

Possible paleo-exchange of water masses between the Mediterranean Sea, Marmara Sea and Black Sea

Krasimira Slavova, Ivan Genov

Institute of Oceanology — Bulgarian Academy of Sciences, 9000 Varna, PB. 152;

e-mail:krslavova@hotmail.com; e-mail:ivan_genov01@hotmail.com

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К. Славова, И. Генов — Возможный палеообмен водных масс между Егейским, Мраморным и Черным морями. В этой статье представлен механизм для возможного палеообмена водных масс между Егейским, Мраморным и Черным морями. Ключевой момент согласно интерпретации возможного палеообмена водных масс представляет собой глубина Босфорского прага в течение периода 20 000 — 7000 кал.г. ВР. Определение постоянной глубины для Босфорского прага в течение периода 20 000 — 7000 кал.г. ВР — неправильный подход к интерпретации палеоклиматических и палеогеологических событий в области Черного моря. Из-за этой причины две модели Босфорского прага — глубокая и мелкая праговая модели были приняты. Глубокая модель действительна для первых двух стадий периода 20000 — 14 500 кал.г. ВР. Мелкая модель действительна в течение периода ~12 500—7000 кал.г. ВР. Для последней стадии возможного палеообмена водных масс между Егейским, Мраморным и Черным морями (7500—7000 кал.г. ВР) как результат увеличения глобального уровня моря, воды океанского соленого источника катастрофически вторгнулись в Черное море. Новый момент возможного палеообмена водных масс между Егейским, Мраморным и Черным морями то что однажды начавшееся пресноводное истечение Черного моря к Мраморному морю в 14 000 кал.г. ВР не остановится прежде чем приблизительно 12 500 кал.г. ВР, но продолжит к приблизительно 9500 кал.г. ВР. Этом противоречит теории Ryan et. al., (1997), Aksu и др. (2002). Здесь было приложено новое объяснение для образования более низкого слоя сапропеля в Мраморном море.

Abstract. In this article a way for possible paleo-exchange of water masses between the Aegean, the Marmara and the Black Sea is submitted. A key aspect according to the interpretation on hand of the possible paleo-exchange of water masses is the depth of the Bosphorus sill for the period 20 000 — 7000 cal.yr.BP. Determining an established constant depth for the Bosphorus sill for the period of 20 000 — 7000 cal.yr.BP is an incorrect approach to the interpretation of the paleo-climatic and paleo-geological events in the Black Sea region. Due to this reason two models of the Bosphorus sill — deep sill and shallow sill models have been accepted. The deep sill model is valid for the first two stages of the period 20 000 — 14 500 cal.yr.BP. The shallow sill model is valid for the period ~12 500-7000 cal. yr. BP. For the last stage of possible paleo-exchange of water masses between Aegean, Marmara and Black Seas (7500-7000 cal.yr.BP) as a result of continuing increase in the global sea level, saline ocean water catastrophically entered the Black Sea. The new moment of possible paleo-exchange of water masses between Aegean, Marmara and Black Seas is that once started the freshwater Black Sea outflow to the Marmara Sea in 14,000 cal.yr.BP did not stop until about 12,500 cal.yr.BP but continued to about 9,500 cal.yr.BP. That contradicts the theory of Ryan et. al., (1997), Aksu et al. (2002). A new explanation for the formation of the lower sapropel layer in the Marmara Sea has been offered.

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Key words: Bosphorus sill, paleo-exchange of water masses, sapropel, Aegean Sea, Marmara Sea, Black Sea.

Introduction

In order to testify whether cyclical climatic changes in the Black Sea region (Slavova, 2001) correspond to the facts from the Mediterranean Sea and the Marmara Sea, it is necessary to consider the possible paleo-exchange of water masses between the above mentioned seas and its consequences. This is the sequence of events that proves the differences in the time of sapropel sedimentation in the Aegean (East Mediterranean Sea), the Marmara Sea and the Black Sea. On the basis of ^{14}C dating of sapropels — S1 in the Aegean Sea (Çağatay et al., 2000; Stanley, Blanpied, 1980), the Marmara Sea (Çağatay et al., 2000) and the Black Sea (Димитров, 1982; Ross, Degens, 1974; Jones, Gagnon, 1994) and on the basis of the climatic events (Slavova, 2001), a sequence of the possible paleo-exchange between the water masses of the Mediterranean, Marmara and Black Seas for the period 15,000-7,000 cal.yr.BP is determined. In this article all ^{14}C datings are converted in calendar years BP (BP=before present) on the base of local calendar curve for Black Sea (Slavova, 2002) due to proved necessary of calibration of radiocarbon years in calendar years (Bard et al., 1990; Fairbanks, 1990; Hilgen et al., 1993).

The Straits

The seismic profiles made by the Turkish Navy in the Bosphorus and the Dardanelles illustrate the straits as eroded and today partially filled in with sediments channels whose basic depth is not less shallow than 85 m. The relative basal sill depth of the Dardanelles Strait is respectively 85 m (Ryan et al., 1997).

The bedrock of the Bosphorus reaches to depth of -100 m (Ryan et al., 1997). A crucial moment in the present interpretation of the possible paleo-exchange between the Aegean, the Marmara and the Black Sea is to set up paleo-depth of the Bosphorus sill for the period under discussion (15,000-7,000 cal.yr.BP) and to determine whether the paleo-depth is a constant in the Late Pleistocene-Holocene time as it has been accepted in almost each publications up to now. Different authors recognize different constant depth of the Bosphorus sill after the last glacial period: -85 m (Ryan et al., 1997; Major et al., 2002), -50 m (Degens, Ross, 1972), <20 m (Major et al., 2002), -40 m (Hiscott, Aksu, 2002) etc.

The approach to an examination of the present problem is based and originates from the

idea that the paleo-depth of the Bosphorus sill for the period of 15,000-7,000 cal.yr.BP is a value that is not a constant but changes in the course of time. The reasons for this assertion are presented and studied subsequently in the following text. Determining an established, constant depth for the Bosphorus sill for the period of 15,000-7,000 cal.yr.BP is an incorrect approach to the interpretation of the paleoclimatic and paleo-geological events in the Black Sea region because the depth of the Bosphorus sill depends on the processes of denudation, sedimentation and erosion, as well as on tectonic processes (Demirbag et al., 1999). Due to inadequate data about the paleo-depth of the Bosphorus strait and insufficient explanation of the problem, the following arguments supported by data and dating taken from drillings in the Bosphorus sill are on hand in the present article. For the correctness of the presentation it is important to clarify that the determined changing paleo-depth of the Bosphorus sill for the period of 20,000-10,000 cal.yr.BP is made on the basis of dating and thickness of sediment cover from a drilling in the Central Bosphorus along Çağatay et al. (2000) (fig. 1). The dating and the thickness of the sediments from the drilling BPMB-14 are related to along the Bosphorus in its deepest part (along fareway). Beyond 10,000 cal.yr.BP for the purposes of the study on hand, it is allowed to make this assumption about the paleo-depth of the Bosphorus as it is a logical way to reach to the real value of the sill with the processes of sedimentation and denudation taken into account. Except for the drilling BPMB-14 from the Bosphorus (Çağatay et al., 2000) and the subsequent logical arguments for the paleo-depth of the Bosphorus sill, there are tectonic proofs by Demirbag et al. (1999), for the period after 10,000 cal.yr.BP. Despite the fact that these proofs are of different character, they prove the hypothesis that it was impossible saline oceanic waters to intrude before 7,500 cal.yr.BP because of the paleo-depth of the Bosphorus sill above the global sea level before 7,500 cal.yr.BP. Two models of the Bosphorus sill should be accepted when interpreting the paleo-exchange between the Black Sea and the Marmara Sea — deep sill and shallow sill models, examined by Major et al. (2002). These models are mutually exceptional, as the authors claim. According to this article deep sill and shallow sill models are not mutually exceptional and were manifested at a different time for the studied period in accordance with the exogenous and endogenous processes prevailing in the Bosphorus

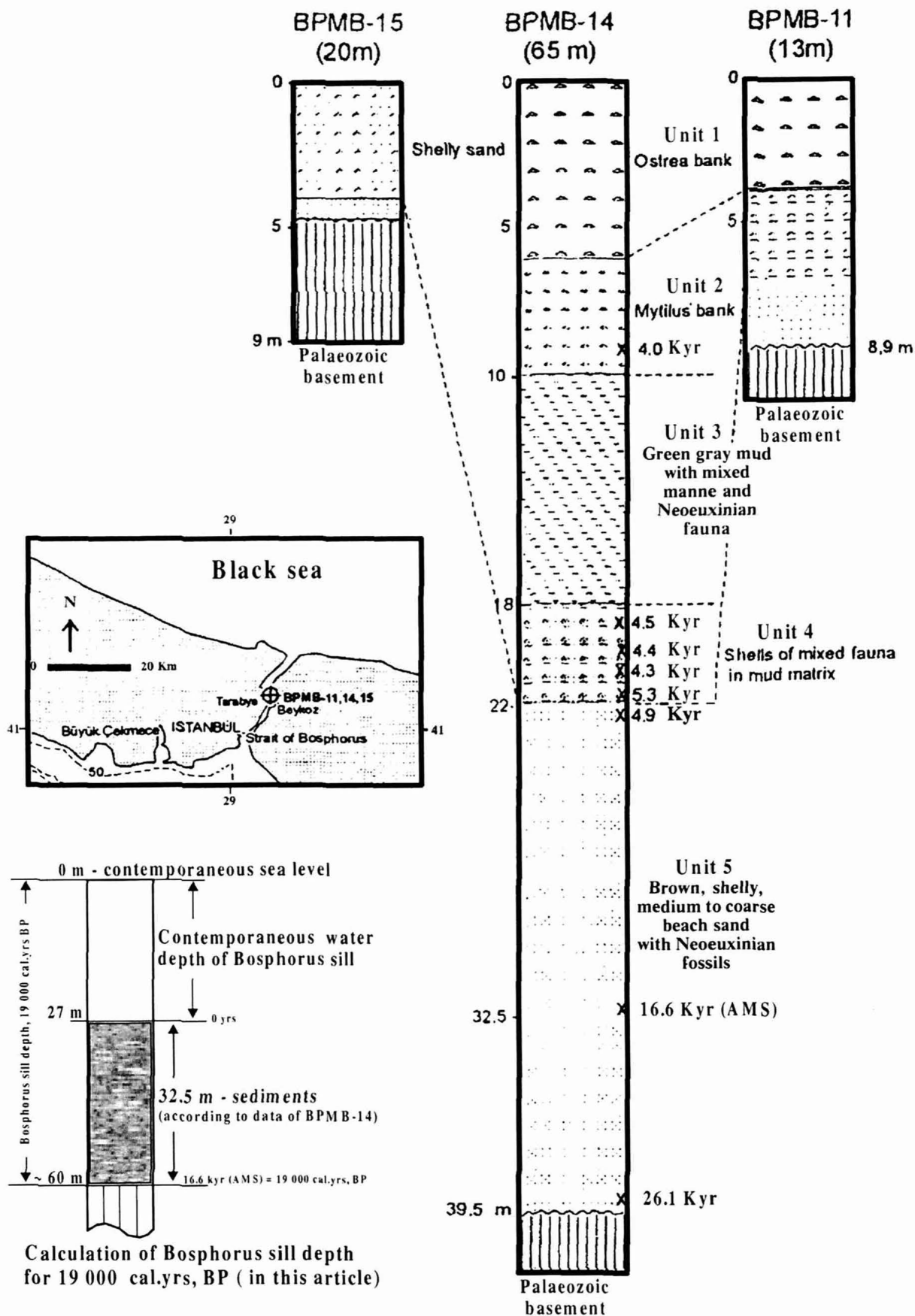


Fig. 1. Cores from the Central Bosphorus strait (by Çağatay et al., 2000 with modification and additions)

Strait. It is not reasonable to accept only one constant in the course of time model, that excludes the other one during the studied period of 15,000-7,000 cal.yr.BP as it is clearly seen in fig. 1 that sediment cover changing in the course of time do exist and should be taken into consideration.

At the contemporary water column for the Bosphorus sill 27 m (Demirbag et al., 1999), and thickness of the sediment cover of core BPMB-14 — 32,5 m (fig. 1) with an age of about 19,000 cal.yr.BP (16 600 ^{14}C yr.BP), the calculated depth of the Bosphorus sill according to the recent sea level is approximately 60 m. Of course, this is just an approximation of the Bosphorus sill paleo-depth but it is a logical way to restore its real value.

Paleo-exchange — Interpretation

During the last Quaternary glaciation — Vurm III the Black Sea turned into a gigantic freshwater lake not connected the Marmara Sea. The Black Sea level fluctuations were not synchronous with the global sea level fluctuations during that period. There is not an unequivocal view about the Black Sea level 20,000—18, 000 cal.yr. BP ago. According to different authors the surface of this lake is extended at different depths from -150 m (Winguth et al., 2000; Ryan et al., 1997), -110m (Pirazzoli, 1996) to - 90 m (Димитров et al., 1979; Demirbag et al., 1999). During the same period the paleo-shores of the Marmara Sea reached to about -100 m (Çağatay et al., 1999), of the Aegean Sea — about -115, -120 m (Fairbanks, 1989) below contemporary sea level.

Approximately 20.000 cal. yr. BP the depth of the Bosphorus sill was about 60 m (fig. 2a). In fig. 1 for Unit 5 data is received that it is brown-shell medium to rough beach sand with Neueuxine fossils. The presence of Neueuxine fossils in the BPMB-14 drilling in the Central Bosphorus for the period before 19,000 cal.yr. BP testifies that 19,000 cal.yr. BP ago the Black Sea level was about and above 90 m with possible oscillations above and below the Bosphorus Strait (Stanley, Blanpied, 1980). In 2360 drilling (Димитров, 1982) the sample 9 was taken from Neueuxine offshore deposits and the absolute age was determined by intact shells from *Dreissena* and it is about 19,300 cal.yr. BP (17 080±510 ^{14}C yr. BP) The 2360 drilling is located in the zone of the peripheral swells at a depth of 91 m. Therefore, the value of about 150 m of the Black Sea level during

the last glacial period that is claimed by some authors (Winguth et al., 2000) is higher. From about 20,000 to 15,000 cal. yr. BP the Black Sea level was approximately -90 m, -100m (fig. 2a)

About 16,350 cal. yr. BP ago (~14000 ^{14}C yr. BP), the face of the base of the Marmara Sea core G6 indicates an accumulation of anaerobic conditions, probably brackish (Stanley, Blanpied, 1980). Cores DM-13 and GM-7 from the Marmara Sea (Çağatay et al., 2000) also indicate an accumulation under anaerobic conditions during that period. At that time well aerated, vertically combined water masses had already come into existence in the Aegean Sea in contrast with the Marmara Sea Lake (Stanley, Blanpied, 1980) (fig. 2a). During the same period sediments with iron sulfides included accumulated in the Black Sea basin (Димитров, 1990).

The conclusion about three entirely separated seas, each with its own water-mass configuration comes logically for the period of maximum low eustatic global sea level about 18,000-15,000 cal.years BP ago (fig. 2a).

About 15,000 cal.yr. BP ago Ist meltwater pulse along the Barbados coral reef is dated — IA (Fairbanks, 1990). The melting led to a rise in the World Ocean level. The discharged velocity of the melted glacial water calculated from the World Ocean level through Barbados is 17 000 km³/y. The World Ocean level was approximately -95 m in 14,500 cal.yr.BP (Fairbanks, 1990).

For the period of 15,000-14,500 cal.yr. BP the climate warming was expressed in quick melting of large glacial covers in North Europe and in the Alps. It also helped for the sudden pull of melted water through the Danube River, the Dnepr River, the Dniester River, the South Bug and the river Don in the Black Sea, (Ryan, Pitman, 1998; Major et al., 2002), (fig. 2b). The Caspian Sea also reacted to the process of glacial melting, raising its shore lines up to the overspill point in the Black Sea through the Manichkata Valley, (Фёдоров, 1996; Major et al., 2002). In 14,500 cal.yr.BP (~12500 ^{14}C yr. BP), the Black Sea was still in its freshwater stage with rapid rise in the level (fig. 2b). The statement about the rise in the Black Sea level at this time is supported by the approximately five times decreasing velocity of sedimentation in core BLKS 9810 and the predisposition to smaller medium grain sizes in the terrigenous component, which in turn, is a prerequisite for the Black Sea shore transgression (Major et al., 2002).

The regional improvement of the climate about 14,500 cal. yr. BP leads to substantial

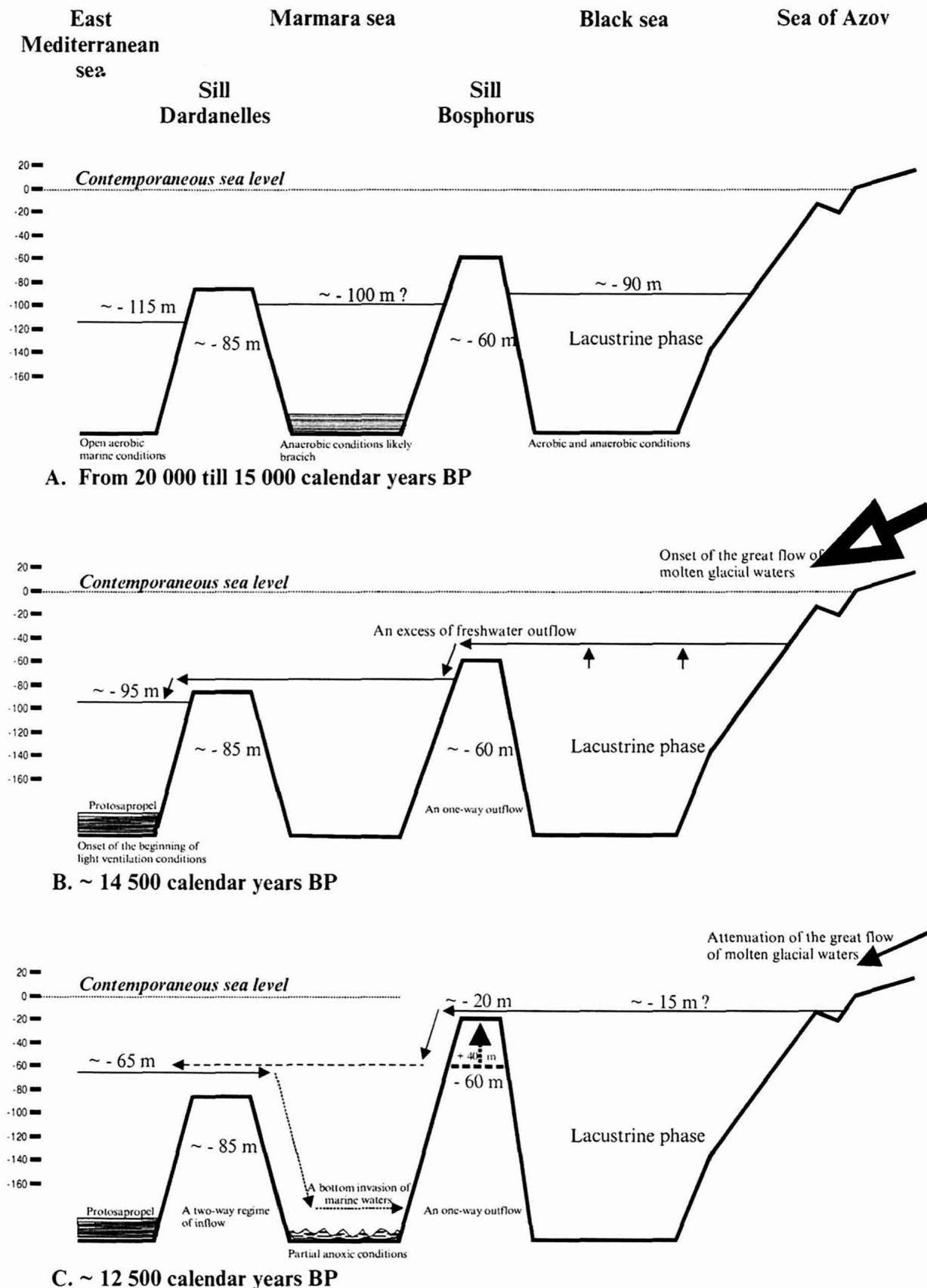


Fig. 2. A possible exchange of water masses between the East Mediterranean sea, the Marmara sea and the Black sea for the period 15 000-7000 cal. yrs BP

rise in the Black Sea level according to Flood et al. (1996) up to 15 m. As a result large volumes of water outflowed from the Black Sea into Marmara Sea through the Bosphorus and later — through the Dardanelles into the Aegean Sea (fig. 2b).

A proof of the Black Sea freshwater outflow to the Aegean Sea is the widespread grey protosapropel layer, normally 2-12 cm thick that lies under the youngest Holocene sapropel in the Aegean Sea (Stanley, Blanpied, 1980). Such protosapropel fix the beginning of stratification and temporary anaerobic conditions in the Aegean Sea and the adjacent Mediterranean basin.

The paleo-depth of the Bosphorus for the period of 15,000-7,000 cal.yr.BP (~12700 — ~6600 ^{14}C yr. BP) is not a constant value. Major et al. (2002) describe two possible models of the Bosphorus sill: a deep sill model — effectively corresponding to the Dardanelles, i.e. approximately -90 ± 5 m, and a shallow sill model — less than -20 m. However, the two models mutually exclude each other. Affirmatively the deep sill model suggested by the authors as a constant value in the time after 14,500 cal.yr.BP can be rebuffed due to the fact that if the Bosphorus sill had depth approximately equal to that of the Dardanelles, i.e. about -85 m, then the sea water from the Mediterranean Sea would have entered the Black Sea in about 14,000 cal.yr. BP (~12000 ^{14}C yr. BP), which is synchronous with the global curve of the World Ocean (Fairbanks, 1990) and the inundation of Marmara Sea from Mediterranean Sea waters. The last logical consequence of the deep sill model is synchronous with the time of formation of sapropels in the Marmara Sea and the Black Sea, (fig. 2d, f). However, the beginning of the creation of the Black Sea sapropel is dated to about 7,500 cal.yr. BP (Jones, Gagnon, 1994).

As far as the shallow sill model of the Bosphorus sill with sill depth less than 20 m (Major et al., 2002) is concerned, it can be accepted but provided that the depth has changed in the course of time. The depth for the period from the last glacial maximum to about 15,000 cal.yr.BP (~12700 ^{14}C yr.BP), is about -65 m, received through calculations from the fig. 1., mentioned in the text above. Çağatay et al. (2000) make a description of three drillings in the Bosphorus Strait. Through the BPMB-14 drilling in the Central Bosphorus (fig.1), he calculates the velocity of sedimentation in the five unites separated in the core. For the bottom part of Unit 5 he cal-

culates velocity of sedimentation 0, 74 m/1000 years, and for the top part of Unit 5—0, 97 m/1000 years. However, the conclusion from the modern studies of different sources (Çağatay et al., 2000; Ryan et al., 1997) is that the lithological Unit 4 under the Bosphorus sill containing sea water and freshwater mollusks was deposited clearly under high energy conditions with erosive lower boundary. The basis of Unit 4 (fig. 1) at 22 m indicates the first appearance of euryhaline marine mollusks in the Central Bosphorus. On the basis of ^{14}C dating of two shell samples found immediately above and below this surface an age of 5,700 cal.yr.BP (5300 ^{14}C yr.BP) is determined for this boundary; the oldest ^{14}C dating obtained on the basis of Unit 4. Çağatay et al. (2000) conclude that this is not the age of the first manifestation of euryhaline mollusks in the Bosphorus drilling but the reason is very fast and chaotic sedimentation in the Unit 4. Therefore, it is impossible to calculate the precise velocity of the upper part of Unit 5 provided that proofs for fast, chaotic and high velocity sedimentation and erosive upper boundary of Unit 5, (fig. 1) do exist. The velocity of 0,97 m/1000 years is diminished and probably it is much higher having in mind the events that occurred 15,000 cal.yr. BP ago and examined in detail in the text. Flood et al. (1996) accept about -15 m to be the depth of the Bosphorus sill approximately 14,000 cal.yrBP (~12000 ^{14}C yr BP). The suppositions in the hypothesis at hand indicate that for the period about 12,500 cal.yr.BP the Bosphorus sill level was about -20 m, (fig. 2c). This means that in the period after the Last Glacial Maximum to 12,500 cal.yr.BP the sediments deposited on the Bosphorus sill are approximately 40 m. The Bosphorus depth increased to about -20 m. The deposited high layer of sediments is a result of the response of the Black Sea to the climatic changes that started about 15,000 cal.yr. BP and of freshwater surplus discharged through the Bosphorus Strait. The quantity of melted glacial water that flowed in the Black Sea through the big European rivers — the Danube River, the Dnester River, the rivers Don, Dnepr, and South Bug and from the Caspian Sea through the Manichkata Valley was enormous. The Black Sea level rose up to about -15 m, (Flood et al., 1996) and large water surplus of fresh water that carried huge quantity of sedimentary material passed through the Bosphorus Strait to the Marmara Sea. Due to reduction in the quantity of melted glacial water, the energy of the Black Sea outflow to the Marmara Sea also decreased

13,000 cal.yr. BP ago. As a result, inevitably very intensive deposition of the surplus of sedimentary material along the Bosphorus Strait and sill respectively should have begun.

After 14,050 cal.yr. BP Black Sea and Mediterranean waters inflowed the Marmara Sea (fig. 2c). The Mediterranean waters were synchronous with the global curve of the sea level (Fairbanks, 1990). The observed changes in cores from the Marmara Sea indicate an early, still limited inflow of water from basins adjacent to the Marmara Sea. The black color of some shells of planktonic foraminifera associated with dark colors of the sediments represent the continuation of reducing conditions as a result of stratification of the deep Marmara Sea waters (Stanley, Blanpied, 1980).

Dinoflagellate cysts *Brigantedinium simplex* and *Spiniferites cruciformis* are sensitive indicators for low-saline marine and freshwater and/or brackish water conditions and respectively can be used for tracing the water masses. The appearance of dinoflagellate cysts *Brigantedinium simplex* 14,000 cal.yr. BP (12,000 ^{14}C yr. BP) ago in core 20 proves that the Black Sea waters flowed and made fresh the surface waters of the Aegean Sea. A proof of the Mediterranean Sea flow into the Marmara Sea in ~14000 cal.yr. BP (~12000 ^{14}C yr) is the prevalence of the medium brackish water conditions in cores 11 and 12 until about 14,000 cal.yr. BP. In about 14,000 cal.yr. BP the quantity of dinoflagellate cysts *Spiniferites cruciformis* significantly decreases and then completely disappeared. in 9,600 cal.yr. BP (9000 ^{14}C yr. BP) in core 12, and in 5,400 cal.yr. BP (5000 ^{14}C yr. BP) in core 11 (Aksu et al., 2002). This delay is probably due to supply of fresh water from the river valleys along the south Marmara Sea shelf.

The inflow of sea waters from the Mediterranean Sea to the Marmara Sea basin 14,000 cal.yr. BP ago proves the boundary between Unit 1 and Unit 2 of cores DM13 and GM7, (Çağatay et al., 2000). The boundary is a mixed layer of marine and freshwater organisms aged about 14,000 cal.yr. BP (12000 ^{14}C yr.BP), and is in consistence with the global curve of the world sea level (Fairbanks, 1990).

According to the theory of Ryan et al. (1997), the Black Sea outflow to the Marmara Sea ceased after the IA meltwater pulse of the glacial melting in 14,500 cal.yr. BP and about 12,500 cal.yr. BP, the Black Sea was again an isolated lake without connection to the Mediterranean Sea due to the established "Younger Dryas" chronozone in Europe. Other authors

(Aksu et al., 1999; Hiscott, Aksu, 2002) maintain the opposite contention that once established after about 11,160-10,560 cal.yr. BP (10,000–9,500 ^{14}C yr.BP) the Black Sea outflow has not stopped until present days. According to the hypothesis on hand and the proofs that will be presented further on, the Black Sea freshwater outflow to the Aegean Sea had not ended after 12,500 cal.yr. BP but continued until 10,000 cal.yr. BP (9,000 ^{14}C yr. BP), and then the level of the Black Sea lake fell below the level of the Bosphorus sill, whose paleo-depth for this period was approximately –17,5 m.

A mini-glacial period "Younger Dryas" is dated to 12,500-11,800 cal.yr.BP ago in Europe. As a result of this event the water supply from the melting of glacial sheets in Europe to the Black Sea decreased. The Black Sea level started to lower. According to Ryan et al. (1997) during this period the Black Sea level fell below the Bosphorus sill level and about 9,000 cal.yr. BP ago the sea level was about –120 m.

According to Major et al. (2002) there are facts that support second pulse of some of the glacial sheets to the South from the Baltic Sea during the period of "Younger Dryas", which could have resulted in significant increase in the supply of melting waters to the Black Sea.

On the Barbados coral reefs an IB melt water pulse of melting glacial water is dated to 11,500 cal.yr. BP ago (Fairbanks, 1990). The climate warming is dated through spore-pollen analysis. The established boundary Pleistocene – Holocene for the western part of the Black Sea is approximately 11,160 cal.yr. BP (~10000 ^{14}C yr. BP, Bozilova, 1973). After the first warming 14,500 cal.yr. BP ago and retarding of the glacial cupolas to the North (Major et al., 2002), the inflow to the Black Sea of melted water during IB – second pulse of melting glacial water decreased. The reasons are the following: on their first retarding the glaciers left in therefore part moraines which from South encompass the hollows dug by their weight in the Earth's surface (as a result of isostatics). During the second pulse of melting glaciers finer deposits reached the moraines created by the IA melt water of glacial water. These deposits made the moraines denser and didn't allow the water to pass through them to the Black Sea. Besides, 11,500 years ago the glacial sheets moved to the North, where the melted waters were more conveniently to flow into the Baltic Sea, then to the North Sea, Atlantic Ocean and the Mediterranean Sea. Probably the quantity of

glacial water melted during the IB pulse of melting and entered the Black Sea Lake was less than that during the IA pulse of melt water but climatic changes compensated it by increasing the precipitations and river inflow.

Aksu et al. (1999) also think that waters from the IB melt water pulse supplied the Black Sea with fresh melted water, keeping its level high and that the Black Sea outflow through the Bosphorus sill did not stopped. A proof of the continuing outflow of the Black Sea to the Marmara Sea after 12,500 cal.yr. BP (fig. 2c) to about 9,500 cal.yr. BP (fig. 2d) is the delta of the south exit of the Bosphorus Strait with an established age from ^{14}C dating in the peripheral prodelta — 10,920-9,570 cal.yr. BP (10 000-9000 ^{14}C yr.BP), core 9, (Aksu et al., 2002). The outflow of the Black Sea started to produce climbing delta at the south end of the strait until 9570 cal.yr. BP (9000 ^{14}C yr. BP). At the beginning of the outflow the Black Sea probably was significantly higher than the Marmara Sea (fig. 2b). The only source that created delta sediments was the strait itself (Aksu et al., 2002). The delta is middle-shelf with upper to fore transition which climbs up to the Marmara Sea direction. The global sea level is consistent with the uprising of the delta for about 10,920-9,570 cal.yr. BP (10000-9000 ^{14}C yr. BP). Approximately 10,920 cal.yr. BP (10000 ^{14}C yr. BP) ago the delta was in subaerial situation in about 9,570 cal.yr. BP (9000 ^{14}C yr. BP) the delta was drowned by the rising sea level of the Marmara Sea. The drowning of the delta about 9,570 cal.yr. BP coincides with the increase in surface salinity of core 9, due to decrease in brackish water outflow through the strait and the rise in the Marmara Sea level the proof of which is the deposition of transgressive type sea mud (Aksu et al., 2002). However, alongside with the increase of the global sea level as a result of the above stated arguments, the height of the Bosphorus sill also increased. In these circumstances inflow of the Marmara Sea waters into the Bosphorus sill after the drowning of the delta was impossible. The depth of the Bosphorus sill about 10,000 BP ago is calculated to be approximately -17,5 m; the reduction of the Black Sea outflow and sediment accumulation in the Bosphorus Strait taken into consideration. Proofs of the early, gradual intrusion of the Mediterranean water in the Black Sea, as Aksu et al. (2002) argue, do not exist.

Another proof of continuous freshwater outflow of the Black Sea lake through the Bosphorus Strait from about 14,000 cal.yr. BP

to about 9,570 cal.yr. BP (9000 ^{14}C yr.BP) is the surface salinity of core 9 (Aksu et al., 2002). In core 9 along the south exit of the Bosphorus Strait, the surface salinity is low until about 9,570 cal.yr. BP (9000 ^{14}C yr.BP) and is consistent with the abundance of fresh and/or brackish water indicators — dinoflagellate cysts *Spiniferites cruciformis*. In about 9,570 cal.yr. BP ago the surface salinity of core 9 increased, that proves the absence or at least decrease in the Black Sea outflow through the Bosphorus sill. However, this is not a reason to assert, as Aksu et al. (2002) speculate, that it proves an intrusion of saline Marmara Sea waters into the Black Sea because it is not proved that core 9 with depth of -64 m was the Bosphorus sill at that time.

Fig. 2d shows formation of sapropel layer in the Marmara Sea about 12,000 cal.yr. BP ago (10600 ^{14}C yr. BP). For the first time Çağatay et al. (2000) reported on the presence of sapropel layer in the Marmara Sea (>1, 5% Corg.), which is partly synchronous with the S1 sapropel of the Eastern Mediterranean Sea but is older than it. On a regional basis the age of the lower sapropel layer can be limited between about 12,000 — 6,900 cal.yr. BP (~10600 and ~6400 ^{14}C yr. BP). The reason for its formation is the intrusion of more saline Mediterranean waters that caused dense stratification of the water column.

The stratification rate of the water column is estimated by the BFOI (benthos foraminifera oxygen index) of Kaiho (1994). The low values indicate anaerobic conditions on the bottom below a stratified water column (Kaminski et al., 2002). Data from the central Marmara Sea and the Aegean Sea, cores 12, 20 show that the values of the lowest BFOI and respectively of the strongest water stratification appeared during the sapropel accumulation from 10680 to 7000 cal.yr. BP (10000 to 6500 ^{14}C yr. BP). The values of BFOI in core 12 are lower than the values of BFOI in core 20 10,800 cal.yr. BP ago. In core 12 BFOI shows rapid increase in the stratification of water column after 13,000 cal.yr. BP (11500 ^{14}C yr. BP). About 9570 cal.yr. BP (9000 ^{14}C yr. BP) in core 12 sudden interruption of the established stratification occurred which probably was a result of the ceased Black Sea outflow. In core 11 once established, the stratification was not interrupted, possibly as a result of freshwater supply from the river waters from the South shelf of the Marmara Sea. In core 20, the BFOI values which indicate stratification established most probably by the Black Sea outflow 14,000

cal.yr. BP ago had not changed until 10 680 cal.yr. BP (10000 ^{14}C yr. BP) and they decreased until 9570 cal.yr. BP (9000 ^{14}C yr. BP), which was synchronous with the paleo-delta in the south part of the Bosphorus Strait. From 9570 cal.yr. BP (9000 ^{14}C yr. BP) to 6410 cal.yr. BP (6000 ^{14}C yr. BP) the stratification in core 20 is very strong but probably once established, it is supported by climatic factors. Besides, the low BFOI — an indicator of an oxygen absence on the bottom — is supported by the stagnation too. BFOI is low in cores 20, 12 and allows formation of sapropel in the Aegean Sea and the Marmara Sea until 7000 cal.yr. BP (6500 ^{14}C yr. BP), (Aksu et al., 2002).

The proofs stated above lead to a conclusion about the continuous outflow of the Black Sea to the Marmara Sea through the Bosphorus Strait until about 9,500 cal.yr. BP and the Black Sea impact on the beginning of S1 sapropel formation in the Eastern Mediterranean Sea 10,150 cal.yr. BP ago. Çağatay et al. (2000) also cites the Black Sea outflow into the Mediterranean Sea as an important factor for the S1 sapropel formation in the Mediterranean Sea and an establishment of brackish sea conditions in the Aegean shelf near the mouth of the Dardanelles about 10,150 cal.yr. BP (9600 ^{14}C yr.) ago.

The question of Mediterranean Sea sapropel origin is still disputable. Different sources of its appearance are cited. According to Stanley, Blanpied (1980) it is due to changes in precipitations to evaporation, marked increase in the discharge from the river areas of the Eastern Mediterranean Sea and partly the river Nile. A massive inflow of freshwater from the Nile is also frequently mentioned as coinciding with the time of S1 sapropel accumulation in the Eastern Mediterranean Sea. This means large-scale climatic changes that caused marked regional dense stratification of water masses, progressive exhaustion of dissolved oxygen and formation of hydrogen sulfide. In other authors' opinions (Aksu et al., 1995; Aksu et al., 2002) the existence of S1 sapropel is regarded as proof of large quantity freshwater outflow from the Black Sea to the Eastern Mediterranean Sea for the period 10,680-6,900 cal.yr. BP (10000-6400 ^{14}C yr. BP). 10150-6900 cal.yr. BP (9600-6400 ^{14}C yr. BP) is indicated as an age of the Mediterranean sapropel S1, (Çağatay et al. 2000; Fontugne et al., 1989).

However, according to the hypothesis on hand the outflow of the Black Sea waters to the Mediterranean Sea stopped until after 9,500 cal.yr. BP, consequently the beginning of the

Mediterranean sapropel S1 formation in 10,150 cal.yr. BP can be explained by the established preconditions of the Black Sea freshwater outflow until that period (deposition of protosapropel and formation of stratification of the water masses of East Mediterranean Sea), (2b, c, d). The prolongation of S1 sapropel formation until about 6,900 cal.yr. BP was not due to the continuous Black Sea outflow, at least until another scientific explanation about the Black Sea "old shorelines" at depth of -90 — -120 m will be found. There are other hypotheses about the Mediterranean S1 sapropel formation. According to Bonloubassi et al. (1999), Rossgnol-Strick, Paterne (1999) the orbital variations and precessional cycles are responsible for the sediment cycles (sapropel and CaCO_3 cycles) in the Mediterranean Sea deepwater sediments. Most probably, the S1 sapropel formation in the Eastern Mediterranean Sea is a complex phenomenon that is influenced not only by one factor — the outflow of the Black Sea freshwaters until 6,900 cal.yr. BP.

In about 10,000 cal.yr. BP (9,000 ^{14}C yr. BP), the Black Sea level fell below the Bosphorus paleo-sill whose depth was about -17,5 m and its outflow to the Marmara Sea was interrupted. (fig. 2d, e). A second mini-glacial period in Europe dated to about 8,200 cal.yr. BP lead to additional decrease in the Black Sea level, (Ryan et al., 1997). In about 10,000 cal.yr. BP in the Marmara Sea prevailed a significant sea regime, the deeper areas remained oxygen deficient. As a result of climatic changes and decreased inflow of river waters, the conditions in the Black Sea are also partially anaerobic (Димитров, 1990).

The Black Sea was an isolated freshwater lake during the period between 9,500 and 7,500 cal.yr. BP (fig. 2e). Proofs of the interrupted Black Sea outflow to the Marmara Sea in about 10,000 cal.yr. BP are the dated old shorelines of the Black Sea from -90 to -120 m below the contemporary sea level with an age of 8200 cal.yr. BP (8080 ^{14}C BP) (Димитров et al., 1979). During that period the area located bottom Bosphorus sill also decreased. The reasons were the influence of external earth forces and denudation a make of peneplain. About 2,000 years the Bosphorus Strait, and respectively the Bosphorus sill were drained and as a result of the weathering as a negative form of the relief, they were filled with products of the weathering. Thus, the paleo-depth of the Bosphorus sill decreased and about 7,500 cal.yr. BP ago it was approximately -14,5 m that is

consistent with the global sea level (Fairbanks, 1990). Demirbag et al. (1999) suggest that the Bosphorus sill was risen to depth of -10 m before about 7500 cal.yr. BP, that is also consistent with the global sea level and is a proof of the impossibility for earlier intrusion of saline oceanic water into the Black Sea. In their article Görür et al. (2001) also conclude that data from their researches are comparable with that of Ryan et al. (1997) and that the Black Sea used to be a freshwater lake before the Mediterranean Sea submergence in 7,500 cal.yr. BP; the Bosphorus sill depth at that time was -15 m, according to them.

About 7,500 cal.yr. BP ago, as a result of continuing increase in the global sea level, saline ocean water catastrophically entered the Black Sea (Димитров et al., 1998; Ryan et al., 1997, 1998; Demirbag et al., 1999; Görür et al., 2001). The event caused a flood along the drained continental shelf of the Black Sea, formation of the Black Sea sapropel (fig. 2f) and hydrogen sulfide contamination. According to Ryan et al. (1997); Çağatay et al. (2000) the disastrous deluge on the freshwater Black Sea lake about 7,500 cal.yr. BP ago caused to powerful erosion of the accumulated unconsolidated sediments and as a result increased depth of Bosphorus sill (fig. 2f). According to Demirbag et al. (1999) the sill that is located today at depths of -27 m is a result of local tectonics. Probably during that period the world ocean level increased and the tectonic processes acted synchronously, thus bringing one and the same result — catastrophic intrusion of more saline ocean waters into the Black Sea through the Bosphorus Strait about 7,500 cal.yr. BP ago.

Conclusions

The discussed above possible paleo-exchange of water masses between the Black Sea, the Marmara Sea and the Aegean Sea lead to conclusions about several new aspects that are not stated in the hypotheses mentioned above.

The new moment that must be considered is that the paleo-depth of the Bosphorus sill, which is a key aspect in understanding the paleo-exchange of water masses between the Marmara Sea and the Black Sea, cannot be accepted as a constant in the course of time. Regarding the paleo-depth of the Bosphorus sill as a constant, independently of its value is a wrong approach to the interpreting and reconstructing the events after 20,000 cal.yr. BP. The huge outflow of the Black Sea waters to

the Marmara Sea, consequently the accumulation, erosion and transportation of sediment material through the Bosphorus as a result from climatic changes has been proved. It is not correct to neglect the processes of destruction, transportation and accumulation of exogenous earth forces.

Once started the freshwater Black Sea outflow to the Marmara Sea in 14,000 cal.yr. BP did not stop until about 12,500 cal.yr. BP (fig. 2b, c) but continued to about 9,500 cal.yr. BP (fig. 2d). That contradicts the theory of Ryan et al. (1997).

The reason for the creation of the Marmara Sea sapropel about 12,000 cal.yr. BP (fig. 2d) was the intrusion of more saline Mediterranean Sea waters into the Marmara Sea, not the intrusion of Black Sea fresh waters, which inflow into the Marmara Sea started after the IA melt water pulse, determined by Fairbanks (1989). This contradicts the hypothesis of Aksu et al. (2000) and Hiscott, Aksu (2002).

The freshwater outflow of the Black Sea through the Bosphorus Strait ended about 9,500 cal.yr. BP (fig. 2e) but was not continuous until 6,000 cal.yr. BP. This contradicts the hypothesis of Aksu et al. (1999).

The catastrophic flood on the Black Sea Lake by the saline oceanic water 7,500 cal.yr. BP ago is the central idea of the hypothesis on hand. The event leads to:

- simultaneous submergence of large regions of the continental shelf, drained as a result of the events after 9,500 cal.yr. BP;
- intrusion of marine organisms immigrants from the Mediterranean Sea;
- simultaneous beginning of organic enrichment of the sediments at any depths below about -200m and sapropel formation;
- anaerobic conditions with dating equal to those of the beginning of sapropel formation;
- sediments on the shelf with dated sea species of mollusks; their age is slightly less than the dating of sapropels and hydrogen sulfide contamination.

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