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Young Danube delta documents stable Black Sea level since the middle Holocene: Morphodynamic, paleogeographic, and archaeological implications

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ABSTRACT

New radiocarbon and optical dates show that the Holocene Danube delta started to build out of a Black Sea embayment ~5200 yr ago. Delta lobe development phases differ by as much as 5 k.y. from previously proposed ages. The new chronology allows for a better understanding of the Danube delta paleogeography, including the demise of Istria, the main ancient Greek-Roman city in the region. Prior reconstructions of sea level in the Black Sea inferred fluctuations to 15 m in range; however, stratigraphy of beach ridges in the delta shows that the relative Black Sea level for the past 5 k.y. was stable in the Danube delta region within −2 m and +1.5 of the current level. Hydroisostatic effects related to a proposed catastrophic reconnection of the Black Sea to the World Ocean in the early Holocene may have been responsible for the sea level reaching the highstand earlier than estimated by models. The new sea-level data suggest that submergence at several ancient settlements around the Black Sea may be better explained by local factors such as subsidence rather than by basin-wide sea-level fluctuations.

Keywords: beach ridges, radiocarbon dating, optical dating, isostasy, marginal basins, Romania.

INTRODUCTION

The development of river deltas affected past coastal civilizations (e.g., Goodfriend and Stanley, 1999) and influences present management decisions for significant segments of the coast (Syvitski et al., 2005). On the northwestern shore of the Black Sea, deposition of sediment discharged by the Danube River, modified by a prevailing southwesterly longshore drift, produced a series of lobes composing the Holocene Danube delta (Fig. 1). The previous chronology for the delta and the proposed links between delta lobe development and Black Sea water-level changes (Panin, 1983; Panin et al., 1983) remain uncertain (Giosan et al., 2005). Here we present a new chronology for the Danube delta and discuss its relevance to coastal evolution, sea-level changes, and archaeology. An accurate understanding of the delta development is also important for the current management of the region, which is one of the world's richest wetland ecosystems in terms of biodiversity.

Coastal deposits can be used to reconstruct past sea-level changes (e.g., van Heteren et al., 2000; Törnqvist et al., 2004). To reevaluate the sea-level variability in the late Holocene Black Sea, we derived a sea-level record by dating fossil beach ridges from the Danube delta. A strongly debated hypothesis posits that a freshened, isolated Black Sea reconnected catastrophically to the world ocean in the early Holocene (Ryan et al., 2003) within several decades (Siddall et al., 2004). Well after the reconnection, total or partial submergence of several Chalcolitic, Greek, and Roman sites (Fig. 1) was explained by sea-level changes usually assumed to be synchronous around the Black Sea (e.g., Draganov, 1995; Shilik, 1997). Advanced early cultures populated the coastal region of the Black Sea before the Neolithic, and the ancient Greeks established colonies on the shores starting in the eighth century B.C. Precise sea-level indicators are needed to clarify the impact of Black Sea water-level fluctuations on these ancient coastal populations because existing sea-level data are widely variable and contradictory (Pirazzoli, 1991).

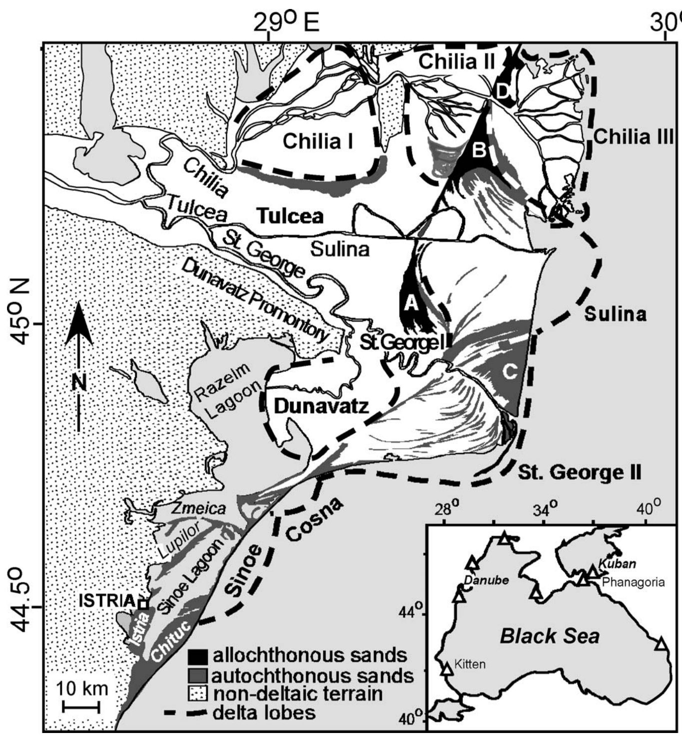

Figure 1. Danube delta morphology and lobe development sequence (after Panin et al. 1983; Giosan et al., 2005). Postulated locations for Cosna and Sinoe lobes are from Panin et al. (1983). Major beach ridge plains are (A) Caraorman, (B) Letea, (C) Saraturile, and (D) Jebrieni. Barrier systems of Zmeica, Lupilor, Istria, and Chituc segment Razelm-Sinoe lagoons. Location of ancient city of Istria is indicated. Inset shows location of Danube and Kuban deltas and several ancient settlements in Black Sea affected by submergence (triangles) from Chalcolitic and Early Bronze Age (ca. 5500 and 4000 yr B.P. for Balkans) to Greek-Roman period (eighth century B.C. to seventh century A.D.).

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BACKGROUND

The Danube delta started as a fluvial-dominated delta in an embayment of the Black Sea (Fig. 1), which was probably sheltered by a barrier (Panin et al., 1983). After reaching the barrier coast, Danube distributaries built four laterally offset lobes. Open-coast delta lobes are wave dominated (Fig. 1), with the exception of the Chilia III, the youngest lobe, which has a primarily fluvial-dominated morphology. The wave-dominated lobes exhibit an asymmetric morphology (Bhattacharya and Giosan, 2003). Longshore drift obstruction at distributary mouths led to extensive beach ridge plain development on the updrift side of these lobes, whereas on the downdrift side, barrier plains developed as a succession of sandy ridges separated by elongated marshes and/or lakes.

Early interpretations of beach ridge juxtaposition patterns established a relative chronology for the open-coast lobes (de Martonne, 1931; Zenkovich, 1956). The St. George I was the first lobe built at the open coast, followed by Sulina; subsequently, the St. George arm was reactivated, developing a second lobe (Fig. 1). Panin (1983) explained the rapid growth of the Sulina lobe as a forced regression during a postulated Black Sea Phanagorian regression (ca. 3000–2000 yr B.P.; Chepalyga, 1984). The subsequent reactivation of the St. George branch was attributed to a channel slope increase at the Phanagorian lowstand (Panin, 1983). Within the remnant shallow basins of the Danube embayment, the northernmost distributary, the Chilia, developed two successive lacustrine deltas before building into the Black Sea (Fig. 1). The Danube delta plain extends southward into several generations of baymouth barriers (Zmeica, Lupilor, Chituc, Istria), delineating the Razelm-Sinoe lagoon system. The Dunavatz arm built a bayhead lobe in the Razelm-Sinoe lagoon after splitting from the St. George branch.

METHODS

Dating wave-deposited coastal facies is difficult, largely because of sediment reworking (e.g., Hopley, 1986; Stanley, 2001). To ensure that ^{14}C dated specimens were contemporaneous with the coastal deposit to be dated, we dated articulated bivalves recovered from beach ridges. Several ridges were also dated using optically stimulated luminescence on quartz sand grains (Duller, 2004). Ridge height was assessed from topographic maps, and the top of the beach-foreshore-backshore facies on dated ridges was used as sea-level index (e.g., van Heteren et al., 2000). Dates and details on coring, sampling, and dating are presented in the GSA Data Repository.[1] Unless otherwise identified, all dates discussed herein are presented as calendar (cal.) yr B.P.

DELTA CHRONOLOGY AND EVOLUTION

On the basis of conventional ^{14}C dating of bivalves, Panin et al. (1983) proposed a chronology for the Danube delta (Fig. 2) consisting of the following phases: (1) the baymouth barrier of the Danube embayment, ca. 12,700–8000 yr B.P.; (2) the St. George I lobe, 10,100–7400 yr B.P.; (3) the Sulina lobe, 7400–1700 yr B.P.; (4) the St. George II and Chilia lobes, 2800 yr B.P. to present. Prior to ca. 9000 ^{14}C yr B.P. or as late as 8400 ^{14}C yr B.P. (10,000–9500 cal. yr B.P. and 9200–8500 cal. yr B.P., respectively), the Black Sea was a freshened lake (Aksu et al., 2002 and Ryan et al., 2003, respectively). Because the water was too fresh to support marine mollusks (Degens and Ross, 1972) such as some of those dated by Panin et al. (1983), we can dismiss the proposition that any of the wave-dominated Danube delta lobes formed before ca. 9000 yr B.P. The youngest dates presented by Panin et al. (1983) suggest that the open-coast Danube delta may be as young as ca. 5000 yr B.P. (Giosan et al., 2005). Cannibalization and redeposition of radiocarbon-dead shells from shallow coastal deposits of a previous marine highstand could explain the old dates of Panin et al. (1983) obtained from multishell samples (Giosan et al., 2005).

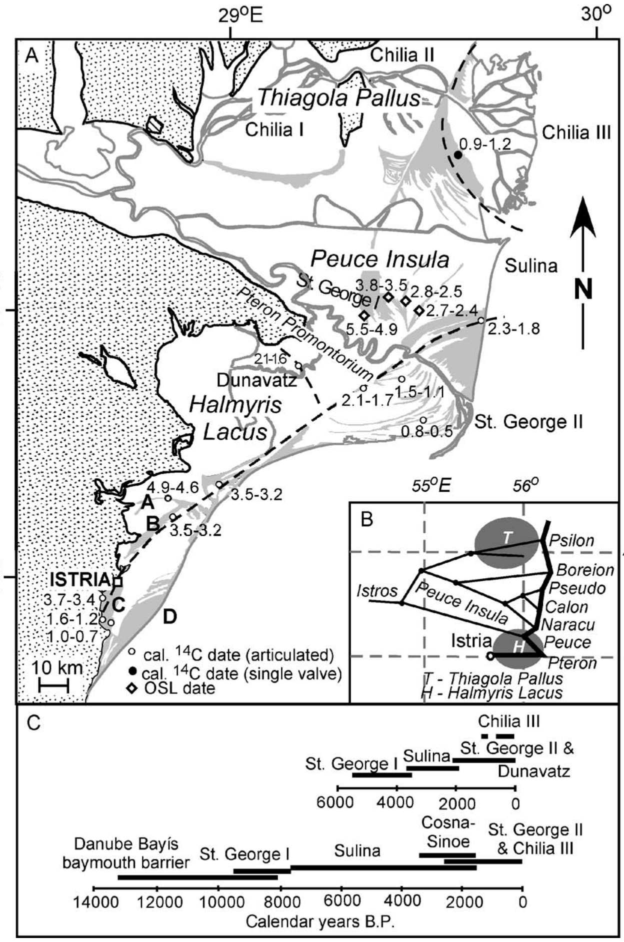

Figure 2. A: Danube delta chronology. Zmeica, Lupilor-Istria I, Istria II, and Chituc barriers are indicated by A, B, C, and D, respectively. Dashed line is inferred coast ca. A.D. 1. OSL—optically stimulated luminescence; cal.—calibrated radiocarbon dates. B: Danube delta after Ptolemy (Stevenson, 1932); latitude and longitude are original coordinates. C: Lobe and/or barrier development chronologies: lower—Panin et al. (1983); upper—this study.

Our new chronology shows that several open coast delta lobes developed thousands of years later than previously suggested (Fig. 2). Optical ages on beach ridge sands, where available, corroborate the ^{14}C dates on articulated shells, supporting their selection as dating targets (Data Repository; see footnote 1). The Caraorman beach ridge plain of the St. George I lobe has been preserved largely intact (Fig. 1). An optical date on one of the most landward beach ridges puts the inception of the plain, and therefore of the open-coast Danube delta, as ca. 5210 ± 280 yr B.P. (Fig. 2). All but the most seaward Caraorman ridges consist of sands drifted alongshore from north of the Danube delta (low heavy mineral content, composed of a resistant assemblage, and high silica content; Panin, 1989). The Caraorman plain continues directly into ridges of the incipient lobe of the Sulina branch (Panin, 1989), composed of autochthonous Danube-derived sands (relatively high heavy mineral content, composed of a varied assemblage, and low silica content). The optical date on a ridge located before this transition constrains the end of the St. George I lobe regressive phase and the start of the Sulina lobe as ca. 3640 ± 140 yr B.P. (Fig. 2). Until between 2200 and 1800 yr B.P., expansion of the Sulina lobe was extensive, and may be related to an augmented discharge during a humid period in Danube's drainage basin (Barber et al., 2004). The approximate end of the Sulina regressive phase agrees with the age of

[1]GSA Data Repository item 2006158, sampling and dating strategies and the rationale for the chronological model, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

2000–1700 yr B.P. for the first beach ridge on the southern half of the St. George II lobe. The older beach ridges of the Letea plain of the Sulina lobe (Fig. 1) are composed either of entirely allochthonous sands or have an additional local contribution from secondary distributaries of the Sulina branch (Panin, 1989). In contrast, the outer beach ridge sets on Letea are made of Danube sands, suggesting the Chilia branch as their updrift source (Panin, 1989). The youngest date on this outer ridge set suggests that the earliest significant input of sand to the open coast from the Chilia occurred no earlier than 1200 yr B.P.

Panin et al. (1983) and Panin (1989) suggested that the Dunavatz distributary built two successive delta lobes at the open coast, the Cosna and Sinoe, between 3800 and 700 yr B.P.; these were subsequently reworked into the barrier systems of the Razelm-Sinoe lagoons (Fig. 1). However, no emergent deltaic deposits connect the postulated lobes to the current inland location of the Dunavatz lobe. Our dates show that the Dunavatz bayhead lobe (Fig. 2) passed the Dunavatz promontory, advancing into the Razelm lagoon, not much earlier than 2000 yr B.P. Thus, the barrier systems in the Razelm-Sinoe lagoon system more likely formed as spits built out of along-shore drifted sand from the updrift Danube delta lobes (Giosan et al., 2005). The Zmeica barrier (Figs. 1 and 2) is either a remnant of the initial Danube embayment barrier or a flanking barrier of the St. George I lobe that stabilized between 4900 and 4500 yr B.P. The Lupilor barrier system (ca. 3500–3100 yr B.P.) stabilized during the trangressive phase of the St. George I lobe and appears to be coeval with the earliest beach ridge set of the Istria strandplain (3700–3300 yr B.P; Fig. 2). The youngest beach ridge set at Istria was built between 1500 and 600 yr B.P. (Fig. 2). At the present shoreline, beach ridge directions on the Chituc barrier are similar to the directions of the youngest Istria set, suggesting that they formed contemporaneously, probably on either side of an inlet. Alternatively, the seaward position of Chituc barrier implies that it is younger than the Istria strandplain. Several young barriers in the Razelm-Sinoe region (younger than 450 yr B.P.) appear to be constructed by lagoonal processes; these barriers are discordant to the general NE-SW orientation of the coast and some of them connect the Chituc, Lupilor, and the Zmeica barriers (Figs. 1 and 2).

DELTA PALEOGEOGRAPHY IN CLASSIC GREEK-ROMAN TIMES

Our chronology is useful in reconstructing the paleogeography of the Danube delta, one of the deltas described in the ancient Greek and Roman texts. On the basis of our chronology (Fig. 2), the Chilia branch was still building its lacustrine delta ca. A.D. 1 in the marshy Thiagola Pallus of Ptolemy (A.D. 85–165 [Ptolemy's lifespan]), and excess water was probably discharged through an inlet, Psilon (Stevenson's translation of Ptolemy's Geography [1932]). The Sulina discharged through several mouths or stomae (Fig. 2B), and its lobe was advanced compared to the present coast (Panin, 1983). The southern arm of the Danube was split into two main distributaries, Dunavatz and St. George. Dunavatz started to build its marshy delta (Strabo, 63 B.C.–A.D. 21 [Strabo's lifespan]) into Halmyris lagoon (Hamilton and Falconer, 1960). Although imprecisely located by Ptolemy, Pteron Promontorium (i.e., the Wing Promontory) is an adequate description of the paleogeography of the region, i.e., the Dunavatz hilly promontory with the attached wing-like lowlands of the incipient Dunavatz lobe and the Lupilor barrier (Fig. 2). In the third century B.C., Apollonius Rhodius (Seaton, 1912) described an island in his *Argonautica*: "For a certain island is enclosed by Ister, by name Peuce, three-cornered, its base stretching along the coast, and with a sharp angle towards the river; and round it the outfall is cleft in two." The long debated location of this "island" (Panin, 1983), the Peuce, which was the birthplace of Alaric the Goth, the conqueror of Rome (Mierow, 1908), appears to be the entire interdistributary terrain between the St. George arm (also named Peuce or Hieron) and the southernmost branch of the Sulina arm at the time. South of Halmyris lagoon, the flourishing Milesian

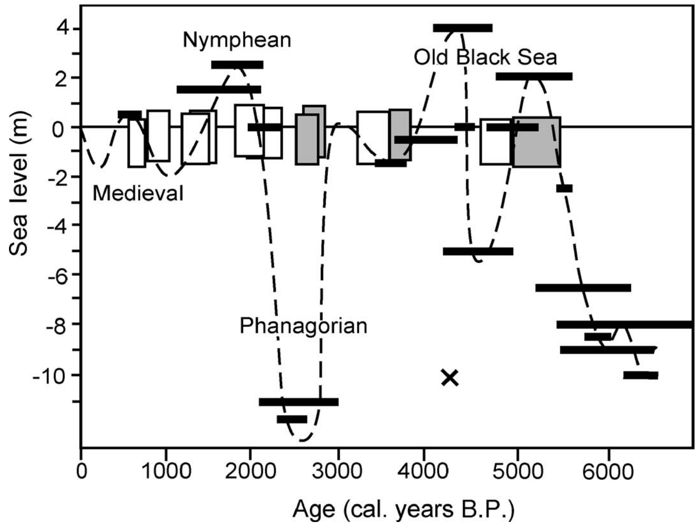

Figure 3. Relative sea-level data for Black Sea since middle Holocene. Danube delta index points are represented by error boxes (white for calibrated radiocarbon dates; gray for optical dates). Previous sea-level curve (after Chepalyga, 1984) is shown as dashed line with 2σ age error intervals (bold line segments; published data do not include estimates for vertical errors). Postulated highstands (Old Black Sea and Nymphean) and lowstands (Phanagorian and Medieval) are indicated (e.g., after Chepalyga, 1984; Shilik, 1997). Date of 4246 B.P. for submerged settlement at Kiten (Fig. 1; Kuniholm et al., 1998) is also plotted (X symbol). Ages in calendar years (cal.) B.P.

colony of Istria had exclusive fishing rights in the delta (Pârvan, 1926). Our dates suggest that the intensive ridge development at the Istria shore may have contributed to the final demise of the city in the seventh century A.D. (Bleahu, 1963).

LATE HOLOCENE RELATIVE SEA LEVEL

Most interpretations of relative sea-level (RSL) data in the Black Sea converge to two major late Holocene events (e.g., Chepalyga, 1984; Shilik, 1997): a higher than present Old Black Sea highstand, followed by a substantially lower than present Phanagorian lowstand (Fig. 3). Estimates for large magnitude (5–15 m) and short duration (centennial) sea-level fluctuations vary (Pirazzoli, 1991), and are not supported by hydrological arguments in a Black Sea connected to the world ocean (Selivanov, 2003). In contrast, dates cited by Kaplin and Selivanov (2004) indicate that the RSL in the Kuban delta region (Fig. 1) was relatively stable after 7000 ^{14}C yr B.P. Our reconstruction suggests that the RSL in the Danube delta region was stable for the past ~5 k.y. to within +1.5 m and −2 m of the current level (Fig. 3), ruling out any large-amplitude, short-term changes (Fig. 3). Therefore, submergence of Chalcolitic and Early Bronze Age settlements located on the Bulgarian coast (Figs. 1 and 3; Draganov, 1995) and of several Greek and Roman settlements around the Black Sea (Fig. 1; e.g., Shilik, 1997), previously attributed to basin-wide sea-level changes, should be reconsidered to take in account local factors. For example, a local subsidence rate of ~2.3 mm/yr is required to account for the ~10 m of submergence of the Bronze Age settlement at Kitten, Bulgaria (Fig. 3), whereas a rate of 2–5 mm/yr is needed to explain subsidence at the ancient Greek city of Phanagoria.

The sea level in the Danube region ca. 6 ka was modeled to between −5 and −8 m (Lambeck and Purcell, 2005). A tectonic contribution, not accounted for by the model, may help explain why the sea level was within 2 m of the modern values 5 k.y. ago or earlier in the Danube delta (Fig. 3). Immediately north of the Danube delta, shallow lagoonal sediments of the last highstand (i.e., the Karangat, corresponding to marine isotopic stage [MIS] 5e) are present ~4 m above sea level (Dodonov et al., 2000). Sea-level indicators of MIS 5e on tectonically stable Mediterranean coasts are also a few meters above the present sea level (Lambeck and Purcell, 2005). An uplift rate for the delta region of <0.1 mm/yr, related to active crustal folding near the southeastern Carpathians, can be estimated for Pliocene–Quaternary time (van der Hoeven et al., 2005). This estimate agrees with the position of the Karangat sediments, but could explain only ~0.5 m of uplift for beach ridges developed ca. 5000 yr B.P. Another contribution to the early relative sea-level rise to modern values could have been hydroisostatic in origin. When the Black Sea lake, with a lowered level at ~−100 m (Ryan et al., 2003), reconnected to the Mediterranean in the early Holocene, the basin was rapidly filled with a 50–70-m-thick water column. The water load may have depressed the outer shelf, which is widest in front of the Danube delta, while lifting the coastal regions independently of ice sheet–related isostasy (Bill Ryan, 2005, personal commun.), thus contributing to an early highstand at the Danube mouths. Our new sea-level record underscores the need for reliable sea-level data for different tectonic blocks of the Black Sea coast and for considering climatic as well as isostatic effects that are typical for marginal basins undergoing episodic isolation from the world ocean.

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