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A revised calendar age for the last reconnection of the Black Sea to the global ocean

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Abstract :

During the last decade, a debate arose regarding the timing and pattern of the last reconnection of the Black Sea "Lake" with the global ocean. On a geochemical basis, the radiocarbon age of Black Sea "Lake" surface water, during the time of reconnection, was determined to be ∼8400 ^{14}C a. BP. Despite the potential bias induced by the hard water effect in lakes, the reconnection age was calibrated without any reservoir age correction, which led to an estimate of ∼9400 cal a. BP. Since knowledge for the actual calendar age has important hydrologic implications that would provide new insights regarding the mechanism of reconnection, determining the actual calendar age for the last reconnection remains important.

Based upon modeling experiments and micropaleontological reconstructions, the Black Sea "Lake" reconnection occurred in two steps, as follows: 1) Initial Marine Inflow (IMI) followed by 2) a period of increasing basin salinity that led to the Disappearance of Lacustrine Species (DLS). In order to better define the actual calendar age for the last reconnection, a review of the sedimentary expressions of the IMI and DLS boundaries was performed in order to correlate them throughout the Black Sea sedimentary environments. This correlation reconciles the apparent inconsistency in the published radiocarbon dataset, and provides the atmospheric radiocarbon age of the last reconnection, which represents the reference for reservoir age calculations and which can be directly calibrated. We determine reservoir ages for the water column, as well as the reconnection calendar age to be 9000 cal a. BP.

At the reconnection with the global ocean, Black Sea "Lake" reservoir ages were non-negligible and water-depth-dependent, consistent with a weak water column stratification during the Early Holocene. The calibrated age of Initial Marine Inflow (9000 cal a. BP) implies that the former Bosphorus sill was shallower by ∼10 m than is commonly assumed in the literature. Compared to the sedimentary context of the Sakarya coastal plain, this result suggests that the level of the isolated Black Sea was below the former Bosphorus sill depth at the time of the last reconnection. Furthermore, a lag of ∼ 900 yr between Initial Marine Inflow and the Disappearance of Lacustrine Species indicates that approximately ten centuries were needed to establish the currently observed two-way flow exchange with the global ocean.

Highlights

► The age of the last reconnection of the Black Sea is under debate. ► The lake to sea transitional layer was correlated across the entire basin. ► The reliable radiocarbon ages dating this layer were compiled. ► This provides the atmospheric radiocarbon age of the last reconnection. ► The last reconnection of the Black Sea occurred at 9000 cal a. BP.

Keywords : Black sea; Reconnection; Reservoir age; Bosphorus sill

1. Introduction

During the last glacial period, and the associated oceanic low-stand, the Black Sea evolved as a giant freshwater lake (e.g. Stoffers et al., 1978, Schrader, 1979). Water level within the Black Sea "Lake", controlled by regional climate, varied independently from global sea level (e.g. Ross et al., 1970). Early interest in Black Sea geology and climatology was reactivated by a hypothesis of catastrophic flooding by Mediterranean waters and an associated abrupt water level rise in the Black Sea during the Early Holocene (Ryan et al., 1997). In addition to challenging the previously prevalent consensus of a smooth reconnection (e.g. Ross et al., 1970; Fedorov, 1971), Ryan et al. (1997), and soon after Ryan and Pitman (1998), argued that instantaneous flooding of the vast north-western continental shelf massively displaced Neolithic farmers and imprinted collective memory through culturally-widespread deluge myths. Since the 90s, an ongoing debate has challenged the validity of the flood hypothesis, as well as its possible cultural consequences (e.g. Görür et al., 2001; Aksu et al., 2002; Ryan et al., 2003; Gökaşan et al., 2005; Hiscott et al., 2007; Yanko-Hombach et al., 2007; Yanko-Hombach, 2007).

The age of the last Black Sea "Lake" to global ocean reconnection is hotly debated as varying between 7,200 ^{14}C a. BP (Ryan et al., 1997) and 10,000 ^{14}C a. BP (Aksu et al., 2002). On the basis of a rough comparison of Black Sea geochemical records with the Greenland ice core records, a calendar age of ~8,900 a. BP was recently estimated (Ryan, 2007). New analytical techniques such as the strontium isotope ratio, a powerful water mass tracer, have brought new arguments to the debate and allowed researchers to date the last reconnection to ~8,400 ^{14}C a. BP (Major et al., 2006). However, in order to provide the calendar age of the last reconnection a major issue still remains - the reservoir correction and calibration of the raw ^{14}C date. Bahr et al. (2005) postulated that no reservoir correction was required in order to calibrate the radiocarbon age, leading to a calibrated age for the last reconnection of ~9,400 cal. a. BP (e.g. Bahr et al., 2005, 2006, 2008; Major et al., 2006; Kwiecien et al., 2008; Giosan et al., 2009). However, since the reservoir ages of lakes are heavily influenced by the dilution of atmospheric $\Sigma^{14}CO_2$ with "dead" ΣCO_2 originating from carbonate dissolution within watersheds (Broecker and Olson, 1961; Mangerud, 1972; Andrée et al., 1986; Stein et al., 2004; Kwiecien et al., 2008; Zhou et al., 2009; Ascough et al., 2010) obtaining a reliable date without a reservoir correction is unlikely.

Determining the actual atmospheric radiocarbon age for the last reconnection, and consequently corresponding calendar age, has important implications. An atmospheric radiocarbon age determination would allow us to decipher the reservoir age for the reconnected Black Sea "Lake", and therefore provide new information relating to the basin's hydrologic system. An actual calendar age would also provide new insights into the ongoing reconnection debate. Indeed, during post-glacial global sea-level rise, age of the last reconnection depends on the depth of the former Bosphorus sill, which still remains uncertain (e.g. Major et al., 2002; Lambeck et al., 2007; Giosan et al., 2009). The former Bosphorus sill depth has, however, important implications for the glacial-deglacial Black Sea "Lake" hydrological system, since it controlled maximum lake level and water exchanges. Therefore, constraining the calendar age of the reconnection implies constraining the depth of the former Bosphorus sill, consequently providing useful information in order to better understand the past hydrology of the vanished Black Sea "Lake".

Independent of a catastrophic or a smooth reconnection, modelling experiments (Boudreau and Leblond, 1989; Lane-Serff et al., 1997; Myers et al., 2003; Soulet et al., 2010) and micropaleontological reconstructions (Mudie et al., 2002, 2004; Giunta et al., 2007; Coolen et al., 2009; Marret et al., 2009; Oaie et al., in press), agree on a gradual basin salinization, as well as on the gradual replacement of fresh/brackish biota by marine biota after an initial marine inflow (Mudie et al., 2002; Ryan et al., 2003; Hiscott et al., 2007; Marret et al., 2009).

Therefore, we compiled published stratigraphical sequences and radiocarbon ages for the Initial Marine Inflow (IMI) and the Disappearance of Lacustrine Species (DLS) boundaries across the entire basin of the Black Sea (Figure 1). From our review of reliable published radiocarbon ages, we propose an atmospheric radiocarbon age of 8,090 ± 120 ^{14}C a. BP for the last reconnection. Knowledge of this atmospheric radiocarbon reference is crucial since it allows the calculation of reservoir ages for two water bodies of the Black Sea "Lake", namely the upper water column (0 to ~400 mbsl; meters below sea level) and the intermediate water column (~400 to 1400 mbsl). In this manuscript, by calibrating the radiocarbon ages of the reconnection event (IMI) and the Disappearance of Lacustrine Species (DLS), we draw conclusions on the depth of the former Bosphorus sill and on the duration needed for the establishment of the currently observed two-way flow exchange with the global ocean.

2. The history of the last reconnection of the Black Sea "Lake"

Both modelling and micropaleontological studies (references above) suggest that after Initial Marine Inflow (IMI), the Black Sea basin salinization occurred gradually, leading to the progressive Disappearance of Lacustrine Species (DLS) and the replacement of fresh/brackish biota by marine biota. Sedimentary expressions of the IMI and DLS boundaries are expected to be different depending upon the Black Sea "Lake" sedimentary environment - the basin, the slope, the continental shelf, and the coastal area (Figure 1).

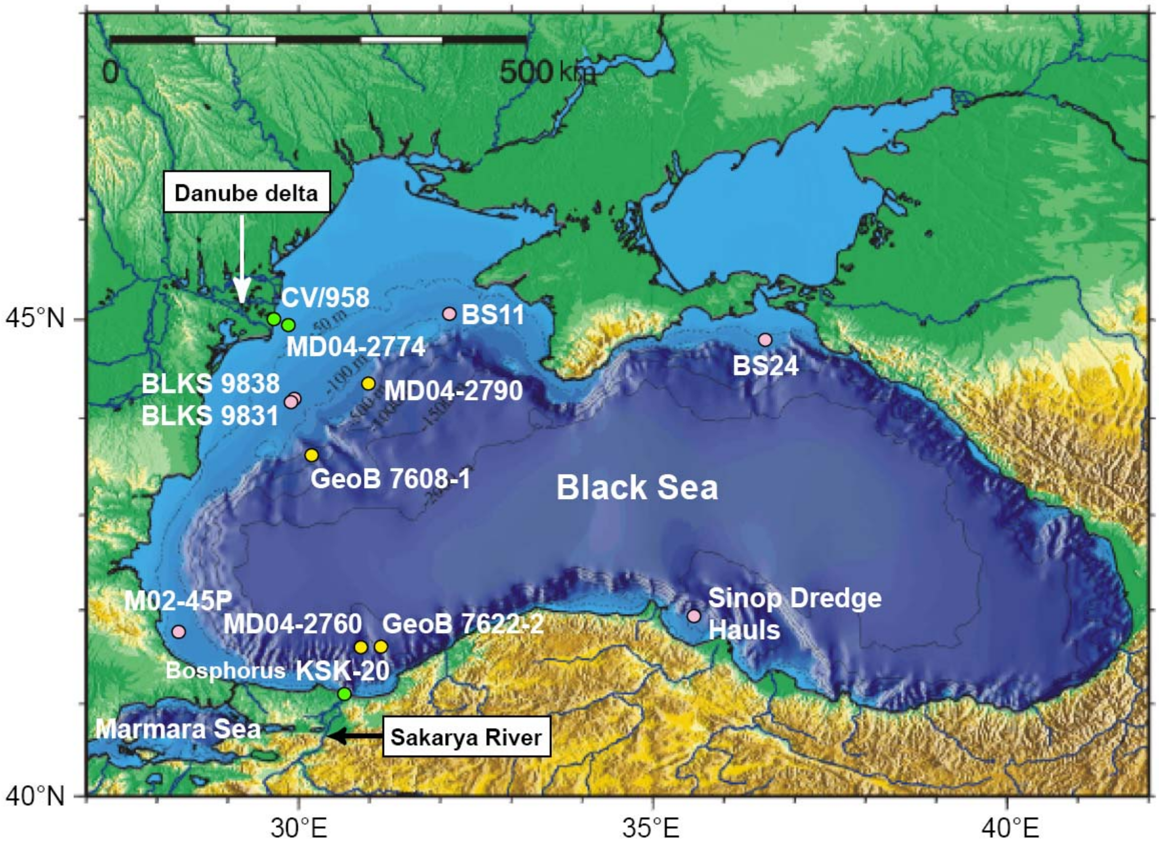

Figure 1: The current Black Sea basin and core locations. The colour of dots indicates the Black Sea geomorphologic environment in which cores were recovered: green for coastal areas; pink for shelf; yellow for slope and basin. Core references are provided in Table 1, except for cores CV/958 and MD04-2774 for which references are provided in section 2.1.3.

Published datasets are spread across the entire basin. Until now, no study has gathered and correlated the various sedimentary expressions of the last reconnection across the entire basin. In this section, we provide a synthesis of the different sedimentary expressions and the radiocarbon ages for the IMI and DLS boundaries across the entire basin (Figure 2).

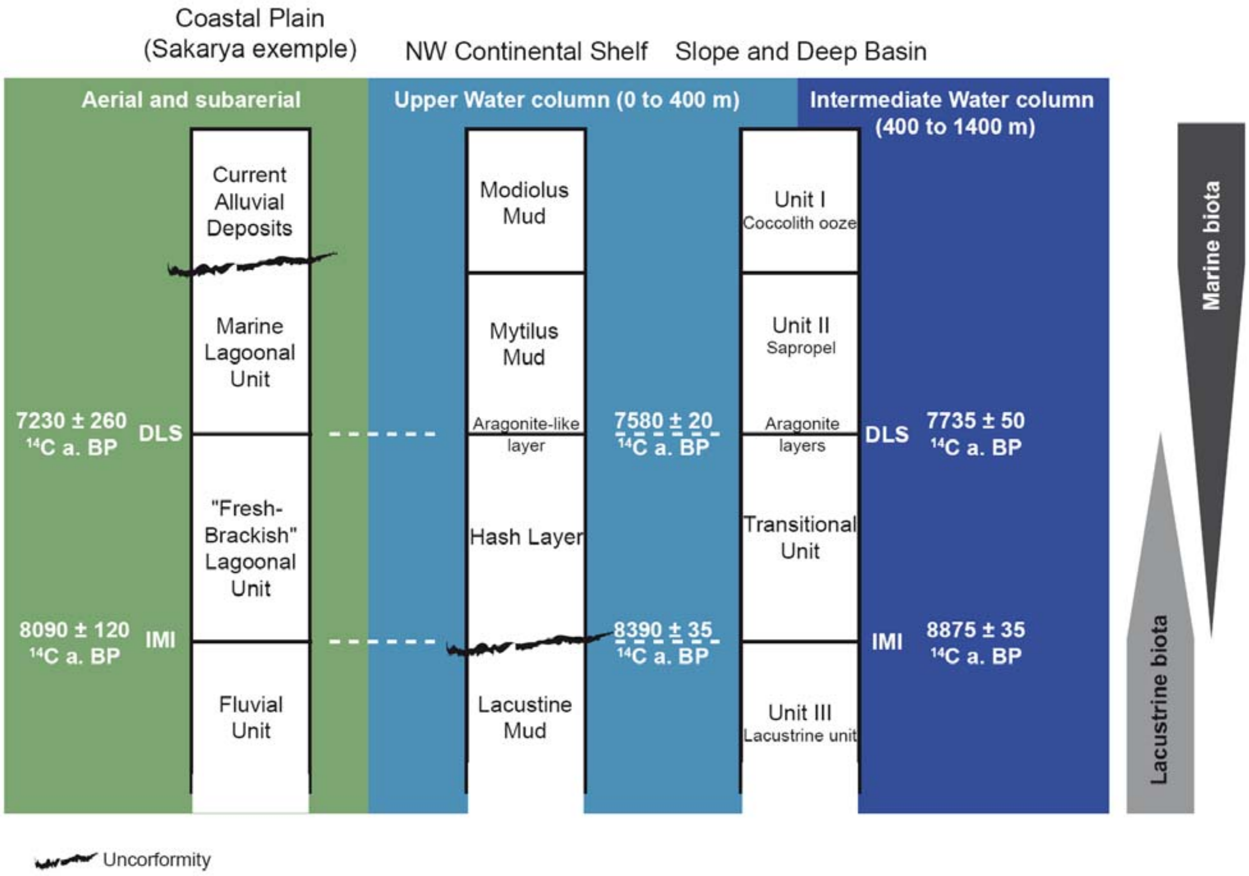

Figure 2: A synthesis of the sedimentary expressions and radiocarbon ages of the Initial Marine Inflow (IMI) and the Disappearance of Lacustrine Species (DLS) boundaries following Black Sea geomorphologic environments and water depths. Note that stratigraphic sequence illustrating the coastal plain is related to the Sakarya coastal area and was modified after Görür et al. (2001) (borehole KSK 20 in Figure 1).

2.1. Sedimentary expressions of the last lacustrine to marine transition across the Black Sea basin

2.1.1. Basin and slope

Late Quaternary sediments of the Black Sea are commonly subdivided into three units (e.g. Ross and Degens, 1974). The uppermost units, Units I and II, represent the last marine stage of the Black Sea. Unit I is characterized by thin coccolith-rich layers. Unit II conformably underlying Unit I is a sapropel characterized by a dark olive green to dark brown thinly laminated mud. Below Unit II is limnic Unit III which represents the last lacustrine stage of the Black Sea (e.g. Ross and Degens, 1974).

Initial Marine Inflow (IMI) is spectacularly recorded within slope and basin sedimentary records by highly-sensitive geochemical proxies (the $^{87}Sr/^{86}Sr$, the Mg/Ca, and the Sr/Ca of carbonate shells) with an instantaneous change from lacustrine to marine signatures (Major et al., 2006; Bahr et al., 2008) (Figure 3). These changes occur concomitantly with a sharp decrease in the sediment carbonate content (Major et al., 2002; Bahr et al., 2005, 2006, 2008; Kwiecien et al., 2008), as well as with a sudden increase in sediment grain size (Major et al., 2002; Bahr et al., 2005) and XRF-Ti/Ca (Bahr et al., 2005) (Figure 3).

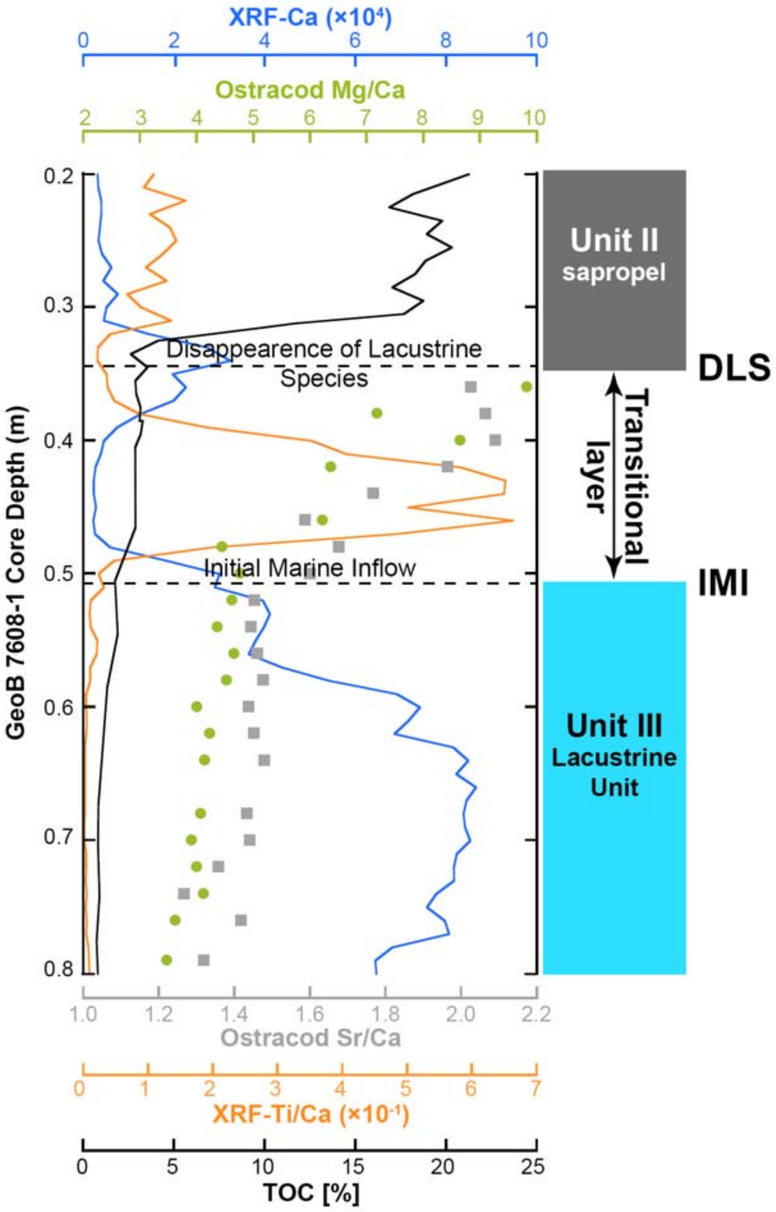

Figure 3: An example of the lacustrine to marine transition from the basin-retrieved sediment core GeoB 7608-1 (Bahr et al., 2005, 2006, 2008). The Initial Marine Inflow (IMI boundary) is characterized by a steep decrease in XRF-Ca intensity concomitant with a peak in XRF-Ti/Ca (also indicated by a peak in the sediment grain size, not shown here), as well as a drastic increase in ostracod Mg/Ca and Sr/Ca. Total Organic Carbon also gently increases. The Disappearance of the Lacustrine Species (the DLS boundary) is characterized by the disappearance of brackish ostracods (i.e. no data for Mg/Ca and Sr/Ca), by an increase in XRF-Ca possibly reflecting the occurrence of the Aragonite Layers, and by a significant overall increase in Total Organic Carbon reflecting the onset of the sapropel deposition.

The onset of Unit II (sapropel) is characterized by the occurrence of thinly laminated layers rich in aragonite crystals (e.g. Giunta et al., 2007; Kwiecien et al., 2008; Ross and Degens, 1974) and by a sharp increase in Total Organic Carbon (Bahr et al., 2008) (Figure 3). In several cores obtained from the NW-slope and from the deep basin, marine coccolithophores appear concomitantly with aragonite layers (Giunta et al., 2007; Coolen et al., 2009), while fresh to brackish ostracods or bivalves persist in the sediments until the appearance of aragonite layers (Major et al., 2002; Bahr et al., 2005, 2006, 2008; Kwiecien et al., 2008). Therefore, aragonite layers represent the Disappearance of Lacustrine Species (DLS). Hence, between the IMI and the DLS a sedimentary layer was deposited (Figures 2 and 3) which indicates the transition from a fresh/brackish to a marine environment (e.g. Ryan et al., 2003; Giunta et al., 2007).

2.1.2. Continental shelf

In the literature, three units are similarly described for the recent sediments of the continental shelf. However, the terminology is not similar to that used for basin and slope sedimentary sequences, and the stratigraphic positions of the IMI and the DLS boundaries are not fully described.

Scherbakov and Baback (1979) classified the sedimentary sequence of the NW continental shelf in three units. The first two units named Modiolus mud and Mytilus mud are rich in marine bivalves (*Modiolus phaseolinus* and *Mytilus galloprovincialis*, respectively). The last unit, conformably underlying these two units is named Dreissena mud, rich in freshwater to brackish bivalves (*Dreissena rostriformis)*.

The Dreissena mud unit unconformably overlies stiff barren muds on the mid-shelf (> 92 m to at least 28 m in water depth) or Dreissena-bearing muds in the outer shelf (Ryan et al., 1997, 2003; Major et al., 2006; Giunta et al., 2007; Lericolais et al., 2007, 2009, 2010; Oaie et al., in press), and bears more diverse salinity tolerant assemblages of molluscs (Ryan et al., 2003) and dinocysts (Mudie et al., 2004) than older sedimentary units. The unit, termed the “hash layer” in the literature, represents the last lacustrine to marine transition (Ryan et al., 1997, 2003; Major et al., 2006; Lericolais et al., 2007, 2009). Interestingly, the “hash layer” is topped by a peculiar layer rich in aragonite-like crystals (Giunta et al., 2007; Oaie et al., in press) which could be equivalent to the aragonite layers typical of the onset of Unit II in slope and basin sedimentary environments (DLS boundary). Therefore, the base and top of the “hash layer” likely represent the IMI and the DSL boundaries, respectively (Figure 3).

2.1.3. Coastal settings

Sea level reconstruction in the Danube delta is now rather well constrained at least since the middle Holocene (Giosan et al., 2006). In an attempt to decipher the evolution of older Early Holocene deltaic-estuarine phases, the Danube delta was recently cored onshore (core CV/958; Giosan et al., 2009) and offshore (core MD04-2774; Lericolais et al., 2010) (Figure 1). In both cores, fluvial deposits of Early Holocene age (Lericolais et al., 2010) were found to be overlain by deltaic front facies deposited in lacustrine settings (Giosan et al., 2009). The deltaic front itself is overlain by marine sediments (Giosan et al., 2009; Lericolais et al., 2010). Giosan et al. (2009) showed that marine sediments unconformably overlie the earlier lacustrine sequence, whereas the scarcity of radiocarbon ages provided by Lericolais et al. (2010) prevented us from determining the IMI and the DLS boundaries that characterized the last lacustrine to marine transition in the Black Sea.

In the SW Black Sea coast, Görür et al. (2001) described a transect of boreholes drilled in the coastal plain near the mouth of the Sakarya River (Figure 1). The base of the sedimentary sequence is characterized by fluvial sediments conformably overlain by lacustrine clay to sand sediments. The lacustrine sediments contain fresh to brackish fauna as well as fluvial gastropods and peats, suggesting a lagoonal marshy environment. The lacustrine facies grades upward into lagoonal and marshy deposits, characterized by alternating layers of clay, silt, and sand mixed with peat layers and Mediterranean fauna. The fresh/brackish lagoonal deposits conformably overlying the fluvial deposits of the Sakarya River (Figure 2) were initially interpreted as representing a high-stand of the Black Sea "Lake" (Görür et al., 2001). In other words, authors suggested that Black Sea "Lake" was flowing into the Marmara Sea at the time of its reconnection to Mediterranean Sea. Contrary to modelling experiments (Boudreau and Leblond, 1989; Lane-Serff et al., 1997; Myers et al., 2003; Soulet et al., 2010) and micropaleontological reconstructions (Mudie et al., 2002, 2004; Giunta et al., 2007; Coolen et al., 2009; Marret et al., 2009; Oaie et al., in press) agreeing on a gradual basin salinization, Görür et al. (2001)'s interpretation does not imply such a transitional hydrologic state between the isolated and reconnected Black Sea as recorded, however, in each sedimentary environment of the Black Sea (Transitional Unit in the slopes and the basin, Figure 2, 3; "Hash Layer" in the shelf, Figure 2). Since such a transitional hydrologic state should have been recorded in Black Sea coastal areas as well, sediments deposited under fresh/brackish lagoonal conditions in the former Sakarya coastal plain are likely to represent this transitional state. Therefore, transitions from the fluvial plain to a fresh/brackish lagoon and from the fresh/brackish lagoon to a marine lagoon are likely to represent the IMI and the DLS boundaries, respectively (Figure 2).

2.2. Radiocarbon ages of the last lacustrine to marine transition

Following the mapping of the Initial Marine Inflow (IMI) and the Disappearance of Lacustrine Species (DLS) from the Black Sea deep basin to the coast (Figure 2), we compiled the reliable radiocarbon ages for these boundaries published in recent studies (Ballard et al., 2000; Görür et al., 2001; Major et al., 2002; Bahr et al., 2005; Lamy et al., 2006; Hiscott et al., 2007; Kwiecien et al., 2008; Marret et al., 2009; this study) (Figure 2, Table 1).

Based upon inter-comparisons of geochemical records on cores retrieved at different water depths, Bahr et al. (2005, 2006) showed that the water column was stratified from ~15 cal. a. BP until the last reconnection (IMI boundary). Following these results and in agreement with Kwiecien et al. (2008), the water column as well as the corresponding compiled radiocarbon ages (Table 1) were divided into two main groups (intermediate water column, ~400 to ~1400 mbsl; and upper water column, 0 to ~400 mbsl). A third group contains atmospheric radiocarbon ages (Table 1). The IMI and DLS boundaries were dated to 8875 ± 35 (n=2) and 7735 ± 50 (n=1) ^{14}C a. BP for the intermediate water column, and 8390 ± 35 (n=5) and 7580 ± 20 (n=6) ^{14}C a. BP for the upper water column, respectively (reported ages are weighted means by variance; Table 1). A piece of wood dated to 8090 ± 120 ^{14}C a. BP displays the IMI atmospheric radiocarbon age, while a DLS atmospheric age of 7230 ± 260 ^{14}C a. BP is provided by a peat layer (Görür et al., 2001) (Table 1). The last two radiocarbon ages are fundamental since they represent atmospheric references for reservoir age calculations and, once calibrated, the calendar ages of the two major transitions that characterized the last reconnection Black Sea.

Table 1: The compilation of radiocarbon ages dating the Initial Marine Inflow (IMI) and the Disappearance of Lacustrine Species (DLS), classified according to the dated radiocarbon reservoir. Reservoir ages are calculated by subtracting the DLS/IMI atmospheric radiocarbon age from the DLS/IMI radiocarbon age of the water body.

Reference	**Core**	**Sample code**[a]	**Dated Material**	**Dated Boundary**	**Selection Criterion**	**Radiocarbon Age (^{14}C a. BP)**[b]	**Sample Reservoir Age (^{14}C yr)**[c]
ATMOSPHERE							
Görür et al. (2001)	KSK-20	–	Peat Layer	DLS	Stratigraphic review	7230 ± 260	–
Görür et al. (2001)	KSK-20	–	Wood	IMI	Stratigraphy review	8090 ± 120	–
SURFACE WATER - UPPER WATER COLUMN (0-400 m water depth)							
Ballard et al. (2000)	Dredge Hauls	OS-21659	*Turricaspia caspia lincta*	DLS	Youngest limnic biota	7460 ± 55	230 ± 266
Ballard et al. (2000)	Dredge Hauls	OS-21660	*Turricaspia caspia lincta*	DLS	Youngest limnic biota	7590 ± 55	360 ± 266
Ballard et al. (2000)	Dredge Hauls	OS-21661	*Turricaspia caspia lincta*	DLS	Youngest limnic biota	7480 ± 55	250 ± 266
Lamy et al. (2006)	GeoB 7622-2	KIA-25753	*Mytilus galloprovincialis* larval stage	DLS	Onset of sapropel	7625 ± 55	395 ± 266
Hiscott et al. (2007, 2010) Marret et al. (2009, 2010)	M02-45P	TO-11438	*Monodacna pontica*	DLS	Geochemistry and Palynology	7560 ± 60	330 ± 267
This study[d]	MD04-2790	SacA 13276	Ostracods	DLS	Onset of sapropel	7640± 30	410 ± 262
						DLS weighted mean	**DLS mean Reservoir Age**
						7580 ± 20	**350 ± 260**
Major et al. (2006)	BLKS9838	ETH-22159	*Dreissena sp.*	IMI	Oldest biota with marine ^{87}Sr/^{86}Sr	8275 ± 70	185 ± 139
Major et al. (2006)	BLKS9831	ETH-22158	*Dreissena sp.*	IMI	Oldest biota with marine ^{87}Sr/^{86}Sr	8360 ± 75	270 ± 142
Major et al. (2006)	BS11	ETH-23747	*Dreissena sp.*	IMI	Oldest biota with marine ^{87}Sr/^{86}Sr	8415 ± 70	325 ± 139
Major et al. (2006)	BS24	ETH-23753	*Dreissena polymorpha*	IMI	Oldest biota with marine ^{87}Sr/^{86}Sr	8550 ± 80	460 ± 144
Hiscott et al. (2007) Marret et al. (2009)	M02-45P	TO-11142	*Truncatella subcylindrica*	IMI	Geochemistry and Palynology	8380 ± 70	290 ± 139
						IMI weighted mean	**IMI mean Reservoir Age**
						8390 ± 35	**300 ± 125**

Table 1 (continued)

Reference	Core	Sample code[a]	Dated Material	Dated Boundary	Selection Criterion	Radiocarbon Age (^{14}C yr BP)[b]	Reservoir Age (^{14}C yr)[c]
INTERMEDIATE WATER COLUMN (400 to 1400 m water depth)							
Bahr et al. (2005)	GeoB 7608-1	KIA-21464	Ostracods	DLS	Onset of Sapropel	7735 ± 50	505 ± 265
						DLS weighted mean	**DLS mean Reservoir Age**
						7735 ± 50	**505 ± 265**
Kwiecien et al. (2008)	MD04-2760	KIA-26699	Gastropods	IMI	Steep decrease in XRF-Ca intensity	8820 ± 55	730 ± 132
Kwiecien et al. (2008)	MD04-2760	KIA-25679	Ostracods	IMI	Steep decrease in XRF-Ca intensity	8910 ± 45	820 ± 128
						IMI weighted mean	**IMI mean Reservoir Age**
						8875 ± 35	**785 ± 125**

[a] Görür et al. (2001) did not provide the sample code but indicated that the measurements were carried out by Geochron Laboratories

[b] All of the radiocarbon ages reported here were measured using the Accelerator Mass Spectrometry (AMS) method, except those of Görür et al. (2001) which are conventionnal datings corrected for $\delta^{13}C$

[c] Uncertainties are propagated using the partial derivative theory.

[d] Sample of monospecific *Candona sp.* picked just below the aragonite layer in core MD04-2790 (352 mbsl). Measurement was performed by Accelerator Mass Spectrometry at the "Laboratoire de Mesure du Carbone 14" in Saclay, France

3. Reservoir age at the last reconnection

The reservoir age of any water mass reflects the difference between its radiocarbon content and the contemporary atmospheric radiocarbon content, with the water mass always being depleted in radiocarbon (e.g. Arnold and Anderson, 1957; Craig, 1957; Suess and Revelle, 1957; Stuiver and Polach, 1977; Bard, 1988). The resulting effect is that the radiocarbon age of a water body is systematically older than the contemporary atmospheric radiocarbon age. Therefore, we calculated the reservoir age for each of the compiled radiocarbon ages by subtracting the atmospheric radiocarbon age of the boundary they date (Table 1).

At the time of the reconnection (IMI) and the disappearance of fresh to brackish biota (DLS), the upper water column showed similar reservoir ages (300 ± 125 and 350 ± 260 ^{14}C yr, respectively, Table 1), in rough agreement with a previous reservoir age estimations (Ryan, 2007). However, our results are in disagreement with previous studies that inferred a negligible reservoir age (Bahr et al., 2005; Kwiecien et al., 2008). The discrepancy could be due to the use of an unsuitable reference value in the latter studies.

At the reconnection (IMI boundary), reservoir age calculated for the intermediate water column is larger compared to reservoir age for upper water column (785 ± 125 against 300 ± 125 ^{14}C yr, respectively, Table 1), in agreement with recent reservoir age estimations (Kwiecien et al., 2008). Recent studies based upon geochemical data (Bahr et al., 2006, 2008) suggest water column stratification at least at the Initial Marine Inflow (IMI boundary). According to Bahr et al. (2006, 2008), the water stratification persisted since the onset of the Bølling-Allerød period, due to climate-driven evaporation during the last 6 millennia preceding the last reconnection (15 to 9 cal. ka. BP). Geochemical records (δ^{18}O and Mg/Ca and Sr/Ca obtained on ostracods) suggest then a sudden homogenization of the water column between IMI and DLS boundaries, likely driven by the saline intrusion of marine waters into the Black Sea (Bahr et al., 2006, 2008). Reservoir ages of upper (350 ± 260 ^{14}C yr) and intermediate (505 ± 265 ^{14}C yr) water columns are statistically undistinguishable at the DLS boundary and therefore support a homogenous water column during the Black Sea transitional state between fresh/brackish to marine.

4. The calendar age of the last reconnection - implications for the Black Sea hydrologic system

Once reliable atmospheric radiocarbon ages for the IMI and the DLS boundaries are known, calendar ages can be determined by utilizing the most recent calibration curve (Reimer et al., 2009), which lead to ages of 8995 ± 145 and 8080 ± 250 cal. a. BP, respectively. Apparently, the salinity threshold needed to eradicate fresh/brackish biota was reached slowly (~900 yr), reflecting a slow Black Sea salinization in accordance with the conclusions of recent studies (e.g. Ryan et al., 2003; Hiscott et al., 2007; Marret et al., 2009; Soulet et al., 2010).

Overall, the calendar age of the reconnection (IMI boundary) is crucial for deciphering the former Bosphorus sill depth and subsequent implications in the ongoing reconnection debate, and for evaluating the involvement of the catastrophic drainage of the ice-dammed lake Agassiz-Ojibway in the Black Sea “Lake” reconnection, as recently postulated (Turney and Brown, 2007).

4.1. Catastrophic drainage of lake Agassiz-Ojibway and Black Sea “Lake” reconnection

Recently, the last Black Sea “Lake” reconnection was suggested to have occurred between 8,350 and 8,230 cal. a. BP (Turney and Brown, 2007) leading to the hypothesis that the catastrophic drainage of the former ice-dammed lake Agassiz-Ojibway ~8,470 a. ago (Barber et al., 1999) and associated 1.4 m sea level rise, triggered this last reconnection. Our results suggest that the last reconnection, dated to 8,995 ± 145 cal. a. BP, preceded by ~500 yr the catastrophic drainage of the ice-dammed lake Agassiz-Ojibway. The discrepancy comes from the fact that Turney and Brown (2007) constrained the maximum age of the last reconnection by using the youngest fresh/brackish mollusc reported in the literature (7,460 ± 55 ^{14}C a. BP; Ballard et al., 2000) whereas the first dated fresh/brackish mollusc displaying a ^{87}Sr/^{86}Sr ratio typical for marine water signature was ~1000 ^{14}C yr older (8,550 ± 80 ^{14}C a. BP; Major et al., 2006). This invalidates a trigger of the Black Sea “Lake” reconnection by the catastrophic drainage of ice-dammed lake Agassiz-Ojibway.

4.2. The Marmara Sea gateway two-way flow establishment and the former Bosphorus sill depth

In basin and slope sedimentary environments, the DLS boundary corresponds to both the Disappearance of Lacustrine Species (e.g. the disappearance of *Candona sp.* ostracods, see Figure 3) and to the onset of sapropel deposition (Figure 3). The DLS boundary occurs 900 yr latter, after Initial Marine Inflow (IMI boundary), indicating that, whatever the mechanism of the reconnection (smooth or abrupt), the establishment of the two-way flow that currently characterizes the Marmara Sea gateway occurred gradually in response to a slow, but continuous, salinity increase and attendant density differentiation in deep waters of the Black Sea.

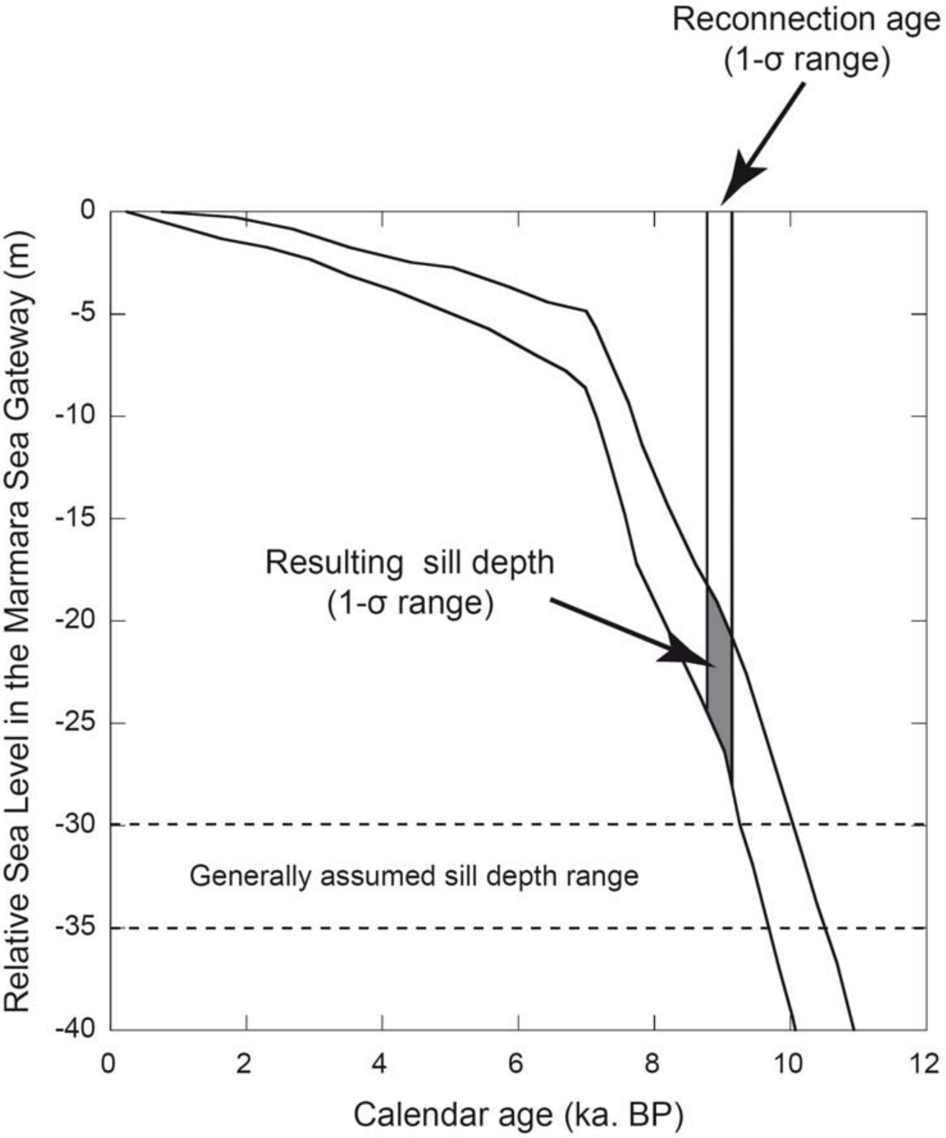

Figure 4: Predicted relative sea level for the Marmara Sea gateway (from Lambeck et al., 2007) and the resulting Bosphorus sill depth (gray area) for the last reconnection (the IMI boundary).

An interesting by-product of our review of reconnection radiocarbon ages is that we are able to constrain the depth of the Bosphorus sill, a key player in the history of the reconnection (Figure 4). Indeed, during post-glacial global sea level rise, the timing of the first marine water intrusion into the Black Sea was only controlled by the Bosphorus sill depth. Determining the age of IMI boundary implies estimating the Bosphorus sill depth at the time of the reconnection. Based upon the sea-level curve model for the Marmara Sea gateway, from the Dardanelles to the Bosphorus Straits, which takes into account isostatic theory and regional sea-level data from the Mediterranean Sea (Lambeck et al., 2007), we determined that the Bosphorus sill depth was 23 ± 5 mbsl at the time of the reconnection (IMI boundary; 8960 ± 185 cal. a. BP). In studies related to the Black Sea reconnection, a Bosphorus sill depth of ~30-35 m in water depth, corresponding to the current sill depth, is commonly assumed. Therefore, our results suggest that the sill depth was ~10 m shallower than commonly assumed (e.g. Ryan et al., 1997; Hiscott et al., 2007; Giosan et al., 2009).

Finally, the depth of the Bosphorus sill also corresponds to the upper limit of the Black Sea level during its isolated phase. If the Black Sea was outflowing into the Marmara Sea as suggested by several workers (e.g. Görür et al., 2001; Aksu et al., 2002; Hiscott et al., 2007), its level would have inevitably been higher than the former Bosphorus sill depth. In the Sakarya coastal plain, the fresh/brackish lagoonal sedimentary environment described by Görür et al. (2001), which we interpreted as representing the transition between the Black Sea lacustrine and marine states, lies at 28 mbsl conformably on fluvial deposits of the Sakarya river. This suggests that prior to the last reconnection, the level of the isolated Black Sea was below the Bosphorus sill depth. Therefore, at the time of the reconnection, the isolated Black Sea could not have been outflowing into the Marmara Sea. This observation is in agreement with recent results from the Danube delta (Giosan et al., 2009).

5. Conclusions

Our approach provides the atmospheric radiocarbon age of the last Black Sea “Lake” reconnection and consequently a reference for calculating the reservoir age of the Black Sea “Lake”. Contrary to previous assumptions (e.g., Bahr et al., 2005; Kwiecien et al., 2008), our results suggest that the reservoir age was not negligible in the upper water column. Our results also reconcile the apparent inconsistency in the published radiocarbon dataset, an inconsistency likely due to differences in reservoir ages throughout the Black Sea “Lake” water column. Our synthesis improves the chronology of the last reconnection, occurring at 8995 ± 145 cal. a. BP. This finding shows that the reconnection was not related to catastrophic drainage of the ice-dammed lake Agassiz-Ojibway. We also show that the replacement of lacustrine biota by marine biota occurred in about 900 yr, a time slice required for the onset of the two-way flow circulation currently observed in the Marmara Sea gateway. Finally, our results imply estimating the former sill depth of the Bosphorus strait to 23 ± 5 m in water depth. Compared to the sedimentary context of the Sakarya coastal plain, this result suggests that the level of the isolated Black Sea was below the former Bosphorus sill depth. Further sedimentological investigations in coastal areas, as well as new radiocarbon ages on terrestrial remains are required to strengthen the validity of our approach.

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