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# Compilation of geophysical, geochronological, and geochemical evidence indicates a rapid Mediterranean-derived submergence of the Black Sea's shelf and subsequent substantial salinification in the early Holocene

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ABSTRACT

Our knowledge of rate and processes in which semi-enclosed environments alternate from lacustrine to marine is commonly limited because of the paucity of specific proxies for sea level and salinity. Here we investigate the timing, rate, and key mechanisms involved in the transformation of the previously isolated Black Sea-Lake to the modern partly-enclosed marine sea using a suite of geophysical, geochemical, and geochronological methods. Cores were collected in transects across shelves of Ukraine, Romania, Bulgaria, and Turkey. Biogenic carbonate from these cores was analyzed for radiocarbon and strontium, oxygen, and carbon isotopes. Strontium results indicate that the submergence of the Black Sea shelf at 9300 calendar years BP was caused by the ingress of Mediterranean water and was abrupt, taking <40 years. The seismic reflection profiles show a uniform drape of subsequent sediment over aeolian dunes indicating a drowning with no time for erosion accompanying the submergence. Moisture measurements beneath the uniform drape indicate that the shelf was dry before submergence and the shoreline of the Preboreal lake may have regressed to beyond 120 mbsl. Mollusks colonized the newly submerged substrate of the inner shelf at the same time as they colonized the outer shelf. The succession of mollusk species with shells whose strontium isotope composition has a marine component indicates a rising salinity. The transformation of the lake to a sea is affirmed by increases in the shells' strontium and oxygen isotopic ratios towards the external ocean value.
Radiocarbon years are calibrated to calendar years by tuning the oxygen and carbon isotope composition of the mollusk record to that of the U/Th dated Sofular Cave stalagmites. The match shows a reduction of the lake's prior high reservoir age accompanying the inflow of the Mediterranean water. In 900 years the salinity reached a threshold that excluded all previous Black Sea lacustrine fauna. These results imply that any substantial postglacial submergence of the Black Sea shelves did not occur prior to entry of Mediterranean water.


## 1. Introduction

The Black Sea is a large and deep meromictic body of water connected to the global ocean via a system of straits and intermediate seas. Currently, the water exchange involves excess freshwater outflow and marine water inflow across the Strait of Bosporus above a 35 mbsl sill. The exchange is dynamic, and changes between glacial and interglacial periods. During glacial periods, when global sea level falls below the level of the Black Sea's outlet, the lake surface cannot rise above the elevation of the outlet sill and is instead controlled by the regional hydrologic budget. As a consequence, the sea remains isolated from the global ocean and evolves over time into a lake (Arkhangel'skiy and Strakhov, 1938; Brujevich, 1952). When deglaciation raises the external sea level above the level of the outlet, the lake reverts to a sea for the duration of the interglacial highstand (Schrader, 1979; Zubakov, 1988).

The most recent reconnection of the Black Sea with the Mediterranean has been placed, with broad consensus, in the early Holocene, between 7000 and 9000 $^{14}$C years (Ross et al., 1970; Strakhov, 1971;

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Deuser, 1972; Kuprin et al., 1974; Scherbakov and Babak, 1979; Degens et al., 1980; Dimitrov, 1982; Jones and Gagnon, 1994; Ryan et al., 1997; Aksu et al., 2002; Dimitrov and Dimitrov, 2004; Major et al., 2006; Dimitrov, 2010; Nicholas et al., 2011; Soulet et al., 2011b; Filipova-Marinova et al., 2013; Nicholas and Chivas, 2014).

The level of the Black Sea–Lake prior to the connection remains a subject of disagreement. Kuprin et al. (1974), Scherbakov and Babak (1979), and Konikov et al. (2007) proposed that the Black Sea-Lake experienced a significant regression, exposing most of its shelf and turning it into a terrestrial landscape out to a shoreline between 80 and 100 mbsl. This regression is supported by pervasive erosion observed in reflection profiles that cross the Ukraine, Romanian, Bulgarian, Russian, and Turkish shelves (Ryan et al., 1997; Demirbag et al., 1999; Aksu et al., 2002; Hiscott et al., 2002; Algan et al., 2007; Glebov and Shel'ting, 2007). The element of disagreement arises from interpretation of data regarding the level of the water surface in the Black Sea-Lake at the time of the introduction of Mediterranean water. Was the lake surface below the level of the inlet such that the ingress of salt water involved a transgression of the exposed shelf? Or was the lake already at the elevation of the inlet?

Four different hypotheses for the Black Sea-Lake level currently exist (Fig. 1). One hypothesis assigns the maximum regression to 18,000 $^{14}$C years, followed by a gradual transgression to the Black Sea outlet (placed at 35 mbsl) and completed before entry of saltwater (Kuprin et al., 1974; Kaplin and Shecherbakov, 1986; Pirazzoli, 1996; Kaplin and Selivanov, 2004; Balbanov, 2007; Sorokin and Kuprin, 2007). A second hypothesis places the maximum regression at 11,000 $^{14}$C years, recognized as the Younger Dryas period of the late Pleistocene, followed by a rapid freshwater transgression ending at ~ 10,000 $^{14}$C years ago at the level of the outlet (Bosporus sill) and also completed prior to the connection of the Mediterranean Sea with the Black Sea-Lake (Aksu et al., 2002; Hiscott et al., 2002; Hiscott et al., 2007a; Hiscott et al., 2007b). Yanko-Hombach et al. (2014) and Mudie et al. (2014) have proposed that the surface of the Black Sea-Lake was never lower than 30 mbsl in the early Holocene prior to its evolution to a sea. A third hypothesis also recognizes a regression in the Younger Dryas period, but one that persists into the Preboreal and ends with an abrupt transgression exclusively caused by a cascade of Mediterranean saltwater that begins when the rise of external eustatic sea level reaches the inlet (Lericolais et al., 2007; Nicholas et al., 2011). A fourth hypothesis recognizes a significant regression confined to the Preboreal period, immediately before the rapid transgression from the entry of Mediterranean water (Dimitrov, 1982; Ryan et al., 1997; Major et al., 2002; Ryan et al., 2003; Dimitrov and Dimitrov, 2004; Ryan, 2007; Dimitrov, 2010).

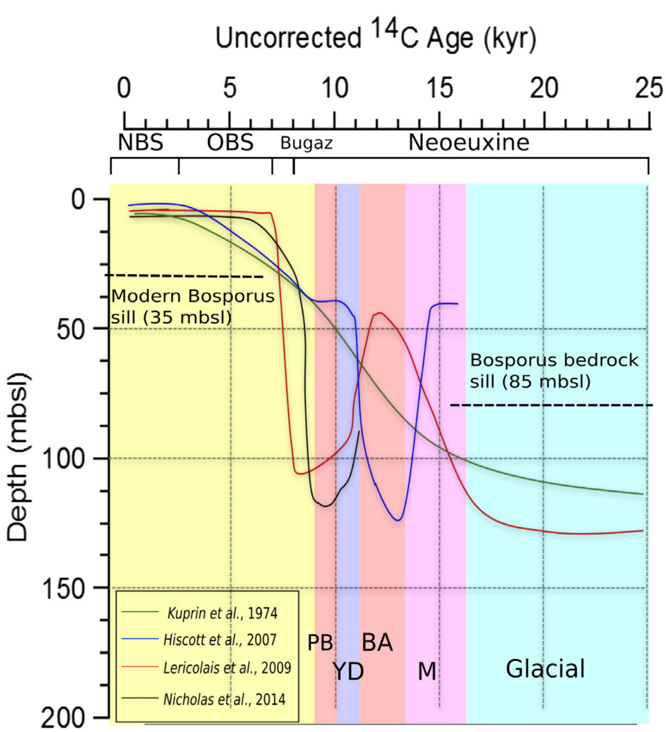


**Fig. 1.** Four previously published water level reconstructions for the post -Glacial to Holocene Black Sea: Hypothesis 1, green line (Kuprin et al., 1974); hypothesis 2, blue line (Hiscott et al., 2007a); hypothesis 3, red line (Nicholas et al., 2011); hypothesis 4, black line (Ryan et al., 1997). M refers to the Black Sea Meltwater event, PB to Preboreal, YD to Younger Dryas, and BA to Bølling/Allerød. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The variations between each of the individual hypotheses arise from differing age models and interpretation of available data to show whether the early Holocene transgression was indeed fresh or marine. The traditional Black Sea chronology (Fig. 1) divides Black Sea late Pleistocene and Holocene history into four stages based on changes in the mollusk assemblage (Nevesskaya, 1965): (1) Neouxine, an interval of time that encompasses the Black Sea glacial and deglacial until its connection with the Mediterranean; (2) Bugaz, an interval of time where both fresh and marine mollusk shells exist in the same deposit; (3) Old Black Sea, an interval of time following the Bugaz in which the salinification is gradually taking place; (4) New Black Sea, an interval of time during which the Black Sea attained its modern salinity level. This paper re-evaluates each of these hypotheses with additional $^{14}$C, $\delta^{18}$O, $\delta^{13}$C, and $^{87}$Sr/$^{86}$Sr measurements on mollusk shells from all of the Black Sea margins together with complementary reflection profiles and bathymetry. A new age model aligns the traditional Black Sea chronological scheme to one that incorporates changes in the radiocarbon reservoir of the Black Sea-Lake surface water.

## 2. Methods and Materials

Reflection profiles were acquired on the 1993 *Akvanavt* (Ryan et al., 1996; Ryan et al., 1997), 1998 BLaSON1 and 2002 BLaSON2 (Lericolais et al., 2007), and 1998 Bulgarian navy ship *Hydrograph* (Genov, 2014) expeditions (Fig. 2 from the Ukrainian, Romanian, Bulgarian, and Turkish shelf areas of the Black Sea). Chirp profiles U-A and U-B were retrieved from the Ukrainian margin during the 1993 *Akvanavt* expedition. Chirp profiles R-A and R-B were retrieved from the Romanian margin during the 1998 BLaSON1 expedition. Chirp profile B-A was retrieved during the 2002 BLaSON2 expedition from the Bulgarian margin. Boomer-sourced reflection profiles B-B and B-C were retrieved during the 1998 expedition with the Bulgarian navy ship *Hydrograph* from the Bulgarian margin. Perspective dune view was retrieved as part of the Emine transect also during the latter expedition. Chirp profiles T-A, T-B, and T-C were retrieved during the 2002 BLaSON2 expedition from the Turkish margin.

Cores were collected on transects across the Black Sea shelf during: (1) joint Russian-US expedition, AK93, in 1993 on board the *R/V Akvanavt* that surveyed western Crimea and Kerch region of the outer continental shelf, (2) a joint French-Romanian BlaSON1 expedition in 1998 that surveyed Romanian region of the inner and outer continental shelf aboard the *R/V Suroit*, (3) a 1998 survey of the Bulgarian shelf with the *R/V Hydrograph*, (4) a 2001 expedition aboard *R/V Akvanavt* across the Russian shelf, (5) a French-Romanian BLaSON2 survey in 2002 that surveyed the Bulgarian and Turkish regions of the outer continental shelf, (6) a collaborative Israel, Turkey, and US expedition in 2005 aboard the *R/V Mediterranean Explorer* on the western Turkish margin, and (7) expeditions in 2009 and 2011 on the Bulgarian margin aboard the *R/V Akademik* (Fig. 2). A full list of cores used in this study is listed in Supplementary material 1.

When penetrating the seabed the cores encountered a distinct coquina that rests directly on a shelf-wide erosion surface called reflector α (Aksu et al., 2002; Hiscott et al., 2002). This erosion surface extends landward from beyond the shelf edge into coastal limans (Naukova, 1984). Mollusks in the coquina along with ostracods in the earlier