# DANUBE RIVER SEDIMENT INPUT AND ITS INTERACTION WITH THE NORTH-WESTERN BLACK SEA: RESULTS OF EROS-2000 AND EROS-21 PROJECTS

Nicolae PANIN, Dan JIPA

National Institute of Marine Geology and Geo-ecology – *GEOECOMAR*
23-25, D. Onciul Str., 70318 Bucharest, Romania; Tel/Fax: +40-1-252.25.94

**Abstract.** The River Danube influence is determinant for the sedimentation on the north-western and western Black Sea area. After the year 1970, consequently to the building of the Iron Gates dams, the Danube River sediment discharge diminished to 30-40% of the previous value. At the end of a 12,000 years evolution marked by active progradation, during the last decades the Danube Delta became mostly inactive partly due to the anthropic interventions. The deficit of sediment influx lead to intense erosional processes of the deltaic littoral. On the Black Sea north-western shelf two main areas, with contrasting sedimentary processes, have been identified: the internal, Danube sediment-fed shelf and the external, sediment-starving shelf. The modern highstand sedimentary history of the north-western Black Sea deep area is marked by the cessation of the Danube deep sea fan active development. The main depositional units within the north-western Black Sea are described.

**Key words:** Danube River, Danube Delta, Black Sea, sediment discharge, delta development, shoreline migration, littoral erosion, sediment-starved shelf, Danube Deep-Sea Fan.

## 1. INTRODUCTION

### 1. 1. Objectives of the paper

The European River - Ocean System Project (EROS) represents a major pan-European long-term contribution to the "Land-Ocean Interactions in the Coastal Zone" (LOICZ) core-project of the International Geosphere - Biosphere Programme (IGBP). Specifically EROS-2000 and EROS-21 were devoted to the study of the Black Sea - River Danube geosystem, as it constitutes an ultimate example of a dramatic deterioration of the fluvial, deltaic, coastal and marine environments. One of the specific questions addressed by these two projects was: what are the short- and long- term environmental consequences of the natural and anthropic changes in river sediment supply and what are the interactions between the river and the sea recorded through the sedimentary processes as function of climatic and sea level changes, neotectonics as well as anthropic activities impact.

Within this framework the present paper objective is to evaluate the sedimentary conditions controlling the interactions between the Black sea and the River Danube. Accordingly, pertinent informations will be presented concerning the Lower Danube River, Danube Delta and the main sedimentation zones of the north-western Black Sea (littoral, continental shelf and deep sea areas) (Fig.1). To facilitate a better understanding of the river-sea relations, the Holocene history of the Danube delta (as the main interaction territory) will be shortly presented. Special attention will be paid to the modern trends of the sedimentary factors governing the interacting system, mostly to the anthropic changes affecting the River Danube, the most important sediment supplyer of the Black Sea.

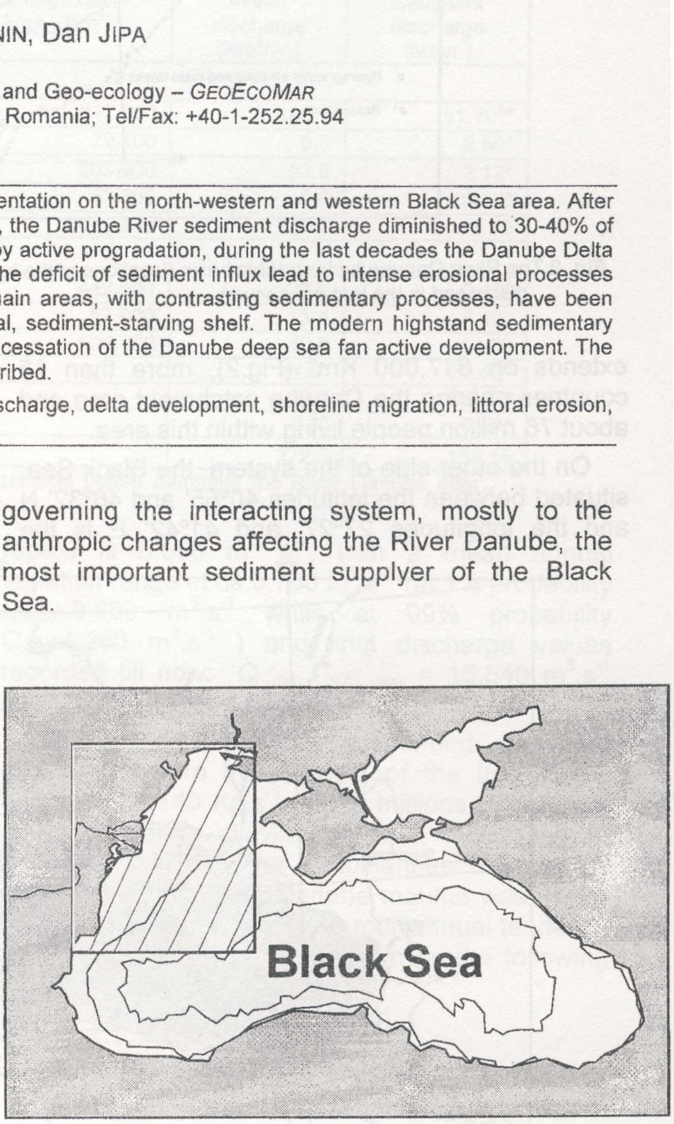


**Fig. 1** Index map of study area

### 1. 2. General setting

The River Danube is one of the end-terms of the Danube - Black Sea geosystem; this is one of the most important European waterways, flowing 2,857 km across the continent from the Schwarzwald Massif down to the Black Sea. The Danube is listed after the River Volga as the second biggest river in Europe. Its drainage basin

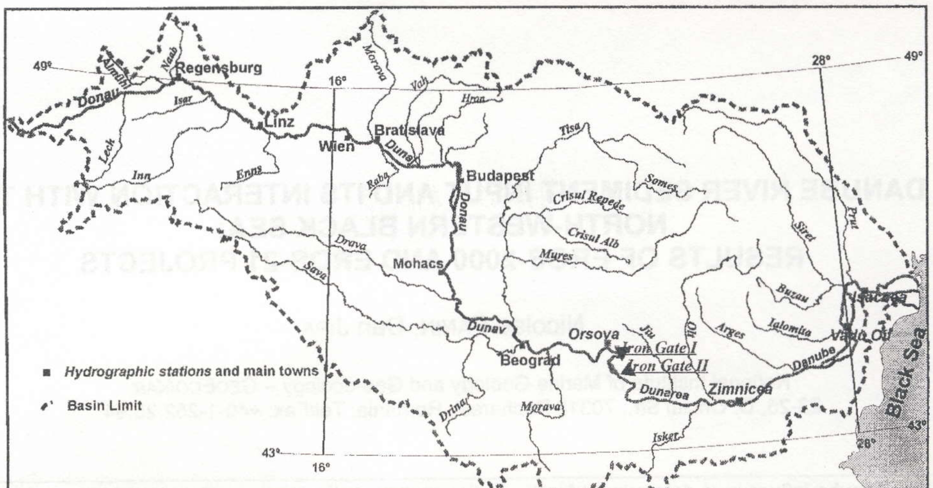


**Fig. 2** The River Danube hydrographic basin (locations of the hydrologic stations and of the Iron Gates I and II dams discussed in the text are shown)

extends on 817,000 Km$^2$ (Fig.2), more than 15 countries sharing the Danube catchment area and about 76 million people living within this area.

On the other side of the system, the Black Sea, situated between the latitudes 40°55' and 46°32' N and the longitudes 27°27' and 41°42' E is the largest land-locked sea, connected to the Mediterranean Sea only through a very narrow Bosphorous-Dardanelles system of straits (Fig. 3).

The north-western Black Sea continental shelf is very wide (~ 127,000 Km$^2$) representing almost 94 % of the total shelf geomorphologic province or about 30 % of the Black Sea total area, while the water volume above this shelf region is only about 6,500 Km$^3$ (~ 1.2 % of the total water volume of the Black Sea). The north-western Black Sea is receiving the largest tributaries of the Pontic basin:

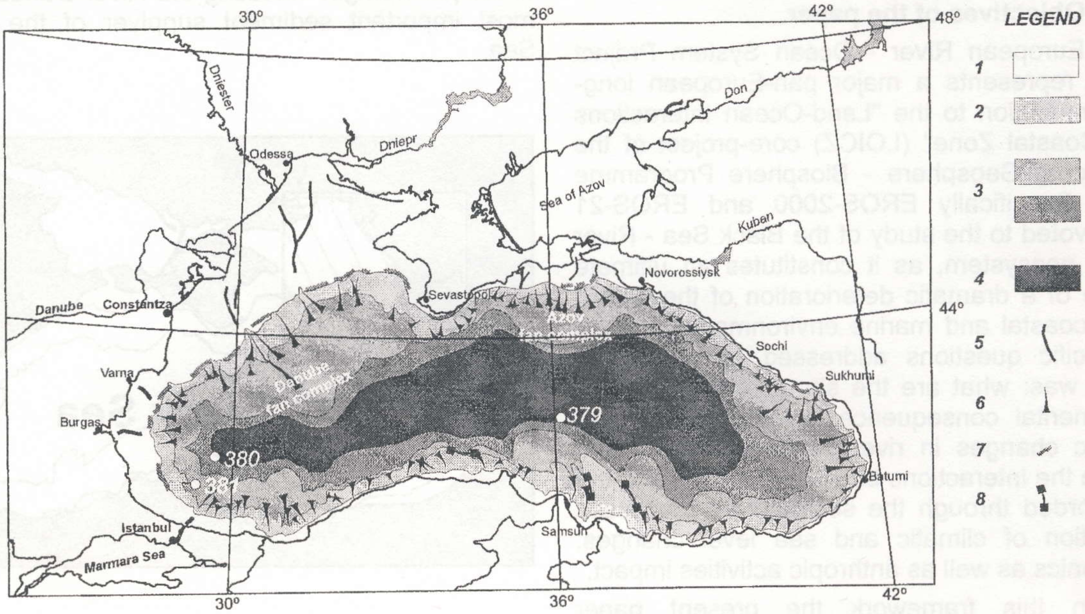


**Fig. 3** Geomorphologic zonation of the Black Sea (after Panin & E. and G. Ion, 1997)
Legend: 1, continental shelf; 2, continental slope; 3, basin apron: 3 a - deep sea fan complexes; 3 b - lower apron; 4, deep sea (abyssal) plain; 5, paleo-channels on the continental shelf filled up with Holocene and recent fine grained sediments; 6, main submarine valleys - canyons; 7, paleo-cliffs near the shelf break; 8, fracture zones expressed in the bottom morphology.

the Danube, Dniestr, Dniepr and Southern Bug rivers. Draining a territory almost twice the Black Sea area, the Danube River is the largest and the most important water and sediment supplier of this marine basin (Table 1). Presently the Danube influence is determinant for the sedimentation on the north-western Black Sea shelf area. Danube role extends far southward up to the Bosphorous region, as well as down to the deep sea floor. The other three tributaries of the north-western Black Sea (Dniestr, Dniepr and Southern Bug) are no significant suppliers of sediments, discharging their sedimentary load into lagoons separated by beach barriers from the sea.

In turn the Black Sea strictly controls the Danube and Ukrainian rivers sedimentation role through the sea level variations.

**Table 1.** Fluvial water and sediment discharge into the Black Sea

| Rivers | Length (Km) | Drainage basin Area ($Km^2$) | Water discharge ($Km^3$/yr.) | Sediment discharge (Mt/yr.) |
|---|---|---|---|---|
| **I. North-Western Black Sea** | | | | |
| • Danube | 2,860 | 817,000 | 190.7 | 51.70** |
| • Dniestr | 1,360 | 72,100 | 9.8 | 2.50* |
| • Dniepr | 2,285 | 503,000 | 52.6 | 2.12* |
| • Southern Bug | 806 | 63,700 | 2.6 | 0.53* |
| *Sub-total I:* | | *1,455,800* | *255.7* | *56.85* |
| **II. Sea of Azov** | | | | |
| • Don | 1,870 | 442,500 | 29.5 | 6.40* |
| • Kuban | 870 | 57,900 | 13.4 | 8.40* |
| *Sub-total II:* | | *500,400* | *42.9* | *14.80* |
| *III. Caucasian coast rivers* | | | *41.0** | *29.00** |
| *IV. Anatolian coast rivers* | | | *29.7* | *51.00** |
| *V. Bulgarian coast rivers* | | | *3.0** | *0.50** |
| *TOTAL:* | | | *372.3* | *152.15* |

(*data from Balkas et al., 1990; ** multiannual mean discharge before damming the River Danube after Bondar, 1991; Panin, 1996).

The Danube Delta is playing a buffer role between the system end-terms: the River Danube and the Black Sea. The Danube Delta is situated between 44° 25' and 45° 30' northern latitude and between 28° 45' and 29° 46' eastern longitude, being bordered by the Bugeac Plateau to the North and by the Dobrogea orogenic area to the South. The Delta can be divided into three major depositional systems (Fig.4): the sub-aerial *delta plain* of about 5,800 $Km^2$, the *delta front* (~1,300 $Km^2$) and the *prodelta* (~6,000 $Km^2$) (Panin, 1989).

## 2. PRESENTATION OF DATA

### 2.1. River Danube

This chapter relys on data resulted from hydrologic measurements carried out since 1931, which have been analysed and homogenised. These data are stored in databases of the National Institute of Meteorology and Hydrology (NIMH) and the National Institute of Marine Geology and Geo-ecology *(GeoEcoMar)*.

#### *2.1.1. Natural flow regime*

The Danube fluvial system is characterised by the following data (Almazov et al., 1963; Stançik et al., 1988): length (as already mentioned) of the river course- 2,860 Km; drainage basin of ca. 817,000 $Km^2$, with a mean annual rainfall of 816 mm, a mean annual evaporation of 547 mm and mean annual runoff of 246 mm. The average annual water discharge at the delta beginning (apex) is 6,550 $m^3 s^{-1}$, with a mean annual variation range of ca.5,700 $m^3.s^{-1}$ (at 1% probability $Q_{m99}$=9,980 $m^3.s^{-1}$ while at 99% probability $Q_{m1}$=4,240 $m^3.s^{-1}$ ) and limit discharge values recorded till now: $Q_{max.\ 1970\ year}$ = 15,540 $m^3.s^{-1}$ and $Q_{min.\ 1954\ year}$ = 1,610 $m^3.s^{-1}$.

The average annual suspended sediment discharge before the building of the Iron Gates dams was 2,140 $Kg.s^{-1}$ (67,5 millions t/year), out of which sandy alluvia ca. 10%. According to Bondar (1991), the multiannual sediment discharge at the River Danube mouths was: $R_D$ = 51.7 millions t/year, while the multiannual tendency shows a decrease as it is shown by the following function (Bondar, 1993):

$$R_D = 16688.9 - 7.803 \times t,$$

where t is the time in years.

Taking into account a long time series of almost 130 years, the same author appreciates (Bondar, 1991) the multiannual water discharge of the River Danube into the Black Sea at $Q_D$ = 6.047 $m^3.s^{-1}$ with a tendency of slight increase (Bondar,1993):

$$Q_D = -1226.6 + 3.921 \times t$$

Probably this increasing tendency is only apparent, actually reflecting the impact of gradual damming of the River Danube and losing the wetlands buffering zones where the evapo-transpiration was very high.

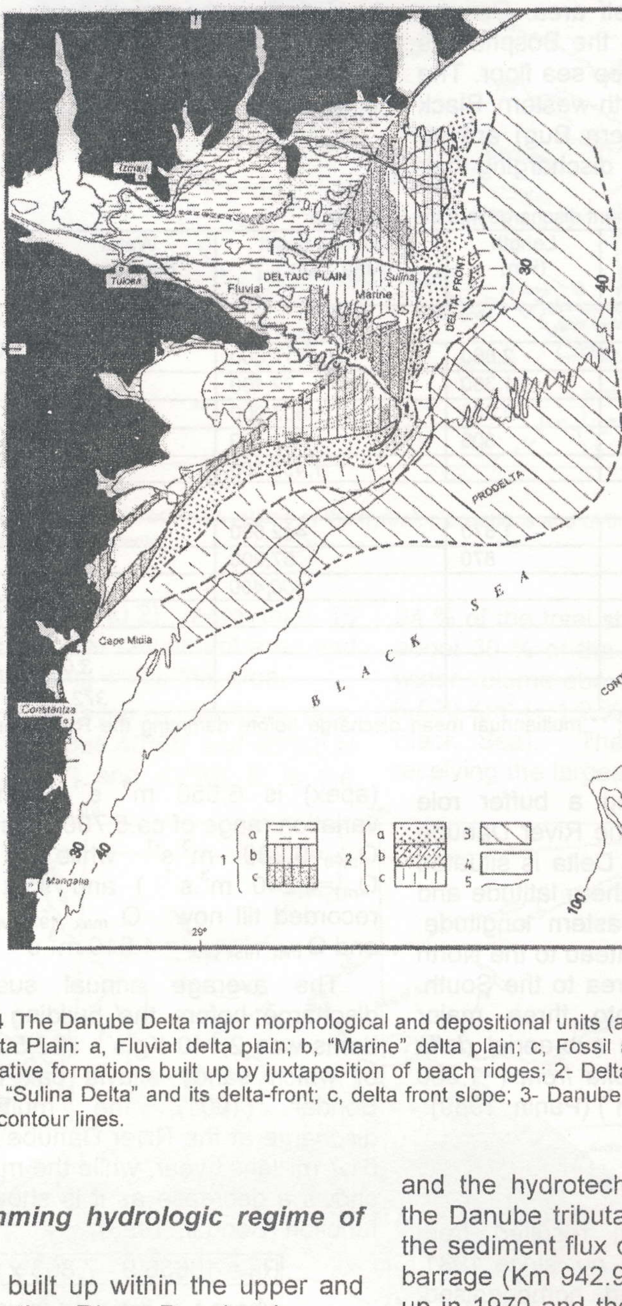


**Fig. 4** The Danube Delta major morphological and depositional units (after Panin, 1989).
Legend: 1- Delta Plain: a, Fluvial delta plain; b, "Marine" delta plain; c, Fossil and modern beach-ridges and littoral accumulative formations built up by juxtaposition of beach ridges; 2- Delta Front: a, delta front platform, b, relicts of the "Sulina Delta" and its delta-front; c, delta front slope; 3- Danube Prodelta; 4- Continental Shelf area; 5- Depth contour lines.

### *2.1.2. After damming hydrologic regime of the river*

The list of dams built up within the upper and middle sections of the River Danube is very impressive. We are only mentioning the impounding reservoirs at Bad Abbach (Km 2401)* and Regensburg (Km 2381), the barrages at Geisling (Km 2354) and Straubing (Km 2324), the dam at Vilshofen (Km 2230), the cascade of 15 regulating dams between Ulm and Ingolstadt, the dam at Jochenstein at the German-Austrian border and rather recently, the hydropower plant at Gabcikovo (Km 1842).

Within the Lower Danube two barrages (Iron Gates I and Iron Gates II or Ostrovul Mare) (Fig.2) and the hydrotechnical amelioration works along the Danube tributaries have changed dramatically the sediment flux of the Danube. The Iron Gates I barrage (Km 942.95 from the Black Sea) was built up in 1970 and the second one, at Ostrovul Mare (Km 864) has dammed the river in 1983.

The works achieved on the Upper and Middle Danube River inevitably led to the decrease of the Danubian sediment flux. Nevertheless the river sediment load was partly restored along the downstream reaches by riverbed scouring and through the sediments supplied by the tributaries. On the contrary the Iron Gates I and II barrages are deeply disturbing the water and sediment flux of the river downstream reaches. The sediment flux at the upper limit of Lower section of the River Danube is estimated at about 30 million t/yr., amount which is trapped in the barrage lake Iron Gates I. Consequently to the building of Iron Gates I dam and to the hydrotechnical amelioration works

* Distance from the mouth zone upstream the river.

along the Danube tributaries, the sediment discharge decreased by ca. 30-40% at Zimnicea station (Km.553), by about 45 % at Vadu Oii (Km 247) and by ca.10 % at Isaccea station (M.54 +500, close to the beginning of the delta)(Fig.2). The erection of the second Iron Gates barrage, at Ostrovul Mare (Km.864), induced a really catastrophic decreasing of the sediment discharge: in all the stations the measured sediment discharge dropped by 50 to 70 % compared to the mean value of pre-damming sediment flux regime (60-70 % at Zimnicea and Vadu Oii, and about 50 % at Isaccea) (Fig.5,6). So, at present, one can estimate that the Danube total average sediment discharge could not be larger than 25-35 million t/yr., out of which 4-6 million t/year sandy material.

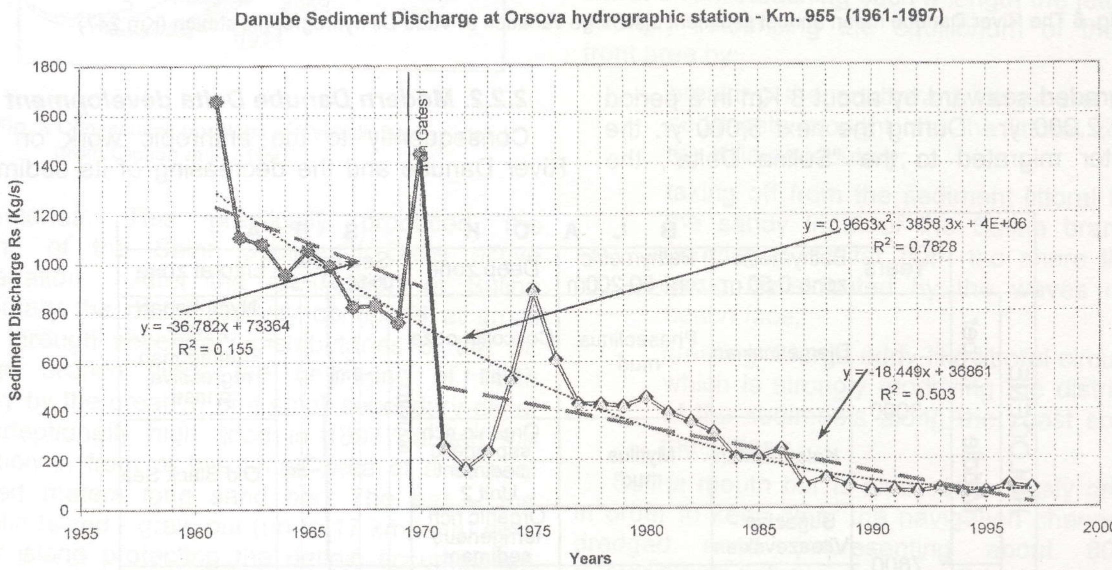


**Fig. 5** The River Danube mean annual sediment discharge variation at Orsova hydrographic station (Km 955, within the limits of Iron Gates I barrage lake)

### *2.1.3. Distributary meanders cut-off*

The direct anthropic changes within the Danube Delta started after the Danube European Commission establishment in 1856 and were oriented especially on the improvement of the navigation by cutting-off the meander bends of Sulina distributary and building up a system for its mouth protection.

The rectification of the Sulina arm was carried out in 1868-1902 period and shortened this branch by about 25% (83.8 Km before the cut-offs and only 69 Km now a day).

This cut-offs programme brought about a redistribution of water and sediment discharge among the delta distributaries. The Sulina discharge increased from 7-9 % up to 16-17 % in 1921 (Almazov et al., 1963) and to about 18-20% of the total Danube discharge at present.

Recently, starting in the year 1983, a similar cut-off programme has been carried out along the St.George distributary. In about 10 years all its meander bends were rectified and the total length of the branch was shortened by about 32 Km causing the beginning of a new process of water and sediment discharge redistribution among the delta distributaries.

## 2.2. Danube Delta

### *2.2.1. Danube Delta Holocene development*

The Danube Delta is mainly formed during the Upper Pleistocene high-stands (Karangatian, Surojskian) and in the Holocene. Its present-day geomorphology expresses the interaction of the river (sediment and water discharges, flow energy etc.) and the sea (wave and littoral currents regime, sea level changes etc.) during the last 12,000 years (Fig.7). The main stages of the Danube Delta evolution during the Holocene have been evidenced and timed by the corroboration of geomorphologic, textural, geochemical, mineralogical data, fauna analyses and mainly by $^{14}C$ dating (Panin, 1974, 1989, 1996; Panin et al., 1983).

The different phases of Delta development showed active progradations followed by strong erosions. The "St.George I Delta", built up by Paleo-St.George distributary (9,000 - 7,200 y BP),

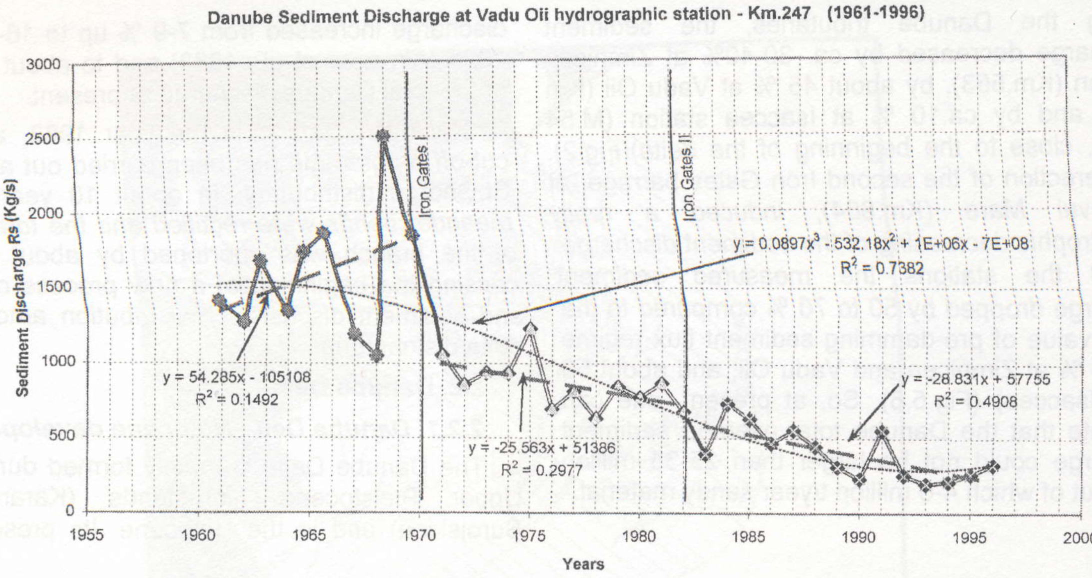


**Fig. 6** The River Danube mean annual sediment discharge variation at Vadu Oii hydrographic station (Km 247)

has prograded seaward by about 8 Km in a period of about 2,000 yr. During the next 5,000 yr. the depocenter migrated to the "Sulina Delta", the

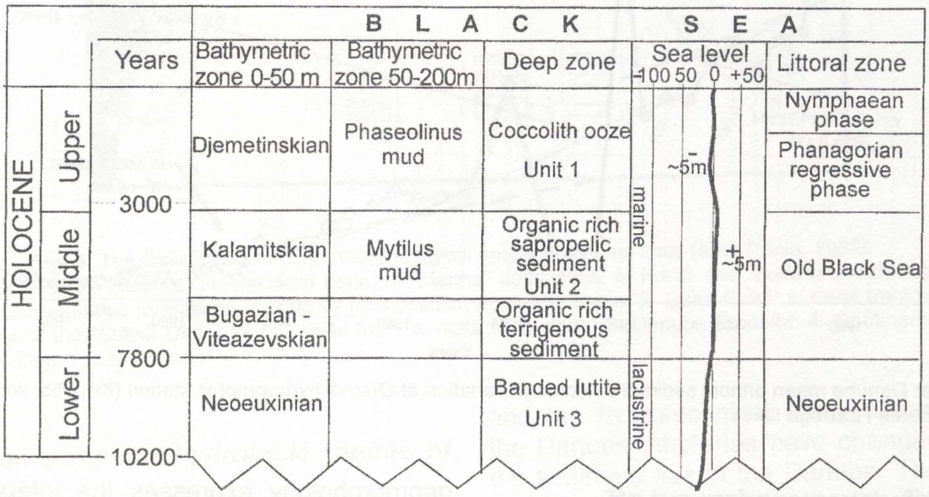


**Fig. 7** Black Sea Upper Quaternary Stratigraphy and sea level variations. (from Panin, 1983, after Sherbakov et al., Fedorov, 1982 and Degens and Ross, 1972 with adaptations; references in Panin, 1983)

progradation of which could be evaluated at 30-35 Km (the average advancing of the coastline: 6-10 m/yr.). In the last phase of delta development (2,800 yr. BP - present) the depocenters moved once again towards the newly formed distributary Kilia in the north and the reactivated St.George arm; consequently, during this last 2,800-2,000 yr. the newly formed Kilia Delta and St.George II Delta have prograded by 16-18 Km (mean advancing 8-10 m/yr.). At the same time the Sulina Delta was gradually eroded, its coastline regressing by about 10-12 Km.

### *2.2.2. Modern Danube Delta development*

Consequently to the anthropic work on the River Danube and the decreasing of its sediment discharge, the Danube Delta became mostly inactive, apart from two restricted sections (Kilia distributary delta and the small St. George distributary delta).

After a period of intense progradation Kilia Delta front reached deeper water area. This is why the modern time advancement of this delta slowed down, as more sediment is required to move forward in deeper water.

Due to its anthropic rectification, which will be described below, Sulina distributary took away part of the sediment load from Saint George and Kilia

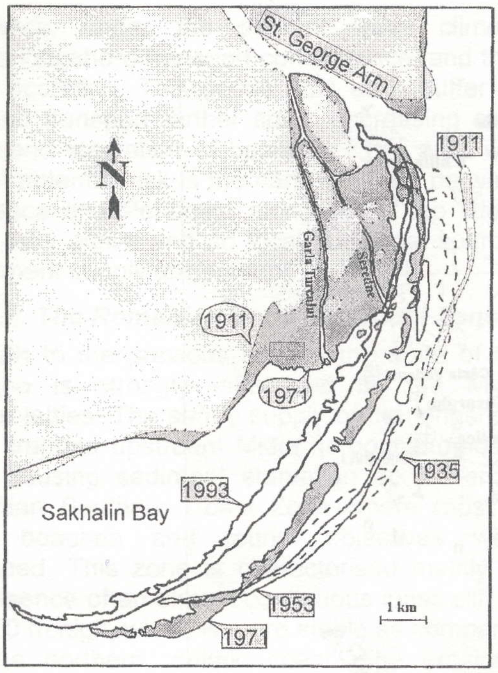


Fig. 8 Consecutive positions of Sakhalin barrier island (from Giosan et al., 1997)

distributaries. This practically produced the ceasing of the Saint George II Delta active progradation. After the rectification of Sulina distributary the deltaic activity continued at small scale through secondary distributaries of the St. George branch since the beginning of 19-th century by the creation of a small secondary delta. An exceptionally high flood in 1897 caused the formation in front of this small delta of a several hundred meters long sand bar. The bar – the Sakhalin Island - grew out (up to 17 km long) as a barrier island protecting the deltaic accumulation (Fig.8). During its evolution Sakhalin Island displayed backstepping migration through overwashing, with the tendency to get attached to the secondary delta front.

### 2.3. NW Black Sea littoral zone

The north-western Black Sea littoral zone consists of Ukrainian and Romanian sections. The Ukrainian one, placed north of the Danube Delta (from Jibriany to Odessa) is characterised now-a-day by a sediment starving regime. The beaches are fed only trough the erosion of the near-shore bottom and by loess cliffs abrasion, the sandy sediment load of the Dnieper, Southern Bug and Dniester being settled within the lagoons.

The Romanian section of the Black Sea littoral zone could be divided into two units (Fig.9): the Danube Delta coastal zone, and the so called Southern Unit (from Cape Midia to the Romanian-Bulgarian border).

#### *2.3.1. The Danube Delta coastal zone*

This littoral section could be characterised by a longshore sediment drift along the Delta, generated by the winds-wave-longshore currents system, with potential values varying in different places from 0 to 1.230 million m3/yr (Giosan et al., 1997). Intense erosion processes are affecting the delta littoral situated south of Sulina mouth (Kosyan & Panin, 1996).

The intense activity of Kilia Delta always represented a threat for the navigation at the Sulina branch mouth. As proposed by Hartley's project, jetties have been built flanking the Sulina mouth for protecting the navigable canal from the Kilia-born sediments drifted longshore southward. Jetties building kept on since 1858. In 1861 the length of jetties was 1,412 m, in 1925 - 3,180 m, in 1939 - 4,150 m, in 1956 - 5,773 m, now a day - about 8 Km. Reaching such a length the jetties are strongly influencing the equilibrium of the delta front area by:

- breaking the southward longshore drift of sediments brought into the littoral zone by the Kilia distributary;
- taking off from the sediment littoral budget the sandy input of the Sulina branch by carrying it too far from the shore line for being redistributed by the waves on the beach face;
- creating a large eddy-like littoral circulation, which is strongly modifying the distribution of the sediments along the coast south of the jetties.

Sulina mouth bar is also continuously dredged in order to keep clear the navigation channel, the dredged sand (representing about 800,000 $m^3$/year) being dumped away offshore removing it from the littoral sedimentary budget.

The combined effect of these two anthropic activities deeply disturbed the littoral sedimentation processes in the Sulina-St.George littoral section of the delta transforming it into one of the most actively eroded zones of the Romanian Black Sea shore. In the last 15 years, the coast was permanently eroded, the coastline regression being of 5 - 30 m/yr. As already mentioned, this section is situated in a zone with a tendency of recession lasting since about 2,500 yr. It is the Sulina Delta front, which during this period of time retreated more than 10-12 Km. Thus, the discussed section is under a very strong erosional process induced by anthropic activities, added to a historical tendency of coast regression.

The Table 2 presents the eroded area within the Sulina-St.George section of the Danube Delta littoral zone since the beginning of the 20-th century.

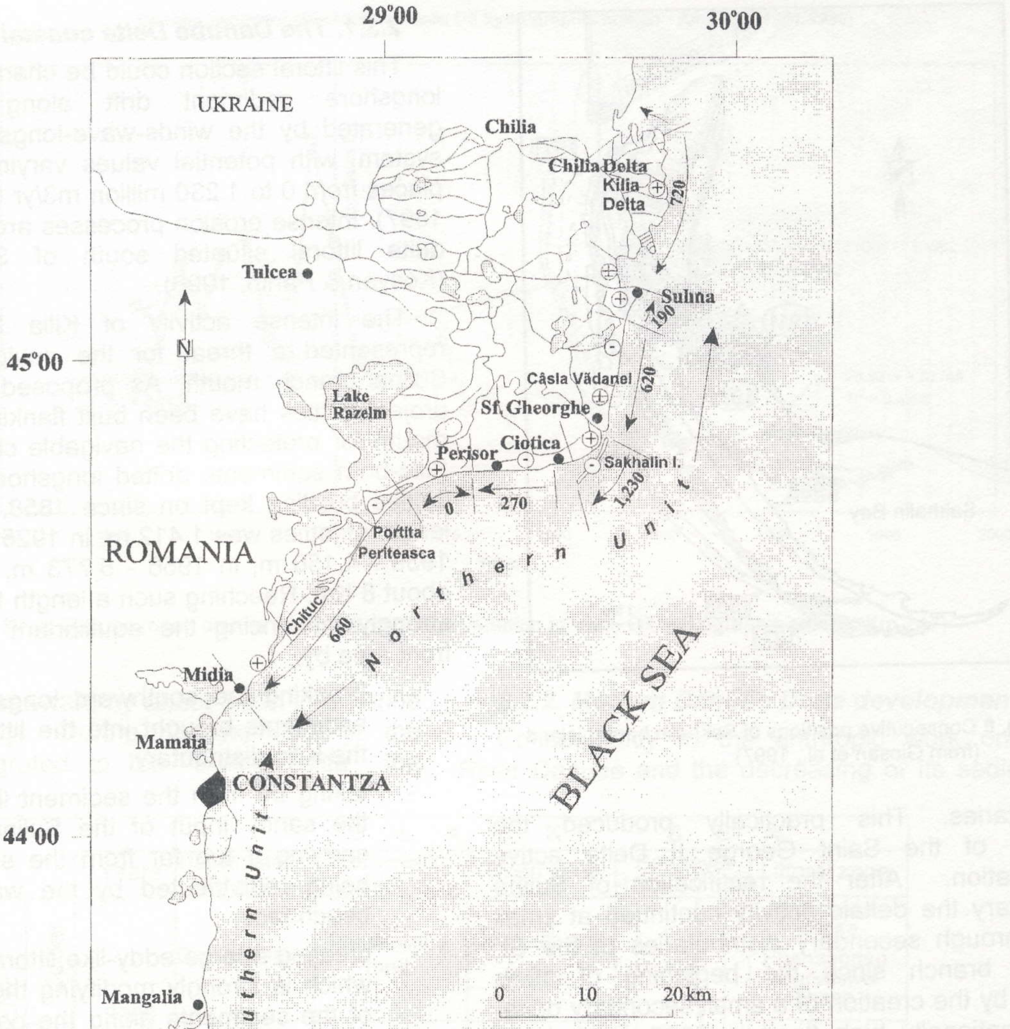


Fig. 9 Romanian Black Sea coast and the longshore sediment transport model for the Danube Delta coast. Transport rates in thousands of cubic meters per year. Circled + and - represent advancing and retreating sections respectively (after Giosan et al., 1997)

Table 2 - The area of the Danube Delta territory between Sulina and St.George distributaries lost as a result of marine erosion in 1909-1985 period

| Period of time | Eroded area (Km$^2$) |
|---|---|
| 1909 - 1952 | 22.25 |
| 1952 - 1960 | 2.95 |
| 1960 - 1985 | 6.50 |

Shoreline recession rates over 10 m/year were also registered along the Sakhalin barrier island, south of Ciotica and between Portita and Chituc on the southern barrier beaches.

Advances of the shoreline are reported only for very restricted sections (few Km each) as: immediately south of Sulina jetties because their protection and eddy like littoral circulation, behind Sakhalin island where St. George secondary delta is actively prograding, being protected by the island and within the southern end of Chituc Littoral Formation due to the sediment transport obstruction exerted by Midia harbour jetties.

Sfântu Gheorghe distributary discharges about 800,000 m$^3$/year of sand. The potential sediment transport indicates that the average rate of beach retreat on northern Sakhalin, which was about 35 m/yr., would more than double if this sediment input would disappear. The sand passing the southern tip of Sakhalin Island contributes to the island platform building, and it is not able to feed the beaches farther south since the shoreline orientation changes abruptly. Continued retreat of the island will enhance bypassing of sediments to the south.

The change in coast orientation south of

Periteasca, under the present wave climate, favours longshore transport convergence, and thus beach accretion. This sector acts as a buffer for the sand transport farther south, increasing even more sand starvation of beaches. The area with highest potential risk is the narrow barrier between Periteasca and Periboina along which the littoral drift is very active and no local additional sources of sediment supply are present.

### *2.3.2. The Romanian Southern Coast Zone*

South to the previous section the state of the shoreline is strongly influenced by the Midia harbour jetties. The sandy supply of the longshore drift is trapped upstream Midia harbour protection dikes, causing sediment starvation of the entire Romanian Southern Coast Zone where most of public beaches and tourist objectives were developed. This zone is characterised mainly by the presence of an almost continuous loess cliff up to 12-20 m high, which is more stable as compared with the northern, deltaic coast. The erosional processes are still active under the influence of the marine abrasion and gravitational processes, the cliff line retreating with the average rate of 50 cm/year (Selariu, 1971 and Serbănescu, 1969, in Kosyan & Panin, 1996). The erosion is more active on the accumulative beaches intercalated in between the cliffs. The shores, south of Constantza, receive no Danube originated sandy sediments. As there is no other source to supply siliciclastic sand material, the shore deposits of this area are of organic origin, coming through the mechanical workout of the littoral shells.

## 2.4. NW Black Sea continental shelf

On the north-western Black Sea shelf area, the dispersal pattern of the Danube sediment supply points out to the existence of two main areas with different depositional processes (Panin et al., in press): the Danube sediment fed internal shelf and the sediment starving, external shelf (Fig. 10).

### *2.4.1. Internal, Danube sediment fed shelf*

The sediment fed area in the neighbourhood of the Danube Delta includes of delta front unit (about 1,300 $Km^2$) and off-shoreward, at the base of the delta front to 50-60 m depth, the prodelta covering an area of more than 6,000 $Km^2$. Its southern boundary is more difficult to define on account of the strong southward drift of fine grained sediment load discharged into the sea by the Danube, which is stumping the prodelta limit.

Out of the area defined as prodelta unit, the internal, western zone of the Romanian shelf stand out as the shallow marine area (less than 50 -60 m water depth), which receives clayey and siltic sediments, supplied by the Danube River. Moving as suspended load, the sediment flux goes beyond the area in front of the Danube Delta but does not reach the eastern, external shelf zone. Under the influence of the dominant currents the clayey-silty sediment flux moves southward toward the Bulgarian shelf, keeping within the western shelf area, close to the shoreline and finally discharges

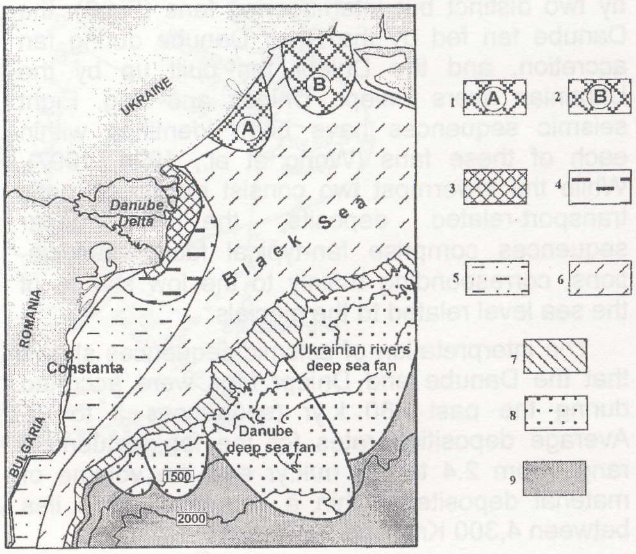


**Fig. 10** Main sedimentary environments in the north-western Black Sea (after Panin et al, 1998)

Legend: 1-2, Areas under the influence of the Ukrainian rivers (A-Dniester and B-Dnieper) sediment discharge; 3, Danube Delta front area; 4, Danube prodelta area; 5-6, Western Black Sea continental shelf areas (5, area under the influence of the Danube originated sediment drift; 6, sediment starved area); 7, Shelf break and the uppermost continental slope zone; 8, Deep-sea fans area; 9, Deep sea floor area.

the sediment load towards the deep sea zone in the pre-Bosphorous region.

### *2.4.2. External, sediment starving shelf*

Situated outside the area covered by the Danube fed sediment flux the external, eastern part of the continental shelf represents an area practically deprived of clastic material. Within this sediment starving shelf area the condensed sediment accumulation is of biogenic origin, producing organic thin cover on relict sediments or concentrations of shells. The Danubian sediments seldom reach the shelf area north and Northwest of the Danube mouths. Dniester and Dniepr, the main rivers north of Danube Delta, are themselves, as already mentioned, no significant suppliers of sediment for the north-western Black Sea shelf. Consequently the sediment starving status characterises almost the whole Black Sea continental shelf west of the Crimean Peninsula.

### 2.5. Deep sea zone of the western Black Sea

During the Upper Quaternary, in correlation to the sea-level fluctuations of this period of time, very large accumulations of sediments were formed in the deep-sea zone of the North-Western Black Sea, mainly on the continental slope and apron areas. This accumulations are represented by two distinct but interfingering fans (Fig.8): the Danube fan fed by the River Danube during fan accretion, and the Dniepr fan built up by the Ukrainian rivers Dniepr, Dniestr and Bug. Eight seismic sequences have been identified within each of these fans (Wong et al., 1994, 1997). While the lowermost two consist mainly of mass transport-related deposits, the six upper sequences comprise fan-typical facies associations, corresponding mainly to the low stands of the sea level related to the glacials.

The interpretation of seismic sequences shows that the Danube and Dniepr fans were accreted during the past 480 k.yr (sequences 3 to 8). Average deposition rates for the fan sequences range from 2.4 to 7.2 m/k.yr and the volume of material deposited within a sea level cycle lies between 4,300 $Km^3$ and 9,590 $Km^3$.

Within the deep-sea zone of the Black Sea the existing accumulation of recent sediments is represented by coccolith ooze overlying sapropelic or organogen sediments (Ross et al., 1970) pointing out the domination of the organic component over the detrital one. Very seldom and locally spread gravitationally transported material and mainly hemipelagic sediments are occurring within the slope, apron and abyssal zones, during this high stand sea level.

## 3. DISCUSSION OF DATA

### 3.1. Sea level variations

The eustatic fluctuations of the Black Sea level, from the end of the Pleistocene till present, roughly (in spite of short out of phase episodes) correspond to level variations reported for the oceanic basins (Fig.11). In the last two thousand years, the Black Sea level rose by ca. 4 m (Fedorov,1982). During the last century the maregraphic observations have confirmed the continuation of the tendency of rising by 2-4 mm/year of the relative sea level (2.595 mm/yr. - Selariu, 1972; 3.73 mm/yr. at Sulina and 2.67 mm/yr. at Constantza - Bondar, 1989). The values of subsidence within the coastal area nearby the Danube Delta are of 1.5 - 1.8 mm/yr., so the relative sea level rising is the algebraic sum of this phenomenon and the absolute rising of the sea level. These data point out that during the modern period the rise of the sea level in the Black Sea basin is active and continuous. Consequently the sea level rise change appears as the most important natural factor influencing the sedimentation within the north-western Black Sea.

### 3.2. Lowstands sedimentary environment in the north-western Black Sea

It is generally accepted that the lowstands during the Quaternary correspond to the glacials, the last of which was the Würmian (Neoeuxinian) with the minimum lowering (about -130 m) at ~18 K.yr.BP. The main sedimentary feature of a sea level lowstands and especially of the beginning of ice melting are the strong erosion on the continent, the very high value of sediment flux entering the marine basin and the progradation of the depocenters towards and even beyond the shelf edge. In the north-western Black Sea this state is illustrated by the large deep-sea accumulation of sediments now recognised as the Danube deep-sea Fan Complex. The six upper sequences evidenced by seismic assessment of the fan (Wong et al., 1997) comprise fan-typical facies associations and correspond to the glacial low stands of the sea level. The sequences are separated from each other by condensed sections interpreted as hemipelagic sediments of sea level highstands during interglacials. In addition to the channalised turbidity currents, mass transport processes that result in slumps, slides and debris flows played a major role in fan construction.

### 3.3. The modern highstand sedimentary environment in the north-western Black Sea

As pointed out by the eustatic curve (Fig.11) since the Late Pleistocene till the present time the Black Sea level was dominantly rising. The immediate consequence of the sea-level rise were the landward retreat of the deltaic system as depocenter and of the littoral zone, as well as the drastic diminishing of the Danube sediment supply.

The building up of the Danube Delta far away from the shelfbreak during the last ~11,700 yr. represent the depositional stage at highstand of the sea level. The evolution phases of the Danube Delta were obviously influenced by small scale sea-level variations (for instance the Phanagorian regressive phase), as well as by the possible autocyclic shifting of the main sediment supply between the Danube distributaries and correspondingly of depocenters from one area to another. The outer shelf, the slope and the deep-sea zones including the fan-complexes are sediment-starved, characterised by prevalent hemipelagic sedimentation.

The reduction of sediment flux during the highstands was presently aggravated by a series of anthropic alterations of the River Danube natural flow regime. First of all the meander belts cut-offs programmes carried out successively on Sulina distributary (the end of 19-th - the beginning of the

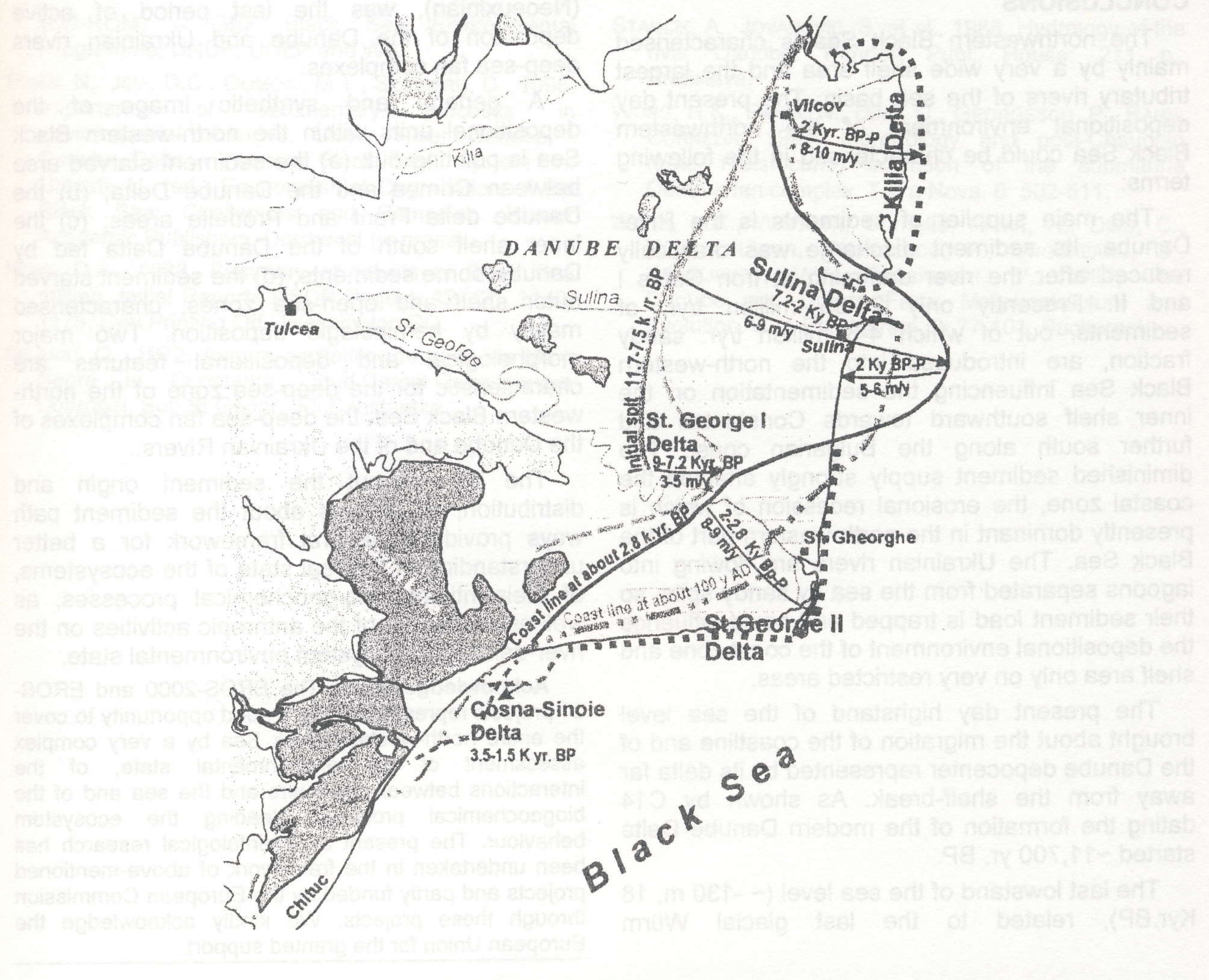


**Fig. 11** The Danube Delta evolution during the Holocene and correspondent coastline position changes (Panin & E. and G. Ion, 1997).

20-th centuries) and on St.George branch (in the 1980's) brought about a redistribution of water and sediment fluxes among the distributaries favouring cessation or on the contrary activation of different delta lobes progradation.

The rather recently erected Iron Gates hydroelectric dams (as well as other hydrotechnical works) dramatically reduced (by 50-70 %) the sediment supply of the littoral zone and of the entire north-western Black Sea. 25-35 million t/yr., out of which 4-6 million t/yr. sandy material is the only amount of sediments supplying the inner shelf and, respectively the littoral zone. The littoral sedimentary budget became since 1970 strongly uncompensated and the shoreline erosional recession is presently dominant in the north-western part of the Black Sea.

Anthropic activities within the littoral zone again are at the origin of the strengthening of local coastal zone recession. For instance the structures built up at the mouth of Sulina distributary, in accordance with Sir Charles Hartley's project (approved by the European Danube Commission in 1858), together with the dredging operations for maintaining the navigable depth at the Sulina mouth bar are the main factors inducing the strongest erosion of the beaches in the Sulina-St.George section of the delta littoral.

The present day reduced Danubian sediment supply is only covering the inner, western part of the wide shelf area of the north-western Black Sea. Consequently the eastern outer shelf and the open-sea zones are sediment starved and the depositional regime is exclusively hemipelagic. The shelf area situated north and east of the Danube Delta up to Crimea is also deprived of sediment supplies because the Ukrainian rivers (Dniestr, Dniepr and Southern Bug) are flowing into lagoons and their sediment load is trapped there.

## CONCLUSIONS

The northwestern Black Sea is characterised mainly by a very wide shelf area and the largest tributary rivers of the sea basin. The present day depositional environment of the northwestern Black Sea could be characterised in the following terms:

The main supplier of sediments is the River Danube. Its sediment discharge was drastically reduced after the river damming at Iron Gates I and II. Presently only 25-35 million t/yr. of sediments, out of which 4-6 million t/yr. sandy fraction, are introduced into the north-western Black Sea influencing the sedimentation on the inner shelf southward towards Constantza and further south along the Bulgarian coast. The diminished sediment supply strongly affected the coastal zone, the erosional recession of which is presently dominant in the north-western part of the Black Sea. The Ukrainian rivers are flowing into lagoons separated from the sea by sandy spits, so their sediment load is trapped and could influence the depositional environment of the coast zone and shelf area only on very restricted areas.

The present day highstand of the sea level brought about the migration of the coastline and of the Danube depocenter represented by its delta far away from the shelf-break. As shown by C14 dating the formation of the modern Danube Delta started ~11,700 yr. BP.

The last lowstand of the sea level (~ -130 m, 18 Kyr.BP), related to the last glacial Würm (Neoeuxinian), was the last period of active deposition of the Danube and Ukrainian rivers deep-sea fan complexes.

A general and synthetic image of the depositional units within the north-western Black Sea is pointing out: (a) the sediment starved area between Crimea and the Danube Delta; (b) the Danube delta Front and Prodelta areas; (c) the inner shelf south of the Danube Delta fed by Danube-borne sediments; (d) the sediment starved outer shelf and open-sea zones, characterised mainly by hemipelagic deposition. Two major morphological and depositional features are characteristic for the deep-sea zone of the north-western Black Sea: the deep-sea fan complexes of the Danube and of the Ukrainian Rivers.

The data about the sediment origin and distribution, as well as about the sediment path ways provide a general framework for a better understanding of the real state of the ecosystems, of their intimate bio-geochemical processes, as well as of the role of the anthropic activities on the river-delta-sea geosystem environmental state.

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## REFERENCES

ALMAZOV, A.A., BONDAR, C., DIACONU, C., GHEDERIM, Veturia, MIHAILOV, A.N., MITA, P., NICHIFOROV, I.D., RAI, I.A., RODIONOV, N.A., STANESCU, S., STANESCU, V., VAGHIN, N.F., 1963, Zona de vărsare a Dunării. Morfografie hidrologică: 396 p., Ed. Tehnică, Bucharest.

BONDAR, C., 1989, Trends in the evolution of the mean Black Sea level. Meteorology and Hydrology, 19, 2: 23-28, Bucharest.

BONDAR, C., 1993, Secular evolution of some components of the hydrological Danube regime and of the mean level of the Black Sea. Proceed.World Coast Conf., p.891-893.

BONDAR, C., STATE, I., CERNEA, D., HARABAGIU, Elena., 1991, Water flow and sediment transport of the Danube at its outlet into the Black Sea. Meteorology and Hydrology, 21, 1: 21-25, Bucharest.

FEDOROV, P.V., 1982, Post-glacial transgression of the Black Sea and level changes during the last 15,000 years. In: Changes of sea levels during the last 15,000 years, 151-156 (in Russian), Moscow.

GIOSAN, L., BOKUNIEWICZ, H., PANIN, N., POSTOLACHE, I., 1997, Longshore Sediment Transport Pattern along Romanian Danube Delta Coast. Geo-EcoMarina, 2: 11-24, Bucharest.

KOSYAN, R.D., PANIN, N., 1996, Black Sea Coastal Zone. Technical Report on Coastal Erosion Economic Effects and their Valuation, 70 pp. GEF&UNDP Black Sea Environmental Programme PCU, Istanbul.

PANIN, N., 1974, Evolutia Deltei Dunării în timpul Holocenului. Inst.Geol., St. Tehn. Econom., Seria H - Geol. Cuaternar., 5: 107-121, Bucharest.

PANIN, N., 1983, Black Sea coast line changes in the last 10,000 years. A new attempt at identifying the Danube mouth as described by the ancients. Dacia, N.S., XXVII, 1-2: 175-184, Bucharest.

PANIN, N., 1989, Danube Delta. Genesis, evolution and sedimentology. Rev. Roum. Géol. Géophys. Géogr., Ser.Géographie, 33: 25-36, Bucharest.

PANIN, N., 1996, Danube Delta. Genesis, evolution, geological setting and sedimentology. Geo-Eco-Marina, 1: 7-23, Bucharest.

PANIN, N., PANIN, Stefana, HERZ, N., NOAKES, J.E., 1983, Radiocarbon dating of Danube Delta deposits. Quaternary Research, 19: 249-255, Washington.

PANIN, N., ION, Elena, ION, G., 1997, Black Sea Geography and Geology, in: Black Sea GIS

(CD-ROM) – GEF Black Sea Environmental Programme, UNDP, UNEP and WB.

PANIN, N., JIPA, D.C., GOMOIU, M.T., SECRIERU, D., 1998, Importance of sedimentary proceses in environmental changes: Lower River Danube - Danube Delta - Western Black Sea System. In: Unluata U. (ed.) Environmental Degradation of the Black Sea: Challenges and Remedies. Kluwer Academic Publishers, Dordrecht (in press).

ROSS, D.A., 1978, Summary of results of Black Sea drilling. Initial Reports DSDP Project, 42, (2), 1149-1178, Gov.Printing Off., Washington DC.

SELARIU, O., 1972, Asupra oscilatiilor de nivel ale Mării Negre la Constanta. Stud.Cercet.Geogr.asupra Dobrogei, Soc.St.Geogr., Fil.Constantza

STANCIK, A., JOVANOVIC, S. et al., 1988, Hydrology of the river Danube. Perioda Publ. House: 271 p., Bratislava.

WONG, H.K., PANIN, N., DINU, C., GEORGESCU, P., RAHN, CORNELIA, 1994, Morphology and post-Chaudian (Late Pleistocene) evolution of the submarine Danube fan complex. Terra Nova, 6: 502-511.

WONG, H.K., WINGUTH, Cornelia, PANIN, N., DINU, C., WOLLSCHLÄGER, GEORGESCU, P., UNGUREANU, G., KRUGLIAKOV, V.V., PODSHUVEIT, V., 1997, The Danube and Dniepr Fans: Morphostructure and Evolution. Geo-Eco-Marina, 2: 77-101, Bucharest.