

Events and data concerning the Black Sea evolution after the last glacial peak: A comment

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Abstract: The main point of the study is the juxtaposition in the characteristics of the Black Sea, such as salinity and water level, for the last ~20,000 years. These characteristics have been depending on climate changes and geological events that occurred during this time interval. The Black Sea Basin has undergone significant ecological and geological changes since the end of the Pleistocene (following the Last Glacial Maximum). The study’s main motif is to synchronize events and data from previous and new studies. This study includes some new data on rice-like aragonite at the base of sapropel sediments and radiocarbon dating of reef mussels. A medium surface salinity curve for the Black Sea Basin is derived for the studied time period. The sudden change in salinity is associated with rapid increase in water level in the basin following the penetration of saltier waters through the Bosphorus. The conclusion was drawn after comparing current hypotheses.

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INTRODUCTION

The main specifics of the Black Sea Basin, such as salinity, water level and temperature, have been changing since the Last Glacial Maximum (LGM). Many researchers have studied and proven these changes during this period of time (e.g., Giosan *et al.*, 2012; Mertens *et al.*, 2012; Genov *et al.*, 2014; Nicholas and Chivas, 2014; Briceag *et al.*, 2019; Maret *et al.*, 2019; Huang *et al.*, 2021; Ion *et al.*, 2022). However, the main shortcomings of the research so far are: the lack of exact correlation between the changes in sea (lake) level related to

climatic and geological events and data; the corresponding changes in salinity of the water body (or part of it); and that the reasons for some of these changes have not been determined. The main reason for such omissions is that there exist conflicting hypotheses for the evolution of the Black Sea Basin during the considered time span: the “outflow” hypothesis – gradual transition from lake to sea (e.g., Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022); the “flood” hypothesis – quick transition from lake to sea (e.g., Lericolais *et al.*, 2011; Nicholas and Chivas, 2014; Yanchilina *et al.*, 2017, 2019); and the third hypothesis of Genov (2009, 2016, 2018).

One dividing line in these studies is the manner/mechanism by which the basin turned from a lake into a slightly saline continental sea: gradually (Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022) or suddenly (Genov, 2009, 2016, 2018; Lericolais *et al.*, 2011; Nicholas and Chivas, 2014; Yanchilina *et al.*, 2017, 2019). Another dividing line between them is the exact moment when the basin began to convert from a lake to a sea: at the end of the Early Holocene (Genov, 2009, 2016, 2018; Slavova *et al.*, 2016a, b; Koleva-Rekalova *et al.*, 2018) or at an earlier time (Lericolais *et al.*, 2011; Nicholas and Chivas, 2014; Yanchilina *et al.*, 2017, 2019; Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022). Therefore, establishing the correct hypothesis about the ecological development of the Black Sea (lake) after the LGM is a major objective. The following tasks must find a solution for this purpose: 1) selection of a water level change curve during the studied time period; and 2) tracking and connecting climatic, environmental and geological data to this curve.

The first task is carried out by considering and comparing different age models and, as a result of this comparison, an age model is selected a base. Based on the age model selection, the exact curve of change of the basin water level after the LGM is determined, and that curve is applied in carrying out solving the second task. It is possible if examples in

studies providing compelling evidence for the selected curve exactness exist.

Once the basin water level curve is selected, the second task can be completed, if logical and consistent explanations are found for the maximum number of existing data.

The changes in the Black Sea Basin water specifics are relevant for explaining the replacement of some organisms with others, for determining the specific borderline habitats of these species, for determining the gas hydrates stability zone in the Black Sea sediments, but also for solving archeology related and other tasks.

MATERIAL AND METHODOLOGY

The reef rock samples from depths of 20 m and 15 m under the frame of NSP (National Scientific Program approved and financed by the Bulgarian Ministry of Education and Science, Task WP I.4.3-1; <https://nnpos.wordpress.com>) and seismic record B2CH96 (Lericolais *et al.*, 2011) from the western Black Sea are used in this study. A comparative petrographic analysis of the samples from the white laminae found at the sapropel base (Holocene Unit 2 of Ross and Degens, 1974) from three sedimentary cores extracted from three dif-

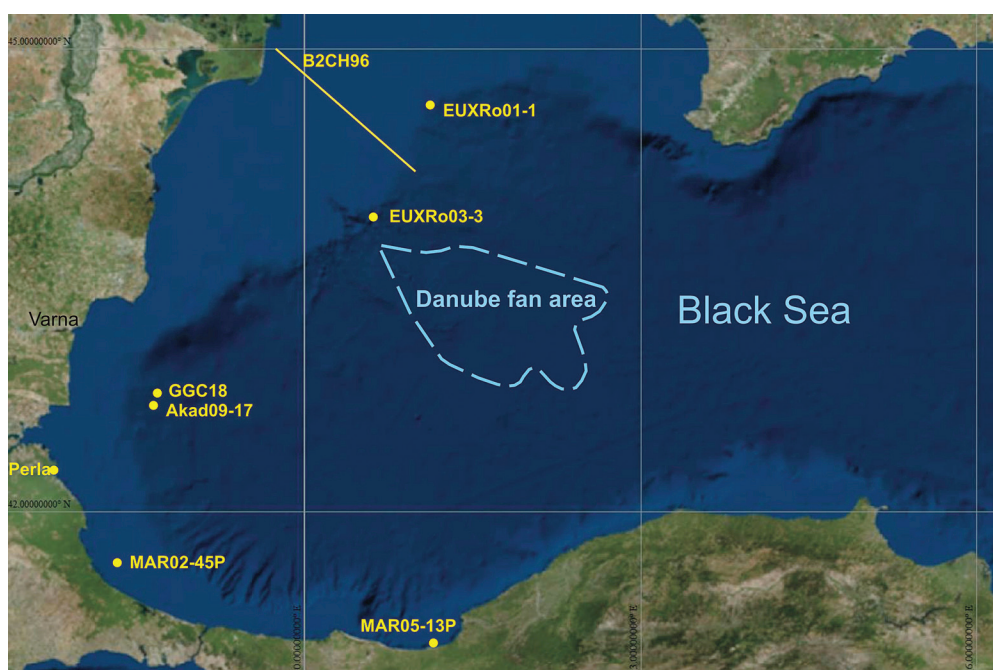


Fig. 1. Area of investigation: cores EUXR01-1, EUXR03-3, GGC18, Akad09-17, MAR02-45P, MAR05-13P; reef sampling in front of Perla Beach; seismic profile B2CH96.

ferent depths in the western Black Sea was carried out. Cores EUXRo01-1 (228 m below present-day sea level – bpdsl) and EUXRo03-3 (615 m bpdsl) were collected in 2011 on board R/V Mare Nigrum of the MARINEGEOHAZARD project, and Core AKAD09-17-(1022 m bpdsl) was collected in 2009 on board R/V Akademik during the implementation of Project DO 02-337, BSF. Data for surface salinity in the Black Sea Basin from cores MAR02-45P, MAR05-13P (Mertens *et al.*, 2012) and GGC-18 (Coolen *et al.*, 2009; Huang *et al.*, 2021) are also used (Fig. 1; see also [Appendix A](#)).

An age model was chosen by analyzing three age models for the Black Sea (Mertens *et al.*, 2012; Ankindinova *et al.*, 2020; Huang *et al.*, 2021) in order to juxtapose in time the Black Sea (lake) evolution-related specifics for the last 20,000 years. This was necessary to place all considered events and data in one (*i.e.*, uniform) time scale. Three correlation curves have been constructed (Mertens *et al.*, 2012, table 2; Ankindinova *et al.*, 2020, table 2; Huang *et al.*, 2021, Table 1) and used to transform from one age model to another (Fig. 2; see also [Appendix B](#)). These curves were analyzed based on their form, with suppositions made about the causes.

A curve of the Black Sea level change after the LGM has been proven. The determining criterion

for such a curve is its capacity to explain maximum number of existing data. Current water level curves (Lericolais *et al.*, 2011; Nicholas and Chivas, 2014; Genov, 2016, 2018; Yanchilina *et al.*, 2017, 2019; Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022) for the studied basin are compared. The Black Sea level curve is also supported by summary seismostratigraphic analysis and microscope (petrographic) studies.

Following the selection of the basin level curve for the last 20,000 years, data on water surface salinity and climate were attached to that curve. Two curves for water surface salinity in the Black Sea Basin (Mertens *et al.*, 2012; Huang *et al.*, 2021) were used.

The persistence of *Mytilus* and *Dreissena* (bivalves) is tracked following the reference guide of Neveskaya (1965). In order to clarify the Black Sea environmental conditions, published radiocarbon data of bivalve shells were used.

The radiocarbon ages of the shells in the reef rock samples recovered at 20 m and 15 m depth of Perla Beach were determined (Fig. 1). The radiocarbon analyses of two mussel shell samples were carried out in the TÜBİTAK AMS laboratory (Doğan *et al.*, 2021). Millipore water was used to clean the samples in an ultrasound bath, followed by acid

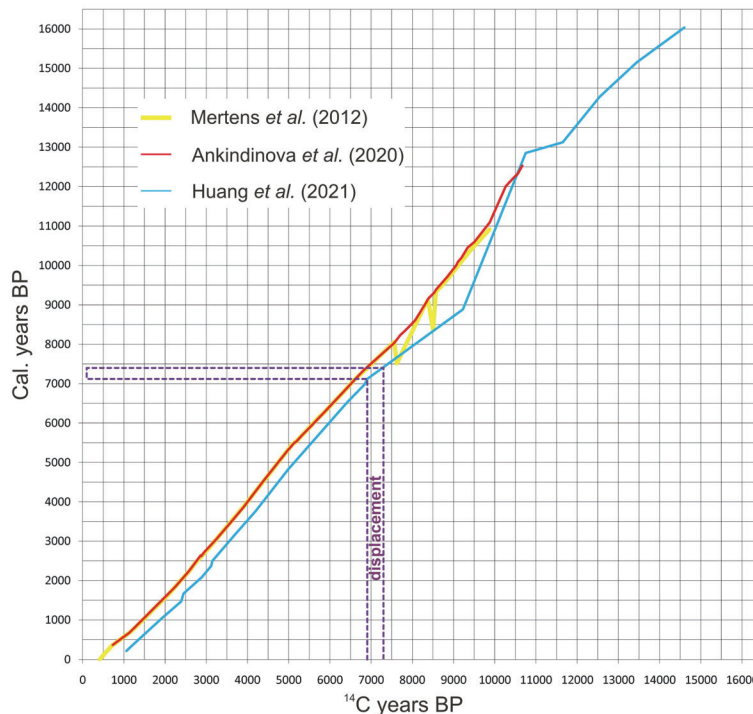


Fig. 2. Constructed correlation curves.

leaching and Millipore water washes to neutralize the pH. The other stages of sample treatment that took place before AMS measurement were carried out in accordance with the procedures outlined by Doğan *et al.* (2023a). Radiocarbon measurement was performed, using the AMS TÜBİTAK 1 MV system (Doğan *et al.*, 2023b).

RESULTS

Selection of age model

In order to select an age model to be used for the changes in water level curve after the LGM, we need to overcome the problem of different values for the Black Sea reservoir offset represented by several authors (Kwiecien *et al.*, 2008; Soulet *et al.*, 2011; Yanchilina *et al.*, 2017; Williams *et al.*, 2018). There is also a discrepancy in the calibration of calendar years due to the application of various defined curves (Marine13, IntCal13 – Reimer *et al.*, 2013; IntCal20, Marine 20 – Heaton *et al.*, 2020) following the correction of raw radiocarbon years due to the reservoir effect. The statement is confirmed by the different calibrations of identical radiocarbon years in successive publications by the same authors (compare Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022). An example illustrating discrepancies in the raw radiocarbon year conversion into calendar years is given in Fig. 2, which shows three calibration curves, according to Mertens *et al.* (2012), Ankindinova *et al.* (2020) and Huang *et al.* (2021). Comparing these curves, we find that all of them are zigzag lines in the range of 7.5–12 ^{14}C kyrs BP, while the curve from the data of Huang *et al.* (2021) demonstrates additional complications in the time interval of 2–3.5 ^{14}C kyrs BP and is significantly displaced against the other two curves. In this study, the calibration curve with age data from Ankindinova *et al.* (2020) is accepted as the most accurate compared to the other two curves shown in Fig. 2, because of its slight deviations. Moreover, it largely coincides with the Mertens *et al.* (2012) calibration curve. A possible explanation for the zigzag curves within the interval of 7.5–12 ^{14}C kyrs BP is that they are connected to a specific event in the considered basin. In the following text, we will endeavor to prove that the event in question is a regression in the Black Sea Lake ending around 7.5 ^{14}C kyrs BP.

Therefore, in order to avoid all the inaccuracies and discrepancies listed above within the Late Pleistocene–Holocene time span when comparing different events and facts, it is logical to operate with uncorrected radiocarbon years.

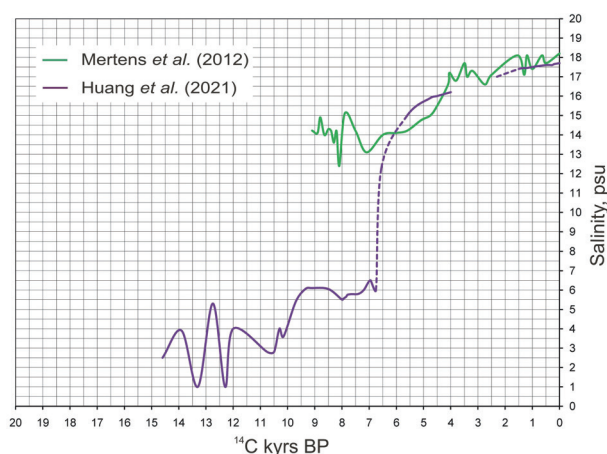


Fig. 3. Surface water salinity curves (Mertens *et al.*, 2012; Huang *et al.*, 2021) transformed to a time scale of ^{14}C years.

It is also necessary to note that the calibration curves (Fig. 2) were applied to a transformation of the surface water salinity values of the considered basin dated in calendar years (Mertens *et al.*, 2012; Huang *et al.*, 2021) into salinity values dated in uncorrected radiocarbon years (Fig. 3; see also Appendix C).

Determination of an accurate curve of the Black Sea level change for the last 20,000 years

Current hypotheses

In modern studies of the Black Sea (lake) evolution after the LGM, two hypotheses are mainly proposed (Fig. 4a, b). Lericolais *et al.* (2011), Nicholas and Chivas (2014) and Yanchilina *et al.* (2017) support the hypothesis that the initial low basin water level at the end of the Pleistocene and at the beginning of the Early Holocene increased sharply after the sudden incursion of saline Mediterranean waters through the Bosphorus (Fig. 4a). The essence of the second hypothesis consists of constantly rising water level at the end of the Pleistocene and into the Holocene (Fig. 4b; Ankindinova *et al.*, 2020; Aksu and Hiscott, 2022). According to both hypotheses, the Black Sea Basin was transformed from a fresh-water (brackish) lake into an internal (semi-closed), slightly saline sea during the Early Holocene. However, each hypothesis provides a different explanation for how the basin became saline. According to the second “outflow” hypothesis, it was a gradual process over time due to a diffuse mix of more sa-

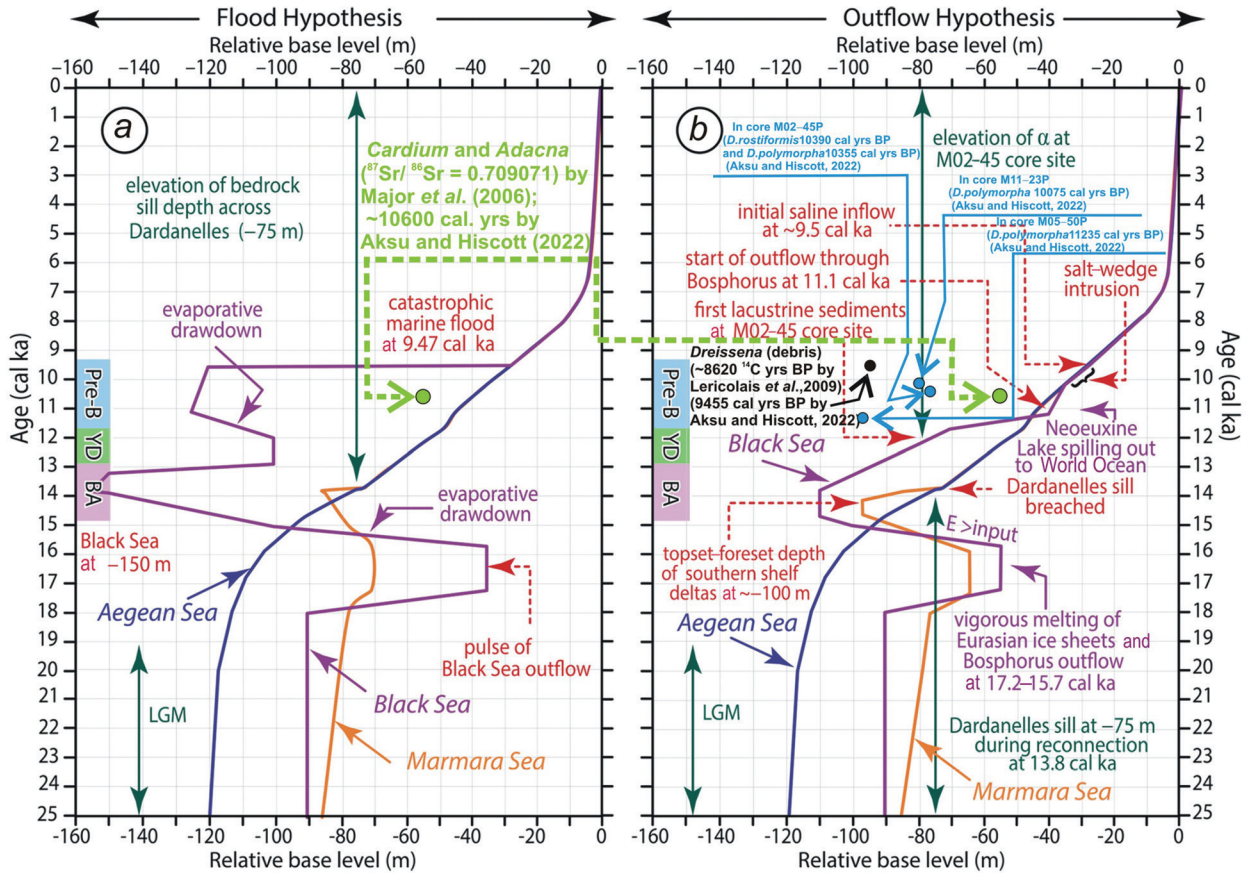


Fig. 4. Black Sea level curves by “flood” and “outflow” hypotheses (Aksu and Hiscott, 2022) with additions.

line and fresher or slightly saline waters. In the first “flood” hypothesis, a rapid change in salinity following a massive intrusion of saline water into the brackish lake is suggested. However, both hypotheses face insurmountable difficulties in explaining a number of facts:

1) In both hypotheses, the water level oscillations of the studied basins (the Marmara and the Black Sea), immediately after the LGM, are simply assumptions, because it is not clear why the regression of the Black Sea Basin is much faster than the regression of the Marmara Basin in the interval of 14.7–15.7 calendar kyrs BP (Fig. 4). Taking into account that the Black Sea Lake is much larger and has a higher initial water level than the Marmara Sea Basin, with much larger river flows into it compared to the river flows into the Marmara Sea, and that its geographical location is north of the Marmara Sea, such a statement is simply illogical. Moreover, according to radiocarbon dating (Ion *et al.*, 2022), there is no re-sedimentation between 20,000 and 14,000 years BP, while there should be

one on the continental slope caused by the significant regression between 16,000 and 14,000 years shown in Fig. 4.

2) Both hypotheses cannot explain the fact: bivalve shells (*Cardium* and *Adacna*) found in the Black Sea (lake) at a depth of 55 m and dated at about 10,850 calendar yrs BP (~9,580 ^{14}C yrs BP) (according to the age model of Aksu and Hiscott, 2022: ~10,600 calendar yrs BP), with a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.709071, which is close to the modern Black Sea ratio values (Major *et al.*, 2006; Fig. 4). This contradicts the assumption that, before ~10,000 years BP (*i.e.*, ~9,000 ^{14}C years BP, according to the age model of Aksu and Hiscott, 2022), there was no intrusion of saline water from the Marmara Sea through the Bosphorus. Nicholas and Chivas (2014) reported similar data in their fig. 14.6. – *Cardium* (marine) older than 9,000 ^{14}C yrs BP (~10,000 calendar yrs BP according to Aksu and Hiscott, 2022).

3) The outflow hypothesis (Fig. 4b) cannot explain why numerous shells of *Dreissena rostriformis* and *Dreissena polymorpha*, which inhabit

the littoral zone according to Neveskaya (1965), are found outside the wave activity zone at much greater depths. The following examples illustrate the depths of such remains found in sedimentary cores, taking into account the shells' age and the corresponding Black Sea (lake) water level at the same time according to the quoted hypothesis: according to Aksu and Hiscott (2022, tables 1, 2; fig. 21b), *Dreissena rostriformis* with age dating ~10,390 calendar yrs BP (~9,370 ¹⁴C yrs BP) and *Dreissena polymorpha* with age dating ~10,355 calendar yrs BP (9340 ¹⁴C yrs BP) in core M02-45P must have lived at about 40 m depth, *Dreissena polymorpha* with age dating ~11,235 calendar yrs BP (~9,880 ¹⁴C yrs BP) in core M05-50P must have lived at about 45 m depth, *Dreissena polymorpha* with age dating ~10,075 calendar yrs BP (~9,105 ¹⁴C yrs BP) in core M11-23P must have lived at about 45 m depth, etc. The fact that *Dreissena* shells (in debris, hash layer) found in cores B2KS24, B2KS26 and B2KS21, about 96 m and 112 m below the modern sea level with radiocarbon ages 8620±50, 8430±50, 8710±50, 8760±40, 8600±50 (Lericolais *et al.*, 2009), converting the first ¹⁴C age into calendar age by means of Aksu and Hiscott's (2022) table 2, *i.e.*, 9455±95 calendar years, means that they must have been at a depth of about -66 m according to the same authors' fig. 21b. Analogously, according to the same figure, the depths at which *Dreissena rostriformis* with ages 8,820, 8,690 and 8,170 ¹⁴C yrs BP from core 45B at 107.44 m below modern sea level (Nicholas and Chivas, 2014) lived are greater than littoral depths, too (Fig. 4b).

In addition, Aksu and Hiscott (2022) changed the depth of core M11-22 in their fig. 12, thus they distorted the geological setting.

A third hypothesis (Genov, 2009, 2016, 2018) has been proposed and, according to that hypothesis, it is assumed that, as a result of arid conditions in the southeastern European region during the Early Holocene, regression occurred within the studied basin. The regression was suddenly interrupted by the incursion of saline waters through the Bosphorus due to a rising World Ocean level. The incursion of saline waters into the isolated brackish Black Sea Lake took place about 7500 ¹⁴C yrs BP. The salt waters quickly increased the basin salinity and its level. According to this hypothesis, the Black Sea (lake) level between the end of the LGM and the beginning of the Early Holocene regression mentioned above increased at different speeds. The Early Holocene regression is an important point in the hypothesis of turning the Black Sea Lake into an inner semi-closed sea. The seismostratigraphic sub-

division of seismic records under the Black Sea bottom and the petrographic studies of white laminae at the base of sapropel deposits provide evidence for the regression.

Subsequently, when the reservoir offset should be specified for the Black Sea, the water level change according to this hypothesis in a time scale of uncorrected radiocarbon years may be converted into a scale of calendar years (Vadsaria *et al.*, 2022, fig. 2) by applying the existing defined curves (Marine13, IntCal13 – Reimer *et al.*, 2013; IntCal20, Marine 20 – Heaton *et al.*, 2020) or others.

Not discussed data from the “outflow” and “flood” hypotheses

Seismostratigraphy

The modern understanding of seismostratigraphic subdivision of a seismic record is based on the recognition of the following genetic units in one sequence: transgressive (T), forced regressive (FR), lowstand normal regressive (LNR) and highstand normal regressive (HNR) (Catuneanu, 2017, 2020; Catuneanu *et al.*, 2009, 2011; Zecchin, 2007).

In several articles (Genov, 2016, 2018, 2020; Slavova *et al.*, 2016a; Koleva-Rekalova *et al.*, 2018; Genov *et al.*, 2021) on seismic records with different locations in the western part of the Black Sea, genetic seismic units from two sequences (earlier sequence: HNR-2, FR-2, LNR-2, T-2 and later sequence: HNR-1, FR-1, T-1), showing identical development of the basin, have been distinguished. Where possible, seismic units have also been linked to radiocarbon ages (Genov, 2016, 2018, 2020). The younger sequence is incomplete, *i.e.*, absence of unit LNR-1, showing a sudden onset of the transgression (T-1) after the regression (FR-1) that implies fast transition of the basin from lake to sea. The Black Sea level change according to the hypothesis of Genov (2009, 2016) is confirmed by the seismostratigraphic subdivision of seismic record B2CH96 (Lericolais *et al.*, 2011) intersecting almost the entire Black Sea shelf and part of the continental slope (Figs 5, 6). In this paper, adjustments were made to Genov's (2016) seismostratigraphic interpretation of this seismic record. However, these additions are not significant enough to modify the Black Sea level curve after the LGM in accordance with Genov (2016). This seismostratigraphic subdivision also indicates that, as a result of the regression (FR-1) of the later sequence, the sediments from the upper section of the previous sequence were eroded and resedimented. Moreover, significant erosion

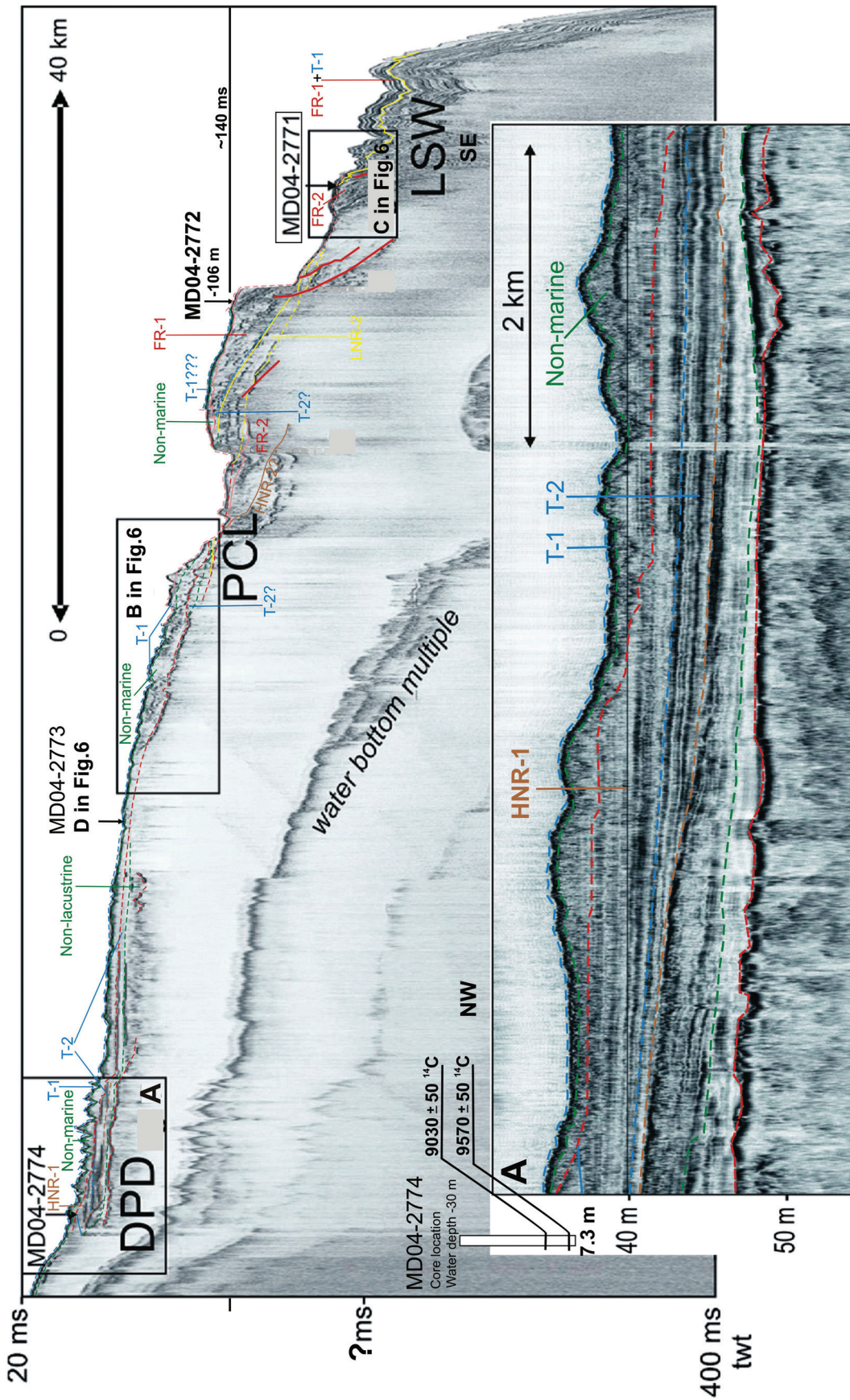


Fig. 5. Stratigraphic subdivision of seismic section B2CH96 (after Lericolais *et al.*, 2011, and Genov, 2016): genetic units of older sequence (HNR-2, FR-2, LNR-2, T-2), genetic units of later sequence (HNR-1, FR-1, T-1). Sequence stratigraphic surfaces: subaerial unconformity (SU) – dashed red line; basal surface of forced regression (BSFR) – brown line; correlative conformity (CC) – dashed yellow line; regressive surface of marine erosion (RSME) – pink line; maximum regressive surface (MRS) – yellow line; transgressive ravinement surface (TRS) – dashed green line; maximum flooding surface (MFS) – dashed blue line. Other surfaces: delineation of the shallow-water sediments – dashed brown line; tectonic disturbance (gravity fault or slip fault) – red line; shoreline trajectory – blue line; erosion surface of the underwater currents – dashed pink line.

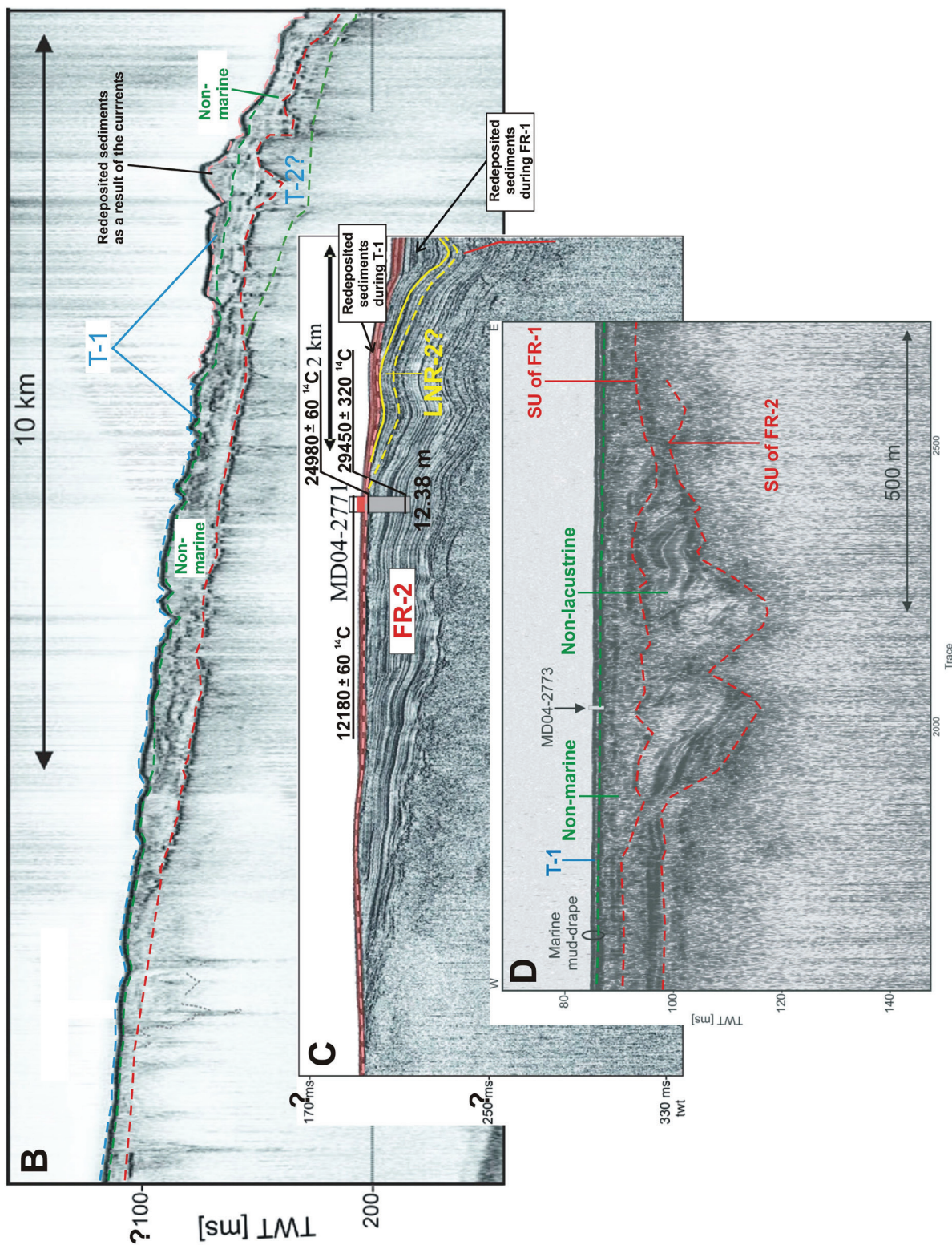


Fig. 6. Continuation of Fig. 5.

and re-deposition of sediments from both sequences from rim currents have been identified near the shelf edge and the uppermost part of the continental slope. The statement that the red clays below the bottom of the Black Sea are connected to the LNR-2 unit (Genov, 2020) is confirmed. The subdivision of the seismic record clearly indicates that sediments from this unit (LNR-2) have been eroded from rim currents and redeposited, as shown in core MD04-2771 (Lericolais *et al.*, 2010) (Figs 5, 6). Finding this unit (LNR-2) means that, after the LGM (*i.e.*, FR-2 according to Genov, 2016, 2018), there was initially a smooth and slow increase in the lake level from –105 m to about –100 m compared to modern sea level and only then a faster basin water level rise occurred, *i.e.*, unit T-2 (Figs 5, 6).

Microscopic (petrographic) studies

Genov *et al.* (2014) emphasized the importance of studying white laminae observed in the Black Sea Unit 2 – sapropel. Subsequently, microscopic studies took place on white laminae in the base of sap-

ropel sediments from cores Euxro03-3, EuxRo01-1 (Slavova *et al.*, 2016b; Koleva-Rekalova *et al.*, 2018) and AKAD 09-17 (Fig. 1). All studied white laminae in cores EUXRo03-3 and EUXRo01-1 are composed predominantly of aragonite rice-like crystals and spheroidal aggregates (spherulites). The spherulites are rarely preserved; commonly, they are crushed into smaller pieces, some of which show a fan-like shape (Koleva-Rekalova *et al.*, 2018, fig. 2E). In core AKAD09-17, only aragonite rice-like crystals are observed. The materials of the white laminae are devoid of coccoliths in the three studied cores. The rice-like grains most often have lengths around and below 0.02 mm, occasionally larger in cores EUXRo03-3 and EUXRo01-1 (Fig. 7a, b). In core AKAD09-17, the number and size of rice-like grains are lower compared to cores EUXRo03-3 and EUXRo01-1, the predominant size being below and around 0.010 mm (Fig. 7c, d). Within the basin deepening, shrinking in size and number of aragonite crystals is observed. Most likely, the reason is related to the additional mechanical processing of those *in-situ* formed crystals within

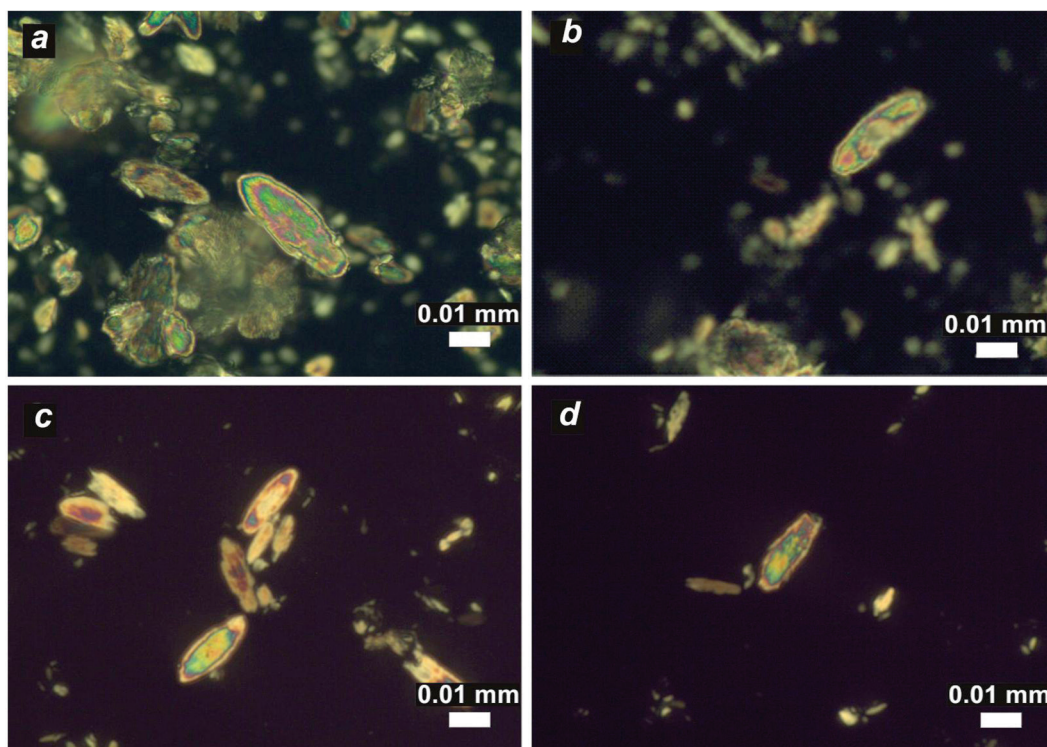


Fig. 7. Microphotographs of smear slides of the aragonite crystals: a) in the center two aragonite crystals with rice-like morphology and sizes larger than 0.02 mm (core EUXRo01-1); b) an aragonite rice-like grain with sizes larger than 0.02 mm (core EUXRo03-3); c) some aragonite rice-like crystals with sizes around and smaller than 0.01 mm (core AKAD09-17); d) an aragonite rice-like crystal with size around 0.01 mm (core AKAD09-17). All microphotographs are in cross-polarized light.

the surf zone during their gravitational transfer to deeper basin parts as a result of such longer transportation. The rice-like aragonite crystals found in all three deep sea cores are applied as a criterion for water level lowering (FR-1) under evaporation after 9,000 ^{14}C yrs BP and to support the hypothesis of sudden incursion of Mediterranean Sea saltwater into the Black Sea at the end of the Early Holocene (T-1) (Fig. 8). It has been proposed that “these types of ‘rice’ grains originate from elongated needle-like aragonite crystals that were initially (inorganically) precipitated in the sea floor during sea level regression. Subsequently, during sea level transgression, they were mobilized by gravity flows and were re-sedimented in deeper parts of the basin. Thus, the rice-shaped grains evolved as a result of the transport of the needle-like aragonite crystals” (Nikitas *et al.*, 2023). Moreover, various authors report that white inorganic laminae are not ubiquitous in all Black Sea cores (Ross and Degens, 1974; Georgiev, 1984; Guinta *et al.*, 2007), which is most probably defined by their gravitational transfer to deep water. The specific form of aragonite crystals at the base of the sapropel may not be observed or be very difficult to perceive in areas with restless or significant terrigenous sedimentation, as well as in distant from the shelf edge deepwater sections.

Radiocarbon measurements

The salinity of the Black Sea Basin at any given time in the past is important for explaining when and how freshwater organisms were replaced by saltwater species, and also for determining the physicochemical limits of saltwater species habitats. Therefore, several rock samples from the reefs in front of Perla Beach (Fig. 1) were recovered for radiocarbon dating. Fossilized *Ostrea edulis* from the reef base (–20 m bpsl) and other shells of unspecified species in a reef rock sample taken at an average depth of –15 m bpsl have been studied. The radiocarbon age of *Ostrea edulis* from the reef base is 5004 ± 40 ^{14}C yrs, and the radiocarbon ages of the shells of the indeterminate mussel species from an average depth of –15 m bpsl are 4392 ± 40 ^{14}C yrs and younger than this (Appendices D, E).

DISCUSSION

Salinity and water level

Comparing the Black Sea level changes by Genov (2016, 2018) and the surface salinity change (Fig. 3) on one joint figure (Fig. 8) allows us to estimate

how real and coordinated these changes are. Considering the proximity of the water level curves for the Black Sea, Marmara and Aegean (World Ocean) basins at about 10,000 ^{14}C yrs BP, we assume that, after that time, the existence of euryhaline species in the Black Sea basin is possible. This is demonstrated in Fig. 8 with the outlines for salinity limit values of *Mytilus galloprovincialis* according to Neveskaya (1965). If we outline the salinity border values of *Dreissena rostriformis* as provided by the same author and take into account the surface salinity curve by Huang *et al.* (2021), we obtain a section for both species’ joint existence within the interval 10.0–6.5 ^{14}C kyrs BP. In order to narrow down the section to the exact moment of the change from stenohaline to euryhaline species, it is necessary to make some adjustments and clarifications on the Black Sea Basin surface salinity curves.

According to Huang *et al.* (2021; Fig. 3), the surface salinity between 14.6–6.75 ^{14}C kyrs BP oscillated from fresh water values to values for brackish water. If we assume that these oscillations are due to redeposits connected with the lake level changes (Fig. 8) through turbid inflows caused by location changes in rim currents that eroded sediments, and if we accept approximately the average values for this salinity, it will not significantly change the Black Sea (lacustrine) freshwater–brackish conditions during this interval of time. Moreover, if for the interval 6.75–0 ^{14}C kyrs BP we recognize that Huang *et al.*’s (2021) age model curve demonstrates significant deviations when compared with the other two (Fig. 2), and accept the fact that the accumulation and accommodation of plankton organisms (*Isochrysidales*) into the sediments is slower due to their microscopic size, and the basin rapid stratification following the saline water intrusion through the Bosphorus, then the average surface salinity change curve for the Black Sea will look like as shown in Fig. 8. This curve corresponds with the result obtained for the time of substitution from freshwater mollusks to saltwater mollusks (~7200 ^{14}C yrs BP) by Ballard *et al.* (2000; Fig. 8; see also Appendix F). The age of 7700 calendar yrs BP (~7200 ^{14}C yrs BP) is also essential in the model of Boudreau *et al.* (2022), in spite of their different approach.

Furthermore, the reasons for the high values of basin surface water salinity during the period 9.1–7.5 ^{14}C kyrs BP by Mertens *et al.* (2012; Fig. 3) must be explained. The Black Sea regression (FR-1) for the period 9–7.5 ^{14}C kyrs BP, as a result of evaporation following eventual saline water inclusion during the previous period 10.0–9.0 ^{14}C kyrs BP, is illustrated in Figs 5–8. Therefore, the study

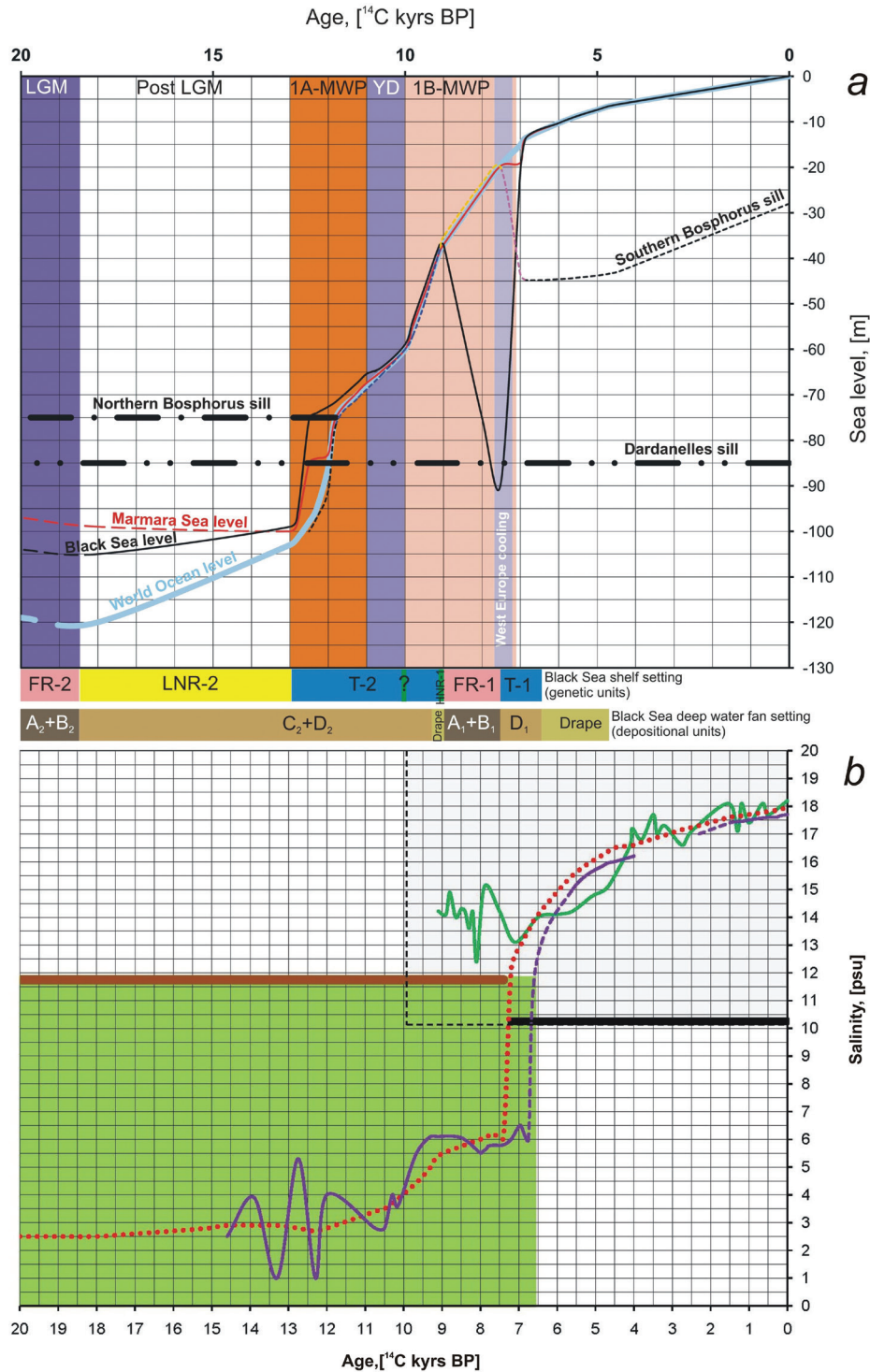


Fig. 8. Data synchronization (^{14}C years): a) water levels, climatic events, sills and sequence stratigraphic units (Genov, 2016, 2018). Black Sea/lake level – black line; Marmara Sea level – red line; World Ocean level (Mediterranean Sea) – blue line (Fairbanks 1990); Southern Bosphorus sill increase as result of colliding water currents – dashed black line; Southern Bosphorus sill increase in estuarine conditions – dashed dark blue line; Southern Bosphorus sill increase under the influence of wave activity – dashed yellow line; Southern Bosphorus sill erosion – dashed light violet line; Last Glacial Maximum (LGM), Younger Dryas (YD), Melt water pulse (MWP); b) salinity: averaged basin surface salinity – red dots line; basin surface salinity (Mertens *et al.*, 2012) – green line; basin surface salinity (Huang *et al.*, 2021) – violet line; water salinity suitable for existence of *Mytilus galloprovincialis* – grey area (Neveskaya, 1965); water salinity suitable for occurrence of *Dreissena rostriformis* – green area (Neveskaya, 1965); time interval for existence of freshwater/brackish mollusks – thick brown line (Balard *et al.*, 2000); time interval for occurrence of saltwater mollusks – thick black line (Balard *et al.*, 2000).

of Mertens *et al.* (2012) demonstrates high salinity values during the period 9.1–7.5 ^{14}C kyrs BP (~10,000–8,000 calendar years according to the age model of Aksu and Hiscott, 2022), because the investigated cores M02-45P and M05-13P are located only on the shelf, *i.e.*, where regression is significantly evinced by increasing salinity due to intense water evaporation and the emergence of isolated water bodies. Measurements of salinity in cores BC53 and GeoB7625-2 from the deep part of the basin (Mertens *et al.*, 2012) refer primarily to the interval beyond 7.3 ^{14}C kyrs BP (~7.75 cal yrs BP) and are not relevant to the interval discussed above. Therefore, the existence of *Dreissena rostriformis* aged 8,840 ^{14}C yrs BP (9590 calendar years according to Aksu and Hiscott, 2022, table 2) in core M02-45P is compelling evidence of re-sedimentation due to the Early Holocene regression (FR-1) (Genov, 2020) as it could not survive in salinity over 12 ppm (Neveskaiya, 1965; Fig. 8). In addition, the re-deposits in the same core shown by (Genov, 2020, table 1) also confirm this regression. Hence, given the dating of samples from this core used by Ankindinova *et al.* (2020) to create an age model, it means that the irregularities in their calibration curve for the interval 7.5–10.7 ^{14}C kyrs BP (Fig. 2) could be a consequence of the Early Holocene regression (FR-1). Similarly, this conclusion may be transferred to the other calibration curves for the same interval.

Different researchers calculate significantly different values of reservoir offset for the interval 7.5–12 ^{14}C kyrs BP (Kwiecien *et al.*, 2008; Soulet *et al.*, 2011; Yanchilina *et al.*, 2017; Williams *et al.*, 2018), which is evidently a problem concerning the correction of raw radiocarbon years, a fact that could also be associated with the Black Sea Basin's regressive development. It indicates that the finalization of the basin regression was at about 7.5 ^{14}C kyrs BP, followed by an intensive transgression reflected in the sharp change in surface water layer salinity (Fig. 8).

Therefore, only the data from core GGS18 (Huang *et al.*, 2021), extracted from a depth of 971 m, and cores BC53 and GeoB7625-2 (Mertens *et al.*, 2012), which are not located on the shelf, should be considered trustworthy data on basin surface salinity. The traced approximate surface salinity curve for the Black Sea Basin during the period 20–0 ^{14}C kyrs BP (Fig. 8) corresponds to the aforementioned cores and data, as well as to the curve for basin water level change (Genov, 2016, 2018).

Moreover, the interpretation by Genov (2020) that an increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Yanchilina *et al.*, 2017; Ankindinova *et al.*, 2019; Aksu and

Hiscott, 2022) may have occurred during the Black Sea Lake's regressive development provides no arguments in favor of a gradual change in basin salinity. The rice-like aragonite grains at the base (onset) of the sapropel (Unit 2; Ross and Degens, 1974) provide further evidence for the existence of a low-stand at the water level before their accumulation, *i.e.*, immediately before the formation of Unit 2 (Fig. 7). Seismostratigraphic subdivision also confirms the presence of an Early Holocene regression (FR-1; Figs 5, 6).

Therefore, the “flood” hypothesis (Yanchilina *et al.*, 2017; Aksu and Hiscott, 2022), promoting a too early onset (~9500 cal. years BP; Fig. 4; ~8,800 ^{14}C yrs BP – Nicholas and Chivas, 2014) of sudden inundation of the Black Sea Lake by Mediterranean (Marmara) seawaters with higher salinity, cannot explain the brackish nature of the Black Sea water (maximum ~6.5 psu) until about 7,500 ^{14}C yrs BP (Fig. 8) or ~8,000 calendar yrs BP (Ankindinova *et al.*, 2020; Fig. 2).

In order to convert the Black Sea curves (basin level and middle surface water salinity) from radiocarbon years to calendar years, the selected in the text above calibration curve of Ankindinova *et al.* (2020) as the most accurate compared to the other two curves shown in Fig. 2 can be applied (Fig. 9).

Application of curves of the Black Sea environmental changes after 10,000 ^{14}C yrs BP

The rapid change in Black Sea water salinity after 7500 ^{14}C yrs BP, *i.e.*, ~8,000 calendar yrs BP stated in the present study (Figs 8, 9), is confirmed by studies of the phytoplankton (Haptophyta – Coolen *et al.*, 2009; Huang *et al.*, 2021), ostracods (Williams *et al.*, 2018) and dinocysts (Filipova-Marinkova *et al.*, 2013).

The possible existence of *Mytilus galloprovincialis* in the Black Sea earlier than 7,500 ^{14}C yrs BP is explained by the intrusion of this species through the Bosphorus Strait before 9,000 ^{14}C yrs BP (~10,000 calendar years – Fig. 9) where water with salinity >10 psu existed (Neveskaya, 1965), *i.e.*, close to the Black Sea side of the strait (Fig. 8). Subsequently, during the Early Holocene regression (FR-1), as a result of significant evaporation, favorable conditions for the survival of *Mytilus galloprovincialis* occurred (see Mertens *et al.*, 2012; see also Fig. 8), and its corresponding redeposit in the shelf and further below in the shrinking Black Sea Lake. Due to these basin development features, whole shells of this species dated at >7,500 ^{14}C yrs BP are rare (Nicholas and

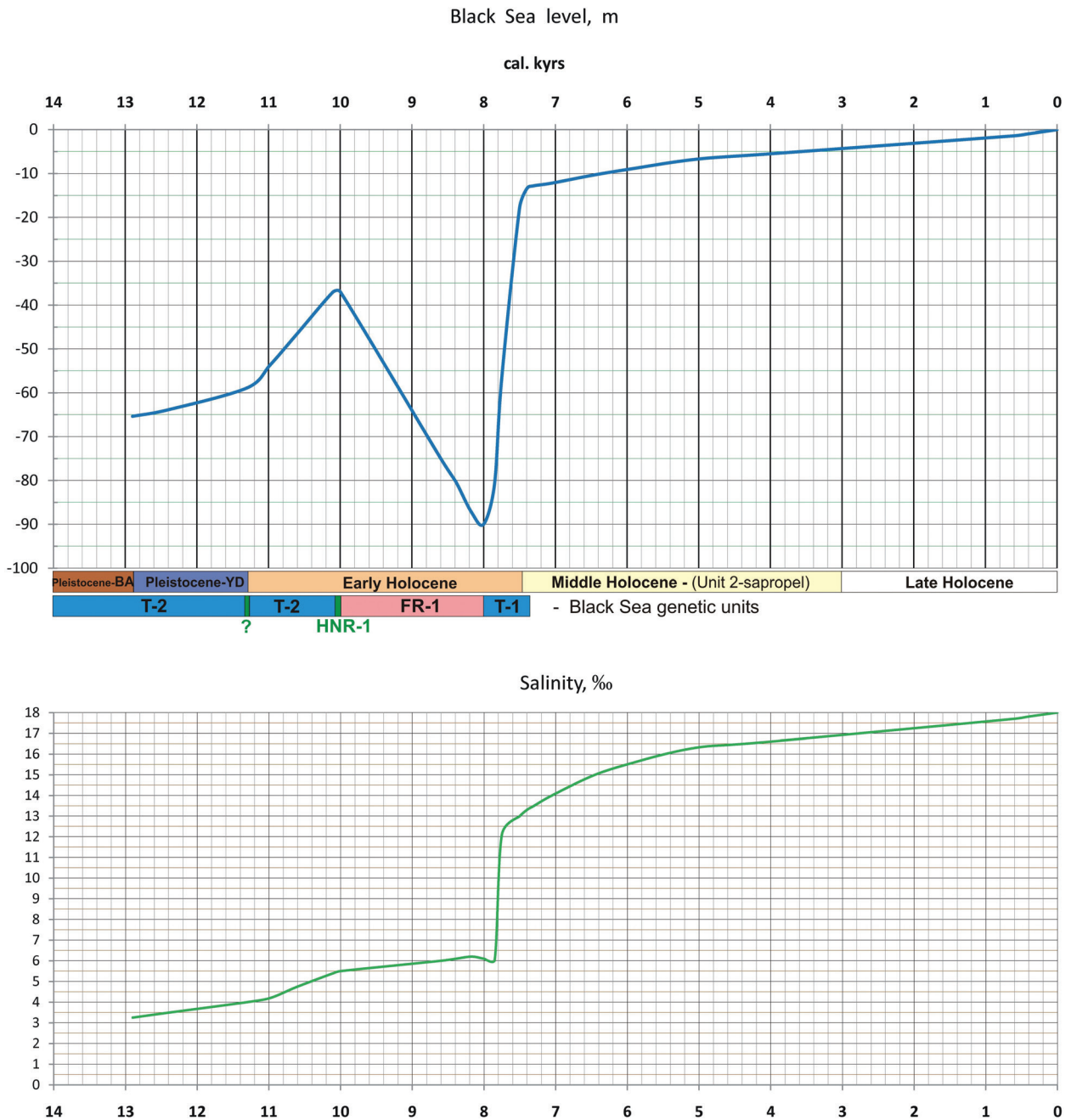


Fig. 9. Data synchronization (calendar years): Black Sea level – blue line; averaged basin surface salinity – green line; Bolling-Allerod (warm interval of time) – BA; Younger Dryas (cold interval of time) – YD; Early Holocene (warm interval of time in SE Europe).

Chivas, 2014). The steady presence of *Mytilus galloprovincialis* in the Black Sea is associated with the T-1 transgression, conditioned by the sudden insertion of saltwater from the Marmara Sea (Mediterranean) at $\sim 7,500$ ^{14}C yrs BP ($\sim 8,000$ calendar yrs BP). This means that the rapid salinity change is, in turn, associated with rapid increase in water level (Figs 8, 9). Considering the age of *Mytilus gallopro-*

vincialis shells (6,520 ^{14}C yrs BP) found at a depth of ~ 90 m bpdsl (Lericolais *et al.*, 2009) and the sea level curve by Genov (2016; Fig. 8), the maximum depth of existence for the species must be 80 m bpdsl. This conclusion is advanced, provided that the shell findings have not been transported by underwater currents. We exclude the *Mytilus galloprovincialis* data collected near the Bosphorus (such as those in cores

M05-50P M05-51G, and similar to Ankindinova *et al.*, 2020, and Aksu and Hiscott, 2022) due to the presence of constant strong high salinity bottom currents coming from the Marmara Sea and flowing into the Black Sea, which can redeposit the shells from the bottom of the strait or from a relatively small depth on the Black Sea shelf in the deeper areas.

The lack of suitable abiotic factors (salinity S ‰ and temperature T °C) for the spread of *Ostrea edulis* in the Black Sea before the marine transgression ~7.5 ¹⁴C kyrs BP is evident from Fig. 8. The oldest sections of the Black Sea reefs, in front of the Perla Beach (Primorsko; at a depth of –20 m) were sampled. The dating of a fossilized *Ostrea* shell indicates an age of ~5,000 ¹⁴C BP (Appendix D), which is among the oldest ages measured in the basin. Without claiming to be exhaustive, reported radiocarbon dates (¹⁴C kyrs BP) of *Ostrea edulis* in the Black Sea are as follows: 5.14±0.27 (Filipova-Marinova and Christova, 2001); 4.59±0.07 (Switoch *et al.*, 1986); 4.4 (Porotov, 2007); 3.12±0.05 and 0.29±0.09 (Krastev *et al.*, 1990). The first appearance in the Bosphorus is dated at 5.3 ¹⁴C kyrs BP (Algan *et al.*, 2001), *i.e.*, the mass appearance of *Ostrea edulis* in the Black Sea does not correlate with the transition from lake to sea phase of the basin ~7.5 ¹⁴C kyrs BP (Genov *et al.*, 2020). This means that the necessary salinity of ~16 psu according to the approximate salinity curve in this paper (Fig. 8) and other life conditions of this species in the studied basin were reached about 5,000 ¹⁴C years (5,350 calendar years; see Fig. 9).

Climate (temperature) and water levels of the Black Sea and the World Ocean

Considering that ice volume and ocean level are directly interlinked (Lambek *et al.*, 2014, Harison *et al.*, 2019), we can advance the following reasoning. The LGM, as an ice age, is described by constant reduction in the ocean level and an increase in ice in the poles, *i.e.*, a cool climate (Fig. 8; for the Black Sea Lake, LGM is the FR-2 cause). This means that the Heinrich-2 and 3 climate events are from this ice age. But the Heinrich-1 climate event does not belong to the LGM, because it is preceded by an increase in the ocean level caused by a slight climate improvement. The probable reason for this event is the cooling water circulation of melted glacial waters from the poles to the equator expressed in the overall cooling of the Earth's atmosphere, cold peak Heinrich-1. The direct transfer of water from glaciers to the oceans took place in short periods, while the transfer of glacier water through the land was

slowed due to the formation and filling of intermediate basins. This means that, after the LGM, the temperatures were still very low and the waters reaching the Black Sea Lake slightly increased its water level – LNR-2 (Fig. 8). The red clays in the western and northern parts of the Black Sea are connected with LNR-2 (Yanchilina *et al.*, 2019; see also Figs 5, 6). The significant climate improvement after the Heinrich-1 peak is the cause of MWP-1A (melt water pulse 1A) and the melting of large amounts of ice in Northern Europe. This warming during the Bolling-Allerod period reflected a significant increase in the water levels of the oceans and the Black Sea Lake (T-2), so the Black Sea Lake began to drain off to the Mediterranean and the World Ocean. Consequently, the inflow of glacier waters to the Black Sea was slowed down due to the withdrawal of Scandinavian glaciers northward and the opening of the Baltic Sea to the World Ocean (Genov, 2009, 2016). However, the ubiquitous transfer of huge amounts of melted glacier water from the poles to the equator caused a new widespread climate cooling – YD (Younger Dryas cold period). The water surfaces of the oceans and the Black Sea Lake were approximately leveled at the end of YD as a result of the cold climate (Genov, 2018). The subsequent warming in the Early Holocene after YD caused a new inflow of melted glacial water (MWP-1B), though mainly to the World Ocean and to a lesser extent to the Black Sea Lake (Figs 8, 9). The gradual withdrawal of the glaciers supplying the Volga River reflected in a gradual decrease in the water flow to the Caspian Sea Lake and its connection to the Black Sea Lake was severed (HNR-2). The increased transfer of cold glacier waters to the Atlantic caused climate cooling near the coastal regions during the Early Holocene. However, during this period, the climate inside the continents, far from the oceans, remained significantly warmer. The warm climate caused significant evaporation, causing the Early Holocene regression (FR-1) in the Black Sea Lake (Figs 5–9). Continued increase in the World Ocean's level transformed the Black Sea Lake into an inner semi-closed sea after the Bosphorus threshold was overcome (T-1).

CONCLUSIONS

The placement of all events and data considered in one time scale allows the following conclusions to be made:

- 1) The sea level change curve by Genov (2016, 2018), compared to other Black Sea level curves

for the last 20,000 years, provides better consistency with the available basin data. Provided that the reservoir offset value is precisely calculated for the Black Sea basin, the time measurement for this level curve could be converted from radiocarbon years into calendar years. It means that the environmental changes in the basin occurred both abruptly and quickly, at 7,500 ^{14}C yrs BP (~8000 calendar years BP), as a result of saltwater incursion through the Bosphorus Strait;

2) The curves discussed above illustrating the surface salinity changes in the Black Sea (lake) are adapted to the level change in the basin according to Genov (2016, 2018). An average curve for the surface salinity changes in the Black Sea basin for the last 20,000 years has been obtained;

3) Using this average surface salinity curve, it is concluded that the *Ostrea edulis* settlement in the Black Sea took place at 16 psu surface water salinity before ~5,000 ^{14}C yrs (~5350 cal. yrs).

4) Following the Black Sea level curve of Genov (2016, 2018), the *Mytilus galloprovincialis* habitat maximum depth should be accepted as ~80 m below the modern sea level.

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APPENDIX A. Sampling locations. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

APPENDIX B. Age conversions. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

APPENDIX C. Salinity. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

APPENDIX D. Radiocarbon dating. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

APPENDIX E. Documentation. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

APPENDIX F. Average curve of surface salinity. (This material is available online at https://geologica-balkanica.eu/sites/default/files/supplementary/Genov_Geol_Balc_53-2_2024_Appendices.zip.)

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