90 m a.s.l. and possibly more, indicating a very important regression. However, the regressive phase indicated by several authors before the younger Early Khvalynian highstand (hv1-2) that led to the Chocolate Clays deposition (Fig. 5c, d), was not identified through the reviewed here data (Fig. 5b); only one OSL date at ca 19 kyr could suggest a small water level change at that time (Fig. 5a).

The Hyrcanian transgression started at 55.2 cal kyr BP or even before and ended at ca 43.5-42.9 cal kyr BP. Contrary to the conclusions of Sorokin et al. (2018) and Yanina (2020), this highstand appears to be younger than ca 80 kyr and would not thus belong to the Late Khazarian highstand (Fig. 5b, d). Its timing corresponds to the older part of the Hyrcanian that was classified as a palaeoKhvalynian highstand ending at around ca 20 kyr BP by Lavrushin et al. (2014; Fig. 5b, c). However, our results show that the Hyrcanian highstand is clearly separated from the Early Khvalynian highstand by the deep Atelian lowstand (second phase) that reduced the Caspian Sea to its Middle and South basins. Thus, the Hyrcanian is a separate highstand between the Late Khazarian and Early Khvalynian ones.

### 5.3.2. Water level change

The pattern of the Caspian water level change is summarized in Fig. 6. The Atelian lowstand indicated as **at-1** from 70 to 55.2 cal kyr BP, has only been recognised in the Northern Peri-Caspian coast at altitudes around 0 to 5 m a.s.l. (Tkach et al., 2016; Költringer et al., 2020) and thus the

precise water level during this time cannot be estimated due to the lack of data. The Hyrcanian highstand is indicated as **hc** and the corresponding box plot on Fig. 6 shows its age distribution. Samples that have mostly been collected from the Northern Caspian Sea basin are located at the highest altitudes of ca -60 m a.s.l., for the most part of the **hc** phase, and reach even -37 m, and -3 m a.s.l. at the end of this highstand. Taking into account (i) the altitude of these samples, (ii) the water depth estimation up to 80 m for samples at -60 m a.s.l. (Bezrodnykh et al., 2017), and (iii) the presence of Hyrcanian sediments at the altitude of about 20 m a.s.l. in the Manych area (Popov, 1961), it is proposed that the water level should have reached 20 m a.s.l. to allow the overflow of the Caspian water into the Black Sea through the Manych Pass, as it was indicated by several studies (Popov, 1957; Sorokin et al., 2018; Yanina, 2020). Subaerial sediments at -5 and +7 m a.s.l. limited the water level below these values at the beginning of the transgression. The very close ages obtained at the limit between the Hyrcanian highstand and the Atelian lowstand **at-2** make the transition poorly-defined but occurring very rapidly between 43.5 and 42.9 cal kyr BP. According to the data, the water level at the beginning of the regression at-2 decreased below ca -60 m and above -90 m a.s.l. and possibly beyond -90 m a.s.l. in its phase of maximal extension; this is in agreement with the water level at ca -140 m a.s.l. reported by Lokhin and Maev (1990). During the first phase of Early Khvalynian transgression **hv1-1** (from ca 36 to 22 cal kyr BP), the Caspian Sea level reached an altitude above the highest altitude known for marine sediments but below the lowest altitude of subaerial sediments, both indicated by linear regressions (all  $R^2$  are higher than 0.97) on Fig. 6. Moreover, the data indicate that after the fast water level rise up to -10 m a.s.l. at 36 cal kyr BP, the water level gently increased and reached an altitude of 10 m a.s.l. at 22 cal kyr BP. During the Early Khvalynian 2 (**hv1-2**) between 22 and 13 - 12.5 cal kyr BP, the Caspian Sea rose and reached at least ca 40 m a.s.l. between 17 and 13 cal kyr BP. The current results refine the elevation already published in other studies indicating an altitude of 50 m a.s.l. although without dating of the corresponding

sediment (*e.g.* Varushchenko et al., 1987). According to this hydrological reconstruction, the maximum stand of the Caspian Sea would have happened during the Early Khvalynian 2.

#### *5.4. Driving mechanisms of the major Caspian Sea hydrologic changes*

Changes in the water level in the Caspian Sea may be related to various factors, among which tectonics and climate. According to previous works relating to tectonics, its impact on the change of water level at the scale of several tens of metres (as discussed in the present article) is considered negligible (*e.g.* Allen et al., 2002; Bochud, 2011; Naderi Beni et al., 2013). Nevertheless, Lavrushin (personal communication) points out the possible discharge of large amounts of artesian water from deep aquifers present in the Caspian Sea sediments during intense tectonic compression that could have participated in the transgressive periods. Although such hypothesis could be further confirmed by taking into account the geodynamic parameters as well as the characterisation of these interbedded aquifers in terms of water capacity (amount of water being possibly mobilized to produce such transgressions), this information is not yet available. On the other hand, the timescale considered in this paper covers the last glacial period, *i.e.* Weichselian in Western Europe, equivalent to Valdai in European Russia and climate change has had an important impact on the Caspian Sea water balance. The sediments of the Caspian Sea integrate the climate evolution from very different geographical and climatic zones of its catchment area and thus record this local, but also larger, supra-regional context. This implies an impact of (i) varying influences of different air masses such as westerly, polar air, Siberian anticyclone, North Atlantic Oscillation (NAO) and even El-Niño Southern Oscillation (ENSO) that would have played a role in the Late Pleistocene (Molavi-Arabshahi et al., 2016; Nandini-Weiss et al. 2019; Arpe et al., 2019), and of (ii) modifications of the Caspian Sea catchment area (Grosswald, 1993; Mangerud et al., 2004; Chepalyga, 2007; Vandenberghe et al., 2014), including its possible connection to the Arctic Ocean as proposed for the

Akchagylian transgression at the Plio-Pleistocene limit (Hoyle et al., 2021), and the recurrent flow of the Amu Darya into the Caspian Sea over the Quaternary (Leroy et al., 2020). Some or all of these factors can obviously act together and many authors have proposed them as drivers of hydrologic modifications (*e.g.* Velichko et al., 1987; Grosswald, 1993; Mamedov, 1997; Leonov et al., 2002; Shkatova, 2010; Mangerud et al., 2004; Chepalyga 2003, 2005, 2007; Sidorchuk et al., 2009; Yanina et al., 2018; Arpe et al., 2019).

During last glaciation in the East of the Caspian area in western High Asia (Tien Shan, Alai, Pamir, Hindu Kush; Fig. 1a), the most extensive glacial phase occurred during the marine isotope stages MIS 5–3 (Fig. 5e and f) in which glaciers reached their maximal extent during MIS 4 and at the first half of MIS 3 (Abramowski et al., 2006; Zech, 2012; Zhang et al., 2016; Stübner et al., 2017; Batchelor et al., 2019). According to these authors, glacial advances remained only limited during MIS 2, probably reflecting enhanced arid conditions caused by the weakened westerlies and strengthened Siberian High. To the north, the maximal extent of the Eurasian ice sheets has been reached, owing to the cold and humid climate conditions at: (1) ca 90 – 80 kyr for the Early Weichselian/Valdai, (2) ca 60–50 kyr for the Middle Weichselian/Valdai, and (3) ca 25 – 15 kyr for the Late Weichselian/Valdai (Svendsen et al., 2004) (Fig. 1a solid line: violet, yellow and white respectively, Fig. 5f). Moreover, Mangerud et al. (2004) indicated water emptying into the Caspian Sea from ice-dammed lakes formed in the southern front of the Siberian and East European ice sheets at ca 90 and 20 kyr. The chronology of these glaciations and the highstands of the Caspian Sea, from the Late Khazarian through the Hyrcanian to the Early Khvalynian, seem to be well coordinated.

#### 5.4.1. Eurasian ice sheets and the Caspian Sea

##### Late Khazarian highstand

During the Early Weichselian/Valdai glacial maximum at about 90-80 kyr, meltwater was transported from the southern front of the Siberian ice sheet into the Caspian Sea via the Turgay Pass, the Aral Sea and the Uzboy River (Fig. 1a, violet dashed line and arrow), and then to the Black Sea via the Manych Pass (Mangerud et al., 2004). This highlights that the Caspian Sea catchment included much of northwestern and western Asia at that time. The time span corresponds to the end of the Late Khazarian transgression. Yanina and her collaborators (Yanina et al., 2018; Yanina, 2020) have placed the Hyrcanian highstand there and have considered that this represents the second/younger part of the Late Khazarian highstand (Fig. 5d and f). Furthermore they indicate that it corresponds to the high stand observed in the Black Sea at the same time (end of Karangatian and Tarkhankutian highstands). Generally humid conditions at ca 90-80 kyr are attested by high stands of lakes such as Van and Konya, and by  $\delta^{18}\text{O}$  isotopic record from the Soreq cave, all in the Middle East (Bar-Matthews et al., 1999; 2000; Kuzucuoglu et al., 1999; 2010, Stockhecke et al., 2014; Pickarski et al., 2015).

#### Early Khvalynian highstand

According to Mangerud et al. (2004), during and after the LGM, large amounts of water inflowing into the Caspian Sea occurred following the melting of the southern Scandinavian Ice Sheet (SIS) margin. At about the same time, in the western part of the East European Plain, both a southward release of the SIS meltwater into the Black Sea via the Dnieper River (between 17.2 and 15.7 cal kyr BP) and a westward one into the North Atlantic via the “Fleuve Manche” (between ca 20 and 16.7 cal kyr BP) occurred (Soulet et al., 2013; Toucanne et al., 2010) (Fig. 1a, two dashed white lines and arrows). Some authors, who also indicate westward and via Dnieper meltwater discharge routes, propose that only limited amount of glacial meltwater flowed into the Volga River (Panin et al., 2020). However, considering the time interval between ca 20 and 13 cal kyr BP, this coincides with the second phase of the Early Khvalynian highstand (hv1-2) and the deposition of the Chocolate



Clays in the Caspian Sea until its Middle basin. Very low  $\epsilon_{Nd}$  values of the specific illite-rich Chocolate Clays from the lower Volga and Middle basin of the Caspian Sea make it possible to clearly identify their source in the Baltic Shield area, implying the melting of the SIS and transport of this detrital material into the Caspian Sea by fluvioglacial waters via the Volga River (Tudryn et al., 2016; Fig. 1a, dashed white line and arrow into the Caspian Sea). According to Vandenberghe et al. (2014), the permafrost degradation on the East European Plain started at 17–15 kyr BP. This certainly contributed in supplying additional detrital material and water into the Caspian basin that reached ca 40 m a.s.l. as recorded between ca 17 and 13 cal kyr BP (and even 50 m a.s.l.). Such a highstand of the Caspian Sea and the impact of the mudflow on it were proposed by some authors for ca 16-14 kyr BP (Leonov et al., 2002; Lavrushin et al., 2014). During this time, the European part of the Caspian catchment area has widened towards the north and when water level rose high enough, water also flowed into the Black Sea via the Manych Pass (Figs. 1 and 6).

The correlation between the Late Weichselian/Valdai and the first phase of the Early Khvalynian highstand, hv1-1, that started at ca 36 cal kyr BP (Fig. 5b,f), is less clear. This phase coincides with the relatively humid conditions in Central Asia across today's deserts (Yang and Scuderi, 2010; 40-30 kyr BP) and high lake levels such as Manas (37-32 kyr BP) and Issyk Kul (45-22 kyr BP; Rhodes et al., 1996; Jelinowska et al., 1995; Fan et al., 2012; Rosenwinkel et al., 2017). In the Middle East, the data are more contrasted but as a whole, they indicate increased water levels from ca 40 until at least ca 20 kyr BP in lakes Zeribar, Iran (Snyder et al., 2001; Wasylikowa et al., 2006) and Lisan (Bartov et al., 2002), as well as changing water levels in the Anatolian Lakes Tuz and Van (Kuzucuoglu et al., 1999, 2010; Stoskhecke et al., 2014; Pickarski et al., 2015). In the Iranian Lake Urmia, the water level is indicated as high by some authors (Djamali et al., 2008; Tudryn et al., 2021) and as low by others (Stevens et al., 2012). Core-sediment parameters from the SW Black Sea show a dry environment in Northern Anatolia between ca 40 and 32 cal kyr BP, but more humid conditions from ca 30 to 20 cal

kyr BP. In the Black Sea, Yanina (2020) indicates the Surozh transgression between 40 and 25 kyr BP but notices that not all investigators on the Late Pleistocene of the Pontian basins agree on this highstand. Finally, in the Caspian Sea catchment area, data from the middle Kura River valley document a Caspian Sea regressive phase before ca 37 cal kyr BP and a clearly transgressive one between ca 27 and 13 cal kyr BP (Ollivier et al., 2015).

#### 5.4.2. Glaciers of western High Asia and the Caspian Sea

During the Middle Weichselian/Valdai glaciation at ca 60 -50 kyr, water from ice-dammed lakes in the southern front of the Siberian and East European ice sheets did not outflow into the Caspian Sea (Mangerud et al., 2004; Fig. 1a, yellow solid line). The highstand of the Caspian Sea from 55.2 (and even before) to 43.5-42.9 cal kyr BP, which could have reached ca 20 m a.s.l. and that is considered here as being related to the Hyrcanian highstand (Fig. 6), must thus have been caused by other factors. Between ca 60 and 45 kyr BP, relatively humid conditions with enhanced precipitations and higher temperature are recorded in the Middle East through highstands recognised in the sedimentary sequences of Lakes Van (ca 60-45 kyr) and Lisan (ca 55-47 kyr, today's Dead Sea), of the Black Sea (ca 54-45 kyr) and in the Soreq cave deposits (ca 57-52 kyr) (Bar-Matthews et al., 2000; Bartov et al., 2002; Kuzucuoglu et al., 2010; Kwiecien et al., 2014; Shumilovskikh et al., 2014; Pickarski et al., 2015). In western Asia, this period corresponds to the maximum extension of high and low altitude glaciers at ca 80-60 and at ca 55-40 kyr respectively (Abramowski et al., 2006; Zech, 2012; Zhang et al., 2016; Stübner et al., 2017; Batchelor et al., 2019). The Amu Darya and Syr Darya have their sources in the Pamir and Tian Shan respectively (Fig. 1a). The deglaciation had to cause an important flow of melting water and sediment into the Aral Sea and afterwards to the Caspian Sea, or even directly to the Caspian Sea by way of the Amu Darya, as it is known for the Holocene (Leroy et

al., 2007, 2020, 2022; Naderi Beni et al., 2013). It is proposed that the scenario of the synergy of the relatively humid general conditions added to the inputs of meltwater from the glaciers of western High Asia (dashed yellow lines and arrows, Fig. 1a, Fig. 5f) was the key mechanism leading to the rise of the Caspian Sea level and therefore to the Hyrcanian transgression.

Sediments from the Aral Sea have not been extensively studied and the history of the area is not well known. Nevertheless, Burr and collaborators (2019) presented a study of cored sequence starting at ca 17.6 kyr cal BP. They proposed glacial meltwater from the Tien Shan, Pamir, and other mountain systems in the modern-day Aral Sea watershed, carried by the Syr Darya and Amu Darya as the most likely main source of water. These authors highlighted that

LGM glacial advances in the region were not as large as those during stages MIS4–3, but that they still produced widespread glacial deposits (Abramowski et al., 2006; Zech et al., 2012; Stübner et al., 2017). Taking into account (i) the intense meltwater evacuation from the western High Asia through the Syr Darya and Amu Darya known for the LGM, (ii) the water transport into the Caspian through the Aral Sea or even directly by the Amu Darya, (iii) the evacuation of meltwater into the Caspian Sea for the Early and Late Weichselian/Valday by possible ways in conformity with the climatic and geographical context, and (iv) the perfect correlation between highstand of the Caspian Sea and the deglaciation in the west Asian Mountains during the middle

Weichselian/Valday, it is therefore proposed that meltwater from the glaciers of western High Asia was a key mechanism leading to the rise of the Caspian Sea level and therefore to the Hyrcanian transgression. It is noteworthy that according to Shumilovskikh et al. (2014), freshening of the Black Sea water occurred at ca 54 and ca 32–25 kyr BP. These authors suggest that it might have been caused by humid phases in the Black Sea region and/or a possible Caspian Sea connection. The 54-kyr phase corresponds to the time within the Hyrcanian highstand whose sediments in the Manych Pass indicate the overflow of water from the Caspian Sea into the Black Sea.

### 5.4.3. Atelian lowstand

Several studies described the Atelian lowstand as a long period between 75 and 40 kyr (Yanina, 2020; Yanina et al., 2020) or between 130 and 60 ka for the so-called palaeoAtelian phase (Lavrushin et al., 2014; Fig. 5c, d). However, the relation between climate change and such a long-term regression seems to be unclear. The Atelian particularity is difficult to relate to the pattern of global climate change in the marine isotopic stages and the North Greenland Ice core (NGRIP, Fig. 5c,d,e,f). According to the current investigation, the Atelian appears to be split into two regressive periods separated by the Hyrcanian highstand (Fig. 5a, b). Both reflect the obvious decrease of the Caspian Sea level after its highstand related to the huge arrival of the meltwater. Later on, when ice sheet or glacier retreated enough, fluvioglacial water was no longer supplied and subsequently, water balance became negative. Then all the hydrologic conditions were met for the advent of a regression. The lower Atelian lowstand can be linked to the halt of the melting of the Siberian ice sheet at the end of isotopic stage MIS 5 and during MIS 4 (Fig. 5b, e and f). The data gathered here cannot allow an estimation of the water level decrease: it is only possible to consider, according to published seismic-acoustic profiles (Yanina, 2020), that the regression was not very deep, this possibly because of the relatively humid conditions in the area in relation with growing mountain glaciers in western High Asia during MIS 4 (*e.g.* Abramowski et al., 2006; Zech, 2012). The upper Atelian, a deep regression until as much as ca -90 m a.s.l. (even more) occurring from 43.5-42.9 to 36.0 cal kyr BP, is recorded after the Hyrcanian highstand which is well correlated with the retreat of the western High Asian glaciers and which resulted from the meltwater supply to the Caspian Sea (Fig. 5b and f), as proposed here.

Such pattern of the Caspian Sea water level change as a first order of transgressions and regressions seems to be related to the major growth and decrease of both the ice sheet to the north of Eurasia and

glaciers in the western High Asia. In addition, it is necessary to include the influence of the local contribution of precipitation, snowmelt and glacial meltwater from the surrounding mountains also recharging the Caspian basin and evaporation.

Finally, given the amplitude of the Caspian Sea level fluctuations, the question of the impact of hydro-isostasy on highstand and lowstand elevation may arise.

According to a simplified model used by Lachenbruch and Morgan (1990), a column of solid lithosphere of given height and average density, in isostatic equilibrium above a ductile asthenosphere of uniform density  $\rho_a$  ( $3200 \text{ kg.m}^{-3}$ ) at an elevation  $\varepsilon$  may be considered. If the surface of the lithosphere is submerged by sea water of density  $\rho_w$  ( $1000 \text{ kg.m}^{-3}$ ) and depth  $h_w$ , the lithosphere will sink and the total column of water  $h_{\text{total}}$  required to produce a transgression of height  $h_w$ , is the sum  $h_w$  and the isostatic subsidence due to the additional water pressure:

$$h_{\text{total}} = h_w(\rho_a/(\rho_a - \rho_w)) = 1.45h_w$$

Thus, an increase of the water level by 100 m ( $h_w = 100 \text{ m}$ ) is possible with the total water input of  $h_{\text{total}} = 145 \text{ m}$ . The model indicates that hydro-isostasy produces the effect of a greater need for water supply by a factor of 1.45 with respect to the simple change in water level observed.

However, this is a maximal estimation, since the rigidity of the lithosphere may support part of the additional charge, reducing thus the hydro-isostatic subsidence. This effect depends of the structure and age of the lithosphere. In the northern part of the Caspian Sea, the rigidity of the rather old lithosphere may be quite important, whereas in the southern part recent tectonic events may have reduced the rigidity. Thesuard et al. (2012) published a global map of equivalent elastic thickness (EET) where, for the Caspian Sea, they provide values of around 100 km. Such a large elastic thickness and using an average diameter of 500km for the Caspian Sea, the isostatic deformation is reduced to about 5%, needing thus 105 m of water column in order to reach 100 m effective

transgression (Turcotte and Schubert, 1982). This result shows that the role of hydro-isostasy is negligible in driving the transgression/regression cycles discussed here.

## 6. Conclusions

As revealed by the current synthesis, dating the sediments of the Caspian Sea area, both from the coast and its Northern and Middle basins, gives a fairly precise overall representation of the major hydrological changes that the Caspian Sea experienced during the Late Pleistocene.

This made it possible to draw the following conclusions.

The Early Khvalynian transgression presents two main parts. The first phase of the Early Khvalynian (hv1-1) took place between 36 and 22 cal kyr, water level having increased and reached ca 10 m a.s.l.. The second Early Khvalynian phase (hv1-2), took place between 22 and 12.5 cal kyr BP with a maximal water level of at least 40 m a.s.l between 17 and 13 cal kyr BP.

The Caspian water level experienced a two-step lowstand between ca 68.3 and 36.0 kyr, *i.e.* the Atelian, which was interrupted between 55.2 and 43.5- 42.9 cal kyr BP by the Hyrcanian highstand. During the late stage of the Atelian lowstand (at-2) between 43.6-42.9 and 36 cal kyr BP, the water level dropped down to -90 m a.s.l., possibly more. The importance of the early stage of the Atelian regression (at-1), between ca 68.3 and 55.2 kyr, could not be estimated but according to seismic-acoustic profiles, it was much less pronounced than its later deep stage.

The Hyrcanian highstand (hc) started at 55.2 or even before and finished at 43.5–42.9 cal kyr BP, the water level having reached even 20 m a.s.l. in its late phase. It was demonstrated that this highstand is independent from the previous Late Khazarian one.

The younger phase of the Early Khvalynian (hv1-2) and the Late Khazarian highstands both match with the very large meltwater inputs in the Caspian Sea basin from the southern front of

Scandinavian and Siberian ice sheets respectively. Fluvioglacial waters were evacuated to the Caspian Sea (i) via the Volga River from the SIS and (ii) via the Turgay pass, Aral Sea and Uzboy River from the Siberian ice sheet. On the contrary, the Hyrcanian highstand is mainly attributed to the meltwater from the western High Asia glaciers, both Syr Darya and Amu Darya transporting fluviglacial waters into the Aral Sea and later on into the Caspian Sea.

As a second important outcome, realistic time spans (and boundaries) were determined for the hydrological periods - highstands and lowstands - of the Caspian Sea basin. Reliable, calibrated ages can thus be formally associated to one or another specific phase. Finally, this review shows a possible way of approaching other periods of the late Quaternary, namely the beginning of the Late Pleistocene and the Holocene, during which water level changes have been recognised and dated but clearly still need to be better constrained.

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## Figure captions

Figure 1.

Maps of the Caspian Sea created using GMT freeware software (Wessel et al., 2013) with, on both maps, indication of: (i) the modern Caspian Sea shoreline at -28 m a.s.l. (black line), (ii) the Caspian Sea level at 50 m a.s.l. (light blue line) indicating the maximum extent of the water during the Early Khvalynian highstand, (iii) the Manych Strait.

1a: (i) Present-day catchment area, (ii) the Last Glacial Maximum ice sheet extent at ca 19 cal kyr BP (solid white line) after Hughes et al. (2015), (iii) the Early and Middle Weichselian/Valdai ice sheet extent at 90 kyr (solid violet line) and at 60 ka (solid yellow line) respectively after Mangerud et al. (2004) and Svendsen et al. (2004), and (iv) the Middle Weichselian/Valdai glaciers approximate extend in the western High Asia (dashed yellow line) after Abramowski et al. (2006), Zech (2012) and Pickarski et al. (2015), (v) meltwater drainage paths (white, yellow and violet dashed arrows);

1b) Date location: (i) red dots indicate the location of individual date sites as given in Table 1, and (ii) red circles indicate areas of the geographically grouped dates: (1) Northern Peri-Caspian, (2) Manych, (3) Dagestan and Azerbaijan, (4) Mangyshlak, (5) Western Turkmenia and Northern Iran, (6) Northern Caspian basin, (7) Middle Caspian basin.

Figure 2. Lithostratigraphy of four sedimentary sections along a North-South transect of the Caspian Sea with a) location of sections (sections b and c from Northern Peri-Caspian area and sections d and e off shore), b) site of Srednaya Akhtuba (after Kurbanov et al., 2020; Költinger et al., 2020 for *b1*, and Yanina et al., 2017 and Makeev et al., 2021 for *b2*), c) site of Kopanovka (after Svitoch and Makshaev, 2020), d) North Caspian Sea basin (after Bezrodnykh et al., 2015; Yanina et al., 2018), e)

Middle Caspian Sea basin (core GS20; after Leroy et al., 2014; Tudryn et al., 2016). The ages mentioned in these stratigraphic sections are indicative and expressed in kyr. Detailed stratigraphic terms: post-Khv cont: post Khvalynian continental; deposits; Neocasp: Neocaspian highstand; Mang: Mangyshlakian lowstand; Khv and hv: Khvalynian highstand; Atel: Atelian lowstand; Hyrcan: Hyrcanian lowstand; Hazar: Khazarian highstand.

Figure 3. Dates (with error bars) of sediments from the Caspian Sea with chronological attribution as given in the literature:

3a) All dates: (i) black diamond: Early Khvalynian highstand, (ii) orange cross: Atelian lowstand, and (iii) green circle: Hyrcanian highstand;

3b) Dates of Early Khvalynian highstand from the Northern Peri-Caspian area according to location;

3c) Dates of Early Khvalynian highstand from the Caspian coast and core sediment according to seven geographically defined areas and unidentified samples from the Northern Peri-Caspian and Dagestan (see in the text).

For 3b) and 3c): (i) black diamond: calibrated  $^{14}\text{C}$  dates, (ii) red diamond: OSL dates, (iii) light blue diamond: Th/U dates.

Figure 4. Statistical data presenting a) age distribution diagram for samples from Early Khvalynian and Hyrcanian highstands, b) age distribution diagram for marine and coastal samples from Early Khvalynian highstand, c) values used in statistical comparison of oldest Early Khvalynian ages and Hyrcanian ages. The age distribution is presented in a) the interval from 54-56 to 10-12 cal kyr BP, and in b) the intervals from 50-52 to 10-12 cal kyr BP and, in more detail, from 19-20 to 12-13 cal kyr BP.



Figure 5. Data for Caspian Sea sediments:

5a) age with error bars versus altitude of samples: (i) Early Khvalynian highstand, (ii) Atelian lowstand, and (iii) Hyrcanian highstand;

5b to 5d) major highstands and lowstands according to b) this study, c) Lavrushin and collaborators (2014), and d) Yanina (2020);

5e) NGRIP ice core record of  $\delta^{18}\text{O}$  (North Greenland Ice Core Project Members, 2004),

5f) Marine Isotope Stages, timing of maximal extent for the Weichselian/Valdai IS: ice sheet (light blue line) and for glaciers in western High Asia (deep navy blue) according to Mangerud et al. (2004), Svendsen et al. (2004), Abramowski et al. (2006), Zech (2012) and Pickarski et al. (2015).

Fig. 6. Major Caspian Sea hydrologic changes:

6a) Dates with error bars *versus* altitude and Caspian Sea water level change between 70 and 12 cal kyr BP. Grey circles: dates from Caspian Sea sediments, orange crosses: dates from subaerial sediments, **at-1** and **at-2**: Atelian lowstand with its early and late phases respectively, **hc**: Hyrcanian highstand, **hv1-1** and **hv1-2**: Early Khvalynian highstand with its early and late phases respectively.

The **hv1-2** is characterised by the highest water level indicated between 17.0 and 13.0 cal kyr BP.

Solid lines indicate the linear regressions between points used for establishing the water level as being between marine samples - black line, and subaerial samples - yellow line ( $R^2 > 0.97$ ). Box

plots indicate the age distribution for Hyrcanian and first phase of the Early Khvalynian highstands.

Dates for altitudes indicated above -20 m a.s.l. have been obtained from sediments of the today's

Caspian Sea coast, those below -30 m a.s.l., are from under water cores from its Northern and Middle basins.

6b) Extent of the Caspian Sea during Hyrcanian (hc) and Early Khvalynian (hv1-1 and hv1-2) highstands, and Atelian lowstand (at-1 and at-2).

Table 1.  $^{14}\text{C}$ , OSL/TL and  $^{230}\text{Th}/^{234}\text{U}$  dates obtained for Early Khvalynian and Hyrcanian highstands and for Atelian lowstand according to authors indicated on column 2 according to following numbers: (1) Makshaev and Svitoch, 2016; (2) Arslanov et al., 2016; (3) Svitoch et al., 2009; (4) Arslanov et Yanina, 2008; (5) Svitoch and Makshaev, 2020; (6) Arslanov et al., 2013; (7) Leonov et al., 2002; (8) Tudryn et al., 2013; (9) Dolukhanov et al., 2009 and 2010; (10) Mamedov, 1997; (11) Bezrodnykh et al., 2015; (12) Bezrodnykh et al., 2004; (13) Sorokin, 2011; (14) Yanina et al., 2018; (15) Kurbanov et al., 2014; (16) Varushchenko et al., 1987; (17) Svitoch, 2009; (18) Arslanov et al., 2002; (19) Tudryn et al., 2016; (20) Sorokin et al., 2018; (21) Yanina et al., 2020; (22) Badyukova E.N., 2007; (23) Sorokin et al., 2014; (24) Kroonenberg et al., 2010; (25) Kakroodi et al., 2015; (26) Kurbanov et al 2020; (27) Tkach et al., 2016; (28) Költringer et al., 2020; (29) Bezrodnykh et al., 2017; (30) Yanina et al., 2017; (31) Svitoch et al., 2008b; (32) Leroy, this study; (33) Rychagov, 1977; (34) Zastrozhnov et al., 2020; (35) Arslanov et al., 1978; (36) Richards et al., 2017. The geographical coordinates and the altitudes of the locations are indicated according to the information given in the references and on Google Earth.  $^{14}\text{C}$  ages calibrated using the IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal BP) (Reimer et al., 2020; Stuiver et al., 2021). Abbreviation: *D.* - *Didacna*, *Dr* – *Dreissena*.

Figure 1

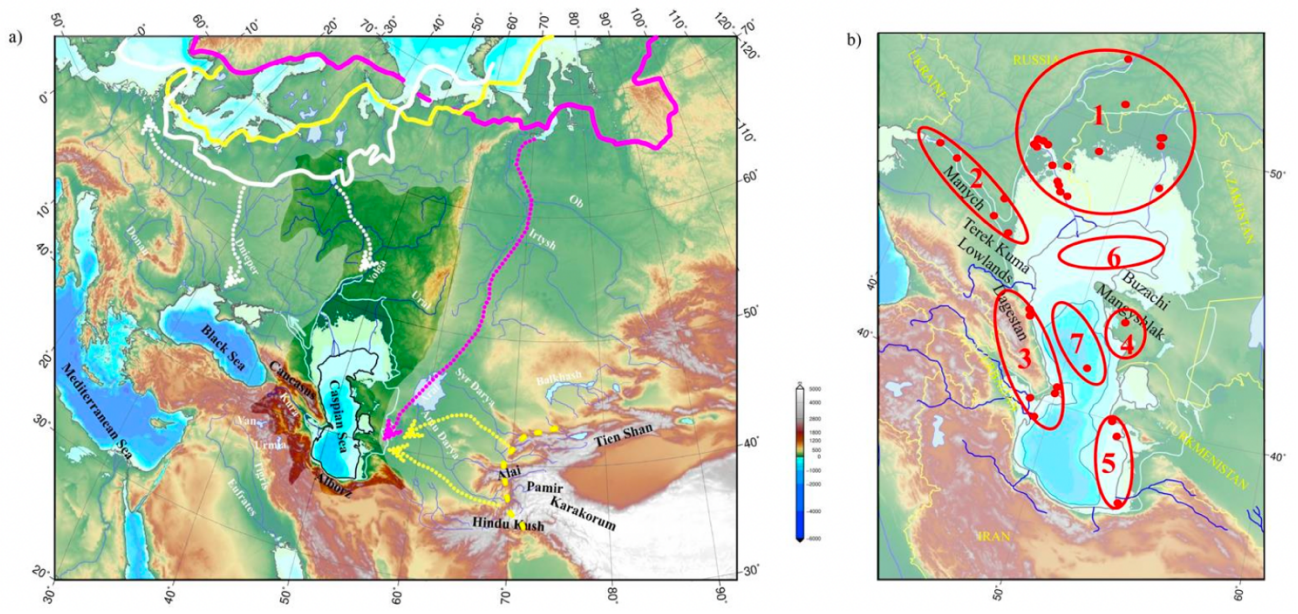


Figure 2

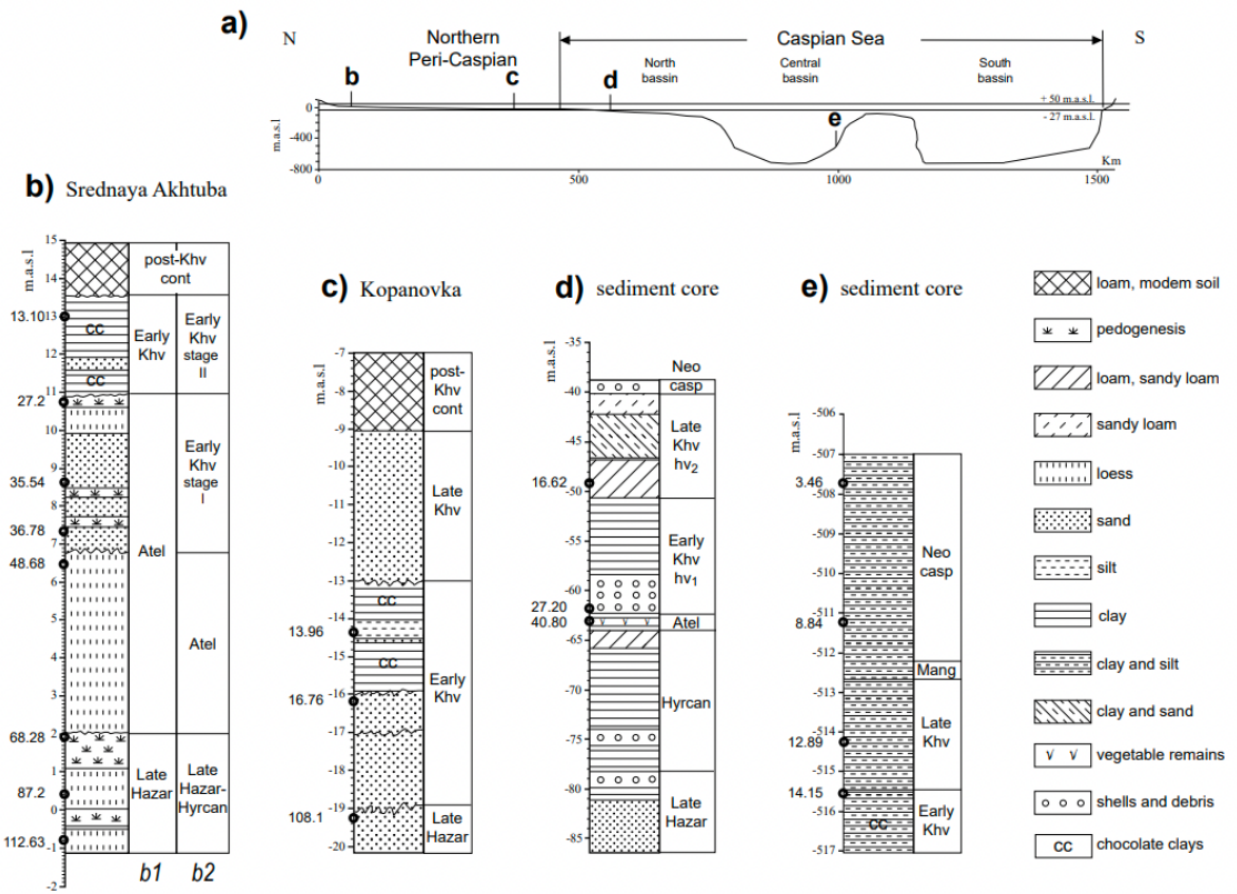


Figure 3

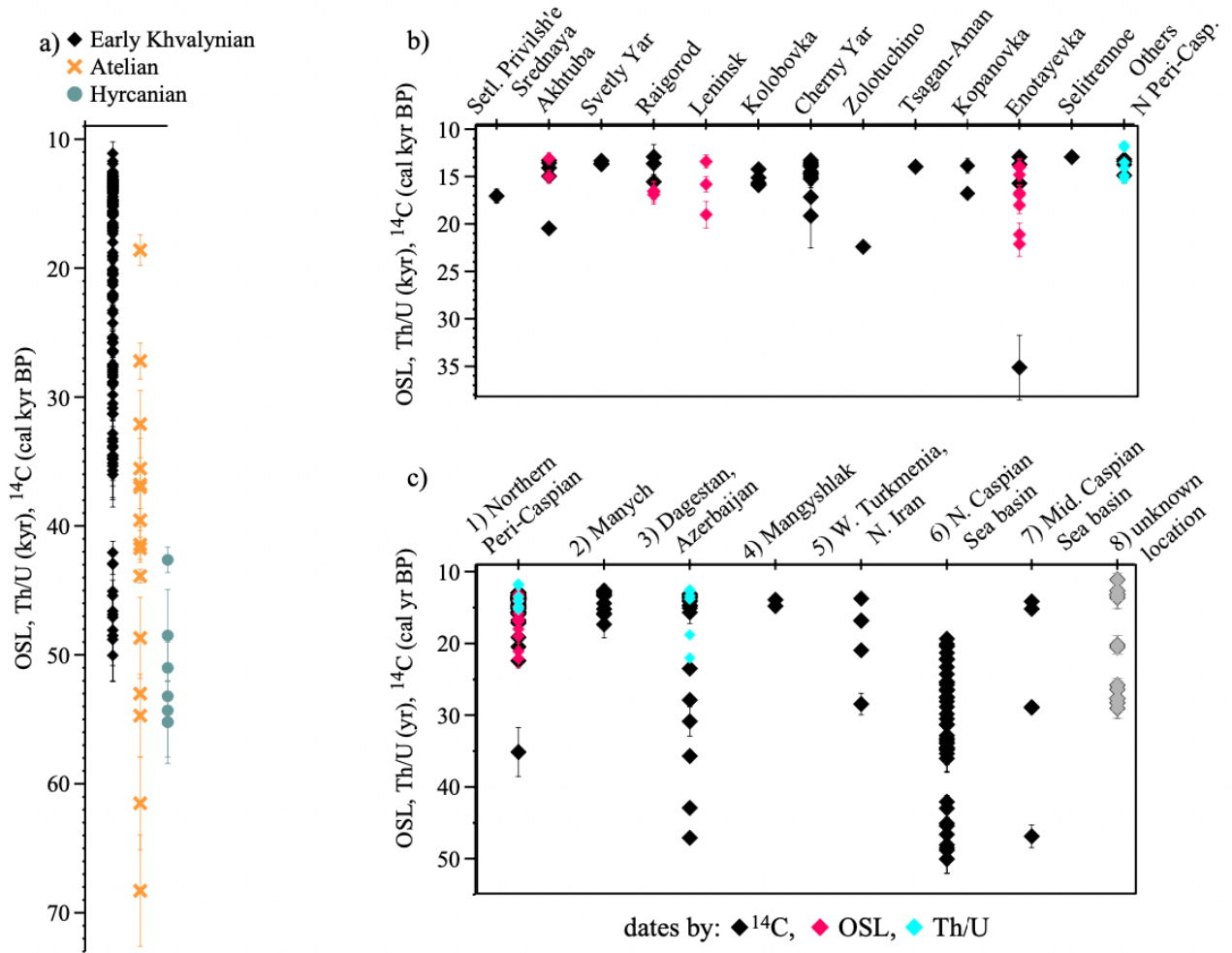
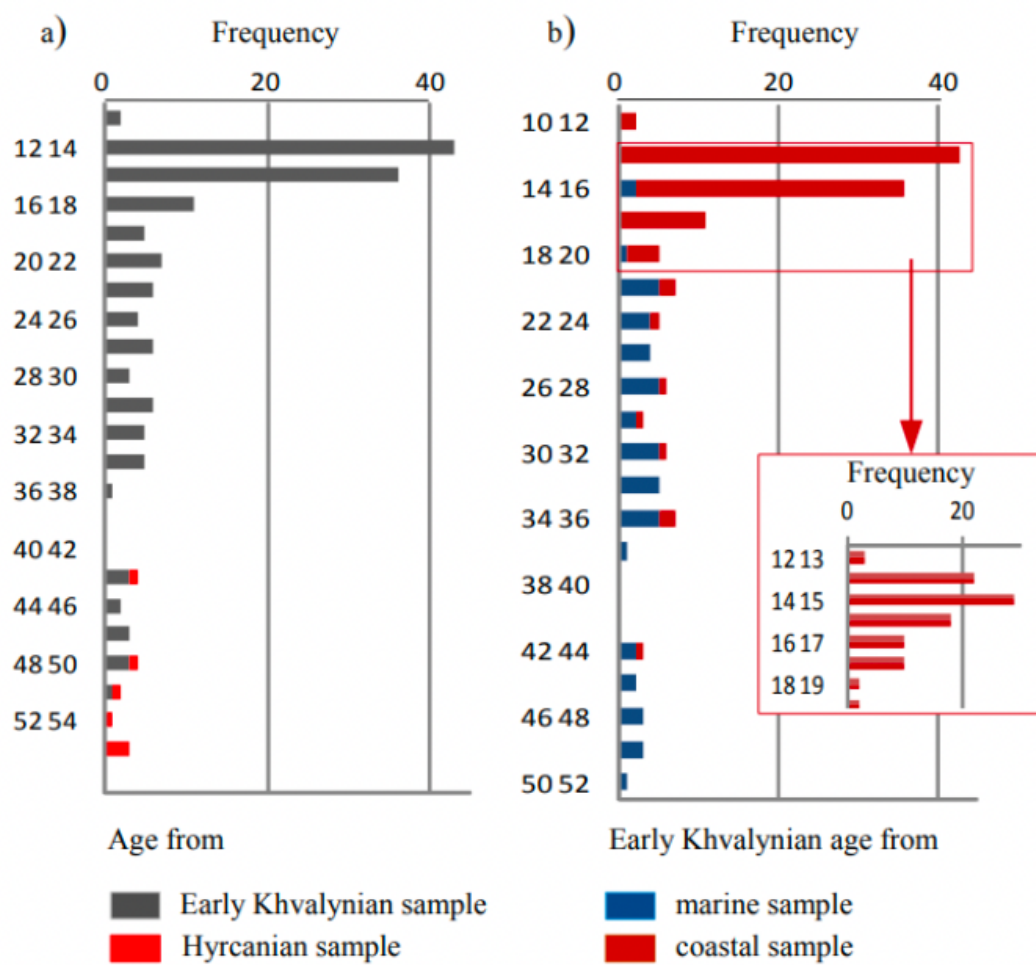


Figure 4



c)

	Early Khvalynian	Hyrcanian
Number of values n	19	9
Mean X	49.147	51.212
Variance s <sup>2</sup>	21.353	15.967
Standard deviation s	4.62	3.996

Figure 5

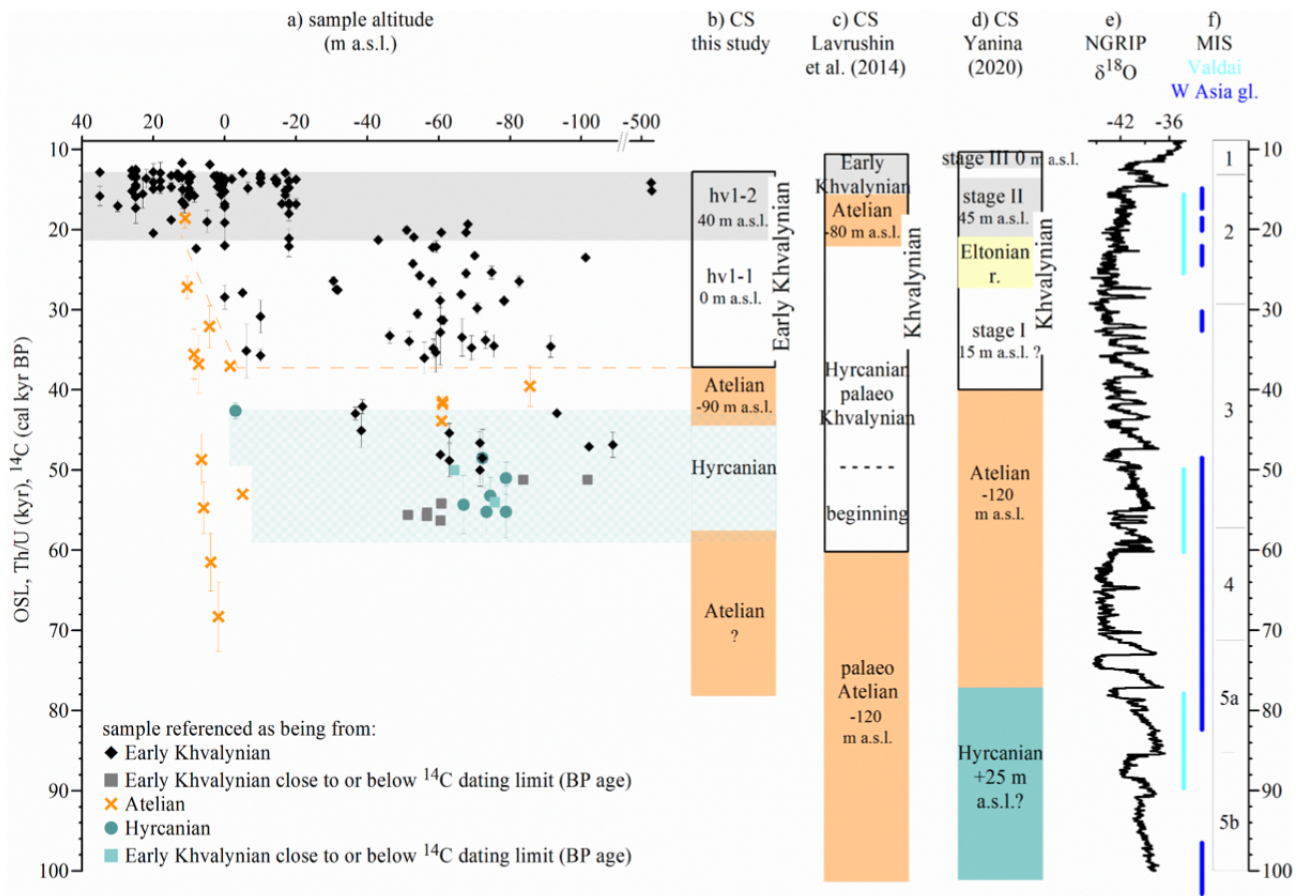


Figure 6

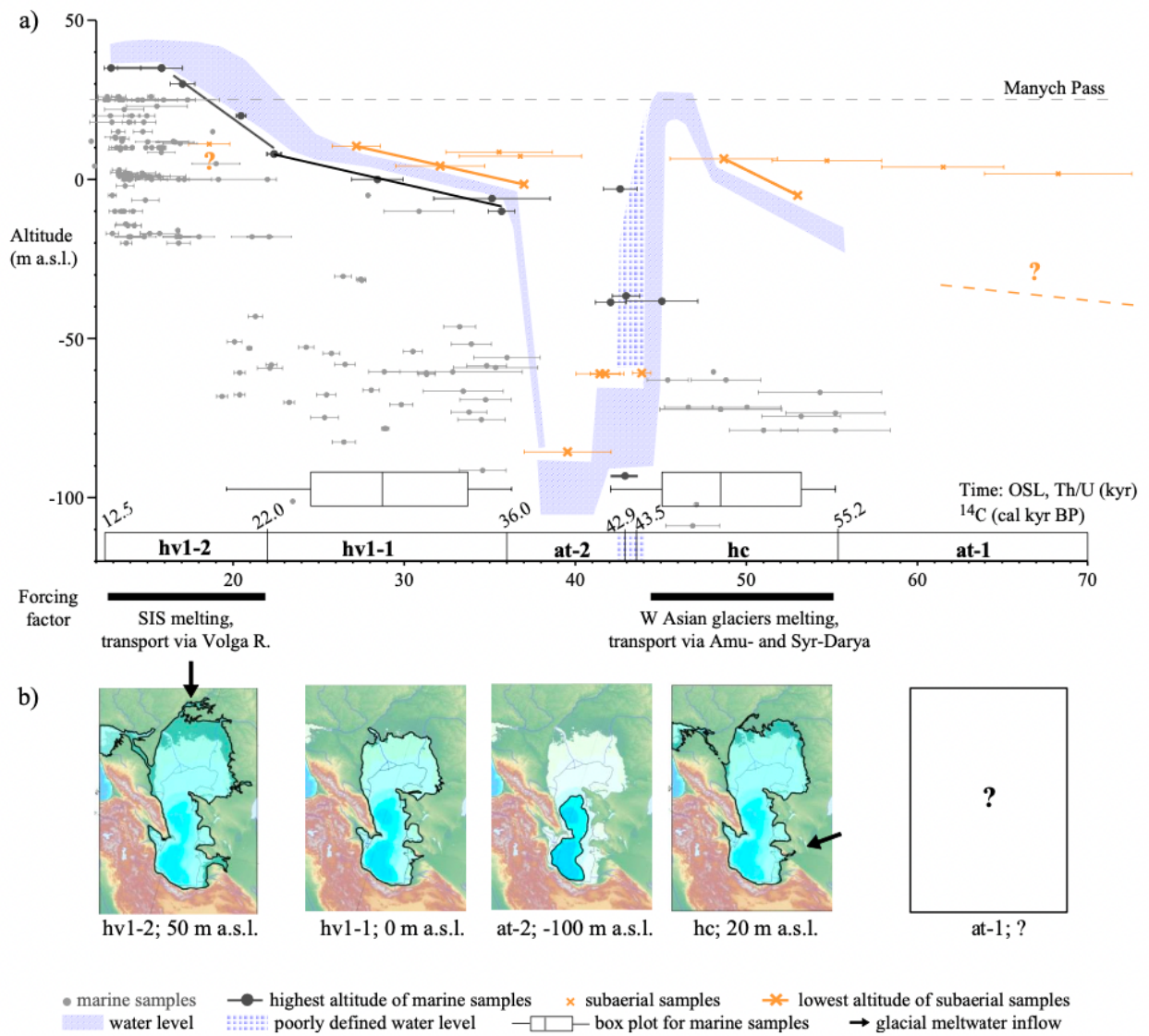




TABLE 1

Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.)	Comments	Material	<sup>14</sup> C Age		1 σ		2 σ			
							yr BP	±	cal yr	+	-	+	-	
Early Khvalynian transgression														
Northern peri-Caspian														
1	1	LU-7032		0			11 760	cv	13 630	150	150	150	250	
2	1	LU-7033	Svetly Yar	48°29'10.37"; 44°46'36.42"	-2		thin-valved shells	11 790	230	13 680	240	320	510	525
3	1	LU-7034		3			11 450	210	13 335	215	235	410	425	
4	1	LU-7035		2			thin-valved shells	11 890	150	13 760	235	240	300	315
5	1	LU-7036		1			thin-valved shells	12 690	230	15 040	505	475	880	690
6	1	LU-7038		0			thin-valved shells	12 790	210	15 235	295	400	915	615
7	1	LU-7039		2			thin-valved shells	11 380	210	13 270	175	195	435	465
8	1	LU-7040		1			thin-valved shells	11 650	150	13 515	175	220	335	280
9	1	LU-7041		1			thin-valved shells	12 000	140	13 890	270	175	380	335
10	1	LU-7042		1			thin-valved shells	12 360	110	14 475	315	350	395	470
11	6	LU-6835	Cherny Yar	48°01'55.47"; 46°06'43.04"	18	For these samples, apparently too high altitudes have been indicated in the referenced papers.	<i>D. protracta</i>	12010	200	13 925	325	630	470	895
12	2, 6	LU-6836		20	<i>H. plicatus</i>		11810	120	13 675	160	115	225	345	
13	2, 6	LU-6848		20	<i>D. protracta</i>		12480	230	14 670	420	400	795	790	
14	2, 6	LU-6847		15	<i>D. protracta</i>		12550	280	14 780	510	460	920	895	
15	7, 9, 16, 19, 33	MGU-18		0			shell	15800	1320	19 135	1645	1640	3390	3260
16	9, 22, 33	GIN-66		1		shell	12500	140	14 685	340	335	535	485	
17	9, 22, 16, 33	LG-93		0		shell	14080	100	17 145	115	150	275	250	
18	7, 9, 33	GIN-187	settlement Privolzh'e	52°57.50'; 48°35.52'	30		shell	14030	250	17 040	380	340	720	775
19	1, 5	LU-7037		13			thin-valved shells	11 680	150	13 550	185	200	360	440
20	7, 19, 9	AA 37367	Srednaya-Akhtuba	48°43' 00.37"; 44°51'59.7"	20		shell	12580	70	14 950	305	175	480	265
21	7, 19, 9	AA 37366		20			shell	12120	180	14 070	305	695	475	785
22	8, 19	H3578		20			organic matter	16930	120	20 455	170	130	295	340
23	9, 33, 35	LU-1358	Nearby Srednyana Artuba	48°42'21.6" 44°57'18"	15		<i>Didacna</i>	11390	200	13 280	170	175	400	330
24	2, 6	LU-6846		1			<i>D. protracta</i>	13320	360	16 025	525	550	1080	1070
25	2, 6	LU-6918		-3			<i>D. polymorpha</i>	12690	440	15 010	765	640	1395	1310
26	7, 19, 9	AA 37365	Tsagan-Aman	47°33'02.69"; 46°40' 49.99"	0		shell	12470	80	14 645	275	305	395	400
27	7, 19, 9	AA 37203		0			shell	12445	75	14 605	250	265	380	385
28	7, 19, 9	AA 37204		0			shell	12060	130	13 945	155	140	345	380

Dating reference	Lab. Number	Site	Coordinates Lat. (N) Long. (E)	Altitude (m a.s.l.)	Comments	Material	<sup>14</sup> C Age		1 σ		2 σ			
							yr BP	±	cal yr	+	-	+	-	
29	2, 6	LU-6019	Selitrennoe	47°10'22.10"; 47°26'45.90"	-5		<i>D. ebersini</i>	11000	160	12 935	155	140	230	245
30	7, 19, 9	AA 37368		10			shell	13240	45	15 900	85	80	165	160
31	7, 19, 9	AA 37202	Kolobovka	48°39'21.06"; 45°28'29.34"	10		shell	13170	85	15 805	130	130	255	265
32	7, 19, 9	AA 37201		10			shell	13070	100	15 660	150	165	335	300
33	9, 33, 35	LU-1353	Solyanka by Kolobovka	48°30'36" 45°52'48"	-17		<i>Dr polymorpha</i>	12690	100	15 120	145	155	545	375
34	9, 33, 35	LU-1359	Pologoe	48°28'23" 45°57'2.3"	-14,5		<i>Didacna</i>	12010	340	14 025	540	765	785	1070
35	9, 33, 35	LU-1357	Zamishche	45°57'2.3"	-14,5		<i>Dr polymorpha</i>	12210	150	14 215	360	575	425	660
36	9, 16, 33	MGU-22	Zolotuchino	47°10'22.10"; 47°26'45.90"	8	(16) quotes Kaplin 1972	shell	18460	220	22 390	280	215	420	540
37	9, 10, 33	MGU-23		-6	(10) quotes Svitoch et al., 1981			30700	1500	35 125	1735	1670	3400	3695
38	5, 9	MSU-793		-14	(5) quotes Parunin et al., 1989		<i>D. protracta, D. trigonoides, Dr polymorpha</i>	11820	250	13 720	260	300	560	635
39	33	MGU-24	Enotaevka	47°14'35.30"; 47°1'29.58"	-17			11000	250	12 940	220	200	370	470
40	5, 9, 33	MSU-25		-17	(5) quotes Kaplin et al., 1972		<i>D. protracta, D. trigonoides, Dr polymorpha</i>	13100	300	15 700	435	455	1150	950
41	5	LU-8741		-16			<i>Dreissena, Didacna</i>			16760	260			
42	2, 5, 6	LU-6917	Kopanovka	47°27'32.70"; 46°48'51.61"	-2		<i>D. polymorpha, D. rostriformis, M. caspia</i>	11870	370	13 850	550	415	765	1180
43	2, 6	LU-6874		23			<i>D. protracta</i>	13030	630	15 540	1080	970	1785	1800
44	2, 6	LU-6919	Raigorod	48°25'49.82"; 44°57'41.10"	22		<i>D. protracta, D. subcatillus</i>	11630	530	13 630	740	540	1150	1630
45	2, 6	LU-6873		18			<i>D. ebersini, Hypanis plicatus</i>	11040	460	12 910	445	590	1300	1090
46	2, 6	LU-6020	Aral-Sor, Northern Caspian	49° 3' 42"; 48° 11' 57"	10		<i>D. protracta</i>	11270	140	13 175	105	150	280	275
47	2, 9, 6	LU-841	Inder lake, Lower Ural	48°27'58.86"; 51°54'59.91"	10		<i>D. protracta, D. subpyramidata</i>	11490	330	13 390	330	360	640	675
48	2, 9, 6	LU-846	Chapaev, Lower Ural	50°08'32.3"; 51°10'52.82"	28	(9) quotes as LU-864A - inverted nr	<i>D. protracta</i>	11830	200	13 710	220	290	460	450
49	9, 5, 16, 33	MGU-19	Gorky Eric	48°11'49.61"; 46°52'54.60"	-7	(16) quotes Kaplin 1972, indicates as Hv2	<i>D. protracta</i>	12600	240	14 865	525	415	800	760

Dating reference	Lab. Number	Site	Coordinates Lat. (N) Long. (E)	Altitude (m a.s.l.)  (± 1 m)	Comments	Material	<sup>14</sup> C Age		1 σ		2 σ			
							yr BP	±	cal yr	+	-	+	-	
<b>Manych area</b>														
50	2, 6	LU-6022	Ergeni, Kalmykiya	46°19'9.74"; 44°25'30.59"	35		<i>D. protracta, D. trigonoides</i>	13180	340	15 815	515	500	1220	1130
51	3, 2	Gr.A.33717			26		<i>D. ebersini</i>	12740	50	15 190	75	75	180	155
52	2, 6, 3	LU-5725	Zunda-Tolga	45°36'38.32"; 44°15'41.56"	26		<i>D. protracta</i>	10670	140	12 630	150	130	530	270
53	3, 4, 6, 2	LU-5726			26	the same layer	<i>D. ebersini</i>	11420	220	13 310	200	185	415	450
54	3	MSU-1553?	Podmanok-2			? the same nr as below	<i>Didacna</i>	8070	120	8 960	300	215	360	340
55	3	MSU-1553			25		<i>Didacna</i>	14000	680	15 930	870	995	1870	1780
56	4, 9	MGU-1491	Manych Balabino	47°13'5.74"; 40°8'38.25"	25		shells <i>in situ</i>	14300	680	17 330	840	910	1875	1590
57	3, 4	MSU-1489			25	indicated also as MGU-1889	mollusc shells of variable composition	25690	3000	29 940	2965	3305	6230	6275
58	2, 6	LU-5853			35		total sample	19330	240	23 320	300	400	490	520
59	2, 6	LU-5952	Manych	45°36'38.32"; 44°15'41.56"	35	the same deposits	<i>D. trigonoides (rejuv?)</i>	10900	200	12 860	130	200	395	380
60	2, 3, 4, 6	LU-5768			25		<i>Hypanis plicatus</i>	11470	180	13 350	175	140	275	405
61	2, 6	LU-6021	Chogray	45°13'24.42"; 45°15'3.13"	25		<i>D. protracta</i>	12150	900	14 420	1240	1130	2325	2590
62	2, 4, 3, 6	LU-5769	Lake Manych		20		<i>D. protracta</i>	10930	370	12 820	350	485	1025	705
63	2, 6	LU-5854	San-Manych	46°58'29.13"; 41°18'12.17"	13		Shells debris, archeological site	11210	130	13 115	145	175	285	230
<b>Azerbaijan, Dagestan</b>														
64	10				-10	(10) quotes Badinova et al., 1976		31310	320	35 690	300	340	775	600
65	10		Zykh Lake	40°21'17.00"; 49°59'29.00"	-10	(10) quotes Svitoch et al., 1981		26700	1000	30 860	1000	1000	2040	2350
66	10		Ajikabul city, Lower Kura	39°58'59.88"; 48°55'30"	-5	(10) quotes Parunin et al., 1989		30680	7000	27 880	???			
67	24				-101					23480				
68	24		Modern Kura delta	39°20'46.39"; 49°22'6.35"	-102					47070				
69	24				-93					42903				
70	9, 33, 35	LU-490A	Azerbaija Siazan v.	41°6' 49°7'12"	15	sample analyzed by both <sup>14</sup> C and U/Th methods	<i>D. parallella Bog</i>	12520	140	14 715	355	365	545	515
71	33	MGU-130	Razina village					11300	400	13210	220	440	900	780
72	2, 6, 9, 18	LU-424A			1	as h2 in (9)	<i>D. parallella, D. praetrigonoides</i>	13100	490	15 660	705	850	1580	1390
73	2, 6, 9, 18	LU-424B	Turali	42°56'40.72"; 47°34'30.88"	1	as h2 in (9)		12720	400	15 060	735	610	1255	1155
Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.)  (± 1 m)	Comments	Material	<sup>14</sup> C Age  yr BP	<sup>14</sup> C Age ±	<sup>14</sup> C Age cal yr	1 σ +	1 σ -	2 σ +	2 σ -	
74	2, 9, 17, 18, 6	LU-426A	Manas river mouth	42°43'25.09"; 47°43'0.37"	25	A - external shell side	<i>D. parallella</i>	11600	400	13 535	440	475	805	1040
75	17, 6	LU-426B			25	B - internal shell side		12500	300	14 700	535	460	905	915
76	9, 33	LU-425B			-10			11740	180	13 615	185	180	320	420
77	9, 33	LU-425A			-10			11180	180	13 080	205	185	325	325
78	9, 33	MGU-98	Rubas river	41°56'18"; 48°22'56"	-10			11600	140	13 460	145	130	280	295
79	9, 33	MGU-IOAN-38			-10			12150	200	14 145	360	645	545	770
80	9, 33	MGU-99	Ullubiyev	42°35'57.22"; 47°48'00.78"	0			12050	90	13 925	120	110	175	215
<b>East and South Caspian sea coasts</b>														
81	2, 4, 6	LU-5800A	Mangyshlak	43°29'60.00"; 52°14'60.00"	18	A external shell side	<i>D. praetrigonoides</i>	12020	130	13 910	130	150	380	315
82	2, 4, 6	LU-5800B			18	B internal shell side		12550	210	14 775	445	390	705	700
83	15	LU-7111	Cheleken p., Turkmenistan	39°29'25.71"; 53°17'13.16"	-20		<i>D. praetrigonoides</i>	11870	160	13 740	225	255	330	345
84	15	LU-7113			-20		<i>D. umbonata</i>	13870	230	16 810	365	290	680	605
85	9, 10, 9, 33	LU-826	Krasnovodsk p.	39°57'5.86"; 52°53'45.98"	0	(10) cite Arslanov et al., 1988	<i>Didacna</i>	24200	700	28430	680	680	1500	1200
86	35	LU-1361						13920	740	16810	950	1095	1990	1930
87	25	47B	Iran	37°09'56.48"; 54°03'23.36"	-53	core sediment	ostracoda <i>Cyprideis</i>	17367	65	20 940	80	65	155	230
<b>Location unidentified; either Dagestan or lower Volga</b>														
88	9, 33	LG-147						8680	170	9 745	250	370	330	460
89	9, 33	MGU-1042						9500	700	10 890	1100	940	1765	1860
90	9, 33	MGU-1044						9700	330	11 100	530	510	890	1005
91	9, 33	MGU-1039						10770	330	12 635	460	460	950	700
92	9, 33	MGU-1037						11280	700	13 190	1020	890	1950	1970
93	9, 33	MGU-1034						11290	380	13 200	425	375	740	880
94	9, 33	MGU-792						11760	200	13 640	280	165	405	425
95	9, 33	LU-828						16700	550	20 180	665	665	1315	1305
96	9, 33	IOAN-90						17000	350	20 535	465	410	955	890
97	9, 33	IOAN-91						21500	300	25 785	430	240	615	605
98	9, 33	IOAN-93						22100	730	26 385	600	805	1555	1310
99	9, 33	IOAN-94						23450	600	27 690	530	680	1280	1495

Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.)	Comments	Material	<sup>14</sup> C Age		1 σ		2 σ		
							yr BP	±	cal yr	+	-	+	-
100	9, 33	IOAN-92					23400	500	27 630	460	515	1160	1070
101	9, 33	IOAN-132					24000	1300	28 265	1010	945	2150	1930
102	9, 33	LG-149					24830	170	29 040	165	150	360	450
Northern Caspian Sea basin, core sediments													
103	11, 14	LU-6132		-59	(20.2-20.3)		18250	270	22 145	305	315	735	680
104	11, 13, 14	MGU-1673		-53	IGS-1 (13.65-13.75)		20195	200	24 265	295	260	450	560
105	11, 13, 14	MGU-1672		-58	IGS-1 (18.9-19.3)		22230	300	26 540	440	395	595	605
106	11, 12, 14, 29	MGU-1556	area 2	-61	IGS-3 (21.0-22.5)	mollusc shell	27200	340	31 290	225	270	530	620
107	11, 13, 14, 29	MGU-1616		-61	IGS-3 (22.2-22.3)		27215	330	31 305	225	250	490	570
108	11, 14, 15	LU-7025		-60	(21.3-21.6)		28550	1950	32 825	1965	1964	4070	4050
109	12	MGU-1587		-58	IGS-3 (24.5-25.0)		18330	150	22 230	130	145	320	265
110	12	MGU-1588	area 1	-55	IGS-3 (21.1-21.2)	shell	21460	200	25 740	155	210	490	280
111	12	MGU-1589		-43	IGS-3 (9.0-10.1)		17645	160	21 300	335	355	415	545
112	12, 14	MGU-1555	area 4	-75	IGS-2 (21.7-21.9)	shell	21090	320	25 345	300	400	810	610
113	12, 14	MGU-1591		-83	IGSs-1 (29.4-29.6)		22190	400	26 465	460	445	685	775
114	12, 14	MGU-1592		-70	IGS-1 (16.9-17.2)		19325	175	23 270	260	420	315	475
115	12, 14, 21	MGU-1593	area 5	-68	IGS-1 (15.1-15.2); as Hv2 in (21)	shell	16075	120	19 345	145	150	320	255
116	12	MGU-1598		-75	IGS-1 (22.3-23.7)		30085	600	34 505	495	695	1380	1245
117	12	MGU-1599		-72	IGS-1 (19.3-19.4)		>30000	6000	>34055	5235	6490	12375	10695
118	13, 14	MGU-1600	area 1	-52	IGS-2 (18.0-18.4)	shell	29520	480	33 920	490	535	1170	925
119	13, 14, 11, 21	MGU-1674	area 2	-51	IGS-1 (11.9-12.1); as Hv2 in (14), (11), (21)	shell	16650	100	20 075	150	135	430	310
120	13	MGU-1652		-69	well 3 (15.9-16.5)		30340	700	34 755	640	690	1500	1405
121	13	MGU-1653		-66	well 2 (13.1-13.3)		23890	260	28 065	310	26°	485	630
122	13	MGU-1654		-60	well 2 (7.3-7.5)		24650	350	28 830	410	375	915	845
123	13	MGU-1655	area 5	-54	St. 5 (0.9-1.15)	shell	26250	350	30 500	340	320	550	590
124	13	MGU-1667		-73	IGS-2 (20.2-20.4)		29380	450	33 785	460	540	1040	845
125	13	MGU-1668		-71	IGS-2 (17.7-17.8)		25635	300	29 825	490	300	675	595
126	13	MGU-1669		-68	IGS-1 (14.6-14.7)		21170	250	25 450	235	280	560	480
127	20, 23	CAMS 162563	area 1	-72	IGS-1 (38.0-38.1)	Gasteropoda			46600	1400			
128	20, 23	same	area 1	-72	IGS-1 (38.0-38.1)	Micromelania caspia	cal of 46600?		50030	1983			
129	20, 23	CAMS 162561	area 2	-63	IGS-1 (28.4-28.6)				45400	1200			
130	20, 23	same	area 2	-63	IGS-1 (28.4-28.6)	D. ebersini	cal of 45400?		48800	2029			

Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.)	Comments	Material	<sup>14</sup> C Age		1 σ		2 σ		
							yr BP	±	cal yr	+	-	+	-
131	20	UBA 25110	area 3	-60	IGS-2 (21.4-21.5)	D. ebersini		>	48069				
132	6	LU-6884	area 2	-59	(19-20 m)	D. subcatillus	30360	610	34 820	550	550	1160	1285
133	6, 31	LU-5953	Rakushechnaya a.	-67	IGS-1 (31.5-31.7 m)	D. subcatillus, D. protracta submedia	29200	1220	33 440	1450	1170	2340	2520
134	14, 29	LU-6484		-59	(20.0-20.2)		30950	1050	35 340	1050	1015	2460	2500
135	14	LU-6131	area 2	-56	(16.9-17.0)	shell	>=31570	1050	36 005	1295	970	1940	2980
136	14	MSU-1507	area 3	-61	(21.6-21.8)	shell	16900	120	20 380	140	140	325	350
137	14, 12	MSU-1557	area 4	-68	(14.6-14.7); as Hv2 in (12)	shell	16900	110	20 380	125	130	315	295
138	14, 12	MSU-1597		-91	(37.6-37.9)		30150	610	34 575	505	675	1365	1280
139	23*, 29	CAMS 162569	Rakushechnaya a.	-72	IGS-5 (38.70-38.75); as Girkanian in (29)	D. subcatillus	46000	1300	48 490	1435	1660	3565	2770
140	23*	CAMS 163751		-46	ISG-5 (7.00-7.54)	D. ebersini	28830	150	33 235	220	335	940	540
141	23*	CAMS 163752	Korchagina a.	-51	ISG-5 (12.31-12.34)	D. ebersini	55600	3000					invalid age for calibration
142	23*	CAMS 163753		-57	ISG-2 (17.45-17.80)	D. subcatillus	55700						invalid age for calibration
143	23*	CAMS 163754		-60	ISG-2 (21.40-21.50)	D. subcatillus	56300	3300					invalid age for calibration
144	32	UBA-18410		-57	IGS-1 (20.97)	gasteropods	55332						invalid age for calibration
145	32	UBA-18411		-61	IGS-1 (24.9)	shell	54188						invalid age for calibration
146		B-252163		-30,5	(depth in coring: 1,45m)		22180	130	26420	310	430	410	490
147		B-262219		-31,3	(depth in coring: 0,80m)		23190	140	27460	150	130	215	250
148		B-262220	R. Emba mouth	-31,7	(depth in coring: 1,20m)	Ostracods	23290	140	27520	140	135	230	230
149		B-252167		-38,6	(depth in coring: 8,60m)		37670	720	42060	340	400	880	655
150		B-252160		-36,6	(depth in coring: 7,10m)		39380	870	42960	625	780	800	1300
151		B-252161		-38,2	(depth in coring: 8,75m)	Dreisena	42370	1230	45060	995	1015	2090	2115
Middle Caspian Sea basin, core sediments													
152	23*	CAMS 162564		-84	IGS-3 (10.30-11.05)	D. ebersini	51200						invalid age for calibration
153	23*	CAMS 162566		-102	IGS-3 (28.60-28.85)	D. cristata	51200						invalid age for calibration
154	23*	CAMS 159399	area Khazri	-78	IGS-3 (5.2-5.35)	D. praetrigonoides	24630	80	28 855	115	100	175	225
155	23*	CAMS 159403		-78	IGS-3 (5.2-5.35)	D. parallella	24700	80	28 925	120	100	185	200
156	23*	CAMS 159400		-109	IGS-3 (35.7-35.9)	D. subcatillus	44560	850	46 855	845	830	1575	1685
157	19	Poz-16739		-516		ostracods	12260	60	14150	100	80	275	650
158	19	interpolation		-517	Middle Caspian core	interpolation for the core base			15180	100	80	275	650

U/Th	Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.) (± 1 m)	Comments	Material	U/Th and OSL Age		
								yr	±	
	159	5	LU-843	Mergenevo	49°56'12.32"; 51°18'38.84"	4	(5) quotes Arslanov et al., (1988)	11900	400	
	160	2, 9, 6, 33	LU-846	Chapaev	50°08'323; 51°10'52.82"	10	(9) quotes as LU-864A - inversed nr	<i>D. protracta</i>	15240	600
	161	2, 6, 33	LU-841	Inder lake	48°27'58.86"; 51°54'59.91"	10		<i>D. protracta</i> , <i>D. subpyramidata</i>	14100	500
	162								14900	400
	163	2, 6, 33	LU-426A	Manas, Dagestan	42°43'25.09"; 47°43'0.37"	25		<i>D. paralella</i>	12500	300
	164	2, 6, 18, 33	LU-426B						12700	450
	165	10		Amiya Cap, N Apsheron	40°35'40.03"; 49°59'24.66"	0	(10) quotes Arslanov et al., 1978		22000	4500
	166	2, 6, 9	LU-424A	Turali, Dagestan		1	as Hv2 in (9)	<i>D. paralella</i> , <i>D. cristata</i> , <i>D. praetrigonoides</i>	13350	440
	167	2, 6, 9	LU-424B						1	as Hv2 in (9)
	168	33, 35	LU-844	Kozacharevo (Chapaev)	50°15'36"; 51°6'36"	12		<i>D. protracta</i> , <i>D. subpyramida</i>	11700	1500
	169								LU-845	<i>D. protracta</i>
	170	33, 35	LU-490A	Azerbaijan Siazan v.	41°6"; 49°7'12"	15		<i>D. paralella Bog</i>	18800	1100

OSL	Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.) (± 1 m)	Comments	Material	U/Th and OSL Age			
								yr	±		
	171	26, 27, 28, 30	150806	Srednaya Akhtuba	48°42'01"; 44°53'37"	13	chocolate clay (cc) top	13100	600		
	172	26, 27, 28, 30	150807			12	sand in CC	15000	700		
	173	26	160803	Raygorod	48°25'53"; 44°58'02"	12	sand	16500	900		
	174	26	160804					cc	16600	1100	
	175	26	160805					cc	16900	1000	
	176	26	170803					9	sand	13400	700
	177	26	170804	Leninsk	48°43'09"; 45°09'31"	8	cc	15800	800		
	178	26	170806					5	grey clay and sandy loam	19000	1400
	179	34	152544	Enotayevka area (Kosika2/3)	47°06'14.3"; 47°11'28.4"	-18	sandy loam, layer 13 (upper part)	16700	800		
	180	34	152545					-18	sandy loam, layer 13 (lower part)	18000	900
	181	34	152545					-18	the same level	14800	700
	182	34	152546					-18	sand, layer 12 (lower part)	13900	800

OSL	Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.) (± 1 m)	Comments	Material	U/Th and OSL Age			
								yr	±		
	183	34	152546	Enotayevka area (Kosika2/3)	47°06'14.3"; 47°11'28.4"	-18	the same	21100	1200		
	184	34	152552					-18	layer 11 (upper part)	14000	800
	185	34	152552					-18	the same	22100	1300
	186	34	152553					-18	layer 11 (lower part)	14000	800
	187	34	152553					-18	the same	16900	1000

<sup>14</sup>C Age    <sup>14</sup>C Age    1 σ    2 σ  
yr BP    ±    cal yr    +    -    +    -

#### Atelian regression

##### <sup>14</sup>C Northern Caspian Sea basin, core sediments

188	14, 21, 29	IG-4542	area 2	48°01'55.47"; 46°06'43.04"	-61	(21.75-21.85)	humic acid	40830	100	43 880	440	310	535	395		
189	14, 21, 29	IG-4541						-61	(22.0-22.11)	36680	850	41 435	465	665	1390	940
190	14, 21, 29	CAM 163762						-61	(22.0-22.11)	37100	660	41 740	350	425	860	675
191	21, 31	LU-5951	Rakushechnoe a.		-86	IGS-1 (50.65)	<i>D. nalivkini</i>	34640	1000	39 545	1050	1340	2540	1895		

U/Th and OSL Age

yr    ±

##### TL Northern peri-Caspian

192	5		Cherny Yar	48°01'55.47"; 46°06'43.04"	-2	(5) quotes Shakhovets 1987	37000	4000
193	5						-5	53000

##### OSL

193	26	160806	Raygorod	48°25'53"; 44°58'02"	11	loess	18600	1200	18600	1200		
194	26	170807	Leninsk	48°43'09"; 45°09'31"	4	paleosol	32100	2600	32100	2600		
195	26, 27, 30	150809	Srednaya Akhtuba	48°42'01"; 44°53'37"	10	loess or paleosol 1	27200	1400	27200	1400		
196	26, 27, 30	150810					9	alluvial sand	35540	3110	35540	3110
197	26, 27, 30	150812					7	alluvial sand	36780	3580	36780	3580
198	26, 27, 30	150814					7	untypical sandy loess	48680	3140	48680	3140
199	28						6	loess	54700	3200	54700	3200
200	28						4	loess	61500	3600	61500	3600
201	26, 27, 30	150822					2	paleosol 2	68280	4310	68280	4310

Dating reference	Lab. Nr	Site	Coord. Lat. (N) Long. (E)	Alt. (m a.s.l.) (± 1 m)	Comments	Material	<sup>14</sup> C Age yr BP	<sup>14</sup> C Age ± cal yr	1 σ	2 σ	
									+	-	
<b>Girkanian transgression</b>											
<sup>14</sup> C	<b>Northern Caspian Sea basin, core sediments</b>										
202	20, 14	CAMS 166531		-64	IGS-1F (30.8)		50500				
203	20	CAMS 162562	area 1	-65	IGS-1F (31.3-31.35)	<i>D. subcatillus</i>		age indistinguishable from background			
204	20, 14	CAMS 166532		-67	IGS-1F (33.4)			54300	3600		
205	20, 14	CAMS 159402		-76	IGS-1 (41.15-41.2)	<i>D. subcatillus</i>	54000				
206	20, 14	CAMS 159401	area 2	-79	IGS-1 (44.25-44.36a)	<i>D. subcatillus</i>		55200	3200		
207	20, 14	CAMS 159404		-79	IGS-1 (44.25-44.36b)	<i>D. cristata</i>		51000	2000		
208	20	CAMS 162567		-65	IGS-3 (30.77-30.84)	<i>Dr. Rostriformis</i>		age indistinguishable from background			
209	20, 14	CAMS 163755	area 3	-73	IGS-2 (34.1-34.7)	<i>D. subcatillus</i>		55200	2900		
210	20, 14	CAMS 163756		-74	IGS-2 (35.4-35.41)			53200	2300		
211	23, 29	CAMS 162569	Rakushechnaya a.	-72	IGS-5 (38.70-38.75); as Early Khvalyn in (23)	<i>D. subcatillus</i>	46000	1300	48 490	1435 1660 3565 2770	
<b>Northern peri-Caspian</b>											
212	8	Ts2 I281	Tsagan Aman	47°33'02.69"; 46°40' 49.99"	1	shell <i>D. trigonoides</i> group	38810	940	42620	510 440 985 1470	

\* no information if ages are BP or cal BP, we considered as BP

a. area  
p. peninsula  
Hv2 - Late Khvalynian

## References

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- (9) Dolukhanov et al., 2009; 2010 (10) Mamedov, 1997
- (11) Bezrodnykh et al., 2015
- (12) Bezrodnykh et al., 2004
- (13) Sorokin, 2011
- (14) Yanina et al., 2018
- (15) Kurbanov et al., 2014 (17) Svitoch, 2009
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