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Compilation of geophysical, geochronological, and geochemical evidence indicates a rapid Mediterranean-derived submergence of the Black Sea's shelf and subsequent substantial salinification in the early Holocene

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ABSTRACT

Our knowledge of rate and processes in which semi-enclosed environments alternate from lacustrine to marine is commonly limited because of the paucity of specific proxies for sea level and salinity. Here we investigate the timing, rate, and key mechanisms involved in the transformation of the previously isolated Black Sea-Lake to the modern partly-enclosed marine sea using a suite of geophysical, geochemical, and geochronological methods. Cores were collected in transects across shelves of Ukraine, Romania, Bulgaria, and Turkey. Biogenic carbonate from these cores was analyzed for radiocarbon and strontium, oxygen, and carbon isotopes. Strontium results indicate that the submergence of the Black Sea shelf at 9300 calendar years BP was caused by the ingress of Mediterranean water and was abrupt, taking <40 years. The seismic reflection profiles show a uniform drape of subsequent sediment over aeolian dunes indicating a drowning with no time for erosion accompanying the submergence. Moisture measurements beneath the uniform drape indicate that the shelf was dry before submergence and the shoreline of the Preboreal lake may have regressed to beyond 120 mbsl. Mollusks colonized the newly submerged substrate of the inner shelf at the same time as they colonized the outer shelf. The succession of mollusk species with shells whose strontium isotope composition has a marine component indicates a rising salinity. The transformation of the lake to a sea is affirmed by increases in the shells' strontium and oxygen isotopic ratios towards the external ocean value.

Radiocarbon years are calibrated to calendar years by tuning the oxygen and carbon isotope composition of the mollusk record to that of the U/Th dated Sofular Cave stalagmites. The match shows a reduction of the lake's prior high reservoir age accompanying the inflow of the Mediterranean water. In 900 years the salinity reached a threshold that excluded all previous Black Sea lacustrine fauna. These results imply that any substantial postglacial submergence of the Black Sea shelves did not occur prior to entry of Mediterranean water.

1. Introduction

The Black Sea is a large and deep meromictic body of water connected to the global ocean via a system of straits and intermediate seas. Currently, the water exchange involves excess freshwater outflow and marine water inflow across the Strait of Bosporus above a 35 mbsl sill.

The exchange is dynamic, and changes between glacial and interglacial periods. During glacial periods, when global sea level falls below the level of the Black Sea's outlet, the lake surface cannot rise above the elevation of the outlet sill and is instead controlled by the regional hydrologic budget. As a consequence, the sea remains isolated from the global ocean and evolves over time into a lake (Arkhangel'skiy and Strakhov, 1938; Brujevich, 1952). When deglaciation raises the external sea level above the level of the outlet, the lake reverts to a sea for the duration of the interglacial highstand (Schrader, 1979; Zubakov, 1988).

The most recent reconnection of the Black Sea with the Mediterranean has been placed, with broad consensus, in the early Holocene, between 7000 and 9000 ^{14}C years (Ross et al., 1970; Strakhov, 1971;

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Deuser, 1972; Kuprin et al., 1974; Scherbakov and Babak, 1979; Degens et al., 1980; Dimitrov, 1982; Jones and Gagnon, 1994; Ryan et al., 1997; Aksu et al., 2002; Dimitrov and Dimitrov, 2004; Major et al., 2006; Dimitrov, 2010; Nicholas et al., 2011; Soulet et al., 2011b; Filipova-Marinova et al., 2013; Nicholas and Chivas, 2014).

The level of the Black Sea–Lake prior to the connection remains a subject of disagreement. Kuprin et al. (1974), Scherbakov and Babak (1979), and Konikov et al. (2007) proposed that the Black Sea-Lake experienced a significant regression, exposing most of its shelf and turning it into a terrestrial landscape out to a shoreline between 80 and 100 mbsl. This regression is supported by pervasive erosion observed in reflection profiles that cross the Ukraine, Romanian, Bulgarian, Russian, and Turkish shelves (Ryan et al., 1997; Demirbag et al., 1999; Aksu et al., 2002; Hiscott et al., 2002; Algan et al., 2007; Glebov and Shel'ting, 2007). The element of disagreement arises from interpretation of data regarding the level of the water surface in the Black Sea-Lake at the time of the introduction of Mediterranean water. Was the lake surface below the level of the inlet such that the ingress of salt water involved a transgression of the exposed shelf? Or was the lake already at the elevation of the inlet?

Four different hypotheses for the Black Sea-Lake level currently exist (Fig. 1). One hypothesis assigns the maximum regression to 18,000 ^{14}C years, followed by a gradual transgression to the Black Sea outlet (placed at 35 mbsl) and completed before entry of saltwater (Kuprin et al., 1974; Kaplin and Shecherbakov, 1986; Pirazzoli, 1996; Kaplin and Selivanov, 2004; Balbanov, 2007; Sorokin and Kuprin, 2007). A second hypothesis places the maximum regression at 11,000 ^{14}C years, recognized as the Younger Dryas period of the late Pleistocene, followed by a rapid freshwater transgression ending at ~ 10,000 ^{14}C years ago at the level of the outlet (Bosporus sill) and also completed prior to the connection of the Mediterranean Sea with the Black Sea-Lake (Aksu et al., 2002; Hiscott et al., 2002; Hiscott et al., 2007a; Hiscott et al., 2007b). Yanko-Hombach et al. (2014) and Mudie

et al. (2014) have proposed that the surface of the Black Sea-Lake was never lower than 30 mbsl in the early Holocene prior to its evolution to a sea. A third hypothesis also recognizes a regression in the Younger Dryas period, but one that persists into the Preboreal and ends with an abrupt transgression exclusively caused by a cascade of Mediterranean saltwater that begins when the rise of external eustatic sea level reaches the inlet (Lericolais et al., 2007; Nicholas et al., 2011). A fourth hypothesis recognizes a significant regression confined to the Preboreal period, immediately before the rapid transgression from the entry of Mediterranean water (Dimitrov, 1982; Ryan et al., 1997; Major et al., 2002; Ryan et al., 2003; Dimitrov and Dimitrov, 2004; Ryan, 2007; Dimitrov, 2010).

The variations between each of the individual hypotheses arise from differing age models and interpretation of available data to show whether the early Holocene transgression was indeed fresh or marine. The traditional Black Sea chronology (Fig. 1) divides Black Sea late Pleistocene and Holocene history into four stages based on changes in the mollusk assemblage (Nevesskaya, 1965): (1) Neoeuxine, an interval of time that encompasses the Black Sea glacial and deglacial until its connection with the Mediterranean; (2) Bugaz, an interval of time where both fresh and marine mollusk shells exist in the same deposit; (3) Old Black Sea, an interval of time following the Bugaz in which the salinification is gradually taking place; (4) New Black Sea, an interval of time during which the Black Sea attained its modern salinity level. This paper re-evaluates each of these hypotheses with additional ^{14}C, δ^{18}O, δ^{13}C, and ^{87}Sr/^{86}Sr measurements on mollusk shells from all of the Black Sea margins together with complementary reflection profiles and bathymetry. A new age model aligns the traditional Black Sea chronological scheme to one that incorporates changes in the radiocarbon reservoir of the Black Sea-Lake surface water.

2. Methods and Materials

Reflection profiles were acquired on the 1993 *Akvanavt* (Ryan et al., 1996; Ryan et al., 1997), 1998 BLaSON1 and 2002 BLaSON2 (Lericolais et al., 2007), and 1998 Bulgarian navy ship *Hydrograph* (Genov, 2014) expeditions (Fig. 2 from the Ukrainian, Romanian, Bulgarian, and Turkish shelf areas of the Black Sea). Chirp profiles U-A and U-B were retrieved from the Ukrainian margin during the 1993 *Akvanavt* expedition. Chirp profiles R-A and R-B were retrieved from the Romanian margin during the 1998 BLaSON1 expedition. Chirp profile B-A was retrieved during the 2002 BLaSON2 expedition from the Bulgarian margin. Boomer-sourced reflection profiles B-B and B-C were retrieved during the 1998 expedition with the Bulgarian navy ship *Hydrograph* from the Bulgarian margin. Perspective dune view was retrieved as part of the Emine transect also during the latter expedition. Chirp profiles T-A, T-B, and T-C were retrieved during the 2002 BLaSON2 expedition from the Turkish margin.

Cores were collected on transects across the Black Sea shelf during: (1) joint Russian-US expedition, AK93, in 1993 on board the *R/V Akvanavt* that surveyed western Crimea and Kerch region of the outer continental shelf, (2) a joint French-Romanian BlaSON1 expedition in 1998 that surveyed Romanian region of the inner and outer continental shelf aboard the *R/V Suroit*, (3) a 1998 survey of the Bulgarian shelf with the *R/V Hydrograph*, (4) a 2001 expedition aboard *R/V Akvanavt* across the Russian shelf, (5) a French-Romanian BLaSON2 survey in 2002 that surveyed the Bulgarian and Turkish regions of the outer continental shelf, (6) a collaborative Israel, Turkey, and US expedition in 2005 aboard the *R/V Mediterranean Explorer* on the western Turkish margin, and (7) expeditions in 2009 and 2011 on the Bulgarian margin aboard the *R/V Akademik* (Fig. 2). A full list of cores used in this study is listed in Supplementary material 1.

When penetrating the seabed the cores encountered a distinct coquina that rests directly on a shelf-wide erosion surface called reflector α (Aksu et al., 2002; Hiscott et al., 2002). This erosion surface extends landward from beyond the shelf edge into coastal limans (Naukova, 1984). Mollusks in the coquina along with ostracods in the earlier
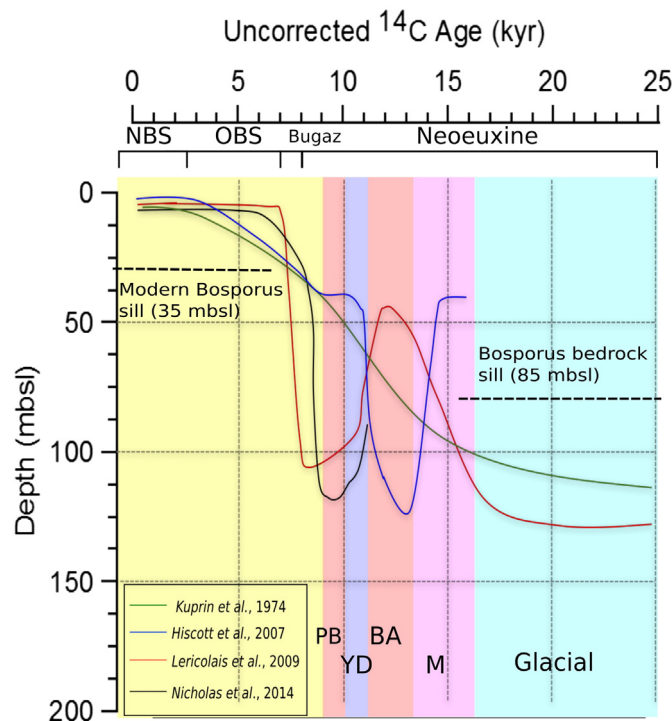

Fig. 1. Four previously published water level reconstructions for the post -Glacial to Holocene Black Sea: Hypothesis 1, green line (Kuprin et al., 1974); hypothesis 2, blue line (Hiscott et al., 2007a); hypothesis 3, red line (Nicholas et al., 2011); hypothesis 4, black line (Ryan et al., 1997). M refers to the Black Sea Meltwater event, PB to Preboreal, YD to Younger Dryas, and BA to Bølling/Allerød. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
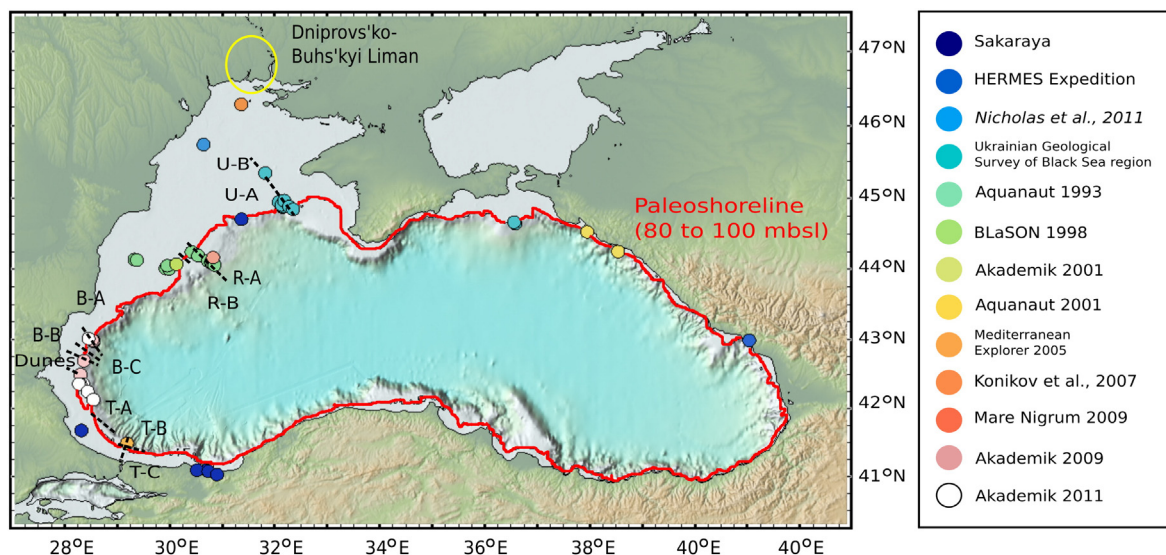
Fig. 2. Location of cores (colored circles), reflection profiles (dotted lines), limans (yellow line), and inferred paleoshoreline (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

deglacial and glacial age sediment, and specimens from the younger cover were analyzed for radiocarbon, stable isotopes, and strontium isotopes. Analyses were also made on material from boreholes into the Sakarya coastal plain (Görür et al., 2001) via a vibra-core on the inner Ukrainian shelf (Konikov et al., 2007).

Moisture measurements of sediment in cores collected on the *R/V Akvanavt* were made by a resonance probe and converted to water content by weighing the sediment before and after drying. The bulk density of the sediment was measured by weighing the sediments in a pre-measured and pre-weighed container.

Mollusks and ostracods retrieved from the cores were analyzed for radiocarbon, stable isotopes, and strontium isotopes. For preparation for ^{14}C age measurements, the mollusks and ostracod shells were sonicated for 30 s in quartz distilled water and methanol to remove contaminating surface detrital matter. Samples were analyzed following carbonate hydrolysis and CO_2 reduction at Woods Hole Oceanographic Institution and ETH-Zurich. Additional ^{14}C ages were utilized from Major et al. (2006), Major et al. (2002), Konikov et al. (2007), Görür et al. (2001), Apakidze and Burchuladze (1987), Lericolais et al. (2007), Ivanova et al. (2007), Soulet et al. (2011a), Soulet et al. (2011b), and Nicholas et al. (2011).

Stable isotopes were measured by gas-source mass spectrometry at the Department of Earth and Planetary Sciences at Rutgers University (Mortlock, 2010) and at Rensselaer Polytechnique Institute (RPI) (Cohen, 2011). A fragment weighing approximately 700 to 1200 µg of shell material was taken from each mollusk specimen. Prepared samples were loaded onto a Multi-prep device attached to a Micromass Optima Stable Isotope Mass Spectrometer and reacted in 100% phosphoric acid at 90 °C for 800 s. Values are reported with respect to V-PBD through the analysis of an internal laboratory standard that is routinely calibrated against NBS-19. The errors associated with the measurements are 0.04 and 0.06 ‰ for δ^{13}C and δ^{18}O, respectively. Additional δ^{13}C and δ^{18}O are supplemented to the existing stable isotope records from earlier work (Major, 2002; Major et al., 2006; Cohen, 2011).

For ^{87}Sr/^{86}Sr isotope analyses, mollusk and ostracod shells were leached using a procedure modified from Bailey et al. (2000) following the sonification treatment. The first leach consisted of a one-minute sonification of the sample in 0.1 N hydrochloric acid. The isotope ratios were measured by a dynamic multi-collector on a VG Sector 54 thermal ionization mass spectrometer (TIMS) at Lamont-Doherty Earth Observatory. The ^{87}Sr/^{86}Sr ratios were corrected for mass fractionation through normalizing to ^{86}Sr/^{88}Sr = 0.1194. Beam size was maintained

at close to 4.5×10^{-11} A for ^{88}Sr. The measurements were further corrected for instrumental drift by analysis of NBS987 which gave ^{87}Sr/^{86}Sr = 0.71026 ± 2.3-05, 2σ external reproducibility, n = 7. All ^{87}Sr/^{86}Sr ratios are further corrected relative to the NBS987 standard's ^{87}Sr/^{86}Sr value of 0.71024. The errors presented in this paper are the in-run 2σ error of the mean. Our investigation also includes previous ^{87}Sr/^{86}Sr measurements from some of the same cores (Major et al., 2006; Cohen, 2011). Age control of the isotopic measurements is provided by AMS ^{14}C dates on the same shell material.

3. Age model

The age model for assembling all of the isotope measurements in chronological order is created by deriving ^{14}C reservoir ages for the late Pleistocene and Holocene stages of the Black Sea history, and then using the ^{14}C reservoir ages to convert the measured ^{14}C dates into calendar years (Reimer et al., 2013). The time-varying ^{14}C reservoir ages are obtained by comparing the δ^{18}O and δ^{13}C compositions of mollusks as a function of their measured ^{14}C age from all of the available shelf cores to δ^{18}O and δ^{13}C measurements in nearby U/Th dated stalagmites in the Sofular Cave (Fleitmann et al., 2009; Badertscher et al., 2011). Tuning mollusk δ^{18}O to the Sofular Cave δ^{18}O is supported by the assumption that the δ^{18}O composition precipitated in the carbonate of the cave reflects the evaporated surface water δ^{18}O of the Black Sea-Lake (Fleitmann et al., 2009; Badertscher et al., 2011). Tuning mollusk δ^{13}C to the Sofular Cave δ^{13}C assumes a common source of carbon, one that responds to a change in the distribution of C_3 and C_4 plants and that supplies both the carbonate in the Sofular Cave and the dissolved carbonate in the Black Sea. The method and the corresponding illustration are provided in Supplementary material 5. Meltwater, Older Dryas, Bølling/Allerød, Younger Dryas, and Preboreal periods are identified, as specifically reflecting changes in Black Sea climate. Their corresponding calendar ages are 16,300 to 15,000 years, 15,000 to 14,800 years, 14,800 to 12,900 years, 12,900 to 11,900 years and 11,900 to 9300 years, respectively. Younger Dryas is identified as a peak in δ^{13}C whereas Bølling/Allerød and Preboreal as troughs in δ^{13}C.

The ^{14}C ages from mollusks retrieved from Sakarya coastal plain, perched ponds, and paleo-river beds are given a zero ^{14}C reservoir correction with the understanding that since these specimens previously inhabited an environment predominantly fed by river-water with permanent exposure to the atmosphere, this water is assumed to have equilibrated to the atmospheric ^{14}C age.

The ^{14}C reservoir ages from Nowaczyk et al. (2012) are calculated from finding values that convert their derived calendar ages to ^{14}C ages and subtracting the calculated ^{14}C ages from their measured ^{14}C age in the same sediment sample. For the glacial period prior to 18,000 calendar years BP, our adopted ^{14}C reservoir ages are set approximately between those of Soulet et al. (2011a) and Nowaczyk et al. (2012) as a compromise between modest differences. For the Holocene period post connection, the ^{14}C reservoir adopted in this paper is set to rise progressively to that of the modern surface ^{14}C reservoir of the Black Sea of 460 ^{14}C years (Jones and Gagnon, 1994).

4. Results

4.1. Reflection Profiles

4.1.1. Ukraine Margin

Chirp profile U-A (Fig. 3) descends from 45 to 140 mbsl across the middle and outer Ukraine shelf and all the way to the uppermost slope. The shelf is not entirely smooth, but instead is populated by mesas separated by depressions. Buried channels are encountered between the mesas (Fig. 3a, b).

A belt consisting of 100 to 200 meter wide linear ridges spans an area that is 1–2 km-wide and tens of km-long between 75 and 85 mbsl (Fig. 3a). Ryan et al. (1996) and Naudts et al. (2006) interpret these ridges as coastal dunes. The dunes are situated landward relative to an incline interpreted as a paleo-shoreface (Ryan et al., 1996). Seaward, a smooth ramp delineates a former wave-cut terrace cut into a shelf-edge pro-delta (Naudts et al., 2006). The dunes rest above a splay of filled channel terminations whose strata are truncated by the shelf-wide erosion surface (Fig. 2). A thin (1 to 2 m thick) sedimentary drape rests on this erosion surface and is present everywhere across the shelf.

The cores located landward of the dunes penetrate the drape and recover sediments comprising the drape and the underlying coquina that rests on the erosion surface. Some material of the eroded substrate is occasionally recovered in the core catcher (that component of a coring device that retains material from falling out as the coring device is retrieved). The material derived from the hard ground is shell free, stiff, and with minor sand. Cores seaward of the dunes and shoreface

encounter two erosion surfaces. The older one is identified as α and the younger as $\alpha1$ by adoption to the nomenclature of Aksu et al. (2002). The cores penetrate well below the two erosion surfaces and successfully sample sediment that belongs to the underlying seaward-dipping reflectors (Fig. 3).

4.1.2. Romanian Margin

Chirp profile R-1 from the Romanian shelf (Fig. 4a) extends from 125 to 300 mbsl. Where sampled, the substrate consists of three depositional units identified as: (1) the surficial drape, (2) sediment dated to a range between 10,260 and 11,100 ^{14}C years, and (3) sediment older than 14,900 ^{14}C years. A coquina separates each of these units. The older coquina sits upon erosion surface α and the younger coquina upon erosion surface $\alpha1$. The surficial drape is a 1–2 m thick uniform cover that is also observed on the Ukrainian shelf (Popescu, 2008; Lericolais et al., 2009). This drape thins to <0.5 m on the outermost shelf based on recovery in BLKS98-06 (135 mbsl), BLKS98-07 (163 mbsl), BLKS98-08 (186 mbsl) and 09-SG-13 (200 mbsl). On the slope, the cover then thickens to >0.5 m as shown by δ^{18}O measurements on bulk carbonate in BLKS98-09 (240 mbsl) and BLKS98-10 (378 mbsl). In 09-SG-13, the drape has a mollusk assemblage rich in *Modiolus phaeseolina*, belonging to the New Black Sea stage. A paleoshoreline follows the 90 mbsl isobaths on the Romanian shelf (Fig. 4b). A belt of dunes lies landward and in oblique orientation to the shoreline (Lericolais et al., 2007). The dunes rest directly on the shelf-wide erosional surface α, colored red, and are covered by the surficial drape. As also observed on the Ukrainian shelf, a coquina is present in the base of the drape.

4.1.3. Bulgarian Margin

Chirp profile B-A (Fig. 5) crosses the Bulgarian middle and outer shelf off Cape Emine from 30 to 170 mbsl. The same surficial drape as observed on the Ukraine and Romanian margins is also omni-present and thins seaward. Once again, the drape rests on the α erosion surface, here also colored red. Landward of the 90 mbsl isobath, the substrate beneath the erosion surface is acoustically opaque due to strong attenuation of acoustic energy. Between 90 and 110 mbsl, there is a row of ridges that are similar in shape, size, and orientation to those identified as subaerial coastal dunes on the Ukraine (Ryan et al., 1997) and
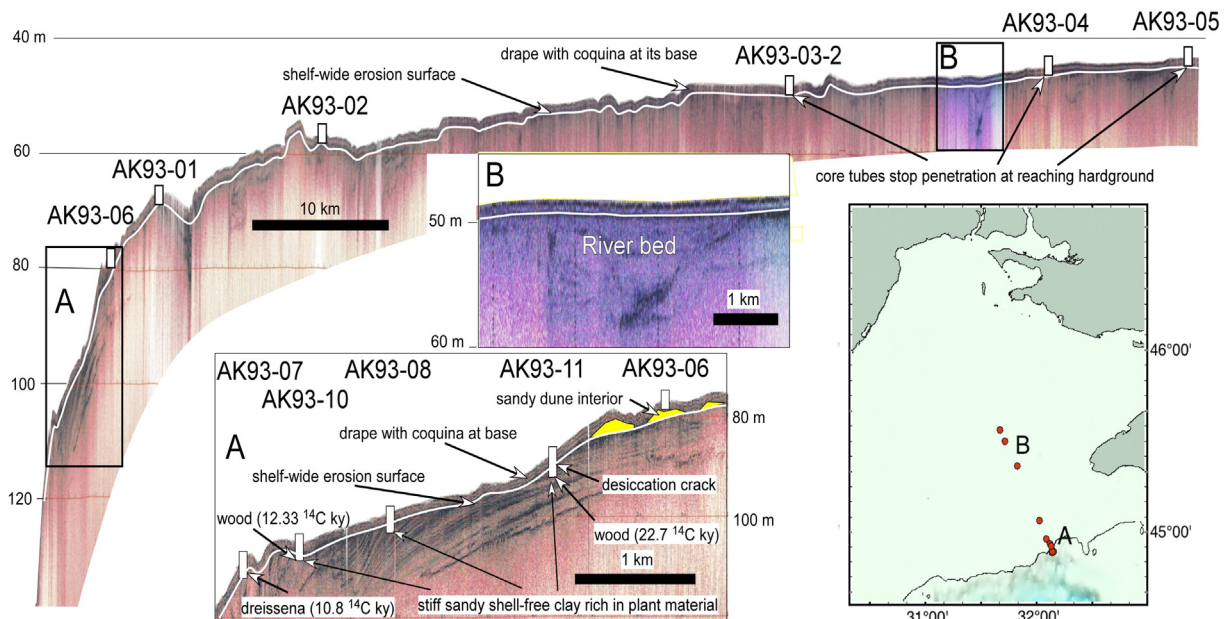

Fig. 3. The U-A and U-B chirp profiles across the outer and middle Ukrainian margin with location of cores AK93-06, 01, 02, 03-2, 04, and 05. The map inset (lower right) indicates the location of these chirp profiles in the Black Sea. White line indicates the shelf wide erosion surface and yellow, the dune interior. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
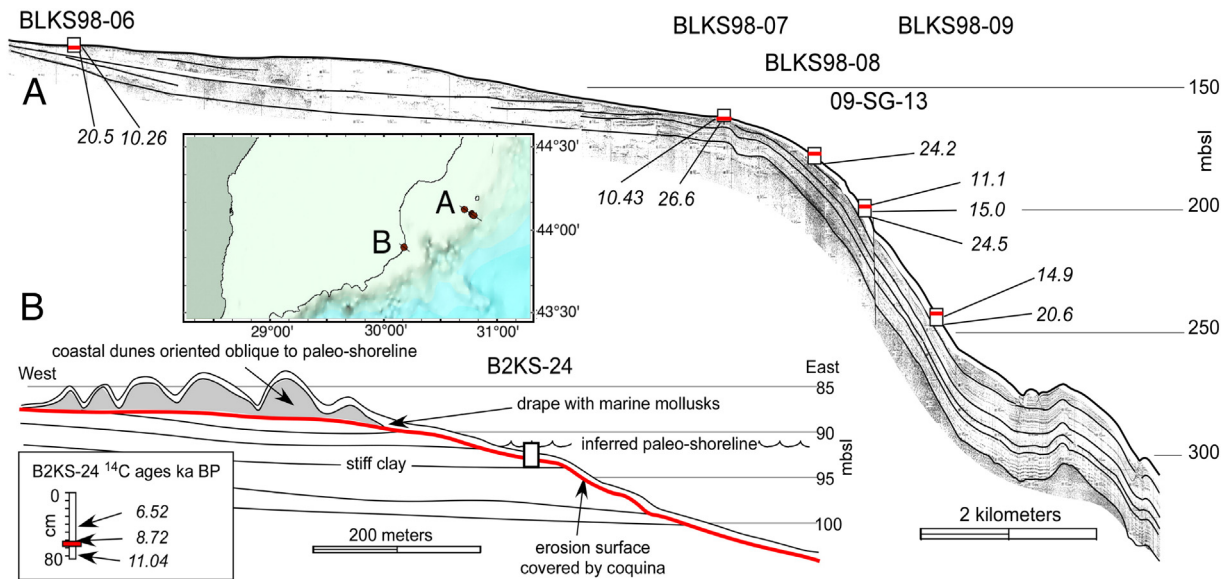
Fig. 4. (a) The R-A chirp profile from the outer Romanian margin with superimposition of cores BLKS98-09, 08, 07, and 06; (b) R-B chirp profile with the superimposition of B2KS-24 adapted from Lericolais et al. (2007). The 95 mbsl contour indicates the inferred paleoshoreline.

Romanian (Lericolais et al., 2007) margins. These dunes also rest on the α erosion surface. Cores AKAD09-19 and AKAD01-AB18 penetrated into the dune interiors and recovered mud-free sand consisting mostly of pulverized shells, rounded quartz grains with a frosty texture, and sand-sized lithic fragments. Core AKAD09-28, recovered from strata located seaward of the paleoshoreline, penetrated into three deposition units: (1) the surficial drape, (2) sediment dated to ~10,200 ^{14}C years, and (3) sediment older than 14,150 ^{14}C years with coquina separating each unit, respectively.

Also shown are two boomer-type reflection profiles B-B and B-C obtained in 1998 with the Bulgarian navy ship *Hydrograph* (Genov and Slavova, 2004) upon which nearby cores have been projected (Fig. 6). The greater acoustic penetration of the boomer sound source allows the dunes to be observed as superimposed on the truncated foreset beds. The internal reflectors of these beds can be traced seaward as bottom-set beds sampled in cores AKAD01-AB17 and AKAD09-28 on the cape Emine Transect (Fig. 6). On the west end of the profile, erosion has cut so deep as to expose much older conformable layers (blue) beneath the drape and the coquina bed. These conformable layers clearly predate the overlying clinoforms and are separated from the clinoforms

by another erosion surface. They subcrop beneath the dunes with the older strata exposed at shallower depths relative to younger strata.

Where mapped in detail on the Emine Transect, the coastal dunes are oriented oblique to the shoreface (Fig. 7) but in the opposite orientation to the dunes on the Romanian margin. Gravity cores AKAD09-19 and -20 attempted to penetrate into the dune interior without success. Only the surficial drape with a thickness reaching 0.9 m was recovered. However, core AKAD09-28 beyond the shoreface was able to sample late glacial and post-glacial sediments as well as the coquina deposit and its overlying drape.

The strata beneath the proposed offshore ramp on the outermost shelf contain two hiatuses evident in the chirp profile. These two hiatuses separate three deposition units in AKAD09-28: (1) the surficial drape, (2) sediments dated to 10,200 ^{14}C years, and (3) sediments dated to 14,150 ^{14}C years and older. This succession is identical to one encountered beyond the paleo-shoreline on the outermost Ukrainian and Romanian shelves. The dark gray mud below the older hiatus is stiff, as observed during core splitting on board the Akademik 2009 cruise. Mud cracks were observed in the top of this firm clay. The cracks are filled with and covered with pulverized shell debris. The uppermost
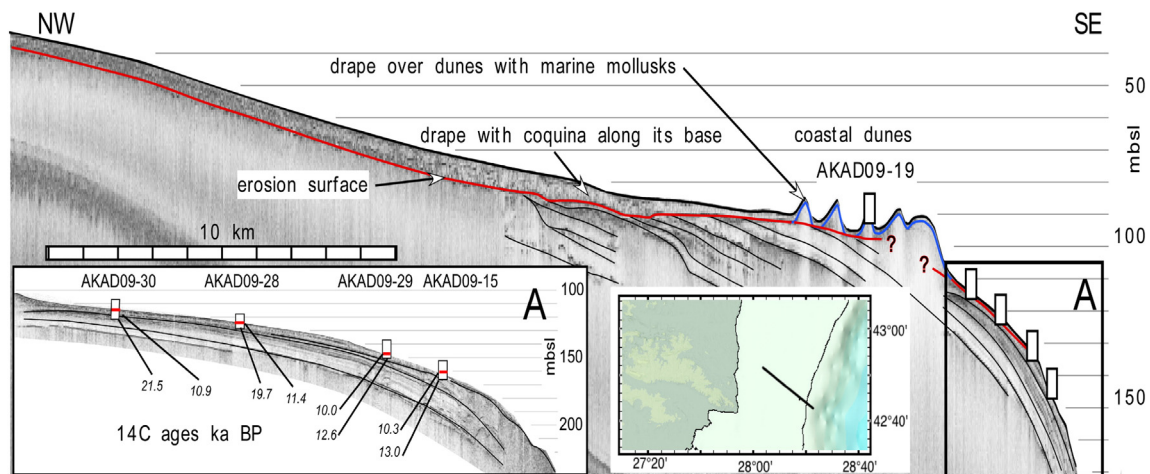

Fig. 5. The B-A chirp profile with the superimposition of cores AKAD09-19, AKAD01-AB18, AKAD01-AB20, AKAD01-AB17, AKAD09-28. The red line traces the erosion surface α from the middle shelf to the uppermost slope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
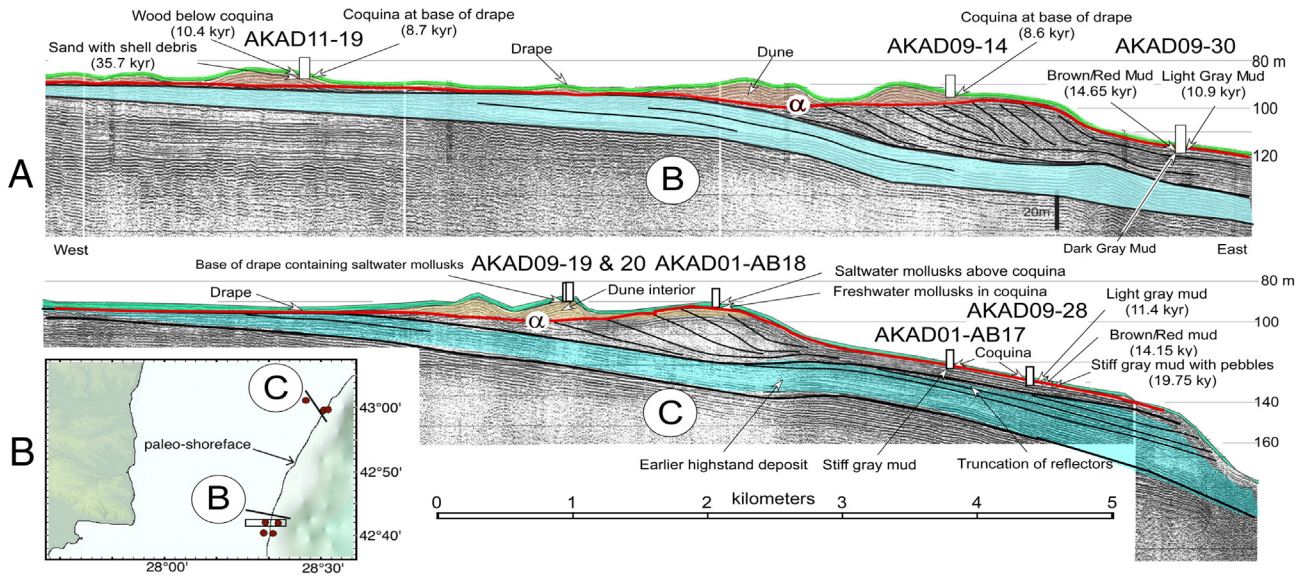
Fig. 6. Reflection profiles (a) B–B and (b) B–C. Cores AKAD11-19, AKAD09-14, and AKAD09-30 are superimposed upon B–B and AKAD09-19, AKAD01-AB18, AKAD01-AB17, and AKAD09-28 upon B–C. Rectangle indicates the location of Fig. 7.

0.1 m of the firm clay contains pieces of wood. This mud overlies brown clay that is ^{14}C dated to 14,150 ^{14}C years and belongs to the same lithology as sampled on the Romanian margin and attributed to an episode of post-glacial melt-water flooding (Major et al., 2002; Bahr et al., 2006; Major et al., 2006; Soulet et al., 2011a). In turn the shell debris is overlain by light gray mud with articulated mollusks in sandy lenses and dated to 10,200 ^{14}C years. On top of this mud is another bed of shell debris belonging to the younger coquina. The drape over the dunes is 0.25 m thick and consists of sediment belonging to the Bugaz, Old Black Sea, and New Black Sea stages, all with marine mollusks.

4.1.4. Turkish margin

Chirp profile T-A is located on the outermost Turkish shelf north of the entrance of the Bosporus Strait (Fig. 8a). This profile is oriented west-to-east in the distal region of a network of branching channels that presently funnel Mediterranean salt water from the strait into the heads of submarine canyons (Di Iorio and Yüce, 1998; Flood et al., 2009; Hiscott et al., 2013).

An acoustically transparent drape is observed that thins seaward and reaches beyond the shelf break, similar to the behavior of the surficial cover on the previously described shelves (Fig. 8a). However, on the Turkish margin there are two notable differences. One difference is a somewhat chaotically bedded and highly reflective deposit in the center of the profile that belongs to the internal cores of the levees of branching channels formed beginning with the inflow of Mediterranean saltwater from the Bosporus (Ryan et al., 2013). The other is the wavy character of the transparent layer shaped by the inflowing more saline Mediterranean water that is currently traveling (into the page) through the two channels shown in the figure. Core MedEx05-10 sampled the transparent drape adjacent to one of the channels and confirmed that it contains the Bugaz, Old Black Sea, and New Black Sea stages of the Holocene with exclusively saltwater mollusks.
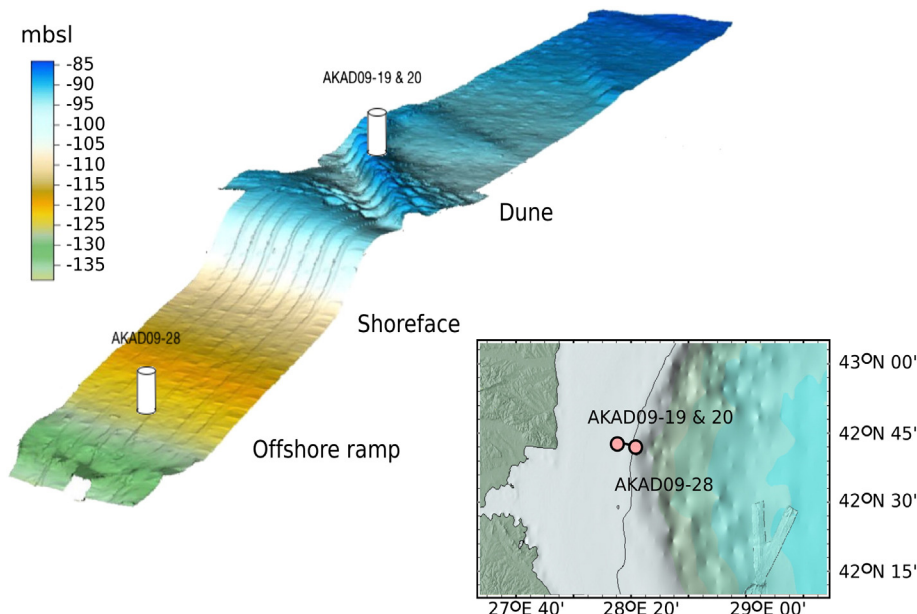

Fig. 7. Perspective view of the dune field, shoreface, and offshore ramp on the Emine Transect. The location of cores AKAD09-19, 09-20, and 09-28 is indicated.
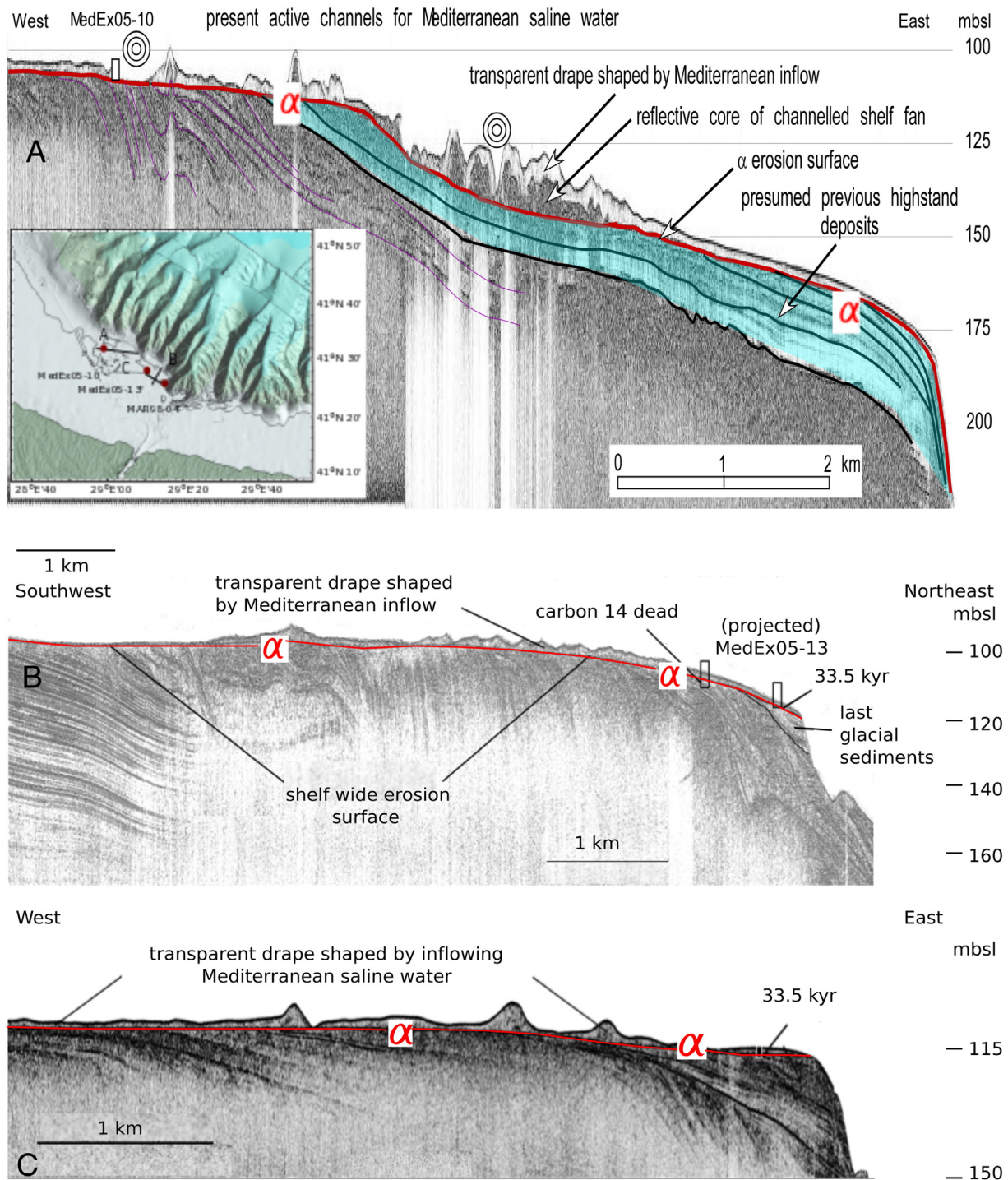
Fig. 8. Chirp profiles (a) T-A; (b) T-B; (c) T-C. Medex05-10 is superimposed upon T-A and Medex05-13 is superimposed upon T-B.

The α erosion surface beneath the drape truncates older seaward-dipping strata out to an abrupt change in gradient at 115 mbsl. Here are strata are assigned to the previous interglacial highstand (shown in blue in Fig. 8a). These strata are also truncated by the α erosion surface right out to the shelf break at 180 mbsl. The most severe erosion has occurred beneath the highly reflective interiors of the channel deposit in the center of the profile.

Chirp profile T-B (Fig. 8b) once again illustrates the widespread truncation of strata by the α erosion surface. This surface has been reached and penetrated by MedEx05-13 as described in Ryan et al.

(2013). MedEx05-13 encountered a 0.15 m thick mud-free gravel and pebble deposit corresponding to the erosion surface. The gravel is predominately round and flat and consists mostly of mudstone and sandstone. However, the pebbles are angular. The latter consists of quartzite, schist and gabbro abundant in the Paleozoic bedrock of the Bosporus Strait. The sediment below the α erosion surface is a stiff shale, rich with intact specimens of *Mytilus galloprovincialis* that are radiocarbon-dead. Core MAR98-04 nearby also penetrated through the α surface and retrieved a white mussel (presumably *Dreissena rostriformis*) with a ^{14}C age of 33,550 (Aksu et al., 2002). Thus, sediments

of presumed glacial age are only present at the very edge of the shelf, and make their appearance at the same depth as they do in profile T-A on the Bulgarian margin.

The absence of sediments of >14,000 ^{14}C years at depths shallower than 110 mbsl on the margin of Turkey north of the Bosporus Strait is further confirmed in chirp profile T-C (Fig. 8c) where MAR98-04 is precisely placed on the profile. Thus, in summary, on all four margins (Ukraine, Romania, Bulgaria and Turkey), sediments of > 14,000 ^{14}C years are observed only in a narrow belt on the outermost shelf. Where present, the strata are partly truncated at the level of the α erosion surface landward of the paleoshoreline and at the level of a younger erosion surface α1 seaward of the paleoshoreline. This younger erosion surface is identified and analyzed in the Section 4.

4.2. Description of the Sediments

4.2.1. Lithology, faunal composition and ages

The surficial sediment drape in cores from the shelf consists of three lithologies. The upper is a light-colored olive-green mud with no silt or sand and especially rich in saltwater *Modiolus phaseolina*, commonly articulated when handled carefully. The middle lithology is a dark-green mud, richer in organic carbon and without *Modiolus phaseolina*. This lithology contains abundant saltwater *Mytilus galloprovincialis* (sometimes referred to as *Mytilus edulis*), *Cardium edule* (also referred to as *Parvicardium exiguum* and *Cerastoderma edule*), and occasionally *Mytilaster lineatus*. Articulated specimens of all of these species with bright original coloring are abundant. The shells belonging to *Mytilus galloprovincialis* and *Mytilaster lineatus* are thin and especially fragile, showing no sign of dissolution, except in cores deeper than 150 mbsl. The lower-most lithology is a lighter-colored gray-green mud with minor detrital silt and sand. The diagnostic feature of this layer is white specks on exposed surfaces that consist of tiny bleached fragments of shells belonging almost entirely to the freshwater *Dreissena rostriformis distincta* (from now on used in the text as *Dreissena rostriformis* for simplicity). In this layer there is an overlap of shells belonging to the salt-water environment and those of the fresh and brackish environments. The saltwater specimens are articulated whereas the freshwater specimens are single valves or fragments of valves.

The afore mentioned sediments have a mixture of fresh and marine sediments, previously recognized as the Bugaz stage (Fig. 9) using the traditional Black Sea chronology (Nevesskaya, 1965). Beneath the Bugaz is a sandy coquina with both intact shells, mollusk debris, devoid of the overlying marine mollusks. In previous publications, the coquina has been called a "shell-hash" or "hash layer" because it is coarse-grained and contains fragmented shells (Dimitrov, 1982; Ryan et al., 1997; Major et al., 2002; Major et al., 2006; Lericolais et al., 2007; Lericolais et al., 2009; Dimitrov, 2010). The fragmented shells are a mixture of abraded black and bleached white *Dreissena* sp. The coquina occasionally contains lithic sand, gravel, and small pebbles. These detrital components are usually rounded and the pebbles also flattened. The coquina consists of two units: a lower mud-free unit and an upper, mud-enriched unit. Heavily reworked specimens are absent in the coquina in cores on the middle and inner shelf and are limited to those cores in the vicinity and seaward of the paleoshoreline and seaward of it.

Articulated specimens are occasionally present in the coquina. The articulated bivalves are identified as *Dreissena rostriformis*, *Dreissena polymorpha*, and *Monodacna caspia*. They are accompanied by the gastropods *Turricaspia caspia caspia*, *Theodoxus pallas*, and sometimes *Viviparus viviparus*. *Cardium edule* is also present, but usually only in the upper muddy part of the coquina. *Mytilus galloprovincialis* and *Mytilaster lineatus* only appear in the Bugaz sediments and are never observed in the coquina.

The ranges of specimens in core AKAD11-19 located at 85 mbsl on the crest of a dune on the Varna transect of the Bulgarian shelf are shown in Fig. 9. Here the coquina rests on a black band with wood and plant fragments belonging to Younger Dryas (i.e., a piece of wood has a ^{14}C date of 10,400 ^{14}C years) directly above mud-free sand, a facies attributed to the dune interior. Two units of the coquina, with mud and without mud, are also observed.

In core AKAD11-19, the Bugaz layer is composed of mud with minor sand and has a mixture of fresh, brackish and marine mollusks. When found there, the marine mollusk shells are usually articulated. The contact with the coquina occurs at 43 cm (Fig. 9b). An assemblage of *Dreissena* sp. with *Mytilus galloprovincialis* and *Mytilaster lineatus* from the Bugaz layer is shown in Fig. 9c. An unwashed sample from the coquina with selected specimens of *Dreissena* sp. and *Theodoxus pallasi* that live in both brackish and fresh water is located in a deposit with
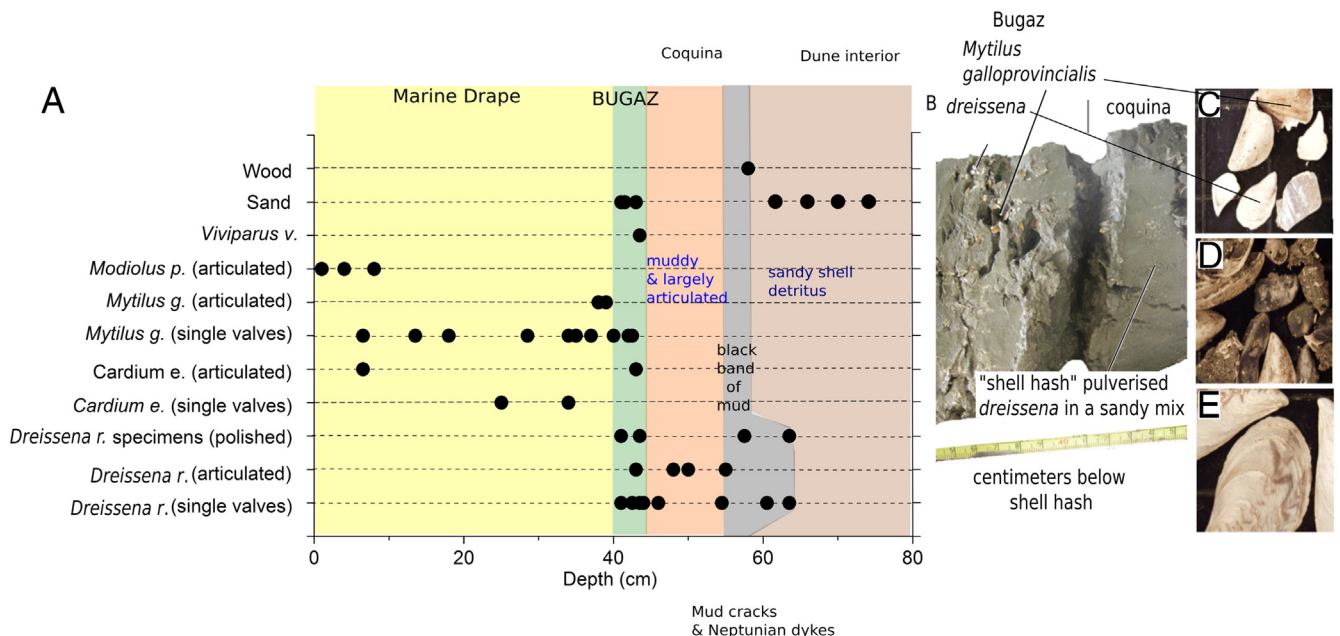

Fig. 9. (a) Range of species and specimens (left) in core AKAD11-19; (b) coquina and Bugaz layers; (c) washed fauna assemblage from the Bugaz; (d) polished *Dreissena rostriformis* specimens; (e) articulated *Dreissena rostriformis* specimens in the Bugaz.

shell sand and mud (Fig. 9d). The fine pulverized shell material appears as white specks in the unwashed-mud adhering to the shells. Some *Dreissena* sp. shells are polished, stained black and otherwise abraded. No species tolerant of saltwater are present in the coquina except for *Cardium edule* that has presumably burrowed into the deposit because it is always found there articulated and in its living orientation.

A black band of mud occurs between 56 and 59 cm, containing pieces of wood, plant, and blackened fragments of *Dreissena rostriformis*. This layer is cut by a mud-crack that extends into the sand beneath. The opening is filled with sandy-mud and contains valves of *Dreissena rostriformis* (Fig. 9e). The sand beneath is mud-free, coarse in texture,

and consists mostly of *Dreissena rostriformis* shell detritus, minerals, and a few pebbles of indurated shale and sandstone.

The coquina contains exclusively lacustrine and brackish water species mixed in sandy mud with scattered small pebbles and pulverized shell debris. The substrate below is even coarser-grained with mostly blackened, abraded, and polished shells mixed into coarse sand composed predominantly of shell debris. Sampled specimens of *Dreissena rostriformis* from the substrate have ^{14}C ages older than 20,000 ^{14}C years. *Dreissena* sp. from the coquina have a narrow range of ages from 8200 to 8800 year BP (^{14}C). The gap in ages between the coquina and its substrate corresponds to the sub-bottom level of the
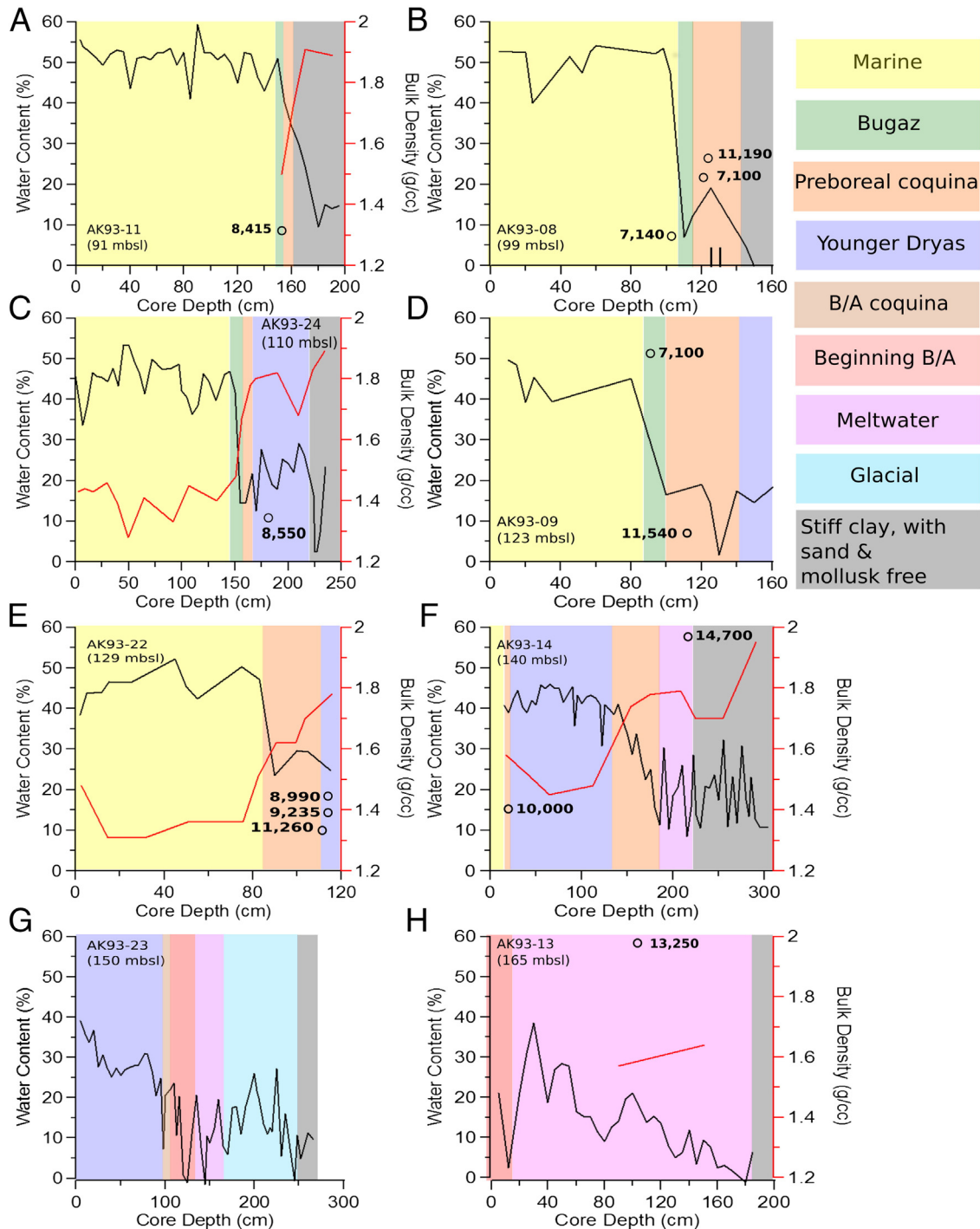

Fig. 10. Water content (%) represented by the black contour and bulk density (g/cm³) represented by the red contour in sediments of (a) AK93-11; (b) AK93-08; (c) AK93-24; (d) AK93-09; (e) AK93-22; (f) AK93-14; (g) AK93-23; (h) AK93-15. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

wide-spread erosion surface (i.e., reflector α) observed in the chirp profiles.

4.2.2. Sediment water content and bulk density

The water content of the sedimentary drape above the youngest coquina is consistently high and approaches 50% (Fig. 10a–h). The bulk density is correspondingly low and mostly less than 1.4 g/cm³. The water content in sediment below the youngest coquina is as low as 10% and the density reaches 1.9 g/cm³. The lowest water content and most dense sediment is in the mollusk-free clay below the α erosion surface. This dense sediment is found in cores as deep as 165 mbsl where it presents resistance to the standard splitting of the recovered sediment cylinder. The water content is also low and density is high in sediments of glacial and meltwater age that lie below the α erosion surface located in cores retrieved seaward of the paleoshoreline. Sediments of Younger Dryas age (Fig. 10c–f) only display low water contents and high bulk densities in cores at elevations above 140 mbsl. It should be noted that the coquina, consisting of loose sand and gravel without mud, releases its porewater as soon as the core is split into two halves for visual examination.

4.3. Isotopic composition of the coquina

The ⁸⁷Sr/⁸⁶Sr composition of mollusks from the coquina and overlying Bugaz deposits in AKAD09-27 and AKAD11-19 cores ranges from 0.70875 to 0.70915 (Fig. 11). *Monodacna caspia* and *Cardium edule* in the Bugaz interval of AKAD09-27 have ⁸⁷Sr/⁸⁶Sr compositions of 0.70908 and 0.709105, respectively. The *Cardium edule* specimen is dated to 6600 ¹⁴C years. *Dreissena rostriformis* from the Bugaz and the top of the coquina (that with the presence of sand) has ⁸⁷Sr/⁸⁶Sr compositions strictly around the value of 0.70895 with ¹⁴C ages that range between 8380 and 8750 ¹⁴C years. In the clean coquina unit, a *Dreissena rostriformis* has an ⁸⁷Sr/⁸⁶Sr value of 0.70875 in AKAD09-27 and 0.70891 in AKAD11-19. The dune interior in AKAD09-27 contains polished *Dreissena* sp. with a ⁸⁷Sr/⁸⁶Sr composition of 0.70879. Another

Dreissena rostriformis from the interior has a ¹⁴C age of 22,500 ¹⁴C years. The dune interior also features two significantly polished specimens identified as *Didacna* of Middle Pleistocene age and *Glycemeris* of Karangatian age (Wesselingh, 2015). Both of these are marine bivalves. The two mollusks have ⁸⁷Sr/⁸⁶Sr composition of 0.70899 and 0.70904, respectively.

The δ¹⁸O composition of the mollusks in AKAD09-27 and AKAD11-19 exhibits an extremely wide range from ~−9.0 to 0.5 ‰ (Fig. 11). In the Bugaz layer, the marine specimens (i.e., *Cardium edule* and *Mytilaster lineatus*) have δ¹⁸O compositions between −0.83 and 0.50 ‰, brackish specimens (i.e., *Dreissena polymorpha*, and *Monodacna caspia*) have δ¹⁸O compositions between 0.5 to −2.0 ‰, and fresh specimens (i.e., *Dreissena rostriformis*) have δ¹⁸O compositions of ~−2 ‰. All of the *Turricaspia caspia* specimens in this layer in AKAD09-27 have δ¹⁸O composition that range between −4.0 and −9.0 ‰. This sedimentary layer also features a *Theodoxus heldreichi* specimen with a δ¹⁸O composition of −4.0 ‰. The dune interior has two abraded *Dreissena* sp. with a δ¹⁸O composition of −6.0 and −8.6 ‰. The two bottom-most *Dreissena* sp. have ¹⁴C dates of 31,400 and 48,100 ¹⁴C years. The aforementioned reworked marine bivalves, identified as belonging to the *Glycemeris* family, have a δ¹⁸O of −1.67 ‰.

4.4. Geographical trends in the geochemical composition of the coquina

The analysis of ⁸⁷Sr/⁸⁶Sr, δ¹⁸O, and ¹⁴C composition in the coquina and Bugaz deposits as a function of present day water depth presents several trends (Fig. 12). The ⁸⁷Sr/⁸⁶Sr composition of the intact mollusks within the coquina deposit increases from 0.70890 to 0.70915 as the water depth at the core sites decreases from 120 to 50 mbsl. From 50 to 20 mbsl, the ⁸⁷Sr/⁸⁶Sr composition then drops to 0.70885. There are no *Dreissena rostriformis* specimens found in the coquina at water depths shallower than 22 mbsl. The specimens landward of 22 mbsl are all marine. A similar trend is identified in the δ¹⁸O composition of mollusks. From 150 to 50 mbsl, the δ¹⁸O composition of the intact

Fig. 11. (a) ⁸⁷Sr/⁸⁶Sr and δ¹⁸O profiles from the Bugaz, coquina, and dune (or barrier island) interior sampled by AKAD09-27; (b) ⁸⁷Sr/⁸⁶Sr and δ¹⁸O profiles from the Bugaz, muddy coquina, and dune interior of AKAD11-19.

Yanchilina Figure 12
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Fig. 12. (a) ^{14}C composition of the mollusks; (b) [87]Sr/[86]Sr composition of the mollusks; (c) δ^{18}O composition of the mollusks. All measurements are presented as a function of shelf depth. Data is provided in Supplementary material 2.

mollusks within the coquina increases from −2.5 to −0.2 ‰. From 50 to 20 mbsl, the δ^{18}O composition declines to −4 ‰.

The ^{14}C ages of the *Dreissena rostriformis* in the coquina are constricted to a time window from 9300 to 8100 ^{14}C years, that of *Dreissena polymorpha* are constricted to a time window 8700 to 7900 ^{14}C years, that of the *Monodacna caspia* to a time window 8100 to 6500 ^{14}C years, and that of *Cardium edule* and *Mytilus galloprovincialis* from the Bugaz layer to a time window of 7900 to 6100 ^{14}C years. These decreasing ages imply successive colonization of the shelf. Furthermore, there is a trend in the ^{14}C age of the *Dreissena rostriformis* towards younger values with decreasing water depth.

4.5. Changes of ^{14}C reservoir age

During the Bølling/Allerød, the ^{14}C reservoir increases to 650 ^{14}C years. Likewise, during the Preboreal, the ^{14}C reservoir rises to at least 1100 ^{14}C years. The estimation only has a lower bound as there are limited

data available immediately before 9300 calendar years. Following the Preboreal, the ^{14}C reservoir age drops from 1100 ^{14}C years to 350 ^{14}C years. This change occurs in a time span of 1500 calendar years. All measurements used single *Dreissena* sp. specimens for matching both their carbon and oxygen isotopic signals to those derived from stalagmites in the Sofular Cave of Turkey.

4.6. Changes in the stable isotope composition

The δ^{18}O rises from −2 ‰ to 0 ‰ in the time range of 9300 to 7800 calendar years BP. However, the magnitude of this change varies by mollusk type. The δ^{18}O composition of *Dreissena* sp. rises from −2 ‰ to −1 ‰ in the time range of 9300 to 8300 calendar years, the δ^{18}O of *Monodacna caspia* rises from −1.3 ‰ to −0.1 ‰ in the time span of 8400 to 7800, and the δ^{18}O composition of marine mollusks (e.g., *Cardium edule* and *Mytilus galloprovincialis*) varies from ±0.5 to around 0 per ‰ through the rest of the Holocene. There are some additional data from Sakarya coastal plain. For an age of around 9200 calendar years BP, a very well preserved and without any significant reworking, a *Dreissena polymorpha* has a highly negative δ^{18}O composition of −9.2 ‰.

The δ^{13}C rises from −0.5 to 1.8 ‰ in the time range of 9300 to 7800 calendar years BP. As with the δ^{18}O composition, this change varies by mollusk type. The δ^{13}C composition of *Dreissena* sp. rises from −0.5 to 1 ‰. The δ^{13}C composition of other transitional (e.g., *Monodacna caspia*) and fully marine species (e.g., *Cardium edule* and *Mytilus galloprovincialis*) ranges from 1.8 to −1 ‰. This drop in δ^{13}C is similar to the drop in δ^{13}C that occurs in the Sofular Cave at 6000 calendar years BP. In the mollusk record this change occurs in a time range of 7700 to 6000 calendar years BP. The δ^{13}C composition of the *Dreissena* sp. from Sakarya coastal plain described above is −7.8 ‰ and not observed in any of the lake deposits.

4.7. Changes in the [87]Sr/[86]Sr composition

The [87]Sr/[86]Sr composition rises from 0.70885 to 0.709104 in the time range of 9300 to 7800 calendar years BP. As with δ^{18}O and δ^{13}C, this change varies by mollusk. The [87]Sr/[86]Sr composition *Dreissena* sp. rises from 0.70885 to 0.709104. The [87]Sr/[86]Sr composition of transitional and marine mollusks varies around 0.709104 with a standard deviation of 0.00005 which is just outside 2 σ for the error associated with the measurements. Three *Cardium edule* specimens that have an [87]Sr/[86]Sr composition in the range of 0.70895 to 0.70905. Two of these specimens are from the Sakarya coastal plain and one other is from a shallow core, 37–82, that was taken from a water depth of −17.7 mbsl. A *Monodacna caspia* specimen from this same core and depth interval in the core, also has a lower [87]Sr/[86]Sr composition. One of the Sakarya *Dreissena polymorpha* specimens gives a [87]Sr/[86]Sr composition of 0.7079. The [87]Sr/[86]Sr composition of the ostracods is identical to the [87]Sr/[86]Sr composition of the mollusks of the same age.

4.8. Limans

A cross section of the Dniprovs'ko-Bush'kyi Liman on the Ukraine coast is adopted from Naukova (1984) and has been constructed from boreholes (Fig. 14). The earliest fill is fluvial sand that blankets an initial gravel and pebble lag deposit. This fill is then covered by red-brown mud attributed to episodes of river flooding. A thin layer of Neoeuxine mud with *Dreissena* sp. covers the flood deposits. The filling then continues during the Bugaz, Old Black Sea, and New Black Sea stages of the Holocene. The modern Dniepr River now occupies a central channel.

5. Discussion

The largest element of disagreement among the aforementioned four hypotheses, arises from the interpretation of data regarding the

elevation of the lake's surface prior to the lake's connection with the Mediterranean Sea. The discussion here reinterprets prior data with the new set of ^{14}C, δ^{18}O, δ^{13}C, and ^{87}Sr/^{86}Sr measurements presented to show that (1) the modern Black Sea shelf was exposed immediately prior to and at the time of the breaching of the Bosporus sill by Mediterranean water, (2) the composition of the Black Sea-Lake was fresh prior to the inflow of Mediterranean water, (3) the Black Sea-Lake level had regressed beyond its paleoshoreline to at least 120 mbsl, (4) the transgression across the shelf was caused by the inflow of Mediterranean water, (5) the transgression was abrupt, (6) salinification that followed the transgression, sufficient to exclude the prior lacustrine mollusks, was completed in 900 years, (7) colonization of the coquina by the mollusks occurred during the period of salinification.

5.1. The Black Sea shelf was a terrestrial landscape at the time of the initial inflow of Mediterranean saltwater

5.1.1. Evidence for widespread erosion

The discovery of a pervasive erosion surface, reflector α, documented in published reflection profiles and profiles presented above is entirely consistent with the deduction formulated many decades ago that much of today's submerged Black Sea continental shelf was once a terrestrial landscape (Kuprin et al., 1974). Additional evidence comes from the observation of: (1) a paleo-shoreline close to the modern shelf edge based on the geometry of buried strata analogous to modern delta and pro-delta deposits (Aksu et al., 2002; Dimitrov and Dimitrov, 2004; Genov, 2004; Genov et al., 2004; Lericolais et al., 2009); (2) meandering shelf-crossing river channels (Ryan et al., 1996; Popescu et al., 2004; Ryan, 2007; Popescu, 2008); (3) relic dunes diagnostic of wind-swept and coastal landscapes (Ryan et al., 1996; Naudts et al., 2006; Lericolais et al., 2007; Ryan, 2007); (4) substantial increase in the density of the sediments below the erosion surface; and (5) peat, grass, leaves, wood, and desiccation cracks at sites where the substrate below reflector α has been successfully sampled (Ryan et al., 1996; Nicholas et al., 2011; Mudie et al., 2014; Nicholas and Chivas, 2014).

5.1.2. Paleo-rivers

The inclined strata that make up the substrate on the Bulgarian and Turkish margins are beveled uniformly with little differential resistance between layers (Figs. 5, 6, and 8). This observation is in contrast to the Ukraine margins (Fig. 3) where the erosion surface is considerably more rugged. The difference may be explained by the abundance of shelf-crossing river channels on the northern margin and their sparseness on the southern margins. As the shoreline retreats during regression, rivers keep pace and cut into the new landscape as they adjust to lowered base level. Such incision created the Dniepr and Dniestr shelf valleys (Konikov et al., 2007; Yanko-Hombach et al., 2014). The mesa act as interfluves.

River-bed infilling commences once a permanent lowstand shoreline has been established. Downstream, gradients decrease and flow velocities drop. Rivers are then able to meander. This allows bedload to accumulate above an initial lag coarse deposit. On the Romanian shelf, cores BLKS98-30 and BLKS98-34 sample fill in a meandering channel between 70 and 76 mbsl that would presumably have been fed by the paleo-Danube (Popescu, 2008). The fluvial sediment below the coquina (dated to 8300 ^{14}C years) is sandy, devoid of mollusks, and accumulated before 23,630 ^{14}C years. The fill of the entrenched Dniepr River is located beneath the floor of the Dniprovs'ko-Bush'kyi Liman (Naukova, 1984). The maximum incision was completed before 17,760 ^{14}C years (Fig. 14).

5.1.3. Aeolian dunes and desert pans

A survey on the mid-shelf (65 to 80 mbsl) off Romania imaged a field of dunes (Fig. 4) with transverse and barchan shapes (Lericolais et al., 2007). The dunes grew directly over the α erosion surface and its underlying river channels (Popescu, 2008). Measurements of dune height versus dune spacing are identical to terrestrial dunes in Colorado and SW Kalahari.

Between dunes are enclosed depressions likened to wind-blown hollows and desert pans. The walls of these depressions display bathtub rings indicative that they periodically filled with water to become ponds that occasionally over-spilled into neighboring ponds (Ryan, 2007). Core BLKS9814, located at 55 mbsl in one such depression between dunes on the inner Romanian shelf, contains dwarfed specimens of *Cardium edule* and *Adacna* from below the coquina. The *Cardium edule* with an age of 9580 ^{14}C years has an ^{87}Sr/^{86}Sr composition of 0.70907 which is substantially more radiogenic than the composition of the Black Sea lake water at that time (0.70890). This discrepancy is ascribed to colonization of perched ponds at elevations high above the paleoshoreline of the Black Sea-Lake (Major et al., 2006). Scherbakov and Babak (1979) describe the same faunal assemblage in sediments from the Sea of Azov which they also interpret to be perched saline ponds during periods of lowered Black Sea level.

The inner and mid-shelf ponds formed during wetter intervals. As the climate became drier during the Preboreal, these ponds shrank, their solutes concentrated, and the environment became suitable only to species such as the *Cardids* that are tolerant of saltier water. The eventual desiccation of the ponds is demonstrated by the migration of dunes across them.

5.1.4. Coastal dunes

In the vicinity of the paleoshoreline, other dunes sit upon the erosion surface. These dunes are smaller in size compared to those dunes located on the mid-shelf and are likened to Lake Superior shoreface ridges (Lericolais et al., 2007). These features (Figs. 3, 4, 5, 6, and 7) are interpreted as coastal dunes. Those cores that penetrated into the interior of the coastal dunes, AKAD09-27 and AKAD11-19, recovered mud-free sand with pulverized shell material directly overlain by the coquina. The shell fragments from within the dune belong to polished and bleached mollusk specimens (Fig. 9d) with ages that range from 21,000 to 48,100 ^{14}C years.

The pulverized shell detritus from the interior of the coastal dunes in the vicinity of the paleoshoreline gives a ^{14}C age of 16,809 ± 319 ^{14}C years. This shell detritus is likely derived from wind ablation and coastal wave action along the paleo-shoreline. If one takes the younger end-member as 8600 ^{14}C years, a value representative of Black Sea water ^{14}C age immediately prior to the inflow of Mediterranean and the older member as 25,000 ^{14}C years, a value representative of the glacial period, the old-member makes up about 75% of the material in the dune interior. This suggests that the dunes were constructed during the glacial and postglacial period at times of a stable paleoshoreline.

The dunes rest on truncated clinoforms, interpreted as forced-regression deposits (Lericolais et al., 2007). The coquina seaward of the paleoshoreline has older reworked mollusks of glacial age and occasional pieces of wood and plant material, some belonging to the Younger Dryas. However, the coquina that rests upon the hardground landward of the coastal dunes does not have reworked material from the substrate below other than minor lithic sand. The clinoforms on the Bulgarian shelf (Figs. 5 and 6) are similar in geometry and depth below sea level to those on the southwest Turkey shelf identified as Δ_1 (Aksu et al., 2002). On both margins topset beds are missing and the seaward dipping foreset beds are truncated by reflector α.

5.1.5. High bulk density and low water content of the substrate

The substantial decrease in measured water content (<20%) and corresponding increase in bulk density to values exceeding 1.8 g/cm^3 (Fig. 10) is attributed to emergence of the lake bed and its desiccation. After subsequent submersion and burial the former terrestrial surface became the substrate below reflector α that has been sampled in the cores. A firm and dry substrate is observed not only beneath reflector

α everywhere, both landward and in the vicinity of the paleoshoreline, but for the sediment below both reflectors α1 and α, seaward of the paleoshoreline. Following the observations and using nomenclature of Aksu et al. (2002), reflector α1 separates sediment of Younger Dryas age (and older) from the coquina, Bugaz, and surficial drape. Superposition of drape over Younger Dryas deposits is only observed seaward of the paleoshoreline as reflector α1 is not present landward of the paleoshoreline on the Ukraine, Romanian, and Bulgarian margins.

Dry and dense sediment identified as the Younger Dryas is present at 110 mbsl in core AK93-24, at 123 mbsl in core AK93-08, and at 129 mbsl in core AK93-22. Dry and dense sediment identified with Younger Dryas and meltwater deposits occur in core AK93-13 at 165 mbsl. The water content is low and bulk density is high in all sediments identified with the Younger Dryas beneath the α1 erosion surface (Fig. 10a–f) and all sediments identified with the meltwater and glacial age beneath the α erosion surface (Fig. 10g–f). The decrease in moisture would have occurred during periods of regression, when the shelf was exposed to the atmosphere allowing for the evaporation of sediment pore water. Hence, the lake surface lay below the paleo-shoreline during periods corresponding to Bølling/Alleød and Preboreal. The regression during the Preboreal was milder, at ~>120 mbsl, relative to that which occurred during the Bølling/Allerød, as deep as ~>150 mbsl.

5.1.6. Peat, grass, leaves, wood, and desiccation cracks

Peat that forms in ponds, bogs, and coastal marshes has been observed in many cores from the Black Sea shelf where it is directly overlain by the coquina (Yanko-Hombach et al., 2007). Although dating of peat does not need prior knowledge of a ^{14}C reservoir age, as do lacustrine samples, analysis of bulk samples risks the incorporation of older material. Individual plant leaves and pieces of wood remove the ambiguity. Mudie et al. (2004) report ages of 8450 ^{14}C years for a sedge leaf and 8890 ^{14}C years for wood from a core at 33 mbsl on the Ukrainian shelf. Even though peat has not been found at elevations below 55 mbsl on any Black Sea shelves, plant roots and wood fragments are present at 99 mbsl associated with desiccation cracks in core AK93-08. Plant leaf fragments are present at 110 mbsl in core AK93-24 and at 126 mbsl in core AKAD09-28. Roots occur again at 123 mbsl in core AK93-09. Plant material in its original setting is strongly suggestive of prior emergence.

5.2. Black Sea was a freshwater lake prior to entrance of Mediterranean water

The inference that the Black Sea-Lake was fresh or only slightly brackish prior to the latest entrance of salt water from the Mediterranean is based on five lines of evidence: (1) benthic fauna, (2) planktonic fauna, (3) dinoflagellates, (4) pore-water chemistry, and (5) isotopic composition of shells and authigenic calcite.

5.2.1. Benthic fauna

The benthic mollusk faunal assemblage in samples below the coquina includes *Dreissena rostriformis*, *Turricaspia caspia*, *Theodoxus pallasi*, *Viviparus viviparous*, and *Unio pictorum*. According to Nevesskaya (1965) and Federov (1963), the latter three species are exclusive to freshwater environments (i.e., lakes and rivers). *Theodoxus pallasi* lives today in Varna Lake, freshwater lagoons, and the most strongly-freshened regions of the Azov Sea. This freshwater mollusk assemblage is distinct and without any of the species belonging to the subsequent saltwater assemblage (e.g., *Cardium edule*, *Mytilus galloprovincialis*, *Mytilaster lineatus*, and *Modiolus phaseolina*). *Cardium edule* and *Monodacna caspia* are clams that burrow into and live within their substrate (Brock, 1979) whereas mussels (such as *Dreissena* sp. and *Mytilus galloprovincialis*) are sessile and live on top of their substrate.

The benthic foraminiferal assemblage in cores on the shelf is entirely composed of oligohaline species (1–5 ppt). *Ammonia caspia*, *P. martkobi tschaudicus*, *M. brotzkajae*, and *E. caspicum* today inhabit river deltas in the Black and Caspian Seas (Yanko-Hombach et al., 2007). Benthic foraminifera are absent (except for reworked specimens) in cores from the slope and basin floor. Therefore, these foraminifera can only be used to estimate the prior salinity of uppermost water column. On the other hand, deep-water salinity can be deduced from bottom-dwelling ostracods. The assemblage from sediment older than the shelf coquina (i.e., belonging to Unit 3 of Ross and Degens (1974)) consists of species encountered today in the Black and Caspian Sea deltas with low salinity (Ivanova et al., 2007; Schornikov, 2011). Just prior to the introduction of saltwater from the Mediterranean, diversity was highest and *Leptocytheridae* species dominated the assemblage (Briceag et al., submitted).

5.2.2. Planktonic fauna

The pelagic components in sediments older than the coquina are juvenile *Dreissena rostriformis distincta* and dinocysts (Wall and Dale, 1974; Mudie et al., 2001). The dinoflagellate assemblage is characterized by dominance of *Pyxidinopsis psilata* (now *Tectodinium psilatum*) and *Spiniferites cruciformis* accompanied by freshwater algae (*Pediastrum* sp. and *Botryoccocccus*) (Marret et al., 2009). *Spiniferites cruciformis* is considered freshwater taxa (Wall and Dale, 1974; Atanassova, 2005) and is abundant in the late glacial deposits of Lake Kastoria (Greece) (Kouli et al., 2001). Mudie et al. (2001) also associate *Spiniferites cruciformis* with very low salinities (3.5–7 ppt), but "probably not entirely freshwater". Although juvenile mollusks and dinoflagellate cysts occur in deep-water cores from the basin floors, they also are only indicators of surface-water salinity.

5.2.3. Dinoflagellates

The dinoflagellate cyst assemblage in the period preceding the connection consists of fresh- to brackish-water species (i.e., *Spiniferites cruciformis* and *Pyxidinopsis psilata*) (Filipova-Marinova et al., 2013). This assemblage reflects sea surface salinity of <7 p.s.u (Deuser, 1972; Wall and Dale, 1974; Mudie et al., 2001; Chepalyga, 2002). This freshwater assemblage does not include any species belonging to the subsequent saltwater assemblage (i.e., *Lingulodinium machaerophorum*, *Spiniferites belerius*, *Spiniferites bentorii*, *Operculodinium centrocarpum*). *Spiniferites cruciformis* and *Pyxidinopsis psilata* are characteristic of water that is cold and of low salinity. The former was observed in the sediments of Lake Kastoria northern Greece that accumulated during the Glacial Period (Kouli et al., 2001). This species is also common to the brackish Caspian and Aral Seas (Marret et al., 2004).

5.2.4. Pore-water chemistry

Brujevich (1952) was the first to observe that the salinity and chlorinity decreased with depth in long cores from the Black Sea. This trend was direct evidence that the interior of the Black Sea had been fresher in the past. Kvasov (1968) linked the estimated timing of this freshening to the late glacial (Neoeuxine) regression and proposed that streambed erosion during a freshwater cascade through the Bosporus spillway to the Sea of Marmara was the causative agent for the lowering of the Black Sea-Lake level.

In a collection of more than two dozen long piston cores examined by (Manheim and Chan, 1974), the downward trend of decreasing chlorinity remained unabated. Thus, the minimum measured interstital-chlorinity values of 5 to 6 g/kg at 12 mbsl in the bottom of a core from 2114 mbsl are maximum values for the prior bottom water. The calculated minima from modeling of diffusion is ~3.5 g/kg for chlorine and thus an equivalent of 6 g/kg for bottom-water salinity (Manheim and Chan, 1974).

Soulet et al. (2010) measured the downward trend of chlorinity using an ultra-long piston core from 358 mbsl. The minimum measured value of dissolved chloride at 28 mbsf is 1.1 g/kg translates to a salinity of 2 ppt (psu). From a best fit of their observed diffusion profile to model calculations, these authors concluded that the late glacial Black Sea-Lake was a freshwater body and posed the possibility that the Black Sea-Lake

remained fresh throughout the deglaciation until the moment of salt-water intrusion from the Mediterranean.

5.2.5. Inferences of water salinity from its isotopic composition

The application of the $^{87}Sr/^{86}Sr$ to fauna that colonized the Black Sea-Lake water prior to the connection of the Black Sea-Lake with the Mediterranean was shown to express the average value of river water feeding the Black Sea-Lake (Palmer and Edmond, 1989; Major et al., 2006; Bahr et al., 2008). These observations lead to interpretations that the basin was predominantly composed of freshwater during the deglaciation and that there were no traces of marine water until its connection with the Mediterranean.

The stable oxygen isotope composition of the surface water, as measured in mollusk shells, increased during the deglacial period, 15,000 BP to 9300 BP, from − 7.5 to ~< − 2 ‰. This is largely ascribed to progressive isotopic enrichment of meteoric water as the earth was coming out of the glaciation (Major et al., 2006; Bahr et al., 2008). The $\delta^{18}O$ isotopic value of the surface water prior to the connection reflected the combined processes of the isotopic composition of rivers flowing into the Black Sea and precipitation.

5.3. Lake was largely regressed immediately prior to its connection with the Mediterranean

The lake level immediately prior to the inflow of Mediterranean water is estimated from: (1) the observation of the hiatus between those sediments deposited prior to the inflow of Mediterranean water and those that are deposited after, (2) the depth extent across the shelf with a measured decrease of water content beneath the coquina, (3) the location of coastal dunes with interior material ^{14}C dated with mollusk shell debris, and (4) the location of the ^{14}C dated peat, wood, and plant remains (Fig. 15). The hiatus extends from the inner shelf and in some locations onto the slope, beyond the shelf break. The black line designates the reconstructed lake level and is constrained by the presence of peat and mollusks. The lake surface is confined below the contemporary peat deposits, coastal and windblown interior dunes, which formed above water and above all deposits belonging to the submerged seabed of the Black Sea (both lacustrine and marine).

The coquina is the first deposit following the submergence of the shelf. Its composition of shells and gravel-size shell debris without mud generates the strong reverberant nature of reflectivity observed in the chirp profiles. Landward of the paleoshoreline, reflector α separates the underlying hardground from the sediments that accumulated after the submergence of the Black Sea-Lake. Seaward of the paleoshoreline, α bifurcates into α and α1. As mentioned earlier, the reflector that corresponds to the younger gap is identified as α1 and that of the older gap is the continuation of reflector α. Reflector α1 separates material of Younger Dryas age and older from those deposited after the submergence of Black Sea-Lake. Reflector α sits below α1 and separates sediments belonging to the Younger Dryas from underlying gray glacial deposits and red muds delivered by enhanced meltwater discharge (Dimitrov, 1982; Major et al., 2002; Ryan et al., 2003; Dimitrov and Dimitrov, 2004; Bahr et al., 2006; Ryan, 2007; Bahr et al., 2008; Soulet et al., 2010). Missing in the two gaps are sediments belonging to the Preboreal and the Bølling/Allerød stages.

The extent of the exposed surface and substrate with low water content suggests that the lake surface stood at least below 120 mbsl at 9300 calendar years (8200 corrected ^{14}C years). Such a substantial Preboreal regression differs from the Black Sea-Lake level history presented in the first three hypotheses in the introduction, none of which attributed a low stand exclusively to the Preboreal warm period. The compiled data makes the conclusion associated with the interpretation from the fourth hypothesis (Dimitrov, 1982; Ryan et al., 1997; Major et al., 2002; Ryan et al., 2003; Dimitrov and Dimitrov, 2004; Ryan, 2007) more plausible.

A number of previous publications assert that the surface of the Black Sea-Lake was already at the elevation of the current Bosporus Sill, 35–40 mbsl prior to the inflow of Mediterranean water (Görür et al., 2001; Aksu et al., 2002; Kaplin and Selivanov, 2004; Yanko-Hombach et al., 2007; Hiscott et al., 2007a; Hiscott et al., 2007b; Giosan et al., 2009; Marret et al., 2009; Hiscott et al., 2010; Yanko-Hombach et al., 2011; Mudie et al., 2014; Yanko-Hombach et al., 2014). In particular, Yanko-Hombach et al. (2014) and Mudie et al. (2014) interpret the wood, sedge-leaf, and co-deposited peat from core 342 from a depth of 30 mbsl as evidence that the surface of the Black Sea-Lake level was at this elevation prior to its connection with the Mediterranean at 8900 ^{14}C years. Although the measured ^{14}C ages on wood and sedge leaf are 8550 ± 40 and 8540 ± 40 ^{14}C years, respectively, the authors use Dreissena sp. and Cardium edule, specimens found above the peat deposit, with measured ^{14}C ages of 9140 and 9620 ^{14}C years to infer an even earlier age of connection of 8900 ^{14}C years. The authors attribute the older age of the specimens to the hardwater effect.

Hiscott et al. (2007a) use mollusks dated between 8570 and 9370 ^{14}C years from core M02-45 at 69 mbsl on the western Turkish shelf to infer that the lake surface had already reached the elevation of its present-day outlet prior to connection. However, specimens of Monodacna caspia and Dreissena polymorpha with ^{14}C dates between 8570 ± 70 to 8840 ± 70 ^{14}C years fall in the range of the same specimens dated from the coquina, attributed here to post-submergence of the Black Sea-Lake by the Mediterranean water. Older specimens from the bottom of this core at 9 mbsf lie below the α_1 surface and belong to seismic unit 1B. According to isopachs of unit 1B, it is confined to a mid-shelf depression, and is absent elsewhere on the western Turkish shelf. Hiscott et al. (2007a) explain this absence as a consequence of an active 50 mbsl wave base. However, wave action did not inhibit the continuous accumulation of the Holocene sediment at much shallower locations on the Ukraine (Konikov et al., 2007) and the Caucasus shelf (Yanko-Hombach et al., 2007).

Such deposits that are found at elevations above the paleoshoreline on the middle and inner Black Sea-shelf and that also date to a period before the connection are anomalous. Very few records exist. On the Romanian Shelf, two Cardium edule specimens from BLKS98-14 at a depth of 55 mbsl are dated at 9580 ± 80 and 9580 ± 90 ^{14}C years. The latter specimen has a $^{87}Sr/^{86}Sr$ composition of 0.709071, a measurement that shows that these mollusks did not inhabit an environment submerged by the Black Sea-Lake and instead, inhabited an environment disconnected from it, such as a perched pond/lake. The mollusks from M02-45 with ^{14}C ages of 9140 and 9620 ^{14}C years interpreted as those belonging to a submerged lake in Yanko-Hombach et al. (2014), Mudie et al. (2014), Giosan et al. (2009), and Hiscott et al. (2007a) are hence, also much more likely to belong to previously existing perched lake/pond environments. Hence, the arguments presented cannot be used to refute that the lake surface lay below the Bosporus inlet without additional analyses. $^{87}Sr/^{86}Sr$ and/or ε_{Nd} measurements would show whether or not these specimens inhabited an environment akin to a pond or lake.

Giosan et al. (2009) assert that the level of the Black Sea-Lake was already at ~30 mbsl at the time of the connection of the Black Sea-Lake with the Mediterranean Sea. Specimens of Dreissena polymorpha from a drill core located in the outermost Danube delta at a level of 40 mbsl were dated to 8660 ± 45 ^{14}C years and 8860 ± 45 ^{14}C years. However, given these ages and our strontium isotope measurements on Dreissena polymorpha of the same age, their presence at the base of the newly-forming delta is consistent with the interpretation that the Black Sea shelf had already been submerged. Boreholes show that the Danube delta began only when sea level reached 35 mbsl. There are no mid- or outer-shelf precursors. $^{87}Sr/^{86}Sr$ and/or ε_{Nd} measurements would conclusively determine whether these Dreissena polymorpha specimens in the base of the delta belonged to a lake prior to connection or a sea after the connection.

Görür et al. (2001) also assert that the Black Sea-Lake transgressed a large fraction of the shelf prior to its connection with the Mediterranean from an observation of a deposit with *Dreissena polymorpha* specimens with co-depositioned wood that is ^{14}C dated to 7230 ± 260 ^{14}C years BP in a core recovered from the Sakaraya coastal plain at 28 mbsl. The authors interpret that the *Dreissena* sp. indicate that the Black Sea was still a freshwater lake with a water surface at or above 28 mbsl. However, *Dreissena polymorpha* alone cannot be used to show that the Black Sea was fresh as the same specimen from other locations has an [87]Sr/[86]Sr composition with a marine signal. An underlying deposit found in alluvial sand was likely formed prior to the connection of the Black Sea-Lake with the Mediterranean due to the identification of peat, a deposit that forms only above water with a ^{14}C date of 8090 ± 120 ^{14}C years. A specimen also found in the alluvial sand and identified as *Dreissena polymorpha* and with a ^{14}C age of 9277 ± 157 ^{14}C years has anomalous [87]Sr/[86]Sr, δ^{18}O, and δ^{13}C composition which requires it to have lived in a fluvial environment and not the Black Sea-Lake.

Hiscott et al. (2002) observed a delta formed at the southern end of the Bosporus Sill. Its formation has been ascribed to Younger Dryas outflow from the Black Sea into the Sea of Marmara. Outflow at this time cannot be excluded, but if it occurred, it predated the Preboreal regression.

5.4. The transgression caused by the Mediterranean water breaching the Bosporus sill

The [87]Sr/[86]Sr composition of every specimen in the coquina with ^{14}C dates 8800 ^{14}C years and younger reflects the contribution of marine [87]Sr/[86]Sr. The *Dreissena rostriformis* all consistently have a [87]Sr/[86]Sr composition of ~0.70895. Taking the pre-transgression [87]Sr/[86]Sr composition of the water as 0.70890, this composition is equivalent to a 1% marine water that has mixed in with the fresh lake water. This indicates that the water that the *Dreissena rostriformis* colonized had, although small, a highly distinguishable fraction of additional marine water and refutes the possibility that the transgression was fresh, as argued by the first two hypotheses listed in the introduction. It is clear that the increase in [87]Sr/[86]Sr is related to a marine contribution and not a change in source of [87]Sr/[86]Sr as the Sr concentration of carbonate also increases significantly during this period (Bahr et al., 2008). During the colonization by *Dreissena polymorpha* and *Monodacna caspia*, the newly added marine water makes up of 2.5 % total volume of Black Sea water. By the time of the final stage of salinification, the [87]Sr/[86]Sr composition of *Cardium edule* requires a contribution of 20% to the total volume. The modern [87]Sr/[86]Sr of Black Sea water is 0.709133 (Major et al., 2006). This value is slightly lower than the modern [87]Sr/[86]Sr composition of the global ocean, 0.709157, and gives a mixture of 75% freshwater and 25% marine.

The 2.0 to 3.0 ‰ change in the δ^{18}O composition of the carbonate also likely reflects the entry of water from the Mediterranean and its mixing with Black Sea-Lake water. Surface Mediterranean water during the Preboreal period in the Black Sea period was ~2‰ (Paul et al., 2001). The slight trend from lower to higher δ^{18}O with decreasing depth is consistent with this observation (Fig. 12). This trend also shows, as does the [87]Sr/[86]Sr and ^{14}C composition, that the three distinct mollusk populations are sampling different water at different times and hence are recording the progression of salinification. Those mollusks from cores nearer to the coast (<45 mbsl) have a lighter δ^{18}O composition, reflecting the influence of rivers. The δ^{13}C composition of *Dreissena rostriformis* and *Dreissena polymorpha* also increase during salinification by 1.0 ‰. This rise can similarly be attributed to the mixing in of Mediterranean water, which had a δ^{13}C composition of ~2.0 ‰ during this period (Emeis et al., 2000).

5.5. Transgression was fast

The rapidity of the transgression is estimated from (1) tuning the stable carbonate composition in the ^{14}C dated mollusk record and the

U/Th dated Sofular Cave to deduce a calendar age for its onset and progression, (2) the change in [87]Sr/[86]Sr as a function of corrected calendar age, (3) observations from the chirp on the Ukrainian, Bulgarian, Romanian, and Turkish shelves, and (4) hydraulic calculations. Aligning the change in the δ^{13}C and δ^{18}O composition in the mollusks with the change in the δ^{13}C and δ^{18}O of the precipitated carbonate of the Sofular Cave during the transition period of the Black Sea surface water confirms that the ^{14}C reservoir of the surface water dropped significantly. Prior to the transgression, at 9300 calendar years, the ^{14}C reservoir age is estimated to have been as large as 1100 ^{14}C years.

A transgression from 120 to 20 mbsl involves an addition of approximately 40,000 to 60,000 km[3] of water or approximately equivalent to 10 % of the Black Sea-Lake water. If this amount of water arrived and thoroughly mixed in instantaneously with Black Sea-Lake water, the [87]Sr/[86]Sr composition of the mollusks that initially colonized the coquina would have rapidly increased to ~0.70905. However, this magnitude of change is not observed. Instead, the [87]Sr/[86]Sr composition measured is 0.70895 and reflects a contribution of no more than 1 to 2 % marine water. The smaller amount suggests that most of the Mediterranean water initially descended into the interior of the lake, similar to what occurs today, before mixing in to any appreciable degree with the overlying fresher lid. Such a phenomenon would be even more efficient and pronounced at the time of the transgression due to the large density contrast between the originally fresh lake water and the incoming Mediterranean salt water.

Similarly, the Mediterranean water would bring in ^{14}C-equilibrated water into the interior. The Black Sea-Lake water on the shelf would retain its large ^{14}C reservoir age until the ^{14}C-equilibrated water arrived and mixed in from below. Hence, the range of ^{14}C dates measured on the mollusks from the coquina cannot be exclusively used to derive the duration of the submergence as was employed by Nicholas et al. (2011) and Nicholas and Chivas (2014). Those authors suggested a duration of 400 years using the difference between ^{14}C dates of peat and uncorrected ^{14}C measurements of mollusks. The range of ^{14}C dates observed in the coquina is rather a reflection of the evolution of the ^{14}C reservoir as more and more ^{14}C equilibrated marine water mixed into the surface from the interior.

Lack of observation of coastal onlap in any of the chirp profiles further suggests that the transgression had to have been abrupt rather than gradual (Figs. 3, 4, 5, 6, 8). If the transgression were slow, a ravinement surface would be formed due to the abrasion of the substrate by wave-action as the shoreline retreated landward. The preservation of sand dunes, hollows, and pans shows that these surfaces were not subject to reworking that would otherwise appear from the destructive processes of the surf zone, as first pointed out by Ryan et al. (1997) and reaffirmed by Lericolais et al. (2007). Instead, the Holocene drape covers the surface beneath it uniformly and without any indication of reworking material from below. The coquina does not contain any significant material from the underlying substrate.

Siddall et al. (2004) estimated the NW Shelf, comprising 94% of the total shelf area of the Black Sea, to have a water volume of ~62,000 km[3]. If one uses the modern inflow of water from the Sea of Marmara through the Bosporus sill at ~315 km[3]/year (Öszoy et al., 1986; Öszoy et al., 1988; Latif et al., 1990) the volume change from 120 mbsl to 30 mbsl would still only have required 200 years. This is an over-estimate because of the much higher density of Mediterranean salt water relative to Black Sea freshwater at the time of the initial connection. Hydraulic calculations suggest a faster transgression. Siddall et al. (2004) use such calculations to show that the infill would take <40 years if the lake surface lay 80 m below the Bosporus sill. Myers et al. (2003) estimate the infill would take approximately 8 years for a volume change of 43,000 km[3]. The flux through the Bosporus at the time of the transgression is likely to have been rapid rather than gradual as erosion, similar to phenomena observed during dam breakage, would increase the depth and width of the inlet allowing more and more water to enter from the Mediterranean.

5.6. Rapidity of salinification

The salinification of the Black Sea-Lake has been previously interpreted to have lasted between 5000 to 7000 years, beginning with the initial connection of the lake with the Mediterranean and ending with the first permanent appearance of coccolithophore *E. huxleyi* (Bukry, 1974; Ross and Degens, 1974; Soulet et al., 2010). Yanko-Hombach et al. (2014) shorten this period to 3600 years based on changes in isotopes and dinocyst data from core MAR02-45 at 69 mbsl. However, the length of time assigned by Yanko-Hombach et al. (2014) does not take into account changes in the ^{14}C reservoir age of the Black Sea water. Hence their duration is over-estimated.

By observing the rate of succession of mollusks in the coquina deposit using the evolving history of decreasing reservoir ages, the salinification required to exclude all of the previous lacustrine species shortens to 900 years. There may even have been an interval of several centuries between the last surviving brackish species (i.e., 7600 ^{14}C years) and the introduction of the first marine species (i.e., 7, 250 ^{14}C years).

At 8400 calendar years (7600 ^{14}C years), the Black Sea crossed a threshold level of increased salinity such that the mollusks of Caspian affinity could no longer survive (Figs. 9 and 13). At this time, the ^{14}C reservoir age dropped to 350 ^{14}C years. The substantial increase in surface water salinity is interpreted from absence of *Dreissena rostriformis* and

Dreissena polymorpha specimens in AK93-05, 37-82, 37-82A cored from 44, 17.7 and 19.6 mbsl, respectively. A core at 47 mbsl, AK93-04, has a *Dreissena polymorpha* specimen but no *Dreissena rostriformis*, also suggesting that at that location, the lake became salty enough that *Dreissena rostriformis* could no longer tolerate such an environment. The oldest specimen at 49 mbsl gives an age of 8330 ± 70 ^{14}C years, at 47 mbsl gives an age of 7930 ± 35 ^{14}C years, at 44 mbsl gives an age of 6960 ± 139 ^{14}C years, and at 27 mbsl gives an age of 7610 ^{14}C years. The specimen retrieved from a core at 44 mbsl calibrates to a calendar age of 8270 years and the specimen retrieved from a core at 17.7 calibrates to a calendar age of 8030 years. Some fresher fauna do persist near rivers and the coast during the salinification as indicated by *Dreissena rostriformis* specimens at 38 mbsl dated to 8660–8860 ^{14}C years from the subsurface of the Danube delta by Giosan et al. (2009).

Sorokin and Kuprin (2007) note that sediment with mixed lacustrine and marine mollusks indicative of transitioning salinity (i.e., Bugaz layer) is not present at locations on the Ukraine shelf shallower than the 20 mbsl isobaths. Sediment with only lacustrine mollusks occur at sites no shallower than the 30 mbsl isobath. Sorokin and Kuprin (2007) conclude from these observations that the rise in salinity necessary to exclude the former lacustrine species was completed before the shoreline reached 20 mbsl. According to Lambeck et al. (2007), sea levels for sites in the Mediterranean place this passage to
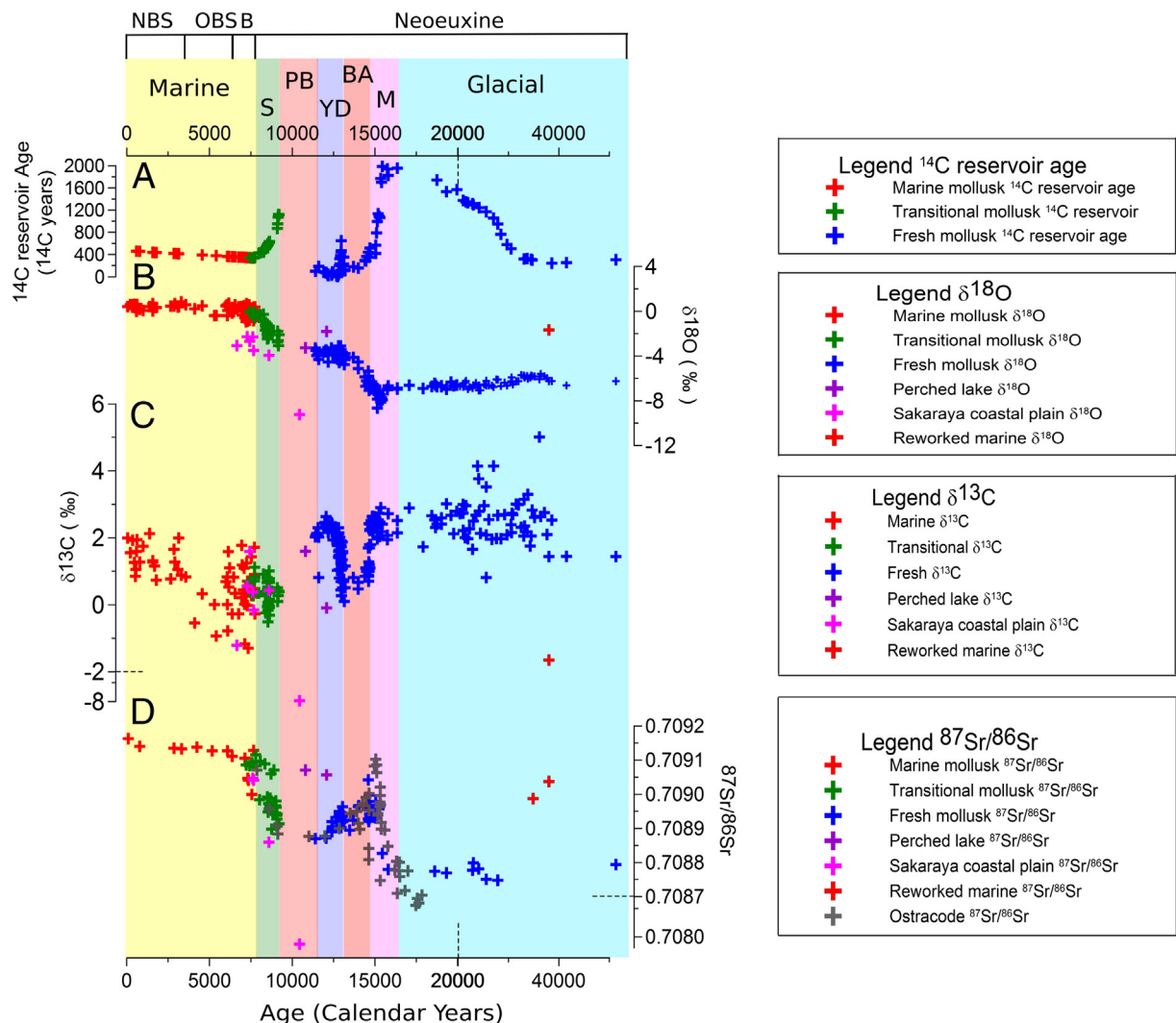

Fig. 13. From top to bottom: (a) calculated ^{14}C reservoir change from 40,000 to present derived from calibrating measured ^{14}C ages to isotope signatures using stalagmites from Sofular Cave; (b) change in δ^{18}O; (c) change in δ^{13}C; (d) change in ^{87}Sr/^{86} Sr. Data is provided in Supplementary material 3.
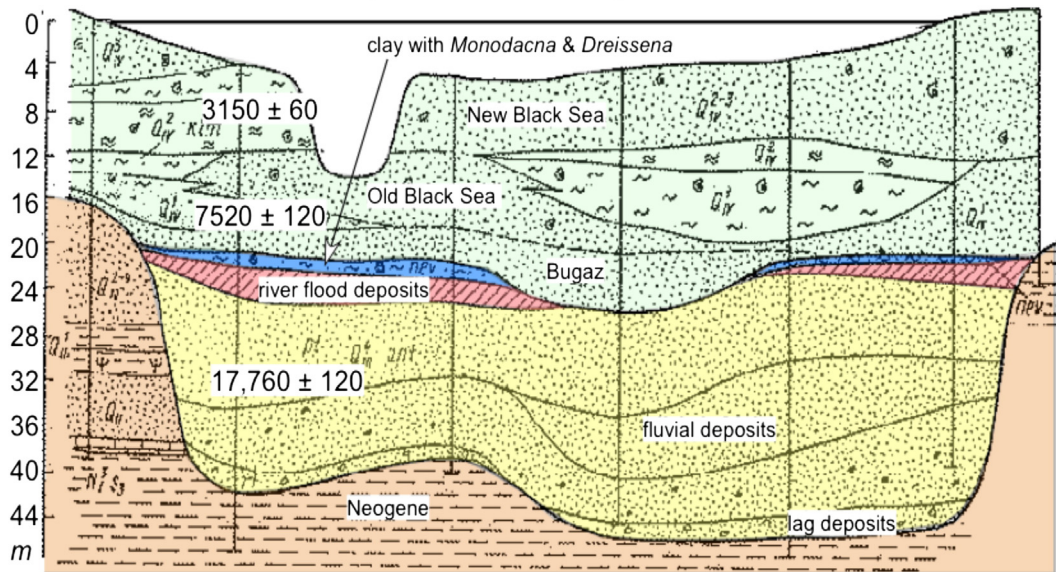
Fig. 14. Dniprov'lo-Bush'kyi Liman adopted from Naukova (1984).

20 mbsl at a time no younger than 8000 calendar years BP. Consequently, the landward limit of the coquina at 30 mbsl is in agreement with a proposed shallow sill depth in the Bosporus Strait at the time of the first entry of the Mediterranean water (Major et al., 2002; Nicholas and Chivas, 2014). From this time on, sea level in the Black Sea rose in tandem with the global eustatic sea level.

This briefer span of rising salinity is consistent with the abrupt shift (and lack of overlap) in the dinoflagellate assemblage from fresh to marine in deep-water cores across the Unit 3/2 boundary of Ross and Degens (1974), as first observed by Wall and Dale (1974), and then by subsequent researchers. Also, the duration of 900 years is consistent

with the estimate by Nicholas et al. (2011) of 1000 years or more from the initial transgressive event, based on the difference between the ^{14}C ages of the oldest freshwater and the first marine mollusks to appear on the transgressive surface. A rapid salinification likewise fits the observations of Giunta et al. (2007) that the early, although not pronounced appearance of *E. huxleyi* and *B. bigelowii*, in the base of Unit 2 sapropel indicates that the surface Black Sea water had already reached 17 psu (very close to its present value) by ~7000 ^{14}C years.

The 900 year period for the salinification of the surface water of the Black Sea is supported by calculations of Myers et al. (2003) using a Bosporus channel width of 1000 m. This channel width is supported by the
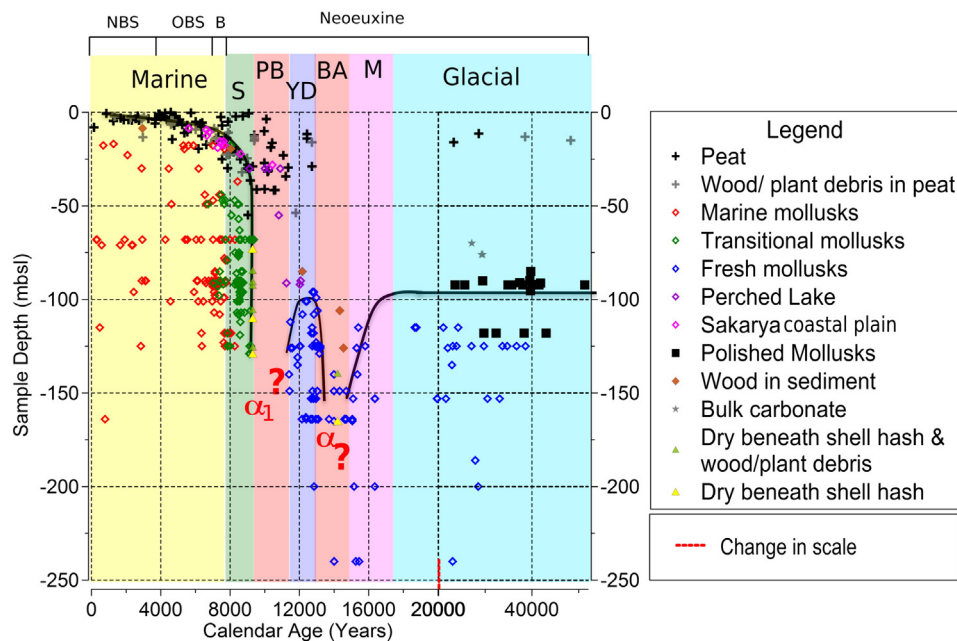

Fig. 15. Black Sea-Lake level (black line) derived from water depth at which mollusks lived with a corresponding calendar age and water depth at which peat formed with a corresponding calendar age. Data is provided in Supplementary material 4.
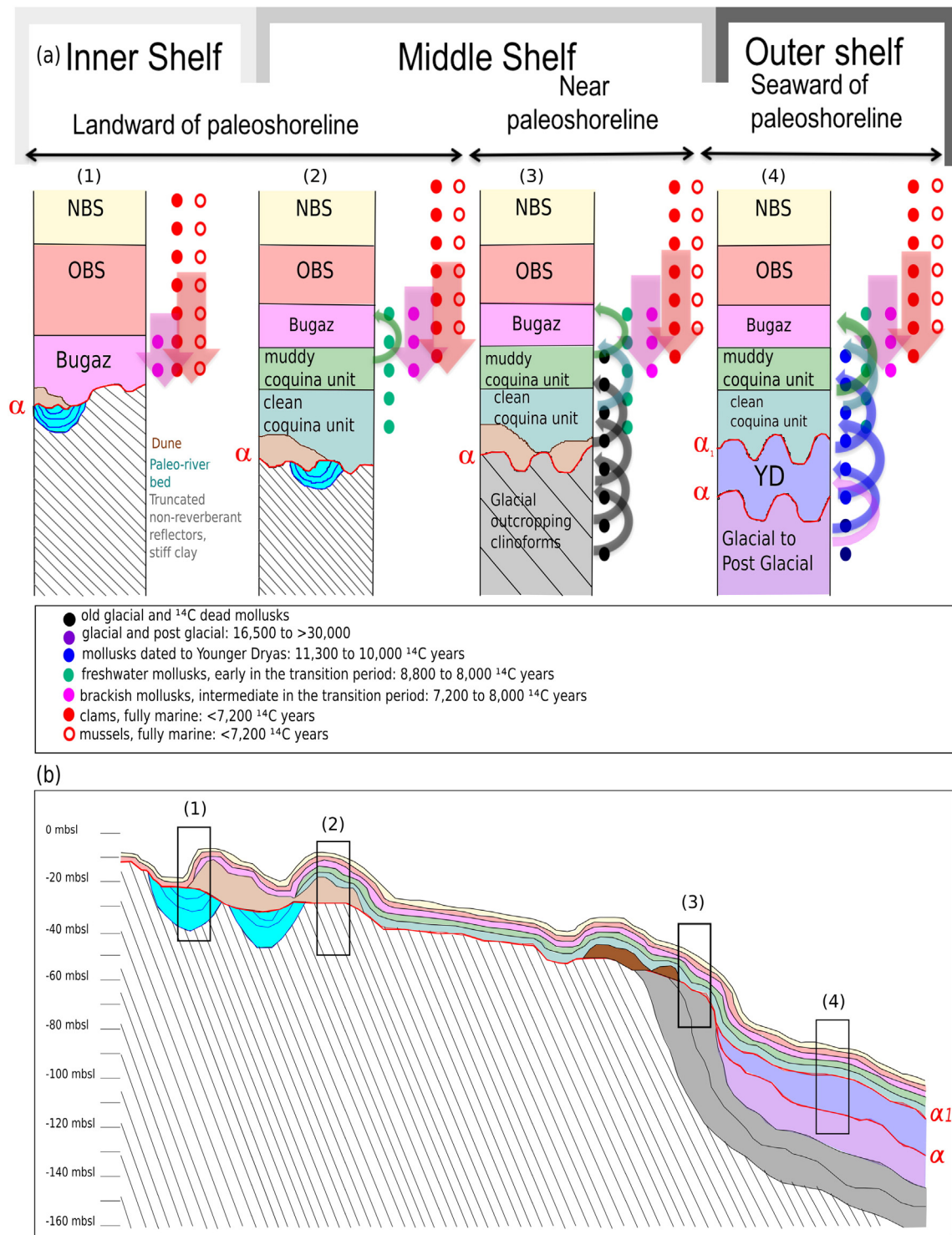
Fig. 16. (a) The varying character and stratigraphic location of the erosion surface, coquina, and Bugaz as a function of cores retrieved landward, in the vicinity of the −95 mbsl inferred paleoshoreline; (b) corresponding typical seismic line across the paleoshoreline from the inner to the outer shelf.

observation of an erosion surface of the Bosporus strait interpreted to be formed by the inflow of water from the Mediterranean into the Black Sea (Gökaşan et al., 2005).

5.7. Rapid successive colonization

The presence of *Monodacna caspia* and *Dreissena polymorpha* shells in the Bugaz layer is not an evidence of continuing brackish salinity but is ascribed to bioturbation, a process that typically churns the upper ~10 cm of the seabed (Fig. 16). The Bugaz layer is rich in shell debris derived from the underlying coquina. *Monodacna caspia* and *Dreissena polymorpha* are never found in an articulated condition. These species are present only as single valves and fragments.

The coquina with the same ^{14}C age distribution everywhere on the shelf represents a successive colonization on the newly submerged former terrestrial landscape. The sequence of post-connection lacustrine, transitional, and marine mollusks in the coquina is the consequence of their progressive appearance and disappearance during rising salinity.

Dreissena rostriformis is traditionally considered as inhabiting a strictly freshwater environment that was inherited from the prior lake. The brackish species only appear later after the lacustrine species were no longer able to adapt to the rising salinity. The marine fauna such as *Cardium edule*, *Mytilus galloprovincialis*, and *Mytilaster lineatus* colonized the seabed only after the salinification was near its completion.

Marine bivalves such as *Cardium edule* dig into and live within their substrate (Brock, 1979). Hence, the clams are occasionally found in the coquina deposit side-by-side with articulated *Dreissena* sp. and *Monodacna caspia*, even though all three species lived at different times and in tolerance to different salinities as indicated by their diverse ^{14}C ages and isotopic compositions. When found within the coquina, the specimens of *Cardium edule* are everywhere articulated and in their living orientation.

6. Conclusions

The evidence in the form of stable isotopes, radiocarbon ages, [87]Sr/[86]Sr measurements, and reflection profiles from shelf cores on the Ukrainian, Romanian, Bulgarian, and Turkish margins allow the evaluation of four competing hypotheses regarding the reconnection of the Black Sea to the Mediterranean and thus the global ocean following the last ice age. Three of the hypotheses are inconsistent with the observations. The evidence supports the fourth hypothesis indicating that a sudden submergence of the Black Sea shelf and subsequent rapid salinification of its water at 9300 calendar years BP was a consequence of the inflow of Mediterranean water.

The data also allow the reconstruction of a detailed sequence of events related to the submergence: (1) The presence of an erosion surface up to a depth exceeding 120 mbsl dated to the Preboreal indicates a substantial regression preceding the inflow of Mediterranean water into the Black Sea; (2) Tuning $\delta^{18}O$ and $\delta^{13}C$ compositions of thoroughly U/Th-dated carbonate precipitated in stalactites from Sofular Cave and Black Sea mollusks shows that the Mediterranean water entered and submerged the Black Sea shelf starting at 9300 calendar years BP. This retreat of the shoreline lasted a maximum of 200 years if the inflow of water was no faster than that occurring today. However, it likely was nearly instantaneous given flow rates at the time of the breaching, lasting no longer than 40 years and possibly as little as a decade according to hydraulic calculations. The absence of detritus from strata beneath the α erosion surface in the initial coquina further supports that the transgression was a rapid flooding event and not a slow ravinement. (3) Given large density differences between fresh and marine water, it is most likely that the dense salty inflowing water initially descended into the deep interior, and the surface water then experienced a somewhat delayed evolution from fresh to marine as more and more salt water filled the interior and progressively mixed with the fresher lid.

Substantial salinification within the first 900 years was sufficient to exclude all of the freshwater and brackish water mollusks inherited from the prior lake. The first marine species did not appear for the few centuries. The transformation from lake to sea is recorded in a coquina where successive appearances and disappearances of mollusks with ^{14}C ages and isotopic compositions are indicative of a greater and greater contribution of water from the Mediterranean to the surface lake layer of ~100–200 m. The continuing sea level rise that followed the initial submergence took place in tandem with the external global ocean.

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Acknowledgments

References

Aksu, A.E., Hiscott, R.N., Kaminski, M.A., Mudie, P.J., Gillespie, H., Abrajano, T., Yaşar, D., 2002. Last glacial-Holocene paleoceanography of the Black Sea and Marmara Sea: stable isotopic, foraminiferal and coccolith evidence. Mar. Geol. 190 (1–2):119–149. http://dx.doi.org/10.1016/S0025-3227(02)00345-6.

Algan, O., Ergin, M., Keskin, S., Gokasan, E., Alpar, B., Kirci, E., Ongan, D., 2007. Sea level changes during the late Pleistocene-Holocene on the southern shelves of the Black Sea. 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, The Netherlands, pp. 603–631.

Apakidze, A.M., Burchuladze, A.A., 1987. Radiouglerodnoe datirovanie arkheologicheskikh i paleobotanicheskikh abraztsov Gruzii (Radiocarbon dating of archaeological and paleobotanical samples in georgia). Metsniereba, Tbilisi, Georgia.

Arkhangel'skiy, A.D., Strakhov, N.M., 1938. Geological structure and history of the evolution of the Black Sea. Izv. Akad. Nauk SSSR. 10, 3–104.

Atanassova, J., 2005. Palaeoecological setting of the western Black Sea area during the last 15,000 years. The Holocene 15 (4), 576–584.

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. http://dx.doi.org/10.1038/NGEO1106.

Bahr, A., Arz, H., 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. Sc. Lett. 241:863–875. http://dx.doi.org/10.1016/j.epsl.2005.10.036.

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. Geosyst. 9 (1). http://dx.doi.org/10.1029/2007GC001683.

Bailey, T.R., McArthur, J.M., Prince, H., Thirwall, M.F., 2000. Dissolution methods for strontium isotope stratigraphy: Whole rock analysis. Chem. Geol. 167, 313–319.

Balbanov, I.P., 2007. Holocene sea-level changes of the Black Sea. 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, Netherlands, pp. 711–730.

Briceag A. Yanchilina A.G. Ryan W.B.F. Stoica M. OaieG. Melinte-Dobrinescu M.C. Late Pleistocene - Holocene paleoenvironmental changes inferred by microfaunal and isotope fluctuations in the Romanian Black Sea shelf, Quat. Res. submitted

Brock, V., 1979. Habitat selection of two congeneric bivalves, *Cardium edule* and *C. glaucum* in sympatric and allopatric populations. Mar. Biol. 54 (2):149–156. http://dx.doi.org/10.1007/BF00386594.

Brujevich, S.V., 1952. Buried fresh water beneath the recent sediments in the Black Sea. Dokl. Acad. Nauk SSSR. 84 (3), 575–577.

Bukry, D., 1974. Coccoliths as paleosalinity indicators—evidence from the Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea-Geology, Chemistry and Biology. Am. Assoc. Petrol. Geol., pp. 353–363 Tuksa, OK.

Chepalyga, A.L., 2002. The Black Sea. In: Velichko, A.A. (Ed.), Dynamics of Terrestrial Landscape Components and Inner Marine Basins of Northern Eurasia during the last 130,000 years. GEOS, Moscow, pp. 170–182.

Cohen, A., 2011. Black Sea low stands during the Holocene and Pleistocene and reconnection with the global ocean. Columbia University, New York.

Degens, E.T., Stoffers, P., Hallam, A., 1980. Environmental events recorded in Quaternary sediments of the Black Sea. J. Geol. Soc. 137, 131–138.

Demirbag, E., Gökasan, E., Oktay, F.Y., Simsek, M., Yüce, H., 1999. The last sea level changes in the Black Sea: evidence from the seismic data. Mar. Geol. 157 (3–4), 249–265.

Deuser, W.G., 1972. Late-Pleistocene and Holocene history of the Black Sea as indicated by stable-isotope studies. J. Geophys. Res. 77 (6), 1071–1077.

Di Iorio, D., Yüce, H., 1998. Observations of Mediterranean flow into the Black Sea. J. Geophys. Res. 104, 3091–3106.

Dimitrov, P., 1982. Radiocarbon datings of bottom sediments from the Bulgarian Black Sea shelf. Bulgarian Academy of Sciences Oceanology. 9, 45–53.

Dimitrov, D., 2010. Geology and non-traditional resources of the Black Sea. Lambert Academik Publishing AG, Germany.

Dimitrov, P., Dimitrov, D., 2004. The Black Sea, the Flood, and the Ancient Myths. Slavena, Varna.

Emeis, K.C., Struck, U., Schulz, H.M., Rosenberg, R., Bernasconi, S.M., Erlenkeuser, H., Sakamoto, T., Martinez-Ruiz, F., 2000. Temperature and salinity variations of Mediterranean Sea surface waters over the last 16000 years from records of planktonic stable isotope and alkenone unsaturation ratios. Paleogeography, Palaeoclimatology, Paaeoecology. 158, 259–280.

Federov, P.V., 1963. Stratigrapfiya Chetvertichnikh otlozhenii Krymskogo-Kavkazkogo poberezhia nekotorye voprosy geologicheskoy istorii Chernogo Moray (Stratigraphy of Quaternary sediments sediments on the coast of the Crimea and Caucasus and some problems connected with the geological history of the Black Sea) (1-7-159).

Filipova-Marinova, M., Pavlov, D., Coolen, M., Giosan, L., 2013. First high-resolution marinopalynological stratigraphy of Late Quaternary sediments from the central part of the Bulgarian Black Sea area. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2012.05.002.

Fleitmann, D., Cheng, H., Badertscher, S., Edwards, R.L., Mudelsee, M., Göktürk, O.M., Fankhauser, A., Pickering, R., Raible, C.C., Matter, A., Kramers, J., Tüysüz, O., 2009. Timing and climatic impact of Greenland interstadials recorded in stalagmites from northern Turkey. Geophys. Res. Lett.:36 http://dx.doi.org/10.1029/2009GL040050.

Flood, R.D., Hiscott, R.N., Aksu, A.E., 2009. Morphology and evolution of an anastomosed channel network where saline underflow enters the Black Sea. Sedimentology 56: 807–839. http://dx.doi.org/10.1111/j.1365-3091.2008.00998.x.

Genov, I.D., 2004. Way and time of swell formation near the Bulgarian Black Sea shelf. CR. Acad. Bulg. Sci. 57 (6), 95–98.

Genov, I., 2014. Seismostratigraphy and the last Black Sea level changes. In: Reports from Bulgarian Academy on Sciences. Geologie 1419–1424.

Genov, I.D., Slavova, K.R., 2004. Chronostatigraphy tuning from correlation of Neoeuxine and Holocene sediments using coring methods from Black Sea shelf. Review of the Bulgarian Geological Society. 65 (1–3), 25–35.

Genov, I., Slavova, K., Dimitrov, P., 2004. Geological events as result from the climatic changes in the Black Sea Region during the period 20000–7000 calendar years BP. Proceedings of the International Symposium of Earth System Science, Istanbul, Turkey. Kelebek and Grafika Group, Istanbul.

Giosan, L., Filip, F., Constantinescu, S., 2009. Was the Black Sea catastrophically flooded in the early Holocene? Quat. Sci. Rev. 28, 1–6.

Giunta, S., Morigi, C., Negri, A., Guichard, F., Lericolais, G., 2007. Holocene biostratigraphy and paleoenvironmental changes in the Black Sea based on calcareous nannoplankton. Mar. Micropaleontol. 63:91–110. http://dx.doi.org/10.1016/j.marmicro.2006.12.001.

Glebov, A.Y., Shel'ting, S.K., 2007. Sea-level changes and coastline migrations in the Russian sector of the Black Sea. 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, Netherlands, pp. 731–773.

Gökaşan, E., Tur, H., Ecevitoğlu, B., Görüm, T., Türker, A., Tok, B., Çağlak, F., Birkan, H., Şimşek, M., 2005. Evidence and implications of massive erosion along the Strait of İstanbul (Bosphorus). Geo-Mar. Lett. 25:324–342. http://dx.doi.org/10.1007/s00367-005-0216-3.

Görür, N., Çagatay, M.N., Emre, O., Alpar, B., Sakinç, M., Islamoglu, Y., Algan, O., Erkal, M., Akkok, R., Karlik, G., 2001. Is the abrupt drowning of the Black Sea shelf at 7150 year BP a myth? Mar. Geol. 176, 65–73.

Hiscott, R.N., Aksu, A.E., Yasar, D., Kaminski, M.A., Mudie, P.J., Kostylev, V., MacDonald, J.C., Lord, A.R., 2002. Deltas south of the Bosporus record persistent Black Sea outflow to the Marmara Sea since ~10 ka. Mar. Geol. 190, 95–118.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Marret, F., Abrajano, J., Kaminski, M.A., Evans, J., Çakiroğlu, A.I., Yaşar, D., 2007a. A gradual drowning of the southwestern Black Sea shelf: evidence for a progressive rather than abrupt Holocene reconnection with the eastern Mediterranean Sea through the Marmara Sea Gateway. Quat. Int. 167–168:19–34. http://dx.doi.org/10.1016/j.quaint.2006.11.007.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Kaminski, P.J., Abrajano, T.A., Yaşar, D., ROchon, A., 2007b. The Marmara Sea Gateway since ~16 ky BP: non-catastrophic causes of paleoceanographic events in the Black Sea at 8.4 and 7.15 ky BP. 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, Netherlands, pp. 89–116.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Abrajano, T.A., Kaminski, P.J., Evans, J., Çakiroğlu, A.İ., Yaşar, D., 2010. Corrigendum to "A gradual drowning of the southwestern Black Sea shelf: evidence for a progressive rather than abrupt Holocene reconnection with the eastern Mediterranean Sea through the Marmara Sea Gateway". Quat. Int. 226 (160).

Hiscott, R.N., Aksu, A.E., Flood, R.G., Kostylev, V., Yaşar, D., 2013. Widespread overspill from a saline density-current and its interaction with topography on the southwest Black Sea shelf. Sedimentology 60, 1639–1667.

Ivanova, E.V., Murdmaa, I.O., Chepalyga, A.L., Cronin, T.M., Pasechnik, I.V., Levchenko, O.V., S.S, H., Manushkina, A.V., Platonova, E.A., 2007. Holocene sea-level oscillations and environmental changes on the Eastern Black Sea shelf. Palaeogeogr. Palaeoclimatol. Palaeoecol. 246:228–259. http://dx.doi.org/10.1016/j.palaeo.2006.09.014.

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

Kaplin, P., Selivanov, A.O., 2004. Late glacial and Holocene sea level changes in semi-enclosed seas of North Eurasia: examples from the contrasting Black and White seas. Palaeogeogr. Palaeoclimatol. Palaeoecol. 209:19–36. http://dx.doi.org/10.1016/j.palaeo.2004.02.016.

Kaplin, P. A.,F. A. Shecherbakov, 1986. Reconstructions of shelf environmemts in the late Quaternary. J. Coast. Res. Special Issue 1, 95–98.

Konikov, E., Likhodedova, O., Pedan, G., 2007. Paleogeographic reconstructions of sea-level change and coastline migration on the northwestern Black Sea shelf over the past 18 kyr. Quat. Int. 167–168:49–60. http://dx.doi.org/10.1016/j.quaint.2006.11.012.

Kouli, K., Brinkhuis, H., Dale, B., 2001. Spiniferites cruciformis: a fresh water dinoflagellate cyst? Rev. Palaeobot. Palynol. 113 (4):273–286. http://dx.doi.org/10.1016/S0034-6667(00)00064-6.

Kuprin, P.N., Scherbakov, F.A., Morgunov, I.I., 1974. Correlation, age and distribution of the postglacial continental terrace sediments of the Black Sea. Baltica 5, 241–249.

Kvasov, D.D., 1968. Paleohydrology of eastern Europe in late Quaternary time. Yezhegodnkkh Chetniyakh Pamyati L.S. Berga Doklady Izd. Nauka, Leningrad, pp. 65–81.

Lambeck, K., Sivan, D., Purcell, A., 2007. Timing of the last Mediterranean Sea: Black Sea connection from isostatic models and regional sea-level data. In: Yanko-Hombach, V., Gilbert, A.S. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate and Human Settlement. Springer, Heidelberg, Germany, pp. 797–808.

Latif, M.A., Oğuz, T., Sur, H.I., Beşiktepe, Ş., Özsoy, E., Ünlüata, Ü., 1990. Oceanography of the Turkish Straits-Third Annual Report. Physical Oceanography of the Turkish Straits. Inst. Mar. Sci.METO, Erdemlo (İçel 1).

Lericolais, G., Popescu, I., Guichard, F., 2007. A Black Sea lowstand at 8500 year BP indicated by a relict coastal dune system at a depth of 90 m below sea level. In: Harff, J., Hay, W.W., Tetzlaff, D.M. (Eds.), Coastline Changes: Interrelation of Climate and Geological Processes. GSA Books. Allen Press, Inc., pp. 171–188.

Lericolais, G., Bulois, C., Gillet, H., Guichard, F., 2009. High frequency sea level fluctuations recorded in the Black Sea since the LGM. Glob. Planet. Chang. 66:65–75. http://dx.doi.org/10.1016/j.gloplacha.2008.03.010.

Major, C.O., 2002. Non-Eustatic Controls on Sea-Level in Semi-Enclosed Basins. Publisher, New York, NY.

Major, C., Ryan, W., Lericolais, G., 2002. Constraints on Black Sea outflow to the Sea of Marmara during the last glacial–interglacial transition. Mar. Geol. 190, 19–34.

Major, C., Goldstein, S., Ryan, W., Lericolais, G., Piotrowski, A.M., Hajdas, I., 2006. The co-evolution of Black Sea level and composition through the last deglaciation and its paleoclimatic significance. Quat. Sci. Rev. 25 (17–18):2031–2047. http://dx.doi.org/10.1016/j.quascirev.2006.01.032.

Manheim, F.T., Chan, K.M., 1974. Interstitial waters of Black Sea sediments: New data and review. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea - Geology, Chemistry and BiologyMem. Am. Assoc. Petrol. Geol.Tusla, pp. 155–180.

Marret, F., Leroy, S., Chalie, F., Gasse, F., 2004. New organic-walled dinflagellate cysts from recent sediments of Central Asian seas. Rev. Palaeobot. Palynol. 129, 1–20.

Marret, F., Mudie, P., Aksu, A., Hiscott, R.N., 2009. A Holocene dinocyst record of a two-step transformation of the Neoeuxinian brackish water lake into the Black Sea. Quat. Int. 197:72–86. http://dx.doi.org/10.1016/j.quaint.2007.01.010.

Mortlock, R., 2010. Description of Stable Isotope Analysis at the Department of Earth and Planetary Sciences. Rutgers University.

Mudie, P., Aksu, A., Yaşar, D., 2001. Late Quaternary dinoflagellate cysts from the Black, Marmara and Aegean seas: variations in assemblages, morphology and paleosalinity. Mar. Micropaleontol. 43, 155–178.

Mudie, P.J., Rochon, A., Aksu, A., Gillespie, H., 2004. Late glacial, Holocene and modern dinoflagellate cyst assemblages in the Aegean-Marmara-Black Sea corridor. Rev. Palaeobot. Palynol. 256, 1–26.

Mudie, P.J., Yanko-Hombach, V., Kadurin, S., 2014. The Black Sea dating game and Holocene marine transgression. Open Journal of Marine Science. 4, 1–7.

Myers, P.G., Wielki, C., Goldstein, S.B., Rohling, E.J., 2003. Hydraulic calculations of postglacial connections between the Mediterranean and the Black Sea. Mar. Geol. 201: 253–267. http://dx.doi.org/10.1016/S0025-3227(03)00225-1.

Naudts, L., Greinert, J., Artemov, Y., Staelens, P., Poort, J., Rensbergen, P.V., De Batist, M., 2006. Geological and morphological setting of 2778 methane seeps in the Dnepr paleodelta, northwestern Black Sea. Mar. Geol. 227:177–199. http://dx.doi.org/10.1016/j.margeo.2005.10.005.

Naukova, D., 1984. Radioulerodnoe datirovanie. In: Shnyukov, E.F. (Ed.), Geologii Shel'fa USSR. Limany, Kiev.

Nevesskaya, L.A., 1965. Late Quaternary bivalve mollusks of the Black Sea: their systematics and ecology. Akad. Nauk SSSR Paleont. Inst. Trydy. 105, 1–390.

Nicholas, W.A., Chivas, A.R., 2014. Late Quaternary sea-level change on the Black Sea shelves. In: Chiocci, F.L., Chivas, A.R. (Eds.), Continental Shelves of the World: Their Evolution during the Last Glacial-Eustatic Cycle. Geological Society, London, pp. 199–212.

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. 30:3769–3790. http://dx.doi.org/10.1016/j.quascirev.2011.09.018.

Nowaczyk, N.R., Arz, H.W., Frank, U., Kind, J., Plessen, B., 2012. Dynamics of the Laschamp geomagnetic excursion from Black Sea sediments. Earth Planet. Sci. Lett. 351–352: 54–69. http://dx.doi.org/10.1016/j.epsl.2012.06.050.

Özsoy, E., Oğuz, T., Latif, M.A., Ünlüata, Ü., 1986. Oceanography of the Turkish Straits-First Annual Report. Physical Oceanography of the Turkish Straits. Inst. Mar. Sci.METU, Erdemlo (İçel 1).

Özsoy, E., Oğuz, T., Latif, M.A., Ünlüata, Ü., Sur, H.I., Beşiktepe, Ş., 1988. Oceanography of the Turkish Straits-SecondAnnual Report. Physical Oceanography of the Turkish Straits. Inst. Mar.Sci.METU, Erdemlo (İçel 1).

Palmer, M.R., Edmond, J.M., 1989. The strontium budget of the modern ocean. Earth Planet. Sci. Lett. 92, 11–26.

Paul, H.A., Bernasconi, S.M., Schmid, D.W., McKenzie, J.A., 2001. Oxygen isotopic composition of the Mediterranean Sea since the Last Glacial Maximum: constraints from pore water analyses. Environmental Science Letters. 192, 1–14.

Pirazzoli, P.A., 1996. Sea-Level Changes: The Last 20,000 years. John Wiley and Sons, New York.

Popescu, I., 2008. Processus sédimentaires récents dans l'éventail profond du Danube (Mer Noire). Geo-Eco-Marina Special Publication N. 2.

Popescu, I., Lericolais, G., Panin, N., N, Ç., Normand, A., Dinu, DC, C., Le Drezen, E., 2004. The Danube submarine canyon (Black Sea): morphology and sedimentary processes. Mar. Geol. 206, 249–265.

Reimer, P.J., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K., Kromer, F.B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., der Plicht, J.v., 2013. Incal13 and Marine13 radiocarbon age calibration curves 0–50,000 years Cal B.P. Radiocarbon 55 (4), 1869–1887.

Ross, D., Degens, E., 1974. Recent Sediments of Black Sea: Sediments.
Ross, D.A., Degens, E.T., MacIlvaine, J., 1970. Black Sea: recent sedimentary history. Science 170, 163–165 (9 October).
Ryan, W.B.F., 2007. Status of the Black Sea flood hypothesis. 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, The Netherlands, pp. 63–88.
Ryan, W.B.F., Pitman, W.C., Major, C.O., Shimkus, K., Moscalenko, V., Jones, G.A., Dimitrov, D., Gorür, P., Sakinç, M., Seyir, H.Y., 1996. An abrupt drowning of the Black Sea shelf at 7.5 kyr BP. Geo-Eco-Marina (Malnas, Romania).
Ryan, W.B.F., Pitman III, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G., Dimitrov, P., Gorur, N., Sakinc, M., Yuce, H., 1997. An abrupt drowning of the Black Sea shelf. Mar. Geol. 138, 119–126.
Ryan, W.B.F., Major, C.O., Lericolais, G., Goldstein, S.L., 2003. Catastrophic flooding of the Black Sea. Annu. Rev. Earth Planet. Sci. 31, 525–554.
Ryan, W.B.F., Vachtman, D., McHugh, C., Çagatay, M.N., Mart, Y., 2013. A channeled shelf fan initiated by flooding of the Black Sea. In: Gofredo, S., Dubinsky, Z. (Eds.), The Mediterranean Sea: Its History and Present Challenges, pp. 11–27.
Scherbakov, F.A., Babak, Y.V., 1979. Stratigraphic subdivision of the Neoeuxinian deposits in the Black Sea. Oceanology 19 (3), 298–300.
Schornikov, E.I., 2011. Ostracods of the Caspian origin in the Azov-Black Sea basin. In: Gross, M. (Ed.), European Ostracologists Meeting Universalmuseum, Graz, pp. 180–184.
Schrader, H.J., 1979. Quaternary paleoclimatology of the Black Sea basin. Sediment. Geol. 23 (1 4), 165–180.
Siddall, M., Pratt, L.J., Helfrich, K.R., Giosan, L., 2004. Testing the physical oceanographic implications of the suggested sudden Black Sea infill 8400 years ago. Paleoceanography 19, PA1024–PA1035.
Sorokin, V.M., Kuprin, P.N., 2007. On the character of Black Sea level rise during the Holocene. 62. Moscow University Geology Bulletin. http://dx.doi.org/10.3103/S0145875207050055.

Soulet, G., Delaygue, G., Vallet-Coulomb, C., Böttcher, M.E., Sonzogni, C., Lericolais, G., Bard, E., 2010. Glacial hydrologic conditions in the Black Sea reconstructed using geochemical pore water profiles. Earth Planet. Sci. Lett. 296:57–66. http://dx.doi.org/10.1016/j.epsl.2010.04.045.
Soulet, G., Ménot, G., Garreta, V., Rostek, F., Zaragosi, S., Lericolais, G., Bard, E., 2011a. Black Sea "Lake" reservoir age evolution since the Last Glacial — hydrologic and climatic implications. Earth Planet. Sc. Lett. 308:245–258. http://dx.doi.org/10.1016/j.epsl.2011.06.002.
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. http://dx.doi.org/10.1016/j.quascirev.2011.03.001.
Strakhov, N.M., 1971. Chemical evolution of the black basin the Holocene. Lithol. Miner. Resour. 3, 263–274.
Wall, D., Dale, B., 1974. Dinoflagellates in Late Quaternary Deep-Water Sediments of Black Sea. Amer. Assoc. Petrol. Geol. (Tulsa).
Wesselingh, F., 2015. Identification of marine mollusks (personal communication).
Yanko-Hombach, V., Gilbert, A.S., Dolukhanov, P., 2007. Controversy over the great flood hypotheses in the Black Sea in light of geological, paleontological, and archaeological evidence. Quat. Int. 167–168, 91–113.
Yanko-Hombach, V., Smintina, E.V., Kadurin, S., Larchenkov, E.P., Motnenko, I.V., Kakaranza, S.V., Kiosak, D.V., 2011. Kolebaniya urovnya Chernogo Moria i adaptatsionnaya strategia drevnego cheloveka za posldenie 30 tysiach let (the Black Sea level change and adaptation strategy of ancient humans for the last 30 thousand years). Geologiya i poleznie iskopamye Mirovogo Okeana (Geology and mineral resources of the World Ocean). 2, pp. 61–94.
Yanko-Hombach, V., Mudie, P.J., Kadurin, S., Larchenkov, E., 2014. Holocene marine transgression in the Black Sea: new evidence from the northwestern shelf. Quat. Int. 345, 100–118.
Zubakov, V.A., 1988. Climatostratigraphic scheme of the Black Sea Pleistocene and its correlation with the oxygen isotope scale and glacial events. Quat. Res. 29 (1), 1–24.