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Testing the physical oceanographic implications of the suggested sudden Black Sea infill 8400 years ago

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[1] We apply a shock-capturing numerical model based on the single-layer shallow water equations to an idealized geometry of the Black Sea and the Sea of Marmara in order to test the implications of a suggested sudden Black Sea infill 8400 years ago. The model resolves the two-dimensional flow upstream and downstream of the hydraulic jump provoked by the cascade of water from the Sea of Marmara into the Black Sea, which would occur during a sudden Black Sea infill. The modeled flow downstream of the hydraulic jump in the Black Sea would consist of a jet that is in part constrained by bathymetric contours. Guided by the Bosporus Canyon, the modeled jet reaches depths of up to 2000 m and could explain the origin of the sediment waves observed at this depth. At a late stage of the infill the modeled jet is attached to the coast and might account for the course of a submerged channel at the mouth of the Bosporus. The preservation of continuous barrier-washover-lagoonal fill systems occurring on the Black Sea shelf is, however, not easily reconcilable with the large flows over the southwest Black Sea shelf predicted by the model. Intensified flow in the upstream basin (Sea of Marmara) is restricted to the immediate vicinity of the Bosporus, suggesting that a sudden reconnection need not have disturbed sediments in the wider Sea of Marmara. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4599 Oceanography: Physical: General or miscellaneous; 4255 Oceanography: General: Numerical modeling; *KEYWORDS:* Black Sea, flood hypothesis, dam break

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1. Introduction

1.1. Background

[2] Considerable controversy has surrounded the nature of the postglacial reconnection of the Black Sea to the Sea of Marmara (Figure 1) since *Ryan et al.* [1997] proposed a catastrophic marine flooding of the Black Sea at 7150 years BP (all dates are given in radiocarbon convention years, i.e., without reservoir correction or further calibration). The key pieces of evidence for the sudden infill were [*Ryan et al.*, 1997]: (1) the abrupt arrival of marine species in the Black Sea; (2) the presence of an apparent subaerial erosion surface above the 150 m bathymetric contour in the Black Sea and; (3) The absence of a coastal onlap in the brackish to marine mud drape above the latest widespread unconformity on the Black Sea shelf. In support for the Ryan hypothesis *Ballard et al.* [2000] uncovered features which seem to indicate the presence of an isolated beach profile at 155 m depth. *Uchupi and Ross* [2000] have observed large hills at depths as great as 2000 m near the Bosporus Canyon and orientated perpendicularly to the canyon axis. *Major et al.* [2003] revised the date for the catastrophic reconnection to 8400 BP. They further argued that a fresh outflow from the Black Sea lake may have been possible during the Younger Dryas prior to the marine connection, but that a subsequent change in the regional water budget led to a sea level drawdown that exposed the shelf to a depth of −55 m or lower prior to the marine connection at 8400 BP. We use the term "sudden infill scenario" to refer to the type of reconnection suggested by *Ryan et al.* [1997] and also known as the "shallow sill" scenario of *Major et al.* [2003].

[3] Prior to the work of *Ryan et al.* [1997], the commonly held view had a relatively fresh Black Sea drain into the Sea of Marmara during the process of gradual reconnection. As global sea level rose, a two way flow was established in the Bosporus with saline water from the Sea of Marmara penetrating into the Black Sea below the fresher outflow. The hydraulics of this type of reconnection have been studied in some depth by *Lane-Serff et al.* [1997]. We shall refer to this alternative hypothesis as the "gradual reconnection," scenario. The gradual reconnec-

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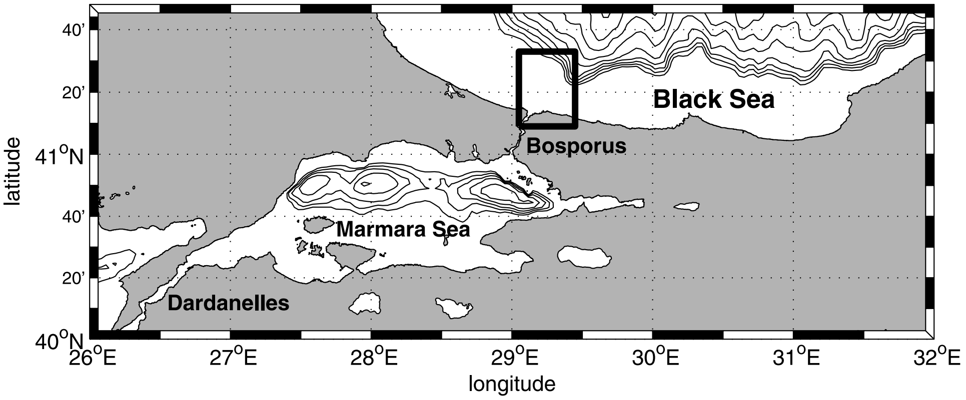

Figure 1. Map of the Marmara and Black Seas (bathymetry from *Smith and Sandwell* [1997]).

tion scenario is supported by evidence from the Sea of Marmara. An outflow delta at the mouth of the Bosporus [*Hiscott et al.*, 2002] and sediment waves near the Dardanelles [*Aksu et al.*, 1999a] orientated toward the Mediterranean have been suggested to be the strongest evidence for the gradual reconnnection [*Aksu et al.*, 2002a, 2002b]. These features are said to be the result of strong Black Sea outflow during a gradual reconnection. It is further assumed that these depositional features would not survive the supposedly strong eastward currents generated by the sudden Black Sea infill [*Aksu et al.*, 1999a; *Hiscott et al.*, 2002].

[4] *Lane-Serff et al.* [1997] consider the physical oceanographic implications of a gradual reconnection on the Black Sea. For the first time we consider the physical oceanographic implications of a sudden infill scenario. We take the suggested boundary conditions of *Ryan et al.* [1997] and *Major et al.*'s [2003] "shallow sill," scenario (i.e., Marmara Sea level, sill depth, Black Sea levels) to force a shock-capturing numerical model. In this way we test their hypothesis against the implications of a possible sudden reconnection on the physical oceanography/sediment record of the Marmara-Bosporus-Black Sea system. Any discussion of the precise timing and implied climatic developments prior to any sudden reconnection are beyond the scope of this paper.

1.2. Bathymetry

[5] The Bosporus Strait connects the Black Sea to the Sea of Marmara with a typical width of 3 km (Figure 1). Along its length the strait is typically 60 m deep with a 40 m deep sill toward the south [*Gregg and Özsoy*, 2002]. At the sill the channel width is 1.5 km (Figure 2). The Bosporus Strait continues into the Black Sea as a submerged channel that splits into two branches. One branch is approximately 15 m deep and curves sharply toward the northwest [*Gregg and Özsoy*, 2002] (Figure 3). The other branch forms a channel 0.2–0.5 km wide and 10–25 m deep which connects the Bosporus Strait to the Bosporus Canyon (Figure 3) [*Aksu et al.*, 2002c]. The head of the Bosporus Canyon is close to the shelf edge where the canyon descends abruptly to depths of approximately 600 m [*Demirbag et al.*, 1999]. The canyon extends to depths greater than 2000 m toward the center of the Black Sea [*Melnik*, 1995].

1.3. Aims

[6] The existing evidence is still deficient in providing a definite answer on the nature of the Holocene Black Sea reconnection to the world ocean. The two and three dimensional flow patterns associated with the different reconnection scenarios are likely to be significant in resolving this problem. A sudden reconnection would involve a saline river crossing the Black Sea shelf and flooding the Bosporus Canyon [*Demirbag et al.*, 1999]. Where Marmara water met the Black Sea a hydraulic jump would be formed. This hydraulic jump might introduce significant potential vorticity gradients into the fluid [*Pratt*, 1983] thereby altering the stability and path of the downstream flow [e.g., *Schär and Smith*, 1993]. Here we explore the flow patterns associated with a sudden infill and attempt to discriminate some of their unique characteristics using a single layer, shock-

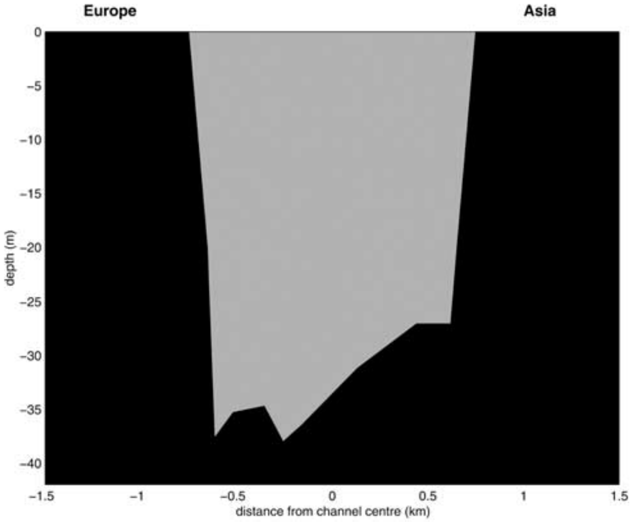

Figure 2. Bosporus cross section at the sill. The bathymetry is modified after *Gregg and Özsoy* [2002].

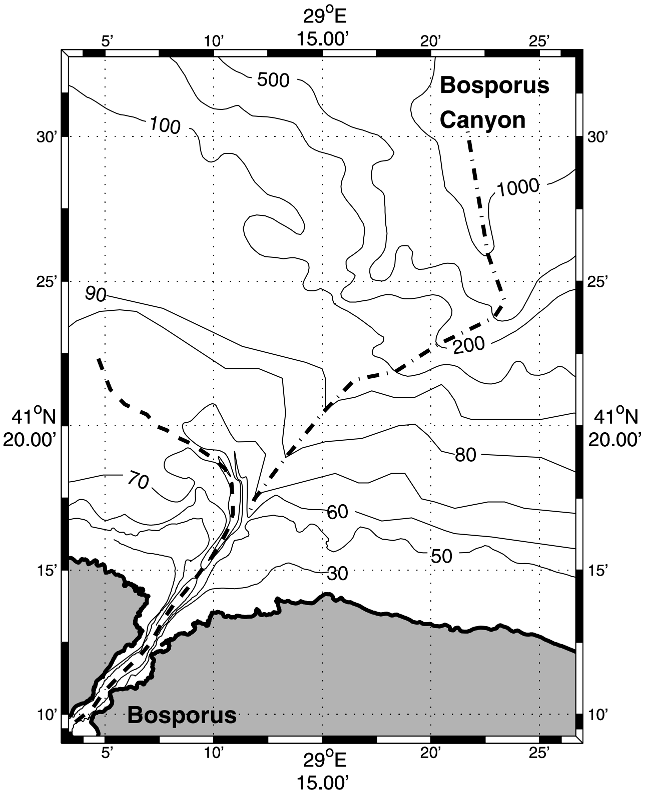

Figure 3. Detailed map of the area within the black box in Figure 1. The dashed line represents the Bosporous thalweg, modified from *Gregg and Özsoy* [2002], and indicates the position of the channel, which turns sharply to the northwest at the mouth of the Bosporus. The dash-dotted line represents the channel crossing the Black Sea shelf from the Bosporus Strait to the Bosporus canyon, adapted from *Aksu et al.* [2002c].

capturing model with bathymetry resembling that of the Black Sea.

2. Method and Limitations

[7] Our approach to understanding the flow patterns associated with a sudden infill has been to work toward first understanding the most significant currents involved in the sudden Black Sea infill and to build on this with later work. Here we explain the reasons for our current approach and its limitations.

[8] The model solves the single-layer shallow water equations in flux form [*Helfrich et al.*, 1999]

$$\frac{\partial}{\partial t}(ud) + \frac{\partial}{\partial x}\left(u^2 d + {}^1\!/_2\, g d^2\right) + \frac{\partial}{\partial y}(uvd) - fvd = -gd\frac{\partial h}{\partial x} - c_f u\sqrt{u^2+v^2} + \upsilon\nabla(d\nabla u), \tag{1}$$

$$\frac{\partial}{\partial t}(vd) + \frac{\partial}{\partial y}\left(v^2 d + {}^1\!/_2\, g d^2\right) + \frac{\partial}{\partial x}(uvd) + fud = -gd\frac{\partial h}{\partial y} - c_f v\sqrt{u^2+v^2} + \upsilon\nabla(d\nabla v), \tag{2}$$

$$\frac{\partial}{\partial t}d + \frac{\partial}{\partial x}ud + \frac{\partial}{\partial y}vd = 0, \tag{3}$$

where u and v are the layer average velocities in the x and y directions, respectively, d is the fluid layer depth and h is the bottom elevation. The Coriolis frequency is f and g is the acceleration due to gravity. In these calculations the coefficient of lateral friction υ is set to a small nominal value of 0.1 $m^2\ s^{-1}$ to avoid numerical instability. The bottom drag coefficient, c_f, was fixed at 0.003. In all cases $g = 9.81$ m s^{-2} and $f = 9.5 \times 10^{-5}$ s^{-1}, a value appropriate for the latitude of the Bosporus. The model time step, nondimensionalized by f was 5×10^{-6}. In order to represent the reservoir-strait configuration it was necessary to construct an irregular grid of smoothly varying sized cells known as a curvilinear grid. The grid consists of 320 points along the domain by 80 points. The curvilinear domain consists of two reservoirs connected by a narrow strait (Figure 4a). Orlanski type radiation boundary conditions were used at the upstream and downstream limits of the domain [*Orlanski*, 1976]. Slip conditions were imposed on any vertical sidewalls on the edges of the domain. Further details of the numerical methods and testing can be found in the work of *Helfrich et al.* [1999] and *Helfrich and Pratt* [2003]. The model permits fluid to flow over dry land, allowing us to initiate the model using a step function at the sill to represent the initial sea level in the Sea of Marmara (Figure 4b). The level in the Sea of Marmara is set at the global sea level at 8400 BP, which was 30 m below modern levels [*Fairbanks*, 1989]. Following the initiation of the model the fluid within the domain flowed into the lower (Black Sea) reservoir, where it forms a hydraulic jump. The model was run to a quasi-steady state to give the results discussed below. Additional model integrations were carried out to assess the robustness of the model result to the values chosen for the bottom drag coefficient, c_f, the lateral friction coefficient, υ, and the model time step. The model result proved insensitive to order of magnitude changes in each. The model result is in agreement with simple, inviscid nonrotating hydraulic theory [*Gill*, 1977].

[9] A simplified bathymetry was used to facilitate running the model and interpreting results while preserving the principal features of the seafloor. The model domain consists of two basins 1200 m and 2000 m deep, representing the Sea of Marmara and the Black Sea, respectively. All depths are referenced to modern sea level. The upstream (Marmara) basin was allowed to very slowly empty into the lower (Black Sea) basin (Figure 4). Owing to the large volume of the basins neither the water level in the basins nor the sill flux changed significantly during the period of the model runs once steady flow was established at the sill. The Bosporus is represented in the model by a 60 m deep, 3 km wide, 30 km long channel with a 40 m deep sill, which is situated 10 km from the Sea of Marmara and 20 km from the Black Sea (Figure 4). A 15 m deep channel connects the Bosporus to the Bosporus Canyon. The modeled canyon cuts into the Black Sea shelf approximately 20 km from the mouth of the Bosporus reaching depths of up to −600 m. The canyon extends down to the center of the Black Sea [*Melnik*, 1995]. The strait, channel, and the canyon are in

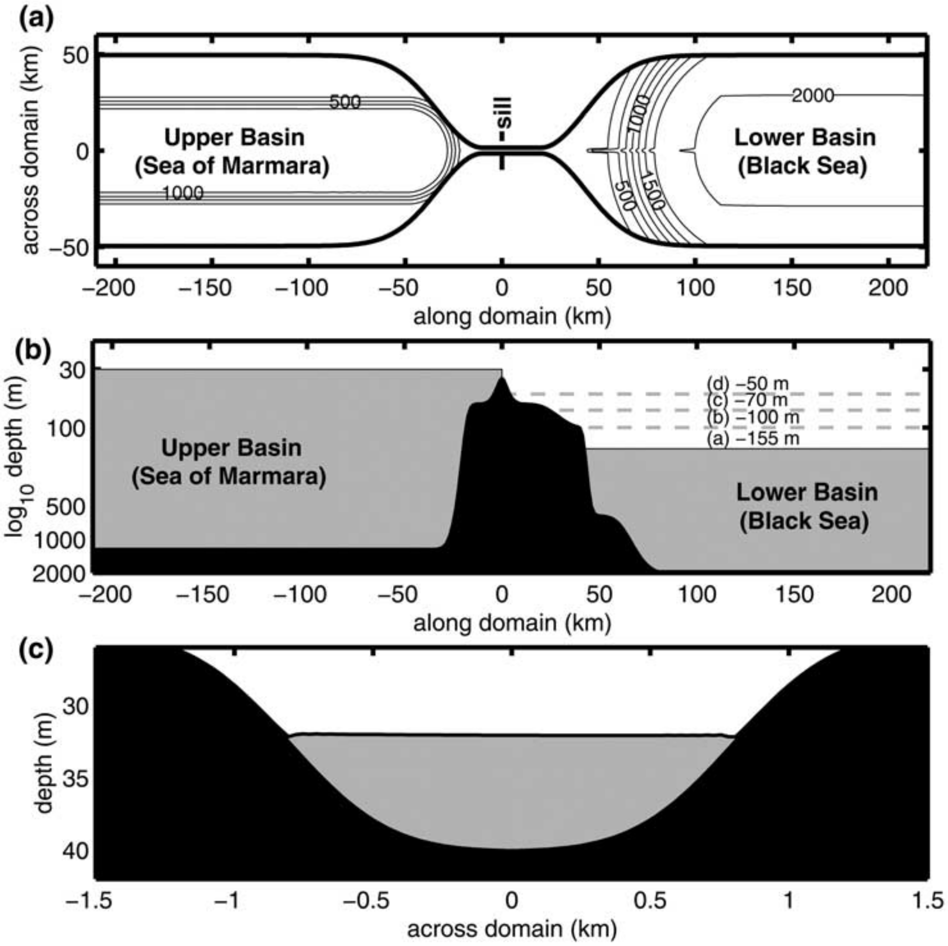

Figure 4. The model domain: (a) plan view; (b) depth along the central axis of the domain. The gray area represents the initial water levels for the case when the lower (Black Sea) basin is set to −155 m. The labeled dashed lines represent the Black Sea levels prescribed for the other model runs (see text for details); (c) cross section of the model channel at the sill. The gray area represents steady state water levels at the sill.

line with each other and are symmetric about the longitudinal (y) axis of the model. The dimensions and slopes of the strait, channel and canyon, and their relative positions on the shelf are similar to those of the actual Black Sea. The width of the strait, channel and canyon is kept constant at 2 km and they are all parabolic in cross section.

[10] Two mechanisms have been suggested for the dam break; tectonic movement [*Demirbag et al.*, 1999] and erosion of an earth dam [*Ryan et al.*, 1997]. The mechanism of the dam break would affect the nature of the flow adjustment immediately after the event, but not the general characteristics of the flow once it had fully developed. Further uncertainty is involved with modeling the flow immediately following reconnection since the presence of vegetation makes it difficult to predict appropriate values for the friction coefficients c_f and ν. We therefore concentrate on the "infill period," following the establishment of the saline river connecting the Bosporus to the Black Sea up until the Black Sea has reached the level of the Sea of Marmara. Here we are primarily interested in the flow downstream of the hydraulic jump located where the saline river meets the Black Sea.

[11] Ideally we would run the model continually from the start of the infill until the lower basin was at the same level as the upper basin. Given computing limitations this would take a prohibitively long period of time so instead we prescribe four different levels for the lower (Black Sea) reservoir. These levels represent four different stages of the infill (Figure 4b). During the infill water leaving the Sea of Marmara flows through the Bosporus to meet the Black Sea. Where Marmara water meets the Black Sea a hydraulic jump is formed. The four prescribed Black Sea levels are chosen so that the hydraulic jump is situated: (1) within the Bosporus Canyon at −155 m; (2) at the head of the Bosporus Canyon at −100 m; (3) on the Black Sea shelf at −70 m; and (4) within the Bosporus Strait at −50 m. The upper (Marmara) reservoir level was set at −30 m, the level found at 8400 years BP [*Fairbanks*, 1989] (Figure 5). This approach has allowed us to consider the currents close to the Bosporus resulting from the suggested sudden infill but not

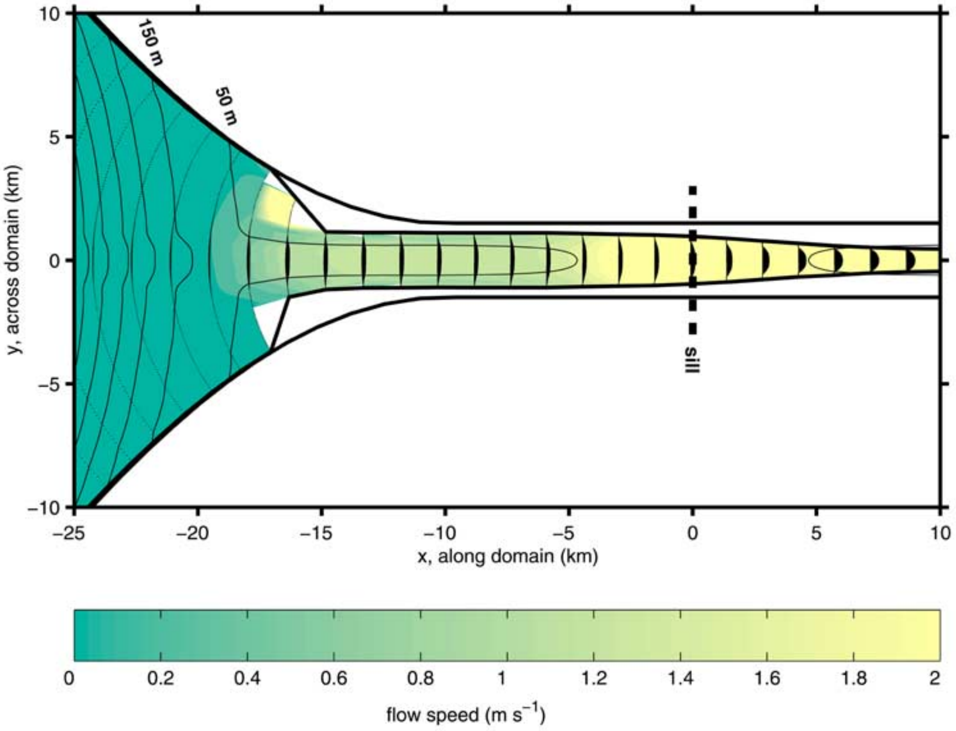

Figure 5. The steady state flow in the upper (Marmara) basin. The flow is from left to right in the image. The outer thick black line represents the limit of the model domain. The water's edge is marked by the heavy black line within the model domain. The contours are isobaths marked above the plot. This flow is identical in all of the model runs. Note the reduced flow speed in the Sea of Marmara.

the wider, basin-scale circulation which may evolve over long periods of time in the filling (Black Sea) basin.

[12] *Demirbag et al.* [1999] give evidence based on local faulting mechanisms that the sea level in the Black Sea was at −105 m at the time of the sudden infill, not −155 m as suggested by *Ballard et al.* [2000]. *Major et al.* [2003] suggest a drawdown sea level in the Black Sea as shallow as −55 m. Our results take into account the uncertainty in the Black Sea level at the time of the sudden reconnection by considering the infill at several initial levels in the Black Sea.

[13] As the saline Marmara water flowed into the fresh Black Sea during the suggested sudden infill there would be a tendency for this water to be subducted under the less dense Black Seawater. In addition to this baroclinic response there would also be a barotropic response associated with the tendency of Marmara water to push the Black Seawater sideways out of its path. In two-layer fluid flows involving a mixed response such as this, the velocity of the baroclinic motions is generally of the order of $(g'D)^{1/2}$ where g' is the value of gravity reduced in proportion to the density difference between the saline and the fresh water and D is the fluid depth. For the problem at hand $g'/g \cong 1/50$. On the other hand, the barotropic velocities produced by the Marmara fluid running down the slope into the Black Sea will be of the order of $(gD)^{1/2}$ and therefore be an order of magnitude larger than the baroclinic velocity. Because of this scale separation the primary response, at least in the region of the channel and upper canyon, will be primarily barotropic. This serves as justification for using a homogeneous shallow-water model in this initial consideration of the flows resulting from sudden reconnection.

[14] The model does not include an embedded sediment transport model. Consequently there is no feedback between the flow structure and the bathymetry. In a first step toward a more realistic model we make only first-order inferences about the possible sediment redistribution based on the general flow patterns generated by the model during various stages of the sudden infill. Given these limitations it is important to emphasize that we are looking for a qualitative result, i.e., where is the flow intense and what are the flow patterns?

3. Results

[15] The first notable observation to take from the model is the length of time it would take for the Black Sea to reach the level of the Sea of Marmara. The difference in the volume of the Black Sea between the 30 m and 155 m isobaths is approximately 6.2×10^{13} m^3. The flux into the Black Sea during the sudden infill given by the model is 5.8×10^4 m^{3}s^{-1}. It would therefore take approximately 34 years to fill the Black Sea level to −30 m from an initial level of −155 m [*Ballard et al.*, 2000]. The estimate presented here is considerably longer than the 5 years quoted by *Ryan et al.* [1997]. *Myers et al.* [2003] find a maximum flux into the Black Sea of 1.75×10^5 m^{3}s^{-1} which they estimate would fill a drawn down Black Sea in

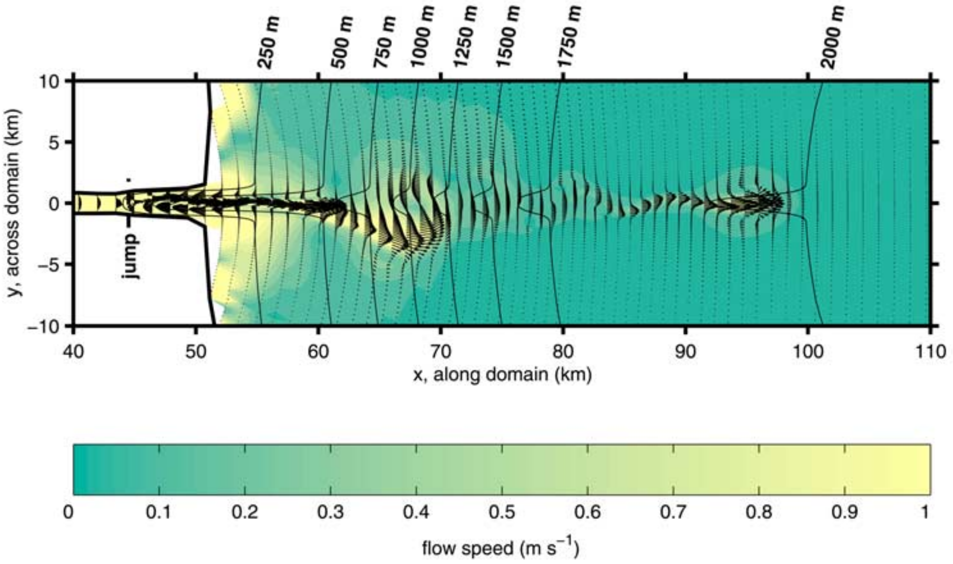

Figure 6. Snapshot of the flow in the lower (Black Sea) basin when it is set to −155 m so that the hydraulic jump occurs within the Bosporus canyon. The arrows represent the depth-integrated flux. The water's edge is marked by a heavy black line. The contours are isobaths marked above the plot. The canyon guides the jet to depths as great as 2000 m. Note the recirculation at 65 km downstream.

approximately 8 years. The Bosporus bathymetry used in the present model reduces the channel cross section at the sill. In this model the water level in the upstream reservoir has been lowered from 25 m to 10 m [*Fairbanks*, 1989], the extra lowering implied by the re-dating of the sudden infill to 8400 years BP [*Major et al.*, 2003]. These two factors reduce the hydraulically controlled flux and thereby considerably increase the length of time it would take to fill the Black Sea. It would take approximately 24 years to fill the Black Sea to −30 m below modern levels from an initial level of −105 m [*Demirbag et al.*, 1999] and 11 years to fill it from an initial level of −55 m [*Major et al.*, 2003].

[16] The flow in the upstream (Marmara) basin is steady with respect to time and is independent of the Black Sea level. Consequently it is identical for all our model runs and we need only discuss it once. Figure 5 shows the area in the immediate vicinity of the mouth to the Bosporus in the Sea of Marmara. Note the flow speed in the Sea of Marmara is less than 0.01 m s^{-1} not far from the Bosporus mouth. This is principally due to the flow conserving volume in the Sea of Marmara. The flow only accelerates as it reaches the relatively narrow and shallow Bosporus mouth. Such an effect would be even more marked in the actual Sea of Marmara, which is wider compared to the Bosporus than in the model. The larger velocities (2 ms^{-1}) at the mouth are concentrated to the left of the strait looking downstream due to the effect of Earth's rotation on the flow (i.e., the side of the basin that supports the upstream propagating Kelvin wave produced by the dam-break). The delta observed by *Hiscott et al.* [2002] at the Bosporus mouth in the Sea of Marmara occurs to the right of the channel looking downstream, away from the strongest currents associated with the infill. This may indicate that either the deltaic deposits originally accumulated where they are now preserved and they were left undisturbed by the strong flow or that the delta has been eroded to the left of the strait during the sudden infill. The model indicates that the velocities in the Sea of Marmara associated with a sudden infill of the Black Sea may not have left any other significant signature in the Marmara or Dardanelles sediment record. The impli-

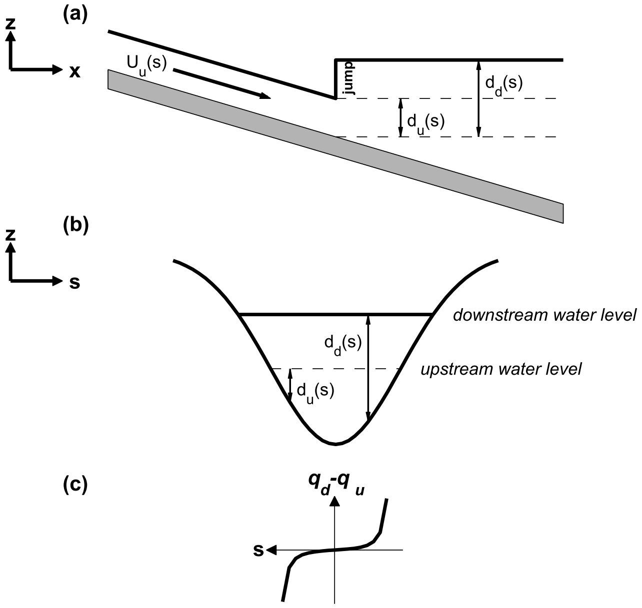

Figure 7. Schematic of the variables used in equation (4). (a) Along channel transect. (b) Cross channel transect. (c) Potential vorticity distribution across the channel. See text for details.

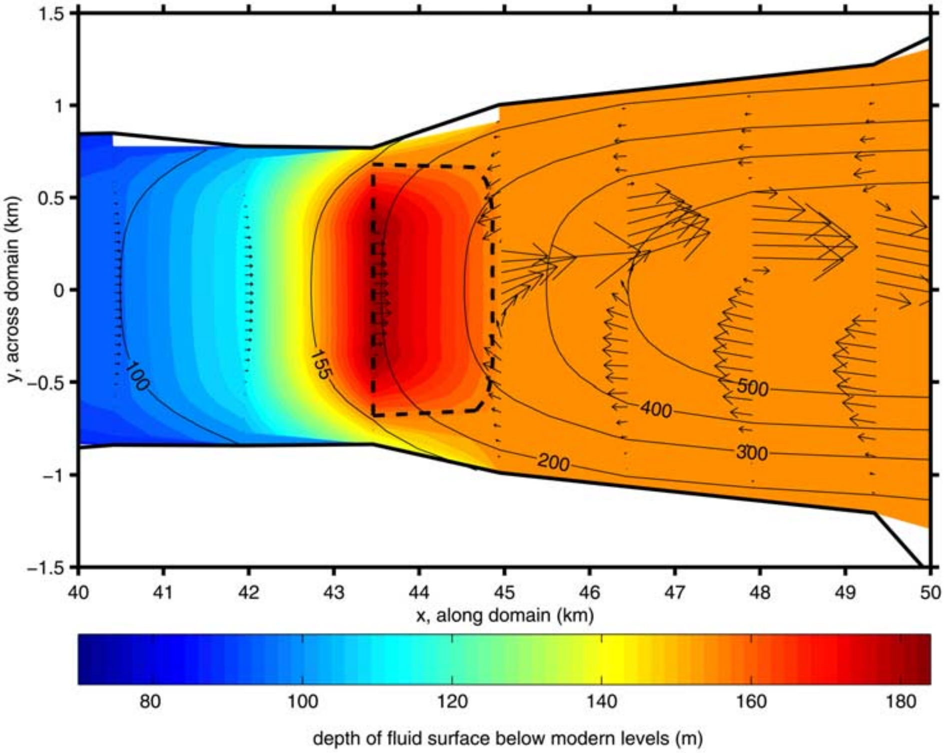

Figure 8. The flow in the vicinity of the hydraulic jump when the lower reservoir is at −155 m. The flow is qualitatively similar for all of the runs. The arrows represent the depth-integrated flux. The water's edge is marked by a heavy black line. The contours are isobaths in meters. The hydraulic jump is enclosed by a dashed line and represents a sharp change in the fluid level. Note the emergence of a jet downstream of the hydraulic jump.

cation that the presence of the delta demonstrates that the Black Sea flowed into the Sea of Marmara at some stage or other during the glacial recovery remains [*Hiscott et al.*, 2002]. However, the physical evidence of the delta does not necessarily exclude the sudden reconnection scenario.

[17] When the Black Sea is at −155 m the flow from Marmara meets Black Seawaters within the Bosporus Canyon. Where the two water masses meet a hydraulic jump exists (Figures 6 and 7). Downstream of the hydraulic jump a jet forms. The jet meanders between the exposed canyon walls before emerging into the open Black Sea. In the open Black Sea the submerged Bosporus Canyon provides a topographic constraint on the flow which guides the meandering jet away from the jump, allowing velocities as large as 0.5 m s^{-1} in water as deep as 2000 m depth. Such a jet may explain the hills at 2000 m depth observed by *Uchupi and Ross* [2000]. The hills reduce in size with increasing distance from the Bosporus as would be anticipated from the modeled jet, whose velocity decreases with distance from the Bosporus. This explanation does not exclude the possibility that the hills result from a turbidity current and are not related to a sudden reconnection. As the modeled canyon becomes less steep toward the center of the Black Sea the jet is less constrained topographically. The amplitude of the jet meanders increases and varies with time. In some cases recirculation zones are occasionally formed (see flow at 65 km downstream in Figure 6).

[18] The jet is formed as the result of the generation of vorticity $\partial v/\partial x - \partial u/\partial y$ within the hydraulic jump. To an observer facing downstream, the jump gives rise to positive (cyclonic) vorticity on the left side of the channel and negative vorticity on the right side. This distribution is notable in being opposite of what is observed for flow in the lee of an isolated obstacle [e.g., *Schär and Smith*, 1993]. There, the hydraulic jump gives rise to a wake or vortex street in the downstream flow.

[19] The distribution of vorticity observed in the present flow can be explained through consideration of the change in potential vorticity

$$q = \frac{f + \partial v/\partial x - \partial u/\partial y}{d} \tag{4}$$

that occurs across a hydraulic jump. Consider an idealized jump consisting of a discontinuity in depth that occurs along a curved path that crosses the channel. *Pratt* [1983] has shown that the change in q across the discontinuity at any point is given by

$$q_d(s) - q_u(s) = \frac{1}{u^{(n)}d}\frac{\partial}{\partial s}\left\{\frac{[d_d(s) - d_s(s)]^3}{d_u(s)d_d(s)}\right\}, \tag{5}$$

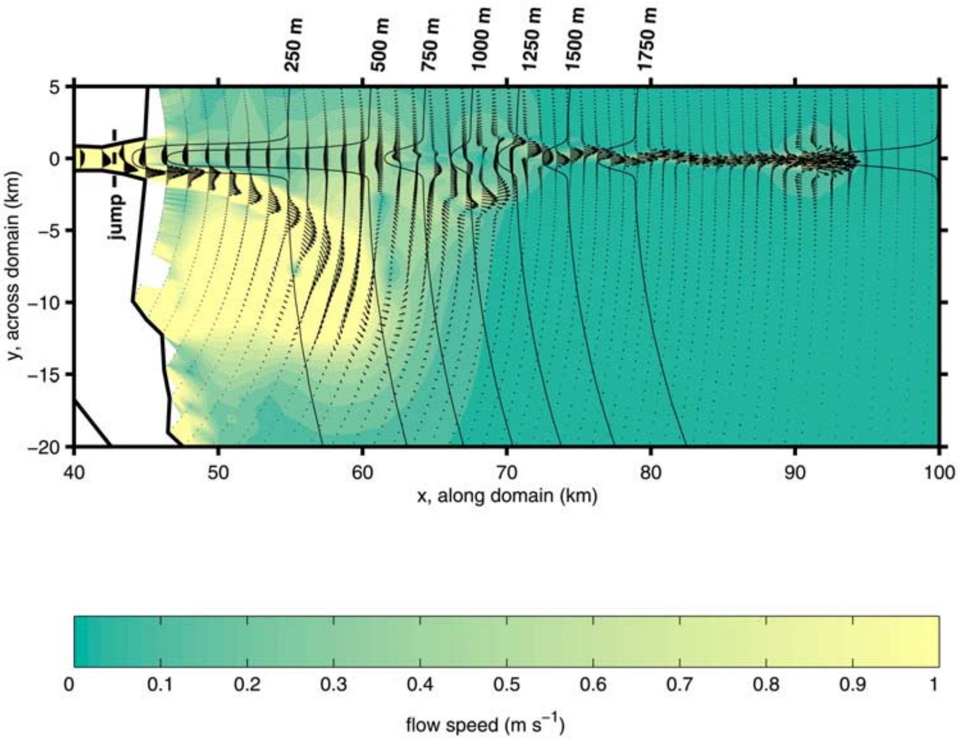

Figure 9. Snapshot of the flow in the lower (Black Sea) basin when it is set to −100 m so that the hydraulic jump occurs at the canyon head. The arrows represent the depth-integrated flux. The water's edge is marked by a heavy black line. The figure is a snapshot of the complicated flow pattern resulting from this time-dependent regime. The large velocity flows in the deep parts of the canyon in Figures 8 and 9 represent fluid which became trapped by the influence of the canyon while the jet was within the canyon. The large velocity flows over the shelf area represent the path of the jet traveling over the Black Sea shelf at the present time step.

where $u^{(n)}$ is the velocity normal to the discontinuity, s is arc length measured along the discontinuity, and $(\ )_u$ and $(\ )_d$ represent quantities measured slightly downstream and upstream of the jump (Figure 7a). The coordinate s increases from right to left as seen by the upstream observer.

[20] Next consider the application of (5) to an idealization of the jump observed in the model (Figure 7b). Rotational effects are negligible near the jump in the model and therefore f is set to zero in the present example. In addition free surface is assumed to be level across the channel and the depth discontinuity to be perpendicular to the channel axis. The upstream flow is parallel and uniform ($v = 0$, $u =$ constant) and therefore $q_u = 0$. The jump amplitude ($d_d(s) - d_s(s)$) is constant and the differentiated term on the right-hand side of (5) is therefore controlled by the denominator, which decreases to the left and right of the channel center. The differentiated term therefore increases away from the channel center and it follows that $q_d > 0$ to the left and $q_d < 0$ to the right (Figure 7c). With the neglect of f, q_d is proportional to the vorticity of the fluid downstream of the jump, the distribution of which is consistent with a jet-like velocity profile. This process can be observed in Figure 8, where such a jet emerges downstream of the hydraulic jump. Further discussion of the fluid dynamics associated with a hydraulic jump of this type are beyond the scope of this paper. We refer the reader to *Pratt and Lundberg* [1991] for a review of flow hydraulics.

[21] At later stages of the infill, when the Black Sea level has risen to −100 m and −70 m, the jet is time-dependent and intermittently escapes the influence of the canyon (Figures 8 and 9). When the jet is within the Black Sea canyon the flow is guided by the topography. Thus large flow velocities may reach the deep Black Sea regardless of the precise level of the Black Sea at the time of the infill. When not guided by the canyon the jet meanders over the Black Sea shelf and collapses into two recirculation zones on either side of the jet. Figures 8 and 9 show snapshots of the complicated flow patterns resulting from this time-dependent regime. The large velocity flows in the deep parts of the canyon in Figures 8 and 9 represent fluid which became trapped by the influence of the canyon while the jet was within the canyon. The large velocity flows over the shelf area represent the path of the jet traveling over the Black Sea shelf at the present time step. This type of meandering flow is one mechanism which may have formed the sharply turning channel at the mouth of the Bosporus, another will be discussed below.

[22] When not guided by the canyon we anticipate that the scouring of the shelf by the jet would create important feedback between the flow and the bathymetry. At later

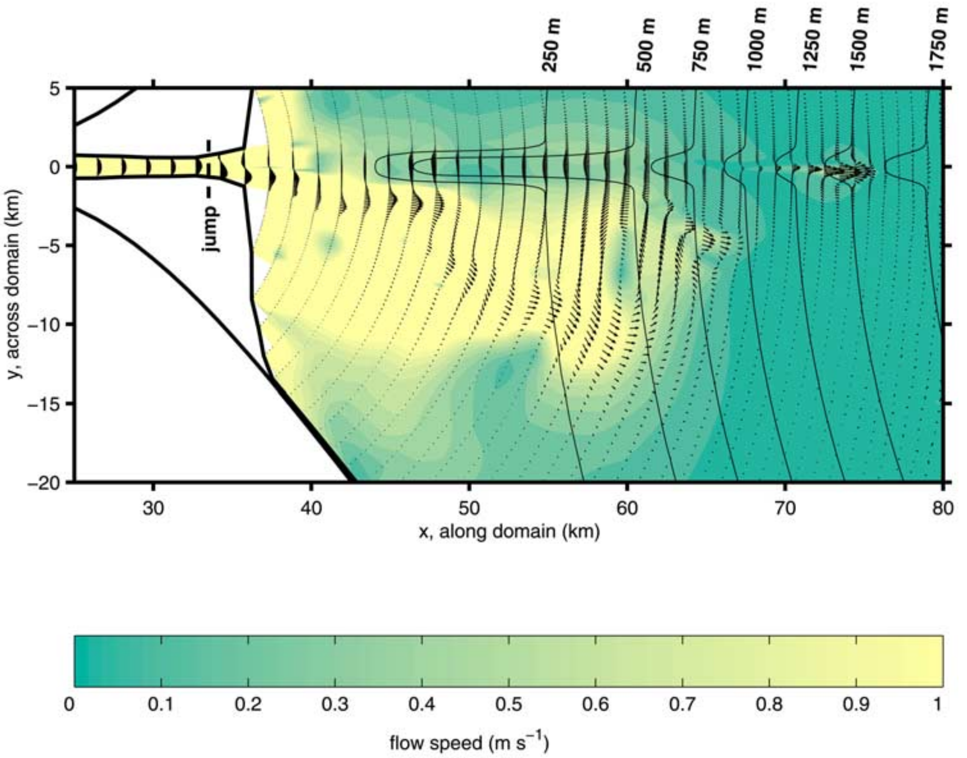

Figure 10. Snapshot of the flow in the lower (Black Sea) basin when it is set to −70 m so that the hydraulic jump occurs on the Black Sea shelf. The arrows represent the depth-integrated flux. The water's edge is marked by a heavy black line. The figure is a snapshot of the complicated flow pattern resulting from this time-dependent regime. The large velocity flows in the deep parts of the canyon in Figures 8 and 9 represent fluid which became trapped by the influence of the canyon while the jet was within the canyon. The large velocity flows over the shelf area represent the path of the jet traveling over the Black Sea shelf at the present time step.

stages of the infill such a channel may have been filled in. How the real flow over the shelf area would behave is therefore difficult to comprehend without an embedded sediment transport model. There are many canyons which cut into the Black Sea shelf in the vicinity of the Bosporus [*Melnik*, 1995]. It is possible that the jet could leave the Bosporus Canyon and migrate over the shelf to an adjacent canyon. In fact the modeled flows are strong enough (i.e., $\gg 1$ m s^{-1}) to have a dominantly erosive character for sediments in the clay to sand grain-size range [*Allen*, 2001] and possibly to erode a new canyon adjacent to the Bosporus. The alternate canyon would then guide the flow much as the Bosporus Canyon does in our model runs.

[23] The presence of lag deposits and the thin sedimentary cover over the unconformity created by the last sea level lowstand on the Black Sea shelf [*Aksu et al.*, 2002c] are both consistent with a predominantly erosional regime in the vicinity of Bosporus reflecting strong flows in the recirculation zones adjacent to the Bosporus shelf channel. Preservation of continuous barrier-washover-lagoonal fill systems on the shelf, as interpreted by *Aksu et al.* [2002c], would not be possible within these recirculation zones, unless the flow was trapped within a channel. It is possible that the channel over the Bosporus shelf was deeper at the time of the sudden infill and therefore capable of constraining the jet and preventing it from flowing over the shelf. Alternately, the intricate pattern of across-shelf and along-shelf ridges, sand waves, and sand fields surveyed by *Aksu et al.* [1999b, 2002c] might perhaps be the result of erosion/deposition of shelf sediments under the strong flows when the Bosporus jet escapes the influence of the canyon (Figures 8 and 9).

[24] With the Black Sea level at −100 m and −70 m the meandering jet always tends to the right looking downstream, when it is not within the canyon. At a later period of the infill, when the Black Sea level is at −50 m a stable jet is formed along the left hand coast. Whether the jet moves to the left or right of the canyon is dependent upon the phase of the meander as it enters the open Black Sea. It is therefore predominantly the relationship between the distance downstream of the jump that the jet is restricted within a strait or exposed channel and the wavelength of the unstable jet which determines which side of the canyon the jet will emerge on. This effect can be seen in Figures 8, 9, and 10. Biases in the potential vorticity of the jet due to the effect of Earth's rotation and across-channel asymmetry in the bathymetry will also play a role in determining the flow direction. These combined effects create uncertainty as to which coast the path of the jet might tend to during the later stages of the infill. The results shown here should

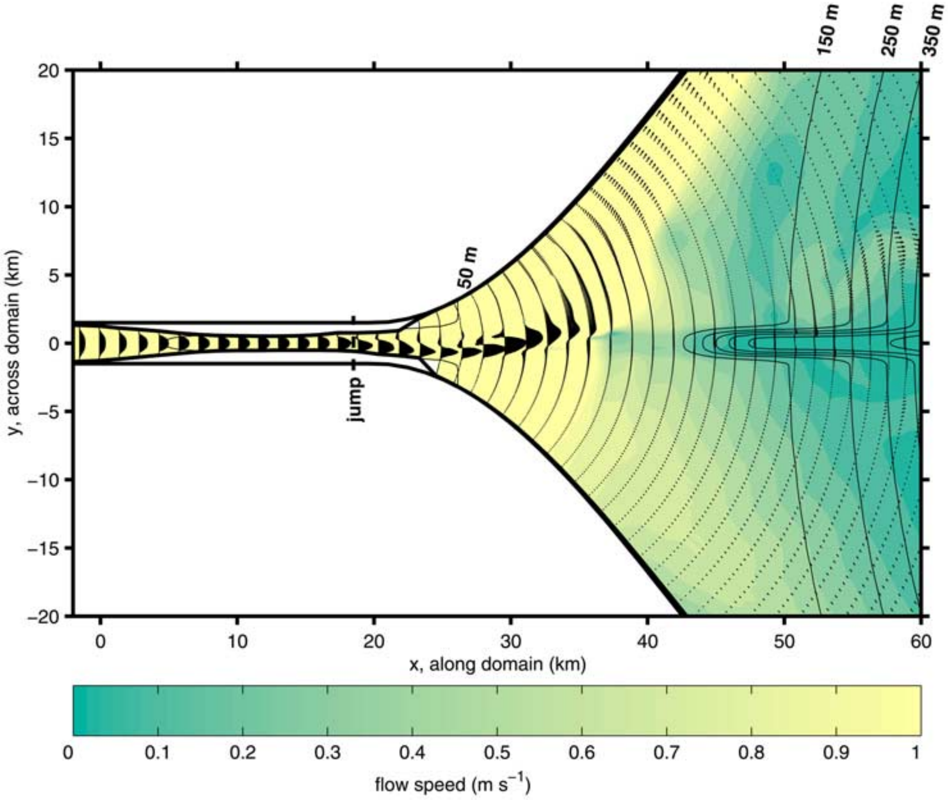

Figure 11. Snapshot of the flow in the lower (Black Sea) basin when it is set to -50 m so that the hydraulic jump occurs within the Bosporus. The arrows represent the depth-integrated flux. The water's edge is marked by a heavy black line. On leaving the Bosporus Strait the jet attaches to the coast and flows along it. Such a jet may have been responsible for scouring the northwestern channel at the Bosporus mouth (cf. Figure 3).

therefore be interpreted as not indicating which side of the canyon the jet will tend toward but rather that it will eventually tend to one side and not the other. We are not able to state with any certainty whether the jet will tend to the left or right of the canyon. However, we expect that, once the jet has taken a given path, scouring of the sediment would encourage the jet to maintain the same path over time. Further investigations with an embedded sediment transport model would be necessary to fully understand the sediment-flow interactions.

[25] Once the Bosporus has started to fill at -50 m (Figure 11) the flow is restricted within the strait until it emerges in the Black Sea. If the jet attaches to the coast shortly after exiting the channel it remains stable and moves along it. The potential vorticity across the coastal jet is negative and monotonic, indicating that the jet is stable [*Pedlosky*, 1987]. The sharp turn in one of the submerged channels leaving the Bosporus is consistent with the existence of such a jet (cf. Figures 3 and 11). We emphasize that, for the reasons expressed above, it is merely coincidence that the modeled jet (Figure 11) travels left as it leaves the Bosporus, in apparent agreement with the submerged channel. The model merely predicts the existence of such a coastal jet, not its direction. An alternative explanation for the course of the modern submerged channel is that it results from the effects of faulting parallel with the modern coast [*Demirbag et al.*, 1999].

[26] As the levels of the Sea of Marmara and the Black Sea equalized, the velocities associated with the intruding Marmara water would have reduced. Since the formation of the channel at the Bosporus mouth would occur toward the end of the infill, subsequent periods of lower velocities suggest that it would be left as a relict feature of the sudden infill. In the most rapid part of the jet closest to the coast velocities exceed 1 m s^{-1} which would make the flows strongly erosive for particles in the clay to sand grain-size range. The presence of the submerged channel indicates that the flow may have scoured the sediment here, as would be expected if such a coastal jet existed at a late stage of the suggested sudden infill. The velocity of the jet reduces away from the coast, where one might expect to find sedimentary features such as sand waves.

4. Conclusions

[27] Three classes of modeled flow correspond with increasing depths of the Black Sea during the suggested sudden infill. When the Black Sea level is below the canyon head at -155 m (Figure 6) the flow appears as a meandering jet constrained by the canyon. When the Black Sea is at

the depth of the Bosporus Canyon head or the Black Sea shelf at −100 m and −70 m (Figures 8 and 9) the flow varies with time between a jet trapped within the canyon and a broader jet which escapes the canyon. When the Black Sea level is within the Bosporus Strait at −50 m (Figure 11), the jet attaches to either coast on leaving the strait and moves along it as a stable coastal current.

[28] Despite the limitations of the modeling, considerable insight has been gained regarding the flows in the Black Sea which may have resulted from the suggested sudden infill 8400 years ago. The model results are consistent with some existing observations of geological features in the areas which would appear to be affected during a sudden infill of the Black Sea. We are able to suggest a possible formation mechanism for the hills observed by *Uchupi and Ross* [2000] at 2000 m depth. The model also suggests an explanation for the sharp turn observed in the submerged channel at the Bosporus mouth. Furthermore, rapid flows associated with the sudden infilling may not be present in the Sea of Marmara or the Dardanelles, thus leaving intact the preexisting outflow delta. However, the current model is at odds with the preservation of coastal barrier systems in the Black Sea within the recirculation zones of a jet unconstrained by a shelf channel. Any attempt to a definitive interpretation of the erosional-depositional features present on the shelf in the vicinity of Bosporus should rely on extensive survey data that allow for a detailed description of the continuity of those features and on their extensive coring and dating. Further modeling with an embedded sediment transport model and layered shock-capturing models is expected to improve insight into the depth-dependent structure of the Bosporus jet during a sudden infill scenario.

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