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Modelling the provenance of detritus flushed through the Strait of Bosphorus, Turkey, during early Holocene outflow from the Black Sea to the world ocean

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ABSTRACT

Source-to-sink tracing of very fine sand supplied to a controversial lower Holocene deltaic lobe in the northeastern Marmara Sea was undertaken using SEM backscatter mapping and quantitative 'mineral liberation analysis' of very fine sand fractions. Forty-two samples from the Kurbağalıdere, Göksu, Golden Horn and Riva watersheds, and from Oligo-Miocene outcrops along the southwestern Black Sea coast, show that each of these potential sources has a distinct mineralogical fingerprint. Comparison with 11 samples from the lower Holocene delta and 19 samples from the overlying mud drape show that no single source can account for the mineral proportions in the sand fractions of these depositional sinks, but a mixed provenance provides good matches. For the deltaic lobe, quantitative mixing based on 250,000 Monte Carlo simulations suggests ~50% contribution from Oligo-Miocene successions of the southwestern Black Sea coast and inner shelf, ~20% contribution from the Göksu stream, and minor contributions from other sources including the Kurbağalıdere stream. This balance of source contributions continued to supply the Holocene mud drape until ~6 cal ka, after which local sources became more important. It is hypothesized that unconsolidated sediment from a number of watersheds was parked along the coast of the Neoeuxine Lake and in the paleo-Bosphorus valley during the MIS 2 lowstand. A rising Neoeuxine Lake, possibly swollen by glacial outburst floods from the Altay region of Central Asia, flushed ~0.5 km^3 of this sediment through the Strait of Bosphorus to the deltaic lobe and permitted it to rapidly advance into the Marmara Sea, which at that time was rising ~1 m each 100 yr. Provenance of the lower portion of the Holocene mud drape is consistent with continued Black Sea outflow throughout the deposition of sapropel M1 in the Marmara Sea.

1. Introduction

During Quaternary deglaciations, a few major spillways accommodated exceptional discharges of meltwater from collapsing northern hemisphere ice sheets. In North America, the primary routes for these meltwater discharges were: (a) the Mississippi, St. Lawrence and Mackenzie corridors capturing Lake Agassiz and Lake McConnell drainage (Teller et al., 2002; Fisher, 2003); (b) the Columbia River valley carrying Lake Missoula floodwaters (Bretz, 1923; Clarke et al., 1984; Baker and Bunker, 1985); and (c) Hudson Strait channeling outbursts from subglacial lakes (coupled with ice surges) to generate North Atlantic Heinrich layers (Nicholl et al., 2012) and the final drainage from Lake Agassiz (Teller et al., 2002). Along the southern margin of the Eurasian icesheet, exceptional discharges from ice-dammed lakes of central Asia (e.g., the 'Altay Floods'; Rudoy and Baker, 1993; Rudoy, 2002; Reuther et al., 2006) were constrained to the Altay–-Turgay–Uzboy–Manych–Marmara spillways (Fig. 1), eventually discharging into the Aegean Sea from ~21–11.7 cal ka (Rudoy, 1998; all dates in this paper have been calibrated to calendar years with Oxcal 4.2 software, the Intcal13 and Marine13 calibration curves, and reservoir ages explained in Supplementary Table Supp-A). The name 'Marmara Spillway' is used here for the first time, and refers to the Strait of Bosphorus, Marmara Sea and Strait of Dardanelles during times of deglacial melting of continental ice sheets. Today, this string of waterways is not an active spillway and is instead called the 'Marmara Sea Gateway' (Fig. 2; Aksu et al., 1999) to recognize its importance as an oceanographic link between northern and temperate latitudes. The route and impact of the Altay Floods are described in Supplementary Text Supp-B.

During the Late Quaternary, a number of large lakes also formed along the southern margin of the Scandinavian Ice Sheet. The overlapping lobes of the Scandinavian and Barents-Kara ice sheets were sufficiently large to block and divert, to the south, formerly northward-flowing rivers such as the Ob and Yenisey rivers (Fig. 1; Lehmkuhl et al., 2007; Zolnikov and

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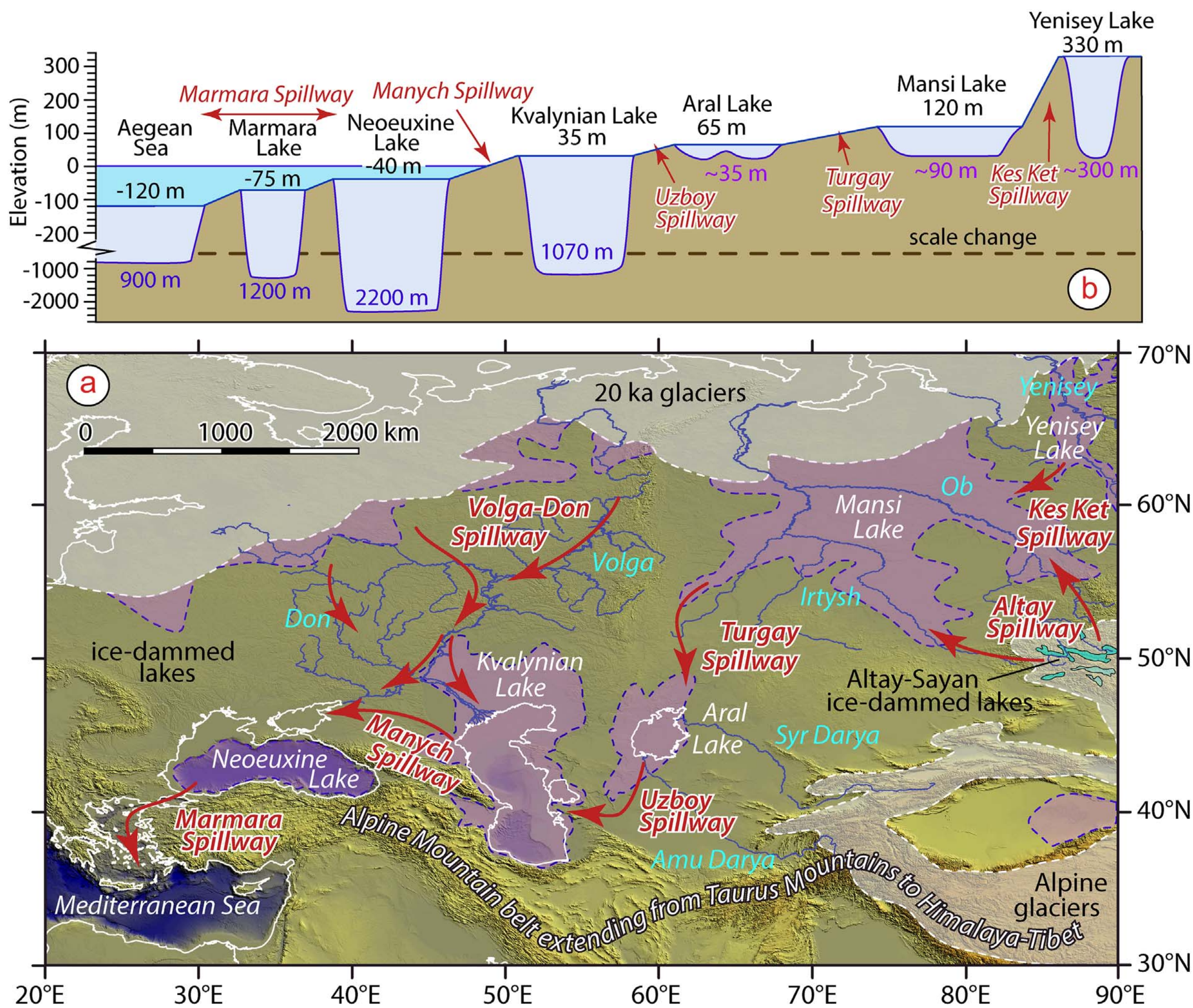

Fig. 1. Location map of west-central Eurasia showing spillways that developed during the latest Pleistocene and early Holocene associated with the catastrophic emptying of ice-dammed lakes. NW Eurasia lakes and the 20 ka ice margin from Mangerud et al. (2004), Svendsen et al. (2004); Altay-Sayan lakes (including the Chuya, Kuray, Uymon, Yaloman, Abay and Dzhasaterskoye lakes) from Rudoy and Baker, (1993), Grosswald and Rudoy (1996), Carling et al. (2002). Purple fill shows the last glacial maximum extents of the Mansi Lake, Aral Lake, Kvalynian Lake (i.e., modern Caspian Sea) and Neoeuxine Lake (i.e., modern Black Sea) (from Grosswald, 1998). Coastline and major rivers are from NOAA National Geophysical Data Center, coastline (GSHHG) extracted from (http://www.ngdc.noaa.gov/mgg/shorelines/shorelines.html). Topography compiled using GeoMapApp (Ryan et al., 2009). (b) Schematic cross-section across the glacial meltwater route connecting the paleo Mansi Late to the Aegean Sea across the Aral, Kvalynian and, Neoeuxine lakes and Marmara Sea showing the linking spillways (from Baker, 2007). Black numbers above catchments are elevation of the lake/sea level during the last glacial maximum according to Baker (2007), although many researchers place the Neoeuxine Lake and Marmara Lake at lowest elevations close to − 100 m. Blue numbers below catchments are the present-day water depths. Purple numbers are the estimated depths of the Yenisay, Mansi and Aral lakes during the early Holocene. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Guskov, 2009; Blomdin et al., 2014; Agatova et al., 2015). This diversion linked the Baltic Basin to the Volga and Don rivers, funnelling additional meltwater to the Kvalynian (today's Caspian Sea) and/or Neoeuxine (today's Black Sea) lakes (Mangerud et al., 2004; Svendsen et al., 2004).

In the Caspian Sea and Black Sea basins, Late Pleistocene overspilling waters have been called upon to explain the introduction and accumulation of distinctive so-called 'chocolate clays' and reddish-brown clays in the interval 17.2–15.7 cal ka (Major et al., 2006; Yanko-Hombach, 2007; Thom, 2010; Tudryn et al., 2016). In the Marmara Sea, distinctive sedimentary facies that might be linked to deglacial or lake-outburst event(s) have been recognized by the authors (Hiscott et al., 2002, 2007a; Aksu et al., 2016). These consist of (a) a yet-uncored progradational body at the southern Bosphorus exit that is older than ~16.2 cal ka, (b) a lower Holocene (~11.1–10.2 cal ka) progradational delta-like lobe at the southern Bosphorus exit (Fig. 3), and (c) at least the lower part of a lower–middle Holocene sapropel (~11–6.75 cal ka) that is widespread across the Marmara Sea. The geometry of the two delta-like lobes indicates that they were sourced directly from the Strait of Bosphorus (Aksu et al., 2016). For this reason, they were called 'strait deltas' by Hiscott et al. (2002). The early Holocene age of the uppermost deltaic lobe has been confirmed independently by Köprülü et al. (2016). Sand mineralogy of the upper lobe confirms that it cannot have been sourced from the nearby Kurbağalıdere stream (in this paper, rivers are defined as those water courses with annual average discharge $\geq 10\ m^3\ s^{-1}$, and smaller water courses are called streams; see Supplementary Table Supp-C for characteristics of streams and rivers in the study area).

According to Aksu et al. (2016), the volume of sediment in the uppermost progradational lobe (~0.5 km^3) is comparable to the volume that Gökaşan et al. (2005) calculated to have been eroded from the floor of the Strait of Bosphorus during the Late Quaternary. However, the composition of the bedrock flanking the strait appears to lack key features of the sand mineralogy of the uppermost deltaic lobe, in particular its high content of K-feldspar (12–15 vol%; Aksu et al., 2016). For example, the Carboniferous Trakya Formation is widespread on the western side of the Strait of Bosphorus (Fig. 4), but its feldspars are almost entirely albite (Okay et al., 2010). The Göksu stream and one tributary of the Riva River (Fig. 5) drain the only large granite and granodiorite body that might be a source for first-cycle K-feldspar. An aeromagnetic map covering the vicinity of the Strait of Bosphorus (Ateş et al., 2003) picks out this granite but no other large igneous bodies on land or along the floor of the strait.