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The Black Sea
Flood Question
Changes in Coastline, Climate
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TIMING OF THE LAST MEDITERRANEAN SEA–BLACK SEA CONNECTION FROM ISOSTATIC MODELS AND REGIONAL SEA-LEVEL DATA

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Abstract: Water levels in the Mediterranean and Black Seas since the Last Glacial Maximum have varied substantially across the region because of the influence of the melting of the last great ice sheets in redistributing ice and water over the Earth’s surface. This spatial variability is significant for discussions of the timing of water exchange between the Aegean and Black Sea, which reached ca. −10 m relative to present sea level at 12 ky calBP. In the absence of direct observational evidence, sea-level change at sill locations is predicted here using isostatic models that have been calibrated against observational data from other Mediterranean localities. If one assumes a depth of −32 m for the Bosphorus sill, the Black Sea is predicted to have been reached by rising Mediterranean water between about 10.3 and 9.5 ky calBP. Alternatively, if the Bosphorus bedrock gorge at −100 m depth is adopted as the sill, then the first Mediterranean influx over the shallower Dardanelles sill at −80 m is predicted to have occurred between 15 and 13.7 ky calBP.

Keywords: sea-level prediction, glacio-hydroisostasy, sill height, Black Sea, Marmara Sea

1. INTRODUCTION

The connection between the Black Sea and the Mediterranean Sea via the Sea of Marmara remains a controversial issue. Was there a catastrophic flooding of the Black Sea when a rising Mediterranean Sea breached the Bosphorus sill as Ryan et al. (1997, 2003), Ryan and Pitman (1998), Major...
et al. (2002), and Ryan (this volume) have proposed, or was the connection one of gradual water exchange as described by Aksu et al. (2002), Hiscott and Aksu (2002), and Hiscott et al. (this volume)? And when did this event occur? Some researchers place the first post-LGM (Last Glacial Maximum) incursion of Mediterranean water into the Black Sea as early as 12,800 BP (one of the two scenarios presented by Major et al. 2002), while others date it later. It took place about 11,000–10,500 BP according to Aksu et al. (2002) and Hiscott and Aksu (2002), but it was later still at 9100 BP according to Kaminski et al. (2002). A date of 8400 BP has been proposed in Ryan et al. (2003) and in the second scenario of Major et al. (2002), and it was placed as recently as 7100 BP in Ryan et al. (1997).

If sea-level change is known or can be predicted, and the depths of the topographic barriers separating the Aegean and Black Seas are also known, then it becomes possible to predict the timing of the first contacts between the Aegean, Marmara, and Black Seas. The principal sources of uncertainty would be (1) the accuracy of the local sea-level curve, and (2) whether there has been significant modification of the sills by erosion, sedimentation, or local tectonics.

This paper employs a predictive approach to estimating the timing of inter-basin connection based upon isostatic models of sea-level change that have been calibrated against regional Mediterranean sea-level data. Previous studies have used the Barbados sea-level curve of Fairbanks (1989)—e.g., Aksu et al. (2002)—or earlier models by Milliman and Emery (1968)—e.g., Ryan et al. (1997)—or Chappell and Shackleton (1986)—e.g., Aksu et al. (2002)—to estimate the timing of the post-LGM flooding of the Black Sea by the Mediterranean without first testing whether these local sea-level functions are appropriate for the Black Sea sill location. In fact, as demonstrated by Lambeck (1995, 1996), sea levels from the Aegean to the Black Sea vary substantially because of the combined effects of glacio- and hydroisostasy, even in the absence of tectonics. Furthermore, the results can be expected to differ from observed values at Barbados or similar sites because Mediterranean and Black Sea levels were strongly influenced by the nearness of the former European ice sheet and by the coastline geometry of the ocean basins into which the glacial meltwater drained (Lambeck and Purcell 2005).

There appear to be no sea-level observations from areas near the Bosphorus and Dardanelles sills that controlled the exchange of water between the Aegean and the Black Sea, so instead we use a regional model for the Mediterranean that has been compared to sea-level data from tectonically stable regions. The calibrated model is then used to predict sea-level change at the sills based on the assumptions that (1) there was no tectonic contribution to the sea-level signal or that this has been corrected in some way, and (2) lateral variation in the effective parameters that define the Earth’s response to changing water and ice loads on time scales of $10^4$ years is unimportant.
The first assumption has been tested against sites where the position of the last interglacial shoreline is known. The second assumption must remain an article of faith until full three-dimensional mantle response models have been developed and tested against observational data. Until this is achieved, the following predictions must be based on a range of effective earth model parameters that yield predictions consistent with field data that have been obtained across the region. The data used include information from Israel (Sivan et al. 2001, 2004), from locations in Greece where vertical tectonic displacements are believed to be small (van Andel and Shackleton 1982; Lambeck 1996), from Italy (Lambeck et al. 2004), and from the French Mediterranean (Lambeck and Bard 2000). These data span the critical period during which the sills guarding the Black Sea were likely to have been breached by a post-LGM Mediterranean transgression.

2. PREDICTION OF MEDITERRANEAN SEA LEVEL

The model predicts sea-level change due to the growth and decay of the ice sheets of the last glacial cycle, i.e., from the last interglacial to the present. It incorporates the planet’s deformation as well as the variations in gravitational field caused by shifting ice and water loads and their redistribution over the Earth’s surface. Meltwater returns to the oceans, and as it does, the configuration of the ocean basins and the shape of their margins become time dependent, but throughout the process, the ocean surface remains equipotential. Ice loads are constrained by examining the response of the crust (mainly reflected by sea-level change) in the formerly glaciated areas, while the time history of the total ice volume is inferred from sea-level data far from the glaciated regions. The most recent discussion of the theory used here is in Lambeck and Johnston (1998) and Lambeck et al. (2003). The theory is consistent with that of, for example, Mitrovica and Milne (2003). Model parameters for the Mediterranean appear in Lambeck and Purcell (nd), and the ice-volume equivalent sea level used is that of Lambeck and Chappell (2001).

Figure 1 illustrates the predicted sea level (relative to today’s values) in the Mediterranean and Black Sea for ca. 12,000 BP. It clearly shows the spatial variability in sea-level response that can be expected across the region. The dominant high frequency spatial signal is due to the changes in sea-floor loading by meltwater added since the onset of post-LGM deglaciation. This is seen primarily as a subsidence within the basins, such as the Black Sea and the Western Mediterranean, and a relative uplift of adjacent land bodies. Superimposed on this is a longer wavelength variation, mainly with a north-south trend, that is
the planet’s sea-level response to changes in ice load over northern Europe and North America, details of which may be found in Lambeck and Purcell (nd). Thus, the Black Sea will have a different sea-level response than, say, the Levantine coast, which lies farther from the former ice loads.

Figure 1. Predicted sea level across the Mediterranean at 12,000 calBP. Predictions assume tectonic stability of the crust but include glacio-hydro-isostatic effects based on realistic ice and earth models that have been calibrated against observational data from across the region (from Lambeck and Purcell 2005).

This spatial variability is further illustrated in Figure 2 as a time series at the four Mediterranean sites discussed below. In this case, predictions for Villefranche (on the French Mediterranean coast) and Tirins (Peloponnese, Greece) are very similar, but they differ from the Levantine coast result by ~10 m at 10,000 years BP. As a consequence, one should not use a sea-level curve from any other location in the Mediterranean as a proxy for change in the Bosphorus without first correcting for differential isostatic effects. Likewise, one cannot use the Barbados sea-level function unless it can be demonstrated that the isostatic effects are fortuitously the same for these sites as they are for the Black Sea sills.

In this paper, we calibrate the isostatic rebound model at locations in the Mediterranean where vertical tectonic displacements are small or known (from the MIS 5.5 shoreline elevation), we estimate effective earth and ice sheet parameters that describe the observed response, and then we interpolate to locations of particular interest, in this case the connection between the Mediterranean and the Black Sea. Figure 1 shows one result of such an interpolation for the Mediterranean and Black Sea basins as a whole.
In the next section, predictions are based on the Lambeck and Purcell (2005) model, and accuracy estimates depend upon uncertainties in both the earth- and ice-model parameters, as well as the accuracy of the global ice volumes for the post-LGM period, as discussed therein. The model predictions have been successfully tested against observations from outside the Mediterranean, including the Barbados data (see Lambeck et al. 2002).

Figure 2. Predicted sea levels at four Mediterranean locations based on the model in Figure 1.

3. CALIBRATION OF THE SEA-LEVEL MODEL

Figure 3 illustrates predicted sea levels at several localities and compares them to observed values for the same locations. Figure 3A describes the Carmel coast of Israel. Here, underwater and coastal archaeological research has provided constraints on the local sea-level curve from ~9500 calBP to the present. The offshore evidence includes submerged prehistoric settlements, water wells, and shipwrecks whose ages can be established by $^{14}$C dating (e.g., Galili and Weinstein-Evron 1985; Galili et al. 1988; Galili and Nir 1993). The onshore evidence includes remnants of anchorages, slipways, piscinas, quarried ponds, and water wells (e.g., Raban 1981, 1983; Raban and Galili 1985; Galili and Sharvit 1999; Sivan and Galili 1999), but we have used only those indicators that can be related to sea level and whose age determinations are believed to be reliable. Generally, the predictions are consistent with the observational data, although the latter are limited to times after ~9 ky BP.
Figure 3. Comparison of predicted and observed relative sea levels at four Mediterranean localities. Upper and lower limits for predicted values (the grey zone) are based on uncertainties in the model parameters; for details, see Lambeck and Purcell (2005). Observational accuracies or upper and lower limits are shown where appropriate. Data sources are discussed in the text.

Figure 3B compares several sites in the Greek Peloponnese, where tectonic stability is suggested by the occurrence of the Last Interglacial sea levels at a few meters above present sea level (Kelletat et al. 1976; van Andel 1987). Data from several sites have been combined here: from the heads of the Argolikós, Messiniakós, and Lakonikós Gulfs, from Navarinou Bay (Kraft et al. 1975, 1977, 1980), and a LGM sea-level estimate from the Argolikós (van Andel and Lianos 1984). Some spatial variability between these sites is predicted, but this is less than the observational accuracy. The results have been combined here into a single sea-level curve. Predicted values are for the mean of the sites, and the associated accuracy includes the contribution from the expected spatial
variability. Much of the evidence is again of a limiting nature; upper limits are
provided by terrestrial material and lower limits are provided by marine materi-
al. Agreement of the predicted sea levels with this evidence is again satisfactory,
although the data points before ~ 7 ky BP are few.

A more detailed Holocene record with data extending back 10,000 years
is available from the Versilia Plain of northern Tuscany (Antonioli et al. 2000).
The continental sediments generally lie above, and the marine materials lie
below, predicted values (Figure 3C). Data from other Italian localities that are
either tectonically stable, or where tectonic corrections can be made, are also
consistent with the model back to about 11,000 BP (e.g., from Cape Palinura,
Calabria, and the North Adriatic; Lambeck et al. 2004). The fourth locality is on
the French Mediterranean coast where sea-level indicators of variable quality
extend back to the LGM (Lambeck and Bard 2000). For convenience, and
because the observational accuracies are generally larger than the predicted
spatial variability for the observation sites, the field data have here been pro-
jected onto a single sea-level curve, which is compared with the predicted values
in Figure 3D. Here also, the agreement is satisfactory, and from this brief
comparison, as well as from comparisons with other localities beyond the
Mediterranean (Lambeck et al. 2002), we conclude that the model predictions
provide a satisfactory interpolation device for calculating sea-level change in
unsurveyed areas, in this case for the Aegean–Marmara–Black Sea connection.

4. PREDICTED SEA LEVEL AT THE
MARMARA AND BLACK SEA SILLS

Two sill locations are considered, one at the southern end of the
Bosphorus (Figure 4A) and the other within the Dardanelles near Cape Nara
Burun (Figure 4B). In addition, sea-level profiles have been predicted along a
section from the Aegean to the Black Sea that runs through the Dardanelles, the
Sea of Marmara, and the Bosphorus (Figure 4C). One immediate observation is
that the predicted sea levels for the two sill locations are substantially different:
~5 m at 10,000 BP and >9 m after 14,000 BP. Also notable is that the Black Sea
prediction lies well below that for the localities illustrated in Figure 3 and that
observations from none of these sites would form a good proxy for sea level in
the upper Bosphorus.

We therefore use the model predictions, calibrated against observed data
from the other localities, to estimate the times at which the sills would likely
have been breached. For example, if the present Bosphorus sill depth of ~ 32
m (Major et al. 2002) is used, then the Mediterranean water in the Marmara basin
would have reached this elevation between about 10,300 and 9500 calBP.
Figure 4. Predicted sea levels at two sill locations between the Aegean and Black Seas; present sill depths and predicted times of transgression are indicated. A. The Black Sea sill at the southern end of the Bosphorus, with two possible sill depths (its present depth at $\sim 32$ m and bedrock depth at $\sim 100$ m). B. The Dardanelles sill near Cape Nara Burun at a depth of $\sim 80$ m. C. Variation in predicted sea level for selected intervals along an Aegean to Black Sea transect. Variation within the Dardanelles is generally small, and the precise location of this sill is not important.

the spread reflecting the uncertainty in the model predictions. This compares with the limits of 9400 calBP and 8000 calBP proposed by Major et al. (2002) and Ryan et al. (2003), respectively. Alternatively, if the $\sim 100$ m bedrock depth is adopted as the top of the ancient barrier, then the first post-LGM Mediterranean inflow is predicted to have occurred between 15,700 and 14,600 calBP, with the proviso that there was no higher barrier in the Dardanelles at that time. If the Dardanelles sill was at $-80 \pm 5$ m (Major et al. 2002), then this
elevation would have been breached between 15,000 and 13,700 calBP, the uncertainty reflecting both the model’s limitations and the uncertainty in the reported sill depth. This compares with the dating of 15,000 to 12,800 calBP proposed by Major et al. (2002). Note that at these early times, circulation between the northern Aegean and the rest of the Mediterranean was much more restricted than it is today (Lambeck 1996).

4. CONCLUSION

In the absence of direct observational evidence for relative sea-level change within the Aegean-Black Sea corridor, glacio-hydro-isostatic models are used here as interpolation devices to predict changes at sill locations that are understood to have controlled the exchange of water between the Aegean, Marmara, and Black Seas. The absolute accuracy of the model predictions rests on the ability to separate the parameters that describe the Earth’s response to loading and those that define the surface ice loads. When the model is used for interpolation purposes only, full decoupling of the parameters is not critical, provided that the model parameters are calibrated against regional sea-level data. For the examples used here, agreement is satisfactory and within the accuracies of both the observational evidence and the model predictions.

Based on these results, and in the absence of local tectonic movements, we estimate that, assuming that the Bosphorus sill elevation has remained unchanged at ~ −32 m, the Mediterranean reached this height for the first time since the LGM at between 10,300 and 9500 calBP, and the Dardanelles sill, at ~ −82 m, was reached between 15,000 and 13,700 calBP. Being higher than the low-level bedrock Black Sea sill, this also establishes the alternative timing for the Black Sea flooding by the Mediterranean.

Accuracy of the observational evidence is generally not high, however, and improved results are desirable from the region if these times of transgression are to be refined. Obtaining improved estimates will require additional high-accuracy information on local sea-level change in the region. In this regard, data from the Black Sea coast itself may be useful, particularly away from tectonically active zones, because of the variation predicted to occur here (Figure 1).

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