Quaternary Science Reviews 148 (2016) 29–43

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# The Ponto-Caspian basin as a final trap for southeastern Scandinavian Ice-Sheet meltwater

Alina Tudryn [a,*], Suzanne A.G. Leroy [b], Samuel Toucanne [c], Elisabeth Gibert-Brunet [a], Piotr Tucholka [a], Yuri A. Lavrushin [d], Olivier Dufaure [a], Serge Miska [a], Germain Bayon [c]

[a] GEOPS, Univ. Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504-509, 91405, Orsay, France
[b] Environmental Science, Brunel University London, Uxbridge, UB8 3PH, London, UK
[c] Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Unité de Recherche Géosciences Marines, F-29280, Plouzané, France
[d] Geological Institute (GIN), Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 117036, Russia

ARTICLE INFO

*Article history:*
Received 23 December 2015
Received in revised form
23 June 2016
Accepted 29 June 2016

*Keywords:*
Caspian sea
Black sea
SIS deglaciation
Early Khvalynian transgression
Chocolate clays
Red layers
Clay minerals
Neodymium isotopes
Pollen
Late Pleistocene

ABSTRACT

This paper provides new data on the evolution of the Caspian Sea and Black Sea from the Last Glacial Maximum until ca. 12 cal kyr BP. We present new analyses (clay mineralogy, grain-size, Nd isotopes and pollen) applied to sediments from the river terraces in the lower Volga, from the middle Caspian Sea and from the western part of the Black Sea. The results show that during the last deglaciation, the Ponto-Caspian basin collected meltwater and fine-grained sediment from the southern margin of the Scandinavian Ice Sheet (SIS) via the Dniepr and Volga Rivers. It induced the deposition of characteristic red-brownish/chocolate-coloured illite-rich sediments (Red Layers in the Black Sea and Chocolate Clays in the Caspian Sea) that originated from the Baltic Shield area according to Nd data. This general evolution, common to both seas was nevertheless differentiated over time due to the specificities of their catchment areas and due to the movement of the southern margin of the SIS. Our results indicate that in the eastern part of the East European Plain, the meltwater from the SIS margin supplied the Caspian Sea during the deglaciation until ~13.8 cal kyr BP, and possibly from the LGM. That led to the Early Khvalynian transgressive stage(s) and Chocolate Clays deposition in the now-emerged northern flat part of the Caspian Sea (river terraces in the modern lower Volga) and in its middle basin. In the western part of the East European Plain, our results confirm the release of meltwater from the SIS margin into the Black Sea that occurred between 17.2 and 15.7 cal kyr BP, as previously proposed. Indeed, recent findings concerning the evolution of the southern margin of the SIS and the Black Sea, show that during the last deglaciation, occurred a westward release of meltwater into the North Atlantic (between ca. 20 and 16.7 cal kyr BP), and a southward one into the Black Sea (between 17.2 and 15.7 cal kyr BP). After the Red Layers/Chocolate Clays deposition in both seas and until 12 cal kyr BP, smectite became the dominant clay mineral. The East European Plain is clearly identified as the source for smectite in the Caspian Sea sediments. In the Black Sea, smectite originated either from the East European Plain or from the Danube River catchment. Previous studies consider smectite as being only of Anatolian origin. However, our results highlight both, the European source for smectite and the impact of this source on the depositional environment of the Black Sea during considered period.



## 1. Introduction

Climate change in Europe during the Last Glacial Maximum (LGM; ca. 26–19 kyr BP) and the subsequent deglaciation have been intensively investigated through various archives leading to recently published compilations that focus on both the extent and timing of the last European Ice Sheet (EIS) (Hughes et al., 2015; Stroeven et al., 2015; Toucanne et al., 2015). During the LGM and until the complete melting of the ice sheet after 9.7 cal kyr BP (Stroeven et al., 2015), the EIS affected environmental conditions not only locally but also on a much wider scale. As a prominent example of this, glacigenic sediments were deposited as far away as the Eastern North Altantic and the Bay of Biscay through meltwater

* Corresponding author.
*E-mail address:* alina.tudryn@u-psud.fr (A. Tudryn).

http://dx.doi.org/10.1016/j.quascirev.2016.06.019

pulses originating at the southern margin of the Scandinavian Ice Sheet (SIS, itself part of the EIS system). The meltwater was funneled from Baltic lowlands by ice-marginal valleys and by the so-called Channel River (Toucanne et al., 2009, 2010). Part of the meltwater from the southeastern side of the SIS could have been evacuated into the Caspian and Black Seas via the Volga and Dniepr Rivers respectively, as it has been postulated by many authors (e.g. Mangerud et al., 2004; Soulet et al., 2013). Indeed, both rivers drain the East European Plain that constitutes partly their catchment area, and their northern extent is close to, or on the limit of the southeastern SIS margin during the LGM and the deglaciation.

In the Western Black Sea, the so-called Red Layers form part of the Late Quaternary sedimentary sequence (Major et al., 2002; Strechie-Sliwinski, 2007; Soulet et al., 2013). Their formation has been attributed to the transport of sediments into the Black Sea by meltwaters from the southern SIS margin during the last deglaciation (Soulet et al., 2011a). On the river terraces in the lower Volga, the so-called Chocolate Clays are present. They constitute part of sediments deposited during the Early Khvalynian transgression of the Caspian Sea in the Late Pleistocene (e.g. Varuschenko et al., 1987). Nevertheless the precise timing of this transgression, as well as the origin of Chocolate Clays (even if considered as being deposited in cold climatic conditions) and time of their deposition are not clearly established, and still debated (e.g. Leonov et al., 2002; Badyukova, 2010; Yanina, 2012; Tudryn et al., 2013a; Sorokin et al., 2014; Arslanov et al., 2015; Bezrodnykh et al., 2015; Makshaev and Svitoch, 2015 and papers cited therein). As Kroonenberg et al. (1997) pointed out, accurate dating of the Early Khvalynian transgression, and determination of the origin of the Chocolate Clays, would aid in clarifying the relationship between global climate (the primary driving mechanism), Caspian Sea level and the evolution of hydrological systems on the East European Plain, and provide major arguments for causal mechanisms.

In this context we propose a detailed sedimentological, palynological and geochemical study based on sediments from the western part of the Black Sea, from the river terraces in the lower Volga and from the middle basin of the Caspian Sea. Based on our results and on recent findings concerning the Caspian and Black Seas as well as SIS evolution, the aim of this study is to ascertain the source areas of clay minerals deposited in the Ponto-Caspian basin during the last deglaciation. Further to this, we intend to identify the origin of Chocolate Clays deposited in the Caspian Sea during the Early Khvalynian transgression to improve the chronological framework for this transgression and to establish its causal mechanisms.

## 2. Setting

### 2.1. SIS southern margin at the LGM

Studies of sediments along to the southern and eastern SIS margin reveal the complexity of the spatiotemporal evolution of the SIS. The ice margin was marked by end moraines and hummocky landscapes with frequent ice-dammed lakes spanning from Lake Onega in Russia to northern Germany (Svendsen et al., 2004; Stroeven et al., 2015).

The precise timing for SIS fluctuations is still debated; nevertheless the timing for westward meltwater routing via ice-marginal valleys from the Baltic lowlands is quite well known. Indeed, based on glacigenic sediments from the southern SIS margin deposited in the Bay of Biscay, Toucanne et al. (2015) proposed a revised chronology for the LGM and post-glacial ice sheet evolution in this area. According to these authors, the main Channel River meltwater releases occurred before the LGM and during the deglaciation. They were produced by five phases of the large-scale ice-margin retreats: (i) during Heinrich Stadial 3 (HS3: between ~31 and 29 cal kyr BP), (ii) during HS2 (between ~26 and 23 cal kyr BP), (iii) at ~22.5–21.3 cal kyr BP, (iv) at ~20.3–18.7 cal kyr BP and finally (v) from ~18.2 to 16.7 cal kyr BP (first part of HS1; between 18 and 15 cal kyr BP). At around 17 cal kyr BP, the Channel River stopped its activity; according to Toucanne et al. (2010), meltwater then flowed towards the Nordic Seas.

In the southern part of the SIS (i.e. Baltic lowlands of Poland and Germany), a succession of three moraine belts, the Brandenburg-Leszno, Frankfurt-Poznań and Pomeranian (Pomorska), was identified from the LGM and dated (Rinterknecht et al., 2006, 2008; 2012, 2013; Dzierżek and Zreda, 2007; Marks, 2015). The new chronology proposed by Toucanne et al. (2015) identifies the Brandenburg-Leszno ice advance between ~23.4 and ~20.3 cal kyr BP. The Brandenburg-Leszno phase ended with a significant ice retreat dated at ~20.3–18.7 cal kyr BP. The Frankfurt-Poznań ice advance occurred between ~18.7 and ~18.2 cal kyr BP, while the Pomeranian one was between ~16.7 and ~15.7 cal kyr BP.

In the southeastern part of the SIS, recent reconstructions of its deglaciation that include the recalibration of previously published dates (Rinterknecht et al., 2008), indicate that the south Baltic coast was already ice free at 15–14 kyr (Stroeven et al., 2015; Hughes et al., 2015). Stroeven et al. (2015) proposed that the local LGM was reached at ~19 cal kyr BP in Belarus (Orsha phase), Lithuania (Gruda phase), Latvia and Estonia. This local LGM has been correlated with the Frankfurt-Poznan phase to the west, while in the northeastern sector in Russia, it was reached at 17 cal kyr BP, and broadly correlates with Pomeranian ice advance. According to Svendsen et al. (2004) and Hughes et al. (2015), the maximum position of the ice sheet advance was reached there at ~20–18 kyr. The outermost ice sheet limit during its maximum formed three major lobes in the Russian sector (Hughes et al., 2015; Stroeven et al., 2015). But the exact extent in the area of the Rybinsk basin is still not clearly established. As pointed out by Marks (2015), the deglaciation steps in the Russian sector are not well known; nevertheless, at least the Vepsian (probably corresponding to the Pomeranian phase in central Europe), Sebezha, Luga and Neva phases of ice sheet advance have been identified. The Luga phase was derived from the last ice sheet margin that extended to the south of Lake Onega, and it was considered as having occurred at ~14.2 cal kyr BP. Afterwards, the Neva phase was dated at ~13 cal kyr BP (Marks, 2015). This is in good agreement with data from the eastern shore of Lake Onega, which indicate that this area was deglaciated between 14.4 and 12.0 kyr BP (Saarnisto and Saarinen, 2001), and with recent compilation of Hughes et al. (2015).

During the LGM, the East European Plain belonged to the zone of continuous permafrost including the middle basins of Dniestr, Dniepr and Don (Bogutskiy et al., 1975; Velichko et al., 1996) as well as the Volga catchment area and the northern shoreline of the Caspian Sea from that time (Yanina, 2012). According to Vandenberghe et al. (2014), permafrost degradation started as early as 17–15 kyr BP.

### 2.2. The Ponto-Caspian basin - study area

The Black and Caspian Seas (Fig. 1) belong to the Ponto-Caspian region. They are relicts of the East Paratethys, and became individualized during the Pliocene (Varuschenko et al., 1987; Forte and Cowgill, 2013; Yanina, 2014; Van Baak, 2015). Caspian and Black Seas are intracontinental, effectively closed and semi-closed reservoirs of waters and thus very sensitive to climatic changes. They have important part of their catchment areas in the East European Plain and, during the Quaternary, were subjected to large amplitude water-level fluctuations (more than 100 m) (e.g. Serebryanny, 1982; Varuschenko et al., 1987).

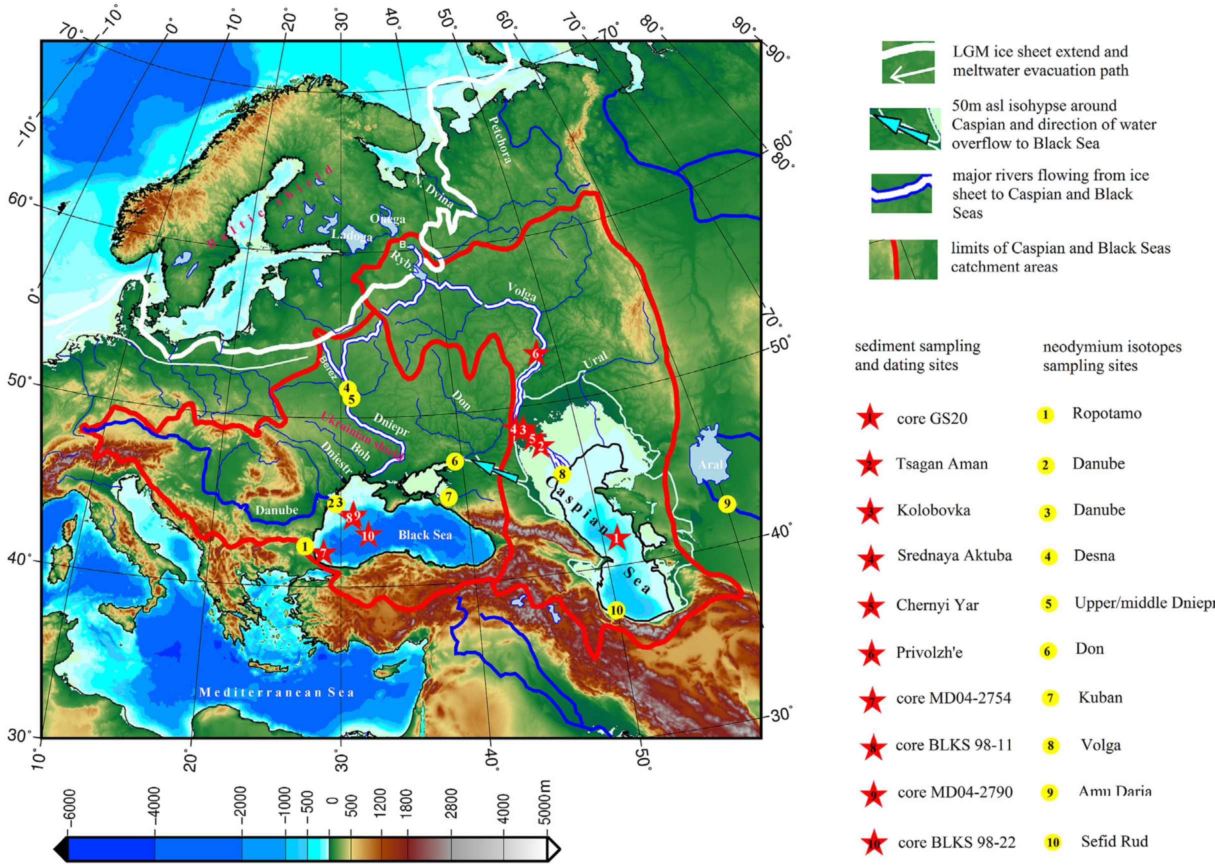



**Fig. 1.** Map of the Caspian and Black Seas with their present day catchment areas (red lines) and the LGM ice sheet extend at ~19 cal kyr BP (white line) after Hughes et al. (2015). Sediment sites and dating locations - numbered red stars: (1) core GS20 (479 m water depth), (2) Tsagan Aman, (3) Kolobovka, (4) Srednaya Akhtuba, (5), Chernyi Yar, (6) Privolzh'e settlement and cores: (7) core MD04-2754 (453 m water depth), (8) core BLKS 98-11 (500 m water depth), (9) core MD04-2790 (352 m water depth), (10) core BLKS 98-22 (2100 m water depth). Modern $\varepsilon_{Nd}$ site locations - numbered yellow dots: Rivers (1) Ropotamo, (2) and (3) Danube, (4) Desna, (5) Upper/middle Dniepr, (6) Don, (7) Kuban, (8) Volga, (9) Amu Darya, (10) Sefid Rud. The light blue line around the Caspian Sea at 50 m asl, indicates the maximum extent of the Caspian Sea during the Early Khvalynian transgression. Blue arrow between Caspian and Black Seas: Kuma-Manych Strait and direction of water overflow during the Early Khvalynian Transgression. White line and the arrow to the south of the LGM extend – westward evacuation path for meltwater. Map created using GMT freeware software (Wessel et al., 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.2.1. *Caspian Sea*

The Caspian Sea, which today lies at 27 m below sea-level, is the world's largest inland water body (390,000 km$^2$; 66,100 km$^3$) without connection to the world ocean (Fig. 1). It is a reservoir of brackish waters, with a catchment area of 3.5 million km$^2$, which extends northwards over 15° of latitude to the East European Plain. The salinity of the Caspian Sea varies from the north to the south within the range of 1–13.5‰; this variation is particularly strong in the north due to the large freshwater supply by the Volga River, in other areas average water salinity is of ~12.5‰ (Dumont, 1998). The Volga River contributes >80% of the Sea's total inflow (237 km$^3$ yr$^{-1}$ on average), drains the eastern part of the East European Plain and has a catchment area of 1.4 million km$^2$ (Kroonenberg et al., 1997; Dumont, 1998).

According to many authors (Varuschenko et al., 1987; Kroonenberg et al., 1997; Dumont, 1998; Svitoch, 1997; Dolukhanov et al., 2009), the Late Khazarian and Khvalynian transgressions occurred during the Late Pleistocene, from about 130 kyr. The Atelian regression (−120 to −140 m asl) occurred after the Late Khazarian (−10to – −5 m asl), whereas the Enotayevian regression (−80 to −100 m asl) separated the Early (maximum +50 m asl) and Late Khvalynian (maximum 0 m asl) transgressions. In the Holocene, the Mangyshlak regression and finally the Neocaspian transgression were evidenced. This general pattern of successive transgressions and regressions was complicated by second order variations of Caspian water level with various time constants and by change in the hydrographic network. Today the Caspian Sea is divided into three basins, each of about the same area, but differing in depth and volume. These are 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). During the Late Pleistocene transgressions, when water level reached 0 and even +50 m asl, the area to the north of the Caspian Sea, which is not currently submerged, formed an additional shallow water basin (Fig. 1).

### 2.2.2. *Black Sea*

The Black Sea is one of the largest anoxic basins in the world, with an area of 432,000 km$^2$, a water volume of 534,000 km$^3$, a mean depth of 1240 m, and a maximal depth of 2206 m (Ross et al., 1974) (Fig. 1). It is nowadays connected to the Mediterranean Sea through the Bosporus Strait, the Marmara Sea and the Dardanelle Strait. The Black Sea is characterized by the presence of a halocline between 100 and 200 m depth separating near-surface water having salinity of ~18‰, from a deep, more saline water of ~22.5‰. This lower body of water is of Mediterranean origin that induces anoxic conditions below 150 m bsl (Bahr et al., 2005; Strechie-Sliwinski, 2007). The north-western part of the basin drains European rivers, the largest being the Danube (catchment area of 817,000 km$^2$) and the Dniepr (catchment area of 504,000 km$^2$). To the South, Anatolian rivers supply today more than 33% of the total sediment input into the Black Sea (Popescu, 2002); but they represent only 8% of the total freshwater discharge.

The connection with the Mediterranean Sea has been interrupted frequently over the history of the Black Sea (Deuser, 1974) and the Black Sea's status oscillated between lacustrine (during glacial low stands of the ocean) and marine (during interglacial high stands) (Badertscher et al., 2011). The connection was previously located on the Sakarya Strait (Gürbüz and Leroy, 2010). For the last glacial–postglacial transition, two hypotheses have been proposed to explain the Mediterranean-Black Seas re-connection: a catastrophic (Ryan et al., 1997) or a gradual event, with the "Black Lake" freshwater inflow into the Mediterranean Sea at either ~17 kyr BP or ~9.5 cal kyr BP, with, after ~9.8 kyr BP possible oscillating manner allowing a periodic migration of Mediterranean organisms into the Black basin, and finally the marine water arrival into the "Black Lake" at ~7.6 cal kyr BP (Aksu et al., 2002; Hiscott et al., 2007a,b; Nicholas et al., 2011; Yanko-Hombach et al., 2007, 2014). This last reconnection was recently constrained as occurring gradually between ~9.0 and ~8.0 cal yr BP (Soulet et al., 2011b).

### 2.3. The Ponto-Caspian basin - Red Layers and Chocolate Clays

The Red Layers in the Western Black Sea constitute four individualized intervals of reddish-brown silty sediment and were deposited between ~17.2 and ~15.7 cal kyr BP, when the Black Sea was a giant lake due to lowstand conditions (Soulet et al., 2011a). On the basis of neodymium isotopic values, they were interpreted as being a consequence of spillway events from the proglacial lake Disna into the Upper River Dniepr (Soulet et al., 2013). Before and after this event, sediment deposited in deep basin of the Western Black Sea was attributed to a supply by the Danube River (Lericolais et al., 2013; Constantinescu et al., 2015).

The Chocolate Clays were deposited during the Early Khvalynian, the largest Caspian Sea transgression recorded for the Late Quaternary. During this transgression, the maximal Caspian Sea water level raised up to +50 m asl (e.g. Varuschenko et al., 1987)(Fig. 1) implying important modifications of its shoreline, especially in the now-emerged northern flat part, where Chocolate Clays are known. The Chocolate Clays comprise a part of the Early Khvalynian sequence and are mostly confined to the middle and lower reaches of the Volga River and its delta. Their detailed description and distribution (including, to a lesser extent, the area of the lower Ural River, Fig. 1) are given by Makshaev and Svitoch (2015) and in papers cited therein, the oldest has been published in Russian already in 1856. Due to discrepancies between results from different dating methods, the age of the Early Khvalynian transgression is still ambiguous ($^{14}$C ages: 56.0–7.0 kyr BP, U/Th ages: 24.2–9.6 kyr, TL ages: 71.0–16.0 kyr) (Varuschenko et al., 1987; Mamedov, 1997; Leonov et al., 2002; Bezrodnykh et al., 2004; Badyukova, 2007; Svitoch et al., 2008; Shkatova, 2010; Sorokin et al., 2014 and papers cited therein). Mamedov (1997) and Shkatova (2010) claimed that the Early Khvalynian transgression corresponded to warming between 32 and 24 kyr BP. Nevertheless, many authors correlate that transgression with the LGM itself or to the last deglaciation (Leonov et al., 2002; Chepalyga, 2003, 2005, 2007; Svitoch et al., 2008, Svitoch, 2009; Tudryn et al., 2013a; Yanina, 2012; Arslanov et al., 2015). Large quantities of inflowing water could have been related to ice-dammed lakes formed in the southern front of the Siberian and east European ice sheets (Grosswald, 1993; Mangerud et al., 2004; Chepalyga, 2005). According to Chepalyga (2003, 2005; 2007), these proglacial lakes created a "Great Proglacial Drainage System" in Northern Eurasia with water flowing through the Aral Sea and River Uzboy into the Caspian Sea between 21 and 17 kyr BP, and the Caspian Sea water overflowed into the Black Sea through the Kuma-Manych Strait (22 m asl) between 17 and 15 kyr BP. Other authors suggested that levels of ice-dammed lakes in northern East European Plain in the upper Volga and Northern Dvina region were too low to feed sufficiently the Caspian Sea to produce high water level during the Early Khvalynian transgression. In this case the high-stand conditions of the Caspian Sea could be better explained climatically: by high precipitations (snow) and rapid snow melting during the spring (Sidorchuk et al., 2009) or by a low evaporation rate during the last glaciation (Velichko et al., 1987). According to Vandenberghe et al. (2014), permafrost degradation started as early as 17–15 kyr BP, and thus certainly acted on supplying additional detrital material and water into the Caspian basin. Finally, recently published data from sediment cores collected from the northern basin of the Caspian Sea indicate that Early Khvalynian sediment consists of two lithologically different parts (Bezrodnykh et al., 2015). The lower part (2.5–5.0 m thick) consists of alternation of shelly detritus of variable size with a sandy or clayey matrix, and clays with inclusions of shells and shelly detritus. The upper part (8–10 m thick) is composed of clays with variably thick sand intercalations. The base of this sequence is, after $^{14}$C dating, of ~34 cal kyr BP (Bezrodnykh et al., 2015), or even possibly ~56 kyr BP (Sorokin et al., 2014). $^{14}$C ages of shells from different Chocolate Clays sections in Volga River terraces, show values between ~14.5 and 13.3 cal kyr BP (Makshaev et al., 2015; Makshaev and Svitoch, 2015).

## 3. Material and methods

### 3.1. Material collection

#### 3.1.1. Caspian Sea

The 995 cm long Kullenberg sediment core SR-9418 GS20 (named GS20 thereafter, but called GS18 in Leroy et al., 2014), was collected from the middle basin of the Caspian Sea (41°32′53″N; 51°06′04″E; water depth of 479 m) (Fig. 1). It has already been analyzed for chronology, magnetic mineralogy, carbonate content and micropalaeontology (ostracods and palynology) (Boomer et al., 2005; Leroy et al., 2014; Tudryn et al., 2014), and presents a Late Pleistocene and Holocene record (Fig. 2a,b,c). Sediments from river terraces in the lower Volga were sampled directly from accessible outcrops in Srednaya Akhtuba (~20 m a.s.l., 48°43′00.37″N, 44°51′59.72″E), in Kolobovka (~10 m a.s.l., 48°39′21.06″N, 45°28′29.34″E) and in Tsagan-Aman (~0 m a.s.l., 47°33′02.69″N, 46°40′49.99″E) (Fig. 1, Photo 1b,c,d). The details of sampling (about 150 samples of 8 cm$^3$ perspex cubes were obtained) and results of magnetic and clay minerals, palynological studies, as well as $^{14}$C dating of this sequence representing part of Early Khvalynian transgression of the Caspian Sea during the Late Pleistocene, are reported in Tudryn et al. (2013a) and in Leonov et al. (2002). The core from the middle basin of the Caspian Sea was collected during a cruise that took place in 1994. Sampling of Early Khvalynian sedimentary sequences accessible from river terraces in the lower Volga in Srednaya Akhtuba, Kolobovka and Tsagan-Aman, was achieved during a French-Russian field trip in September 1997. Both were obtained as part of the multidisciplinary study of the palaeolimnology of the Caspian Sea "Understanding the Caspian Sea Erratic Fluctuations" (an EU-INCO-Copernicus collaboration), conducted by a team that included five authors of this paper.

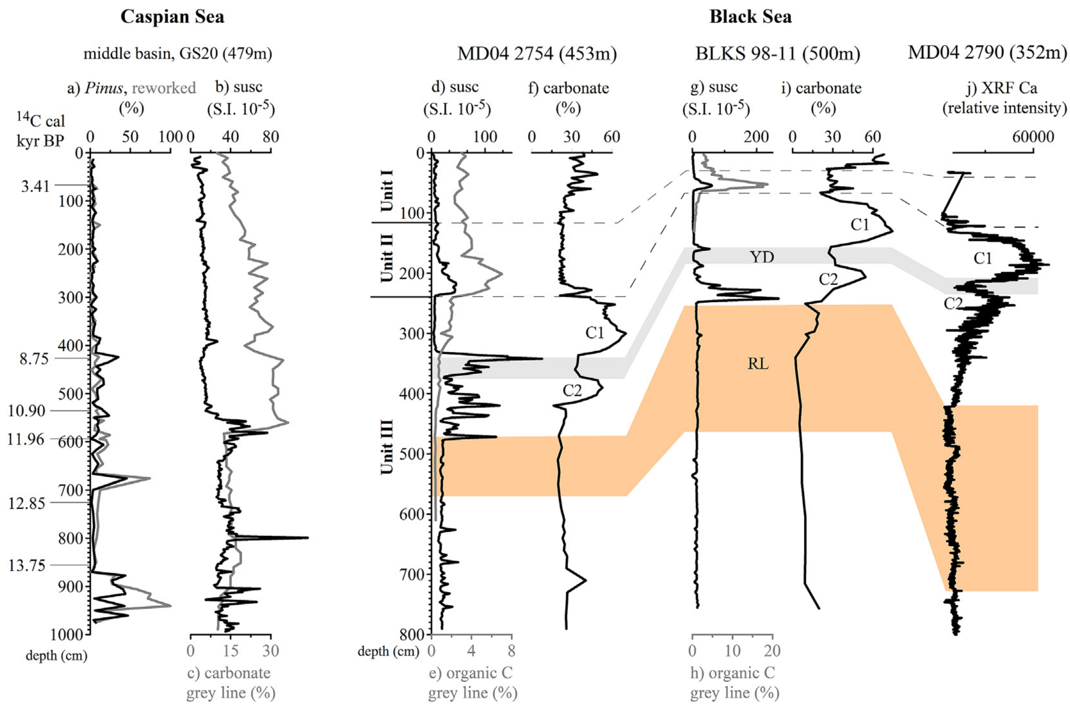



**Fig. 2.** Data from sediment cores for middle basin of the Caspian Sea (core GS20, 479 m water depth) and for the Black Sea - southwestern part (core MD04-2754, 453 m water depth) and - northwestern part (core BLKS 98-11, 500 m water depth and core MD04-2790, 352 m water depth). a) pollen data: *Pinus* and reworked pollen percentages, b), d) and g) magnetic susceptibility, c), f) and i) Ca and Mg carbonate content, e) and h) organic carbon content, j) XRF Ca intensity. Data are presented on a depth scale. For core GS20, ages ($^{14}C$ cal kyr BP) are reported on the left side of the depth scale. For cores from the Black Sea, lithological Unit I, Unit II and Unit III are shown. RL – Red Layers, YD – Younger Dryas, C1 and C2 – carbonate peaks 1 and 2. Data for core GS20 from the Caspian Sea are presented after Boomer et al. (2005), Leroy et al. (2014) and Tudryn et al. (2014). Data for Black Sea are presented after Strechie-Sliwinski (2007) and Tudryn et al. (2012) for cores BLKS 98-11 and MD04-2754, and after Soulet et al. (2013) for core MD04-2790. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.1.2. Black Sea

The 757 cm long Kullenberg sediment core BLKS 98-11 was collected from the slope of the NW Black Sea (44°03.02′N, 30°53.12′E; water depth 500 m), in the axis of the Danube River during a cruise as part of the French-Romanian program Blason1 in 1998 (Fig. 1). The 32 m long Calypso core MD04-2754 (41°59.23′N, 28°40.99′E; water depth 453 m) was obtained from the slope of the SW Black Sea, during the ASSEMBLAGE 1 cruise and as part of the European program ASSEMBLAGE (Fig. 1). Sediments from core BLKS 98-11 and seven upper meters from core MD04-2754 were previously studied for chronology, magnetic mineralogy, carbonate content, organic carbon and nitrogen contents and their isotopic signatures (Strechie et al., 2002; Strechie-Sliwinski, 2007)(Fig. 2d–h).

## 3.2. Methods

*Clay minerals and grain-size analysis.* Clay minerals from the Black and Caspian Seas were identified by XRD on oriented mounts of non-calcareous clay-sized (<2 mm) particles with PANalytical diffractometer, following the laboratory routine at the GEOPS laboratory, Université de Paris Sud (Liu et al., 2007, 2008). The oriented mounts were obtained according to a method described by Liu et al. (2004). Three XRD runs were made, following air-drying, ethyleneglycol solute treatment for 24 h, and heating at 490 °C for 2 h. The identification of clay minerals was mainly made according to the position of the (001) series of basal reflections on the three XRD diagrams. Semi-quantitative estimates of peak areas of the basal reflections for the main clay mineral groups of smectite (including mixed-layers) (15–17 Ä), illite (10 Ä) and kaolinite/chlorite (7 Ä) were carried out on the glycolated curve (Holtzapffel, 1985) using the MacDiff software (Petschick, 2000). Relative proportions of kaolinite and chlorite were determined based on the ratio of 3.57:3.54 Ä peak areas. Based on the XRD method, the semi-quantitative evaluation of each clay mineral has an accuracy of 5%. Grain-size distribution measurements of carbonate-free sediment from core GS20, Caspian Sea, were carried out on a Malvern Mastersizer 2000 device, at the GEOPS laboratory, Université de Paris Sud.

*Palynological analyses.* Ninety-two samples for the top 666 cm of core GS20 were palynologically studied for palaeoenvironmental reconstructions, both terrestrial and aquatic (Leroy et al., 2014). Twenty-two of them were treated at Université Catholique de Louvain (Belgium) by the heavy liquid method (Thoulet solution at a density of 2.1). The remaining seventy samples were treated at Brunel University (UK) by the HF method. On average the sample volume was 1.1 ml. Initial processing of samples involved the addition of sodium pyrophosphate to deflocculate the sediment. Samples were then treated with cold hydrochloric acid (from 10% to pure) and cold hydrofluoric acid (60%), and HCl (10%) again. The residual organic fraction was screened through 125 and 10 μm mesh sieves. Final residues were mounted on slides in glycerol and sealed with varnish. An additional 22 samples, below 666 cm depth (treated with the HF method), were treated but not published in Leroy et al. (2014) because of a suspected different taphonomy. The *Pinus* percentages are calculated on the sum of terrestrial pollen grains (that includes *Pinus*, but not reworked grains). The reworked percentages are calculated on the same sum, that does not include them and hence values higher than 100% can be reached. In the Lower Volga from the Srednaya Akhtuba outcrop, six samples were chosen from fine-grained levels. The processing of 1.9–2.7 ml of sediment, following the HF method described for the

GS20 core, did not yield any palynomorphs.

*Neodymium.* We measured Nd isotope ratios of fine-grained detrital fractions extracted from a series of the Caspian Sea sediments from three key locations. Sample selection was based on recorded changes in clay mineralogy. One measurement was made on the Early Khvalynian Chocolate Clays sample from Srednaya Akhtuba. Two others were made on samples from core GS20, at 970 cm and 770 cm depth. Additional analyses were performed on recent sediments from the Kuban, Don and Ropotamo rivers, all tributaries of the Black Sea, as well as from River Sefid Rud that drains the southern Caspian Basin and River Amu Darya (Fig. 1). The neodymium isotopic composition of terrigenous sediment is a powerful tracer for geographical provenance; it reflects to a large extent the mean age of the corresponding source region and is preserved during erosion and transport processes (Goldstein and Jacobsen, 1988). In this study we analyzed the fine clay-silt detrital fraction (<63 μm) of the sediment, for comparison with the Nd isotopic compositions of sediments recently reported by Soulet et al. (2013) and Toucanne et al. (2015). Dried fine-grained fractions (typically ~ 0.5 g) were crushed using an agate mortar and pestle. The terrigenous fraction of each sediment sample was digested by alkaline fusion (Bayon et al., 2009) after removal of all carbonates, Fe–Mn oxide and organic components using a sequential leaching procedure (Bayon et al., 2002). Prior to analyses, Nd was separated by ion exchange chromatography (see details in Bayon et al., 2012). Isotopic measurements were performed at the Pôle Spectrométrie Océan, Brest (France), using a Thermo Scientific Neptune multi-collector ICPMS. Mass bias corrections on Nd were made with the exponential law, using $^{146}Nd/^{144}Nd = 0.7219$. Nd isotopic compositions were determined using sample-standard bracketing, by analysing JNdi-1 standard solutions every two samples. Mass-bias corrected values for $^{143}Nd/^{144}Nd$ were normalized to a JNdi-1 value of $^{143}Nd/^{144}Nd = 0.512115$ (Tanaka et al., 2000). In this study, both measured $^{143}Nd/^{144}Nd$ ratios and literature data are reported using the $\varepsilon_{Nd}$ notation, which corresponds to the deviation of any measured Nd isotopic ratio relative to the present-day value of the Chondritic Uniform Reservoir (CHUR): $[(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1] \times 10^4$; using $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ (Jacobsen and Wasserburg, 1980). Note that the estimated uncertainty on measured $\varepsilon_{Nd}$ values, inferred from repeated analyses of JNdi-1 standard solution is typically of about ±0.3 ε-units.

## 4. Results

### 4.1. Lithology and chronology

#### 4.1.1. Caspian Sea

*4.1.1.1. Lithology. Core GS20:* The sediment from the middle basin of the Caspian Sea (core GS20) presents fine silty deposits described in details in Tudryn et al. (2014) and in Leroy et al. (2014). They are characterized as a whole by an alternation of black and grey/brownish laminae that rapidly disappear under oxidizing conditions (Photo 1a). These laminae reflect changes in magnetic mineralogy between greigite (an iron sulfide $Fe_3S_4$ in black laminae) and magnetite (an iron oxide $Fe_3O_4$ in grey/brownish laminae), and are of early diagenetic origin, as it is the case for sediment from the South basin of the Caspian Sea (Jelinowska et al., 1998, 1999; Leroy et al., 2013a,b). In the lower part of core GS20, from the bottom at 995 cm–~870 cm, the sediment became brownish or slightly pink/reddish in oxidizing conditions, while above it became rather grey-greenish.

*River terraces:* Early Khvalynian sediments from river terraces in the lower Volga studied here, are formed by chocolate-colour clays (or silts), well known from literature as Chocolate Clays (e.g. Leonov et al., 2002; Badyukova, 2007; Chepalyga, 2007; Svitoch, 2009; Shkatova, 2010; Makshaev and Svitoch, 2015, and papers cited therein). The Chocolate Clays from Srednaya Akhtuba, Kolobovka and Tsagan-Aman are more or less regularly interbedded by thin, horizontal sandy or silty yellow laminae (Photo 1b,c). Scarce macrobiological remains were observed. These sediments suggest a rather calm depositional environment, and visually may resemble varved sediments in periglacial lakes (Tudryn et al., 2013a). This sequence, of different thickness in each outcrop (2.0 m in Srednaya Akhtuba, 3.4 m in Kolobovka and 1.4 m near Tsagan-Aman), begins at the bottom with a grey/green sandy and silty sediment with oxidation traces.

*4.1.1.2. Chronology. Core GS20:* Six radiocarbon dates for core GS20 were already obtained from ostracod shells and have been used to build an age-depth model after calibration by the IntCal13.14C curve (Reimer et al., 2013) and application of a 370 years reservoir effect (Boomer et al., 2005; Tudryn et al., 2014; Leroy et al., 2014)(Fig. 2). Sediments in core GS20 accumulated between ~14.6 and ~2 cal kyr BP. More specifically between ~14.6 and 12 cal kyr BP or from the bottom to 600 cm depth, the sedimentary rate is of ~0.15 cm $yr^{-1}$.

*River terraces:* The studied here Early Khvalynian sediment in river terraces in the lower Volga was poor in biological remains. Nevertheless, one $^{14}C$ AMS date was obtained on total organic carbon preserved fraction from Chocolate Clays on a sample from Srednaya Akhtuba (Tudryn et al., 2013a), and ten $^{14}C$ AMS dates were made on marine shells from Chocolate Clays and interbedded silts from Srednaya Akhtuba, Kolobovka and Tsagan Aman, as well as from two other sites - Chernyi Yar and the Privolzh'e settlement (Fig. 1)(Leonov et al., 2002). The age obtained on total organic carbon corresponds to ~20 cal kyr BP (Tudryn et al., 2013a). This was obtained from sample representing the upper part of the sequence, and is consistent with an Early Khvalynian event around the LGM. Although the analyzed organic carbon is of non-identified origin, it could come from the basin and thus reflect the LGM time, or at least partly from the catchment area and thus be older than the time of the clay deposition.

Dates obtained on mollusc shells were previously published without application of a calibration model (Leonov et al., 2002). After application of the calibration IntCal13.14C curve (Reimer et al., 2013), the new chronology has become established between ~19.1 and 13.9 cal kyr BP (Table 1). Since these molluscs were living in shallow, well-mixed and oxygenated environments (Tudryn et al., 2013a), we assume no hard-water effect in the basin and consider an equilibrium of water carbon system with atmosphere $CO_2$.

#### 4.1.2. Black Sea

*4.1.2.1. Lithology.* In both cores from the Black Sea, three distinct lithostratigraphic units, previously reported by Ross and Degens (1974) and Hay et al. (1991) for deep-sea sediments, were identified (Fig. 2). The lowest unit, Unit III, consists of alternating light and dark silts deposited under lacustrine conditions. They include brownish/reddish silts (Photo 1e), named Red Layers (Major et al., 2002; Strechie-Sliwinski, 2007; Soulet et al., 2013). These silts present a sequence of varying thickness in both cores and are interbedded by thin grey silty bands. The Red Layers are followed by dark, greigite-rich, and light-coloured, carbonate-rich bands. Unit II is a carbonate-poor, fine-grained sapropel that shows variation in organic matter content, with high values in the lower half and marked decrease in the upper half. The lower limit of the sapropel indicates the beginning of the Black Sea – Mediterranean Sea connection. The uppermost unit, Unit I, is characterized by alternating light and dark microlaminations deposited since the first occurrence of *Emiliana huxleyi*, a coccolithophore that largely

**Table 1**
$^{14}C$ dates obtained for Early Khvalynian Chocolate Clays from river terraces in the lower Volga. One date obtained on organic carbon (Tudryn et al., 2013a), and 10 dates obtained on mollusks shells by Leonov et al. (2002) and calibrated using the atmospheric calibration curve IntCal13 (Reimer et al., 2013; Stuiver and Reimer, 1993).

| Site | Lat. | Long. | Material | Measured 14C yr BP | Error ± yr | Age 14C cal yr BP s1 | Mean 14C cal yr BP | Error ± yr |
|---|---|---|---|---|---|---|---|---|
| Srednaya Akhtuba | 48°43′00.37″N | 44°51′59.72″E | C org. | 16930 | 120 | 19924–20181 | 20053 | 130 |
| (+22–25 m asl) | 48°43′00.37″N | 44°51′59.72″E | Shell | 12580 | 70 | 14763–15099 | 14932 | 169 |
| | 48°43′00.37″N | 44°51′59.72″E | Shell | 12120 | 180 | 13734–14277 | 14006 | 272 |
| Kolobovka | 48°39′21.06″N | 45°28′29.34″E | Shell | 13240 | 45 | 15821–16011 | 15916 | 95 |
| (+10 m asl) | 48°39′21.06″N | 45°28′29.34″E | Shell | 13170 | 85 | 15689–15971 | 15831 | 142 |
| | 48°39′21.06″N | 45°28′29.34″E | Shell | 13070 | 100 | 15468–15835 | 15652 | 184 |
| Tsagan Aman | 47°33′02.69″N | 46°40′49.99″E | Shell | 12470 | 80 | 14377–14882 | 14630 | 253 |
| (0 - +2 m asl) | 47°33′02.69″N | 46°40′49.99″E | Shell | 12445 | 75 | 14304–14775 | 14540 | 236 |
| | 47°33′02.69″N | 46°40′49.99″E | Shell | 12060 | 130 | 13762–14070 | 13917 | 155 |
| Chernyi Yar (0 m asl) | 48°03′N | 46°07′E | Shell | 15800 | 1320 | 17517–20772 | 19145 | 1628 |
| settl. Privolzh'e (+30 m asl) | 52°57.50′N | 48°35.52′E | Shell | 14030 | 250 | 16666–17405 | 17036 | 370 |

comprises the light bands. Different lithological characteristics, such as sapropel in Unit II, two carbonate rich bands in Unit III, magnetic minerals changes, which are visible through magnetic susceptibility variation, and Red Layers are identified here by laboratory analyses and visually. These characteristics, that reflect environmental changes in the Black Sea and its catchment area, are ubiquitous in the Black Sea, as shown in numerous investigations. For instance, carbonate and XRF-Ca analyses for cores collected on the slope (Fig. 2f,i,j) and in the deep Black Sea, as in core BLKS 98-22 (Fig. 1), highlight similar variation in the Ca content in Unit III, with its two peaks labeled as C1 and C2 (Major et al., 2002; Strechie et al., 2002; Bahr et al., 2005, 2006, 2008; Strechie-Sliwinski, 2007; Kwiecien et al., 2008; Soulet et al., 2011b).

*4.1.2.2. Chronology.* Recent investigations allowed chronology establishment (Soulet et al., 2011a, 2011b, 2013). According to these authors, the deposition of the Red Layers, identified in the lacustrine Unit III, occurred during Heinrich stadial 1 (HS1) from ~17.2 to ~15.7 cal kyr. BP. The two following peaks in Ca intensity coincide with the Bølling–Allerød interstadial for peak C2 (~14.70–~12.65 cal kyr BP), and with the Early Holocene for peak C1 (~11.70–~8.99 cal kyr BP) periods. The decrease in the Ca intensity observed between these episodes is correlated to the Younger Dryas cold event (~12.65–~11.70 cal kyr BP). The marine inflow from Mediterranean Sea into the Black Sea started after the C1 peak at ~8.99 cal kyr BP, and resulted in the establishment of marine conditions at ~8.08 cal kyr BP and the formation of sapropel-rich sediments at the sea bottom (Unit II). The base of the youngest Unit I is dated at ~2.72 cal kyr BP (Jones and Gagnon, 1994). All these specific parts of the sequence were well identified in cores BLKS98-11 and MD04-2754 and allowed the establishment of a precise chronological frame (Fig. 2d–i).

### 4.2. Clay mineralogy, grain-size, pollen and neodymium analyses

The results are presented on a calendar age scale from 19 to 12 cal kyr BP (Fig. 3). Two cores from the Black Sea indicate a continuous record that is shown from 18 cal kyr BP onwards. Results from the Caspian Sea are composed of sediments from the middle basin, which begin at ~14.6 cal kyr BP, and of sediments from the river terraces in the lower Volga, which finish at ~13.9 cal kyr BP.

#### 4.2.1. Caspian Sea

*Pollen:* In core GS20, below 666 cm, three strands of information make us suspect a different source for the palynomorphs than for the upper part of the core. It is i) the irregular presence of high percentages of *Pinus* pollen (Fig. 2a and 3a) and the occasional occurrence of *Sphagnum* spore, ii) the very high occurrence of reworked pollen grains (loss of ornamentation, increase in opacity and often pre-Quaternary taxa) representing at times more than 100% of the terrestrial sum of well-preserved pollen grains (Figs. 2a and 3a), and iii) the very low palynological concentrations (below 2000 pollen and spores per ml). The absence of *Pinus* in the vegetation around the middle basin of the Caspian Sea and its presence at great distance in the south (Tagieva and Veliev, 2014) and in the north of the area (Bolikhovskaya and Kasimov, 2010; Tudryn et al., 2013a; Richards et al., 2014) suggest a stronger contribution from river sources to the sediment than later on, after 12.44 cal kyr BP. The highest values of *Pinus* and reworked elements are reached at the bottom of the core below 877 cm depth (~13.83 cal kyr BP) (Fig. 3a). Then a single peak is found at 676 cm (12.56 cal kyr BP) and afterwards very moderate values are found upward until 383 cm or 8.19 cal kyr BP. The absence of palynomorphs in samples from the river terraces in the lower Volga is largely related to the oxidising environment unfavourable to palynomorph preservation.

*Clay minerals and granulometry:* The Early Khvalynian Chocolate Clays on river terraces in the lower Volga are clearly dominated by illite that reaches 80%. It is followed by kaolinite, chlorite and smectite but these minerals present low abundances. The interbedded silts show broadly similar contents of illite and smectite. As contents of these minerals were measured for sediments from Srednaya Akhtuba and Kolobovka, they are reported on Fig. 3c (indicated as dots) taking into account ages obtained from mollusc shells from these sites (Leonov et al., 2002) and their subsequent calibration. In the middle basin of the Caspian Sea, the sediment, from the bottom of core GS20 until ~14–13.8 cal kyr BP, displays similar patterns as for the Early Khvalynian sediments, with illite as dominant mineral (reaching 60%), and low values for kaolinite, chlorite and smectite (Fig. 3c indicated as lines). After that, and up to 12.0 cal kyr BP, illite decreases while smectite increases and became the most abundant mineral. Granulometric analysis of core GS20 sediment shows fine particles sizes (Fig. 3b).

*Neodymium:* Nd isotopic compositions of the sediment were obtained for three key locations with regard to changes of clay minerals (Table 2, Fig. 3d red stars). The measurement made on the Early Khvalynian Chocolate Clays sample from Srednaya Akhtuba displays a $\varepsilon_{Nd}$ value of −17.7. Two other measurements were made on the sediment from the middle basin (core GS20) where illite was dominant, at 970 cm depth (~14.4 cal kyr BP), and where illite decreased and smectite become dominant, at 770 cm depth (~13.2 cal kyr BP). The results are respectively −14.0 for the first and −10.4 for the second sample.

#### 4.2.2. Black Sea

Changes in contents of clay minerals are more pronounced in

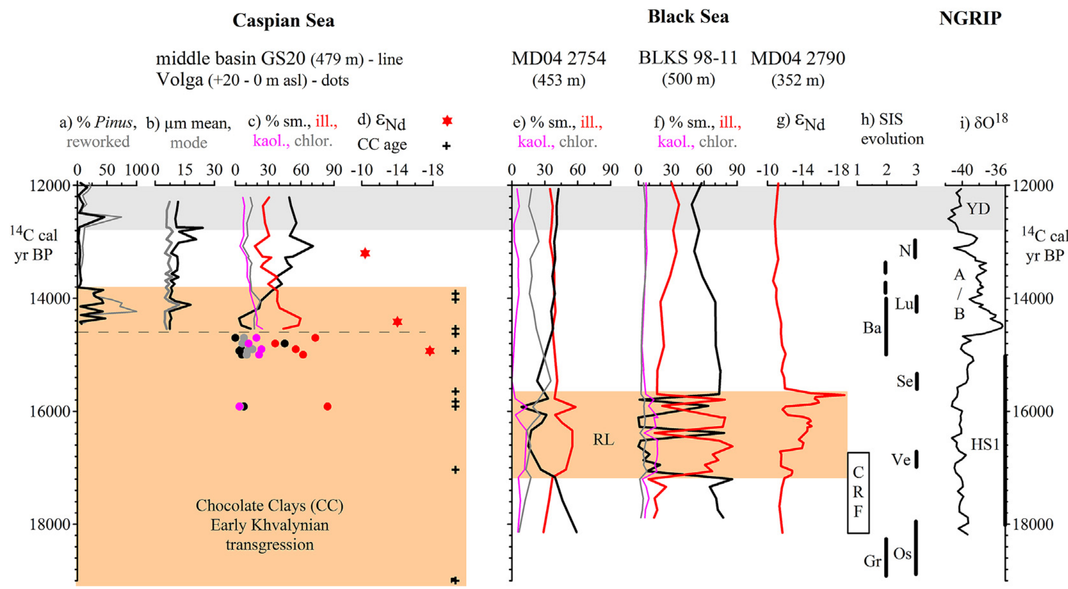
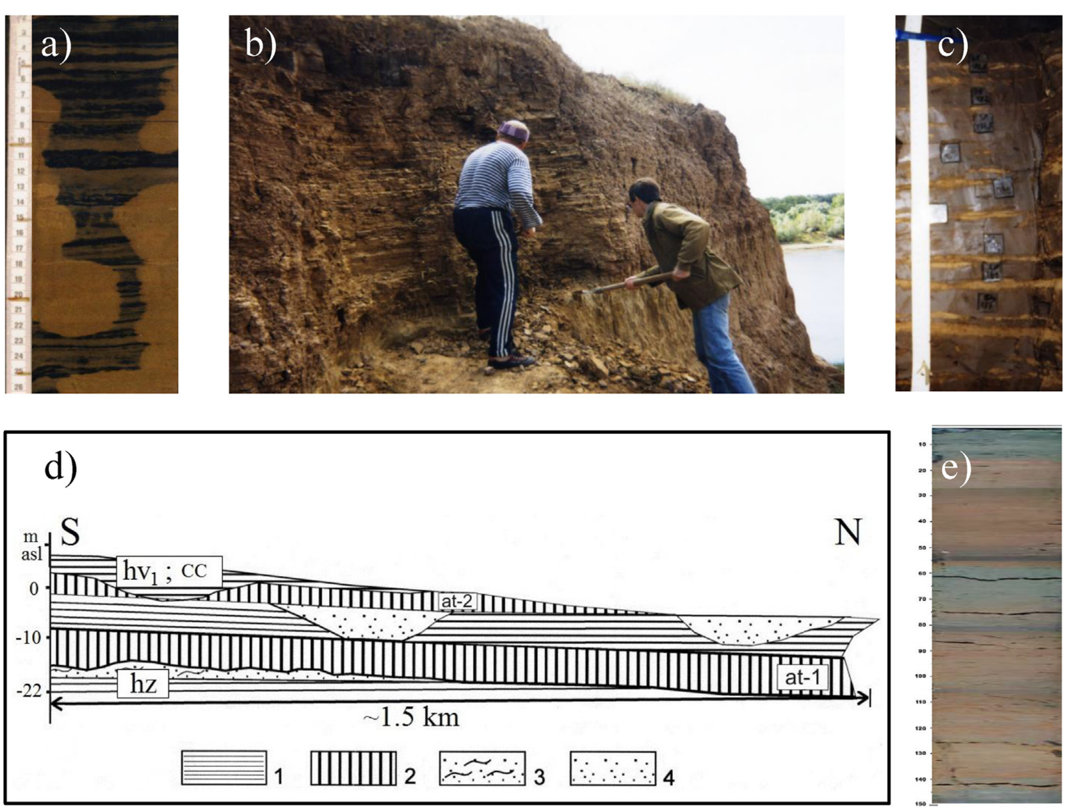



**Fig. 3.** Data for Caspian (a, b, c, d) and Black (e,f,g) Seas sediments on an age scale from 19 to 12 cal kyr BP. a) *Pinus* and reworked pollen percentages, core GS20, b) mean grain size (black line) and mode (grey line), core GS20, c) clay minerals contents, lines for core GS20 and dots for river terraces in the lower Volga, dashed line separating core GS20 and river terraces records, d) red stars: $\varepsilon_{Nd}$ values, black crosses: $^{14}$C cal kyr BP ages obtained on shells from Chocolate Clays (CC) in river terraces in the lower Volga (Leonov et al., 2002; this study), e) clay minerals contents for core MD04-2754, f) clay minerals contents for core BLKS 98-11, g) $\varepsilon_{Nd}$ values for core MD04-2790 after Soulet et al. (2013), h) SIS margin evolution: 1) timing for Channel River floods (CRF) after Toucanne et al., 2015, 2) Gr - Gruda and Ba - Baltija Moraines advances, Lithuania (Marks, 2015), 3) Os – Ostashkov, Ve – Vepsian, Se – Sebezha, Lu – Luga and N – Neva Moraines advances, northern Russia (Marks, 2015), i) the NGRIP ice core record of $\delta^{18}$O (North Greenland Ice Core Project Members, 2004), YD – Younger Dryas, B - Bølling, A – Allerød, HS1 – Heinrich Stadial 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)




**Photograph 1.** a) core GS20, details of early diagenetic lamination of the sediment and oxidation process after opening of the core (917–943 cm depth), photograph taken by M. Destarac, Dept. of Geology, Museum d'Histoire Naturelle, Paris, b) Chocolate Clays on river terraces in the lower Volga, Srednaya Akhtuba, photograph taken by A. Tudryn, c) details of Chocolate Clays, Srednaya Akhtuba, 200–150 cm depth, photograph taken by A. Tudryn, d) simplified cross section from Tsagan Aman, river terraces in the lower Volga, modified from Lavrushin et al. (2014): hz – Khazarian transgression, at-1 and at-2 – Atelian regression, hv$_1$ – Early Khvalynian transgression, CC – Chocolate Clays, 1 – clays and silts of marine origin, 2 – sub-aerial silts, 3 – fine grained sand, 4 – sand, e) core BLKS 98-11, lithological Unit III – details of Red Layers (286–439 cm depth), (Popescu in Lericolais et al., 2005).

**Table 2**
Neodymium isotopic signatures of samples from Caspian Sea and some rivers from the Caspian and Black Sea catchment area.

| N° | Name | Country/Sea | Lat (N) | Long (E) | 143Nd/144Nd (2SD) | εNδ(±0.3)* | Source |
|---|---|---|---|---|---|---|---|
| *River terraces* | | | | | | | |
| 1 | Volga (SA175) | Russia | 48°43′00 | 44°51′59 | 0.511732 ± 4 | −17.7 | this study |
| *River mouths* | | | | | | | |
| *2* | Ropotamo | Bulgaria | 42°22′10 | 27°16′09 | 0.512263 ± 5 | −7.3 | this study |
| *3* | Danube | Romania | 44°53′02 | 29°36′50 | 0.512179 ± 4 | −9.0 | Soulet et al., 2013 |
| *4* | Danube | Romania | 44°53′28 | 29°37′33 | 0.512176 ± 4 | −9.0 | Soulet et al., 2013 |
| *5* | Dniepr | Ukraine | 51°42′47 | 30°37′37 | 0.511917 ± 7 | −14.0 | Soulet et al., 2013 |
| *6* | Desna | Ukraine | 51°11′38 | 30°56′40 | 0.511990 ± 8 | −12.6 | Freslon et al., 2014 |
| *7* | Don | Russia | 47°09′33 | 39°24′58 | 0.511903 ± 7 | −14.3 | this study |
| *8* | Kuban | Russia | 45°04′50 | 38°35′51 | 0.512177 ± 40 | −9.0 (0.77) | this study |
| *9* | Volga | Russia | 45°42′47 | 47°55′12 | 0.512021 ± 8 | −12.0 | Soulet et al., 2013 |
| *10* | Amu Darya | Uzbekistan | 42°13′20 | 60°06′55 | 0.512151 ± 8 | −9.46 | this study |
| *11* | Sefid Rud | Iran | 37°27′55 | 49°56′15 | 0.512302 ± 10 | −6.5 | this study |
| *Sedimentary core* | | | | | | | |
| 12 | G20 (770 cm) | Caspian Sea | 41°32′53 | 51°06′04 | 0.512104 ± 5 | −10.4 | this study |
| 13 | G20 (970 cm) | Caspian Sea | 41°32′53 | 51°06′04 | 0.511192 ± 4 | −14.0 | this study |

core BLKS 98-11 than in core MD04-2754 (Fig. 3e,f). Nevertheless the general pattern is quite similar between 18.0 and ~15.7 cal kyr BP. Smectite is a clearly dominant mineral at the beginning of two sequences until ~17.2 cal kyr BP. Between 17.2 and 15.7 cal kyr BP, when Red Layers are present in the sediment, smectite decreases while illite became dominant, with nevertheless some short-term and significant changes. After that, in core BLKS 98-11, smectite dominates reaching 60%, while in core MD04-2754, smectite and illite broadly are in equal contents. Chlorite and kaolinite present low values. Nevertheless in core MD04-2754, chlorite is clearly higher, and increases towards 15.7 cal kyr BP. Nd isotopic compositions of the recent sediments from Rivers Don, Kuban and Ropotamo present values of −14.3, -9 and −7.3 respectively (Table 2).

## 5. Discussion

### 5.1. Caspian Sea

During the Early Khvalynian transgression, the Caspian Sea water level varied from maximal values of +50 m asl to 0 m asl and several transgression phases are reported (e.g. Leontiev et al., 1977). In the northernmost part of the Caspian Sea of that time, the very characteristic Chocolate Clays were deposited. Today they are found in this now-emerged area, including river terraces in the lower Volga. Despite numerous studies on this subject, some questions still remain open and particularly the exact timing of this transgression, its correlation with climatic events in the northern Hemisphere and the time and origin of the Chocolate Clays deposit.

#### 5.1.1. Sources of detrital material for the Caspian Sea

The main change in taphonomy in core GS20 after ~13.80 cal kyr BP suggests a shift from a period with strong river transport to a period when pollen transport by air was dominant. Although it is impossible to find out which was the most important river reaching the middle basin, it is likely that the Volga played an important role in the supply of the detrital material there. This issue of detrital material origin is discussed below.

*5.1.1.1. Clay minerals.* On the whole, the grain-size of all the sequences in the middle basin and in Chocolate Clays from the river terraces in the lower Volga indicates a dominance of fine-grained particles. Clay fraction mineralogy in the middle basin shows a major change exactly at the same time as a change in pollen transport (Fig. 3a, c line). Before ~13.8 cal kyr BP, clays are essentially composed of illite, with kaolinite as the second mineral, followed by chlorite, while smectite is almost absent. A similar pattern, with a large quantity of illite is recorded for Early Khvalynian Chocolate Clays in the river terraces in the lower Volga from this study (Fig. 3c dots), and from other sites, such as Svetly Yar, Torgun, Novoprivolnoye and until the moraine clay loam in the Upper Volga (Makshaev and Svitoch, 2015). The source of the Chocolate Clays, deposited in the northernmost part of the Caspian Sea during the Early Khvalynian transgression, is obviously in the catchment area of the Volga River in the East European Plain. This suggests that the lower part of the sequence from the middle basin recorded arrivals of Chocolate Clays which were transported by the River Volga to this site and that this supply stopped at ~13.8 cal kyr BP. Above, illite, kaolinite and chlorite decrease and smectite becomes the major clay mineral.

Clay minerals in river, lacustrine and marine sediments reflect the intensity of chemical and physical weathering of their source area (Chamley, 1989). This weathering depends on the lithology, climate and morphology of the considered environment and results in surface soils or sediment. On the East European Plain, climatic oscillations between warm and cold conditions during the Pleistocene resulted in an alternation of subaerial and subaqueous sediments; but alternation of soils and loess reflecting these oscillations predominates. Almost the entire East European Plain area is covered with these Pleistocene deposits. Under cold climates, the production of clays essentially depends on physical weathering and illite is the dominant mineral. Under temperate climate, chemical weathering prevails and smectite appears. Smectite in the dominant clay mineral in paleosols from the East European Plain and is associated with chemical weathering during warm Pleistocene stages (Perederij, 2001). High contents of smectite were reported in the Permian-Triassic red clays of the middle Volga region (Makshaev and Svitoch, 2015), in the northern Caspian Sea sediments of the river terraces in the lower Volga deposited during the Late Khazarian transgression (Tudryn et al., 2013a), and in the northern Black Sea, Kerch Peninsula sediments from the Karangatian transgression (Dodonov et al., 2000), the latter two identified as occurring during the Eemian (Mikulin) interglacial. The supply of the smectite must have been a result of soil erosion during this time. Broadly the same content of smectite and illite were reported from Ukrainian loess horizons (Perederij, 2001) that were deposited as a result of physical weathering during cold and dry climate. After this author, in sediments from the central part of the East European Plain, kaolinite is present but chlorite is quite scarce, but it is known from the lower Don and lower Dniepr (Chamley, 1989).

Considering the above, the dominance of smectite in sediments from the middle basin of the Caspian Sea after ~13.8 cal kyr BP (Fig. 3c line) suggests the erosion of the smectite-bearing rocks from the catchment area of the River Volga. In the Early Khvalynian Chocolate Clays, the absence of smectite rules out this source of detrital material. The large contents of illite indicate the mobilization of the illite-rich area and/or physical weathering in the East European Plain, or the supply from the Baltic Shield area during melting of the SIS. Indeed, Chamley (1989) pointed out an abundant occurrence of illite in Pleistocene clays in Scandinavia, which illustrates a long physical weathering through glacier action. Both East European and Scandinavian sources for Chocolate Clays were already considered (e.g. Leonov et al., 2002; Tudryn et al., 2013a). Nevertheless, as these deposits are very similar to varved clays, Leonov et al. (2002) and Chepalyga (2007) suggested that Chocolate Clays resulted from the formation of mudflows rather than from the melting waters of an ice sheet. According to these authors, meltwater should transport sediments with more scattered grain sizes than those which were deposited. Mudflows could be related to the degradation of permafrost in the periglacial zone, which was widespread in the Volga catchment. Another interpretation for Chocolate Clays deposition suggested by Badyukova (2010) is that the deposition took place in a basin-like periglacial lake or lagoon with varved sediments: fine deposits during winter below ice cover and particles with various grain sizes during summer.

*5.1.1.2. Neodymium isotopic compositions.* To clearly identify the source area of clays delivered into the northern and middle basins of the Caspian Sea, and thus to ascertain their origin either from East European Plain or Baltic Shield area meltwater-induced deposition, we measured the neodymium isotopic composition ($\varepsilon_{Nd}$) on fine-grained sediments from three key locations with regard to clay mineral changes. Old cratonic source regions typically exhibit lower $\varepsilon_{Nd}$ values than younger rock formations. According to geophysical and structural reconstructions, the East European Craton that consists of three segments (Fennoscandia, Sarmatia and Volgo-Uralia) is buried under the Upper Proterozoic and Phanerozoic rocks. Precambrian rocks outcrop in the Baltic and Ukrainian Shields (Bibikova et al., 2009). Recently, Toucanne et al. (2015) showed that very low $\varepsilon_{Nd}$ values (between $-23.3$ and $-17.6$) characterize sediments transported by rivers (Kiiminkijoki, Neva) draining the eastern part of the Precambrian Baltic Shield; i.e. one of the oldest geological formations in Europe (Bogdanova et al., 2008). Slightly higher Nd isotopic signatures, between $-16.4$ and $-14.1$, characterize the sediment carried by rivers draining the south-east of the Baltic catchment area (Rivers Narva, Gauja, Daugava, Neman and Vistula, North European Plain, southern side of the SIS during the LGM). These values vary from $-16.5$ to $-13.7$ for LGM glacigenic sediment collected alongside the SIS south margin in Germany and Poland. This highlights both the input of Baltic Shield material in the North European Plain by the southern SIS margins (Kjær et al., 2003), and the westward transport of sediment from Poland and the Baltic States in continuous, extensive ice-marginal valleys (Krzyszkowski et al., 1999). Additional information on $\varepsilon_{Nd}$ for the East European Plain are available for some rivers supplying the Caspian and Black Seas today, with a value of $\varepsilon_{Nd}$ $-12$ for sediments from the lower Volga, -14 for the Upper/middle Dniepr, -9 for the lower Danube (Soulet et al., 2013) and $-12.6$ for Desna (Freslon et al., 2014) (Fig. 1). Complementary data from this study provide values of $-14$ for the lower Don, -9 for the Kuban (Rivers Don and Kuban flowing into the Azov Sea), -7.3 for River Ropotamo (southwestern Black Sea, Bulgarian coast), and $-6.5$ and $-9.5$ for Asian rivers Sefid Rud and Amu Darya respectively (Table 2, Fig. 1). These data clearly indicate different neodymium isotopic compositions and thus different sediment sources.

Early Khvalynian Chocolate Clays, from river terraces in the lower Volga at Srednaya Akhtuba, consist essentially of illite (Fig. 3c dots), and the sample measured for $\varepsilon_{Nd}$, shows a very low value of $-17.7$ (Fig. 3d red star). This clearly identifies its old source being in the Baltic Shield area, implying the melting of the SIS and transport of detrital material into the Caspian Sea by fluvioglacial waters via the River Volga. The lower part of sediment core GS20 from the middle basin of the Caspian Sea is rich in illite in the same way as the Chocolate Clays from the river terraces of the lower Volga (Fig. 3c red line between ~14.6 and 13.8 cal kyr BP). The sample from this part of the sequence displays higher $\varepsilon_{Nd}$ value ($-14.0$); nevertheless it always remains as low as for sediments related to the Baltic Shield area (Soulet et al., 2013; Toucanne et al., 2015). This allows the clear identification of this sediment as being deposited during the Early Khvalynian transgression, as is the case for Chocolate Clays on river terraces in the lower Volga. The measurement obtained from the sediment, from the middle basin where smectite was dominant (Fig. 3c line above ~13.8 cal kyr BP), presents $\varepsilon_{Nd}$ value of $-10.4$.

Change in clay mineralogy and in measured values of $\varepsilon_{Nd}$, as well as change in the pollen signature, highlights the change of the detrital material source area here. The supply from the SIS was either too weak to transport the detrital material until the middle basin of the Caspian Sea or was stopped. This suggests the modification of the northern River Volga catchment area at ~13.8 cal kyr BP and a sufficient retreat of the south margin of the SIS to the North; so that the meltwater was no longer transported into the Caspian Sea. After that, the East European Plain area, rich in smectite, became the dominant provider of detrital material.

*5.1.2. Chronology*

The identification of the Early Khvalynian sediments in the middle basin of the Caspian Sea shows the extent of the SIS impact to the south and the Volga River capacity to transport glacigenic material. Core GS20 has a continuous record from ~14.6 cal kyr BP, and the upper limit of this impact is clearly identified at ~13.8 cal kyr BP, when illite decreases and smectite becomes dominant. $^{14}$C dates, obtained on shells collected in the Chocolate Clays from river terraces in the lower Volga studied here, show ages from ~19 to ~13.9 cal kyr BP (Fig. 3d black crosses, Table 1). A ~20 cal kyr BP $^{14}$Cage estimate for a sample of non-identified organic matter shows that meltwater was supplied into the Caspian Sea, including its middle basin, during the deglaciation until ~13.8 cal kyr BP, and possibly at least from the LGM. These data, and these of Russian scientists (Makshaev et al., 2015; Makshaev and Svitoch, 2015), provide a clear frame for the timing of the Chocolate Clays deposition during the Early Khvalynian transgression, when the water level reached at least +20–0 m asl (sites studied here), and its ending phase at ~13.8 cal kyr BP. This timing is in very good agreement with that recently published by Arslanov et al. (2015). Indeed, these authors obtained ages between 16 and 14 cal kyr BP for transgressive stages of the Early Khvalynian basin with sea levels of +35 and + 22 m asl. These authors point out also that the maximum stage of +50 m asl has remained undated until now.

## 5.2. Sources of detrital material for the Black Sea

On the whole, smectite and illite alternately dominate the clay fraction of the sediment. Their content in core BLKS 98-11, that was collected in the axis of the Danube River on a slope of the platform constructed by sediment supplied by the Danube and Dniepr Rivers, is much higher than in core MD04-2754, which was collected close to the western Turkish shoreline of the Black Sea. This indicates that the main sources of smectite and illite must have been in the catchment area of the Danube or/and Dniepr, and that these minerals must have been transported by these northern rivers.

*5.2.1. Red Layers 17.2–15.7 cal kyr BP*

In the Black Sea sediments, the two cores BLKS 98-11 and MD04-2754 show the dominance of illite in the Red Layers (Fig. 3e,f), as it is the case for the Chocolate Clays in the Caspian Sea. On Fig. 3g, results of the $\varepsilon_{Nd}$ analyses for core MD04-2790 obtained by Soulet et al. (2013) are also presented. This core was collected from 352 m depth, in the same area as core BLKS 98-11 (500 m depth). The very low values of $\varepsilon_{Nd}$, between −18.7 and −12.2, have been recorded for the Red Layers, which were deposited in four steps. This is expressed by changes of neodymium isotopic signatures and by changes in clay mineralogy (Fig. 3e, f and g). Soulet et al. (2013) interpreted low $\varepsilon_{Nd}$ values as being a result of the release of meltwater originating from a proglacial Lake Disna linked to the SIS, and transported into the Black Sea by the River Dniepr via the River Berezina (Fig. 1). This interpretation does not take into account the geological context of the River Dniepr catchment area. Indeed, its catchment area includes partly the Ukrainian Shield, and that could explain low $\varepsilon_{Nd}$ values obtained by Soulet and collaborators (2013) for the Red Layers in core MD04-2790 and for sample of modern sediment from the Upper/middle Dniepr ($\varepsilon_{Nd}$ value of −14).

Our study shows that the Red Layers deposited in the Black Sea and the Chocolate Clays deposited in the Caspian Sea between actual river terraces in the lower Volga and its middle basin, are the same kind of material. That confirms the interpretation concerning the origin of the Red Layers in the Black Sea (linked to the SIS meltwater) proposed by Soulet et al. (2013). Indeed, no connection between the catchment area of the River Volga and Ukrainian Shield exists, and the low values of $\varepsilon_{Nd}$ in the Caspian Sea Early Khvalynian sediments can only be explained by their origin close to the Baltic Shield and in relation with the SIS activity.

*5.2.2. Sediments between 18.0 and 17.2 and between 15.7 and 12.0 cal kyr BP*

Before the appearance of the Red Layers at 17.2 cal kyr BP, the neodymium isotopic compositions recorded in core MD04-2790 of the Black Sea, display values between −12 and −11 (Fig. 3g, data after Soulet et al., 2013). The same values are recovered after the Red Layers deposition at 15.7 cal kyr BP. Moreover from ~14.0 cal kyr BP onwards, they increase above −11. The clay mineralogy for these two intervals recorded on core BLKS 98-11 is largely dominated by smectite that decreases after ~14.0 cal kyr BP but is still dominant until 12.0 cal kyr BP (Fig. 3f). In core MD04-2754, the smectite and illite show the same pattern before the Red Layers deposition. After their deposition, broadly equal proportions of smectite and illite are recorded (Fig. 3e). It should be noted that higher contents of chlorite are present in this core on the whole.

As observed above, the content of smectite is much higher in core BLKS 98-11 (collected on a slope of the platform, in the near vicinity of the Danube and Dniepr mouths), than in core MD04-2754 (collected farther away from river mouths). This suggests that the principal source of smectite must be related to the activity of the Danube or Dniepr. Such European origin of the smectite in the Black Sea sediments is generally not considered. Indeed, Stoffers and Müller (1972) attributed smectite to an Anatolian origin where it is common (e.g. Tudryn et al., 2013b), and illite to an European origin, and this interpretation of clay minerals origin in the Black Sea sediments has been accepted so far (e.g. Major et al., 2002). In core MD04-2754, clay minerals changes until 15.7 cal kyr BP are similar to these described for core BLKS 98-11 (Fig. 3e,f), indicating the same main source area. After the Red Layers deposition, smectite increases while illite decreases. They present broadly similar contents between ~15.0 and 12.0 cal kyr BP. Contents of chlorite are higher than before and than in core BLKS 98-11. This difference indicates the relative decrease of the previous source impact on this site, and the increased influence of another one: a southwestern or southern source area, probably Bulgarian or Anatolian, where Stoffers and Müller (1972) reported higher contents of chlorite.

*5.3. A Ponto-Caspian trap and the SIS deglaciation*

Our work shows that during the last deglaciation, the Ponto-Caspian basin collected meltwater and fine-grained sediment transported from the southern margin of the SIS via the Dniepr and Volga Rivers. It resulted in the deposition of characteristic red-brownish/chocolate coloured illite-rich sediments that originated from Baltic Shield area. After that, smectite-rich sediments were deposited in the Caspian and Black Seas. This common general evolution for the two seas was nevertheless differentiated over time due to the specificities of their catchment areas and to the movement of the southern limit of the SIS.

The catchment area of the Black Sea reaches Northern Belarus, Southern Lithuania and Latvia through the Dniepr and Berezina basins. The deglaciation started there before 18.3 cal kyr BP with the recession of the Gruda phase ice sheet (Rinterknecht et al., 2008; Hughes et al., 2015) (Fig. 3h-2). According to some authors, Baltija, the youngest phase of the ice margin readvance, finished at ~14 cal kyr BP and the recession steps were definitely terminated at ~13.3 cal kyr BP (Rinterknecht et al., 2008; Marks, 2015). Meltwater and the detrital material from this area was only partly supplied into the Black Sea between 17.2 and 15.7 cal kyr BP (Soulet et al., 2013; this study)(Fig. 3e,f,g). Another route for meltwater was towards the North Atlantic via ice-marginal valleys from the Baltic lowlands and the Channel River (Fig. 3h-1) dated between 18.2 and 16.7 cal kyr BP (Toucanne et al., 2015). Further ice-sheet readvance during the Baltija phase did not reach the northern limit of the Dniepr catchment area to produce the meltwater evacuation into the Black Sea during its recession.

The southern limit of the SIS margin in Russia cuts the actual catchment of the River Volga in the Lake Beloye, and probably even today's reservoir Rybinsk area (Svendsen et al., 2004; Hughes et al., 2015; Stroeven et al., 2015), both are to the south of Lake Onega (Fig. 1). The maximal extend of the SIS there was attained around 20–18 kyr (Svendsen et al., 2004; Hughes et al., 2015), and after that at least four advances were identified (Fig. 3h-3). According to Svendsen et al. (2004), only the last one (the Neva, ~13 cal kyr BP) did not reach the River Volga catchment area; the Luga phase, i.e. the previous phase, began its recession after ~14.2 cal yr BP. Our study shows that this deglaciation timing from the LGM until ~14 cal kyr BP corresponds exactly with the supply of the Chocolate Clays (via River Volga) into the Caspian Sea as far as at least its middle basin during the Early Khvalynian transgression, and with its end recorded at ~13.8 cal kyr BP. Recent publications proposed that the SIS southeastern margin retreated to the north of Lake Onega before 14 cal kyr BP (Stroeven et al., 2015; Hughes et al., 2015). However our data indicate that it must have occurred slightly later, since the Caspian Sea was fed by meltwater until ~13.8 cal kyr BP.

As pointed out by Arslanov et al. (2015), the beginning of the Early Khvalynian transgression remains to be assessed. Indeed, according to radiocarbon dating on sediments collected from northern, shallow water basin of the Caspian Sea, it started at ~34 cal kyr BP (Bezrodnykh et al., 2015), or even possibly at ~56 kyr BP (Sorokin et al., 2014). These sediments present the Early Khvalynian sequence of several meters thick and offer the possibility for future precise identification of Chocolate Clays (as those deposited in actual river terraces in the lower Volga and in the middle Caspian basin) there. According to Bezrodnykh et al. (2004, 2015), their upper part (8–10 m thick), is composed of clays with variable-thickness sand intercalations and was deposited at depths of approximately 100 m. $^{14}C$ ages on mollusk shells display values such as ~23.8 and ~21.6 cal kyr BP. These ages are older than those obtained on mollusk shells and on organic matter from the Chocolate Clays in river terraces in the lower Volga (Leonov et al., 2002; Tudryn et al., 2013a; Makshaev and Svitoch, 2015; this study) but still correspond to LGM. In the Southern basin of the Caspian Sea, Late Pleistocene reddish sediments were reported and suggested to correspond to Chocolate Clays (Kroonenberg et al., 2010; Kakroodi et al., 2015). Further clay minerals and especially neodymium isotopes studies should allow the clear identification of this material as transported locally or supplied from the north until the southern basin of the Caspian Sea. Clay minerals and neodymium isotopes studies should also allow the identification of the nature and origin of Chocolate Clays deposited in the actual river valley in the lower Ural, described by Makshaev and Svitoch (2015).

Our data show different timings in the meltwater supply into two major areas of the Ponto-Caspian basin. They inform indirectly on the southern SIS margin extent in the East European Plain and on meltwater evacuation routes. In the western part the East European Plain, both a westward release into the North Atlantic (between 18.2 and 16.7 cal kyr BP; Toucanne et al., 2015) and a southward one into the Black Sea (between 17.2 and 15.7 cal kyr BP) occurred (Soulet et al., 2013; this study). For the eastern part of the plain, apart from a northern direction into the Barents Sea (Svendsen et al., 2004), only a southern direction into the Caspian Sea was possible, that led to the Early Khvalynian transgressive stage(s) from LGM until ~13.8 cal kyr BP (this study). According to Arslanov et al. (2015), the Early Khvalynian transgressive stages between 16 and 14 cal kyr BP reached the water level of ~22–~35 m asl, and that resulted in the Caspian Sea water overflowing into the Black Sea through the Kuma-Manych Strait (22 m asl) during this time and even until ~12.8 cal kyr BP, when water level dropped so that it could not reach Kuma-Manych Strait. Our data from the Caspian Sea confirm the possibility of such timing. Nevertheless the cores studied here from the western Black Sea area show that clay minerals originating from the SIS margin were deposited between 17.2 and 15.7 cal kyr BP and that they were transported by the River Dniepr. Cores were thus probably collected too far from Kuma-Manych Strait to record the overflow from the Caspian Sea through clay mineralogy after 16 cal kyr BP, or the overflow could happen concurrently with meltwater arriving into the Black Sea by the Dniepr River.

## 6. Conclusions

This work allowed establishment of the following conclusions:

The Early Khvalynian Chocolate Clays from the lower Volga and middle basin of the Caspian Sea consist essentially of illite. Very low $\varepsilon_{Nd}$ values for this sediment clearly identify its 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.

The Early Khvalynian transgressive stage(s) leading to the Chocolate Clays deposition in the lower Volga and middle basin of the Caspian Sea took place during the deglaciation and possibly from the LGM. As recorded by sediments from the Caspian Sea (values of $\varepsilon_{Nd}$, clay mineralogy and pollen signature), the Chocolate Clays deposition finished at ~13.8 cal kyr BP. At that time, the southeastern margin of the SIS has retreated back so far northward that the meltwater was no longer transported into the Caspian Sea.

The cessation of fluvioglacial supply into the Caspian Sea resulted in the modification of the northern part of the River Volga catchment area and a proportionally increased influence from the drainage of East European Plains area, its part that is rich in smectite. Thus the latter became the dominant clay mineral in sediments after ~13.8 cal kyr BP.

Our results show that illite is the dominant clay mineral in the Red Layers deposited in the Black Sea between ca. 17.2 and 15.7 cal kyr P, that these Red Layers and the Chocolate Clays from the Caspian Sea present the same kind of sediment, and confirm that Red Layers originated from the Baltic Shield area and were transported into the Black Sea from the southern SIS margin during the deglaciation by Dniepr River, as proposed Soulet et al. (2013).

Before the deposition of the Red Layers in the Black Sea (between ca. 18 and 17.2 cal kyr BP) and after the deposition of the Red Layers/Chocolate Clays in both seas (from ~15.7 in the Black Sea and from ~13.8 cal kyr BP in the Caspian Sea), smectite became the dominant clay mineral until 12 cal kyr BP. The East European Plain is identified as the source for smectite deposited in the Caspian Sea sediments. In the Black Sea, smectite originated either from the East European Plain or from the Danube River catchment area. This is an important result since previous studies considered smectite as only being of Anatolian origin.

Our investigation shows that during the last deglaciation the Ponto-Caspian basin collected meltwater and acted as a trap for fine-grained sediment transported from the southeastern margin of the SIS via the Dniepr and Volga rivers. In the eastern part of the East European Plain, the supply of meltwater from the SIS margin into the Caspian Sea took place during the LGM and the subsequent deglaciation. That led to the Early Khvalynian transgressive stage(s) and so-called Chocolate Clays deposition on river terraces in the lower Volga and until at least the middle basin of the Caspian Sea. The meltwater supply stopped at ~13.8 cal kyr BP; this indicates that the southeastern SIS margin retreated so far north that the meltwater was no longer transported into the Caspian Sea. In the western part the East European Plain, both a westward release of meltwater into the North Atlantic (from ca. 20 to 16.7 cal kyr BP; Toucanne et al., 2015) and a southward one into the Black Sea (between 17.2 and 15.7 cal kyr BP) occurred (Soulet et al., 2013; this study).

## Acknowledgements

This work is part of the French INSU-CNRS-DYTEC Program and of the European project “Understanding the Caspian Sea Erratic Fluctuations” (EU Contract 15-CT96-0112) for Caspian Sea area investigations. Jean-Charles Fontes, Françoise Gasse and Piotr Tucholka were the architects of the Caspian Sea project, and Françoise was its leader. The team included scientists from France, Russia, Turkmenistan, Azerbaijan, Italy and Belgium. For the Black Sea, this work is a contribution to the French–Romanian BLASON Programme in the north-western part of the Black Sea, and to the “Assessment of the Black Sea Sedimentary System Since the Last Glacial Extreme” (ASSEMBLAGE) project funded by the European Commission Grant EVK3-CT-2002-00090. Our gratitude goes to G. Lericolais, project leader, and to French, Romanian, Russian, Turkmenian, Azerbaijanian, Italian and Belgian teams working with us on these projects for productive discussions and support. We thank especially E. Spiridonova, M.P. Antipov, V. Lavrushin, V. Kharchenko, F. Chalié (they sampled the Chocolate Clays with Yu. A. Lavrushin and A. Tudryn from river terraces in the lower Volga in Srednaya Akhtuba, Kolobovka and Tsagan-Aman during a field trip in September 1997), F. Guichard, P.J. Giannesini, D. Badaut-Trauth, N. Panin, C. Strechie-Sliwinski, P.N. Kuprin, H. Zeyen and Master students, who actively contributed to this work. The present results would not have been possible without the support of the numerous European institutions, especially IFREMER-Genavir and CEA (France), GeoEcoMar, Bucharest (Romania), IAEA (Vienna), Russian Academy of Sciences, and the Russian Navy, that latter allowed us to use a military ship during the Caspian Sea expedition. We are grateful to G. Soulet and T. Pinchuk, they collected sediments from Rivers Ropotamo, Kuban and Don for $\varepsilon_{Nd}$ analyses. P. Collins and T. Hoyle (Brunel University) have kindly checked the English of the manuscript. The authors are grateful to the two anonymous reviewers for their comments and information that allowed an improvement of the final version.

## References

Aksu, A.E., Hiscott, R.N., Yasar, D., Isler, F.I., Marsh, S., 2002. Seismic stratigraphy of Late Quaternary deposits from the southwestern Black Sea shelf: evidence for non-catastrophic variations in sea-level during the last ~10 000 yr. Mar. Geol. 190, 61–94.

Arslanov, Kh A., Yanina, T.A., Chepalyga, A.L., Svitoch, A.A., Makshaev, R.R., Maksimov, F.E., Chernov, S.B., Tertychniy, N.I., Starikova, A.A., 2015. On the age of the Khvalynian deposits of the Caspian Sea coasts according to 14C and 230Th/234U methods. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2015.05.067.

Badertscher, S., Fleitmann, D., Cheng, H., Edwards, R.L., Göktürk, O.M., Zumbühl, A., Leuenberger, M., Tüysüz, O., 2011. Pleistocene water intrusions from the mediterranean and Caspian seas into the Black Sea. Nat. Geosci. 4, 236–239.

Badyukova, E.N., 2007. Age of Khvalynian transgression in the Caspian Sea region. Oceanology 47 (3), 400–405.

Badyukova, E.N., 2010. Evolution of the northern Caspian Sea region and the Volga delta in the late Pleistocene–Holocene. Oceanology 50 (No. 6), 953–960.

Bahr, A., Lamy, F., Arz, H.W., Kuhlmann, H., Wefer, G., 2005. Late glacial to Holocene climate and sedimentation history in the NW Black Sea. Mar. Geol. 214, 309–322.

Bahr, A., Arz, H.W., Lamy, F., Wefer, G., 2006. Late glacial to Holocene paleoenvironmental evolution of the Black Sea, reconstructed with stable oxygen isotope records obtained on ostracod shells. Earth Planet. Sci. Lett. 241, 863–875.

Bahr, A., Lamy, F., Arz, H.W., Major, C., Kwiecien, O., Wefer, G., 2008. Abrupt changes of temperature and water chemistry in the late Pleistocene and early Holocene Black Sea. Geochem. Geophys. Geosystems 9, Q01004. http://dx.doi.org/10.1029/2007GC001683.

Bayon, G., German, C.R., Boella, R.M., Mitton, J.A., Taylor, R.N., Nesbitt, R.W., 2002. An improved method for extracting marine sediment fractions and its application to Sr and Nd isotopic analysis. Chem. Geol. 187, 179–199.

Bayon, G., Barrat, J.-A., Etoubleau, J., Benoit, M., Revillon, S., Bollinger, C., 2009. Determination of rare earth elements, Sc, Y, Zr, Ba, Hf and Th in geological samples by ICPMS after Tm addition and alkaline fusion. Geostand. Geoanal. Res. 33, 51–62.

Bayon, G., Dennielou, B., Etoubleau, J., Ponzevera, E., Toucanne, S., Bermell, S., 2012. Intensifying weathering and land use in iron age central Africa. Science 335, 1219–1222.

Bezrodnykh, Yu, Romanyuk, B., Deliya, S., Magomedov, R., Sorokin, V., Parunin, O., Babak, E., 2004. Biostratigraphy and structure of the Upper Quaternary deposits and some paleogeographic features of the north Caspian region. Stratigr. Geol. Correl. 12 (1), 102–111 (in Russian).

Bezrodnykh, YuP., Deliya, B.P., Romanyuk, B., Sorokin, V.M., Yanina, T.A., 2015. New data on the upper Quaternary Stratigraphy of the north Caspian Sea. Dokl. Earth Sci. 462 (1), 479–483.

Bibikova, E.V., Bogdanova, S.V., Postnikov, A.V., Popova, L.P., Kirnozova, T.I., Fugzan, M.M., Glushchenko, V.V., 2009. Sarmatia–Volgo-Uralia Junction zone: isotopic–Geochronologic characteristic of supracrustal rocks and Granitoids. Stratigr. Geol. Correl. 17 (6), 561–573.

Bogdanova, S.V., Bingen, B., Gorbatschev, R., Kheraskova, T.N., Klozov, V.I., Puchkov, V.N., Volozh, Y.A., 2008. the East european Craton (Baltica) before and during the assembly of Rodinia. Precambrian Res. 160 (1–2), 23–45.

Bogutskiy, A.B., Velichko, A.A., Nechaev, V.P., 1975. Paleocryogenic processes on the western Ukraine in the upper and middle Pleistocene. In: Velichko, A.A. (Ed.), Problems of the Paleogeography of the Loessic and Peryglacial Regions. Institute of Geography of USSR Academy Sciences Press, Moscow (in Russian), pp. 80–89.

Bolikhovskaya, N.S., Kasimov, N.S., 2010. The evolution of climate and landscapes of the lower Volga region during the Holocene. Geogr. Environ. Sustain. 2 (3), 78–97. Available at: http://www.geogr.msu.ru/GESJournal/.

Boomer, I., Von Grafenstein, U., Guichard, F., Bieda, S., 2005. Modern and Holocene sublittoral ostracod assemblages (Crustacea) from the Caspian Sea: a unique brackish deep-water environment. Palaeogeogr. Palaeoclimatol. Palaeoecol. 225, 173–186.

Chalié, F., Escudié, A.S., Badaut-Trauth, D., Blanc, G., Blans-Valleron, M.-M., Brigault, S., Desprairies, A., Ferronsky, V.I., Giannesini, P.-J., Gibert, E., Guichard, F., Jelinowska, A., Massault, M., Mélières, F., Tribovillard, N., Tucholka, P., Gasse, F., 1997. The glacial-post glacial transition in the southern Caspian Sea. C. R. Acad. Sci. Paris, IIa, t 324, 309–316.

Chamley, H., 1989. Clay Sedimentology. Springer, New York, 623 pp.

Chepalyga, A.L., 2003. Late glacial great flood in the Black Sea and Caspian Sea. In: Annual Meeting and Exposition, Seattle, USA, November 2-5, 460 pp.

Chepalyga, A.L., 2005. Epoch of extreme flooding as a prototype of the Noachian flood. Ponto-Caspian basins and northern dimension. In: Proceedings of the IV All-Russia Conference on the Quaternary Studies. Geoprint Publishers, Syktyvkar, pp. 445–447 (in Russian).

Chepalyga, A.L., 2007. Late Glacial great flood in the Ponto-Caspian basin. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 119–148.

Constantinescu, A.M., Toucanne, S., Dennielou, B., Jorry, S.J., Mulder, T., Lericolais, G., 2015. Evolution of the Danube deep-sea fan since the last glacial maximum: new insights into Black Sea water-level fluctuations. Mar. Geol. 367, 50–68.

Deuser, W.G., 1974. Evolution of anoxic conditions in Black Sea during Holocene. AAPG Mem. 20, 133–136.

Dodonov, A.E., Chepalyga, A.L., Mihailescu, C.D., Zhou, L.P., Markova, A.K., Trubikhin, V.M., Simakova, A.N., Konikov, E.G., 2000. Last-interglacial record from central Asia to the northern Black Sea shoreline: stratigraphy and correlation. Neth. J. Geosci. 79, 303–311.

Dolukhanov, P.M., Chepalyga, A.L., Shkatova, V.K., Lavrentiev, N.V., 2009. Late Quaternary Caspian: sea-levels, environments and human settlements. Open Geogr. J. 2, 1–15.

Dumont, H.J., 1998. The Caspian Lake: history, biota, structure, and function. Limnol. Oceanogr. 43 (1), 44–52.

Dzierżek, J., Zreda, M., 2007. Timing and style of deglaciation of northeastern Poland from cosmogenic 36Cl dating of glacial and glaciofluvial deposits. Geol. Q. 51 (2), 203–216.

Forte, A.M., Cowgill, E., 2013. Late Cenozoic base-level variations of the Caspian Sea: a review of its history and proposed driving mechanisms. Paleogeogr. Palaeoclimatol. Palaeoecol. 386, 392–407.

Freslon, N., Bayon, G., Toucanne, S., Bermell, S., Bollinger, C., Chéron, S., Etoubleau, J., Germain, Y., Khripounoff, A., Ponzevera, E., Rouget, M.-L., 2014. Rare earth elements and neodymium isotopes in sedimentary organic matter. Geochim. Cosmochim. Acta 140, 177–198.

Goldstein, S.J., Jacobsen, S.B., 1988. Nd and Sr isotopic systematics of river-water suspended material: implications for crustal evolution. Earth Planet. Sci. Lett. 87, 249–265.

Grosswald, M.G., 1993. Extent and melting history of the Late Weichselian ice sheet, the Barents-Kara continental margin. In: Peltier, W.R. (Ed.), Ice in the Climate System, NATO ASI Series, vol. 1.12. Springer-Verlag, Berlin Heidelberg, pp. 1–20.

Gürbüz, A., Leroy, S.A.G., 2010. Science versus myth: was there a connection between the Marmara Sea and lake sapanca? J. Quat. Sci. 25 (2), 103–114.

Hay, B.J., Arthur, M.A., Dean, W.E., Neff, E.D., Honjo, S., 1991. Sediment deposition in the Late Holocene abyssal Black Sea with climatic and chronological implications. Deep-Sea Res. 38, S1211–S1235.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Marret, F., Abrajano, T., Kaminski, M.A., Evans, J., Cakiroglu, A.I., Yasar, D., 2007a. A gradual drowning on the southwestern Black Sea shelf: evidence from a progressive rather than abrupt Holocene reconnection with the eastern Mediterranean Sea through the Marmara Sea Gateway. Quat. Int. 167–168, 19–34.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Kaminski, M.A., Abrajano, T., Yasar, D., Rochon, A., 2007b. The Marmara Gateway since ~16 ka: non-catastrophic causes of paleoceanographic events in the Black Sea at 8.4 kyr and 7.15 kyr. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, The Netherlands, pp. 89–117. The Black Sea Flood Question.

Holtzapffel, T., 1985. Les minéraux argileux: préparation, analyse, diffractométrique et détermination, vol. 12. Soc Geol Nord Publ, p. 136.

Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2015. The Last Eurasian Ice Sheets – a Chronological Database and Time-slice Reconstruction. DATED-1. Boreas. 10.1111/bor.12142, ISSN 0300–9483.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. Earth Planet. Sci. Lett. 50, 139–155.

Jelinowska, A., Tucholka, P., Guichard, F., Lefèvre, I., Badaut-Trauth, D., Chalié, F., Gasse, F., Tribovillard, N., Desprairies, A., 1998. Mineral magnetic study of late Quaternary South Caspian Sea sediments, palaeoenvironmental implications. Geophys. J. Int. 133, 499–509.

Jelinowska, A., Tucholka, P., Badaut-Trauth, D., 1999. Magnetic mineral variations of South Caspian Sea sediments at laminae scale. Phys. Chem. Earth (A) 24, 823–828.

Jones, G.J., Gagnon, A.R., 1994. Radiocarbon chronology of Black Sea sediments. Deep-Sea Res. I 41 (3), 531–557.

Kakroodi, A.A., Leroy, S.A.G., Kroonenberg, S.B., Lahijani, H.A.K., Alimohammadian, H., Boomer, I., Goorabi, A., 2015. Late Pleistocene and Holocene sea-level change and coastal paleoenvironment evolution along the Iranian Caspian Shore. Mar. Geol. 361, 111–125.

Kjær, K.H., Houmark-Nielsen, M., Richardt, N., 2003. Ice-fow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian Ice Sheet: signature of palaeo-ice streams. Boreas 32, 130–148.

Kroonenberg, S.B., Rusakov, G.V., Svitoch, A.A., 1997. The wandering of the Volga delta: a response to rapid Caspian Sea-level change. Sediment. Geol. 107, 189–209.

Kroonenberg, S.B., Aliyeva, E., de Baptist, M., Hoogendoorn, R.M., Huseynov, D., Huseynov, R., Kasimov, N.S., Lychagin, M., Missiaen, T., De Mol, L., Popescu, S., Suc, J.P., 2010. The Caspian Region, Moscow. In: Pleistocene Connection and

Holocene Separation of the Caspian and Black Seas: Data from the Modern Kura Delta, Azerbaijan, International Conference, pp. 17–20.
Krzyszkowski, D., Gizler, H., Jodlowski, J., Dobosz, T., 1999. Quaternary geology and geomorphology in the zone of the maximum extent of the Weichselian ice sheet between Slawa Slaska and Swieciechowa, western Poland. Quat. Stud. Pol. 16, 47–66.
Kwiecien, O., Arz, H.W., Lamy, F., Wulf, S., Bahr, A., Röhl, U., Hang, G.H., 2008. Estimated reservoir ages of the Black Sea since the last glacial. Radiocarbon 50 (1), 99–118.
Lavrushin, YuA., Spiridonova, E.A., Tudryn, A., Chalié, F., Antipov, M.P., Kuralenko, N.P., Kurina, E.E., Tucholka, P., 2014. The Caspian Sea: hydrological events of the late Quaternary,. Bull. Comm. Study Quat. 73, 19–51 (in Russian).
Leonov, Y.G., Lavrushin, Y.A., Antipov, M.P., Spiridonova, E.A., Kuz'min, Y.V., Jull, E.J.T., Burr, G.S., Jelinowska, A., Chalié, F., 2002. New age data on sediments of the transgressive phase of the Early Khvalyn transgression of the Caspian Sea. Dokl. Earth Sci. 386 (2), 748–751.
Leontiev, O.K., Maev, E.G., Rychagov, G.I., 1977. Geomorphology of the Coasts and Bottom of the Caspian Sea. Moscow State University, Moscow, pp. 1e180 (in Russian).
Lericolais, G., Maltese, L., Assemblage partners, 2005. Assemblage Deliverable 12: Lithological Logs, Digital Photographs, Gamma and Magnetic Susceptibility Logs: European Community, Energy, Environment and Sustainable Development, Deliverables of the EVK3-CT-2002–00090 European Project.
Lericolais, G., Bourget, J., Popescu, I., Jermannaud, P., Mulder, T., Jorry, S., Panin, N., 2013. Late Quaternary deep-sea sedimentation in the western Black Sea: new insights from recent coring and seismic data in the deep basin. Glob. Planet. Chang. 103, 232–247.
Leroy, S.A.G., Lahijani, H.A.K., Reyss, J.-L., Chalié, F., Haghani, S., Shah-Hosseini, M., Shahkarami, S., Tudryn, A., Arpe, K., Habibi, P., Nasrollahzadeh, H.S., Makhlough, A., 2013a. A two-step expansion of the dinocyst *Lingulodinium machaerophorum* in the Caspian Sea: the role of changing environment. Quat. Sci. Rev. 77, 31–45.
Leroy, S.A.G., Tudryn, A., Chalié, F., López-Merino, L., Gasse, F., 2013b. From the Allerød to the mid-Holocene: palynological evidence from the south basin of the Caspian Sea. Quat. Sci. Rev. 78, 77–97.
Leroy, S.A.G., Lopez-Merino, L., Tudryn, A., Chalié, F., Gasse, F., 2014. Late Pleistocene and Holocene palaeoenvironments in and around the middle Caspian basin as reconstructed from a deep-sea core. Quat. Sci. Rev. 101, 91–110.
Liu, Z., Colin, C., Trentesaux, A., Blamart, D., Bassinot, F., Siani, G., Sicre, M.A., 2004. Erosional history of the eastern Tibetan Plateau over past 190 kyr: clay mineralogical investigations from the southwestern South China Sea. Mar. Geol. 209, 1–18.
Liu, Z., Colin, C., Huang, W., Le, K.P., Tong, S., Chen, Z., Trentesaux, A., 2007. Climatic and tectonic controls on weathering in south China and Indochina Peninsula: clay mineralogical and geochemical investigations from the Pearl, Red, and Mekong drainage basins. Geochem. Geophys., Geosystems 8, Q05005. http://dx.doi.org/10.1029/2006GC001490.
Liu, Z., Tuo, S., Colin, C., Liu, J.T., Huang, C.Y., Selvaraj, K., Chen, C.T.A., Zhao, Y., Siringan, F.P., Boulay, S., Chen, Z., 2008. Detrital fine-grained sediment contribution from Taiwan to the northern South China Sea and its relation to regional ocean circulation. Mar. Geol. 255, 149–155.
Major, C., Ryan, W.B.F., Lericolais, G., Hajdas, I., 2002. Constraints on Black Sea outflow to the Sea of Marmara during the last glacial–interglacial transition. Mar. Geol. 190, 19–34.
Makshaev, R.R., Svitoch, A.A., 2015. Chocolate clays of the northern Caspian Sea region: distribution, structure, and origin. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2015.07.018.
Makshaev, R.R., Svitoch, A.A., Yanina, T.A., Badyukova, E.N., Khomchenko, D.S., Oshchepkov, G.V., 2015. In: IGCP 610 Third Plenary Conference and Field Trip, Astrakhan, Russia, 22–30 Septembre 2015.
Mamedov, A.V., 1997. The late Pleistocene-Holocene history of the Caspian Sea. Quat. Int. 41/42, 161–166.
Mangerud, J., Jakobsson, J., Alexanderson, H., Astakhov, V., Clarke, G.K.C., Henriksen, M., Hjort, C., Krinner, G., Lunkka, J.-P., Möller, P., Murray, A., Nikolskaya, O., Saarnisto, M., Svendsen, J.I., 2004. Ice-dammed lakes and rerouting of the drainage of northern Eurasia during the last glaciation. Extent of the Last Glacial Maximum in Eurasia. Quat. Sci. Rev. 23, 1313–1332.
Marks, L., 2015. Last deglaciation of northern continental Europe, Cuadernos de Investigation Geografica. Univ. la Rioja 41 (2), 279–293.
Nicholas, W.A., Chivas, A.R., Murray-Wallace, C.V., Fink, D., 2011. Prompt transgression and gradual salinisation of the Black Sea during the early Holocene constrained by amino acid racemization and radiocarbon dating. Quat. Sci. Rev. 30 (27–28), 3769–3790.
North Greenland Ice Core Project Members, 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. Nature 431, 147–151.
Perederij, V.I., 2001. Clay mineral composition and palaeoclimatic interpretation of the Pleistocene deposits of Ukraine. Quat. Int. 76/77, 113–121.
Petschick, R., 2000. MacDiff 4.2.2 (Online). Available: http://servermac.geologie.un-frankfurt.de.Reiner.htlm (Cited 01-12-2001).
Popescu, I., 2002. Processus sédimentaires récents dans l'éventail profond du Danube (Mer Noire). Unpublished PhD thesis. Université de Bretagne Occidentale - Université de Bucarest, 282 pp. Available on. http://archimer.ifremer.fr/doc/2002/these-1206.pdf.
Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 55, 1869–1887.
Richards, K., Bolikhovskaya, N.S., Hoogendoorn, R.M., Kroonenberg, S.B., Leroy, S.A.G., Athersuch, J., 2014. Reconstructions of deltaic environments from Holocene palynological records in the Volga delta, northern Caspian Sea. Holocene 24 (10), 1226–1252.
Rinterknecht, V.R., Clark, P.U., Raisbeck, G.M., Yiou, F., Bitinas, A., Brook, E.J., Marks, L., Zelcs, V., Lunkka, J.P., Pavlovskaya, I.E., Piotrowski, J.A., Raukas, A., 2006. The last deglaciation of the south eastern sector of the Scandinavian Ice Sheet. Science 311, 1449–1452.
Rinterknecht, V.R., Bitinas, A., Clark, P.U., Raisbeck, G.N., Yiou, F., Brook, E.J., 2008. Timing of the last deglaciation in Lithuania. Boreas 37 (3), 426–433.
Rinterknecht, V., Braucher, R., Böse, M., Bourlès, D., Mercier, J.L., 2012. Late Quaternary ice sheet extents in northeastern Germany inferred from surface exposure dating. Quat. Sci. Rev. 44, 89–95.
Rinterknecht, V., Börner, A., Bourlès, D., Braucher, R., 2013. Cosmogenic 10Be dating of ice sheet marginal belts in Mecklenburg-Vorpommern, Western Pomerania (northeast Germany). Quat. Geochronol. 19, 42–51.
Ross, D.A., Degens, E.T., 1974. Recent sediments of the Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea - Geology, Chemistry and Biology, vol. 20. AAPG Memoir, Tulsa, Oklahoma, USA, pp. 253–292.
Ross, D.A., Uchupi, E., Prada, K., MacIlvaine, J.C., 1974. Bathymetry and microtopography of Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea - Geology, Chemistry and Biology, vol. 20. AAPG Memoir, pp. 1–10.
Ryan, W.B.F., Pitman, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A., Dimitrov, P., Gorür, N., Sakinç, M., Yüce, H., 1997. An abrupt drowning of the Black Sea shelf. Mar. Geol. 138, 119–126.
Saarnisto, M., Saarinen, T., 2001. Deglaciation chronology of the scandinavian ice Sheet from the Lake Onega basin to the saupausselka end moraines. Glob. Planet. Change 31, 387–405.
Serebryanny, L.R., 1982. Postglacial Black Sea fluctuations and their comparison with the glacial history of the Caucasian high mountain region. In: Kaplin, P.A., et al. (Eds.), Sea and Oceanic Level Fluctuations for 15,000 Years. Nauka Press, Moscow, pp. 161–167.
Shkatova, V.K., 2010. Paleogeography of the Late Pleistocene Caspian Basins: geochronometry, paleomagnetism, paleotemperature, paleosalinity and oxygen isotopes. Quat. Int. 225, 221e229. http://dx.doi.org/10.1016/jquaint.2009.05.001.
Sidorchuk, A. Yu., Panin, A.V., Borisova, O.K., 2009. Morphology of river channels and surface runoff in the Volga River Basin (East European Plain) during the Late Glacial Period. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2009.03.007.
Sorokin, V., Yanina, T., Guilderson, T., Bezrodnykh, Yu, Kuprin, P., 2014. In: Age of the Khvalynian Deposits of the Northern Caspian Sea According AMS $^{14}C$ Dating, IGCP 610 Second Plenary Meeting and Field Trip, Baku, Azerbaijan, 12–20 October 2014. http://www.avalon-institute.org/IGCP610.
Soulet, G., Ménot, G., Garreta, V., Rostek, V., Zaragosi, S., Lericolais, G., Bard, E., 2011a. Black Sea "Lake" reservoir age evolution since the Last Glacial—hydrologic and climatic implications. Earth Planet. Sci. Lett. 308 (1–2), 245–258.
Soulet, G., Ménot, G., Lericolais, G., Bard, E., 2011b. A revised calendar age for the last reconnection of the Black Sea to the global ocean. Quat. Sci. Rev. 30, 1019–1026.
Soulet, G., Ménot, G., Bayon, G., Rostek, F., Ponzevera, E., Toucanne, S., Lericolais, G., Bard, E., 2013. Abrupt drainage cycles of the Fennoscandian ice Sheet. Proc. Natl. Acad. Sci. U. S. A. 110 (17), 6682–6687.
Stoffers, P., Müller, G., 1972. Clay mineralogy of Black Sea sediments. Sedimentology 18, 113–121.
Strechie, C., André, F., Tudryn, A., Tucholka, P., Guichard, F., Lericolais, G., 2002. Magnetic minerals as indicators of major environmental change in Holocene Black Sea sediments : preliminary results. Phys. Chem. Earth, A/B/C 27 (25–31), 1363–1370.
Strechie-Sliwinski, C., 2007. PhD thesis. Changements environnementaux récents dans la zone de Nord-Ouest de la mer Noire, vol. special 1/2007. Université Paris Sud, GeoEcoMar, p. 270.
Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B.W., Harbor, J.M., Jansen, J.D., Olsen, L., Caffee, M.W., Fink, D., Lundqvist, J., Rosqvist, G.C., Strömberg, B., Jansson, K.N., 2015. Deglaciation of Fennoscandia. Quat. Sci. Rev. http://dx.doi.org/10.1016/j.quascirev.2015.09.016.
Stuiver, M., Reimer, P.J., 1993. Radiocarbon 35, 215–230.
Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingolfsson, O., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lys, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F., Stein, R., 2004. Late Quaternary ice sheet history of northern Eurasia. Quat. Sci. Rev. 23 (2004), 1229–1271.
Svitoch, A.A., 1997. The regime of the Caspian Sea level reconstructed using paleogeographic data. Water Resour. 24 (1), 9–18.
Svitoch, A.A., 2009. Khvalynian transgression of the Caspian Sea was not a result of water overflow from the Siberian Proglacial lakes, nor a prototype of the Noachian flood. Quat. Int. 197, 115–125.
Svitoch, A.A., Yanina, T.A., Antonova, V.M., Van der Plicht, J., 2008. The Khvalynian Fauna on the manych depression. Dokl. Earth Sci. 421A (6), 987–991.

Tagieva, E.N., Veliev, S.S., 2014. Environment and the first agricultural-cattle breeding culture of Azerbaijan. The basic stages of interaction. Reg. Res. Russ. Geogr. Ser. № 2, 95–107 (in Russian).
Tanaka, T., et al., 2000. JNdi-1: a neodymium isotopic reference in consistency with La Jolla neodymium. Chem. Geol. 168, 279–281.
Toucanne, S., Zaragosi, S., Bourillet, J.F., Cremer, M., Eynaud, F., Van Vliet-Lanoe, B., Penaud, A., Fontanier, C., Turon, J.L., Cortijo, E., Gibbard, P.L., 2009. Timing of massive 'Fleuve Manche' discharges over the last 350 kyr: insights into the European ice-sheet oscillations and the European drainage network from MIS 10 to 2. Quat. Sci. Rev. 28 (13–14), 1238–1256.
Toucanne, S., Zaragosi, S., Bourillet, J.F., Marieu, V., Cremer, M., Kageyama, M., Van Vliet-Lanoë, B., Eynaud, F., Turon, J.L., Gibbard, Ph, 2010. The first estimation of Fleuve Manche palaeoriver discharge during the last deglaciation: evidence for Fennoscandian ice sheet meltwater flow in the English Channel ca 20-18 ka ago. Earth Planet Sci. Lett. 290 (3–4), 459–473.
Toucanne, S., Soulet, G., Freslon, N., Silva, J.R., Dennielou, B., Zaragosi, S., Eynaud, F., Bourillet, J.-F., Bayon, G., 2015. Millennial-scale fluctuations of the European Ice Sheet at the end of the last glacial, and their potential impact on global climate. Quat. Sci. Rev. 123, 113–133.
Tudryn, A., Strechie-Sliwinski, C., Guichard, F., Tucholka, P., Fontugne, M., Lericolais, G., Panin, N., Colin, C., Collette, G., Thodiard, E., 2012. Environmental changes for last 18 kyrs recorded in sediments of the Black Sea. Quat. Int. 279–280, 502. Abstracts.
Tudryn, A., Chalié, F., Lavrushin, YuA., Antipov, M.P., Spiridonova, E.A., Lavrushin, V., Tucholka, P., Leroy, S.A.G., 2013a. Late Quaternary Caspian Sea environment: late Khazarian and early Khvalynian transgressions from the lower reaches of the Volga River. Quat. Int. 292, 193–204.
Tudryn, A., Tucholka, P., Ozgur, N., Gibert, E., Elitok, O., Kamaci, Z., Massault, M., Poisson, A., Platevoet, B., 2013b. A 2300-year record of environmental change from SW Anatolia, Lake Burdur, Turkey. J. Paleolimnol. 49,647–662.
Tudryn, A., Giannesini, P.J., Guichard, F., Badaut-Trauth, D., Tucholka, P., Boomer, I., 2014. The role of iron minerals in laminae formation in Late Pleistocene sediments of the Caspian Sea,. Quat. Int. 345, 68–76.
Van Baak, C.G.C., 2015. Mediterranean-paratethys connectivity during the late miocene to recent. Utrecht Stud. Earth Sci. vol. 87.
Vandenberghe, J., French, H.M., Gorbunov, A., Marchenko, S., Velichko, A., Jin, H., Cui, Z., Zhang, T., Wan, X., 2014. The Last Permafrost Maximum (LPM) map of the Northern Hemisphere: permafrost extent and mean annual air temperatures, 25–17 ka BP. Boreas 43 (3), 652–666.
Varuschenko, S.I., Varuschenko, A.N., Klige, R.K., 1987. Changes in the Regime of the Caspian Sea and Non-terminal Water Bodies in Paleotime. Nauka, Moscow pp.239 (in Russian).
Velichko, A.A., Klimanov, V.A., Belyaev, A.V., 1987. Caspian and Volga river 5.5 and 125 thousands years before. Priroda 3, 60–66 (in Russian).
Velichko, A.A., Morozova, T.D., Nechaev, V.P., Porozhnyakova, O.M., 1996. Paleocryogenesis, Soils and Agriculture, 150 pp. Nauka Publishers, Moscow (in Russian).
Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J.F., Wobbe, F., 2013. Generic mapping tools: improved version released. EOS Trans. AGU 94, 409–410.
Yanina, T.A., 2012. Correlation of the late Pleistocene paleogeographical events of the Caspian Sea and Russian plain. Quat. Int. 271, 120–129.
Yanina, T.A., 2014. The Ponto-Caspian region: environmental consequences of climate change during the Late Pleistocene. Quat. Int. 345, 88–99.
Yanko-Hombach, V., Gilbert, A.S., Dolukhanov, P., 2007. Controversy over the great flood hypotheses in the Black sea in the light of geological, paleontological and archaeological evidence. Quat. Int. 167–168, 91–113.
Yanko-Hombach, V., Mudie, P.J., Kadurin, S., Larchenkov, E., 2014. Holocene marine transgression in the Black sea: new evidence from the northwestern Black Sea shelf. Quat. Int. 345, 100–118.