

Long term sediment dynamics on Danube delta coast

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ABSTRACT: Most of the coast of the Danube delta is severely eroding, although the northernmost distributary (the Chilia) which collects most of the water and sediment discharged by Danube can sustain a continuous progradation of its lobe. Sediment drift patterns for the Romanian deltaic coast, based on a sand budget and predicted potential net sediment transport, indicate that shoreline behavior is mainly prescribed by energetic waves with an acute angle of attack. Shoreline behavior is negatively influenced by the natural and human-induced decrease of the Danube's sediment discharge, and by the jetties and dredging practice at Sulina mouth and Midia Harbor. The Sfântu Gheorghe deltaic lobe appears to be polygenetic with significant sediment sources which are both fluvial and marine, and with both cross-shore and longshore agents controlling the sediment redistribution.

INTRODUCTION

Many deltas around the world have been eroding due to anthropogenic alteration of both water and sediment discharge, coupled with vigorous longshore sediment transport and relative sea level rise. A report of the Romanian Center for Marine Geology and Geoecology (RCMGG, 1994) documented shoreline recession of the Danube delta related to: (1) the alternate channel extension process which regulates the sediment discharge of the Danube's distributaries (cf. Wright, 1985); (2) a general decrease in the river sediment discharge; (3) the energetic wave regime; (4) the effect of coastal engineering structures; and (5) the relative sea level rise. The tidal processes are not important since the Black Sea has a tidal range of 7 to 12 centimeters (RCMGG, 1994).

In this study, long term sediment dynamics along Danube delta coast is analyzed based on estimates of the natural and anthropogenic sediment sources and sinks, and of the longshore sediment transport rates. Information, mainly from the Romanian literature, on the sediment dynamics in the study area is reviewed and discussed. A conceptual model for the evolution of the southern Sfântu Gheorghe deltaic lobe is presented.

1. STUDY AREA

The Romanian coast has two geomorphic units (RCMGG, 1994): a southern unit extending from the border with Bulgaria to Midia and a northern unit from Midia to the border with Ukraine (Figure 1). The southern unit is characterized by eroding cliffs and loess, protected in places by narrow beaches. The northern unit, investigated in the present study, consists of the low-relief Danube delta coastal plain and an adjacent baymouth barrier complex.

1.1 Wind and Wave Climate

The average wind speed in the northwestern Black Sea is between 5 and 6.5 m/s (Bulgakov et al., 1992). The predominant wind directions during the year, as they were measured at meteorological stations on the coast, are from the north, west, and south (Ciulache, 1992). The annual modal direction for onshore winds is from the northeast. During the summer months, however, the predominant direction is onshore from the south-southeast while it is from north-northeast in winter (Diaconu et al., undated, as cited in RCMGG, 1994). Because the Romanian sector is relatively short, the wind regime does not vary significantly along the coast (see data presented by Ciulache, 1993). Storms are prevalent from the north and northeast, with an average wind speed of

9.8 m/s and a duration ranging between 8 and 22 hours (Diaconu et al., undated, as cited in RCMGG, 1994).

Waves arrive at the coast from all offshore directions about 50% of the year (Diaconu et al., undated, as cited in RCMGG, 1994). Of these 60-85% are local wind waves, and 15-40% swells. Details on the wave climate will be presented in the "Results" section.

1.2 River Discharge

In the late 1980s, the water discharge of the Danube was about 200 km³/year, with a total sediment load of about 40x10⁶ metric tons/year (Bondar et al., 1992). Bedload has been estimated to be between 4.5 and 10% of the total sediment discharge. Bondar et al. (1992) documented an increase of 14% in the water discharge and a decrease of 40% in the total sediment load between 1858 and 1988. The biggest reduction (about 30%) in the sediment discharge was recorded immediately after 1970 when the Iron Gate dam closed on the upstream Danube (RCMGG, 1994). Today, the Danube has three main active distributaries. The northern Chilia arm discharges

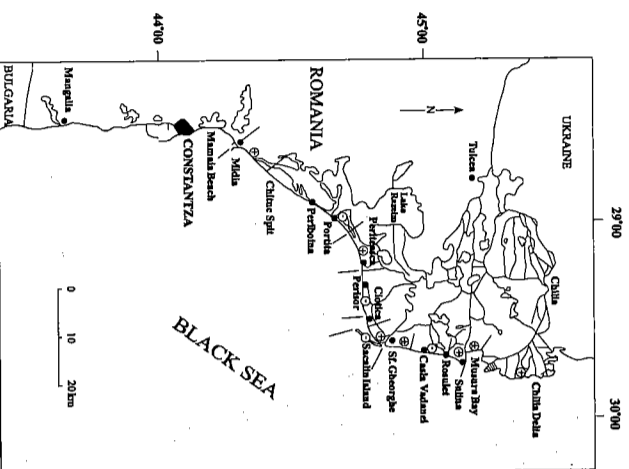


Figure 1. Romanian Black Sea coast. Danube delta coast (including the adjacent, genetically related, baymouth barrier in front of Razelm-Sincoe lagoons) extends from Chilia to Mifida. Sectors with retreating shoreline are indicated by - while those with advancing shorelines by ⊕.

63% of the total Danube sediment load (Bondar et al., 1992). The total sediment discharge of Sulina and Stantula Gheorghe distributaries is 17% and 20% respectively. The mouths of each major distributary act as river dominated estuaries with salt-wedge penetration of the sea water during the months of low riverine discharge (Bondar, 1972). Because the average discharge is relatively high, most of the bedload is temporarily deposited as a mouth bar (Bondar, 1972). The buoyant riverine plumes (Bondar, 1972; Wright, 1977) of the distributaries are deflected to the south due to the Coriolis force and to the cyclonic gyral circulation in Western Black Sea (Bondar, 1964).

1.3 Danube Delta Evolution

The modern Danube delta (Figure 2) formed during the Holocene (Panin, 1989) by an alternate channel extension process (Wright, 1985): one to four main distributaries were active at the same time, the one with highest gradient and consequently sediment discharge, building a deltaic lobe. Contemporaneously, previously built lobes might reshape or slowly prograde, depending on the extent of their sediment discharge relative to marine dispersive processes. Most of the deltaic lobes have changed their appearance from cuspat to lobate, and the reverse (Panin, 1974), as a function of distributary sediment discharge, local intensity of

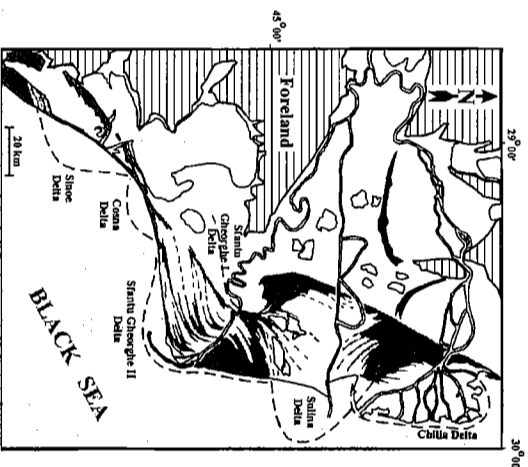


Figure 2. Danube delta lobes - simplified geomorphic map (after Panin, 1989). Marine sandy ridges (dark grey) and lacustrine sandy ridges (black) alternate with finer fluvial and lacustrine sediments (white).

marine processes, and geometry of the receiving basin. The evolution of Danube delta is illustrated by the orientation, morphology, and succession of the former beach ridges (Figure 2; Panin, 1974).

Dominance of the Chilia distributary increased in the last 300 years (Mikhailova, 1995) at the expense of the other lobes (Panin, 1974). The high sediment discharge of this distributary sustains a continuous, intense progradation. The wide, shallow shelf, and relatively low energy wave climate at Chilia mouth favors the development of a symmetrical lobate delta (Figure 2). Other earlier lobes (Figure 2) were either completely eroded (Cosna, Sincoe) or in the process of reshaping (Sulina).

The southern deltaic lobe of Stantula Gheorghe is slowly prograding. It displays a dichotomy in facies: whereas the updrift side is a strandplain, the downdrift side consists of sand ridges alternating with lagoon, marsh and fluvial deposits (Panin, 1974). The southern sand ridges apparently originated as barrier islands (Panin, 1974) on the river mouth bar. Shustskiy (1989) suggested that these sand ridges are fluvial cheniers but no unequivocal data is presented in sustaining his hypothesis. Based on C¹⁴ dating of shells, Panin (1983; Figure 3) sketched the evolution phases of the southern wing: the progradation rate was slow at the beginning of the lobe development (about 1.5 m/year between 2,800 to 2,300 B.P.), increased sharply between 2,300 and 2,000 B.P. to about 25 m/year, and decreased to about 7 m/year afterwards. There is geomorphic evidence (Panin, 1974) showing that about 2,000 years ago the lobe's progradation style changed through the formation of a first secondary lobe delta at the mouth (Figure 3). Vespreneanu (1983) analyzed the evolution of the Stantula

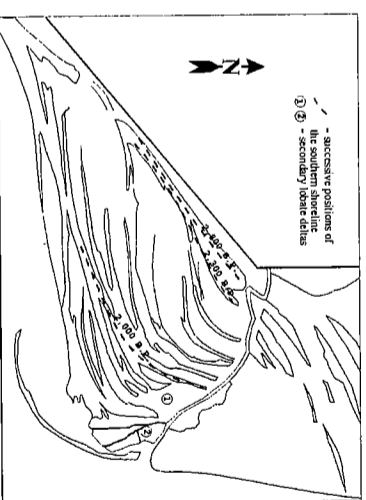


Figure 3. The evolution of the southern wing of Stantula Gheorghe lobe (dating on shells from Panin, 1983). Sandy ridges (gray) alternate with finer fluvial and lacustrine sediments (white).

Gheorghe mouth using maps spanning the last 200 years. He recognized three evolutive stages: an estuary stage prior the development of Sacalin barrier island, and a secondary delta stage and a final marsh stage afterwards. Today, the discharge of Stantula Gheorghe distributary is the same magnitude (i.e. 0.8-1x10⁶ m³/year) as the sediment provided by the sediment drift at the mouth (Giosan et al., submitted). The discharge of water is apparently great enough year-round to prevent the southward deflection of the mouth by barrier spit elongation from the updrift side. However, since the sediment drift from north is high, a subaqueous spit-leeve develops periodically on the northern side of the mouth (Vespreneanu, 1983). Sacalin barrier island developed from a bar that emerged at the end of the last century, offshore the mouth of Stantula Gheorghe distributary, following an extreme river flood (Panin, 1974).

1.4 Deltaic Coast Dynamics

After the closure of Iron Gate dams upstream Danube in 1970s beach erosion became almost generalized on the entire coast south of Chilia lobe (RCMGG, 1994, Vespreneanu and Stefanescu, 1988; Figure 1). Shoreline changes have also been strongly influenced by the dredging of Sulina mouth bar (RCMGG, 1994) which starves the downdrift coast of about 800,000 m³/year of sand. Long jetties at Sulina mouth and Mifida harbor (Figure 1) modify the nearshore circulation system: they intercept the longshore drift from the north redirecting part of it to the offshore, and create sheltered, highly depositional areas in their lee to the south (Almazov et al., 1963; RCMGG, 1994; Giosan et al., submitted) with the sediment drift reversed relative to the southward general direction. However, the subaqueous delta of Stantula Gheorghe is the most important sediment sink in the area, controlling the behavior of the coast downdrift of it. Bondar et al. (1983) have estimated that between 1858 and 1968, about 5,000,000 m³/year of sediment accumulated on the subaqueous delta in front of Sacalin Island. After its emergence as an offshore bar during an extreme river flood, Sacalin Island has continuously increased in length to the south while retreating landward. Textural characteristics show that the island has been built with sand originating from both Stantula Gheorghe distributary and Sulina eroding lobe (Giosan, 1993). The northern half has already welded to the mainland marshes of the Stantula Gheorghe secondary delta (RCMGG, 1994). The island retreat apparently is controlled by the

washover and breaching processes (RCMGG, 1994) superimposed on an accretionary regime indicated by island elongation, rapid closure of storm breaches, and continuous building of the island subaqueous platform (Bondar et al., 1983).

Previous estimates indicate extremely high longshore sediment transport along the deltaic coast. Based on shoreline changes, Shnitsky (1984) estimated the net longshore transport along Chilia lobe at 720,000 to the south. This high transport rate is supported by the shoaling rate of over 1,100,000 m³/year estimated by Bondar and Harabagiu (1992) on the northern side of Sulina jetties. The shoaling rate of at least 500,000 m³/year (Bondar and Harabagiu, 1992) on the southern side of the jetties should be a direct estimate of the net longshore transport in the reversal zone south of Sulina, but the natural shoaling in this area was clearly overestimated because an unknown but substantial amount of sand retrieved from Sulina harbor was discharged on the beach in the 1980s. South of the reversal zone to Sfântu Gheorghe, the net transport was previously estimated to about 700,000 m³/year southward (RCMGG, 1994) based on a sediment budget. Farther south along the Chituc spit, Bondar et al. (1980) estimated the longshore transport by using synoptic wind data to hindcast the wave climate. The calculated drift was directed southward at a rate between 900,000 and 1,100,000 m³/year to the 9 m isobath.

2. METHODS

The present study integrates new estimates of the sediment drift with various data on the Danube delta sediment dynamics published especially in the Romanian literature in the last 30 years. Additionally, the dynamics of Sfântu Gheorghe mouth area and Sacalin barrier island was examined.

A sand budget was the first method used to estimate the longshore sediment transport rates for the study area. The active beach, gradients in the longshore transport, and river sediment input were assumed to be the only sources or sinks for sediment for the entire study area. The above assumptions, however, would not be valid along the barrier beach of Sacalin Island, since the cross-shore transport by washover and breaching (RCMGG, 1994), and especially offshore loss along the delta front (Jianu and Selariu, 1970; Bondar et al., 1984), are likely to be important. A sand budget, therefore, was not calculated for Sacalin Island. Volume charges for the sand budget were calculated using the end-point shoreline change rates published by Vesprieanu

and Stefanescu (1988) for the period between 1962 and 1987. The original data were collected on a network of 37 monuments as suberial beach profiles, and reduced to the Romanian Black Sea vertical datum. A hybrid model was used to estimate volumes from shoreline changes: either under assumption that an equilibrium, long-term beach profile is conserved for the advancing shoreline sectors (the "one-line" model; Pelhard-Considere, 1956), or that the beach profile general shape is non-conservative, becoming more gradual where the shoreline retreated (Refaat and Tsuchiya, 1991). Beach gradient reduction was confirmed in the field for the eroding Ebro delta over a scale of several years (Jimenez and Sanchez-Arcilla, 1993). The beach volume change (ΔV) for the advancing sectors was thus computed as (Imman and Dolan, 1989):

$$\Delta V = \Delta x \cdot Z \cdot L \quad (1)$$

and to account for the wedge shaped profile change of the retreating sectors the above formula becomes:

$$\Delta V = \Delta x \cdot Z \cdot L / 2 \quad (2)$$

where Δx is the average shoreline retreat/advance of each sector, Z is the vertical distance over which the deposition or erosion occurs, and L is the sector length. Z was taken from the top of the berm (+0.5 m on average) to the depth of closure which was estimated for each sector. Because suitable submerged beach profile measurements were unavailable for the Romanian coast, the closure depth along the coast was estimated using a sedimentologic proxy: the offshore limit between well-sorted sands (>75% sand) and sands with a higher fine fraction contribution (>25% silt and/or clay-sized material). A detailed sedimentologic map of the Romanian shelf was used for this purpose (RCMGG, 1995). The closure depth determined in this way was never far from the 10-m isobath on open coast, but decreased to values less than 5 m in the lee of Sulina jetties, and of Sacalin barrier island (Figure 4). The closure depth estimate using this criterion was consistent with other estimates for the open coast. Halenmeier's method (1981) indicates annual values for the closure depth between 6 and 12 m. Previous studies of the long-term nearshore changes also indicated a closure depth between 10 and 12 m (Jianu and Selariu, 1970; Bondar et al., 1984).

The statistics of the wave regime were calculated from wave time series data over a 10-year period, between 1972 and 1981. The wave data were

measured by the Romanian Institute for Marine Research (RIMR), at a depth of 11 m, offshore the southern town of Constantza (Julian Postolache, 1995, personal communication). Wave refraction analysis was performed using available wave time

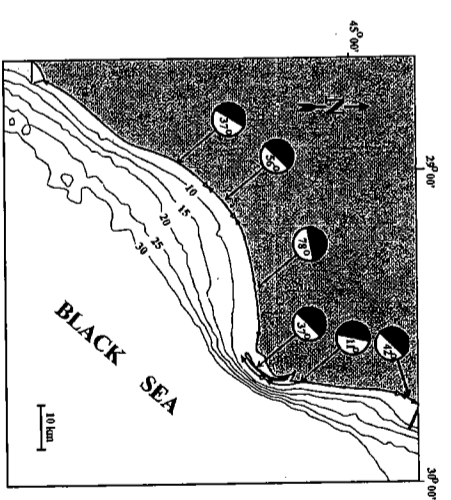


Figure 4. Bathymetry of the study area (depths in meters), with the average orientation of different coast sectors used in computing the potential longshore sediment transport. The well-sorted sand (75% sand) of the high-energy nearshore zone is represented with a grey pattern.

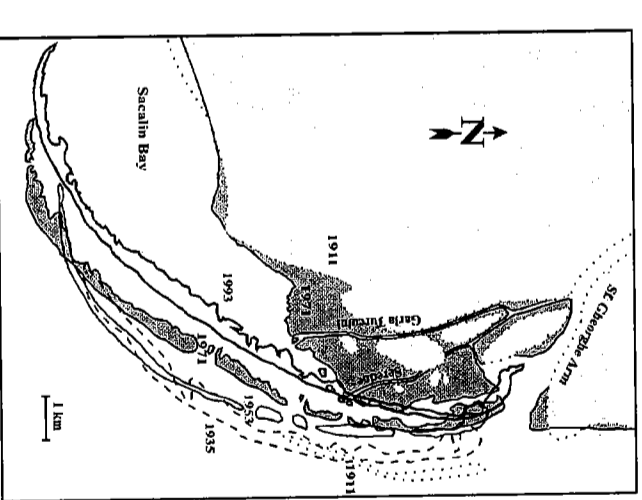


Figure 5. Sacalin Island consecutive positions (after Breier and Teodor, 1979; Găstescu, 1979; and Păun et al., 1994).

series on the study area bathymetry (Figure 4), and potential sediment transport rates were estimated from the wave energy flux (CERC model; U.S. Army Corps of Engineers, 1984). Predicted potential transport was compared to the net longshore sediment transport computed from the sand budget. The behavior of Sacalin barrier island was further examined based on previously published island maps for 1911, 1935, 1963, 1971, and 1979 to 1993 (Figure 5; Breier and Teodor, 1979; RCMGG, 1994). Furthermore, bathymetry changes between 1856 and 1962 were analyzed for the Sfântu Gheorghe mouth. This geomorphic analysis permits only the identification of the main trends in the evolution of the Sfântu Gheorghe mouth area, since the accuracy of the maps cannot be estimated.

3. RESULTS

3.1 Wave Climate

Based on the 10 year-long measurement series it was determined that waves higher than 0.2 m (the lower limit of the wave height that was measurable using the available instrumentation) arrived at the coast from all offshore directions about 51% of the year. The annual average significant wave height was 0.8 m, with a mean period of 5 seconds. Most waves arrived from the northeast-southeast quadrant (Figure 6), the predominant direction and energy flux being from the east.

3.2 Net Longshore Transport

Sediment budget-derived net longshore transport is relatively high as a result of the prevailing E-NE waves superimposed on NNE-SSE general orientation of the coast. The general pattern of the net longshore transport provided by the sediment

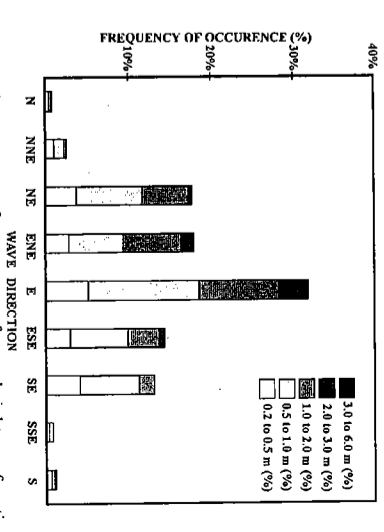


Figure 6. Frequency of occurrence of wave height as a function of their direction of approach to the coast.

