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Holocene marine transgression in the Black Sea: New evidence from the northwestern Black Sea shelf

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ABSTRACT

For two decades, the timing and rate of Holocene marine transgression and the level of the Black Sea prior to the transgression has been the focus of many geological, palaeoecological and archaeological studies. The potential importance of confirming or rejecting the catastrophic flood hypothesis by refining the chronology of the marine transgression and determining the water level of the early Holocene Black Sea (Neoeuxinian) lake is the aim of many ongoing Black Sea palaeoecological studies.

In this report we review previous studies and present new data on the early Holocene marine transgression obtained from multidisciplinary studies of several cores from different parts of the Black Sea. Core 342 from the edge of the Dniester paleovalley on NW shelf is particularly important because it provides wood and leaf material from several peat and muddy peat beds, each up to ~ 10 cm thick, interlayered in a coastal succession with mud, clay, and shell coquina. AMS ages for wood fragments and sedge leaves in the peat layers provide critical new data for calibrating and "re-tuning" of previously published shell and bulk detrital peat ages.

Our multi-disciplinary study of geological material recovered from different shelf areas of the Black Sea refines the chronology of the marine transgression and clarifies conflicting interpretations of the water level and salinity of the Neoeuxinian lake prior to the initial Mediterranean inflow (IMI) and transgression of Mediterranean water in the Holocene, We find that: (1) The level of the Late Neoeuxinan lake prior to the early Holocene Mediterranean transgression stood around -40 m bsl but not -100 m or more as suggested by advocates of catastrophic/rapid/prominent flooding of the Black Sea by Mediterranean water. (2) At all times, the Neoeuxinan lake was brackish with salinity not less that 7 psu. (3) By 8.9 ka BP, the Black Sea shelf was already submerged by the Mediterranean transgression. An increase in salinity took place over 3600 years, with rate of the marine water incursion being estimated in the order of $0.05 \text{ cm}-1.7 \text{ cm a}^{-1}$. (4) The combined data set of sedimentological characteristics and microfossil data establish that the Holocene marine transgression was of a gradual, progressive nature in the early Holocene.

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1. Introduction

For two decades, the timing and rate of Holocene marine transgression and the level of the Black Sea prior this transgression

¹ Recently deceased.

has been the focus of many geological, palaeoecological and archaeological studies (Yanko, 1990; Yanko-Hombach, 2007; Nicholas et al., 2011; Yanko-Hombach et al., 2011a, 2011b). The idea of a catastrophic marine flood that broke open a sediment dam in the Bosphorus Strait, filling a freshwater Black Sea lake with about 30 m of Mediterranean sea water in a few years and driving away early Neolithic farmers (Ryan, 2007, was related to the legend of Noah's Flood despite lack of any direct geological (Görür et al., 2001; Hiscott et al., 2007), palynological (Mudie et al., 2002, 2004; Marret et al., 2009), paleontological (Yanko-Hombach,

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2007), and archaeological evidence (Jablonka, 2002; Yanko-Hombach, 2007, 2011a, 2011b; Dolukhanov et al., 2009). This catastrophic flood hypothesis was proposed in 1997, based on evidence from seven short (about 1.25 m) sediment cores and 350 km of seismic profiles collected on the northern shelf margin of the Black Sea (Fig. 2) at water depths of 49–140 m (Ryan et al., 1997), where a thin layer of sapropelic mud overlies a shelf-wide unconformity (Ryan, 2007).

The speed of this catastrophic marine flooding in a presumed "freshwater Neoeuxinian lake" was estimated by AMS (Accelerator Mass Spectrometry) radiocarbon dating of intact mollusk valves from the sapropel in five cores from water depths of 68–125 m bsl. The individual mollusk shell ages were not listed in the 1997 paper, but they were reported as having an average of 7150 \pm 100 uncal. BP, with all being within error limits of ages for the sapropel-base in nine cores from depths of -200 to -2200 m bsl reported by Jones and Gagnon (1994). In Ryan and Pitman (1998), the calendar ages of these shells differed by up to 110 years but were called "statistically identical", and interpreted as marking an abrupt switch from oxygenated freshwater to euxinic marine conditions. Later, however, studies of oxygen, carbon and strontium isotopes in mollusk shells by Major et al. (2006) led to an earlier age assignment of 8400 \pm 100 BP for the start of a rapid Black Sea Holocene transgression.

The potential importance of confirming or rejecting the catastrophic flood hypothesis by refining the chronology of the marine transgression (Soulet et al., 2011a,b) as well as by quantifying the palaeosalinity (Bahr et al., 2008; Soulet et al., 2010; Mertens et al., 2012) and the water level (Yanko-Hombach et al., 2011a, b) of early Black Sea (Neoeuxinian) lake before this transgression is the aim of many ongoing Black Sea palaeoecological studies.

To pinpoint the time of the marine transgression, Soulet et al. (2011a) recently recalibrated the shell ages using wood samples from Sakarya Delta, because land plant material does not require ¹⁴C marine reservoir age corrections and can be free of lake hardwater errors (HWE). The new age assigned to the IMI by Soulet et al. (2011a) is 8390 \pm 35 BP for Black Sea water above 400 m bsl. The IMI marks the start of the Mediterranean transgression when water of marine salinity began to flow into the Black Sea basin through Bosphorus Strait.



Fig. 1. Map of the Black Sea and adjacent regions, showing the extent of the shelf areas, the connection to Marmara and Aegean seas via Bosphorus and Dardanelles Straits, and locations of key reference cores with 14C ages. Circles mark location of cores described in this paper; dark circle is MAR02-45 core of Hiscott et al. (2007, 2010). 1-Dniestrovian liman, 2-Berezan liman.

Previous efforts to quantify the palaeosalinity of the Neoeuxinan lake prior to the Mediterranean transgression used nonquantitative methods based on ecological affinities of bivalves (Nevesskaya, 1963, 1965) and gastropod mollusks (Il'ina, 1966), ostracods (Yanko and Gramova, 1990; Stoica and Floroiu, 2008; Ivanova et al., 2012), benthic foraminifera (Yanko, 1990; Yanko-Hombach, 2007) and dinoflagellate cysts (dinocysts) (Mudie et al., 2001, 2004; Marret et al., 2009). These non-quantitative data all indicated that Neoeuxinian lake was brackish, with a salinity range between 7 and 12 psu. Paleontological results are in good agreement with pore water salinities in bottom sediments of Neoeuxinian age measured by Manheim and Chan (1974). However, they contradict the data of Soulet et al. (2010) who used interstitial sediment water chlorinity and δ^{18} O values to determine that the Neoeuxinan lake was freshwater ($\sim 1 \text{ psu}$) until ca 9.0 cal ka BP at one site on the Ukrainian shelf margin. However, new quantitative estimates for the Turkish shelf near Bosphorus Strait (Mertens et al., 2012) firmly establish that the surface water salinity was between 8 and 15 psu from 9.3 to 8.6 ka BP.

Efforts to determine the elevation of the Neoeuxinian lake water level before the Holocene marine transgression include the work of Ryan (2007) who described dune fields on the Ukrainian Shelf between -65 and -80 m, and wave-truncated terraces with beachlike berms at -90 to -100 m. The dunes were interpreted as having formed during a post-Younger Dryas regression which reduced the lake surface below the level of the World Ocean. Lericolais et al. (2010) similarly reported seismostratigraphic evidence indicating that, "Following the Younger Drvas, 11.000–8500¹⁴C BP, there occurred a new level lowering to the level of -100 m, identified by the forced regression deposits recorded on the Romanian shelf. This last [data source] and a belt of coastal dunes is also evidenced there by the prodelta at -100 m depth. All these coastal features as well as the incised anastomosed channel system remained preserved on the shelf resulting from a rapid ultimate transgression starting immediately after 8500 ¹⁴C BP" (Lericolais et al., 2010:199). Nicholas et al. (2011) support this idea by writing, "The shelves were subaerially exposed from the LGM to the Younger Dryas (Nicholas et al., 2011:3787)". Thus, these authors concluded that immediately before the Holocene transgression, the Black Sea shelf was subaerially exposed to an isobathymetric depth of ~ -100 m and then the shelf was catastrophically (Ryan, 2007)/rapidly (Lericolais et al., 2007, 2010)/promptly (Nicholas et al., 2011) flooded by Mediterranean water at 8.4–8.6 ka ¹⁴C BP. In contrast, the geological data from medium- to large-scale geological surveys of the NW shelf (Yanko-Hombach, 2007; Yanko-Hombach et al., 2010; Larchenkov and Kadurin, 2011) show that the level of brackish Late Neoeuxian lake was at ~ 40 m bsl in the early Holocene, making catastrophic/rapid/prominent flooding of the Neoeuxinian lake by Mediterranean water in early Holocene impossible. High-resolution survey and core data of Hiscott et al. (2007) also indicate a water depth close to 40 m bsl by 8.6 ka BP (uncal).

The purpose of the present study is to refine the chronology of the marine transgression as well as the water level and salinity of the Neoeuxinian Lake prior to the IMI and Mediterranean transgression in the Holocene. Our primary data include sedimentary, micropaleontological (foraminifera and ostracoda), palynological and radiocarbon studies of selected samples from cores 342, B2 and 45B on the NW shelf of the Black Sea, in front of the Dniestrovian, Berezan limans and to the east of the Danube Delta mouth, respectively (Fig. 1; Table 1). The top section of 72.5 m-long Core 342 drillhole located in a water depth of 30.8 m bsl (Fig. 1; Table 1) at the edge of the Dniester paleovalley (Fig. 2) is extraordinarily valuable because it provides several peat and muddy peat beds, each up to ~ 10 cm thick, inter-layered in a coastal succession with mud, clay, and shell coquina.

 Table 1

 Coordinates, water depth, and length of cores cited in this paper.

Core number	Latitude N	Longitude E	Water depth m	Core length, m	
Geological profile in Fig. 3.					
183	46° 01' 49"	30° 27′ 8″	-9.9	3.0	
334	45° 50' 05"	30° 26′ 30″	-21.7	0.2	
342	45° 43' 09"	30° 34' 28"	-30.8	72.5*	
350	45° 38' 30"	30° 43′ 8″	-36.8	0.15	
385	45° 29' 23"	30° 46' 50"	-40.5	0.15	
383	45° 26' 10"	30° 53′ 0″	-40.6	0.2	
830	45° 25' 23"	31° 0.0′ 5″	-45.3	0.05	
876	45° 21' 03"	31° 0.0′ 6″	-45.2	0.1	
1263	45° 10' 15"	31° 10′ 54″	-49.9	0.2	
1115	45° 05' 59"	31° 16' 58"	-56.5	0.2	
1118	44° 59' 31"	31° 16′ 58″	-60.5	0.2	
1122	44° 50′ 53″	31° 16′ 54″	-64.9	0.15	
1628	44° 43' 15"	31° 16' 49"	-95.0	0.15	
45B	44° 40′ 16″	31° 17′ 30″	-107.0	0.75	
2411	44° 34' 20"	31° 16′ 9″	-435.0	1.5	
Other reference cores in Fig. 1.					
B2	46° 37' 38"	31° 24′56″	+2.0	10.3	
721	42° 59'35.5"	41° 2′ 79″	-14.9	27.5	
MAR02-45	41° 41′17″	28° 19'08"	-69.0	9.0	

The presence of wood fragments and sedge leaves in peat layers provide critical new data (Kadurin et al., 2011) for calibrating and "re-tuning" of previously published (Nicholas et al., 2009, 2010, 2011) shell and bulk peat ages. These authors previously dated the peat-containing core intervals in Core 342 as pre-Boreal – early Holocene age, based on dates from mollusc shells or bulk carbon from muddy peat samples (Nicholas et al., 2009). However, AMS and AAR (Amino-Acid Racemisation) ages of shell fragments and detrital peat suggested that some of these bulk ages were too old. New AAR ages for selected shells and/or detrital peat implied that sedimentary strata on the NW Black Sea shelf were formed as the result of a prompt Mediterranean transgression that raised the Neouxinian lake water level from approximately -100 m to the level of the Bosphorus sill (-35 m) in 300 years, rapidly submerging the inner Ukrainian shelf after 7000 BP (Nicholas et al., 2010, 2011).

We compare our new data with results from other core sites on the Caucasian and Turkish shelf and show that the chronostratigraphy of the Early Holocene transgression remains far from a clear understanding. To reach our goal, we report on: (1) re-examination of the critical section of early Holocene peat inter-layered with peaty mud/silt in Core 342, focusing on use of palynology as a chronostratigraphic tool that can by-pass the requirement for marine reservoir correction; (2) reconstruction of sea level and salinity change on the NW Black Sea shelf and comparison with the Caucasian shelf using benthic foraminifera and ostracoda as the main tool. These studies add new paleoenvironmental data to earlier analyses of the early Holocene environment in the basin (Dolukhanov et al., 2009; Larchenkov and Kadurin, 2011) and re-address the question of a possible catastrophic early to mid-Holocene Black Sea flood.

All radiocarbon dates in this paper are in non-calibrated years BP unless indicated otherwise as cal BP. We prefer conventional ¹⁴C ages because (1) uncertainty surrounds the marine reservoir correction required for Black and Caspian seawater, where living mollusks are much older or younger than the global ocean average of +410 years used for most marine shell-based calibration curves, and (2) controversy and compounding of error are introduced when the early Black Sea lake is classified as "freshwater", requiring no marine reservoir correction.

2. Regional setting

The study area extends over the shelf from the Ukrainian part of the Danube Delta to the west coast of Crimea (Fig. 1). This is a



Fig. 2. Northwest Black Sea study area showing present bathymetry (in m bsl), paleovalleys I – III, locations of cores in present study, shelf section (in square) studied by Ryan et al. (1997), and other important geomorphological features marked by 1–VI.

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key region because: (1) it is the widest (125–240 km) shelf in the Black Sea, encompassing about 25% of the total area of the sea; (2) the inner shelf is landward of the erosional Rim Current that sweeps the outer shelves and upper continental slope (Larchenkov and Kadurin, 2011); (3) it is located within stable platform-type structures with a gentle slope (0.001–0.002°) and no active tectonic movements in contrast to the southwestern and eastern margins on the Anatolian Fault system; (4) it has widespread thick sediment cover deposited from the Danube, Dniester, Bug, and Dnieper rivers in contrast to the narrow shelves along the Turkish coast, where river input and sediment cover is more restricted, resulting in more variable sedimentation rates and Rim Current activity. The inner NW shelf plain to about 40 m bsl is dissected by depressions and troughs with low-gradient floors (less than 1°) and $3^{\circ}-4^{\circ}$ slopes, marking paleovalleys of the major rivers (Fig. 2).

Since 1971, the study area was continuously investigated over the course of: (1) a large-to-medium scale (1:200,000 and 1:50,000) marine geological-ecological survey performed by Prichernomorskoe State Regional Geological Enterprise "Prichernomor GRGP" (Podoplelov et al., 1975; Karpov et al., 1978; Sibirchenko et al., 1983; Gozhik et al., 1987; Avrametz et al., 2007), and (2) marine hydrocarbon gas survey of bottom sediments (Tkachenko, 1971) carried out by the Department of Physical and Marine Geology of Odessa I.I. Mechnikov National University to delineate areas suitable for industrial exploration of mineral resources. The surveys recovered thousands of gravityand vibro-cores, and hundreds of drillhole cores with lengths up to 5 m and 100 m, respectively. Many of these 20,107 cores (total number) were dated by conventional ¹⁴C and other radioactive isotope methods. During the surveys, seabed surface samples were also taken by grab samplers, together with measurements of seawater temperature and salinity to link modern faunas and floras with concurrent oceanographic conditions for semiquantitative paleogeographic reconstructions (Yanko-Hombach, 2007).

During the regional survey, studies were made of morphological, lithological, geochemical, and paleontological markers of paleo-sealevel stands and their geochronology (Yanko-Hombach, 2007), with particular attention to possible influences of neotectonics on paleogeographic reconstructions (Tkachenko et al., 1970). The survey enabled the reconstruction of the Late Quaternary sedimentary history of the Ukrainian shelf from the Matuyama-Bruhnes reversal (last ~780 ka), with particular attention to the history of the basin since the Last Glacial Maximum (LGM), as illustrated here by a geological profile along the Dniester Trough at water depth from -10 to -435 m bsl (Fig. 3).

Today, the surface water salinity on the NW Black Sea shelf varies from ~15.2 psu at the Core 342 site to 18 psu at the Core 45B site. The bottom salinity is quite uniform reaching ~18.0 psu. The salinities are low compared to the global ocean average of 35 psu because Black Sea is a large, deep, almost land-locked basin (Fig. 1), connected to the Eastern Mediterranean Sea and global ocean only through the ~2 km-wide, shallow Bosphorus Strait with sills depth



Fig. 3. Paleo-Dniester valley cross-shelf profile, showing sediment lithology and genetic type, depositional setting and stratigraphic ages. Inset shows shelf bathymetry, locations of transect cores and present-day limans at the seaward end of the Dnieper, Bug and Dniester rivers. Shell detrit = detrital shell fragments.

59 and 38 m on its western and eastern side, respectively, Marmara Sea, and Dardanelles Strait (sill depth 72 m).

The Black Sea has a positive estuarine water circulation that is driven by inflow of saline (~35 psu) bottom water of Mediterranean origin and the outflow of low salinity (\sim 17 psu) surface water formed by mixing of bottom water with freshwater runoff, primarily from the Danube. Dniester, Dnieper and Don rivers, totaling 294-474 km³ a⁻¹ (Esin et al., 2010). During and after the last glaciation, the Black Sea was an isolated lacustrine environment with surface (Bahr et al., 2008) and bottom (Yanko-Hombach, 2007) salinity 7 and 12 psu until Mediterranean waters began breaching the Bosphorus $\sim 10-9$ ka BP (Hiscott et al., 2007; Bahr et al., 2008; Soulet et al., 2011a). It is frequently assumed that before the IMI, Black Sea surface water (0–400 m) was fully mixed, with a fluviatile geochemical signal (Bahr et al., 2008) supporting brackish benthic faunas (Nevesskava, 1963, 1965; Il'ina, 1966; Yanko and Troitskaya, 1987; Yanko and Gramova, 1990; Yanko-Hombach, 2007) and that ¹⁴C ages required no ΔR (marine reservoir correction) value before ~8400 BP (Major et al., 2006; Soulet et al., 2011b). However, divergent AMS ages for an unspecified peat sample and a valve of Dreissena polymorpha with graphite value δ^{13} C -8.7% from 31.95 m bsl in Core 342 (Fig. 3) indicate a possible carbon reservoir age (R) of 600 years for the shell (Nicholas et al., 2011), reflecting carbonate dissolution within the watersheds. A mean IMI reservoir age of 300 ± 125 was determined for the Black Sea surface water (Soulet et al., 2011a). Between the IMI and disappearance of the brackish-water and Ponto-Caspian lacustrine species (called the DLS event) at \sim 7580 BP, the salinity of surface (Mertens et al., 2012) and bottom water (Yanko-Hombach, 2007) increased gradually. Comparison of mollusk versus peat ages from Sakarya coastal plain (Görür et al., 2001) suggested that a mean ΔR of 350 \pm 260 years was an appropriate value for correction of measured mollusk ¹⁴C ages. After 7100 BP, a marine reservoir value of 415 years is applied for the Black Sea marine ¹⁴C ages (Major et al., 2006; Mertens et al., 2012), although modern shell ages actually range between 498 and –308 years.

3. Materials and methods

Core 342 drillhole (72.5 m long) was recovered in July 2006 from –30.8 m water depth on the inner shelf of the Black Sea, using a Bobtail rotary corer 6 m-long, 12 cm in diameter, with a diamond cutter drillbit, mounted on the drilling platform "Diorit". The drillhole is located within the Dniester trough, which extends like an elbow from the Dniesterovian liman to 40 m depth.

Gravity Core 45B was obtained in September 2008 on the outer shelf of the Black Sea at water depth -107.0 m, as part of the HERMES project conducted from the Ukrainian Research Vessel "Vladimir Parshin."

Core B2 drillhole (10.3 m long) was obtained with a rotary corer similar to the Core 342 drilling equipment, located on Berezan spit +2 m above sea level in front of Berezan liman (Table 1; Fig. 2), as part of the Russian–Ukrainian project "The Northwestern Black Sea Region and Global Climate Change: Environmental evolution during the last 20 ka and forecast for the 21st century".

Core 721 drillhole (27.5 m long) was obtained in the mid-1980s by Bobtail rotary coring in Sukhumi Bay on the Caucasian shelf at -14.9 m water depth.

Eighty four samples (12, 5, 11, and 56 samples from \sim 2 cm-thick intervals) from top section of Cores 342 as well as complete cores 45B, B2 and 721, respectively were examined in multidisciplinary studies. Lithological studies were made using the standard sieving and pipette analysis methods for grain-size analysis. Sedimento-logical logs of cores from NW shelf are shown in Fig. 4.



Fig. 4. Sedimentology and sample positions for Core 342, and correlation of this core with other reference cores from Berezan spit (Core B2) and the outer shelf (Core 45B). 1 – Meotic (Upper Miocene) grayish-green clay; 2 – dark-gray clay; 3 – light-brown mud with black organic-rich laminae; 4 – unsorted sand; 5 – light-brown silt with high plasticity; 6 – light-gray moist quartz sand; 7 – light-gray mud; 8 – sandy soil with plant remains; 9 – peat; 10 – light gray mud; 11 – greenish-gray muds; 12 – greenish-gray sand; 13 – *Hydrobia ventrosa*; 14 – broken mollusc shells; 15 – *Modiolus phaseolinus*; 16 – *Mytilus galloprovincialis*; 17 – *Dreissena polymorpha*; 18 – *Cardium edule*; 19 – coquina; 20 – *Mactra subtrucata*.

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Radiocarbon dating was performed on: (1) shells of bivalves and gastropod that were identified prior the measurement following classification of Nevesskaya (1963, 1965) and Il'ina (1966), respectively; and (2) plant material (size >250 µm) extracted from muddy peat or mud with peat fragments (detrital peat of Ukrainian literature).

3.1. Micropaleontology

Samples for micropaleontological (foraminifera and ostracoda) analysis were soaked and washed in distilled water, passed through 63 µm mesh sieve, dried at room temperature to minimise destruction of agglutinated tests of foraminifera, and split with a microsplitter to avoid sample bias; about 300 fossil foraminifera and ostracoda were picked by hand (flotation in CCl₄ was sometimes used) and counted for total abundance per sample (population size) and relative abundance. The total number of foraminifera and ostracoda was calculated in samples of 50 g dry weight. All species were morphologically examined and taxonomically identified as described in Yanko and Troitskaya (1987), Yanko and Gramova (1990) and Dikan' (2006). According to their present day ecological preferences, foraminifera were divided into oligohaline (1-5 psu), strictoeuryhaline (11–26 psu), polyhaline (18–26 psu), holeuryhaline (1–26 psu) (Yanko and Gramova, 1990; Yanko-Hombach, 2007) while osracoda were divided into freshwater (<0.5 psu), oligohaline (0.5-5 psu), mesohaline (5-18 psu) and polyhaline (18-30 psu) (Ivanova et al., 2012). Images of foraminifera and ostracoda were obtained using the SEM at University of Manitoba in addition to standard binocular microscope photographs (Fig. 5).

3.2. Paleosalinity

The paleosalinity in this paper is described as follows: fresh water (<0.5 psu), semi-fresh (0.5–5 psu), brackish (>5–12 psu), semi-marine (>12–18 psu), and marine (>18–26 psu). The UNESCO Practical Salinity Scale of 1978 (PSS78) is used today by oceanographers, rather than parts per thousand (%) (Mudie et al., 2011). The PSS78 defines salinity in terms of a conductivity ratio, and so is dimensionless or expressed as psu (= practical salinity units). On the PSS, the open ocean salinity is generally in the range 30–40 psu while brackish seas/waters have salinity in the range 5–12 psu. The modern Danube Delta estuary has a salinity range from brackish (12 psu) at the outer edge during the dry season to semi-fresh at the upper limit of tidal influence (Pallis, 1916).

Table 2

Radiocarbon ages of dated	samples reported for Core	es 342, B2, 45B, MAR02-45
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3.3. Palynology

Palynological samples from Core 342 were prepared using standard methods for marine palynology that allow for best recovery of pollen, spores and dinoflagellate cysts for palynostratigraphic correlation, and also recovers algal and fungal spores, zoomorphs, micro-charcoal, and other particulate plant material (kerogen) for palynofacies analysis (Batten, 1996; Mudie et al., 2011). The method uses wet sieving of \sim 5 g samples at 125 μ m, then removal of carbonate by chemical digestion in cold 10% Hydrochloric acid for about 1 h. At this stage, tablets or solution of exotic spores or pollen, e.g. Lycopodium or Eucalyptus, are added to provide an estimate of the number of palynomorphs present in the samples after laboratory preparation. After washing the carbonate-free samples with distilled water, the clastic sediment is removed by cold 50% Hydrofluoric acid treatment for ~ 24 h. The concentrated palynological residues are then washed and small amounts are placed on microscope slides using glycerine gel. The palynomorphs are counted using a Zeiss Universal Research microscope with interference contrast lenses, at a magnification of ×400. Identification of the palynomorphs follows the system described by Mudie et al. (2010). Palynostratigraphic correlation was made using the correlation chart of Filipova-Marinova et al. (2013). For the new high resolution studies reported here in Core 342, particles of wood and peat fragments (mostly grass and sedge leaf) were extracted from the same samples that were previously dated using shells or bulk sediment for "peat" analysis (Nicholas et al., 2009, 2010, 2011). The new samples of plant material were prepared by washing the samples on nested sieves with mesh size 250 and 63 um to remove coarser sand, shell and larger microfossils and to concentrate the charcoal, wood and other plant material larger than silt-size. The larger particles of plant material were identified by transmitted light microscope examination of tissue structures and associated pollen or spores (Fig. 6), with reference to the work of Gale and Cutler (2000).

3.4. ¹⁴C and AAR age determination

Before ~2009, most radiocarbon ages for shell, peat or detrital carbon in cores from the NW and Caucasian shelf were obtained from the conventional "Bulk" analysis method that uses large samples (multiple shells >50 g). Since 2009, several samples from Cores 342, B2, 45B, 721 have been dated using the Accelerator Mass Spectros-copy (AMS) method on very small samples (50 mg) of shell or plant material (Nicholas et al., 2009, 2010, 2011), or using the Amino Acid Racemisation (AAR) method for selected mollusk shells (Nicholas et al., 2011). Table 2 shows the materials used for this dating, the ages and the laboratory numbers for the results of these analyses.

Lab No.	Core No.	Core depth, m	Material dated	¹⁴ C BP	¹³ C ‰
OZL582 ^a	342	0.85	Cardium edule valve	9140 ± 60	-4.4
OZM332 ^a	342	0.85	Mytilus (A) single valve	5765 ± 30	0.1
OZM333	342	0.85	Mytilus (B) single valve	4365 ± 30	-1.2
OZL579 ^a	342	1.15	Dreissena polymorpha single valve	9620 ± 60	-8.7
OZL577 ^a	342	1.15	Peat	9020 ± 70	-24.9
OZL581 ^a	342	1.65	Peat	8920 ± 70	-28.1
Beta 315422	342	1.9	Sedge leaf	8540 ± 40	-26.2
Beta 315423	342	1.9	Wood	8450 ± 40	-26.1
Beta 318166	342	2.1	Wood	8890 ± 50	-26.2
Beta 318167	342	2.35	Wood	8860 ± 40	-25.9
Beta 327305	342	2.35	Finely divided peat	8740 ± 50	-27.7
Beta 328090	342	2.35	Detrital peat	8990 ± 40	-27.8
Hd-29092	B2	5.7-5.8	Cardium edule, Mytilus galloprovincialis	3641 ± 31	
ETH-39030					
Hd-28978	B2	8.5-8.6	Cardium edule	5524 ± 33	
ETH-39029					

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Table 2 (continued)

Lab No.	Core No.	Core depth, m	Material dated	¹⁴ C BP	¹³ C ‰
OZL583 ^a	45B	0.31	Mytilus single valve	6530 ± 45	-0.7
OZL580 ^a	45B	0.44	Dreissena rostiformis (A) single valve	8820 ± 70	0.4
OZL578 ^a	45B	0.44	Dreissena rostiformis (B) single valve	8695 ± 50	0.4
OZM331 ^a	45B	0.44	Dreissena rostiformis (C) single valve	8170 ± 60	-0.2
OZL304 ^a	721	2.0	Micro-molluscs	1790 ± 90	0.0
OZL305 ^a	721	8.0	Micro-molluscs	2530 ± 80	0.0
OZL306 ^a	721	15.0	Micro-molluscs	3190 ± 90	0.1
OZL307 ^a	721	22.0	Micro-molluscs	8210 ± 120	0.0
OZK766 ^a	721	26.2	Peat	8530 ± 70	-25.0
TB-346 ^b	721	26.7	Peat	9310 ± 80	
OZK767 ^a	721	26.9	Peat	9370 ± 70	-29.1
TO-11433 ^c	MAR02-45T	0.92	Spisula subtruncata	730 ± 50	
TO-11434 ^c	MAR 02-45T	1.45	Spisula subtruncata	770 ± 50	
TO-11435 ^c	MAR 02-45P	1.43	Spisula subtruncata	730 ± 40	
TO-11006 ^c	MAR 02-45P	2.68	Mytilus edulis	2400 ± 60	
TO-11436 ^c	MAR 02-45P	3.30	Mytilus edulis	5190 ± 50	
TO-11437 ^c	MAR 02-45P	4.12	Mytilus galloprovincialis	5900 ± 60	
TO-11438 ^c	MAR 02-45P	5.16	Monodacna pontica	7560 ± 60	
TO-11142 ^c	MAR 02-45P	6.05	Truncatella subcylindrica	8380 ± 70	
TO-11439 ^c	MAR 02-45P	6.79	Didacna ?praetrigonoides	8570 ± 70	
TO-11440 ^c	MAR 02-45P	7.49	Didacna spp.	8620 ± 70	
TO-11441 ^c	MAR 02-45P	8.64	Dresissena rostiformis	8840 ± 70	
TO-11007 ^c	MAR 02-45P	9.20	Dreissena rostiformis	9370 ± 70	
TO-11442 ^c	MAR 02-45P	9.32	Dresissena polymorpha	9340 ± 70	
TO-11443 ^c	MAR 02-45P	9.45	Theodoxus sp.	9070 ± 70	

^a Nicholas et al., 2011.

^b Yanko and Troitskaya, 1987; Yanko-Hombach, 2007.

^c Hiscott et al., 2007, 2010).

According to Nicholas et al. (2011: 3787), "The AMS 14C record on molluscs from the Black Sea, commonly using single shells, is different to results from conventional radiocarbon methods on bulk mollusc samples consisting of multiple individual shells that commonly inhabited different environments, and may have had different reservoir ages". However, statistical tests performed to determine if the conventional "Bulk" and AMS data sets for a given time interval are significantly different from those for a single Neoeuxinian mollusk population (Yanko-Hombach et al., 2010) show that the two dating methods give similar results although the AMS dating error is lower than the "Bulk" method. As such, the large NW shelf database as a whole provides a large ¹⁴C data set for paleogeographic reconstructions of the late-Glacial to Pre-Boreal lacustrine stages of the Black Sea.

For the new high resolution studies reported here, samples of wood and peat were extracted from the samples previously dated using shells or using bulk sediment for "peat" analysis (Nicholas et al., 2011). The new samples of plant material were prepared by washing the samples on nested sieves with mesh size 250 and 63 μ m to remove coarser sand, shell and larger microfossils and to concentrate the charcoal, wood and other plant material larger than silt-size. The larger particles of plant material were identified by transmitted light microscope examination of tissue structures and associated pollen or spores (Fig. 6), with reference to the work of Gale and Cutler (2000).

4. Results

4.1. Sedimentology and chronology

Sedimentological studies (Fig. 4) of the top section of Core 342 shows that from 3.07 to 1.65 m there are dark brown peat fragments at 1.15 m core depth and three intervals of dark brown peat (at 1.65–1.9 m, 2.1–2.35 m, and 2.7–2.9 m) with occasional mollusk shells (mostly *Dreissena polymorpha*). The peat is inter-layered with dark gray clay or clayey mud with mollusk shells (*Dreissena polymorpha*, *Micromelania caspia*, *Hydrobia ventrosa*). Previously

reported AMS conventional radiocarbon ages (Table 2, OZL measurements) for unspecified peat material in the peat stringers range from 9020 \pm 70 BP at 1.15 m core depth to 8920 \pm 70 BP ("bulk peat") at 1.65 m core depth (Nicholas et al., 2011). However, our new AMS ages on carefully selected plant fragments revealed that sedge leaf and wood samples from core depth 1.9 m are much younger having ages of 8540 \pm 40 and 8450 \pm 40, respectively (Table 2). Above the uppermost peat layer there are 50 cm of darkgray clay and light-gray mud with mollusk shells, including Monodacna caspia caspia (50%), Dreissena polymorpha (48%), Micromelania caspia lincta, Valvata piscenalis, H. ventrosa. This mud is overlain with a 10 cm layer of Dreissena coquina containing peat fragments. A previously reported AMS conventional radiocarbon age for *Dreissena* from this layer is 9620 ± 60 (Nicholas et al., 2011). The coquina layer is overlain by light-gray mud with mollusk shells Cardium edule and Mytilus galloprovincialis. The Cardium shell was dated at 9620 \pm 60; the *Mytilis* shell dated between 5765 \pm 30 and 4365 ± 30 BP (Nicholas et al., 2011). In contrast, cross-correlation of the coquina sediment facies with equivalent lithofacies containing Cardium shells at the base of the Core B2 on Berezan sand spit, and the green mud with *Mytilus* shell at the base of in Core 45B (Table 2) give minimum ages of 5524 \pm 45 BP and 6530 \pm 45 for the top of Core 342 (Fig. 4).

4.2. Micropalaeontology

Microfaunal analysis of Core 45B (Fig. 7) shows three main depositional environments: brackish (core depth 0.45-0.40 m), semi-marine (0.3-0.2 m) and marine (0.2-0.0 m).

Presence of strictoeuryhaline (11–26 psu) and polyhaline (1– 5 psu) Mediterranean species of ostracoda at 8.8 ka BP indicates an influence of Mediterranean water at that time. Their admixture with freshwater and oligohaline species shows that basin had unstable hydrological regime being most probably brackish, possibly with storm water overwash of higher salinity water. A higher percentage of polyhaline ostracoda species at 6.5 ka BP shows an increase in bottom water salinity in course of basin transformation

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Fig. 5. SEM images of key ostracoda (Figures 5.01–5.09) and foraminifera (Figures 5.10–5.20) used to determine salinity and sea level position in this study. RV = right valve; IV = left valve. 5.01. *Graviacypris elongata* (Schweyer, 1949), RV, female, oligohaline, Core 45B: 0.43–0.45 m 5.02. *Leptocythere andrussovi* (Livental, 1929), RV, male, oligohaline, Core 342: 3.07–3.13 m 5.03. *Loxoconcha lepida* Stephanaitys, 1962, LV, female, oligohaline, Core 342: 3.07–3.13 m 5.04. *Leptocythere quinquetuberculata* Schweyer, 1949, RV, oligohaline, Core 342: 3.07–3.13 m 5.05. *Cyprideis torosa* (Jones, 1850), RV, female, oligohaline, Core 342: 0.07–1.0 m 5.06. *Leptocythere striatocostata* Schweyer, 1949, RV, male, oligohaline, Core 342: 0.83–0.96 m 5.07. *Xestoleberis cornelii* (Caraion, 1956), IV, mesohaline, Core 342: 0.8–0.82 m 5.08. *Hiltermannicythere rubra* (Müller, 1894), LV, mesohaline, Core 342: 0.8–0.82 m 5.00. *Mayerella brotzkajae* (Mayer), 1968, oligohaline, Core 721, 27.0–27.1 m 5.11. *Elphidium caspicum azovicum Yanko*, 1989, oligohaline, Core 342, 3.07–3.13 m 5.10. *Anyoneina novoeuxinica* Yanko, 1979, holeuryhaline, Core 721, 27.0–27.1 m 5.13. *Haynesina anglica* (Murray), 1965, holeuryhaline, Core 342, 8.7–8.7 m 5.14. *Porosononino martkobi ponticus* Yanko, 1989, strictoeuryhaline, Core 721, 18.5–18.7 m 5.15. *Canalifera parkerae* Yanko, 1974, strictoeuryhaline, Core 342, 0.55–0.58 m 5.17. *Ammonia compacta* Hofker, 1969, polyhaline, Core 342, 0.8–0.82 m 5.18. *Eggerella scabra* (Williamson), 1858, polyhaline, Core 724, 0.83–0.96 m 5.20. Essyrinx jatzkoi Yanko, 1974, polyhaline, Core 342, 0.83–0.96 m 5.07. *Astones of the stabaline*, 1969, polyhaline, Core 342, 0.83–0.96 m 5.00, 0.82 m 5.10. *Royersia* 2.0, 0.82 m 5.13. *Royersia* 2.0, 0.82

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Fig. 6. Light microscope photographs of plant materials in peat samples used for AMS dating in this study, and various well- preserved animal remains from the cores that mark either delta deposits (e.g. ostracoda linings also found in present-day Chilia lobe of Danube) or liman deposits (microforminifera, flatworm egg capsule, ant mandible, fly pupa).

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Fig. 7. Vertical distribution of ostracoda in core 45B (water depth – 107 m) showing three basic depositional environments: brackish (core depth 0.45–0.40 m), semi-marine (0.3–0.2 m) and marine (0.2–0.0 m). Presence of strictoeuryhaline and polyhaline Mediterranean species of ostracoda at 0.4–0.42 m indicates that Black Sea was already connected to the Mediterranean Sea at 8.8 ka BP.

from brackish to semi-marine conditions. An upwards replacement of oligohaline by strictoeuryhaline and polyhaline species indicates further increase of salinity to marine conditions.

Microfauna in Core 342 (Fig. 8A, B) also show three depositional environments: semi-freshwater ponds in the Paleo-Dniester delta (core depth 3.07–2.1 m), brackish Paleo-Dniestrovian liman conditions (2.0–0.83 m), and semi-marine inner shelf paleoenvironment (0.82–0.0 m). Brackish conditions are indicated by mixture of oligohaline and holeuryhaline (salinity 1–26 psu) foraminifera. Presence of holeuryhaline species among the foraminiferal assemblage starting from the bottom of the core indicates an influence of Mediterranean water from 8.9 ka BP upwards.

Microfossils are rare in Core B2 (Fig. 9) which is represented (from base upwards by dark gray Meotian (Upper Miocene age) clays (10-1-10.3 m) uncomfortably overlain by Holocene sediments. The latter includes dark gray clay (9.3-10.1 m) with mixture of small shells, including marine Cardium edule, M. galloprovincialis, brackish water H. ventrosa that are widespread throughout the coastal zones of Europe and the Mediterranean, and the Caspian species Dreissena polymorpha. The latter tolerates salinity up to 13% and it can coexist with Mediterranean species in sedimentological sequences characteristic of unstable hydrological regimes in the Black Sea basin (Nevesskaya, 1963, 1965). Foraminifera and ostracoda are absent below ~8.5 m depth. Higher in the core, brackish mollusks disappear and from 8.5 to 9.3 m upwards, there are only marine mollusks (Cardium edule, Bittium reticulatum, Theodoxus pallasi, M. galloprovincialis, Ostrea edulis) and as well as holeuryhaline foraminifera such as Haynessina anglica and Ammonia tepida. The AMS radiocarbon age of Cardium shells from this layer is 5524 \pm 33 ka BP (Table 2), showing that this site was below sea level around 6 ka BP in course of the Mediterranean transgression. Microfossils indicate that the hydrological regime in this area was quite unstable as indicated by dominance of holeuryhaline foraminifera that have wide ecological range.

Microfossils in Core 721 (Fig. 10) show three main depositional environments: semi-freshwater (27.5–25.5 m), brackish (25.5–19.5 m) and semi-marine (19.5–0.0 m). The first Mediterranean species of foraminifera appear in the core at depth 26.0 m at 8.5 ka BP while the first *C. edule* shell appears later at 22.0 m, with an age of 8.2 ka BP. Presence of Mediterranean foraminiferal species at the bottom of the core indicates that marine transgression reached the NE inner shelf at 8.5 ka BP when paleowater depth was ~ -40.9 m in Sukhumi Bay on the Caucasian shelf.

4.3. Palynology

Palynological study of Core 342 (Figs. 1, 4, 6 and 11) shows the presence of well-preserved pollen and spores in concentrations ranging from a minimum of ~2500 grains g^{-1} at the base to a maximum of ~54,000 grains g^{-1} in the muddy peat from 1.70 to 1.72 m core depth.

The pollen assemblages include 100 identified tree, shrub and herbaceous terrestrial plant taxa, 16 aquatic plant species, and 11 known fern spore taxa. Moss spores were sparse, making it clear that all the peat samples were derived from coastal marsh vegetation and were not Sphagnum peat deposits washed down the paleovalleys from higher terrain. In addition to these sporomorphs (pollen and land plant spores), the palynological residues also contained various amounts of non-pollen palynomorphs (NPP): 20 kinds of fresh or brackish water algae (e.g. Pediastrum), 22 dinoflagellate cyst (dinocyst) taxa, fungal spores, and various animal remains, including the organic linings of microforaminifera and ostracodes, worm egg capsules and insect remains (Fig. 6). Furthermore, the palynological residues contained variable amounts of palynodebris, including microcharcoal and wood particles, leaf material (exine) and amorphous organic matter (amorphogen) that usually represents marine phytoplankton production (Batten, 1996).

Arboreal pollen spectra for 10 samples from Core 342 (Fig. 11) show a succession from pre-Boreal Pinus-Picea woodland to Boreal Pinus-Picea-Quercus-Ulmus forest, then a more temperate Boreal forest with Carpinus, Castanea, Tilia, Juglans, and Olea. Pollen and spores from a surface grab sample taken near the site during a HERMES cruise in 2010 have been added to the top of the diagram, at 0 cm, to allow comparison of this fossil record with the modern pollen signal. The diagram (Fig. 11) also displays the relative proportions of arboreal pollen (AP = trees + shrubs) to non-arboreal pollen (NAP = terrestrial herbs) and to pollen of fresh- or brackish-water aquatic flowering plants; the amounts of fern spores are shown as percentages of the Total Pollen + Spores. From the base of the core to 1.70 m, there is a gradual increase of tree pollen relative to NAP, while the amount of aquatic pollen remains around 30%. From 1.10 to 0.90 m, there is an increase in amounts of aquatic pollen and ferns, including the marsh fern Thelypteris palustris that grows on floating mats of reed vegetation (locally called pluva) in the modern lower Danube Delta. Above 0.9 m in Core 342, there is sharp drop in aquatic plant pollen, a gradual decline of ferns and a corresponding increase in relative abundance of herb pollen (more than $\sim 40\%$), similar to the pollen spectra for the modern landscape of the Ukrainian coastal steppe.

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Fig. 8. Vertical distribution of foraminifera (A) and ostracoda (B) in core 342 (water depth 30.8 m). A and B show three basic depositional environments: semi-freshwater ponds in the Paleo-Dniester delta (core depth 3.07–2.1 m), brackish Paleo-Dniestrovian liman (2.0–0.83 m), and semi-marine inner shelf (0.82–0.0 m). Dominance of holeuryhaline species among foraminifera starting from the bottom of the core upwards indicates a permanent influence of Mediterranean water since 8.9 ka BP.

Statistical analysis of the pollen spectra, using the CONISS cluster analysis program (Fig. 11), shows the presence of three palynozones that can be related to the classical Blytt-Sernander European pollen zone chronology, following the practice of Balabanov (2007). Giosan et al. (2006) and Filipova-Marinova et al. (2013). Palynozone 1 (3.05-1.90 m) comprises Pinus-Picea assemblages characteristic of the pre-Boreal period; palynozone II (~1.9-0.8 m) contains Pinus-Picea-Quercus-Ulmus assemblages corresponding to the Boreal interval; and palynozone III (0.76-;0.8 m) contains the thermophilic trees Carpinus, Castanea, Tilia, Juglans, and Olea characteristic of the Atlantic period of the regional palynochronology. The sediments above 0.6 m core depth in Core 342 are too coarse for recovery of sufficient palynomorphs to allow analysis but are represented in correlative lithofacies of Core B2 which have a basal age of >6.5 ka BP. The sparseness of samples above 0.6 m in Core 342 results in the surface (0 cm) sample being grouped with the Atlantic pollen zone ($\sim 8-4.5$ ka BP) because of over-representation of Pinus pollen which was extensively planted in recent times. Presence of maize/corn pollen (Zea mays) also marks modern agricultural crops. These anthropogenic artifacts

obscure the pre-historical Sub-Atlantic pollen assemblage features (e.g. high % *Quercus, Ulmus, Carpinus betuloides, Salix* and *Fagus* pollen). The large increase of *Alnus* pollen in the surface sample, however, is typical for the relatively cool, moist Sub-Atlantic period.

Palynofacies analysis investigates the distributions of terrigenous and brackish/marine palynomorphs and kerogen types which characterize the deltaic and coastal barrier lagoon environments shown in Fig. 12A; typical distributions of palynomorphs and phytoclasts associated with these deltaic/lagoonal subenvironments is shown in Fig. 12B; The proportions of these paleoenvironmental markers that were observed in palynology samples from Core 342 are shown in Fig. 12C, together with the amounts of reworked pre-Quaternary pollen and dinocysts/sample.

The detrital peat from 3.05 to 3.17 m in Core 342 is very finegrained and contains a high proportion (\sim 10%) of redeposited pre-Quaternary pollen and spores (Fig. 12C), making it unsuitable for ¹⁴C analysis. Abundant *Glomus*-type fungal spores also indicate the influx of terrigenous sediment from soil erosion upstream (Mudie et al., 2011). The pollen, fern spores and aquatic algae in this sample represent sedge-cattail marsh with an undercover of marsh



Fig. 9. Vertical distribution of foraminifera in Core B2 (present surfacies +2 m) showing a single semi-marine depositional environment. Dominance of holeuryhaline foraminifera in most of the core indicates that this site was submerged during of the Mediterranean transgression around 6 ka BP.

fern (Thelypteris palustris), similar to the modern Danube Delta near the upper limit of tidal influence except that today the common reed *Phragmites australis* is the dominant emergent plant (Pallis, 1916). At 2.35–2.37 m, the base of the middle peat laver also consists of relatively fine-grained plant material with fewer pre-Quaternary spores and *Glomus*, and with larger wood particles that can be separated from finely divided leaf material mixed with rounded whitish grains of unknown origin. An AMS ¹⁴C date for the wood particles from this depth gave an age of \sim 8850 \pm 40 BP, while the bulk detrital organic material gave a slightly older age of 8890 \pm BP. A sample from the top of this middle peat layer (2.1– 2.2 m core depth) contained coarser wood particles with a graphite ^{13}C value of -26.2 and an AMS age of 8890 \pm 50 BP. The wood fragments from these two middle peat-layer samples 25 cm apart in core depth have similar δ^{13} C values (-25.9 to -26.2%) and establish a rapid accumulation rate typical for transgressive silty peats (Badyukova, 2010).

A sample from \sim 1.90 m at the top of the third peat layer contains coarse plant remains that could be sorted into leaves (predominantly monocotyledons) and woody twig fragments (Fig. 6). The aquatic pollen and algal spores indicate a cattail swamp peat and open water with Myriophyllum, marking a semi-freshwater (2-4 psu) coastal pond environment, as also suggested by the stable carbon isotope values for graphite, $\delta^{13}C = -26.15\%$ (freshwater values are typically lighter than -28.0). The AMS ages for leaves and wood in this sample are 8550 \pm 40 and 8450 \pm 40 BP, respectively, differing by ~100 years (20-180 years) which is statistically insignificant. The close age agreement and the statistically identical carbon isotope values from the wood and leaf terrestrial plant sources indicate that this peat layer was in situ; these terrestrial plant ages also provide an accurate baseline atmospheric ¹⁴C age unbiased by the HWE that is associated with shell-derived fossil ages for the Neoeuxinian Black Sea paleoenvironment (Soulet et al., 2011a).

5. Discussion

5.1. Age of the marine transgression

Concerning the age of the Black Sea Holocene marine transgression, Fontugne et al. (2009) show that physico-chemical changes in salt and oxygen produce changes in water mass residence time that affects the amount of dissolved mineral carbon incorporated in mollusk radiocarbon ages, and this leads to large uncertainties in the Black Sea reservoir age (R). Accurate chronology of sediment deposition in the Black Sea and the hydrological evolution of this basin have therefore been hampered by the lack of precise R values and data on their variability. Historically, these uncertainties have contributed to controversial interpretations concerning the last reconnection between the Black and Mediterranean seas: catastrophic inflow versus non-catastrophic gradual or prompt changes in water level and salinity. The past reservoir age value, however, can be quantified either by paired measurements of bulk marine sediment ¹⁴C age (or its contained shell) versus varve chronology counts or by ¹⁴C age differences between samples of in situ terrestrial organic material (wood, leaves, seeds etc.) and marine shell samples. The latter comparison needs strictly contemporaneous samples, which is ideally achieved by selecting terrestrial vegetal macrofossils and marine samples within the same instantaneous time marker, such as a volcanic tephra layer. In our study of Ukrainian Shelf sediments, we do not have a tephra marker but we do have a clear signal for the arrival of deciduous tree pollen markers in the progression from pre-Boreal to Boreal and from Boreal to Atlantic periods as determined by CONISS (Constrained Incremental Sums of Squares) cluster analysis. The cluster analysis was performed on the 20 tree taxa shown in Fig. 11. plus an additional 10 woody species. The Blytt-Sernander palynochronology is accurately dated by varve counts, wood and gyttja peat ages but the arrival of forest tree markers is not an instantaneous event like a volcanic explosion. However, recent studies of varved sediments in Estonia indicate that the sustained occurrence of marker tree pollen species, e.g. Tilia, is established within an interval of about 100 years (Veski et al., 2004). A similar timewindow is expected for the arrival of marker species in nearshore Marmara and Black Sea cores, as evident in the synchronous timing of events such as the Beysidir Occupation Period in the marine and lake cores of southern Marmara Sea (Cordova et al., 2009). The four AMS radiocarbon ages of 8990 \pm 40 to 8450 \pm 40 BP we obtained for wood and sedge leaves from Core 342 from core depths of 2.35-1.90 (equivalent water depths = 33.16-32.71 m bsl) on the Ukrainian Shelf provide critical new data for calibrating and "re-tuning"

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* calculated age

Fig. 10. Vertical distribution of foraminifera in core 721 (depth 14.9 m) showing three basic depositional environments: semi-freshwater (core depth 27.5–20.0 m), brackish (20.0–19.5 m), and semi-marine inner shelf (19.5–0.0 m). An increase of holeuryhaline and appearance of strictoeuryhaline species among foraminifera starting from 20.0 m of the core upwards indicates a permanent influence of Mediterranean water since 8.6 ka BP.

of published shell and bulk peat ages for the NW shelf (Nicholas et al., 2010, 2011). The sedge leaf and wood particles that were separated from the mud matrix at 1.90 m provide AMS ages of ~100 years precision and are ~420–520 years younger than ages of 8920 \pm 60 to 9020 \pm 70 previously obtained by Nicholas et al. (2011) for bulk detrital peat located 26–76 cm higher in Core 342 (Fig. 3, Table 2 Beta Analytic and OZL samples). An age of 9620 ± 60 previously reported for a brackish-freshwater Dreissena polymorpha shell from the upper detrital peat shows that an inaccuracy of >1120 years can arise for shells of the lacustrine paleoenvironmental phase when carbon reservoir values in the semi-isolated, brackish-water Neoeuxinian lake could depart significantly from the marine reservoir correction value of 415 years usually applied to Holocene shells in sediments above –400 m bsl (Siani et al., 2000). A Cardiid shell age dated as 9140 ± 60 from 0.8 to 0.9 m in Core 342 (Nicholas et al., 2010, 2011) lies within the Atlantic period of younger age ($\sim 8-5$ ka BP) and clearly shows that this shell age is also too old by \sim 1000 years, The reported AMS age (Nicholas et al., 2010, 2011) of 9020 \pm 70 for unspecified detrital peat material in the middle of the mud with detrital shell unit (at ~ 1.15 m), is also too old by at least 500 years. The δ^{13} C value of -24.9_{00}° reported for this detrital peat (Nicholas et al., 2011) indicates a higher

paleosalinity for this sample than is expected from the observed kerogen (Fig. 12B) which corresponds to mainly C3 sedge and rush taxa, not C4 grasses and chenopods that can have heavier stable isotope values (Byrne et al., 2001; Lamb et al., 2006). This relatively high δ^{13} C value probably reflects the presence of detrital marine carbon in the unsorted detrital peat sample that was used for dating in the previous studies of Core 342.

In Core 342, dinoflagellate cyst assemblages, algal remains (e.g. *Pediastrum*) and kerogen characteristics (terrigenous wood/leaf particles versus marine amorphogen) show an essentially synchronous switch from brackish water to semi-marine conditions as that recorded by the foraminiferal and ostracod assemblages (Fig. 8A, B). This brackish water/semi-marine boundary lies above 0.97 m in Core 342 (-31.77 m bsl) from the inner Ukrainian shelf. The top of the brackish water dinocyst zone with *Spiniferites cruciformis-Pyxidinopsis psilata* assemblages in the NW Black Sea has been ¹⁴C dated variously as 7.5 and 6 ka BP (Filipova-Marinova et al., 2013); however, in Core 342, the concurrent *Pinus-Picea-Ulmus* assemblages lacking either *Fagus* or large amounts of *Ostrya* establish the age of the youngest peat as >7000-7500 BP.

Previous studies of Core 342 by Nicholas et al. (2009, 2010, 2011) have stated that where mollusc shells are reworked, the enclosing

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Fig. 11. Vertical distribution of pollen in core 342 (water depth 30.8 m) that show pollen spectra of selected indicator trees, percentages of arboreal, herb and aquatic plant pollen and fern spores (% total pollen and spores), and pollen zones determined by CONISS cluster analysis, where 0–2 indicates degree of dissimilarity.

sediments, including pollen, dinoflagellate cysts, foraminifers and ostracods, will also have been reworked. These previous studies imply that palaeoenvironmental reconstructions based on shallow water sediments of the Black Sea shelves (Fig. 13) may be unreliable at scales of resolution finer than the multi-millenial depositional units 1 to 3 delimited by Ryan et al. (1997) or units A, B and C of Hiscott et al. (2007, 2010). Nicholas et al. (2011) postulated that to overcome this complexity, other palaeoenvironmental records are required such as estimated sedimentation rates, amount of shell bleaching and basin-wide comparison of ages for bulk peat versus Dreissena coquina. As sedimentation rate is determined by radiocarbon ages, amounts of shell bleaching in fossils are nonquantifiable, and bulk peat ages even in non-marine sediments commonly have errors of 500-800 years (Grimm et al., 2009), this assessment is not very useful. In contrast, our new data for Core 342 establish that when wood and leaf material of terrigenous plants is separated from the detrital muddy peat, the AMS ages are in good agreement with Black Sea and European pollen zone age ranges and with the age \sim 7.5 ka BP for the marine transgression on the NW shelves indicated by foraminifera, ostracoda, and dinocysts. In contrast, AMS ages for calcareous shells and bulk detrital peat from the same or adjacent samples as the separated plant material are \sim 400–1000 years too old, indicating either reworking as in the modern Danube delta environment (Giosan et al., 2006) or a hardwater carbon reservoir disequilibrium.

Comparison of data from various cores in the Black Sea show that in the NW (Ukarinian) Shelf region, both the outer (Core 45B) and inner shelf (Core 342) were influenced by Mediterranean water at 8.8–8.9 ka ¹⁴C BP, whereas saline water only reached the NE (Caucasian) inner shelf (Core 721) ~400 years later at 8.5 ka BP.

5.2. Level of the Neoeuxinian lake prior the Mediterranean transgression

Previous studies (Kuprin, 2002; Yanko-Hombach, 2007; Yanko-Hombach et al., 2010; Kadurin et al., 2011; Larchenkov and Kadurin, 2011) of the NW Black Sea shelf have shown that at depths below -90 m bsl, Upper Neoeuxinian beds with ¹⁴C ages of 16.7–8.8 ka BP overlie late-glacial lacustrine Lower Neoeuxinian beds. In shallower water, however, the Upper Neoeuxinian sediments overlie alluvial deposits. Neither Lower nor Upper Neoeuxinian sediments contain Mediterranean foraminifera, ostracoda or dinocyst species. Instead they contain a moderate diversity of Caspian immigrant species of foraminifera, ostracoda, and mollusks (Yanko-Hombach, 2007; Yanko-Hombach et al., 2010), and on the SW Shelf - Spiniferites cruciformis dinocyst assemblages (Marret et al., 2009). The mollusks, Dreissenia polymorpha and D. rostriformis dominate inner and outer shelf subregions, respectively. Similar mollusk assemblages inhabit the modern Caspian Sea, where they tolerate salinity up to 13%. Lithologically, the Upper Neoeuxinian beds on the Black Sea shelves are often represented by sand deposits, with areas of bluish-grey mud filling in paleovalleys cut into pre-Late Neoeuxinian strata.

Sometimes a coquina layer of bleached Dreissena shells is present which was called the "Dreissena hash layer" by Ryan et al. (1997), Lericolais et al. (2011), and Nicholas et al. (2010, 2011). This "Dreissena hash layer" has a patchy distribution on top of both Lower and Upper Neoeuxinian beds, and it also occurs as Holocene liman sediments above ~ 0.8 m in Core 342 (Fig. 3). The age of this "Dreissena hash layer" is always younger than 17,400 ka BP and has previously been given as between 9600 and 9140 BP in Core 342 (Fig. 4). As such, the "Dreissena hash layer" of this age does not indicate a lowstand of ~ -100 m as suggested by Ryan et al. (1997), Lericolais et al. (2011), and Nicholas et al. (2010, 2011). Most certainly it was formed below isobath -30 m bsl as indicated by the presence of fine mud layers, but it could have been transported by currents to the deeper part of the Late Neoeuxinian basin; e.g., Arkhangel'sky and Strakhov (1938) reported that reworked Dreissena shells were mass-transported from shallow to deeper parts of the paleo-lake. The Caspian transgression via the Manych Outlet also contributed to a large increase of hydrodynamic activity on the shores of the Late Neoeuxinian lake. This Caspian paleoflood

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Fig. 12. Coastal palynofacies and their diagnostic kerogen markers. A. Model for a modern coastal lagoon setting, showing deep- and shallow water tidal ponds behind beach barriers; B. Characteristic ranges and abundances (relative line thickness) of palynofacies in the model shoreline transect; C. Core 342: measured values (number per g) of palynoclasts, fern spores, fungal spores and dinocysts in 11 samples (black dots) from 305 to 0 cm depth along a hypothetical transgressive shoreline (brown shading). Solid vertical brown bars indicate amounts of reworked pre-Quaternary palynomorphs for each sample, where the largest bar (305 cm) has a count of 20.

event contributed to the transport of the "*Dreissena* hash layer", explaining its patchy distribution and the entry of numerous Caspian organisms that form the Ponto-Caspian assemblages across the present shelf.

On the NW shelf, peat occurs in several cores from depths between *ca.* -46 m and -40.0 m bsl (Fig. 3), either at the top of the Upper Neoeuxinian beds (Core 876), or at the bottom (Core 830), or throughout the sediment layer (Core 383). However, peat interlayered with clay in the alluvial sediments occurs only in the cores taken from water depths -30.8 m (Core 342) and -21.7 m bsl (Core 334) in the upper Paleo-Dniester valley. On the central shelf, the Upper Neoeuxinian beds dovetail with liman sediments at *ca.* -40 m bsl, and then totally disappear in the later Holocene, being replaced by either liman deposits (on the inner shelf only) or by the Novochernomorian mud or sandy muds that presently cap the shelf.

On the basis of these shelf-wide survey data and the new evidence for coastal peat deposits at about 33.16-32.71 m bsl in Core 342, the claim of Lericolais et al. (2011) that the Black Sea shoreline was at -100 m until about 8.5 ka BP does not seem correct. This claim is based on interpretation of dune-like features in CHIRP sonar profiles that were correlated with a short (0.7 m) core of AMS-dated Holocene sediment from shallower water >100 m distant. However, CHIRP sonar profiles have an optimal vertical resolution of 10–15 cm which means that the age correlation for the dune top at -100 m could be 9500 or older. The paleodune

studies of Badyukova (2010) in the Caspian-Black Sea corridor also establish the following principles: 1. there are no opportunities for dunes to persist at the sea bottom in any transgressive scenario for the Black Sea corridor; 2. transgressive parasequences involve the accumulation of lagoonal and marine deposits during rising relative sea level and landward migration of a coastline over coastal plain deposits. The stratigraphic discordance on the NW shelf is regular, and it does not indicate erosion during a catastrophic sea-level rise as interpreted by Lericolais et al. (2011). Our core data are in full agreement with Badyukova's conclusion and we find no lithological sign of drowned windblown dunes described by Lericolais et al. (2011).

In the seaward direction, our lithological data from Cores 1118 (-60.5 m bsl) to Core 45B at 107 m bsl (Fig. 3) correspond to cores of the outer NW Black Sea shelf profile studied by Ryan et al. (1997). Our data show that brackish early Holocene Drevnechernomorian sediments (Bugazian in local terminology, age 9.4–8.1 ka BP) with Ponto-Caspian shells dated ~8.8 ka BP are already present at -107 m bsl, followed by a slow change over 15 cm elevation to semi-marine conditions with *Mytilus* as well as strictoeuryhaline and polyhaline Mediterranean species of ostracoda and foraminifera (Fig. 7).

During the equivalent time interval, sediments of Core 342 on the inner shelf, at depths of -33.16-32.71 bsl in the Paleo-Dniester delta, record the evolution from a coastal semi-freshwater lake to a brackish liman-type paleoenvironment (Fig. 8A, B). Thus, the level



Fig. 13. Comparison of paleoceanographic summary data given by Ryan et al. (1997) for short cores from the Ukrainian shelf and other Black Sea deep water sites (A) and corresponding data from a high resolution study of a long piston core MAR02-45P on the Turkish shelf (B) (from Hiscott et al., 2007). Dinoflagellate species 1–5 are 1. *Lingulodinium machaerophorum*; 2. *Peridinium ponticum*; 3. *Spiniferites bulloides*; 4. *Pyxidinopsis psilata*; 5. *Spiniferites cruciformis*.

of the Late Neoeuxinian lake prior to the IMI and Mediterranean transgression stood at $\sim\!40$ m bsl.

5.3. Salinity of the Neoeuxinian lake

Our microfossil data show that neither the Early nor Late Neoeuxinian basin was freshwater (Ryan et al., 1997; Soulet et al., 2010; Lericolais et al., 2011) in contrast to the conclusions from either a study of pore water salinity in one core at a water depth of -350 m on the Danube transect (Soulet et al., 2010), or from cross-correlation with macrofossil and dinocyst data in various deep water cores (Ryan et al., 1997; see Fig. 13A). Similar conclusions about the lack of evidence for freshwater are reported for more recent dinocyst studies than the pioneer 1973 work cited by Ryan

et al. (1997), including Mudie et al. (2002, 2004), Marret et al. (2009), and Mertens et al. (2012). A vast amount of paleontological data (full reference list is given in Yanko-Hombach, 2007), as well as our new data from Cores 342, 45B and 721, contradicts this freshwater interpretation and shows that the Neoeuxinian Lake was semifreshwater at the LGM, and then was brackish, being aerobic in both cases (Nevesskaya, 1965; Il'ina, 1966; Yanko-Hombach, 2007).

Data from our Core 342 (Figs. 8, 9 and 11) and Core 721 from Sukhumi Bay, Caucasian shelf (Fig. 10), and from the NW Black Sea Core 45B (Fig. 7) dated by Nicholas et al. (2011) do not indicate a rapid transgression of the Late Neoeuxinian Lake bν Mediterranean-sourced water as suggested by Ryan et al. (1997). Previous conclusions regarding a very rapid transgression were based largely on stable carbon isotope data (Ryan et al., 1997; Bahr et al., 2008) and were given without full consideration of all the available data in which the geological history is "conserved." Comparison of the isotopic and dinocyst data from Core MAR02-45 at -69 m bsl on the Turkish Shelf (Fig. 13B) clearly shows the gradual progression of salinization from $\sim 9.3-7$ ka BP (see also Marret et al., 2009; Mertens et al., 2012). In shallow water above 60 m bsl in the Black Sea, Fontugne et al. (2009) show that dissolved inorganic carbon (DIC) in the water is in equilibrium with the atmosphere, establishing that the water is well-mixed. Hence, at these depths there is no cause to postulate that the gradual salinization reflects slow diffusion of salt into the upper water after an initial catastrophic megaflood of Mediterranean water into the deeper basins.

Salinity of the late Neoeuxinian lake at the IMI and beginning of the Mediterranean transgression was at least 7 psu. During the accumulation of the Bugazian beds (9.4–8.1 ka ¹⁴C), salinity reached 13 psu, indicating a brackish/semi-marine regime within the Black Sea at that particular time. The quantitative paleosalinity data of Mertens et al. (2012) show a slow progression of surface salinity change from 9.3 ¹⁴C ka onward. Most paleontological evidence is inconsistent with both a "freshwater" Black Sea and an abrupt salinization that would potentially accompany a rapid/ prompt/catastrophic flood, and much of this evidence has not been cited by the advocates of the Flood Hypothesis.

5.4. Comparison of NW (paleo-Dniester) shelf with Turkish shelf records from 9.3 to 7.2 ka BP

Tree pollen and terrestrial herb pollen assemblages in coeval early Holocene sediments from Core 342 (Fig. 11) and MAR02-45 (Mudie et al., 2007) are essentially the same, indicating a cool moist climate, with local coastal ponds and salt-marshes, including the presence of Pediastrum algae. However, in comparison to the Turkish shelf core MAR02-45, assemblages of Ukrainian shelf Core 342 contain more sedge, grass, and swamp fern spores (Thelypteris palustris), and much larger amounts of herbaceous kerogen, as typical for a deltaic marsh environment like the present-day outer Chilia lobe of the Danube Delta or the inner Dniestrovsky liman (Fig. 2). In contrast, in MAR02-45, lower aquatic pollen abundances, absence of peat layers, and presence of diverse assemblages of Caspian-type dinocysts (Fig. 13B) confirm that this site was already fully submerged by 9.3 ka BP; these palynological data also validate the sedimentological-based interpretation of Hiscott et al. (2007, 2010) that the Turkish shelf was already covered by \sim 30 m of brackish water by 9.3 ka BP. Several other reports of changes in the dinocyst assemblages from high-resolution studies of MAR02-45 and other long (\sim 10 m) cores of Turkish shelf sediments (Bradley et al., 2012; Mertens et al., 2012) further show that the change in early Holocene surface water salinity (top 30 m of the water column) was gradual on shelves both east and west of the Bosphorus channel. Quantitative data obtained from measurement of spine length in the dinocyst *Lingulodinium machaerophorum* establishes that the surface water salinity gradually increased from minimum values of 12.3 \pm 0.91 psu around 7.6 ka BP, reaching present day salinities of 17.1 \pm 0.91 psu around 4.0 ka BP. This salinity increase takes place over 3600 years and ~2 m of core depth, implying a rate of marine water incursion in the order of 0.05 cm.a^{-1.} If we assume that the Black Sea water level is correctly placed as approximately -49 m bsl for the base of MAR02-45P, which has an extrapolated age of 9.5 ka, then the Core 342 latest reliable peat ages of ~8.5 ka at -32 m bsl depth indicate that from 9.5 to 8.5 ka BP, the Black Sea water rose gradually by a total of 17 m (i.e. 49–32 m), giving a transgression rate for the Ukrainian shelf of *ca.* 1.7 cm a⁻¹.

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6. Conclusions

Our multidisciplinary study of geological material recovered from shelf areas of the NW, NE and SW Black Sea indicate that: (1) The level of the Late Neoeuxinan lake prior to the early Holocene Mediterranean transgression stood around -40 m bsl but not -100 m or more as suggested by advocates of catastrophic/rapid/ prominent flooding of the Black Sea by Mediterranean water. (2) Microfossil data from the multiple shelf sites examined show that at all times, the Neoeuxinan lake was brackish with salinity about 7 psu prior to the IMI and Mediterranean transgression. (3) By 8.9 ka BP, the outer Black Sea shelf was already submerged by the Mediterranean transgression. An increase in salinity took place over 3600 years, with rate of the marine water incursion being estimated in the order of 0.05 cm-1.7 cm.a⁻¹. (4) The combined data set of sedimentological characteristics and microfossil salinity data establish that the Holocene marine transgression was of a gradual, progressive nature in the early Holocene.

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References

Arkhangel'sky, A.D., Strakhov, N.M., 1938. Geologicheskoe stroenie i istoriia razvitiia Chernogo moria (Geological Structure and History of the Black Sea). Izdatel'stvo Akademiia Nauk SSSR, Moscow and Leningrad (in Russian).

- Avrametz, V.M., Kakaranza, S.D., Sibirchenko, M.G., Mokrjak, I.M., Shvez, L.K., Makovetskaja, I.M., Eremina, LJu, 2007. Zvit z provedennja geologichnoi ziomky masshtabu 1:200,000 pivnichno-zakhidnoi chastyny shelfu Chornogo moria v mezhakh arkushiv L-36-XIII. –XIV, XV, 1992–2007 (Report on Geological Survey 1:200,000 Within Card Segments L-36-XIII. L-36-XIV, L-36-XV). Prichonomorske DRGP, Odessa, p. 399 (in Ukrainian).
- Badyukova, E.N., 2010. Evolution of the northern Caspian sea region and the Volga delta in the Late Pleistocene–Holocene. Oceanology 50 (6), 953–960. Pleiades Publishing, Inc., Original Russian Text [®]E.N. Badyukova, 2010, published in Okeanologiya 50(6), 1002–1009.
- Bahr, A., Arz, H.W., Lamy, F., Wefer, G., 2008. Late glacial to Holocene paleoenvironmental evolution of the Black Sea, reconstructed with stable oxygen isotope records obtained on ostracod shells. Earth and Planetary Science Letters 241 (3–4), 863–875.
- Balabanov, 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, Dordrecht, pp. 711–730.
- Batten, D., 1996. Palynofacies and palaeoenvironmental interpretation. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principals and Applications, vol. 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, USA, pp. 1011–1064.
- Bradley, L.R., Marret, F., Mudie, P.J., Aksu, A.E., Hiscott, R.N., 2012. Constraining Holocene sea-surface conditions in the south-western Black Sea using dinoflagellate cysts. Journal of Quaternary Science 27 (8), 835–843.
- Byrne, R., Ingram, B.L., Starratt, S., Malamud-Roam, F., Collin, J.N., Conrad, M.E., 2001. Carbon-isotope, diatom, and pollen evidence for late Holocene salinity change in a brackish marsh in the San Francisco Estuary. Quaternary Research 55, 66–76.
- Cordova, C.E., Harrison, S.P., Mudie, P.J., Riehl, S., Leroy, S.A.G., Ortiz, N., 2009. Pollen, plant macrofossil and charcoal records for palaeovegetation reconstruction in the Mediterranean–Black Sea Corridor since the Last Glacial Maximum. Quaternary International 197, 12–26.
- Dikan', N.S., 2006. Sistematica chetvertichnikh ostracod Ukrainy (dovidnuk-viznachnuk) (Sistematics of Quaternary Ostracoda of Ukraine (handbook- determinant)). Institut geologii Natsional'noi aeademii nauk Ukrainy, Kyiv (in Ukrainian).
- Dolukhanov, P., Kadurin, S., Larchenkov, E., 2009. Dynamics of the coastal North Black Sea area in Late Pleistocene and Holocene and early human dispersal. Quaternary International 197 (1–2), 27–34.
- Esin, N.V., Yanko-Hombach, V., Kukleva, O.N., 2010. Mathematical model of the Late Pleistocene and Holocene transgressions of the Black Sea. Quaternary International 225 (2), 180–190.
- 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. Quaternary International 293, 170–183.
- Fontugne, M., Guichard, F., Bentaleb, I., Strechie, C., Lericolais, G., 2009. Reservoir age of the Black Sea waters during anoxic periods. Radiocarbon 41 (3), 969–976.
- Gale, R., Cutler, D.F., 2000. Plants in Archaeology: Identification Manual of Vegetative Plant Materials Used in Europe and the Southern Mediterranean to c. 1500. Westbury Publications and Royal Botanic Gardens, Kew, UK.
- Giosan, L., Donelly, J.P., Constantinescu, S., Filip, F., Ovejanu, I., Vespremeanu-Stroe, A., Vespremanu, E., Duller, G.A.T., 2006. Young Danube delta documents stable Black Sea level since middle Holocene: morphodynamic, paleogeographic, and archeological implications. Geology 34, 757–760.
- Görür, N., Çağatay, M.N., Emre Ö., Alpa, B., Sakinç, M., İslamoğlu, Y., Algan, O., Erkal, T., Keçer, M., Akkök, R., Karlik, G., 2001. Is the abrupt drowning of the Black Sea shelf at 7150 yr BP a myth? Marine Geology 176, 27–34.
- Gozhik, P.F., Karpov, V.A., Ivanov, V.G., Sibirchenko, M.G., 1987. Golotsen severozapadnoy chasti Chernogo moria (Holocene of the Northwestern Part of the Black Sea). Geologicheskii Institut Ukrainskoi Akademii Nauk. Pre-Print 87–41 (in Russian).
- Grimm, E.C., Maher Jr., LJ., Nelson, D.M., 2009. The magnitude of error in conventional bulk-sediment radiocarbon dates from central North America. Quaternary Research 72, 301–308.
- Hiscott, R.N., Aksu, A.E., Mudie, P.J., Marret, F., Abrajano, T., Kaminski, M.A., Evans, J., Çakiroğlu, A.I., 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" [Quaternary International, 167–168 (2007) 19–34]. Quaternary International 226 (1, 2), 160.
- Hiscott, R.N., Aksu, A.E., Mudie, P.J., Marret, F., Abrajano, T., Kaminski, M.A., Evans, J., Çakiroğlu, A.I., Yaşar, D., 2007. 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. Quaternary International 55, 19–34.
- Il'ina, L.B., 1966. Istoriia gastropod Chernogo moria (History of the Gastropods of the Black Sea), vol. 110. Trudy Palentologicheskogo Instituta Academii Nauk SSSR, Nauka, Moscow, pp. 1–155 (in Russian).
- Ivanova, E.V., Murdmaa, I.O., Karpuk, M.S., Schornikov, E.I., Marret, F., Cronin, T.M., Buynevich, I.V., Platonova, T.A., 2012. Paleoenvironmental changes on the northeastern and southwestern Black Sea shelves during the Holocene. Quaternary International 261, 91–104.
- Jablonka, P., 2002. The link between the Black Sea and the Mediterranean since the end of the Last Ice Age: archaeology and geology. In: Wagner, G., Pernicka, E., Uerpmann, H.-P. (Eds.), Troia and the Troad. Springer, Berlin, pp. 77–94.

- Jones, G.A., Gagnon, A.R., 1994. Radiocarbon chronology of Black Sea sediments. Deep-sea Research 41, 531–557.
- Kadurin, S., Mudie, P., Yanko-Hombach, V., Larchenkov, E., 2011. Paleo-Dneister Holocene history: use of palynostratigraphy to assess the validity of dating by amino acid racemisation and C-14 ages of Black Sea shells. In: Abstracts of INQUA, Bern, IGCP 521-INQUA 501 Session "From the Western Mediterranean to the Caspian Sea: a Corridor of Paleoenvironmental Change and Human Response during the Last 30.000 Years", XVIII INQUA Congress, 20–27 July 2011, Bern, Switzerland.
- Karpov, V.A., Ivanov, V.G., Sibirchenko, M.G., et al., 1978. Otchet o geologicheskom izuchenii s s'emke Odesskogo zaliva Chernogo moria masshtaba 1:50,000m (List 36-51-A, B, Γ), 1976–1978. Report on Geological Investigation and Survey 1:50,000 Within Odessa Bay of the Black Sea.
- Kuprin, P.N., 2002. Litologiia osadkov i paleografiia novoevkvinskogo (pozdnii pleistotsen) etapa razvitiia Chernogo moria (Lithology and paleogeography of the Neoeuxinian (Late Pleistocene) stage of the Black Sea). Biulleten' Moskovskogo Obshchestva ispytatelei prirody. Otdel geologicheskii 77 (5), 59–69 (in Russian).
- Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal paleoclimate and relative sea-level reconstructions using δ^{13} C and C/N ratios in organic material. Earth-Science Reviews 75, 29–57.
- Larchenkov, E., Kadurin, S., 2011. Paleogeography of the Pontic Lowland and northwestern Black Sea shelf for the past 25 k.y. In: Buynevich, I., Yanko-Hombach, V., Gilbert, A., Martin, R. (Eds.), Geology and Geoarchaeology of the Black Sea Region: beyond the Flood Hypothesis, GSA Special Paper 473, pp. 71– 88. Colorado, USA.
- Lericolais, G., Popescu, I., Guichard, F., Popescu, S.-M., Manolakakis, L., 2007. Waterlevel fluctuations in the Black Sea since the Last Glacial Maximum. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate and Human Settlement. Springer, Dordrecht, pp. 437–452.
- Lericolais, G., Guichard, F., Morigi, C., Minereau, A., Popescu, I., Radan, S., 2010. A post Younger Dryas Black Sea regression identified from sequence stratigraphy correlated to core analysis and dating. Quaternary International 225 (2), 199–209.
- Lericolais, G., Guichard, F., Morigi, C., Popescu, I., Bulois, C., Gillet, H., Ryan, W.B.F., 2011. Assessment of Black Sea water-level fluctuations since the Last Glacial Maximum. In: Buynevich, I. (Ed.), Geology and Geoarchaeology of the Black Sea Region: beyond the Flood Hypothesis, GSA Special Paper 473, pp. 33–50. Colorado, USA.
- Major, C.O., Goldstein, S.L., Ryan, W.B.F., 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. Quaternary Science Reviews 25, 2031–2047.
- 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 Biology, Memoir, vol. 20. American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 155–180.
- Marret, F., Mudie, P., Alsu, A., Hiscott, R.N., 2009. A Holocene dinocyst record of a two-step transformation of the Neoeuxinian brackish water lake into the Black Sea. Quaternary International 193, 72–86.
- Mertens, K.N., Bradley, L.R., Takano, Y., Mudie, P.J., Marret, F., Aksu, A.E., Hiscott, R.N., Verleye, T.J., Mousing, E.A., Smyrnova, L.L., Bagheri, S., Mansor, M., Pospelova, V., Matsuoka, K., 2012. Quantitative estimation of Holocene surface salinity variation in the Black Sea using dinoflagellate cyst process length. Quaternary Science Reviews 39, 45–59.
- Mudie, P.J., Aksu, A.E., Yaşar, D., 2001. Late Quaternary dinoflagellate cysts from the Black, Marmara and Aegean seas: variations in assemblages, morphology and paleosalinity. Marine Micropaleontology 43, 155–178.
- Mudie, P.J., Rochon, A., Aksu, A.E., Gillespie, H., 2002. Dinoflagellate cysts, freshwater algae and fungal spores as salinity indicators in Late Quaternary cores from Marmara and Black seas. Marine Geology 190, 203–231.
- Mudie, P.J., Rochon, A., Aksu, A.E., Gillespie, H., 2004. Late glacial, Holocene and modern dinoflagellate cyst assemblages in the Aegean-Marmara-Black Sea corridor: statistical analysis and re-interpretation of the early Holocene Noah's Flood hypothesis. Review of Palaeobotany and Palynology 128 (1–2), 143–167.
- Mudie, P.J., Marret, F., Aksu, A.E., Hiscott, R.N., Gillespie, H., 2007. Palynological evidence for climatic change, anthropogenic activity and outflow of Black Sea water during the Late Pleistocene and Holocene: centennial- to decadal-scale records from the Black and Marmara Seas. Quaternary International 167–168, 73–90.
- Mudie, P.J., Marret, F., Rochon, A., Aksu, A.E., 2010. Non-pollen palynomorphs in the Black Sea corridor. Vegetation History and Archaeobotany 19, 531–544.
- Mudie, P.J., Leroy, S.A.G., Marret, F., Gerasimenko, N., Kholeif, S.E.A., Sapelko, T., Filipova-Marinova, M., 2011. Nonpollen palynomorphs: indicators of salinity and environmental change in the Caspian–Black Sea–Mediterranean corridor. In: Buynevich, I., Yanko-Hombach, V., Gilbert, A., Martin, R. (Eds.), Geology and Geoarchaeology of the Black Sea Region: beyond the Flood Hypothesis. GSA Special Paper 473, pp. 245–262. Colorado, USA.
- Nevesskaya, LA., 1963. Opredelitel' dvustvorchatykh molliuskov morskikh chetvertichnikh otlozhenii Chernomorskogo basseina (Guide to the Identification of Bivalves from Quaternary Marine Sediments of the Black Sea), vol. 96. Trudy Palentologicheskogo Instituta Academii Nauk SSSR/Nauka, Moscow, pp. 1–100 (in Russian).
- Nevesskaya, L.A., 1965. Pozdnechetvertichnye dvustvorchatye molliuski Chernogo Moria, ikh sistematika I ekologiia (Late Quaternary Bivalve Molluscs of the Black

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Sea, their Systematics and Ecology), vol. 105. Trudy Paleontologicheskogo Instituta Akademii Nauk SSSR/Nauka, Mosco, pp. 1–391 (in Russian).

- Nicholas, W.A., Chivas, A.R., Murray-Wallace, C.V., Fink, D., 2010. Radiocarbon and amino acid racemisation dating of the post-glacial Black Sea: rapid transgression and gradual salinisation of the paleo-lake by Mediterranean-sourced water. In: Yanko-Hombach, V., Gilbert, A. (Eds.), Abstract Volume of the Sixth Plenary Meeting and Field Trip of IGCP-521 "Black Sea Mediterranean Corridor during the Last 30 ky: Sea Level Change and Human Adaptation" (2005–2010) INQUA 0501 "Caspian-black Sea-mediterranean Corridor during Last 30 ky: Sea Level Change and Human Adaptation" (2005–2010) INQUA 0501 "Caspian-black Sea-mediterranean Corridor during Last 30 ky: Sea Level Change and Human Adaptive Strategies" (2005–2011). Rhodes, Greece, September 27 October 5, 2010, C, pp. 145–147.
- Nicholas, W.A., Chivas, A.R., Kadurin, S., Murray-Wallace, C.V., Fink, D., 2009. Chronology of an early Holocene transgressive black sea. In: Gilbert, A., Yanko-Hombach, V. (Eds.), Extended Abstracts of the Fifth Plenary Meeting and Field Trip of IGCP-521 "Black Sea – Mediterranean Corridor during the Last 30 Ky: Sea Level Change and Human Adaptation" (2005–2010) – INQUA 0501 "Caspian-black Sea-mediterranean Corridor during Last 30 Ky: Sea Level Change and Human Adaptive Strategies" (2005–2011). Izmir-Çanakkale (Turkey), August 22-31, 2009, pp. 129–131.
- 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. Quaternary Science Review 30, 3769–3790.
- Pallis, M., 1916. The structure and history of Plav: the floating fen of the Delta of the Danube. Linnaean Society Journal of Botany 43, 233–290.
 Podoplelov, O.N., Karpov, V.A., Ivanov, V.G., Mokrjak, I.M., Zagorodnij, G.G., 1975.
- Podoplelov, O.N., Karpov, V.A., Ivanov, V.G., Mokrjak, I.M., Zagorodnij, G.G., 1975. Otchet o geologicheskoi s'emki shelfa severo-zapadnoj chasti Chernogo moria masshtaba 1:50, 000, 1973–1975. Report on geological survey 1:50,000 within north-western part of the Black Sea. Krymgeologiia, Odessa, p. 367 (in Russian).
- 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, pp. 3–88.
- Ryan, W.B.F., Pitman III, W.C., Major, C.O., Shimkus, K., Maskalenko, V., Jones, G.A., Dimitrov, P., Görür, N., Sakınç, M., Yüce, H., 1997. An abrupt drowning of the Black Sea shelf. Marine Geology 138, 119–126.
- Ryan, W., Pitman, W., 1998. Noah's Flood: the New Scientific Discoveries about Events that Changed History. Simon and Schuster, New York.
- Siani, G., Paterne, M., Arnold, M., Bard, E., Métivier, B., Tisnerat, N., Bassinot, F., 2000. Radiocarbon reservoir ages in the Mediterranean Sea and Black Sea. Radiocarbon 42 (2), 271–280.
- Sibirchenko, M.G., Karpov, V.A., Ivanov, V.G., Mokrjak, I.M., Zjultsle, V.G., Tatarovskij, V.V., 1983. Otchet po izucheniiu litilogicheskogo sostava donnykh otlozhenii shelfa Chernogo moria s zeliiu sostavleniia geologo-litologicheskoi karty masshtaba 1:200,000 (Report on lithological study of the Black Sea shelf for the preparation of geological-lithological map 1:200,000). Krymgeologia, Odessa, p. 427 (in Russian).
- 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 and Planetary Science Letters 296, 57–66.
- 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 and Planetary Science Letters 308, 245–258.
- Soulet, G., Ménot, G., Lericolais, G., Bard, E., 2011b. A revised calendar age for the last reconnection of the Black Sea to the global ocean. Quaternary Science Reviews 30 (9–10), 245–258.
- Stoica, M., Floroiu, A., 2008. Recent ostracod faunas from MD04-2770 (Black Sea). In: Gilbert A., Yanko-Hombach, V. (Eds.), Extended Abstracts of the Fourth

Plenary Meeting and Field Trip of IGCP-521 "Black Sea – Mediterranean Corridor during the Last 30 ky: Sea Level Change and Human Adaptation" (2005–2010) – INQUA 0501 "Caspian-black Sea-mediterranean Corridor during Last 30 ky: Sea Level Change and Human Adaptive Strategies" (2005-2011). Bucharest (Romania)-Varna (Bulgaria), October 4–16, 2008, p. 173.

- Tkachenko, G.G., 1971. Deiaki dani pro uglevodorodni hasy donnikh vidkladiv pivnichno-zakhidnoi chastini Chernogo moria (Some data about hydrocarbon gases of the bottom sediments of north-western part of the Black Sea). In: Mezhvedomstvennii respublikanskii naukovii sbornik "Geologiia uzberezhzhia i dna Chernogo ta Azovs'kogo moriv u mezhakh Ukrainskoi RSR" (Interdepartmental Republican Scientific Miscellanea "Geology of the Coast and Bottom of the Black Sea and Sea of Azov within the Ukrainian SSR"), vol. 5. Vishcha Shkola, Kiev, pp. 80–85 (in Ukrainian).
- Tkachenko, G.G., Krasnoshchok, A.Ya., Pazyuk, L.I., Samsonov, A.I., Tkachenko, V.F., 1970. Pro rol' nainovishoi diziunktivnoi tektoniki u formuvanni beregovoi linii i morfologii osnovnikh dilianok akvatorii Chornogo ta Azovs'kogo moriv (On the role of the newest disjunctive tectonics on the formation of shoreline and morphology of the major areas of the Black and Azov Seas). In: Mezhvedomstvennii respublikanskii naukovii sbornik "Geologiia uzberezhzhia i dna Chernogo ta Azovs'kogo moriv u mezhakh Ukrainskoi RSR" (Interdepartmental Republican Scientific Miscellanea "Geology of the Coast and Bottom of the Black Sea and Sea of Azov within the Ukrainian SSR"), vol. 4. Vishcha Shkola, Kiev, pp. 24–33 (in Ukrainian).
- Veski, S., Seppä, H., Ojala, H.E.K., 2004. Cold event at 8200 yr B.P. recorded in annually laminated lake sediments in eastern Europe. Geology 32, 681–684.
- Yanko, V., 1990. Stratigraphy and paleogeography of marine Pleistocene and Holocene deposits of the southern seas of the USSR. Memorie della Società Geologica Italiana 44, 167–187.
- Yanko, V., Gramova, L., 1990. Stratigraphy of the Quaternary sediments of the Caucasian shelf and continental slope of the Black Sea on microfauna (foraminifera and ostracoda). Journal Soviet Geology 2, 60–72 (in Russian).
- Yanko, V.V., Troitskaya, T.S., 1987. Pozdnechetvertichnye foraminifery Chernogo moria (Late Quaternary Foraminifera of the Black Sea). Nauka, Moscow (in Russian).
- Yanko-Hombach, V., Kadurin, S., Larchenkov, E., Likhodedova, O., Kakaranza, S., 2010. Was the Black Sea catastrophically flooded in the Early Holocene – a new perspective from the large scale geological survey of the northwestern shelf. In: Yanko-Hombach, V., Gilbert, A. (Eds.), Abstract Volume of the Sixth Plenary Meeting and Field Trip of IGCP-521 "Black Sea – Mediterranean Corridor during the Last 30 ky: Sea Level Change and Human Adaptation" (2005-2010) – INQUA 0501 "Caspian-black Sea-mediterranean Corridor during Last 30 ky: Sea Level Change and Human Adaptive Strategies" (2005–2011). Rhodes, Greece, September 27 – October 5, 2010, C, pp. 221–227.
- Yanko-Hombach, V., 2007. Controversy over Noah's Flood in the Black Sea: geological and foraminiferal evidence from the shelf. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 149–203.
- Yanko-Hombach, V., Mudie, P., Gilbert, A.S., 2011a. Was the Black Sea catastrophically flooded during the post-glacial? Geological evidence and archaeological impacts. In: Benjamin, J., Bonsall, C., Pickard, C., Fischer, A. (Eds.), Underwater Archaeology and the Submerged Prehistory of Europe. Oxbow Books, pp. 245– 262.
- Yanko-Hombach, V., Smyntyna, O.V., Kadurin, S.V., Larchenkov, E.P., Kakaranza, C.V., Kiosak, D.V., 2011b. Kolebaniya urovnya Chernogo moria I adaptatsionnaya strategia drevnego cheloveka za poslednie 30 tysiah let (The Black Sea level change and adaptation strategy of ancient people for the last 30 ka). Geologiya I poleznie iskopaemye Mirovogo Okeana (Geology and Mineral Resources of the World Ocean) 2, 61–94 (in Russian).