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The timing of the Black Sea flood event: Insights from modeling of glacial isostatic adjustment

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ABSTRACT

We present a suite of gravitationally self-consistent predictions of sea-level change since Last Glacial Maximum (LGM) in the vicinity of the Bosphorus and Dardanelles straits that combine signals associated with glacial isostatic adjustment (GIA) and the flooding of the Black Sea. Our predictions are tuned to fit a relative sea level (RSL) record at the island of Samothrace in the north Aegean Sea and they include realistic 3-D variations in viscoelastic structure, including lateral variations in mantle viscosity and the elastic thickness of the lithosphere, as well as weak plate boundary zones. We demonstrate that 3-D Earth structure and the magnitude of the flood event (which depends on the pre-flood level of the lake) both have significant impact on the predicted RSL change at the location of the Bosphorus sill, and therefore on the inferred timing of the marine incursion. We summarize our results in a plot showing the predicted RSL change at the Bosphorus sill as a function of the timing of the flood event for different flood magnitudes up to 100 m. These results suggest, for example, that a flood event at 9 ka implies that the elevation of the sill was lowered through erosion by ~14–21 m during, and after, the flood. In contrast, a flood event at 7 ka suggests erosion of ~24–31 m at the sill since the flood. More generally, our results will be useful for future research aimed at constraining the details of this controversial, and widely debated geological event.

1. Introduction

The shallow Bosphorus and Dardanelles straits in northwest Turkey separate the Black Sea from the Mediterranean Sea and the global ocean system (Fig. 1). At the time of the Last Glacial Maximum (LGM), local sea level was low enough that the connection of the Black Sea to the ocean was broken (Clark et al., 2009). At this time, a freshwater or brackish lake, fed by riverine and glacial meltwater inputs, occupied the Black Sea basin (Yanko-Hombach et al., 2014). At some time during post-LGM period, the rising waters of the Mediterranean breached the shallowest of the sills between the Mediterranean and Black Seas and the present connection between the two water bodies was established (Ryan et al., 2003). The nature of the reconnection remains uncertain. It may have been characterized by a gradual influx of seawater into the lake (Aksu et al., 2002; Hiscott and Aksu, 2002), by a catastrophic flood (Ryan et al., 1997, 2003; Ryan and Pitman, 1998; Major et al., 2002), or by an event of intermediate energy. In any case, the possibility that a cataclysmic natural event occurred has potentially profound archaeological and historical implications for the Neolithic humans living in the area, and has been suggested to be the inspiration for the biblical flood legend (Ryan and Pitman, 1998).

Several other aspects of the Black Sea flood event have also been sources of long-standing debate and controversy. The timing of the event, the location and height of the last sill to be breached, and the pre-flood level of the lake, are all uncertain. We review each of these issues, in turn.

The shallowest of the presently existing sills between the Mediterranean and Black Seas lies at the southern entrance of the Bosphorus strait (see Fig. 1 and Fig. 2). The modern sill is 32–34 m below sea level, and consists of Quaternary sand overlying Paleozoic bedrock (Algan et al., 2001). In contrast, the sill depth at the Dardanelles strait is ~80 m below sea level. The topography of the bedrock in the Bosphorus Strait features three sills 80–85 m below sea level. Sedimentation on these sills initiated prior to 10 ka and continued until 5.3 ka (Algan et al., 2001). For example, Holocene shells have been found at a depth of 70 m in sediment cores (Major et al., 2002). Thus, the formation of the modern sill must have continued through the period of post-glacial sea-level rise. Accordingly, there is no compelling evidence to sug-

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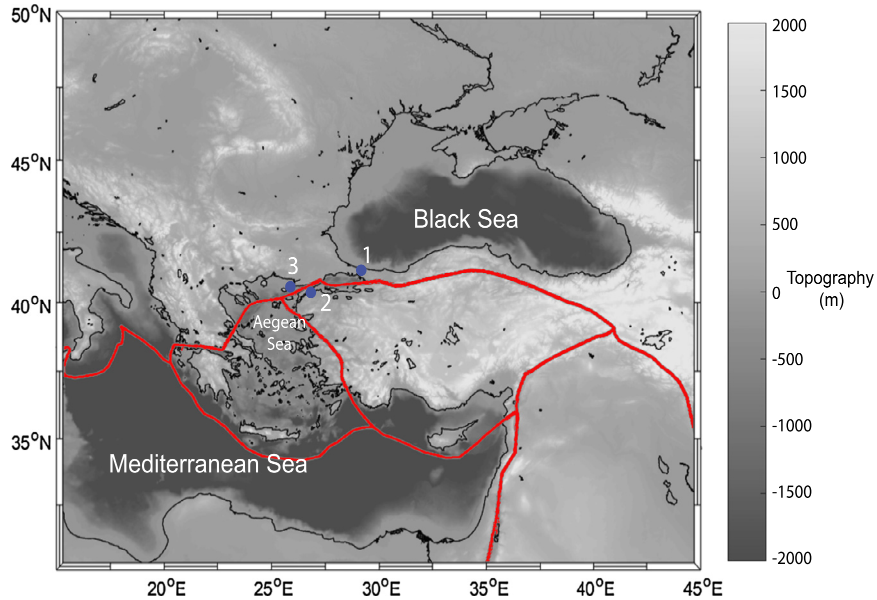

Fig. 1. Topographic map of the eastern Mediterranean Sea and Black Sea region. Thin red lines indicate major plate boundary faults. The three blue dots indicate locations mentioned in the paper: (1) Bosphorus Strait, (2) Dardanelles Strait, and (3) Samothrace. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

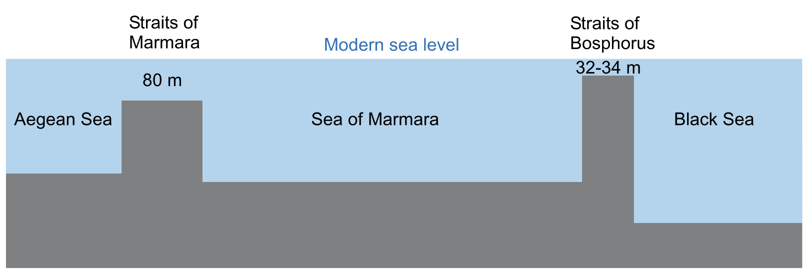

Fig. 2. Schematic cross-section of the modern Black Sea sills, with respect to present-day sea level. The depths of the two sills are drawn to scale relative to each other; the depths of the basins in between are not. The Sea of Marmara has an average depth of ~500 m; the Black Sea quickly drops to ~2000 m depth beyond the Bosphorus.

gest that the elevations of either the modern sill or the bedrock sills is representative of the sill height at the time of the initial ocean incursion into the Black Sea.

The timing of the flooding event is similarly poorly constrained. Soulet et al. (2011) analyzed microfossils from Black Sea sediments and estimated the initial appearance of marine species to be 9 ka. They adopted this value as an estimate of the timing of the sill breach. Yanko-Hombach et al. (2014) used several different paleosalinity proxies in sediment cores from the Black Sea, including macrofossils, microfossils, and pollen, to argue for a gradual marine transgression beginning no later than 8.9 ka. However, other studies have proposed a significantly earlier flooding event. Major et al. (2002) measured the isotopic compositions of mollusk shells, and on this basis suggested that the first marine influx took place at 12.8 ka. Aksu et al. (2002) examined the stratigraphy of the shelf sediments, using cores and seismic profiles, and concluded that the water level in the Black Sea Basin increased at 11–10.5 ka. Ryan et al. (1997) argued for a late, rapid flood at 7.1 ka based on dated shells from sediment cores.

An additional uncertainty is the height of the water surface of the pre-flood lake in the Black Sea basin. Widely diverging estimates of this height, based on various geomorphological and sedimentological arguments, have appeared in the literature. For example, some have argued for a pre-flood surface ~100 m below present sea level (Ryan, 2007; Lericolais et al., 2010; Nicholas et al., 2011), while others have concluded that the water surface was only 30–40 m below present sea level (Giosan et al., 2009; Yanko-Hombach et al., 2014). It has also been suggested that the pre-flood lake was not endorheic, but rather had sufficient inflow to crest the sill and flow into the lower Mediterranean Sea. This implies that the lake surface was at or just above the height of the sill (Algan et al., 2001) and that the reconnection during post-glacial sea level rise did not involve a rapid flood. Finally, there is also evidence that during periods of separation from the global ocean, the Black Sea lake alternated between a high mode with outflow into the Mediterranean during cold periods and an endorheic low mode with significant evaporation during warm periods (Ryan et al., 2003).

Despite broad interest in the Black Sea flood hypothesis, only a single study by Lambeck et al. (2007) has presented geophysical predictions of ice age sea-level change (or glacial isostatic adjustment, GIA) within the region. (An additional study has considered the perturbation to Earth rotation driven by the flood event Spada et al., 1999.) The Lambeck et al. (2007) analysis computed sea-level changes across the last glacial cycle using an ice age model that was tuned to fit relative sea level (RSL) records at several tectonically stable Mediterranean sites, including: Carmel Coast, Israel; Villefranche, France; Versilia Plain, Italy; and Tiryns, Greece, in the Peloponnese. Their prediction of the sea-level history at the Bosphorus and Dardanelles sills allowed them to estimate the timing of the flood event for several different choices for the highest barrier at the time of the breach. For example, adopting the top of the present-day Bosphorus sill (currently at 32–34 m below sea level) as the highest barrier (i.e. assuming that the sill height was not modified by erosion or sedimentation during or after the flooding) they predicted that the connection of the Black Sea and the