Origin, migration pathways and palaeoenvironmental significance of Holocene ostracod records from the north-eastern Black Sea shelf

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Abstract

Micropalaeontological studies of the Black Sea, including ostracod records, have suggested that early Holocene salinity values were between ~5-10 psu, contrasting with present values of 18-22 psu. However, more precise palaeoenvironmental reconstructions based on ostracod assemblages require additional information related to their modern ecological affinities. This study uses modern species information collected from samples with living fauna to interpret the fossil Holocene assemblages of two sediment cores, Ak-2575 and Ak-521 collected from the north-eastern outer shelf of the Black Sea. A total of 37 ostracod species are recorded in the fossil assemblages, with two related to freshwater/oligohaline environments, 23 from Caspian-type environments, and 12 from environments similar to the Mediterranean. Three distinct assemblage zones are identified from Caspian-type dominating in the early Holocene up to 7.4 cal ka BP, a mixed assemblage of Caspian-type and Mediterranean type from 7.4 to 6.8 cal ka BP and a progressive dominance of Mediterranean species from 6.8 cal ka BP. It is very likely that the dominant control of ostracod species occurrence during the period up to ~6.8 cal ka BP is salinity. A range of factors including temperature, biotope and sedimentation rates influenced the species distribution over the last 6.8 cal ka BP.

Key Words

Ostracod assemblages, salinity, brackish water, migration, Caspian Sea, Mediterranean Sea, Sea of Azov, palaeoenvironment, Quaternary.
Introduction

The connection of the Black Sea with the Mediterranean has been episodic during the Quaternary whereas fewer periodic intrusions of water from the Caspian Sea have occurred via the Manych Corridor during the Pleistocene (Chepalyga, 2002, 2007; Bahr et al., 2008; Badertscher et al., 2011; Yanina, 2014). These intrusions have greatly influenced the Black Sea environmental conditions eventually creating the biota that is now inhabiting the basin (e.g. Mudie et al., 2002; Yanko-Hombach, 2007; Marret et al., 2009; Boomer et al., 2010). The present two-way connection between the Black Sea and Marmara Sea was established in the early Holocene (Grigor'ev et al., 1984; Yanko and Troitskaya, 1987; Hiscott et al., 2007; Soulet et al., 2011a) creating a substantial salinity increase in the Black Sea. However, quantitative estimation of such conditions as well as their timing have been heavily debated (Ryan et al., 1997; Aksu et al., 2002; Ryan et al., 2003; Hiscott et al., 2007; Ivanova et al., 2007, 2015; Yanko-Hombach et al., 2007, 2014; Marret et al., 2009; Nicholas et al., 2011). Most of these studies have yielded well preserved macro- and microfossil proxy records, providing insights of past environmental conditions during the Holocene (Atanassova, 2005; Hiscott et al., 2007; Yanko-Hombach et al., 2007, 2014; Ivanova et al., 2007, 2012, 2015; Mudie et al., 2007; Verleye et al., 2009; Boomer et al., 2010; Bradley et al., 2012; Mertens et al., 2012). However, understanding the temporal and spatial changes in assemblages from a variety of locations, taxonomic refinements (Boomer et al., 2010), and more information about modern habitat preferences are a prerequisite for improving Holocene palaeoenvironmental reconstructions, which is the case for ostracods. This microfossil group is particularly suitable for palaeoenvironmental reconstruction
because they are abundant, inhabit a wide range of habitats, are sensitive to environmental change, and their specific assemblage composition reflects definite bottom water conditions (Athersuch et al., 1989; Schornikov, Zenina, 2014).

Two main migration pathways have been postulated to explain the composition of Holocene Black Sea ostracod fauna. The first pathway (Figure 1) enabled the migration of Caspian species during periodic intrusions of water during the Pleistocene, via the Manych Corridor, with the last connection with the Caspian Sea occurring during the Neoeuxinian transgression between 14-15 cal ka BP (Yanina, 2014). These species are tolerant of low-salinity environments such as the present conditions in the Caspian Sea (Boomer et al., 2005). During periods of relative higher salinity, for example in the Holocene or Eemian (Shumilovskikh et al., 2013), the Caspian species did not inhabit the main body of the Azov-Black Sea basin, but survived in low salinity refuges (Schornikov et al., 2011). The second pathway (Figure 1A) allowed the migration of marine species during periods of connection with the Mediterranean (Hiscott et al., 2007; Boomer et al., 2010). Improving our knowledge about the ecological affinities of these two groups will enable to better constrain environmental reconstructions from a period where the Black Sea was isolated from other water bodies up to its reconnection.

This paper aims to provide new insights on the Holocene environmental changes on the north-eastern (Caucasian) Black Sea shelf based on ostracod data from two gravity cores (Ak-521 and Ak-2575). We interpret the fossil ostracod data using modern species and habitat information, from living fauna collected in the Caspian Sea and Azov-Black Sea basin. The paper provides a more detailed examination of
the fossil data presented by Ivanova et al. (2015) using the newly collected modern
data. In addition, new fossil data with taxonomic revisions from core Ak 521, first
published at a lower resolution by Ivanova et al. (2007), are presented. Six species
of Caspian type are reported for the first time in the Black Sea fossil assemblages.
Five of these species, hypothesised to belong to genera of Caspian type, are not
found in the Caspian Sea. They are new undescribed species and shown in open
nomenclature.

**Regional Setting**

The Black Sea has a unique set of characteristics, with surface water salinity about
half of oceanic salinity ranging between 18-22 psu; Murray, 1991; Sorokin, 2002).
Strong stratification of the water column results in the appearance of a hydrogen
sulphide zone in the deep water. In the south-west, the Black Sea exchanges water
with the Marmara Sea, via the Bosporus Strait, with outflowing brackish surface
water replaced by inflowing saline deep water. In the northeast, the Black Sea
exchanges water with the Sea of Azov, via the Kerch Strait (Figure 1). Compared
with the Black Sea, the Sea of Azov is geologically young and very shallow (less
than 10 m); it has a small surface area and much smaller volume. Therefore, it can
be considered as a gulf, or part of the Black Sea (Chepalyga, 2002). In this paper,
we use the term Azov-Black Sea basin. The Caspian Sea is the largest enclosed
body of water on Earth, with water depth ranging from quite shallow in the north (less
than 20m), to relatively deep in the south basin (1025m) (Kosarev, 2005). The Volga
River is the largest water inflow into the Caspian Sea and discharges into the North
Caspian basin. The Caspian Sea is closed with no outlet. In the 20th century, it has
experienced large changes in sea level with drops and increases of ~1-3 m observed (Arpe and Leroy, 2007). The salinity is brackish with ranges between 1 to 13. The salinity increases in a southward direction.

The two sediment cores were taken from the Caucasian Shelf (Fig. 1A, C) between Arkhipo-Osipovka and Dzhubga. In this area, the shelf narrows to a width of 4 to 12 km and generally has a flat surface which slopes slightly (0.2-0.6˚) towards the shelf break at depths of 100-120 m. The shelf can be divided three portions; a coastal area that extends from the shoreline to depths of 25-30 m; a central shelf platform between 30-70 m depth; and the outer shelf that ranges from a depth of 80 m to a sharp shelf break at 95-105 m (Torgunakov et al., 2002).

The surface circulation on the north-eastern shelf is dominated by the counter-clockwise rotating peripheral Rim Current (Bogatko et al., 1979; Öğuz, 1993). On the outer shelf, two water masses are identified in the water column. A well-ventilated surface water mass is present in the upper 50-90 m, above a strong seasonal pycnocline. Salinity measurements at ~44.53°N and 37.93°E during February, May, July and October 2015 show that annual salinity values vary between 17.5 and 19.4 psu (Fig. 2). Seasonal variability depends on depth, with <25 m measurements having a range of ~0.5 psu, 25-75 m depths spanning <0.5 m, and >75 m ranging between ~1 psu. Annual temperature values vary between 7.5°C and 25°C with greatest variability at depths 0-50 m (Figure 2). At depths below 50 m variability decreases to ~2.5°C.

Material and methods
Two gravity cores, Ak-521 (44.26°, 38.54°, water depth -101m, 200 cm long) and Ak-2575 (44.22°, 38.63°, water depth -99m, 186 cm long), were retrieved during cruises of the RV Akvanavt in 2001 and 2007 respectively.

**Fossil Ostracod Analysis**

Samples were sieved through a 100 µm (Ak-521) or 63 µm (Ak-2575) mesh using distilled water. For core Ak-2575, dry fractions (>2 mm, 0.1-2 mm and 0.063-0.1 mm) were weighed to calculate the percent of each fraction in samples, and the total number of ostracods per gram of sediment. The dry fractions 0.1-2 mm (both cores) and 0.063-0.1 mm (Ak-2575 only) were analysed using a binocular microscope. Ostracod valves were described to species level where possible. Ivanova et al. (2007) briefly described a subset of 18 ostracod samples from Ak-521. In this paper, we present the full ostracod record (37 samples), taxonomic revision of previously published work (Table 1), integration with ecological data (Figure 1E; Table 2, Table 3), and species images (Supplementary Figure 1-3). Ostracod assemblages from core Ak-2575 were analysed in 2 cm thick slices from 93 contiguous samples (Supplementary data Table 1). Previously, ostracods from this core were briefly described in Zenina et al. (2013) and Ivanova et al. (2015). SEM images were taken using a Zeiss EVO 40.

The accumulation rate of ostracod valves (OAR) in AK-2575 was estimated using the following equation:

\[ \text{Accumulation rate of valves (cm}^2 \text{ per ka)} = V \times D \times S. \]
Where, \( V = \) valve counts per gram of dry sediment from grain-size fractions between 63-2000 \( \mu \)m; \( D = \) sediment wet density (1.4 g/cm\(^3\)); \( S = \) sedimentation rate (cm/ka) which is based on the age model by Ivanova et al. (2015).

*Modern ostracod samples*

Nine samples collected from the Caspian Sea with a small dredge were analyzed (Figure 1C). Samples I-VI were collected by M.A. Zenina between the 28\(^{th}\) July to 1\(^{st}\) August 2014. Samples VII-IX were collected by E.I. Schornikov on 5\(^{th}\) August 1956 (VII, VIII) and 16\(^{th}\) July 1952 (IX). In this study, we also provide information about ostracod fauna living in the Azov-Black Sea basin, and do not consider species living only in Caspian Sea.

*Lithostratigraphy and chronostratigraphy*

The age model for the two gravity cores Ak-521 and Ak-2575 published by Ivanova et al. (2015) is based on 19 calibrated radiocarbon dates (9 for Ak-521, 10 for Ak-2575). Regional stratigraphic units with calibrated dates of their boundaries (Balabanov, 2009, Ivanova et al., 2015) are also taken into account. The proposed transgression phases include Neoeuxinian (11-10 cal ka BP), Bugazian (10–8.8 cal ka BP), Vityazevian (8.8–7.8 cal ka BP), Kalamitian (7.8–6.9 cal ka BP), Dzhemetinian (6.9–2.6 cal ka BP) and Nymphaean (2.6–0 cal ka BP) (Balabanov, 2009).
Both cores were retrieved close to the shelf break and recovered similar sections of Holocene deposits. This included ~0.5m thick coquina at their base composed of semi-freshwater Caspian type mollusk shells (dominated by *Dreissena rostriformis*) in its lower part and a mixed (Caspian + Mediterranean) mollusk fauna in the upper part (Ivanova et al., 2007, 2015). The coquina marks a high-energy bottom environment at the shelf edge which commenced at the end of the Neoeuxinian stage as shown by the oldest date from the shelly mud layer underlying the coquina in core Ak-521 (11.87 cal ka BP), and lasted up to ~7.4 cal ka BP according to the age model (Ivanova et al., 2015). The sharp, possibly erosional, basal contact of the coquina suggests a hiatus at its base. Another hiatus likely separates the *Dreissena*-dominated coquina from the mixed-fauna one, both belonging to a slowly accumulated high-energy shelf edge facies.

The gradual, although distinct, upper contact of the coquina reflects slowing down of bottom hydrodynamics thus allowing deposition of fine-grained terrigenous mud which was inhabited by *Mytilus galloprovincialis* (the *Mytilus* mud facies).

Sedimentation rates increased up to 95.2 cm/ka during the time interval 7.4-6.8 cal ka, and to 111.1 cm/ka in the interval 6.8—6.5 cal ka BP (Ivanova et al., 2015).

Intercalation of the *Mytilus* mud by thin muddy *Mytilus* coquina beds suggests pulsating sedimentation possibly related to alternation of extreme floods delivering very large amounts of terrigenous suspended material to the shelf edge with periods of depleted mud supply.
Sedimentation rates decreased during the interval 6.5-5.8 cal ka BP to values less than 4.4 cm/ka. A hiatus likely occurs between the 6.27 and 3.59 cal ka dates that separates the *Mytilus* mud facies from the overlying *Modiolus phaseolius* mud facies characterized by low sedimentation rates of 5.0 – 19.3 cm/ka. The *M. phaseolius* dominated shelly mud comprises uppermost parts of both core sections up to the sediment surface. At present, it covers a wide area of the outer shelf landward to depths of ~60 m.

**Results**

Ostracod division into ecological groups based on their modern distribution

The ostracods of Caspian type in the Azov-Black Sea region dwell in shallow water (down to 5 m) (Fig. 1E, Table 2), but in the Caspian Sea they can inhabit considerably greater depths (Table 3). For example, living specimens of *Graviacypris elongata* were found in depths of 50-68 m in the Caspian Sea. Most of the species found in both cores (Table 4) are abundant in silty-sandy mud. *Tyrhenocythere amnicola donetziensis* and *Euxinocythere virgata* were also quite numerous on shelly ground in the Caspian Sea. *T. amnicola donetziensis, E. virgata, G. elongata, Xestoleberis chanakovi, Sarmatina? cf. azeri* can inhabit depths of 30 m. These species are found living in the Caspian Sea (Table 3). Owing to the lack of adequate data on the ecology of Caspian type species, it is not yet possible to separate groups solely based on habitat.
It is possible to differentiate ostracod species of Mediterranean type (Table 4) based on habit preferences (Ivanova et al., 2014; Schornikov et al., 2014). Mud dwellers include *Palmoconcha agilis*, *Cytheroma variabilis*, *Cytheroma marinovi*, *Bythocythere* sp., *Carinocythereis carinata*, *Paradoxostoma simile* and *Xestoleberis cornelii*. Sandy mud dwellers include *Hiltermannicythere rubra*, *Leptocythere multipunctata*, *Callistocythere diffusa* and *Pontocythere tchemjawskii*. *Sagmatocythere rennata* is a sand dweller.

**Fossil distribution of ostracod species**

In total, 37 ostracod species were recorded in the samples taken from the two cores (Table 4). These species can be split into three groups based on their habitat preference type; two are freshwater/oligohaline taxa, 23 taxa are of Caspian type and 12 taxa are of Mediterranean type. Both cores are subdivided into three sections based on assemblage groupings. These sections appear to depend on the variation in salinity and habitat type during the Holocene.

*Assemblage I*

Assemblage I spans the interval from 11.9 to 7.4 cal ka BP which corresponds to core depths 187-144 cm in Ak-2575 and 192-148 cm in Ak-521. The ostracod abundance for core AK-2575 varies from >1 to 31 valves/g and ostracod accumulation rates vary from 6.8 to 870.8 valves/ka yr. Twenty nine species are identified for this period including 23 species of Caspian type. Two are of the freshwater/oligohaline type and three species are the earliest Mediterranean ostracods to appear in the Black Sea (Table 4; Fig. 3, 4). The most abundant
species are *L. lepida*, *Loxocaspia sublepida*, *Amnicythere martha*, *Euxinocythere relicta*, *Amnicythere stepanaitysae* and *G. elongata*. The two freshwater/oligohaline taxa are *Cypria lubeziensis*, which is only found in the deepest samples of core Ak-521 (195-190 cm), and *Fabaeformiscandona* sp. which is recorded in both cores between ~9.6-7.4 cal ka BP. Strong polymorphism is exhibited in a number of Caspian species, especially *A. stepanaitysae*, *L. lepida*, *E. relicta* and *A. martha*. This is highlighted for *A. stepanaitysae* and *E. relicta* in Supplementary Figure 1-2.

The total number of species found per sample decreases towards the upper parts of the interval of Assemblage I. Only three taxa, *L. lepida*, *L. sublepida* and *G. elongata*, are found in the uppermost part of the assemblage interval, around 7.4 cal ka BP (150-152 cm in Ak-2575 and 153-158 cm in Ak-521). In the youngest samples, *L. lepida* increases in relative abundance. There are also Mediterranean type species including *H. rubra*, *Palmoconcha agilis*, in both cores, and sparse specimens of *L. multiplicata* in Ak-2575 are represented both by adult and juvenile valves.

**Assemblage II**

Assemblage II occurs between 7.4-6.7 cal ka BP which corresponds to core depths 144-90 cm in Ak-2575 and 148-88 cm in Ak-521. This assemblage contains a mixture of Caspian and Mediterranean species. The low number of ostracods recorded in Ak-2575 (< 100 valves per sample), prevented determination of the relative abundance of species. The ostracod abundance for core Ak-2575 is low (0 to 3 valves/g). Among the ostracods of Caspian type, *L. lepida* and *G. elongata* are common. In contrast, *L. sublepida* is represented by only two valves in the sample 136-138 cm from Ak-2575. In both cores, the regular appearance of *L. multiplicata*...
is noted from ~7.4 cal ka BP. Furthermore, the species composition in the two cores is slightly different. For example, *P. agilis* was not recorded in core Ak-521.

Assemblage II can be further subdivided into two sub-assemblages occurring at 7.4-7.1 cal ka BP (II-A) and 7.0-6.8 cal ka BP (II-B). The fauna of Caspian type prevails in sub-assemblage (IIA) while taxa of Mediterranean type, such as *H. rubra*, *L. multipunctata* (in both cores) and *P. agilis* (in core Ak-2575) are still only minor components of the assemblage. Ostracod accumulation rates in the lower and middle parts (122 to 96 cm) of Assemblage II is low (0 to 65.1 valves/ka yr), but in the upper part (up to 90 cm, ~6.8 cal ka BP) it increases to 362 valves/ka yr.

In the upper part of IIA, *G. elongata* disappears from the record. In the interval 7.1-7.0 cal. ka BP (122-116 cm in core Ak-2575) the record is barren. There is no data from Ak-521 in this period because of the lower sampling resolution. In Sub-assemblage II-B, species diversity of Mediterranean ostracods becomes higher. Along with the taxa recorded in IIA, the fauna of this period also includes *S. rennata*, *X. cornelii*, *C. marinovi* and *C. variabilis*. The only species of Caspian type found during this period is *L. lepida*, which disappears from the record around ~6.8 cal ka BP. The most typical species in Sub-assemblage IIA are *L. multipunctata* and *S. rennata*. *H. rubra* increases in relative abundance upwards in the assemblage.

**Assemblage III**

Assemblage III spans the interval from 6.8 cal ka BP (90 cm in core Ak-2575 and 88 cm in core Ak-521) to present (Fig 3-4). It is characterized by a depleted fauna of Mediterranean type species, typical of water depths of >50 m. Accumulation rates are relatively high at the oldest boundary before falling in younger samples. Two
species of Caspian type found in core Ak-2575 include a reworked valve of X. chanakovi (found in sample 22–20 cm) and two reworked valves of L. lepida (found in sample 84-82 cm). The ostracod abundance for core Ak-2575 in this period is between >1 to 41 valves/g. Fauna of Mediterranean type in core Ak-2575 is more diverse and is represented by 12 species, while in core AK-521 it only consists of nine species (Fig 3; 4). However, this is most likely due to the more detailed study of core Ak-2575. Indeed, species not recorded in Ak-521 samples such as C. carinata, C. diffusa and P. tchemjawskii are noted as minor components in samples from core Ak-2575.

The upward disappearance of the relatively shallow-water S. rennata and decrease in abundances of L. multipunctata and X. cornelii coincide with the increased occurrence of P. agilis and appearance of Bythocythere sp. in the uppermost part of the cores. This section is split into two sub-assemblages in Ak-2575 depending on the abundance and occurrence of these species. X. cornelii and H. rubra are the most abundant species in Sub-assemblage IIIA during the interval 6.8-6.6 cal ka BP (90–64 cm in Ak-2575). However, the two sub-assemblages cannot be identified in Ak-521 because of the lower sampling resolution. Hence, the data indicates a similar species diversity and relative abundance within this assemblage in both cores. The abundance of the sandy mud dweller L. multipunctata decreases in the lower part of the interval, whereas the mud dweller P. agilis gradually becomes more common in the younger samples. In Ak-2575, two sub-assemblages are divided by a short interval from 6.5 to 6.3 cal ka BP in which only rare valves of P. agilis and H. rubra are found. The sub-assemblage IIIB from the interval 6.3–0 cal ka BP is of a relatively colder type. This is indicated by considerable numbers of P. agilis generally
dominating the ostracod fauna, and by the recording of *Bythocythere* sp., which prefers lower temperatures and inhabits modern assemblages of the Black Sea only at depths of >70 m (Schornikov, 1969). *H. rubra* decreases in relative abundance during this period. A short-term spike of maximal total ostracod abundance (up to 40 valves/g of dry sediment) occurs just above the hiatus, at ~4.2 cal ka BP.

**Discussion**

*Present-day ostracod distribution and implication for palaeoenvironmental reconstruction*

This study investigated the present-day environmental ranges of Caspian-type species. These species currently inhabit the main body of the Caspian Sea (Boomer et al., 2005) but are limited in the Black Sea region to estuaries, rivers, lagoons and lakes (this study, figure 1D, table 2; Schnornikov, 1969, 2011; Opreanu, 2008). They currently account for ~20% of all known ostracods in the Black Sea (Schornikov, 2012). These Caspian-type species have the highest relative abundance in early Holocene sediment records in the BS (Hiscott et al., 2007; Boomer et al., 2010; Bradley et al., 2011; Williams et al., 2011; Ivanova et al., 2015; this study, Figures 3 & 4). Currently environmental reconstructions are limited to suggesting that the early Holocene Black Sea was similar to the modern Caspian Sea. The modern data presented in this study allow some refinement of early-Holocene benthic reconstructions in the Black Sea, a period where salinity and rates of change are contested (see Yanko-Hombach et al., 2007; Bradley et al., 2012).
In-situ data show that ostracods of Caspian type previously found in shallow waters (0-5 m) in the Black Sea region (Schornikov 1969, 2011; Opreanu, 2008; Table 2; Fig.1E) are able to inhabit considerably greater depths in the modern Caspian Sea (Table 3). These two basins are known to be characterized by different salt compositions, with chlorine type in the BS basin and sulphate–hydrocarbonate type in the Caspian Sea (Nevesskaya, 1965; Oceanographic tables, 1975). Our data suggest that the different salt compositions may affect the ostracod species distribution. Notably, species of Caspian type recently inhabiting mesohaline depths in the Caspian Sea (Fig. 1D, Table 3) can tolerate less saline conditions in the Black Sea basin (Fig. 1C, Table 2). This hypothesis is supported by previous findings with other groups of animals (Morduhai-Boltovskoy, 1960).

In contrast to the Caspian type species located in the fringe areas of the Black Sea, Mediterranean-type species inhabit the oxygenated, shallow-water areas that are free of hydrogen sulfide pollution (Caraion, 1962; Schornikov, 1969, 2012) and represent ~80% of reported ostracods in the modern Black Sea (Schornikov, 2012). This fauna consists of species that can tolerate marine conditions in the Mediterranean Sea, as well as brackish salinities and lower temperatures of the Black Sea. For many Mediterranean species, the low salinity (half that of the Mediterranean Sea), and low temperatures are the main barriers to migration into the Black Sea, and thus the Black Sea fauna is a depleted representative of modern Mediterranean fauna. Fauna of the Sea of Azov is further depleted, relative to the Black Sea, due to the lower salinity in the shallow sea, being 1.3 times lower than that of the Black Sea (Caraion, 1962; Schornikov, 1969).
Studies of Black Sea ostracods have referred to endemic marine species (Briceag & Ion, 2014), e.g. *Pontocythere bacescoi* (Caraion, 1960). The finding of *P. bacescoi* valves in the northern part of the Aegean Sea (Schornikov, 1969) suggests that this species is not endemic to the Black Sea. Indeed, it is unlikely that any Mediterranean-type species are endemic to the Azov-Black Sea basin. The Caspian-type ostracods discussed in this study are likely endemic to the Ponto-Caspian region. Studies of late Quaternary Black Sea and Caspian Sea ostracod assemblages illustrate that they have strong affinities to the Neogene assemblages of the eastern Paratethyan basin (Boomer, 2012). Partial or total isolation from the global ocean and generally intense freshwater input from rivers favoured endemism of the ostracod fauna.

Periodic connections between the Black Sea and the Caspian Sea in the Quaternary allowed species migration between the two basins (Chepalyga et al., 2007; Badertscher et al., 2011). They were last connected ~15-14 cal ka BP (Yanina, 2014) and therefore any major migration of Caspian-type ostracods occurred prior to the start of the Holocene, although some of this group were present in the Black Sea prior to this connection (Boomer et al., 2010). Therefore, this means that assemblage change in Holocene ostracod records (this study; Hiscott et al., 2007; Boomer et al., 2010; Bradley et al., 2011; Williams et al., 2011; Ivanova et al., 2015) is a reflection of the migration and/or expansion of Mediterranean-type ostracod populations. This process was driven by the input of water from the Marmara Sea, commencing in the early Holocene (see below) and highlighted by various authors as the dominant control of environmental changes in the Black Sea (Yanko-Hombach et al., 2007; Marret et al., 2009; Nicholas et al., 2011; Soulet et al, 2011a).
**Palaeoenvironmental records from the NE shelf**

The data collected from cores Ak-521 and Ak-2575 provide detailed information about the benthic paleo-environments at the NE Black Sea shelf edge throughout the Holocene. Estimates of water depth in the early Holocene are difficult to quantify using ostracods because of the lack of modern species information. However, the depth was shallower than present but increased until ~4 cal ka BP which corresponds to sea-level curve estimates for the Black Sea (Balabanov et al., 2007; Brückner et al., 2010). The ostracod records show that prior to ~7.4 cal ka BP, the shelf was covered in low salinity water but salinity values increased until ~5.7-4 cal ka BP. The increases in water depth and salinity are linked to the establishment of the two-way flow through the Bosphorus in the early Holocene (Grigor’ev et al., 1984; Yanko and Troitskaya, 1987; Mudie et al., 2004, 2007; Hiscott et al., 2007; Yanko-Hombach et al., 2007).

Following establishment of the two-way flow in the Bosphorus, the data support other studies from around the basin (e.g. Mertens et al., 2012) that suggest changes in global sea-level was the main factor in controlling water level and salinity in the Black Sea. These changes would have been moderated by changes in the precipitation-evaporation budget and discharge from major rivers (Giosan et al., 2012). River inflow of the Danube, Dnieper and Dniester is responsible for ~85% of runoff into the modern Black Sea (Likhodedova and Konikov, 2007) and therefore disproportionally affects the NW Black Sea. However, our records are not sensitive enough to detect these secondary controls on water depth and salinity on the NE Shelf. The
boundaries between the assemblages and sub-assemblages are indistinct. The data in this study do not find evidence of any rapid changes in environmental conditions that were hypothesised by Ryan et al., (2003).

Transformation of the Neoeuxinian environment towards the Holocene marine environment (Assemblage I)

The Caspian-assemblage present between 9.6-7.4 ka cal BP suggests that salinity values ranged between 6 and 11 psu, sea level was greater than 50m, and salt composition was similar to Caspian Sea water (Nevessakaya, 1965; Chepalyga, 2007; Yanko-Hombach et al, 2007, 2014; Ivanova et al., 2007, 2012, 2015). A significant portion of the sediment sequence is represented by a coquina. This coquina is rich in ostracod valves belonging to different ecological groups, possibly due to a variety of biotopes alternating during the very slow and discontinuous coquina deposition in a high-energy bottom water environment. Reworking of ostracod valves might also contribute to the observed high species diversity in the coquina. In Ak-521, Assemblage I contains species of the Caspian type such as Amnicythere sp.1, Loxocaspia cf. immmodulata, Euxinocythere? sp., Amnicythere? sp. 1, Amnicythere sp. 2, which were previously not recorded in either the Black Sea or the Caspian Sea (Agalarova et al., 1961; Mandelstam et al., 1962; Caraion, 1962, 1967; Schornikov, 1969; Stancheva 1989a, 1989b, Boomer et al., 2005, 2010; Yanko-Hombach et al., 2014; Leroy et al., 2014). In the younger sections of this assemblage there is a gradual disappearance of certain species including T. amnicola donetziensis, E. baquana, and E. relicta. This suggests that salinity was increasing throughout the early to mid-Holocene.
The reason for this increase in salinity is linked to the greater input of higher salinity water into the Black Sea from the Mediterranean Sea, via the Marmara Sea (see Hiscott et al., 2007; Mertens et al., 2012) and a rise in sea level (Balabanov et al., 2007). This increase was potentially moderated by the higher levels of precipitation discussed by Göktürk et al. (2011). However, detailed information about past climates of the NE Black Sea region is lacking. In comparison to Western Europe, there are very few studies concerning the Holocene climate conditions for the BS region. The European palaeoclimate reconstructions from Mauri et al. (2015) provide some insights on winter and summer conditions for different time slices from the onset of the Holocene but it is based in a low number of palynological records around the BS. Benthic salinity of less than 2 psu, suggested by Soulet et al., (2011b) is unlikely because the freshwater/oligohaline component is poorly represented, with only two species of ostracods present.

Although Caspian fauna dominate in the early Holocene, the first Mediterranean ostracods appeared on the NE Black Sea shelf at least by ~9.6 cal. ka (Fig. 3, 4). They were represented by *P. agilis*, *H. rubra* and *L. multipunctata*, although the total number of valves is low. In shallower areas, the species composition of the first Mediterranean ostracods is more diverse due to the greater variety of habitats. *C. diffusa*, *Callistocythere mediterranea* (Müller, 1894) are recorded in sediment, *C. variabilis*, *C. marinovi* and *Cytherois* spp. are found together with the species of Caspian type on the NE shelf (Schornikov collections). This suggests that saline water inputted from the Mediterranean reached the north-eastern shelf relatively quickly after the initial establishment of the two-way flow. This suggestion is
supported by the persistent occurrence of euryhaline dinoflagellate cysts and rare specimens of foraminifer *Ammonia tepida* from 9.6 cal ka BP in Ak-2575 (Ivanova et al., 2015) as well as by the foraminiferal data from the NW and SE shelves (Yanko-Hombach et al., 2014).

Co-existence of Mediterranean and Caspian fauna (Assemblage II)

At about 7.4 cal ka BP, salinity reaches a critical limit of ~11-12, and the salt composition of water changes from the Caspian type to the normal oceanic type (Nevesskaya, 1965; Chepalyga, 2002; Yanko-Hombach, 2007). These conditions are unsuitable for the majority of the Caspian type fauna. However, they are also not optimal for Mediterranean ostracods, since the salinity is at the lower limit of their tolerance (Schornikov, 1969). This explains the low ostracod abundance just after the transition between Assemblage I and Assemblage II. Soft shelly mud started to accumulate over the coquina at the NE shelf edge owing to a decrease in bottom water dynamics and increase in fine-grained terrigenous material supply. These environmental changes coincided with the beginning of the large-scale migration of the Mediterranean ostracod fauna to the Black Sea shelf that characterized Assemblage IIA development.

The data presented in this study assume ecological conditions that allowed the coexistence of Mediterranean and Caspian species (Ivanova et al., 2007, 2012, 2015). According to other studies, after the onset of two-way circulation in the Bosporus Strait, ostracod valves of both fauna types occur simultaneously over an extended period of time (Stancheva, 1989b; Yanko-Hombach et al., 2014; Ivanova et
Living specimens of Caspian and Mediterranean types are not reported together in the same samples from the Black Sea and Sea of Azov. Along with the fauna of Mediterranean type, only *C. torosa* was found in the Sea of Azov. This species is able to coexist with representatives of the Caspian type.

However, in different areas of the Black Sea, the appearance of Mediterranean species and thus the lower boundary of the mixed assemblage seem to be slightly diachronous. According to the data from the Bulgarian shelf, this level corresponds to the Bugazian/Vityazian boundary (Stancheva, 1989b). Hiscott et al. (2007) discuss the transition from the Caspian to the Mediterranean type on the SW shelf from 7.3 to 6.0 cal ka BP. Using calibration procedures in Ivanova et al. (2015), this corresponds to ~7.9 to 6.2 cal ka BP. Note that the datum level of the large-scale migration of Mediterranean species cannot be ascertained using the quantitative data on their occurrence (Yanko-Hombach et al., 2014). The less abundant occurrence of Mediterranean ostracods during the large-scale migration event can possibly be explained by their slower migration rates into the Black Sea compared to molluscs, as most part of Podocopa are benthic animals without any pelagic ontogenetic stages.

The Caspian-type ostracod fauna prevails over the Mediterranean fauna throughout the Assemblage IIA interval. This occurs at a very low level of total ostracod abundance (Fig. 4), likely due to dilution by rapidly accumulating shelly mud of the *Mytilus* mud facies (Ivanova et al., 2015). Moderate OAR values support this assumption for core Ak-2575. However, a persistent presence of authigenic gypsum crystals suggests that episodic upwelling of the anoxic deep water onto the shelf
edge might suppress populations of the ostracod fauna. In Ak-521, gypsum crystals are rare and the ostracod fauna is more abundant.

The gradual transition from Assemblage IIA to IIB at about 7.1 – 7 cal ka BP is expressed by a disappearance of most Caspian-type ostracod species except for *L. lepida*. Relatively high diversity and abundance of species of Mediterranean type in the IIB interval (from Ak-2575) indicate that an increase in salinity should exceed the limits of tolerance for species of Caspian type. In this context, the late disappearance of only one ostracod species *L. lepida* and its late occurrence in significant amounts (ten valves per sample) needs further investigation, as a salinity of ~18 psu was reported at that period (Mertens et al., 2012). It is unlikely that *L. lepida* could in situ coexist with a relatively diverse Mediterranean fauna for such a long time because of the significantly different tolerances to salinity conditions (absolute value and salt composition balance). Thus, we assume that the specimens of *L. lepida* found in younger samples are reworked from shallow-water areas where it could inhabit low-salinity conditions. In the early Holocene and late Pleistocene, this species was one of the most abundant (Stancheva, 1982a, b; Boomer et al., 2010). Moreover, reworked valves of the Caspian type ostracods occur in grab samples together with recent ostracods mainly near the southern extremity of the Crimean Peninsula at depths of 60–100 m, in the near-Bosporus area at a depth of 105–415 m (Schornikov, 2011), and in our grab and drag samples from the NE shelf edge, at depths of 80-100 m.

Assemblage IIB differs from IIA because of the higher diversity of Mediterranean-type ostracod fauna. It contains more stenohaline species along with euryhaline
species, which previously dominated. Thus, it demonstrates a migration event via the
Bosporus Strait related to increases in salinity. Significant changes in bottom-water
temperature are documented by variations in the species composition of
Assemblage II. *S. rennata* occurred in significant numbers at the point when
Mediterranean type species increased. At present, this species inhabits depths of 15
to 30 m (Schornikov, 1969) where the bottom water temperature is significantly
higher over the year than on the outer shelf (Fig. 1). Abundant *L. multipunctata* occur
within the same time interval in both cores, although at present it is usually much
abundant in shallower depths.

Hence, Assemblage II suggests that the bottom water temperature was considerably
warmer than at present on the outer shelf during the colonization by Mediterranean
fauna (7.4–6.7 cal ka BP). However, it is not clear when the warm climatic conditions
responsible for the bottom water warming commenced. The warm period during the
mid Holocene (7.4–6.7 cal ka BP) as highlighted by our ostracod records is identified
for winter conditions (1 to 2 °C above modern pre-industrial conditions) from
reconstructed climate conditions by Mauri et al., (2015). In addition, warm and humid
climates were estimated from the pollen record from Yenicağa Lake in northern
Anatolia (Bottema et al., 1995), Lake Van in central Anatolia (Wick et al., 2003; Litt et
al., 2009), Northern Anatolia (Shumilovskikh et al., 2012) and Georgia (Kvavadze
and Connor, 2005), as well as from the Bulgarian Black Sea shelf (Filipova–
Marinova, 2006). According to Shumilovskikh et al. (2012), a warm and humid phase
occurred in Northern Anatolia at ~8.5-5 cal ka BP.

*Onset of the recent bottom environment on the NE Black Sea shelf (Assemblage III)*
Assemblage III consists of only Mediterranean-type species. The composition of Mediterranean type fauna in both transitional (II) and marine (III) assemblages is very impoverished because both studied cores were collected from a relatively deep area (99-101 m) covered with rather uniform soft shelly silty mud. On shallower areas of the eastern shelf, upper Holocene ostracod assemblages are much more diverse (Schornikov et al., 2014).

Salinity almost reaches present-day values during the gradual end of the Assemblage II phase. Further development of the ostracod fauna mainly depended on changes in the bottom water temperature and sedimentation processes. Disappearance of relatively warm-water S. rennata and the decrease in abundance of L. multipunctata at ~6.8 cal ka BP indicate a gradual reduction in bottom water temperature. Other explanations seem unlikely, as there is no evidence of large salinity changes and the biotope (soft silty-pelitic mud) is similar both below and above this level (Fig. 5A). Therefore, the above mentioned changes in composition of the ostracod fauna likely reflect a climate (and bottom water) cooling trend.

However, the accumulation rate of ostracod valves (OAR) sharply accelerated at the transition from Assemblage IIIA (Fig. 4d). This suggests high productivity of the ostracod fauna, although concentration of valves in sediments is rather low owing to their dilution by rapidly accumulated terrigenous mud.

Sedimentation rates slowed down after the very rapid terrigenous mud accumulation related to the Kalamitian high sea level stand (Ivanova et al., 2007, 2015). The hiatus (>1000 years) which likely corresponds to erosion during the Kundukian regressive
phase (Chepalyga, 2002) separates assemblages IIIA and IIIB. This correlates with

*Mytilus* mud and *M. phaseolinus* mud facies respectively. Ostracod abundance and

OAR increased during the transition from IIB to IIIA reflecting favourable conditions

for ostracods, and fall to almost zero values after ~6.5 cal ka BP, according to the

data from core Ak-2575 (Fig. 5E). The short period of suppressed ostracod fauna

before the hiatus might be related to an anoxic water upwelling event.

The species composition of Assemblage III suggests the cooling trend continued up

to the time of the modern assemblage onset at ~5.7 - 4 cal ka BP, although water

conditions were still somewhat warmer than present. Increasing percentages of *P.

agilis* during the time interval from 6.7 to 4 cal ka BP and appearance of

*Bythocythere* sp. at about 4 cal ka BP confirms this suggestion. *Bythocythere* sp. is

found in modern assemblages of the Black Sea only at depths of>70 m (Schornikov,

1969). Therefore, its presence serves as an evidence of bottom water temperature

reduction to present values. The changes in species composition were simultaneous

with the gradual transition from *Mytilus* mud to *Modiolus phaseolinus* mud facies

(Ivanova et al., 2015). *P. agilis* is the most abundant ostracod species on the modern

*M. phaseolinus* mud (Schornikov, 1969). Changes in Assemblage III may be caused

either by facies replacement that was accompanied by the slowing down of mud

sedimentation rates (and thus, also OAR, Fig.4d) or by some bottom water cooling.

Formation of modern assemblages at ~5.7- 4 cal ka BP indicates the onset of

environmental conditions close to present.

Conclusions
Ostracod records of cores Ak-521 and Ak-2575 are generally synchronous and represent the response of ostracod assemblages at the NE Black Sea shelf edge to the major Holocene paleoenvironmental events. During the period \( \sim 11.8 \) to \( 7.4 \) cal ka BP, the ostracod fauna of Caspian type was represented by a relatively diverse range of species. However, the first Mediterranean migrants already appeared at about \( 9.6 \) cal ka BP. A significant portion of the sediment sequence in this period is represented by a coquina that is rich in ostracod valves belonging to different ecological groups. This is potentially explained by a variety of biotopes alternating during the very slow coquina deposition interrupted by hiatuses, in a high-energy bottom water environment that resulted in washing away of mud, reworking of mollusc shells in the coquina, as well as ostracod valves. Many species in the Caspian assemblage are in common with those in the modern Caspian Sea.

The composition of Mediterranean type fauna in the *Mytilus* mud facies overlying the coquina is very impoverished compared to that from shallower areas, likely because of a uniform biotope represented by shelly silty mud. A transitional assemblage occurs between \( 7.4-6.8 \) cal ka BP that contains a mixture of both Caspian and Mediterranean-type species. This occurs at a very low level of total ostracod abundance, likely due to high accumulation rates of the mud. The Caspian-type ostracod fauna dominates over the Mediterranean type until \( \sim 7.1 \) cal ka BP. After this period, Mediterranean fauna became more abundant. Remains of the Caspian-type fauna found in sediments younger than about \( \sim 7.1 \) cal ka BP were likely reworked from shallower freshened areas. They were unlikely to reside together with a diverse range of Mediterranean species, which occupy bottom conditions with a salinity much higher than the tolerance level for the Caspian species. After \( 6.8 \) cal ka
BP, ostracod fauna presented only by Mediterranean-type species became more abundant.

Changes in the ostracod fauna of the NE Black Sea shelf edge during the Holocene reflect the increase in bottom water salinity after the opening of the two-way circulation through the Bosporus Strait and a bottom water cooling trend starting from the mid-Holocene optimum (at ~6.8 cal ka BP) to recent conditions. The bottom water temperature was considerably warmer than at present on the outer shelf during the active colonization by Mediterranean fauna (~7.4 to 6.8 cal ka BP). After 6.8 cal ka BP, warmer-water assemblages were gradually replaced by colder-water ones. The cooling trend continued up to the onset of the modern assemblage ~5.7-4 cal ka BP when water conditions were still somewhat warmer than present. The modern ostracod assemblage is typical of the *M. phaseolina* mud facies on the outer shelf.

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Figure 1. The study region. A – Overview of study area; B- Ponto-Caspian basins during the Late Pleistocene in time of connection of Neoeuxinian (Black Sea) Basin and Khvalynian (Caspian) Basin (adopted from Yanina, 2014); C- Location of cores Ak- 2575 and Ak- 521; D – Sample locations in Caspian Sea, E - Modern distribution of fauna of Caspian type in Azov-Black Seas basin from (Schornikov 1969, 2011; Opreanu, 2008 and new data from the Kuban Delta).

Figure 2. Variation in temperature and salinity with depth at four time intervals from 44.53°N and 37.93°E on north-eastern Black Sea shelf.

Figure 3. Occurrence of ostracods in core Ak-2575. Lithology and calendar ages are based on Ivanova et al. (2015). 2σ range for the calibrated radiocarbon dates 2610 (2360-2800); 3590 (3390-3830); 6270 (6000-6450); 6510 (6300-6690);
6820 (6600-7030); 7150 (6910-7330); 7415 (7250-7580); 7520 (7410-7680); 9440 (9270-9540); 9550 (9470-9690) (all cal yr BP).

Figure 4. Occurrence of ostracods in core Ak-521. Lithology and calendar ages are based on Ivanova et al. (2015). 2σ range for the calibrated radiocarbon dates 4540 (4280-4830); 6120 (5920-6302); 6410 (6270-6640); 6870 (6650-7160); 7420 (7170-7620); 8740 (8380-9130); 8710 (8350-9130); 9150 (8700-9500); 11,870 (11,250-12,430) (all cal. yr BP). Sediment and ostracod occurrence legend in Figure 3.
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assemblages; (M) stratigraphy. (A-D, F, H-J, M) from Ivanova et al. (2015); Ne –
Neoeuxinian (11.8–10 cal ka BP), Bg – Bugazian (10–8.8 cal ka BP), Vt –
Vityazevian (8.8–7.8 cal ka BP), Kl – Kalamitian (7.8–6.9 cal ka BP), Dz –
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Table 2. Modern distribution of ostracod species of Caspian type in Azov-Black Sea basin based on literature data (Schornikov, 1967, 2011; Opreanu, 2008)

Table 3. Modern distribution of some collected ostracod species in Caspian Sea. I-IX samples (see Fig. 1C), *- species is found living; without * - only valves and shells; I-IX- sample numbers, S, t, O2, pH are noted only for sites with living ostracods

Table 4. Species composition of ostracod fauna from the NE outer shelf. Occurrence of species: +++ - abundant, ++ - common, + - rare. Bg – Bugazian (10–8.8 cal ka BP), Vt – Vityazevian (8.8–7.8 cal ka BP), Kl – Kalamitian (7.8–6.9 cal ka BP); Dzhemetinian (6.9–2.6 cal ka BP) according to Balabanov (2007). M- species of Mediterranean type, C – species of Caspian type; F/O – freshwater-oligohaline species. I, IIA, IIB,IIIA, IIIB- Assemblages (see Fig. 3-4)
Supplementary data

Table 1. Ostracod species occurrence in core Ak-2575

Figure 1. SEM images of ostracod species


Figure 2. SEM images of ostracod species

Figure 3. SEM images of ostracod species

1 - *Cytheroma marinovi* Schornikov, 1969, right valve (RV) of female, AK 2575, 30-32 cm. 2 - *C. marinovi*, left valve (LV) of male, AK 2575, 32-34 cm. 3 - *Pontocythere tchernjawskii* Dubowsky, 1939, RV of A-1, AK 2575, 14-16 cm. 4 - *Hiltermannicythere rubra* (Müller, 1894), RV of female, AK 2575, 40-42 cm. 5 - *Tyrrenocyclthera amnicola donetziensis* (Dubowsky, 1926), RV of A-1, AK 2575 182-