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Assessment of Black Sea water-level fluctuations since the Last Glacial Maximum

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ABSTRACT

This paper presents geophysical and core data obtained from several marine geology surveys carried out in the western Black Sea. These data provide a solid record of water-level fluctuation during the Last Glacial Maximum in the Black Sea. A Last Glacial Maximum lowstand wedge evidenced at the shelf edge in Romania, Bulgaria, and Turkey represents the starting point of this record. Then, a first transgressive system is identified as the Danube prodelta built under ~40 m of water depth. The related rise in water level is interpreted to have been caused by an increase in water provided to the Black Sea by the melting of the ice after 18,000 yr B.P., drained by the largest European rivers (Danube, Dnieper, Dniester). Subsequently, the Black Sea

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lacustrine shelf deposits formed a significant basinward-prograding wedge system, interpreted as forced regression system tracts. On top of these prograding sequences, there is a set of sand dunes that delineates a wave-cut terrace-like feature around the isobath −100 m. The upper part of the last prograding sequence is incised by anastomosed channels that end in the Danube (Viteaz) canyon, which are also built on the lacustrine prograding wedge. Overlying this succession, there is a shelfwide unconformity visible in very high-resolution seismic-reflection profiles and present all over the shelf. A uniform drape of marine sediment above the unconformity is present all over the continental shelf with practically the same thickness over nearby elevations and depressions. This mud drape represents the last stage of the Black Sea water-level fluctuation and is set after the reconnection of this basin with the Mediterranean Sea.

INTRODUCTION

The location of the Black Sea, between Europe and Asia, makes its water level dependent on Eurasian climatic fluctuations. This inland sea is a perfect present-day example of a marginal basin where connection changes dramatically with sea level (Ross, 1971, 1978; Ross et al., 1970; Ross and Degens, 1974; Ryan et al., 2003, 1997). The Black Sea is at present the world's largest anoxic basin, making it an important modern analogue for past anoxic conditions, while during the last glacial period, it was a low-salinity oxygenated lake, isolated from the Mediterranean (Deuser, 1972, 1974; Lericolais et al., 2006b; Wall and Dale, 1974).

The marine and lacustrine deposits at the Black Sea represent a valuable archive for the study of past climate changes. During the Quaternary glacial periods, a northern ice cap prevented major East European rivers flowing from north as they do today. During ensuing interglacial periods, these rivers were diverted to the south in the direction of the Black Sea and Caspian Sea receiving basins and consequently have increased the size of these drainage basins (Arkhipov et al., 1995). Therefore, unique conditions specific to the Black Sea were established while this water body became isolated from the global ocean. This isolation results in a sedimentary record without the hysteresis effect, which is the latent period needed by the global ocean to respond to the consequences of ice melting. During these isolation phases, the Black Sea was more sensitive to climate changes than the Caspian Sea is today. Arkhipov et al. (1995) and Chepalyga (1984) interpreted the Caspian Sea fluctuations opposed to those of the global ocean to have caused the possible connection between the Black Sea and the Caspian Sea through the Manych Strait (Fig. 1). When the Black Sea was isolated, both the lack of saltwater input and the increase of freshwater runoff from the rivers led to reduced salinity levels in the Black Sea. This process during the glacial periods, linked to water-level fluctuation, is measured in the fauna succession, which shows an abrupt change from saltwater to freshwater or brackish-water species. The initial hypothesis of a rapid saltwater flooding of the freshwater lake that was the Black Sea in the Late Glacial Maximum (LGM) was proposed in 1996 by Ryan et al. (1996, 1997). The flood hypothesis raised controversy and initiated refutation (Aksu et al., 2002a, 2002b, 1999; Görür et al., 2001; Hiscott and Aksu, 2002; Hiscott et al., 2008, 2002; Yanko-Hombach et al., 2006), but recently also received support (Algan et al., 2007; Eris et al., 2007, 2008; Gökaşan et al., 2005; Lericolais et al., 2007b, 2007c; Siddall et al., 2004). Nevertheless, most of each opposing view is supported by only a small amount of data in the Black Sea, and not all of the 420,000 km^2 have been surveyed using modern scientific equipment and interpretation in light of modern ideas.

Recently, the European Project ASSEMBLAGE (EVK3-CT-2002–00090) provided geophysical and sedimentary data collected in the northwestern part of the Black Sea from the continental shelf and slope down to the deep-sea zone. This project focused on applying sequence stratigraphic models to seismic data recorded on the northwestern Black Sea shelf, in order to correlate the sequences interpreted using seismic stratigraphy methods to sea-level fluctuations.

To achieve the project's objectives, very high-resolution seismic data were acquired during the BlaSON cruises (1998 and 2002) using the research vessel *Le Suroît* and during the ASSEMBLAGE 1 (2004) cruise of the research vessel *Le Marion Dufresne*. During the first two cruises, paleoshorelines and sand ridges were identified, and a set of seismic data was acquired on these targets to support pseudo–three-dimensional (3-D) analyses. This, coupled with a multiproxy approach, emphasizes that the Black Sea water level is dependent on Eurasian climatic fluctuations. This sequence stratigraphy study was validated by dated samples obtained from long cores (up to 50 m long) providing a firm calibration of Black Sea water-level fluctuation since the LGM. These data show that the Black Sea experienced a contemporary rise in water level with the melting of the Fennoscandian ice sheet, followed by a drop of the water level from the Younger Dryas to the Preboreal. This recent lowstand is confirmed by the presence of the forced regression sequences, the wave-cut terrace, and the coastal dunes still preserved on the shelf, even after the Black Sea was rapidly invaded by Mediterranean/Marmara marine waters.

PREVIOUS STUDIES

Already in the seventies, Kuprin et al. (1974) and Shcherbakov et al. (1978) documented the lowstand shorelines of the Black

Sea. Numerous Soviet, Romanian, Bulgarian, and Turkish coring and echo-sounding surveys conducted in the western part of the Black Sea had previously identified a littoral zone near the shelf edge. Several cores cut by these studies penetrated an erosional surface. From the 1990s Romanian data, Popescu et al. (2004) identified the presence of ancient river valleys entrenching the shelf, especially in front of major canyons. Other workers confirmed the shoreline position with the recovery of sand, gravel, and freshwater molluscs typical of the coastal zone (Major et al., 2002b; Ryan et al., 2003). Ostrovskiy et al. (1977) published results on the stratigraphy and geochronology of Pleistocene marine terraces of the Black Sea, where extensive down-cutting of coastal river valleys was recognized as evidence of a major water-level drop of the ice-age Black Sea on the order of –110 m.

A key limitation of this previous research is that no seismic-reflection profiles were published to document their findings, even though one can read that the former eastern country researchers have documented the exposed margin of the Black Sea lake, and that numerous piston and drill cores also confirmed the existence of an ancient coast. The first international publication related to the work done by the Soviet block on this topic was issued from the U.S.-Russia-Turkey expedition of 1993 led by professor Shimkus (Shimkus et al., 1997) with the objective to examine the impact of the Chernobyl contamination in the Black Sea. The results obtained from this joint survey allowed the mapping of the Dnieper River valleys in more detail with reflection profiling methods and explored the coastal deltas on the Ukrainian shelf.

Later reflection profiling gave evidence of the same shelf-wide erosion surface at different Black Sea locations, i.e., on the Romanian shelf (Lericolais et al., 2007b; Popescu et al., 2004), on the Bulgarian shelf (Dimitrov and Peychev, 2005; Dimitrov, 1982; Khrischev and Georgiev, 1991), and on the Turkish margin (Aksu et al., 2002b; Algan et al., 2002, 2007; Demirbag et al., 1999; Okyar and Ediger, 1999; Okyar et al., 1994).

The general assumption about the Black Sea before the Ryan et al. (1997) hypothesis was that the lake's surface had risen correlatively with the global sea level. This required a relatively early connection through the Bosporus Strait. Based on hydrologic considerations, Chepalyga (1984) and Kvasov and

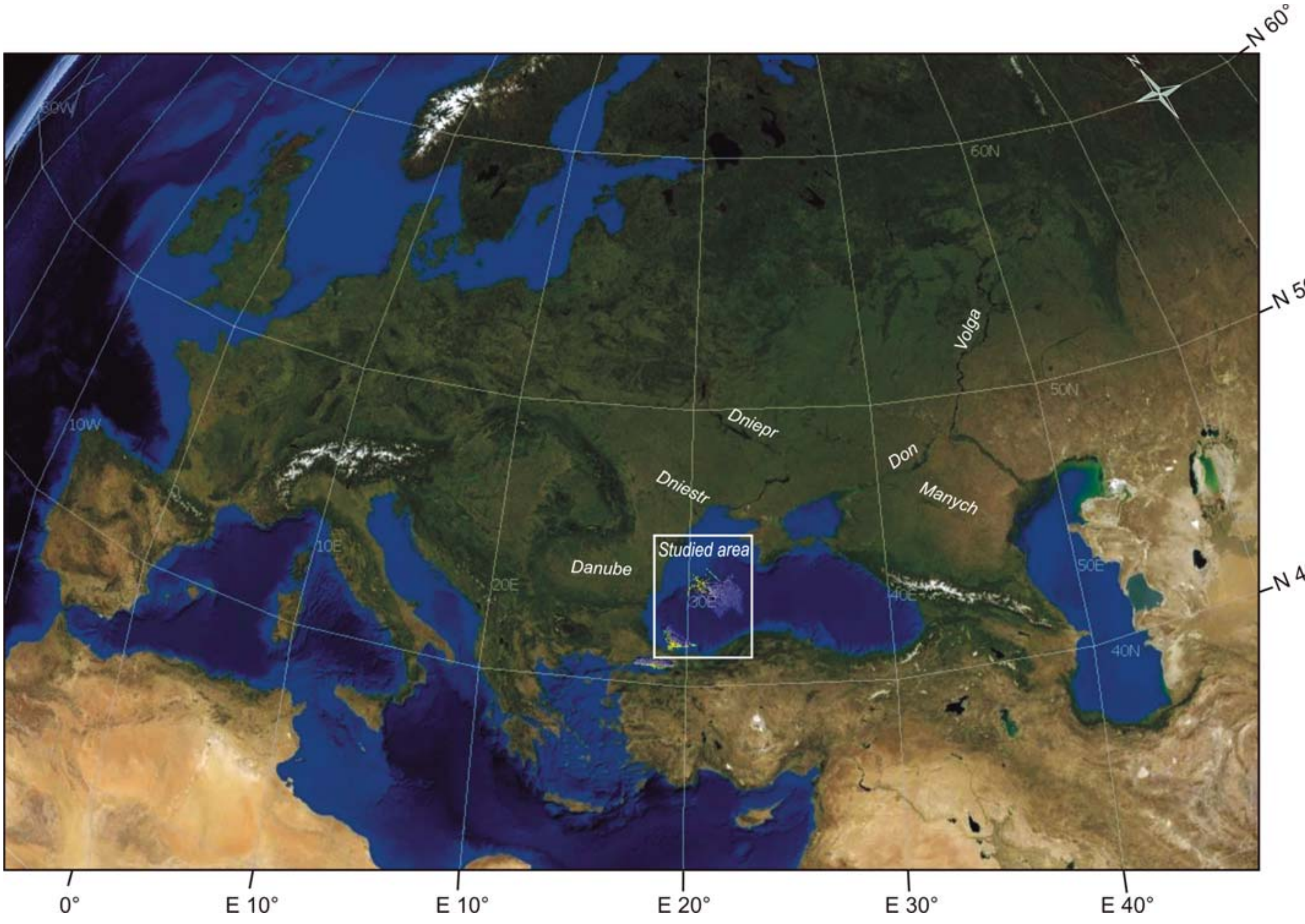

Figure 1. General location of the studied area.

Blazhchishin (1978) stipulated that outflow from the Black Sea through this strait had always been continuous, even at maximum lowstand conditions. For this to be the case, the outlet level of the Black Sea during glacial times would have to have been in concordance with the Black Sea lowstand shorelines. In opposition to the evidence discovered about the depth of the Bosporus sill, Chepalyga (1995) used an old suggestion to place the former Black Sea–Marmara connection in the Sakarya River valley. This idea was consistent with the work of Elmas (2003) who demonstrated that the late Cenozoic tectonics and stratigraphy of northwestern Anatolia allowed a connection between the Sakarya outlet to the eastern arm of the Gulf of Izmit. If such theory is viable, the Black Sea sill controlling its lake level would therefore have been the Dardanelles bedrock sill that is at –85 m (Ryan, 2007).

Recently, a number of researchers have rejected the hypothesis of a deep Black Sea outlet (Bahr et al., 2005, 2006; Major et al., 2002b; Myers et al., 2003). Previously, Lane-Serff et al. (1997) had proposed that a deep outlet would have permitted a vigorous outflow of semibrackish waters from the Black Sea strong enough to keep out Mediterranean saltwater from entering the enclosed basin. However, their hydraulic models only prevented Mediterranean inflow until sea level rose 5 m above the sill. It is now admitted that the increase in salinity in the Sea of Marmara occurred at least 12,000 yr ago, as determined from the mollusc assemblage and stable isotopes (Çagatay et al., 2000; Sperling et al., 2003) and could have been even earlier (Popescu, 2003, 2004).

Authors who are against a late connection of the Black Sea to the Mediterranean sea are now publishing evidence of a late salinization of the Black Sea obtained from their studies conducted on cores recovered on the Black Sea Turkish shelf, e.g., Hiscott et al. (2007) explains that the Ostracoda of Caspian affinity indicate ~5‰ salinity until ca. 7500 yr B.P. Dinocysts and foraminifera confirm a low but rising salinity no later than ca. 8600 yr B.P., and a first major pulse of marine waters was recorded at around 8460 yr B.P. by Marret et al. (2009). Hence, they confirm the previous observations published by Ryan et al. (1997, 2003) and Major et al. (2002a, 2002b, 2006). These results propose that the first marine signal in the Black Sea is recorded between 9000–8000 yr B.P. At that time, the Mediterranean sea level was around –30 m (Lambeck and Bard, 2000; Lambeck et al., 2002) or even less, as the model predictions from the northern coast of Israel indicate sea level at about –13.5 ± 1 m for ca. 8000 yr B.P., whereas observation places it between –14.5 m and –16.5 m (Lambeck et al., 2007; Sivan, 2003). If the Black Sea outflow through a deep connection was truly so vigorous and persistent, it remains to be explained how this outflow could have permitted the early and sustained salinization of the Sea of Marmara at the downstream end of the water cascade.

On the other hand, since the observation of post-LGM lowstand shorelines characterized by wave-cut terraces in different areas of the Black Sea, i.e., at –110 m off Ukraine (Ryan et al., 1997), –100 m on the Romanian shelf (Lericolais et al., 2003, 2007b, 2007c), –122 m for the Bulgarian shelf (Dimitrov, 1982), and –155 m off Sinop where the shelf is really narrow (Ballard et al., 2000), it is necessary to consider a shallow outlet for the Bosporus with interrupted outflow. Even if the subsidence effect since the LGM is negligible (Wong et al., 2005), some consideration has to be taken for the tectonic effect, especially at the foot of major mountain chains such as the Carpathians, the Balkans, the Caucasus, or Anatolia. This effect explains why some 20 m of difference exists for the topset location of the LGM lowstand wedges in different Black Sea areas.

Major et al. (2006), quoting their former work on strontium isotopes published in 2002 (Major et al., 2002b), established that the lake level would have been controlled mainly by the balance of evaporation versus inflow from rivers and rainfall, even though intervals of enclosure of the Black Sea may have been of relatively short duration. These authors also confirm that the Black Sea was an enclosed semibrackish lake during these periods. Lake-level fluctuations might also account for the observed repetition of “cut and fill” in the sediments of the river valleys that cross the shelf (Heller et al., 2001; Koss et al., 1994; Lericolais et al., 2001; Newell, 2001; Popescu et al., 2004; Ryan et al., 2003; Talling, 1998; Zaitlin et al., 1994), as well as the presence of wave-cut terraces on the edges of the shelf (Shimkus et al., 1980). The presence of authigenic aragonite layers correlative with the onset of the sapropel deposit (Giunta et al., 2007) can be correlated to a response to climatic change (Lamb, 2001) despite the hydrothermal influence and calcite precipitation (Peckmann, 2001). A detrital/biogenic source has also been interpreted by Reitz and de Lange (2006) as a possible mechanism for the major part of the aragonite enrichments found in sapropel sediments. Possibly, offshore-directed surface-water flows related to wind stress and/or enhanced runoff (consistent with Mediterranean flooding and enhanced precipitation) during sapropel deposition may have assisted in the transport of near-coastal aragonitic organisms to more coast-remote areas. Recent studies carried out in the Black Sea confirm that authigenic calcite precipitation of calcareous mud appears following the deglacial meltwater delivery (Bahr et al., 2005, 2006; Major et al., 2002b; Ryan et al., 2003) and can be interpreted as a result of water evaporation (Giunta et al., 2007).

SYNTHESIS OF RESULTS OBTAINED IN THE FRAME OF THE ASSEMBLAGE PROJECT

Recently, an assessment of the northwestern part of the Black Sea sedimentary systems from the continental shelf and slope down to the deep-sea zone was provided by the ASSEMBLAGE European Project. Here, we summarize the results of this project, obtained from geophysical data and core analyses. These results provide a solid record of the Black Sea Last Glacial Maximum (LGM) water-level fluctuations and shed new light on the controversy concerning the Black Sea water-level fluctuation since the Last Glacial Maximum.

The ASSEMBLAGE project attempted to assess the last sea-level rise in the Black Sea and provide scenarios quantifying the processes governing the transition of the Black Sea system from a low-salinity lake to a marine state while addressing the variability in this system. Six major observations are used to reconstruct the Black Sea water-level fluctuations since the LGM.

1. The first observation is the existence of a LGM lowstand wedge at the shelf edge offshore Romania, Bulgaria, and Turkey. This observation is completed with the evidence of a second small lowstand wedge dated from 11,000 yr B.P. to 8000 yr B.P. from –100 to –120 m of water depth identified during ASSEMBLAGE cruises on the outer shelf of Romania and Bulgaria and described on the Turkish shelf by Algan et al. (2002). This wedge is associated with the recovery of strata immediately below an observed unconformity consisting of dense, low-water-content mud containing desiccation cracks, plant roots, and sand lenses rich in freshwater molluscs (*Dreissena rostriformis*) with both valves still together.
2. The second observation is deduced from results providing information on the construction of the Danube delta/prodelta, showing that a former prodelta was built up at –40 m after the post-LGM meltwater pulses.
3. The third observation comes from mapping of meandering river channels capped by a regional unconformity and extending seaward across the Romanian shelf to the vicinity of the –100 m isobath.
4. The fourth observation is the presence of submerged shorelines with wave-cut terraces and coastal dunes, or delta mouth bars at depths between –80 to –100 m, below the Holocene Bosporus and Dardanelles Strait outlet sill to the global ocean.
5. The fifth observation to be underlined is that, on the western part of the Black Sea continental shelf, a shelfwide ravinement surface is visible in very high-resolution seismic-reflection profiles.
6. The sixth observation useable for the understanding of the last water-level fluctuation of the Black Sea is the presence of a uniform drape of sediment beginning at the same time above the unconformity with practically the same thickness over nearby elevations and depressions and with no visible indication of coastal-directed onlap across the outer and middle shelf, except in the vicinity of the Danube Delta, where this mud drape is overlapped by recent Danube sediments.

Methods of Data Acquisition

The data were acquired during surveys realized in the framework of two main projects; (1) BlaSON: a French-Romanian bilateral project for which two surveys coordinated by IFREMER (Institut Francais de Recherche pour l'Exploitation de la Mer) were carried out on board the French RV *Le Suroît* in 1998 and 2002, and (2) ASSEMBLAGE: a FP5 European project for which two surveys were carried out on board the French RV *Le Marion Dufresne* in 2004 and the Romanian RV *Mare Nigrum* in 2005. For all these surveys, a differential global positioning system (GPS) system was deployed for accurate (~1 m) positioning, and every vessel was equipped with swath bathymetry systems. Very high-resolution seismic lines were shot simultaneously using a Chirp sonar system. All data acquisition was synchronized and digitally recorded. The navigation profiles presented here are displayed in Figure 2.

The very high-resolution seismic sources were hull-mounted Chirp sonar systems with frequencies ranging between 1.5 and 7 kHz. Their vertical resolution is less than 1 m, with penetration reaching 500 ms in some deep areas where the sediment cover is constituted by soft sediment. On the shelf, the presence of gas-bearing sediments masking the information beneath ~20 m depth below seafloor (bsf) decreases the amount of usable data.

We also present results obtained from cores. The sediment cores were recovered using a Kullenberg piston corer; a conventional one used during BlaSON surveys, and Calypso type one developed for IPEV (French Institute for South Polar Seas) with a long tube (up to 60 m) system. Each of the core sections recovered were cut horizontally into two pieces and scanned to get an image before analyzing the samples. The general properties of the sediments were measured by the Multi System Track (MST) to get P-wave velocity and amplitude, density, impedance, and magnetic susceptibility values. All cores were packaged at 4 °C, and sampling was done at the IFREMER Brest laboratory. Dating was conducted on samples at various distances and various depths from the coast to reveal any possible bias in ages due to coastal or current influence. The Poznań Radiocarbon Laboratory in Poland performed ^{14}C dating.

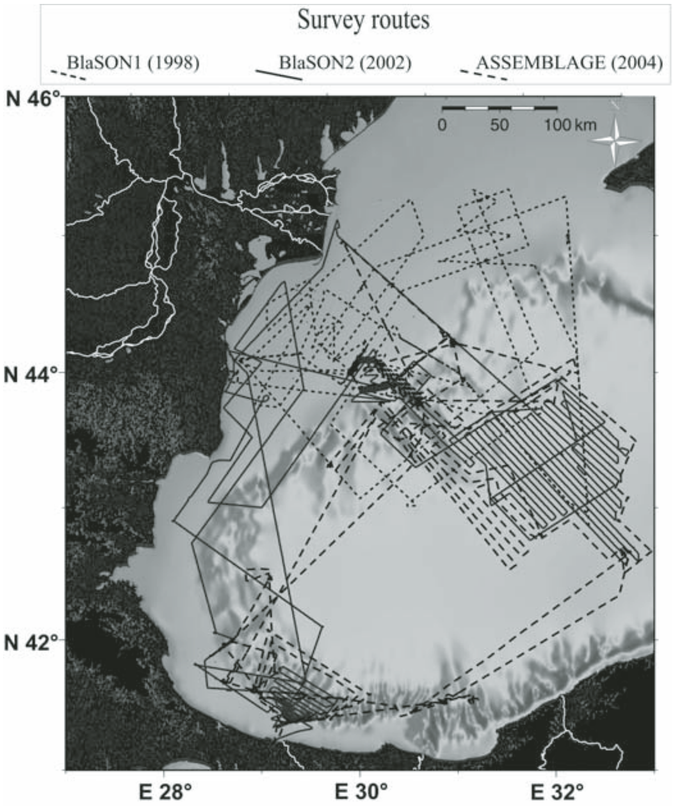

Figure 2. Bathymetry of the semi-enclosed Black Sea basin and BlaSON and ASSEMBLAGE survey route locations.

Before the evidence of wave-cut terraces in the Black Sea, no reliable sea-level markers were described to allow a good sea-level reconstruction (Giosan et al., 2006; Pirazzoli, 1991). Moreover, the lack of radiocarbon ages on in situ materials and the difficulty in calibrating radiocarbon ages in a setting with variable reservoir ages (Giosan, 2007) led to ongoing discussion about the Black Sea water-level fluctuations. At least for the more recent period, Siani et al. (2000) have proposed a reservoir age of 415 ± 90 yr B.P. for the Black Sea, based on six samples from the Black Sea, the Sea of Marmara, and in the vicinity of the Bosporus. One of the reasons for this is that a reservoir age of ~1280 yr was deduced from the occurrence of the Santorini Minoan ash in the Unit II of Jones and Gagnon (1994) from several south Black Sea cores recovered between 400 and 700 m below present sea level (Guichard et al., 1993). If we include documentation from Jones and Gagnon (1994), Bahr et al. (2005), and Kwiecien et al. (2008), then reservoir ages extending from 0 to 1280 yr. For the lacustrine period, no measurement has been proposed for the past. If no terrestrial influence exists, then age and residence time of deep waters will be the main factors. Östlund (1974) calculated ages of deep waters between 1470 yr (at ~600 m) and more than 2000 yr (when deeper than 1400 m). If a low stratification occurs in poorly salted water, then the residence time would be equal or less than 935 yr. The question of which reservoir age should be given to old water of the "Black Lake," depending on depth in the water column, is still a matter of debate, and it is the reason why we still use uncalibrated and uncorrected ^{14}C ages throughout this study for our obtained dates.

The seismic profile and core locations are displayed on Figure 3. Core location, length, and water depth where samples were recovered are presented in Table 1.

First Observation: The Lowstand Wedges (LGM and Preboreal)

The seismic line Chirp B2CH96 (AB on Fig. 3) was shot during the BlaSON2 survey off Romania in front of the Danube delta (Fig. 4). At around 150 m water depth, this line displays prograding parallel but undulating reflectors characterizing a seismic unit LSW1 (Fig. 5). These reflectors toplap at the top of LSW1.

Above the erosional truncation, unit LSW2 is located on the slope part of this dip line. This unit presents reflectors beveling the LSW1 slope slightly to the northwest. Throughout the seismic line, there is a thin unit that corresponds to the mud drape known to be present all over the western Black Sea (Lericolais et al., 2007b; Major et al., 2002b; Ryan et al., 1997, 2003). Age control of these two lowstand wedges is given by the dates obtained from core MD04–2771 and presented in Table 2. Dating of the seismic units interpreted as the LSW1 and LSW2 was possible, and older dates reach back to 29,450 ± 320 ^{14}C yr B.P. for unit LSW1 at 11.90 m on core MD04–2771. This date was obtained on organic matter, but because a *Dreissena* shell sampled at 2.18 m in the same core returned a date of 24,980 ± 160 ^{14}C yr B.P., we can be confident in attributing the deposition of LSW1 to the Last Glacial period.

A second lowstand is evidenced by seismic sequence LSW2. This lowstand wedge has a shape characteristic of a low-energy wedge. Core MD04–2771 confirms that this lowstand wedge started to be deposited around 12,180 ± 60 ^{14}C yr B.P.

On the southwestern part of the Black Sea, another Chirp profile (B2CH56) displays more precisely the two successive lowstand wedges LSW1 and LSW2 (Fig. 5). Age control of these lowstand deposits was obtained from core MD04-2752 (Table 3; Fig. 6) dating *Dreissena* shells. Here again, the LSW1 is correlative to LGM time. It is very clear that LSW2 is a lowstand wedge deposited between 12,010 ± 50 ^{14}C yr B.P. and 8130 ± 50 ^{14}C yr B.P., showing that the Black Sea encountered a second lowstand after the LGM lowstand.

Second Observation: The Post-LGM (Ante–Younger Dryas) Danube Prodelta

The Danube prodelta is located at the coastal part of the Danube delta and can be seen on line B2CH96, section AB (Fig. 3). On the Chirp seismic profile, an erosion surface interpreted as a ravinement surface R1 is identified (Fig. 7). Above this, a prograding wedge U.S.2 is well delimited on the Chirp seismic data; this wedge corresponds to a former prodelta lobe. Another prodelta lobe corresponding to seismic unit U.S.3 presents reflectors onlapping on the previous unit U.S.2. The geometric relationship between these prodelta lobes would have been best imaged on shore-parallel profiles showing in detail the lap-out patterns of seismic reflectors, such as those shown for the Po River prodelta by Correggiari et al. (2005a, 2005b).

Units U.S.2 and U.S.3 (Fig. 7) represent the sites of deposition and progradation at the distal part of the previous Danube River outlets and channels. These prodelta lobes represent part of the main depocenters that extend offshore, being a considerable portion of the prodelta deposit (Correggiari et al., 2005a, 2005b). As seen on Figure 4, these units are the highest part of the dip seismic line and are restricted to the prodelta area. Our data set is not dense enough to be able to decipher prodelta autocyclic processes from external forcing. Nevertheless, their position and nature are in accordance with our interpretation obtained from the comparison of the seismic data interpreted all along the profile and the core results.

Above these prodelta lobes, seismic unit U.S.4 (Fig. 7) is prograding also, but in a more gentle shape. This unit can also be interpreted as a prodelta lobe, but ages obtained on core MD04–2774 return an average age of ca. 9500 ^{14}C yr B.P. (see Table 4). U.S.4 is contemporaneous to the onset of the Preboreal regression responsible of the deposit of LSW2 at the shelf edge as presented in the previous paragraph.

Recent studies (Giosan et al., 2009) confirm that the Danube was building a ramp delta lobe at 8860 ± 45 ^{14}C yr B.P. (ages obtained from *Dreissena polymorpha*). From the morphology of

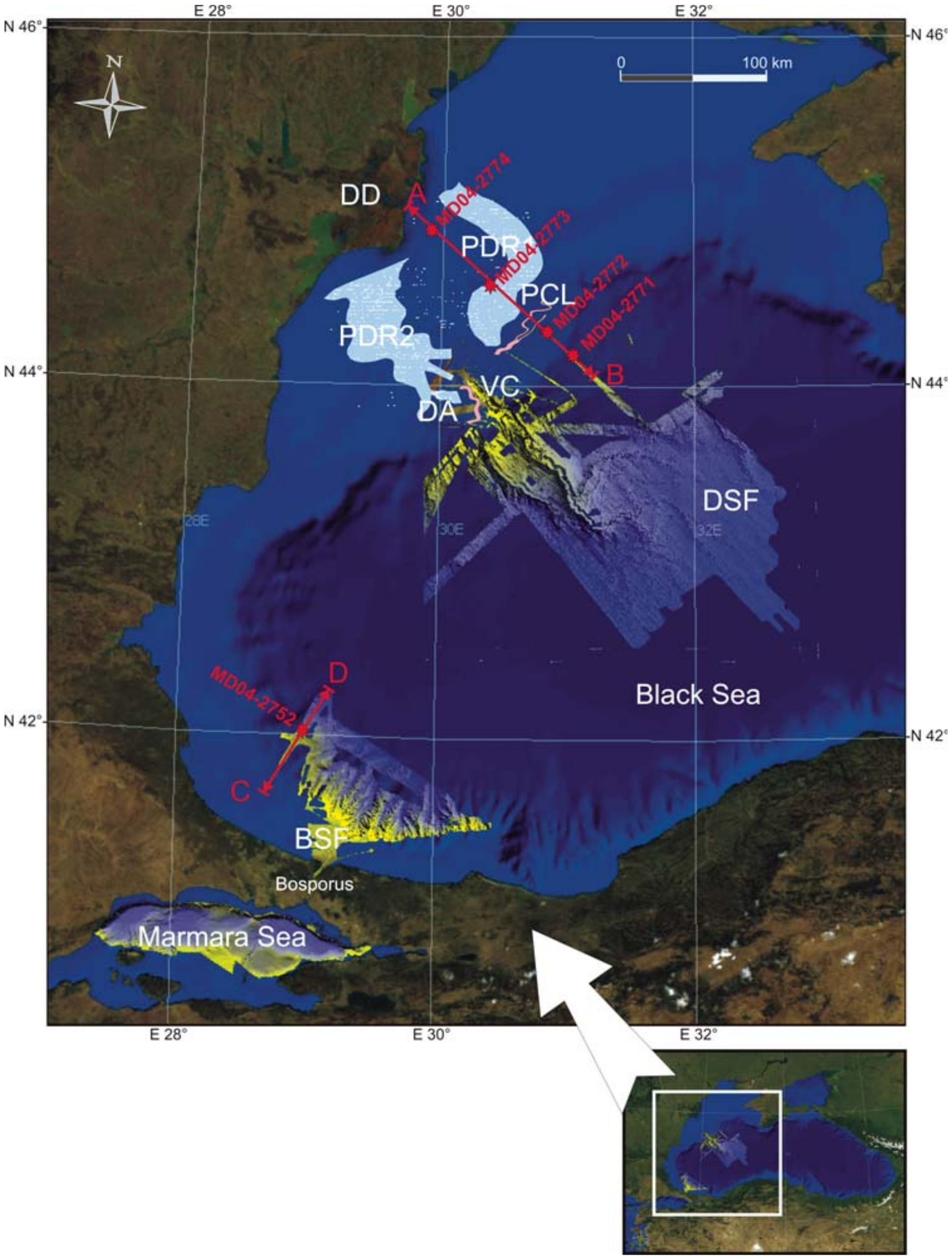

Figure 3. Western Black Sea shelf presenting the location map of the seismic line B2CH96 (A-B) and B2CH56 (C-D) and of the cores MD04–2752, MD04–2771, MD04–2772, MD04–2773, and MD04–2774, along with geomorphologic interpretation issued from previous work (Lericolais et al., 2007c; Popescu et al., 2001, 2004). DA—dune area, DD—Danube delta, PDR1 and PDR2—paleo–Danube River 1 and 2, PCL—paleocoastline, VC—Viteaz Canyon, DSF—Danube deep-sea fan, BSF—Bosporus shallow fan delta.

TABLE 1. CORES PRESENTED IN THIS STUDY WITH THEIR POSITION, LENGTH OF RECOVERY, AND WATER DEPTH AT LOCATION

Core	Latitude (°N)	Longitude (°E)	Core length (m)	Water depth (m)
MD04-2752	41°56.76	28°36.56	24.50	169
MD04-2771	44°16.32	30°54.24	12.38	168
MD04-2772	44°18.07	30°51.56	7.51	106
MD04-2773	44°37.96	30°20.61	3.63	68
MD04-2774	44°57.47	29°50.12	7.30	30

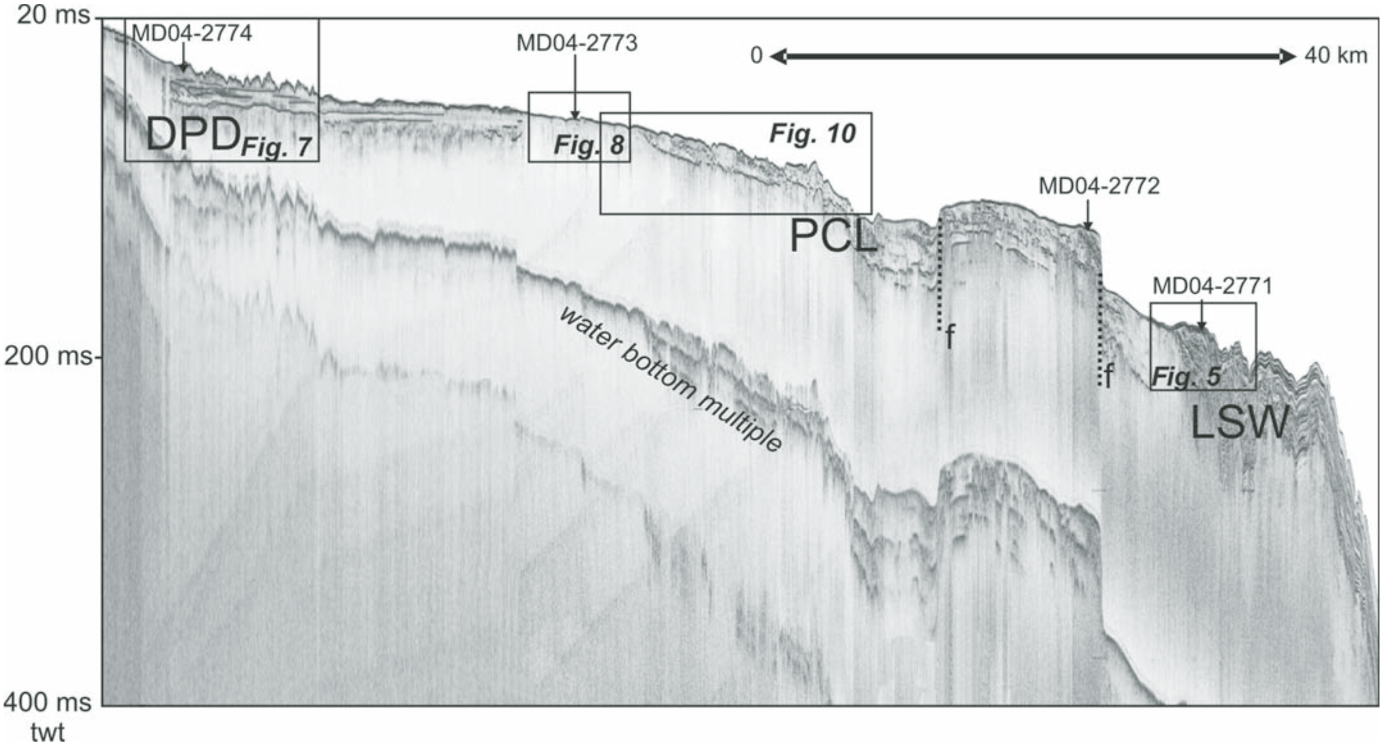

Figure 4. Line B2CH96 with core location (vertical exaggeration is ~200). DPD—Danube prodelta, PCL—paleocoastline, LSW—lowstand wedge, f—faults; TWT—two-way traveltime.

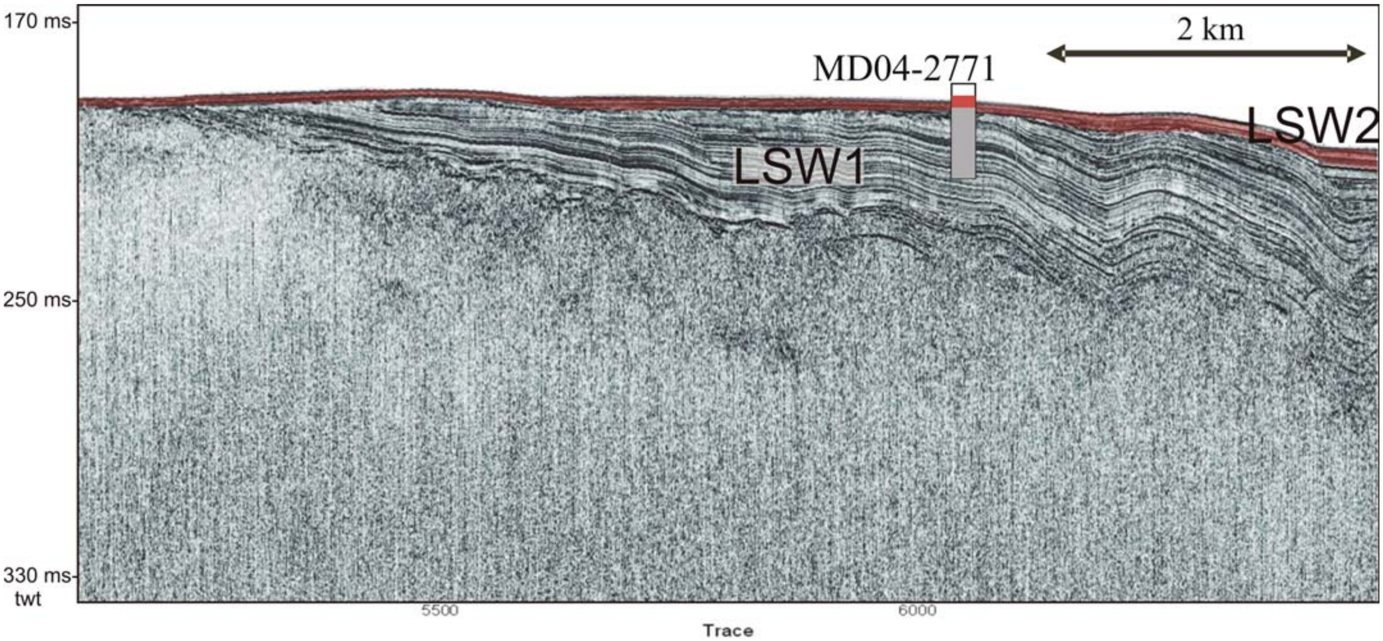

Figure 5. Chirp profile B2CH96: Distal part of Figure 4. Lowstand wedge 1 (LSW1) and LSW2 can be distinguished. TWT—two-way traveltime.

TABLE 2. DATES OBTAINED FOR THE LOWSTAND WEDGES FROM CORE MD04-2771 AND TYPE OF SAMPLES DATED (MOLLUSC OR ORGANIC MATTER)

Core	Water depth (m)	Core length (m)	Depth in core (m)	Age (^{14}C yr B.P.)	Calibrated age* (yr)	Sample	Unit
MD04-2771	168	12.38	0.34	12,180 ± 60	13,650 ± 120	*Dreissena*	LSW2
			2.18	24,980 ± 160	28,840 ± 180	*Dreissena*	LSW1
			11.90	29,450 ± 320	–	Organic matter	LSW1

*Calibrated ages are here as indicator and were obtained using the Radiocarbon Calibration Program Calib5 (Stuiver et al., 1998) with 400 yr for reservoir correction.

TABLE 3. DATES OBTAINED FOR THE LOWSTAND WEDGES FROM CORE MD04-2752 AND TYPE OF SAMPLES DATED (MOLLUSC OR ORGANIC MATTER)

Core	Water depth (m)	Core length (m)	Depth in core (m)	Age (^{14}C yr B.P.)	Calibrated age* (yr)	Sample	Unit
MD04-2752	169	24.50	12.20	8130 ± 50	8605 ± 110	Organic matter	LSW2
			12.30	12,010 ± 50	13,430 ± 100	*Dreissena*	LSW2
			19.85	25,020 ± 180	28,730 ± 300	*Dreissena*	LSW1

*Calibrated ages are here as indicator and were obtained using the Radiocarbon Calibration Program Calib5 (Stuiver et al., 1998) with 400 yr for reservoir correction and Cariacco data for age >24,000 yr.

the lacustrine-marine contact, Giosan et al. (2009) supposed that the Black Sea lake level at that time was around 30 mbsl.

Third Observation: Meandering River Channels Preserved on the Black Sea Shelf

The third observation is deduced from previous Romanian surveys carried out by the GeoEcoMar Institute, where several recent paleoriver channels incising the continental shelf down to –90 m water depth (Popescu et al., 2004) were identified (PDR1 and PDR2 on Fig. 3). These paleochannels are completely filled by sediments and are no longer visible in the bathymetry. These erosive features reach 400–1500 m in width and 20–30 m in depth. They present conventional asymmetry on some cross sections (Fig. 8) and seem to have been beveled by a subsequent phase of erosion. Here also these paleochannels are sealed by the

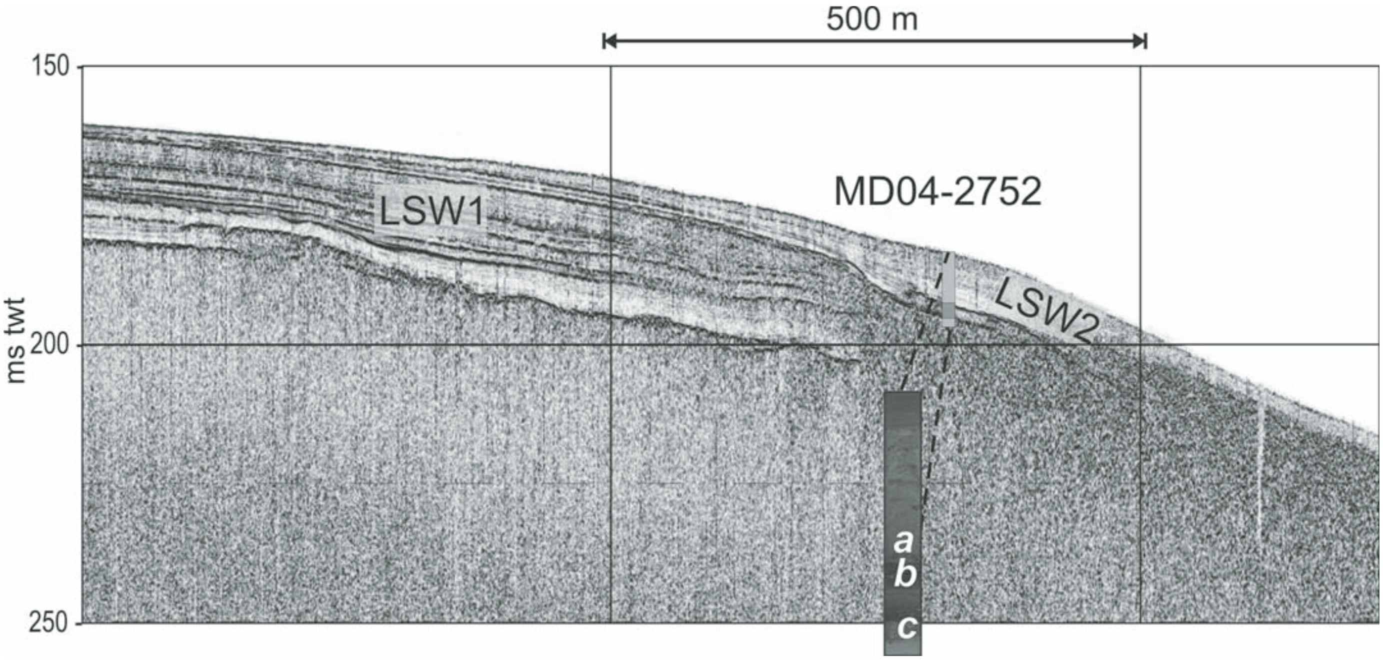

Figure 6. Chirp profile B2CH56: Distal part of segment line C-D on Figure 3 with core MD04–2752 location. Lowstand wedge 1 (LSW1) and LSW2 can be distinguished. Dated core samples are a = 8130 ± 50 ^{14}C yr B.P., b = 12,010 ± 50 ^{14}C yr B.P., c = 25,020 ± 180 ^{14}C yr B.P. (cf. Table 3). TWT—two-way traveltime.

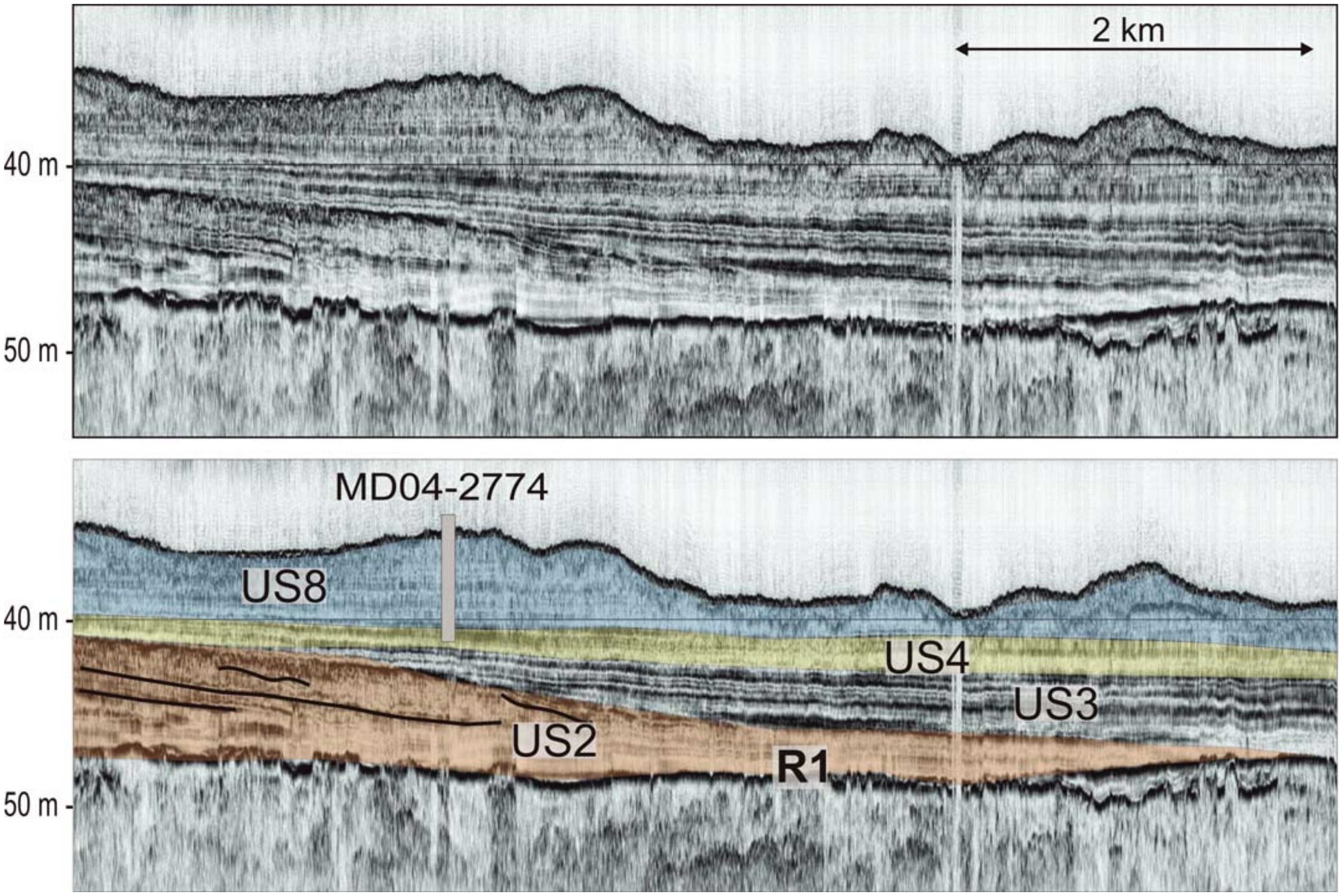

Figure 7. Prodelta section of line B2CH96 with location of core MD04–2774: R1 is a ravinement surface; U.S.2 is a prograding wedge interpreted as a former prodelta lobe; U.S.3 is a retrograding sequence on U.S.2 and can be a second prodelta lobe; U.S.4 is a prograding sequence to be correlated to the forced regression described at –100 m by Lericolais et al. (2006a); and U.S.8 is the present-day prodelta deposit.

mud drape described earlier (Lericolais et al., 2007a; Major et al., 2002b; Popescu et al., 2004; Ryan et al., 2003). For Popescu et al. (2004), the stratigraphic position of these incisions lying directly under the discontinuity at the base of the Holocene strongly suggested that they formed during the last lowstand.

The cartography of these buried channels shows that they are concentrated around two main directions. This distribution leads to their interpretation as anastomosed fluvial systems corresponding to two distinct drainage systems (Fig. 3). These would correspond to former paleo–Danube River flooding on the shelf to the outer shelf, where they apparently split into several arms, similar to a fluvial deltaic structure comparable in size to the modern Danube delta, that lie close to the Danube Canyon (Popescu et al., 2004), also named Viteaz Canyon (VC on Fig. 3). The channels extend right to the paleoshoreline and pass under the belt of coastal sand ridges and depressions. Consequently, the regression that exposed the shelf surface into which the river channels were cut was followed by a transgression that led to the filling of the channels and then to another regression that deflated the channel fills and reexposed the entire region to coastal dune and pan development. The argumentation about the origin of the coastal features at ~–100 m has been presented in Lericolais et al. (2007b).

Core MD04–2773 was recovered at one incised valley section (Fig. 8). The core (Fig. 9) got through the marine drape and

TABLE 4. DATES OBTAINED ON THE CORE MD04-2774 AND TYPE OF SAMPLES DATED (MOLLUSC OR ORGANIC MATTER)

Core	Water depth (m)	Core length (m)	Depth in core (m)	Age (^{14}C yr B.P.)	Calibrated age* (yr)	Sample	Unit
MD04-2774	30	7.3	5.43	9030 ± 50	9720 ± 140	*Pisidium*	US4
			6.91	9570 ± 50	10,440 ± 90	*Pisidium*	US4

*Calibrated ages are here as indicator and were obtained using the Radiocarbon Calibration Program Calib5 (Stuiver et al., 1998) with 400 yr for reservoir correction.

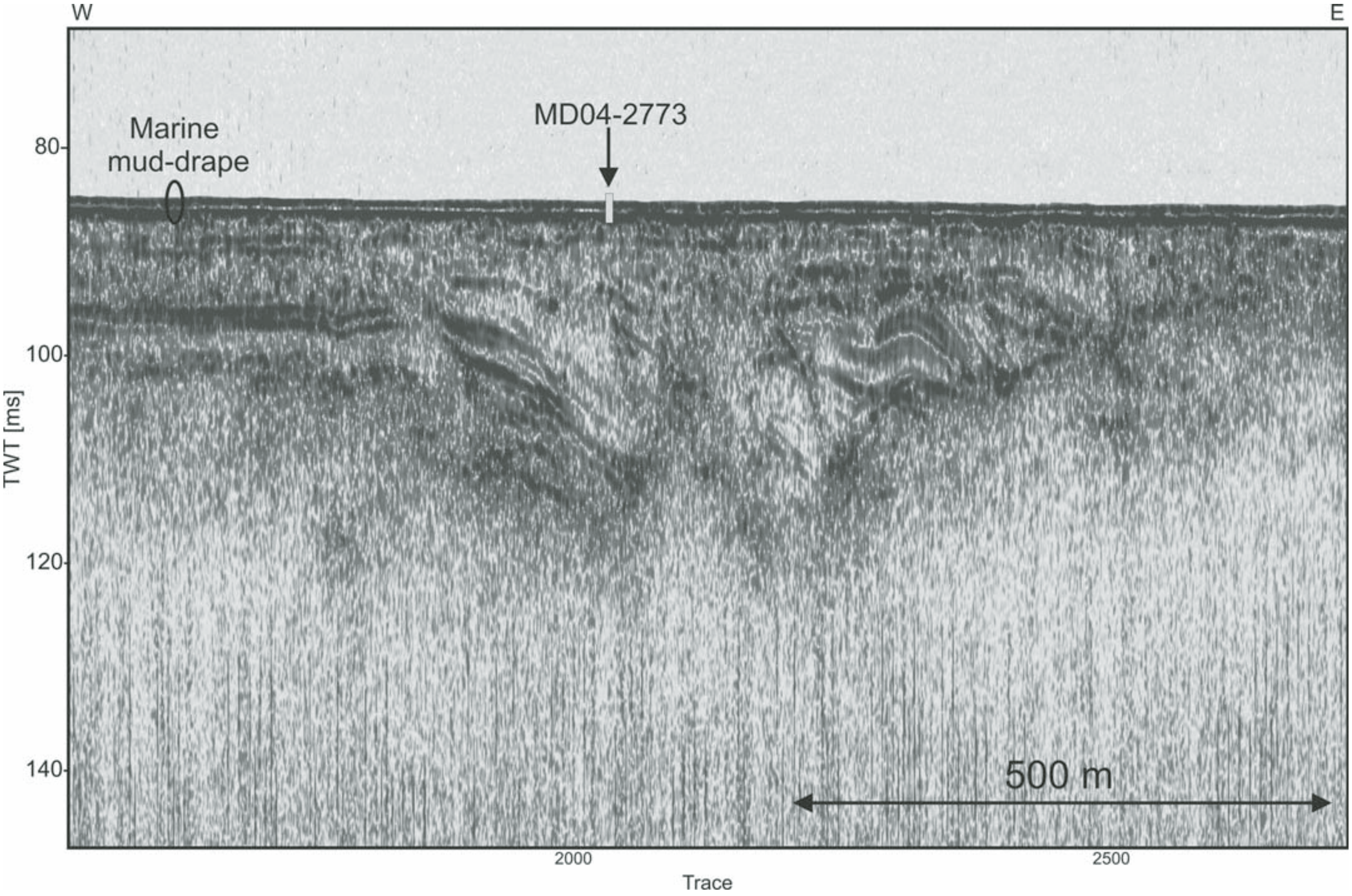

Figure 8. Incised valley section of line B2CH96 with location of core MD04–2773. TWT—two-way traveltime.

passed the *Dreissena* hash layer (Major et al., 2002b) described later herein. Even if the mollusc *Pisidium* sampled at 103 cm in the core (Table 5) is at the limit of the hash layer, it shows that this mollusc is of the same genus as the one collected in core MD04–2774. It is a genus of very small or minute freshwater clams known as pea clams, aquatic bivalve molluscs in the family Sphaeriidae. This confirms that the infilling of the valleys was still active at more than 60 m before the onset of the marine drape.

Fourth Observation: Presence of Submerged Shorelines

The submerged shorelines characterized by the presence of a wave-cut terrace at depths between –80 to –100 m are the key elements of the fourth observation. At the top of this coastal feature recognized on the Romanian shelf, there is a set of coastal dunes or delta mouth bars described by Lericolais et al. (2007a, 2007b). Analysis of the very high-resolution seismic data in pseudo–3-D mode (Lericolais et al., 2009) demonstrates that the lacustrine shelf deposits form an important basinward-prograding wedge system interpreted as a forced regression system tract eroded at the distal part by a wave-cut terrace (see figs. 4 and 5 *in* Lericolais et al., 2009). On line B2CH96, located north of the dune field studied area, the wave-cut terrace is also visible (Fig. 10). On top of the prograding units (FR on Fig. 10), there is a set of sand dunes that delineates a berm-like feature around the –100 m isobath (WCT on Fig. 10), similar to the ones described by Ryan et al. (2003), Popescu et al. (2004), and Lericolais et al. (2007b).

Analyses of cores retrieved from the dune field area demonstrate that the prograding wedges are lacustrine in origin and document a low water level characterized by forced regression–like reflectors mapped from the pseudo–3-D seismic data ~~2~~ (Lericolais et al., 2009). Here, too, the hinge point corresponds to the wave-erosion surface mapped around the –100 m isobath. The ages returned by the core analysis range between 11,000 and 8000 ^{14}C yr B.P., with the formation of dunes being around 8500 ^{14}C yr B.P. The prograding reflectors deepen seaward and are truncated by an erosional surface described as the wave-cut terrace. On the Chirp profile, it is clearly seen that all the area is covered by a drape of less of 1 m thick (see "Sixth Observation: Uniform Drape above the Unconformity"), confirming that the dune system is not active any more. Everywhere across the mid- and outer shelf, the ridges, mounds, and depressions are draped by this thin layer of sediment with a remarkably uniform thickness of no more than a meter (Fig. 11).

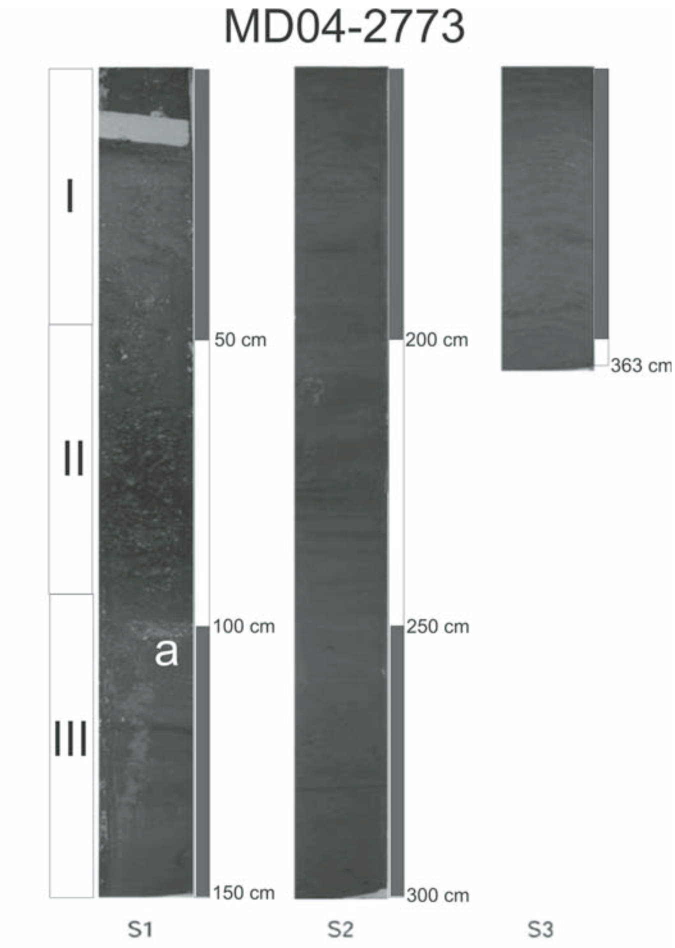

Figure 9. Photo of the core MD04–2773 sections. I—*Modiulus* ecozone; II—*Myttilus* ecozone, III—*Dreissena* ecozone. I and II are marine indicators, while III is from semibrackish state (Giunta et al., 2007). a—*Pisidium* at 103 cm in the core aged 7890 ± 50 ^{14}C yr B.P.

Fifth Observation: Ravinement Surface

On the western part of the Black Sea continental shelf, a shelfwide ravinement surface is always present and can be recognized both on very high-resolution seismic-reflection profiles and in all the collected cores. In the cores, this surface corresponds to the described "hash layer" of Major et al. (Major et al., 2002b). This "hash layer" is composed of debris of whitened *Dreissena*. This corresponds to the surf zone as it is shown on Figure 12 where the present-day washed wave zone is marked by debris of whitened mollusc shells.

Such facts are in favor of a rapid transgression in the Black Sea and are in agreement with the previous works published by Khrischev and Georgiev (1991) and Lericolais et al. (2004, 2007b). Actually, Khrischev and Georgiev (1991) attributed "fast rising" water level to the transition from lacustrine to marine conditions. For them, this change corresponds to a stratigraphic break ("washout") in the cores that interrupts the lacustrine calcite precipitation and is followed by terrigenous mud with marine molluscs. They reported this "washout" in more than 100 cores. This same transition was described for the BlaSON and ASSEMBLAGE cores, where the transition was interpreted as either a ravinement surface or an erosion surface (Lericolais et al., 2007b, 2007c; Major et al., 2002b).

Algan et al. (2007, p. 621) also made the observation of dense, dry mud below the erosional unconformity on the Thrace margin in cores from the shelf edge. These authors noted "a marked contact" between a 2-cm-thick shell-enriched layer and a "stiff clay deposit with low water content at the base of these cores." The ^{14}C age of the shells (*Dreissena* sp.) is 8590 ± 145 yr B.P., comparable to the age of the shell material constituting the "hash layer." Algan et al. (2007, p. 623) considered that "the lithological characteristic of this core indicates that the deposition starts with high-energy condition over the stiff eroded substrate at about −100m, and continued with low-energy, suggesting a rapid deepening of a shallow environment."

Sixth Observation: Uniform Drape above the Unconformity

Along the Black Sea margin, Wong et al. (2005), Algan et al. (2002), Ryan (2007), Ryan et al. (2003), Major et al. (2002b), and Lericolais et al. (2007b, 2007c) already described the presence of a uniform mud drape deposited above the unconformity. This mud drape layer was sampled during BlaSON and ASSEMBLAGE and corresponds in cores to the layer of terrigenous mud containing marine molluscs such as *Mytilus galloprovincialis* and *Mytilus edulis*, *Cerastoderma edule*, and *Cardium edule* (Giunta et al., 2007). This lithologic and biostratigraphic interval on the shelf corresponds to units 1 and 2 in basin sediments as defined by Ross et al. (1970).

This uniform mud drape is clearly seen on the high-resolution seismic profiles obtained by the Chirp sonar system and is displayed for instance on Figures 8 and 11. Its thickness, when calculated from acoustic travel time to meters, corresponds

TABLE 5. DATES OBTAINED ON CORE MD04-2773 AND TYPE OF SAMPLES DATED (MOLLUSC OR ORGANIC MATTER)

Core	Water depth (m)	Core length (m)	Depth in core (m)	Age (^{14}C yr B.P.)	Calibrated age* (yr)	Sample	Unit
MD04-2773	68	3.63	1.03	7890 ± 50	8350 ± 60	*Pisidium*	Incised valley

*Calibrated age are here as indicator and were obtained using the Radiocarbon Calibration Program Calib5 (Stuiver et al., 1998) with 400 yr for reservoir correction.

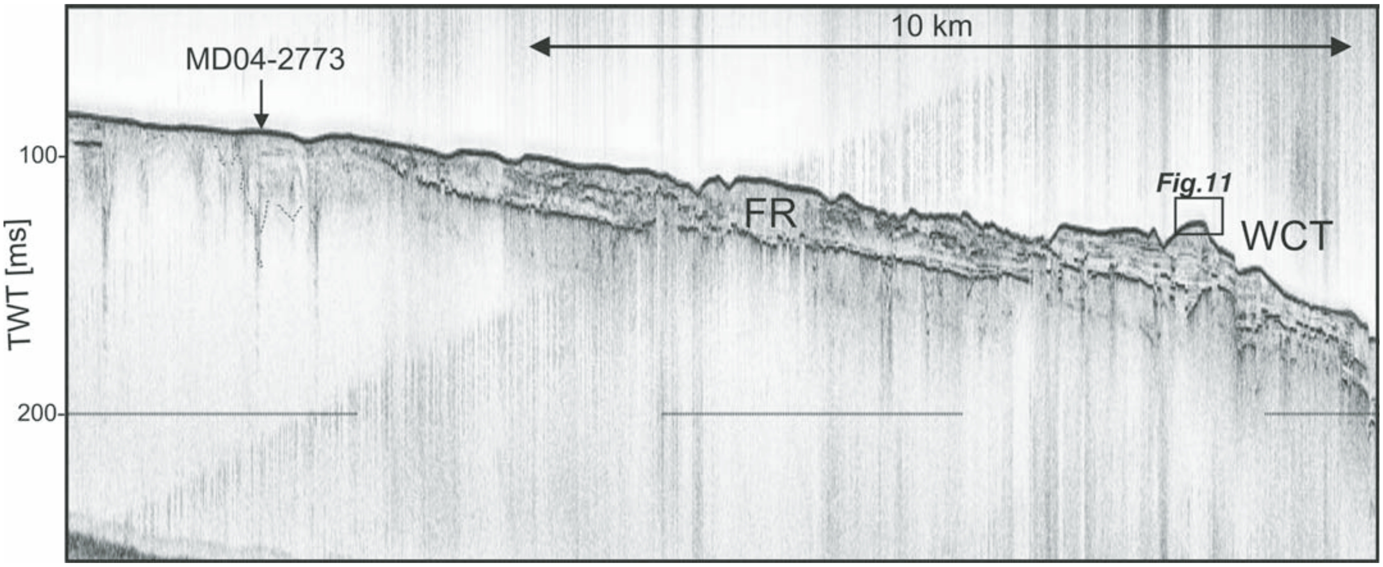

Figure 10. Forced regression (FR) progradation limited basinward by the wave-cut terrace (WCT) visible on section of line B2CH96 with location of core MD04–2773 (note the prograding reflectors inside the FR wedge). TWT—two-way traveltime.

in cores to the layer of terrigenous mud containing marine molluscs. Similar to the Romanian continental shelf, this layer has also been found above the unconformity on other Black Sea margins (Algan et al., 2002, 2007).

Initial deposition of this uniform drape of sediment started at the same time above the unconformity and has practically the same thickness over nearby elevations and depressions, and it presents no visible indication of coastal-directed onlap across the outer and middle shelf. Such a layer deposited over the "hash layer" ravinement surface, composed of in situ mussel molluscs at the bottom of this infra-meter layer, is characteristic of a rapid change. The size and disposition of the *Mytilus edulis* found in the cores are in accordance with the natural biotope of such a species. While the highest biomass is in general recorded at water depths ranging between 5 and 30 m, being lower at deeper depths, and living in niche beyond 40 m (Stea et al., 1994; Westerbom et al., 2002), this is not the case in our cores, where they are abundant everywhere. Such an observation is also an argument in favor of

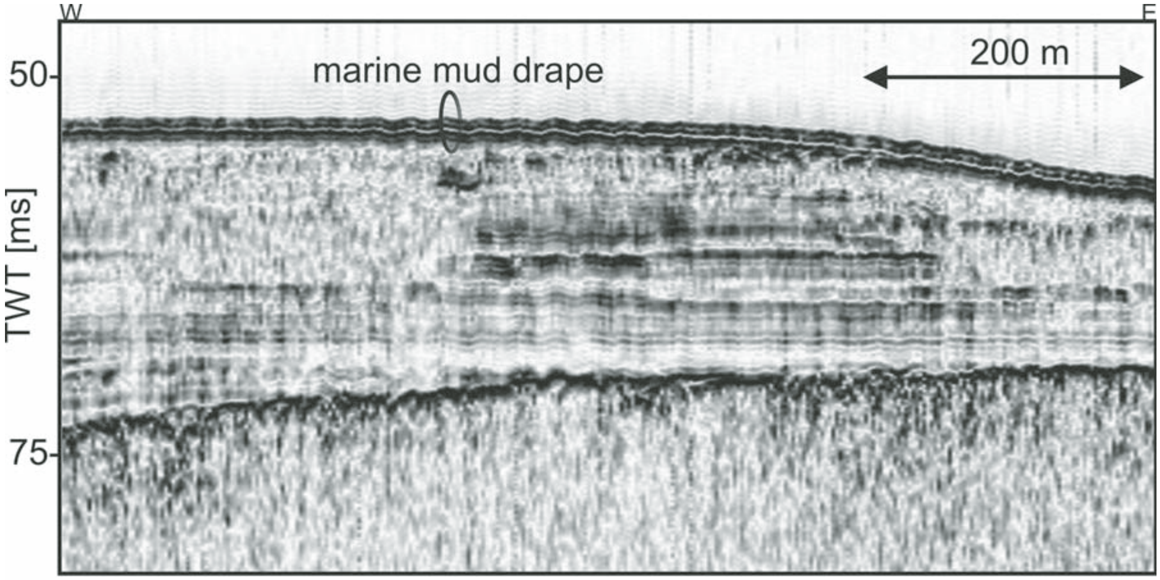

Figure 11. Close-up of Figure 10 Chirp profile B2CH96 showing the seismic signal of the mud drape. TWT—two-way traveltime.

a rapid sea-level rise, making it hard for these mussels to survive the transgression.

SYNTHESIS: WATER-LEVEL FLUCTUATION OF THE BLACK SEA SINCE THE LAST GLACIAL EXTREME

The synthesis presented here corresponds to an essay on the assessment of the last sea-level rise in the Black Sea and supports a scenario quantifying the processes governing the transition of Black Sea system from a semi-freshwater lake to a marine state. This work addresses the important postglacial variability in the Black Sea system, as the transition of this system from a semi-freshwater lake to a marine environment was perhaps one of the most dramatic late Quaternary environmental events in the world. Back to the Last Glacial Maximum, 21,000 yr ago, the Black Sea was probably a giant freshwater to semi–brackish-water lake, as proposed by Arkhangelskiy and Strakhov (1938), or at least a brackish enclosed basin. Its water level stood more than 120 m below than today's level. During ASSEMBLAGE project, analysis of high-resolution seismic-reflection profiles, Chirp and side-scan data together with piston core analyses from surveys taken on the Danube fan, and on the Black Sea shelf, provided new insights into the recent sedimentation processes in the deep northwestern Black Sea.

The deep-sea fan studies (Popescu et al., 2001) demonstrate that the last channel-levee system on the Danube fan developed during the Neoeuxinian lowstand (stage 2) in a semi-freshwater basin with a water level ~120 m lower than today. Sediments supplied by the Danube were transported to the deep basin through the Viteaz canyon (Popescu et al., 2004). Functioning of the deep-sea fan is a good indicator of lowstand periods (Popescu et al., 2001; Winguth et al., 2000; Wong et al., 1997).

Figure 12. The present-day wave action zone showing debris of coquinas at the berm. This hash layer is the modern equivalent of the one described in the Black Sea core and having an average age of 8600 ^{14}C yr B.P.

Because the Black Sea was in a very close vicinity to the Scandinavian-Russian ice cap, the supply of the melting water from the glaciers into the Black Sea through the major drainage system constituted by big European rivers (Danube, Dnieper, Dniester, and Bug) was recorded by a brownish layers described in cores (Bahr et al., 2005; Major et al., 2002b). The water volume brought to the Black Sea after the meltwater pulse 1A (MWP1A) at ca. 12,500 ^{14}C yr B.P. (14,500 yr cal. B.P.) (Bard et al., 1990) was sufficient to raise the water level between –40 m to –20 m, where the *Dreissena* layers were deposited. The –40 m upper limit is interpreted from our records and especially deduced from the construction of the Danube prodelta (Lericolais et al., 2009), which are not exhaustive, and the –20 m limit is certified by Yanko (1990). This last value for the transgression upper limit would have brought the level of the Black Sea even higher to the Bosporus sill, and possible inflow of marine species like Mediterranean dynoflagellate populations can be envisaged (Popescu, 2004). Nevertheless, the rise in the Black Sea water level, which stayed between freshwater to brackish conditions, stopped the deep-sea fan sedimentation.

Palynological studies conducted on BlaSON cores (Popescu, 2004) show that from the Bølling-Allerød to the Younger Dryas, a cool and drier climate prevailed. Northeastern rivers converged to the North Sea and to the Baltic Ice Lake (Jensen et al., 1999), providing reduced river input to the Black Sea and resulting in a receding shoreline. These observations are consistent with some evaporative drawdown of the Black Sea and are correlated to the evidence of an authigenic aragonite layer present in all the cores studied (Giunta et al., 2007; Strechie et al., 2002). This drawdown is also confirmed by the determination of the forced regression–like reflectors recognized either on the dune field mosaics (Lericolais et al., 2009) or on the B2CH96 transect profile and dated to this period. This lowered sea level in the Black Sea persisted afterward. The post–Bølling-Allerød climatic event favored the lowering of the Black Sea water level, and the presence of the coastal sand dunes and wave-cut terraces confirms this lowstand. This had already been observed by several Russian authors who considered a sea-level lowstand at about –90 m depth. Their observations were based on the location of offshore sand ridges described at the shelf edge south of Crimea. The anastomosed buried fluvial channels described by Popescu et al. (2004) that suddenly disappear below –90 m depth and a unique wave-cut terrace on the outer shelf, with an upper surface varying between –95 and –100 m, are therefore consistent with a major lowstand level situated somewhere around –100 m depth. Around the Viteaz Canyon, the paleocoastline was forming a wide gulf into which two rivers flowed (Fig. 3). Previous studies have already proposed a depth of –105 m for this lowstand, according to a regional erosional truncation recognized on the southern coast of the Black Sea (Demirbag et al., 1999; Görür et al., 2001), but also based on a terrace on the northern shelf edge (Major et al., 2002b).

On the Romanian shelf, preservation of the sand dunes and buried small incised valleys are to be linked with a rapid transgression where the ravinement processes related to the water-level rise had no time to erode sufficiently the sea bottom (Benan and Kocurek, 2000; Lericolais et al., 2004). Circa 7500 ^{14}C yr B.P., the surface waters of the Black Sea suddenly attained present-day conditions owing to an abrupt flooding of the Black Sea by Mediterranean waters, as shown by dinoflagellate cyst records (Popescu, 2004). This can also be related with the beginning of widespread and synchronous sapropel deposition across slope and basin floor. At 7160 ^{14}C yr B.P., Popescu (2004) demonstrated a sudden (<760 yr according the resolution of their data) inflow of a very large volume of marine Mediterranean waters, causing an abrupt increase in salinity that attained the present-day euxinic values. This inflow of marine waters is confirmed by the abrupt replacement of freshwater to brackish species by marine species. Furthermore, the model developed by Siddall et al. (2004) shows that ~60,000 m^3 of water per second must have flowed into the Black Sea basin after the sill broke, and it would have taken 33 yr to equalize water levels in the Black Sea and the Sea of Marmara. Such a sudden flood would have preserved lowstand marks on the Black Sea northwestern shelf.

From part of this synthesis and based on the pseudo–3-D geometry of the seismic data interpreted by Lericolais et al. (2009), the water-level fluctuation diagram proposed here (Fig. 13) fits these synthesized observations.

CONCLUSIONS

This synthesis, based on data collected in the Black Sea from a 10 yr project, provides a solid record of water-level fluctuation during the Last Glacial Maximum in the Black Sea. The starting point of this synthesis is based on the evidence at the shelf edge in Romania, Bulgaria, and Turkey of a Last Glacial Maximum lowstand wedge. From the increase of water provided to the Black Sea by the melting of the ice after 18,000 yr B.P. and drained by the largest European rivers (Danube, Dnieper, Dniester), a Danube prodelta was built under ~40 m of water depth, corresponding to the ensuing transgressive system. Subsequently, the Black Sea lacustrine shelf deposits formed a significant basinward-prograding wedge system, interpreted as forced regression system tracts. On top of these prograding sequences, set of sand dunes delineates a wave-cut terrace-like feature around the isobath –100 m. These coastal features as well as the incised anastomosed channel system were preserved on the shelf because the final transgression was fast enough to preserve them. A uniform drape of marine sediment above the unconformity is present all over the continental shelf with practically the same thickness over nearby elevations and depressions. This mud drape represents the last stage of the Black Sea water-level fluctuation and is set after the reconnection of this basin with the Mediterranean Sea. From such behavior, it seems that the sedimentary sequences in the Black Sea were strongly affected by sea-level changes driven by global glaciations and deglaciations. The level of the Black Sea, to a certain extent, was controlled more by the regional climate than by global eustatic changes.

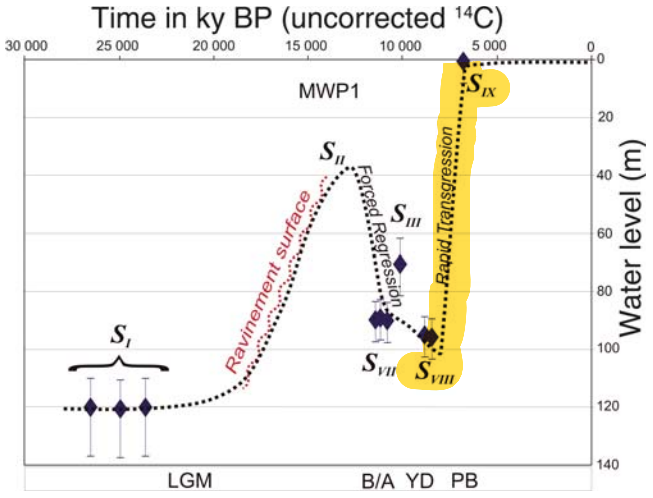

Figure 13. Water-level fluctuation in the Black Sea since the Last Glacial Maximum (LGM). MWP1—meltwater pulse 1A; B/A—Bølling-Allerød; YD—Younger Dryas; PB—Preboreal. S_{I} to S_{IX} are the sequences interpreted and dated from the Romanian Black Sea shelf. (S_{I} dates are: 23,630 ± 180; 24,980 ± 200, and 26,630 ± 230 ^{14}C yr B.P. S_{III} date is: 10,100 ± 50 ^{14}C yr B.P. S_{II}, S_{IV} to S_{VI} revealed no date. S_{VII} dates are: 11,040 ± 50, 10,930 ± 50, and 11,090 ± 50 ^{14}C yr B.P. S_{VII} dates are: 8760 ± 40 and 8600 ± 50 ^{14}C yr B.P. S_{IX} date is: 8620 ± 50 ^{14}C yr B.P.) Figure is modified from Lericolais et al. (2009).

The transition of the Black Sea system from a lacustrine to a marine environment is perhaps one of the best records of climate change on the European continent. Six major observations have documented this Black Sea behavior: (1) existence of two lowstand wedges, one dated from the LGM and covered by a second one dated from 11,000 yr B.P. to 8000 yr B.P. and located at a water depth ranging from –100 to –120 m; (2) a Danube prodelta built up at –40 m after the post-LGM meltwater pulses; (3) a set of meandering river channels capped by a regional unconformity and extending seaward across the Romanian shelf to the vicinity of the –100 m isobath; (4) evidence of submerged shorelines with wave-cut terraces and coastal dunes, or delta mouth bars at depths between –80 to –100 m, below Holocene Bosporus and Dardanelles Strait outlet sill to the global ocean; (5) observation on the western part of the Black Sea continental shelf of a shelf-wide ravinement surface visible in very high-resolution seismic-reflection profiles; and (6) the presence of a uniform drape of sediment beginning at the same time above the unconformity with practically the same thickness over nearby elevations and depressions and with no visible indication of coastal-directed onlap across the outer and middle shelf.

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