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Postglacial connection of the Black Sea to the Mediterranean and its relation to the timing of sapropel formation

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Abstract. The opening of the connection between the Mediterranean and Black Seas as sea level rose above the Bosporus sill has long been associated with the formation of the most recent, Holocene, sapropel deposit (S_1) in the eastern Mediterranean, but the mechanism has remained elusive. We present a model for the opening of the Black Sea, based on hydraulics arguments, which demonstrates that increased freshwater flux out of the Black Sea began 500-1000 years after sea level reached sill depth and that the timescale for the increased freshwater flux that drained the freshwater reservoir of the Black Sea is about 2500-3500 years. We argue that the increased freshwater discharge out of the Black Sea would lead to decreased deep water formation and higher productivity in the surface waters in the eastern Mediterranean, two conditions generally associated with sapropel formation. The delay in increased freshwater flux after the opening of the Black Sea and the period of increased freshwater discharge appear to match the onset and duration of sapropel deposits in the eastern Mediterranean.

Introduction

The near coincidence between the initiation of the most recent sapropel deposit (early Holocene, S_1) in the eastern Mediterranean and the arrival of global sea level at the level of the sill depth of the Black Sea in the Bosporus has long led to the speculation that freshwater effluent from the Black Sea may have been an important factor in initiating sapropel formation [*Olausson*, 1961]. Paleoceanographic proxy data from cores through sapropel S_1 indicate cool, low-salinity waters for the period 9600-6400 years B.P. [*Aksu et al.*, 1995]. The causal mechanism has remained elusive, however, as the size of the freshwater flow through the Black Sea does not seem large enough to reverse the freshwater budget of the eastern Mediterranean basin [*Béthoux*, 1993], as some would argue is necessary to cause sapropel deposits [*Stanley et al.*, 1975; *Sarmiento et al.*, 1988; *Thunell and Williams*, 1989]. In addition, the relative timing of the sea level arrival at sill depth and of the sapropel deposits is confusing, as it remains "to be explained why the opening of the marine connection through the Bosporus Strait would have preceded sapropel formation in the Black Sea by some 2150 years and in the eastern Mediterranean by only 1600 years" [*Rohling*, 1994, p.7]. The relevant chronology is summarized in Table 1.

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Throughout this paper, we report all ages in calendar years (B.P.), derived from reservoir-age corrected ^{14}C ages ($^{14}C_c$; kyrs B.P.) with program Calib3.0 [*Stuiver and Reimer*, 1993], and where necessary after correction of ^{14}C ages for a 400-year reservoir age [*Bard*, 1988; *Broecker et al.*, 1988; *Bard et al.*, 1990].

During the period when Mediterranean water is replacing the freshwater reservoir of the Black Sea, there must be an increased flux of freshwater out of the Black Sea into the Mediterranean basin. This extra flux is determined by the flow at the Bosporus Strait. As an indication of the scale of the extra flux, it is worth noting that if the freshwater volume of the Black Sea of 544,000 km^3 is drained over a period of 2000 years, the average additional freshwater discharge amounts to 8600 $m^3\ s^{-1}$.

Mamayev [1994] used a simple mixing box model to describe the salination of the Black Sea. In this model the exchange flux with the Mediterranean is fixed and the salinity in the Black Sea is assumed uniform. Thus the freshwater content of the Black Sea decays exponentially, with the largest change at the start of the process. A more sophisticated model using a number of boxes with flow and mixing between them was developed by *Boudreau and Leblond* [1989]. They considered two descriptions of the flow between the Mediterranean and the Black Sea: a fixed flow at today's value and a linearly increasing flow from no flow up to present-day flow. The latter description was intended to simulate the effect of increasing sea level on the exchange flow. Boudreau and Leblond's model allows for a more detailed

Table 1. Chronology of Main Events Showing Both $^{14}C_c$ Ages and Calendar Years

Event	$^{14}C_c$ Age	Calendar Years[a]	Comments
Sea level reaches sill depth			
−40 m	9,300[b,c]	9,900	9,900 used for
−60 m	10,300[b,c]	11,300	main model here
Onset of S_1 formation in eastern Mediterranean	7,900[d]	8,300	average 8,700
	8,500[e]	9,000	
Onset of sapropel formation in Black Sea		7,500[f]	

[a]Stuiver and Reimer [1993]
[b]Fairbanks [1989]
[c]Fairbanks [1990]
[d]Jorissen et al. [1993]
[e]Fontugne et al. [1994]
[f]Jones and Gagnon [1994]

description of the development of the vertical structure within the Black Sea. They recognize that the uncertainties in their model are "caused by uncertainty in the Mediterranean water input" (p.165). In order to investigate the consequences of reconnection between the Mediterranean and Black Seas, we have constructed a model based on established hydraulics principles for the evolution of the flow over the Bosporus sill as a function of the sea level relative to the sill depth during the past 10,000 years. Thus we directly calculate the flow between the Black Sea and the Mediterranean and show how it developed over time.

Exchange Prior to 10,000 Years Ago

Sill depth in the Bosporus channel connecting the Mediterranean and Black Seas is variously reported to be between 28 m and 60 m depth below present sea level [*Tolmazin*, 1985; *Oguz et al.*, 1990]. Our interpretation of the bathymetric chart of the Bosporus sill region presented by Oguz et al. is that the sill depth is between 35 and 40 m depth; for our model we use a standard sill depth of 40 m. Prior to about 10,500 years ago, global sea level was more than 60 m below present sea level [*Fairbanks*, 1989] so that the Black Sea existed as a lake disconnected from the Mediterranean; it had been a lake for more than 10,000 years. The Bosporus sill then represented a dam over which any excess freshwater inputs into the lake would spill out and then cascade down in a river to meet the Mediterranean Sea. At present the Black Sea has a positive freshwater budget in that precipitation and river inflows exceed evaporation. Estimates of the net freshwater flow into the Black Sea that ultimately exits through the Bosporus range from 5400 to 12,400 $m^3\ s^{-1}$ [*Tolmazin*, 1985; *Oguz, et al.* 1990], with the classically quoted value being 6800 $m^3\ s^{-1}$ [*Möller*, 1928]. It is thought that the water budget has remained similar over the past 20,000 years, although there may have been somewhat higher river inflows during periods of major deglaciation and perhaps somewhat higher precipitation during the monsoonal interlude 7000-9000 years ago [*Béthoux*, 1993]. For our model, we use a standard net freshwater flow through the Black Sea, Q_0, of 10,000 $m^3\ s^{-1}$.

As a lake, the Black Sea apparently exhibited wintertime deep convection due to net heat loss to the atmosphere so that the deep waters were rejuvenated with oxygen. Such overturning would also mix up the salinity remaining from a previous period of exchange with the Mediterranean, and the slightly saline waters would be flushed out over the Bosporus dam with a turnover time of order 1000 years. Over tens of thousands of years, the salinity of the Black Sea would diminish to negligible amounts. Thus 10,000 years ago the Black Sea was a freshwater lake (Black Lake) spilling out over the Bosporus dam to create a river cascading down to meet the Mediterranean Sea (Figure 1a). Simple hydraulic arguments [*Henderson*, 1966; *Gill*, 1977] can be used to estimate the height, H_L, of Black Lake above the Bosporus dam for a given flux of freshwater, Q_0, into Black Lake and then out over the dam.

For a freshwater flux of 10,000 $m^3\ s^{-1}$, the model (see below) indicates that the level of Black Lake would stand 5.2 m above the dam. When the freshwater entered the Mediterranean, intermixing would occur. Under present-day conditions, when the Mediterranean has a salinity of 38 while the Black Sea surface waters have a salinity of about 18, the fresh tongue (salinities less than 38) emanating at the surface from the Mediterranean exit of the Bosporus-Dardanelles protrudes about 300 km into the northern Aegean Sea [*Robinson et al.*, 1979]. Ten thousand years ago, when the freshwater discharge was about the same size but had a salinity anomaly relative to the Mediterranean about twice that of today, the freshwater tongue might be expected to have protruded farther into the Aegean.

Opening of the Black Sea

As global sea level rose, the level of the Mediterranean would eventually reach the top of the Bosporus dam. Because only a limited volume flux can get past the critical sill control, the freshwater would initially continue to flow out over the sill with effectively no counterflow of Mediterranean water back into the Black Sea (Figure 1b). Even as sea level rose, the flow over the sill would remain a one-layer discharge of freshwater until sea level had risen to a critical height (H_C) approximately 11 m above the sill, when the model shows that the character of the sill flow can switch to a two-layer exchange.

The *Fairbanks* [1989] sea level curve shows that the period from 11,300 to 9300 years ago, when sea level rose from 60 m to 30 m below the present level, represents the fastest change in sea level. With this sea level history, the model indicates that it would have taken a period of order 800 years after sea level reached Bosporus sill depth for sea level to rise enough above the sill for the two-layer exchange between the Black Lake and Mediterranean Sea to become established.

Once sea level rose to this critical depth above the sill, dense Mediterranean water would begin to dribble over the top of the sill (Figure 1c). As sea level continued to rise, the flow of Mediterranean water over the sill would increase and cascade down as a gravity current into the abyssal Black Sea (Figure 1d). To maintain the overall water budget for the Black Sea, the freshwater discharge over the sill would increase. The gravity current would entrain ambient Black Sea water as it descends. The Black Sea would begin to fill from the bottom with this dense fluid, some of which would be re-entrained into the current. The density structure in the Black Sea would develop as a "filling box" [see *Worster and Huppert*, 1983]. For this type of flow the density near the surface does not respond very rapidly to the inflow, and we make the simplifying assumption that we can ignore the mixing. Thus our model gives the maximum possible freshwater outflow, but we will discuss the effect mixing has on this estimate. When the salty Mediterranean water had filled the Black Sea up to within 50 m or so of sill depth (Figure 1e), we consider that the freshwater reservoir in the Black Sea has been effectively drained, and we imagine that a two-layer exchange similar to the present-day situation would have become established.

Model

To model the opening of the Black Sea, we can use steady hydraulics theory, as the sea level rise is very slow compared with the dynamical adjustment time for flow over the Bosporus sill. Initially, the one-layer flow over the Bosporus dam is hydraulically critical, and the height, H_L, of Black Lake above the sill in order to accomplish the freshwater discharge, Q_0, is

$$H_L = 1.5\,(Q_0^2/gW^2)^{1/3}$$

where W is the width of the Bosporus channel, which *Oguz et al.* [1990] estimated to be 500 m, and g is the gravitational acceleration. For a freshwater flux of 10,000 $m^3\ s^{-1}$, H_L is 5.2 m, so the level of Black Lake would stand 5.2 m above the sill.

As sea level rises up to sill depth, the level of Black Lake remains at H_L above the sill in order to maintain the freshwater flux Q_0. As sea level rises above the sill, the level of the Black Sea does not immediately rise; instead, the freshwater discharge over the sill remains critical and equal to Q_0, there is no counterflow of Mediterranean water into the Black Sea, and the freshwater spreads out over the Mediterranean water beyond the sill. As sea level rises up to and beyond H_L, the sill becomes "flooded" (in the single layer sense [*Henderson*, 1966]) and the level of Black Lake begins to rise in concert with sea level. Still there is no counterflow of Mediterranean water across the sill; the freshwater flux, Q_0, continues, but the flow across the sill is now hydraulically subcritical.

Once sea level rises just beyond a critical height, H_C, above the sill, the flow switches to a hydraulically critical two-layer exchange across the sill in which there is a net barotropic flux Q_0. This is the time when Mediterranean water begins to enter the Black Sea with an inflow Q_2. The upper layer outflow of freshwater, Q_1, equals the sum of the barotropic flux, Q_0, and the lower layer inflow Q_2. The critical height H_C at which the flow switches to a two-layer exchange is given by [*Dalziel and Lane-Serff*, 1991]

$$H_C = (Q_0^2/g'W^2)^{1/3}$$

where $g'=g\,(\rho_2-\rho_1)/\rho_2$, ρ_2 is the density of Mediterranean water and ρ_1 is the density of fresh Black Sea water so that $(\rho_2-\rho_1)/\rho_2$ is approximately 0.03 and the corresponding critical height, H_C, is approximately 11 m.

In order to calculate the magnitudes of the outflowing freshwater flux and the inflowing Mediterranean water flux, we need to estimate the height above the sill, H_I, of the interface between the outflowing freshwater and inflowing Mediterranean water. The height of this interface is, in general, a complicated function of the net barotropic flux and depends on the precise geometry of the channel around the sill [see, for example, *Dalziel*, 1991; *Dalziel and Lane-Serff*, 1991]. For simplicity we assume that for a given total depth above the sill of H, the interface height is a linear function of the net flux,

$$H_I/H = 1/2\,(1-Q_0/((g'H)^{1/2}HW)$$

or

$$H_I/H = 1/2(1-(H_C/H)^{3/2}).$$

This approximation is likely to overestimate the interface

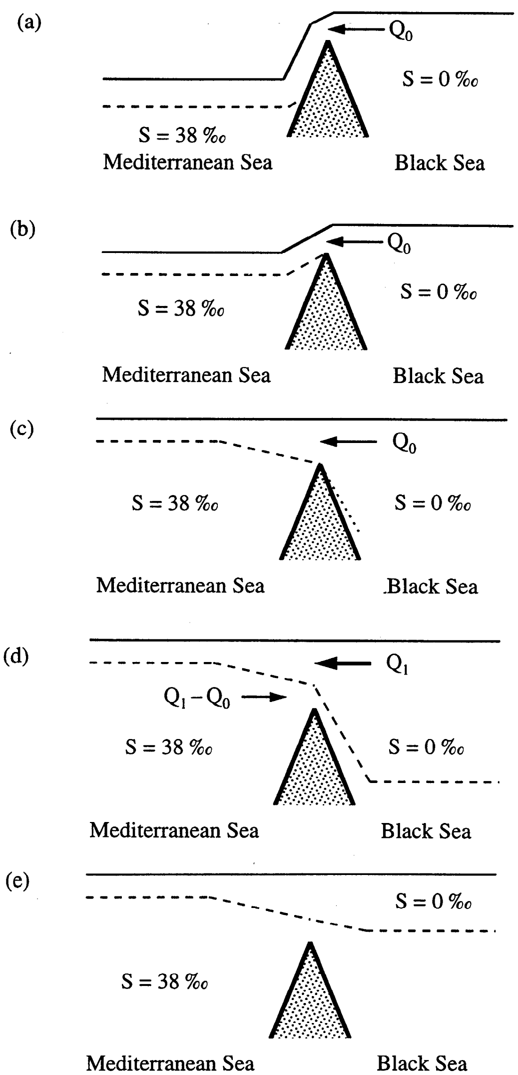

Figure 1. Schematic of the modeled exchange between the Mediterranean and Black Seas across the Bosporus sill at different times for a sequence of heights of the global (Mediterranean) sea level: (a) when sea level was below the sill and the Black Sea was a lake isolated from the Mediterranean; (b) when sea level arrived at sill depth and the Black Sea still stood at a level above the sill to allow the required freshwater discharge; (c) when sea level reaches critical height, H_C, above the sill so that two-layer exchange becomes possible and Mediterranean water begins dribbling over the sill down into the abyssal Black Sea; (d) when sea level is well above the sill so that a full two-layer exchange occurs across the sill and the Black Sea freshwater reservoir is being actively drained as salty Mediterranean fills the deep Black Sea (with our simplifying assumption of no mixing); and (e) when the salty Mediterranean water has filled the Black Sea up to near-sill depth and the freshwater reservoir has been effectively drained. The dotted line represents the interface between dense Mediterranean water and fresh water.

height and the amount of exchange. For example, for the case of a pure exchange flow, with no net flux, our approximation puts the interface at half the fluid depth, whereas the interface is generally below this level [*Dalziel*, 1991]. Such approximation leads to an overestimate of the exchange flux of the order of 15% for the worst case of no net flux in a channel with straight sides (that is, for a pure sill with no contraction in width). However, given other uncertainties in the calculation, such as the use of a rectangular channel (which may contribute a further 10%) and the approximate value of Q_0, this does not make a significant difference to the results.

The conditions at the sill must be hydraulically critical, so that the composite Froude number is unity:

$$\frac{U_1^2}{g'(H-H_I)}+\frac{U_2^2}{g'H_I}=1,$$

where U_1 and U_2 are the velocities in the upper and lower layers, respectively. This, together with the mass conservation equation, $Q_1=Q_0+Q_2$, gives a quadratic equation for the freshwater discharge, the solution of which is

$$\frac{Q_1}{Q_0}=\frac{1+\sqrt{1-\left(1+\left(\frac{H_I}{H-H_I}\right)^3\right)\left(1-\left(\frac{H_I}{H_C}\right)^3\right)}}{\left(1+\left(\frac{H_I}{H-H_I}\right)^3\right)}.$$

The additional freshwater flux, $Q_1 - Q_0$, effectively begins to drain the freshwater reservoir of the Black Sea once the two-layer flow is established. As sea level continues to rise beyond H_C, the amount of deep water inflow increases, with a concomitant increase in the upper layer outflow of freshwater as the two-layer exchange maintains a hydraulically critical condition at the sill. Once all of the freshwater content of the Black Sea has flowed out across the sill and been replaced by high-salinity Mediterranean waters, the two-layer exchange of freshwater and high-salinity Mediterranean water must cease. It is at this point that we assume the exchange is influenced by the presence of saline water in the Black Sea. In practice, the mixing processes will have had an effect on the flow throughout the exchange (see below). Today, the salinity of the upper Black sea waters flowing out into the Mediterranean across the Bosporus sill is about 18.

To establish the timescales of the exchange, we have used the *Fairbanks* [1990] curve of sea level versus time. We have run the model assuming sill depths of 60 m and 40 m and with freshwater inputs of 0, 10,000 and 20,000 m^3 s^{-1} into the Black Sea. For each case, we start the model from the time when sea level is at the level of the sill. From each year's sea level, we estimate the size of the freshwater flux out of the Black Sea, Q_1, from our simplified steady hydraulics theory. We integrate the excess freshwater discharge, $Q_1 - Q_0$, over time and subtract the integrated value from the volume of the Black Sea to determine the remaining freshwater content of the Black Sea reservoir versus time. When this freshwater content becomes zero, we stop the calculation, the freshwater reservoir having been completely depleted. For our standard values of sill depth (40 m) and freshwater input (10,000 m^3 s^{-1}), the model shows that the increased discharge of freshwater begins about 800 years after sea level arrived at sill depth; the freshwater discharge increases by more than 80% as sea level rises; and it takes about 3700 years after the two-layer exchange starts for the freshwater reservoir to be completely discharged (Figure 2). For a sill depth of 60 m but the same input of 10,000 m^3 s^{-1}, the increased discharge begins about 1000 years after sea level reaches sill depth and the discharge more than doubles, reaching a final value of 23,700 m^3 s^{-1} before the reservoir is depleted after 2400 years. Larger freshwater inputs into the Black Sea somewhat surprisingly slow up the depletion of the reservoir, as sea level must rise higher above the sill in order to establish the two-layer exchange and the rise in sea level begins to slow so that the increased exchange takes much longer to establish. The results for a range of freshwater inputs to the Black Sea and different sill depths are summarized in Table 2.

As mentioned, mixing will have an impact on the flow. Initially, however, mixing processes will only have a small effect since the inflow of Mediterranean water will not affect the surface salinity in the Black Sea for some time and the initial changes will, in any case, be small. Eventually, the effective freshwater flux from the Black Sea into the Mediterranean will be reduced because the density difference will be reduced (leading to smaller exchange flows) and because the fresh water content of the Black Sea water will be reduced. If we allow complete mixing in the Black Sea (clearly an extreme case since there is significant stratification at present and we expect stronger stratification in the past), then the standard case we considered above (sill depth 40 m and freshwater input of 10,000 m^3 s^{-1}) gives a maximum effective freshwater discharge of 12,400 m^3 s^{-1} about 1500 years after the exchange flow starts. However, the salinity in this mixing model only reaches 14 by the present day, so clearly the flow is underestimated. It is important to note that the time lag between sea level reaching sill depth and the onset of two-layer flow is unaffected by the processes in the Black Sea.

Discussion

The formation of the S_1 sapropel in the Mediterranean occurred between about 9000 and 6400 (calendar years) B.P. [*Fontugne et al.*, 1994] but may have lasted to about 5300 years B.P. [*Higgs et al.*, 1994]. It is generally thought to be associated with several processes, notably a cessation of deep water formation in the eastern basin [*Rohling*, 1994] and higher productivity in the surface waters of the eastern Mediterranean. The emptying of the freshwater reservoir of the Black Sea would contribute to both these processes. First, the increased freshwater flux out of the Black Sea as sea level rose above the Bosporus sill would reduce the surface water salinity over a large portion of the eastern Mediterranean, increasing the stability between the surface and deep waters and limiting deep convection. Second, the glacial runoff stored in the reservoir may be high in nutrients. Whether the freshwater discharge from the Black Sea would be sufficient to reverse the overall water deficit of the eastern basin is arguable. Scaling down *Béthoux*'s [1980] estimate of the net water loss over the eastern basin to reflect recent direct estimates of the overall water deficit for the entire Mediterranean of 52 cm yr^{-1} [*Bryden et al.*, 1994] suggests that there is at present a net evaporative loss of freshwater of 56 cm yr^{-1} for the eastern basin, or 34,000 m^3 s^{-1}. We believe that the water budget for the Mediterranean has remained similar to the present situation over the past 10,000

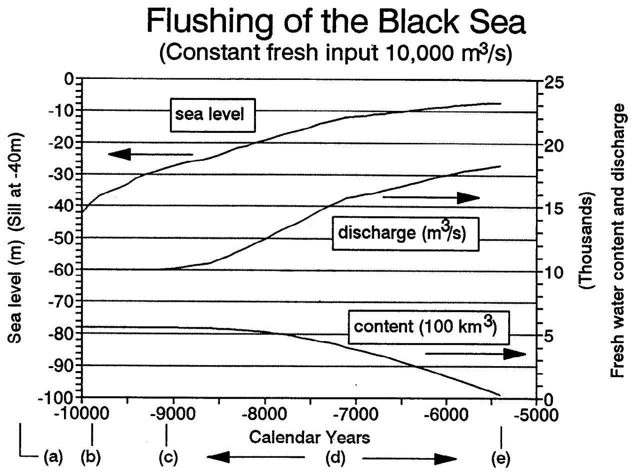

Figure 2. Time history of global sea level, freshwater discharge over the Bosporus sill, and the freshwater content of the Black Sea reservoir for the model run with sill depth at 40 m below present sea level and with a constant freshwater input (precipitation plus river inflows minus evaporation) to the Black Sea of 10,000 $m^3\ s^{-1}$. The letters a-e on the time axis correspond to the times or periods when the modeled flow is as shown in Figures 1a-1e. The *Fairbanks* [1990] curve for the time history of global sea level is shown (adjusted to give calendar years), indicating that sea level reached the Bosporus sill depth of 40 m about 9900 years ago (letter b) and shallowed by about 30 m over the succeeding 3000 years. The freshwater discharge began to increase at about 9100 years B.P. (or 800 years after sea level reached sill depth), as global sea level reached the critical height, H_C, above the sill so that two-layer exchange could be established (letter c). The freshwater discharge into the Mediterranean eventually reaches a maximum rate of 18,300 $m^3\ s^{-1}$ as it drains away the freshwater content of the Black Sea (period for two-layer flow: letter d). For this case, the freshwater content of the Black Sea reservoir became completely depleted over a period of about 3700 years, ending at about 5400 years B.P. (letter e).

years. For the model cases we ran, only the conditions of large freshwater input (20,000 $m^3\ s^{-1}$) to the Black Sea and a sill depth of 60 m yield a freshwater outflow over the Bosporus sill approaching 34,000 $m^3\ s^{-1}$. Thus, while it is possible that the overall water budget of the eastern Mediterranean may have been reversed, we consider it more likely that the increased freshwater outflow over the Bosporus sill merely stabilized a large area of the eastern Mediterranean and reduced the amount of deep water formation so that higher productivity in the surface waters could not be completely oxidized as it sank into the deep waters, resulting in the formation of sapropel deposits.

This model for the opening of the Black Sea appears to offer a reasonable explanation for the timing of the most recent, early Holocene, sapropel S_1. We had previously been confused as to why the opening of the Black Sea should have preceded sapropel formation in the eastern Mediterranean by more than 1200 years. Consideration of the hydraulics of the flow over the sill demonstrates that the increased freshwater discharge from the Black Sea, which is perceived to be fundamental to sapropel formation, does not occur simultaneously with arrival of sea level at sill depth. Instead, there is a time lag until sea level has risen to about 10 m above sill depth, when the increased freshwater discharge begins during the transition to a

Table 2. Summary of the Model Results for Different Sill Depths and Freshwater Inputs into the Black Sea

Sill depth	No Freshwater Input	Freshwater Input 10,000 $m^3\ s^{-1}$	Freshwater Input 20,000 $m^3\ s^{-1}$
40m			
Exchange flow period, years B.P.	9,900-6,800	9,100-5,400	8,300-3,500
Maximum freshwater discharge, $m^3\ s^{-1}$	10,500	18,300	25,600
60m			
Exchange flow period, years B.P.	11,300-8,600	10,300-7,900	9,900-7,300
Maximum freshwater discharge, $m^3\ s^{-1}$	14,100	23,700	32,800

Shown are the periods (in calendar years) over which there is an exchange flow and the value of the maximum freshwater discharge into the Mediterranean. The case for sill depth 40 m and flux 10,000 $m^3\ s^{-1}$ is shown in more detail in Figure 2.

hydraulically controlled two-layer exchange flow. Even after the two-layer flow is established, the enhancement to the freshwater discharge is initially weak, with an increase of 10% taking about 500 years (see Figure 2). We had also been confused as to why sapropel formation in the Black Sea was not simultaneous with that in the Mediterranean, but started later by order 1200 years. Again, the model suggests that the filling of the Black Sea with salty Mediterranean waters is a process that begins only when the two-layer exchange flow across the sill becomes established. By the time the Black Sea is completely filled with Mediterranean waters, 2000-3000 years after the arrival of sea level at sill depth, we would surely expect sapropel deposits in the Black Sea. However, exactly when sapropels would begin to be deposited in the Black Sea would depend on how quickly the oxygen content of the newly entered Mediterranean waters in the deep Black Sea is used up by the detritus raining down from the productivity near the surface. A delay of 500-600 years in the formation of sapropel deposits in the Black Sea after the two-layer exchange process begins at the Bosporus sill does not seem unreasonable.

Finally, the model suggests a rationale for the duration of sapropel deposits, which appears to be about 2500-3500 years in the eastern Mediterranean basin [*Fontugne et al.*, 1994; *Higgs et al.*, 1994]. We associate such a time period with the duration of increased freshwater discharge over the Bosporus sill, that is, with the length of time it takes to drain the Black Sea freshwater reservoir. For the range of sill depths and freshwater fluxes we have used, this time varies from 2400 to 4800 years, the shorter periods being associated with greater sill depths. For a sill at 40 m and a basic freshwater discharge of 10,000 $m^3\ s^{-1}$, the draining of the reservoir takes about 3700 years (with significant extra discharge over a shorter period), a time not dissimilar to the duration of the sapropel deposits. Choosing a slightly greater sill depth, adjusting the sill shape and exchange flow equation, or including a more detailed description of the flow in the Black Sea would enable the timing to be adjusted so that both the initiation of sapropel deposits and their duration could be matched by the period of substantially increased freshwater discharge out of the Black Sea. Such tuning, however, is not fundamental to the nature of the opening of the Black Sea, nor to the mechanism proposed here for the timing of sapropel formation deposits in the Mediterranean and Black Seas.

It should be emphasized that although the model explains the sequence of events following reconnection of the Black Sea during the last deglaciation, the proposed mechanism should not be viewed as the exclusive cause of sapropel formation. Sapropels have been found to occur not only in interglacial periods of high sea levels, but also in glacial and interstadial intervals when sea level was probably considerably below the Bosporus sill depth [*Cita et al.*, 1977; *Thunell et al.*, 1983; *Thunell et al.*, 1984].

In summary, we suggest that the increased freshwater discharge from the Black Sea as sea level rose above the Bosporus sill depth could have had an important influence on the formation of the S_1 sapropel deposits in the eastern Mediterranean basin. The freshwater discharge increased to approximately twice the normal Black Sea freshwater flux as the freshwater reservoir stored in the Black Sea was drained out into the Mediterranean. Such increased discharge would lead to the stabilization of a large portion of the eastern Mediterranean by low-salinity surface waters, which would lead to lower production of deep waters in the eastern Mediterranean even if the increased discharge were not large enough to reverse the overall water deficit of the eastern Mediterranean, and would arguably add nutrients to eastern Mediterranean surface waters, leading to increased productivity. We have shown that there is a lag between the sea level reaching sill depth and the onset of exchange flow. We calculate that the significant increase in freshwater discharge occurs about 1500 years after the opening of the Black Sea and thus corresponds with the observed delay in Mediterranean sapropel deposits after global sea level reached the sill depth of the Bosporus. The 2500- to 3500-year period of increased discharge as the freshwater reservoir of the Black Sea was drained into the eastern Mediterranean also matches the observed timescale of sapropel deposits in the eastern Mediterranean.

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