DANUBE DELTA
GENESIS, EVOLUTION, GEOLOGICAL SETTING AND SEDIMENTOLOGY

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Abstract: The Danube Delta can be divided into three major depositional systems: the delta plain, with a total area of about 5,800 Km^2, from which the marine delta plain area is of 1,800 Km^2; the delta front with an area ca. 1,300 Km^2, divided into delta front platform (800 Km^2) and delta-front slope (ca. 500 Km^2), extending off-shore to a water depth of 30-40 m; the prodelta lies off-shore at the base of the delta-front slope to 50-60 m depth, covering an area of more than 5,500 - 6,000 Km^2.

The delta development is controlled by: the Danube sediment input (the average sediment discharge is ca. 50.10^6 t/y, of which 5-8.10^6 t/y sandy material); the prevalence of winds from the northern sector (40-50% of instances); the predominance of southward trending of marine currents; the long shore sediment drift directed also towards the south; the relatively important values of wave power etc. The interaction of these factors controls the delta morphological type, the geometry of the volumes of deltaic deposits, the asymmetry of the deltas of the Danube distributaries and their development and evolution.

The Danube Delta edifice is built up of a sequence of detrital deposits of tens to 300-400 m thickness, formed mainly during the upper Pleistocene (Karangatian, Surojskian, Neoeuxinian) and the Holocene. The Holocene evolution of the Danube Delta includes the following main phases: (1) the formation of the Letea-Caraorman initial spit, 11,700-7,500 years B.P.; (2) the Sf. Gheorghe I Delta, 9,000-7,200 years B.P.; (3) the Sulina Delta, 7,200-2,000 years B.P.; (4) the Sf. Gheorghe II and Chilia Deltas, 2,000 years B.P. - present; (5) the Cosna-Sinoie Delta, 3,500-1,500 years B.P.

The Danube Delta plain displays a few facies types of sediments, as follows: (I) marine littoral deposits of two types: type **"a"**, formed by the longshore drift from the North (from the mouths of rivers Dniester, Southern Bug and Dnieper), and type **"b"**, of Danubian origin; (II) lacustrian littoral deposits, forming the Stipoc and Rosca-Suez lacustrian spits; (III) fluvial deposits, genetically related to the Danube distributaries system, include several types: bed-load and mouth-bar deposits, sub-aqueous and subaerial natural levees deposits, crevasse and crevasse-splay deposits, point bar and meander belts deposits, decantation deposits into intradeltaic depression and interdistributary area etc.; (IV) marsh deposits; (V) loess-like deposits.

Key words: delta-plain, delta front, prodelta, deep-sea fan complex, water input, sediment input, delta evolution phases, sediments, sedimentary facies, sediment littoral drift, sea level changes.

1. Introduction

The deltas, as known, are sedimentary systems formed by deposition of detrital material carried by rivers to their mouths in either marine or lacustrian basins.

The first to notice the deltoid shape of these systems was, probably, Herodotus studying the Nile Delta nearly 2,500 years ago. His "Histories" provides the first information on the Danube (Istros) and its delta.

Since ancient times the Danube Delta has been the object of interest to European peoples in full development and expansion. Interesting description of geographic features and of some general sedimentation processes at the Danube mouths to the Pontus Euxinus are contained in ancient sources, among which the writings of Polybius, Strabon, Plinius Secundus (Pliny the Elder), Arrianus and especially Claudios Ptolemaios (Ptolemy) are worth mentioning.

Following the Middle Ages "darkness", the investigation of the Black Sea, of the Danube and its delta has developed and got scientific grounds in the second half of the 19-th century and especially in the 20-th century. Without intending to present the evolution of investigations of this area we just mention as particularly important to the study of the Danube Delta the maps or the papers of Spartt (1856), the European Danube Commission (1857, 1871, 1886 etc.), Antipa (1915, 1941), Brătescu (1922, 1942), de Martonne (1931), Vâlsan (1934, 1935), Lepsi (1942), Slanar (1945), Pfannenstiel (1950), Petrescu (1957), Zenkovich (1956, 1960), Cotet (1960), Bleahu (1963), Grumazescu (1963), Liteanu, Pricăjan and Baltac (1961), Liteanu, Pricăjan (1963), Almazov et al. (1963), Banu (1965), Banu and Rudescu (1965), Panin (1974,

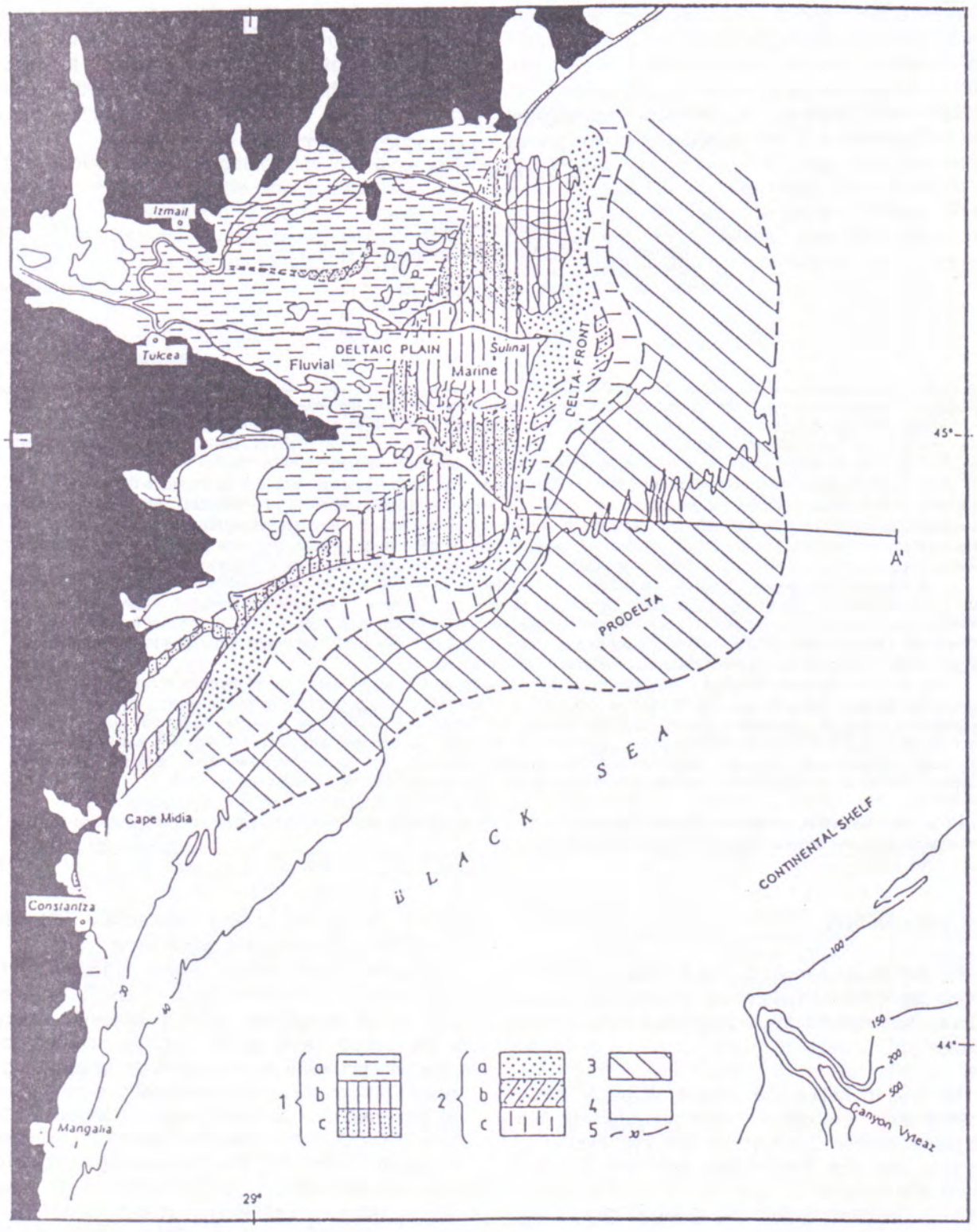


Fig.1 - Major morphological and depositional units of the Danube Delta

Legend: 1. Deltaic plain: a-fluvial; b-marine; c-littoral accumultaive formations built up by juxtaposition of beach ridges; 2. Delta Front: a-platform; b-relics of Sulina Delta and its delta-front; c-slope; 3. Prodelta; 4. Continental Shelf; 5. Water depth contours.

1983, 1989), Gâstescu and Driga (1985), Bondar et al. (1991) etc. Considering the present-day data we may state that the main trends of Holocene evolution of the Danube Delta have been identified by V.P.Zenkovich (1956).

The present paper puts forward the actual data on the geologic constitution, genesis and evolution of the Danube Delta. It is the first time that the whole delta aspects, both subaerial and submarine, are presented. An important amount of unpublished data is included.

2. General morphology of the Delta

The Danube Delta is situated to the North-West of the Black Sea, 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 area to the South.

The Danube Delta can be divided into three major depositional systems: the delta plain, the delta front and the prodelta (Fig. 1). To these is to be added the Danube deep-sea fan placed beyond the shelf break reaching from several hundred meters water depth down to the abyssal plain (just over 2,200 m) (Wong et al., 1994).

2.1. The delta plain starts from the first bifurcation of the Danube, called Ceatal Izmail; here the river divides into two distributaries: a northern one - Chilia, and a southern one - Tulcea.

The Chilia distributary, the most important of the delta system (ca. 62-63% of the total water discharge of the Danube and ca. 65% of its sediment discharge), is 117 Km long and forms a lobate delta with numerous distributaries (two of which are the main ones - Oceacov and Stary Stambul).

The Tulcea distributary flows along 17 Km between Ceatal Izmail and Ceatal Sf. Gheorghe, where it divides into two other branches: Sulina and Sf. Gheorghe. The Sulina distributary was rectified for sea navigation by cutting off the meander loops in the 1868-1902 period, and at present it is 63 Km long. Its water discharge represents about 17.5% of the total Danube discharge. The Sf. Gheorghe distributary is 109 Km long and it takes over ca. 20-21% of the total water discharge and approximately 19.5% of the sediment discharge of the Danube. At its mouth a small secondary delta is formed, with a main branch Sf. Gheorghe-Kedrilles (the prolongation of the main channel) and two subordinate distributaries: Seredne and Gârla Turcului. Near Km 54 from the mouth of Sf. Gheorghe distributary starts the Dunavăt channel, formerly a secondary distributary streaming southwards (initial bifurcation point at Km 60).

The total delta plain area is about 5,800 Km^2 (Fig. 1).

The present-day morphology of the Danube Delta evinces the Jibrieni-Letea-Răducu-Ceamurlia-Caraorman line which marks the boundary between the **upper or "fluvial delta plain"** to the West and the **lower, "marine delta plain",** over an area of ca. 1,800 Km^2, to the East. In the marine delta plain there are numerous beach ridges, which in certain zones generate, by juxtaposition, accumulative littoral formations (among which the most important are: *Jibrieni* - on Ukraine territory, *Letea, Caraorman, Sărăturile, Perisor, Chituc* etc.). In the fluvial delta plain one notes fluvial levees, meander-belt bodies, interdistributary depressions with their hydrographic network and a particular feature, the Stipoc lacustrian spit.

2.2. ***The delta front*** area is of about 1,300 Km^2 and can be divided into: **the delta front platform** (ca. 800 Km^2) and **the delta front slope** (ca. 500 Km^2)(Fig. 1).

The main delta distributaries debouche into zones with different bathymetry: in the North, the Chilia distributary flows into a continental shelf area of 20-25 m depth, while in the South, at the mouth of the Sf. Gheorghe distributary, the water depth is considerably higher: 30-40 m. This differentiates the morphology of the delta front in the two mentioned areas.

The Chilia delta front platform, slightly sloping (0.002-0.004) extends on 1.5-2.5 Km to the isobath of 5-7 m, where from the delta front slope prolongs off-shore as far as about 15 m depth in the North and 20 m depth in the South, being much steeper (0.007-0.01).

The delta front of Sf. Gheorghe branch consists of a platform containing the main distributary mouth-bar, the arcuated lateral littoral bar named "Sakhalin island", the mouth-bars of the Turcu and Seredne secondary distributaries and the area behind the Sakhalin island. The platform reaches the water depth of 12-15 m, sloping at 0.003-0.005. The delta front slope, with dips of 0.008-0.01, extends off-shore to a water depth of 35-40 m.

A peculiar case is noted in front of Sulina distributary. In the Sărăturile-Imputita channel

sector of the coastal zone the delta front platform is less marked, the bottom slopes to the depth of 12-15 m, being of 0.006-0.008. In front of the Sulina distributary mouth and Southward to the parallel of the lake Rosu remnants of Sulina Delta and its front are present (the Sulina Delta has been eroded, as further shown, during the last 2,500 years). Therefore, in the bathymetric interval of 10-20 m the slope is of 0.001-0.003, following off-shore the old front of Sulina Delta to 30-35 m depth with a slope of 0.003-0.006.

2.3. The prodelta lies off-shore, at the base of the delta front to 50-60 m depth, covering an area of more than 5,500 - 6,000 Km^2. The outer eastern boundary of the prodelta in front of the main delta distributaries can be accurately identified (Fig. 1,2). On the contrary, the 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. The influence of this material is felt all over the continental shelf even South of Constantza.

The delta front and especially the prodelta displays a pattern of elongated depressions, swales, resembling some small valleys or submarine channels, 4-10 m deep, bordered by lateral levees or ridges (Fig. 1,2). These channels seem to constitute discharge ways of turbid flow yield by the river distributaries especially at high flood.

Beyond the prodelta seaward there is the **"continental shelf"** with a thin, non-consolidated, actual sediment cover (Fig. 2). Here we can identify the pattern of the channels followed by the Danube during the low sea level periods towards the shelf edge, more precisely to the canyon Viteaz (Fig. 1).

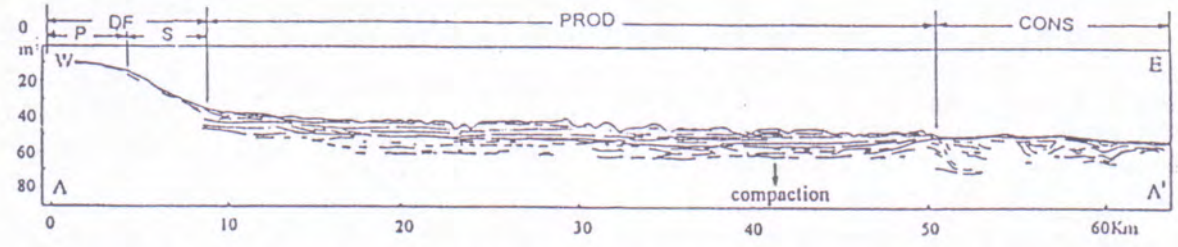


Fig. 2. Geologic section across the submarine part of the Danube Delta. (Legend: DF - Delta front; P - platform; S - slope; PROD - Prodelta; CONS - Continental shelf).

The delta front and especially the outer continental shelf displays all the known types of deformational processes of nonconsolidated sediments, such as: rotational slides, affecting the superficial layer of 10-30 m thick, mass- or mud flows, collapse depressions etc. These movements can occur even at extremely reduced slopes of 0.2-0.5°.

The mentioned **Viteaz canyon** has an average width of 4 Km and relief on the order of 450 m. It is situated approximately along the prolongation of a major, NW-SE - striking fault Peceneaga-Camena in Dobrogea. Since its relief is too large to be accounted for only by subaerial river-cutting during sea-level lowstands, it is likely that that canyon initiation occurred by slumping and related mass wasting processes on the continental slope at fault-controlled location that corresponded to an important depocentre of the Danube mouth during the Pleistocene sea-level fall. The canyon probably widened by retrograde slumping in the course of the subsequent sea-level rise. Nevertheless, on the middle shelf the numerous buried paleochannels followed probably by the Danube during the sea lowstands seem to be directed to the Viteaz canyon head.

The upper and middle continental slope are characterized by thick, well stratified sedimentary sequences. Scars mark places from which sediment packages have been torn, slumped or slided, and have come to rest on the lower slope. Thus, mass wasting processes resulting from slope instability must have played an important role (Wong et al., 1994).

The Danube deep-sea fan occurs offshore Romania, Bulgaria and Ukraine in the northwestern Black Sea (Fig. 3) and extends over 150 Km both in width (NE - SW direction) and length (NW - SE)

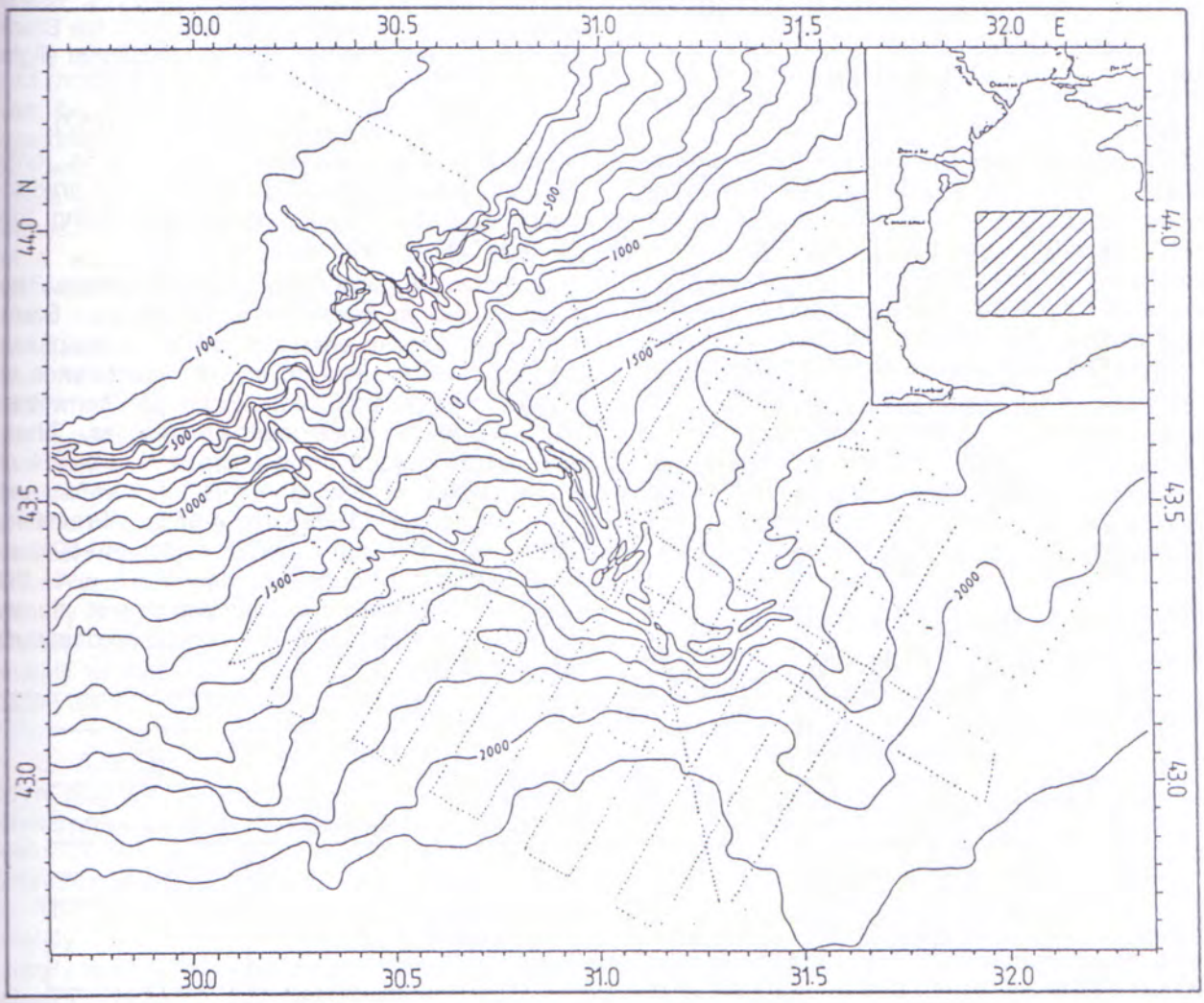


Fig.3 - Danube deep sea fan complex - bathymetry and localisation in the North-Western Black Sea

reaching from several hundred meters water depth down to the abyssal plain (over 2,200 m). The upper slope is degradational. It is characterized by rugged, concave-upward surface, and is dissected by the Viteaz and other submarine canyons as well as channels without levees or with only nascent levees. The aggradational lower slope is dominated by a well-developed channel-levee system and is convex-upward, but its surface is much more regular. Unchannelized flow and turbiditic and hemipelagic sedimentation mark the distal lower slope and the abyssal plain.

3. Processes and dynamic factors controlling the delta morphology and development

a. River input. The Danube fluvial system has the following characteristics (Almazov et al., 1963; Stançik et al., 1988): length of the river course- 2,860 Km; drainage basin of ca. 817,000

Km^2, characterized by 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 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 dam was 2,140 $Kg.s^{-1}$ (67,5 millions t/year), out of which sandy alluvia ca. 10%. After 1970, consequently to the building of this dam and to the hydrotechnical amelioration works along the Danube tributaries, the sediment discharge decreased by ca. 30-40%, so at present one can estimate the Danube average sediment discharge at ca. 40-50 million t/year, out of which 5-8 million t/year sandy material. These are the sediment amounts contributing yearly to the development, or better to say to the maintenance of a relative equilibrium of the Danube Delta edifice.

Accordingly to Bondar (1990), the multiannual sediment discharge at the River Danube mouths is: R_D = 51.7 millions t/year, while the multiannual tendency shows a slight decrease as it is shown by the following function:

R_D = 2,064 - 6.424 (t - 1857), where **t** is the time in years.

The same author appreciates the multiannual (from a long time series of almost 130 years) 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:

Q_D = 5,653 + 5.961 (t - 1857).

Probably this increasing tendency is only apparent, actually reflecting the impact of gradual damming of the River Danube and losing the wetlands buffering zones.

b. Meteorological factors - wind system. The western and north-western areas of the Black Sea basin are marked by active atmospheric circulation, being situated at the interference of the routes of Atlantic and Polar, Mediterranean and Euro-Asian continental air masses. Thus, winds exceeding 2m/s are recorded for 80-90% of a year, winds exceeding 6 m/s for 30-55% and those exceeding 11 m/s for 4-15%. Prevailing winds are from the northern sector (40-50% of instances); the northern winds are also the strongest. The frequency and duration of storms from the northern sector are clearly predominant (more than 55%).

Table 1 (after Patachie et al., 1985; Cristescu et al., 1985 with modifications)

Wind direction	Mean annual frequency %	Mean annual speed (m/s)	Frequency %	Storms v> 8 m/s		
				Mean duration (h)	Mean max. speed (m/s)	Duration at max. speed (h)
N	14-30	6.8	26.9	19.1	17.5	167.0
NE	9-15	6.0	22.7	22.0	17.5	131.0
NW	6-18	5.5	9.0	9.1	11.7	36.0
Northern Sector	**40-50**	**5.0-9.0**	**58.6**	**18.8**	-	-
S	10-17	4.5	12.1	7.4	12.8	37.0
SE	9-11	4.5	4.8	7.1	16.5	23.0
SW	6-10	4.0	4.8	6.2	12.2	26.0
Southern Sector	**30-40**	**3.0-6.0**	**21.7**	**7.1**	-	-
E	**4-10**	**4.0-10.0**	**4.2**	**9.4**	**11.2**	**35.0**
W	**6-16**	**3.0-6.0**	**15.6**	**8.8**	**15.0**	**62.0**
Calm	**0-20**	-	-	-	-	-

Bondar et al, 1992 show that the mean multiannual (for the 1941-1989 period) values of wind frequency and velocity within the littoral zone in front of Constantza being largely predominant from the northern sector (Table 2).

Table 2

Wind characteristics (directions)	N 0°	NE 45°	E 90°	SE 130°	S 180°	SW 225°	W 270°	NW 315°	Calm
Frequency %	14.96	12.40	7.11	11.04	11.16	7.24	15.05	10.53	10.51
Velocity (mean val. m/s)	6.10	6.12	4.25	3.85	3.85	3.50	4.18	4.30	

The calculation has shown that the multiannual mean velocity of winds is 4.65 m/s, the multiannual wind energetic resultant is 7.73 $(m/s)^2$ being oriented from the North, at an azimuth of 8.89° (Bondar et al., 1992).

*c. **Waves***. The waves regime in the western and north-western parts of the Black Sea basin can be characterized as follows (according. to Diaconu et al., 1978): tranquil (smooth) sea (waves below 0.2 m) represents 49.1% of the whole bulk of data concerning the waves, wind waves - 33% and swell, 17.9%. The most frequent wind waves are recorded along NE trending, corresponding to the prevailing wind direction, while from east are recorded almost 40% of swell waves (due to the refraction of waves in shallow water). The mean and maximum heights (5.2 m at Constantza, 7.0 m at Sulina at the jetties end) of wind waves and swell are higher for the eastern direction for which the wind fetch is maximum.

The energy of storm waves reaches important values: on 17-th of February 1979 there was a storm characterized by 12,242 KWh/m, while usually the energy is of approximately 2,000 KWh/m (Spătaru, 1984). This power contributes mainly to the distribution of river sediment input along the delta shore.

*d. **Sea level***. The variations of the Black Sea level depends on seasonal, multiannual or eustatic changes of sea water balance as well as on the deformation of free water surface under the influence of different external forces.

The seasonal sea-water volume changes are mainly due to season variations of river water supply and of rainfall regime: such type of sea level changes reach 20-28 cm amplitudes.

The multiannual fluctuations due to the variations of annual rivers water discharge as a consequence to climatic cycles reach ca. 20 cm.

The eustatic fluctuations of the Black Sea level, from the end of the Pleistocene till present, generally correspond to level variations reported for the oceanic basins. In the last two thousand years, the Black Sea level, on the western seashore rose by ca. 4 m. During the last century the maregraphic observations have shown the tendency of rising by 2-3 mm/year (2.6 mm/year- Diaconu et al., 1985; 2.595 mm/year- Selariu, 1972; 3.16 mm/year- Pascaru, 1968).

Amongst the deformational oscillations seiches, wind surges and tides are to be mentioned. The seiches in the north-western and western areas of the Black Sea have periods from a few minutes to 13 hours and amplitudes from a few centimeters to 2.0 m. The storm surges from northern, north-eastern, eastern and south-eastern directions are positive and the induced sea level rise does not exceed 1.2-1.5 m. The tide in the Black Sea has an average period of 12 hours and 25 minutes and amplitudes only of 7-11 cm (Bondar et al., 1973; Sorokine, 1982).

e. Marine currents and longshore sediment current. The atmospheric circulation and other hydrological and morphological factors determine in the Black Sea a general cyclonal water circulation, within the upper water layer to about 1,000 m depth.

In the north-western and western areas of the sea, the drift current belonging to the cyclonal circulation gets a movement impulse from the water discharge of the rivers debouching into this area (Dnieper, Southern Bug, Dniester, Danube), this current of 50-75 miles width, is following southward to the Bosphorus at a mean speed of 20-30 cm/s. The strong temporary winds from northern sectors double or even triple the current speed, while those from southern sectors diminish and deviate the currents from the general circulation system.

In the Danube Delta littoral area, there is, even during quiet periods, a generally southward current characterized by 5-50 cm/s speed depending on the water supply of rivers. In addition to this current, the winds, of different velocity and stability, generate a complex current system generally corresponding to the wind direction. These wind currents became stable, strong and affect the whole water layer to 40-50 m depth only when the wind velocity exceeds 10 m/s and last more than 10-12 hours. During these events the velocity of wind currents could reach 100-150 cm/s at surface and more than 30-40 cm/s near the bottom.

The prevalence of strong winds from the northern sectors determines the doubling of annual frequency of Southward currents by comparison to the frequency of Northward currents.

The morphologic features of the sea-shore determine local perturbations of the longshore wind currents system. Thus, under the influence of northern winds, the jetties of Sulina distributary, advancing far off-shore (ca. 8 Km), generate an 8-10 Km diameter long ellipsoidal eddy of anticyclonal direction situated to the South of mentioned jetties.

To these marine currents the fluvial outflow is added. The latter penetrate into the sea basin like a turbulent jet, spreading off-shore and being deviated by the Coriolis force to the right, i.e. Southwards.

The wind of certain direction and intensity generates, as already noticed, longshore currents and

wave systems, which cause the movement of littoral sediments in the same direction, this movement is called according to Zenkovich (1962) the sediment "migration". The algebraic sum of all the migrations in a laps of time (usually a year) will have a value and a direction, representing the direction and the intensity of movement of littoral sediments, being called "longshore sediment current" or "longshore sediment drift".

As regards the Danube Delta sea-shore, the longshore sediment current is directed towards the South. Its intensity is high enough to transport the coarse-grained discharge of the Danube many tens of Km South of the distributaries mouths along the shore.

The migration of a contrary direction to the longshore sediment drift, caused by reverse winds, makes possible the occurrence of river borne sediments in the opposite to the drift direction side of the river mouth. This area is called "zone of littoral diffusion", and in the case of the Danube distributaries it lies North of their mouths and has a limited to only a few Km extent.

Another local perturbation of littoral sediment movement is induced by the eddy circulation South of the Sulina jetties.

The southward longshore drift of the Danube sediment load can be recognized through the entire Holocene evolution of the Danube Delta.

4. Relationship between the delta morphology and fluvial and marine controlling factors; Danube Delta morphometry.

The morphology of deltas depends on the river input on the one hand, and on the other hand on the marine factors, especially the wave power and currents. Which are the means of determining the magnitude of these two antagonistic forces and how can one achieve a physical correlation between the morphology of a delta and the two forces?

Wright and Coleman (1971) have defined a ***"discharge efficiency index"*** inferred from the ratio of the discharge per foot of river mouth width (resulting from dividing the total discharge by the total width of all the distributaries) to the wave power per foot of the wave crest. The meaning of this index is the following: the higher the discharge, the higher is the wave power required to rework and redistribute the sediments into a wave-dominated configuration of delta shore. The problem is much more complex, of peculiar interest being the variations in time (seasonal or aleatory) of sediment discharge and of power regime of the sea. Thus, if the discharge peaks coincide with the periods of maximum wave power, the sediment amount carried by the river would be easily redistributed along the coast, favouring the regular and uniform progradation of the delta shore. If the discharge and wave power are out of phase, the river action will be prevailing part of the year, followed by intense processing and redistribution of sediments along the coast in successive beach ridges and spits flanking the river mouths.

As regards the Danube Delta, the peaks of river discharge and wave power are somewhat out of phase (by ca. 2-3 months), thus contributing to the redistribution of river born sediments to successive beach ridges. According to Wright and Coleman (1971) "the discharge efficiency index" of the Danube ranges from 2,324.0 in June to 466.0 in October, the mean value reaching 1,171.0 and the variation coefficient 0.55. These values, 5 times smaller for the mean values and 17 times smaller for the maximum ones than those reported for the Mississippi river, are enough to determine the progradation of the Danube Delta lobes.

The dynamic factors and processes, mentioned above, control the genesis and distribution of the different facies and the geometry of sedimentary bodies. Based on the analysis of 34 deltas Coleman (1986) evinces 6 types of distribution and geometry of sand bodies. The deltas characterized by reduced wave energy, low submarine slope (important wave energy attenuation degree), low longshore drift and relevant sediment discharge, such as those of the rivers Mississippi, Parana and Dniester, exhibit elongated, finger-like sandy bodies following the distributaries trending, usually almost perpendicular to the shore line, mainly consisting of bar deposits.

At higher level of wave power and longshore drift the river-borne sediments are reworked into successive beach ridges, forming parallel to the shore-line bodies of better sorted sand which coexist with finger-like sandy bodies following the distributaries directions. Within their distribution area, the gradual progradation of the coast generates in time, by juxtaposition of these beach-ridges sand bodies, a continuous sand layer. To this category the Danube Delta is assigned.

Wright and Coleman (1971) have proposed several indices regarding the morphology of the deltas, in the end to characterize delta sediment distribution parallel or perpendicular to the shoreline and to make possible the determination of the magnitude of fluvial and marine processes controlling the delta shape and development. The proposed indices will be applied both to the Danube Delta on the whole and to the deltas of the main river distributaries. We may state also

that, by taking into account the delta edifice as a whole, some significant genetic features are not pointed out. The considered indices are the following:

* The **protrusion index (I_{pr})** representing the ratio of the length of the axis of delta maximum advancement (L_m) to the maximum width of the protrusion (W):

$$I_{pr} = L_m/W \qquad (I)$$

* The **crenulation index (I_{cr}),** being the ratio of the delta shoreline length (L_s) to its maximum width (W):

$$I_{cr} = L_s/W \qquad (II)$$

* The **sediment distribution index** or skewness **(Sk)** about the central axis of the deltaic protrusion. It implies the total volume of delta protrusion (V_t), the subaqueous part included (to a 12.5 m depth contour, considering conventionally the approximate seaward limit of sandy river-borne sediments or the outer edge delta-front platform):

$$V_t = \int_{-12.5}^{z} a.dz \qquad (III)$$

where "a" represents the given contour area, and "z" the height above this basal contour.

The distribution index **Sk** corresponds to the ratio of sediment volume on the left (in the Danube Delta case on the North) of the protrusion axis and the sediment volume on the right (on the South) of this axis:

$$Sk = V_N/V_S \qquad (IV)$$

The index values different from 1 show that the protrusion is not symmetrical, the littoral drift having a preferential trending. As regards the NW coast of the Black Sea, where the littoral drift is oriented southward, the value Sk will always be less than 1. The table No.3 below presents the distribution index values of Danube Delta and of the deltas of different distributaries, including the paleodeltas Sulina and Sinoie, which will be described in the following chapters.

The Sk values point to a strong Southward longshore drift, obviously increased in front of Sf. Gheorghe II Delta. However, the presented Sk index values do not show wholly the magnitude of

Table 3

Delta	$I_{pr}=L_m/W$	$I_{cr}=L_s/W$	$Sk=V_N/V_S$
Chilia Delta	0.56	2.84	0.44
Sulina Delta	0.55	1.34	0.57
Sf. Gheorghe II Delta	0.40	1.28	0.27
Sinoie Delta	0.20	1.07	0.43
Danube Delta (global)	0.26	1.66	0.31

this drift which is, in the Danube Delta case, much higher. That because the sediment volume located to the North of the delta protrusion axis is supplied mainly by northern sources (the Bug, Dniester, Dnieper sediment input) and only subsidiarilly by the distributary which had formed the delta under discussion. Thus, in the case of the Sf. Gheorghe II Delta, the sediments from the northern wing (Sărăturile littoral accumulative formation) are generated by the erosion of Sulina Delta. In the same way, the northern wing of Sulina Delta consisting partly of material supplied by the northern sources, to which the northward oriented distributaries add a certain amount of Danube-borne material.

The protrusion and crenulation indices show the relative prevalence of fluvial or marine factors. It is obvious that the Chilia distributary is the most active and its sediment discharge is superior to the capacity of dispersion and redistribution of marine processes.

5. Geologic setting, genesis and Holocene evolution of the Danube Delta

The Danube Delta overlaps the Predobrogean Depression which, in its turn, lies mainly on the Scythian Platform. The boundary of these units to the North Dobrogea Orogen is represented by the Sf. Gheorghe fracture zone which otherwise influences the trending of the Danube course in the Galatzi - river-mouth sector. The sequence of the Scythian Platform cover deposits which constitute the filling material of the Predobrogean Depression displays six sedimentation cycles (Pătrut et al., 1983), as follows: (a) pre-Mesozoic cycle (Paleozoic), calcareous -dolomitic; (b) Lower Triassic cycle, of considerable thickness (400-2,500 m), slightly unconformable over subjacent deposits and consisting of red continental detrital

deposits with interlayered effusive rocks;(c) Middle-Upper Triassic cycle, transgressive, marine, built up of carbonate rocks at the lower part (350-450 m limestones and 500-600 m dolomites) and of detrital rocks (450 m) at the upper part; (d) Jurassic cycle, transgressive, marine, consisting of detrital deposits at the base (Middle Jurassic, 500-1,700 m thick) and carbonate ones at the top (Upper Jurassic, 1,000 m thick in the southern area); (e) Lower Cretaceous cycle, overlying Jurassic deposits, consisting of red continental deposits of varying thickness (ca. 500 m); (f) Sarmatian-Pliocene cycle, overlying different Mesozoic deposits and consisting of alternating clays, sand and sandstones (200-350 m thick).

The Danube Delta is thus situated in an area of high mobility of the Earth crust, repeatedly affected by strong subsidences and important sediment accumulations. The deltaic conditions were settled here during the Quaternary, when the Danube started flowing into the Black Sea basin.

The Danube Delta edifice is formed by sequence of detrital deposits of tens to 300-400 meters thick. The important Quaternary changes of the sea level have strongly influenced the Danube Delta evolution. The Würmian regression, and especially that of the Neoeuxinian stage of the Black Sea (about 18,000-15,000 years BC), when the sea level lowered to ca. -100 m, brought about the intense erosions of the delta deposits. Probably much of the old Quaternary deposits were thus removed. One can still recognize deposits assigned to the Karangatian and Surojskian stages (Würmian interstadial), located eastward of the Letea-Ceamurlia-Caraorman line and preserved behind some erosion relics of the predeltaic relief. The Danube Delta edifice was therefore formed mainly during the Upper Pleistocene (Karangatian, Surojskian, Neoeuxinian) and the Holocene.

The actual geomorphology of the Danube Delta plain expresses the interaction of the river and the sea during the Holocene time (Panin, 1974, 1983; Panin et al., 1983). To decipher the delta evolution, by taking into account the basic processes and factors controlling the genesis and the development of deltas, means in fact to understand the areal distribution of a great number of morphologic features, mainly beach ridges, corroborated with data regarding textural, geochemical and mineralogical facies, faunal assemblages, as well as age determinations by radiocarbon method. The beach ridges can be grouped according to their position and trending into sets which express the progradation stages and can be dated by fauna analyses and mainly by ^{14}C dating and finally point to the evolution of considered delta edifice.

Here are the main stages of the Danube Delta evolution during the Holocene (Panin, 1974, 1983; Panin et al., 1983).

At the beginning of the Holocene, when the sea level rose to about present-day mark, on the delta area existed the so-called "Danube gulf". At its mouth, between the Jibrieni promontory to the North and Murighiol-Dunavăt promontory to the South, a spit was formed during the period 11,700-7,500 years BP named, in accordance with other predecessors, the :**"Letea-Caraorman initial spit"** (Fig. 4).

The initial spit was formed with support points at relief relics forms of the Holocene delta basement, such as the one in the Caraorman area. The material of the initial spit was carried by the longshore sediment drift from an adjoining area, situated in the North, at the mouths of the Southern Bug, Dniester and Dnieper rivers. The sediments of this type are assigned to type **"a"** (Fig. 5). This is the "blocked delta" stage of the Danube, when the river was forming its delta inside a lagoon sheltered by the initial spit.

Between the southern end of the initial spit and the Murighiol-Dunăvat Promontory there was a passage through which the first Danube arm, Paleo-Sf. Gheorghe, flew into the sea. It is here that the first delta of the Danube was formed - the **"Sf. Gheorghe I Delta"** (Fig. 5). Its development is related to the 9,000-7,200 years BP period. At present only the northern part of this delta can be recognized; it is formed by three main sets of fossil beach ridges (Erenciuc, Caraorman-pădure and Caraorman-sat) built up of **"a"** type sediments. Only in the extreme Eastern and youngest part of the Caraorman-sat set can one identify a sediment input of different origin, these are the first, reduced yet, amounts of Danube alluvial load, introduced into the littoral area by the second branch of the river - Sulina distributary. The Sulina sedimentary load was then reworked by the waves and longshore currents and redistributed to the last beach ridges of the Caraorman-sat set.

During the stage of maximum progradation of the "Sf. Gheorghe I Delta", expressed by the Caraorman-sat set of beach ridges, the paleo-distributary Sf. Gheorghe formed meanders of 10-14 Km wave length, amplitudes of 5-7 Km and curvature indices r_m/w exceeding 2.0 (Panin, 1976), the process was probably favored by a very low relief energy. The excessive elongation of the distributary channel and the low relief energy led to a partial filling of the Sf. Gheorghe paleo-distributary. The filling up and gravitational appeal of the depression situated to the North, determined the development of a new branch of

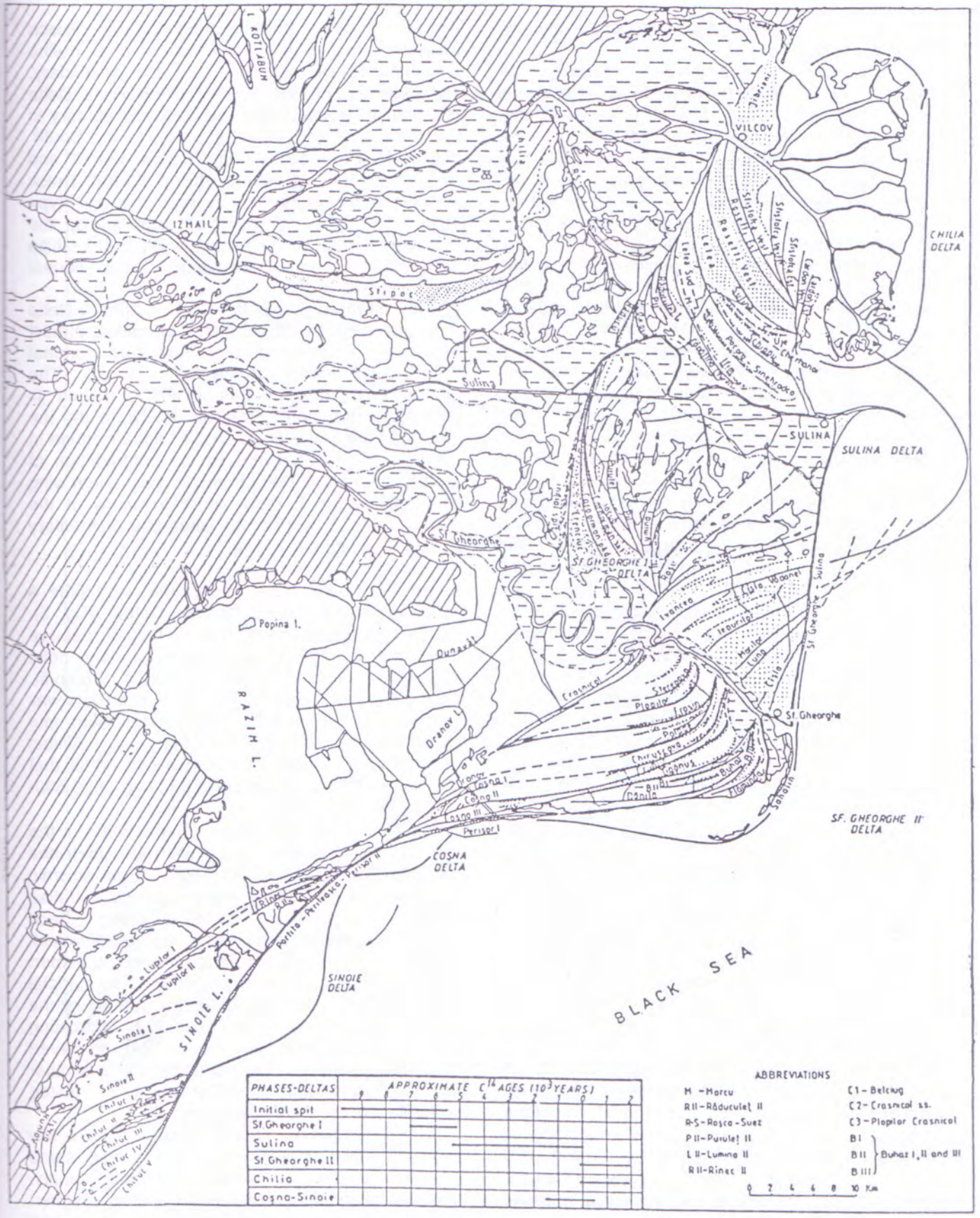


Fig.4 - The Danube Delta geomorphological-sedimentological structure.
The map outlines the main sets of beach ridges and the phases of delta evolution during Holocene

the river- the Paleo-Sulina distributary already mentioned before.

The Paleo-Sulina distributary, bifurcating at Nufăru-Rusca, had meander belts with wave length and amplitudes similar to those of the Paleo-Sf. Gheorghe branch (λ = 14-16 Km, α = 5-7 Km r_m/w = 2.67-2.78).

As the Paleo-Sf. Gheorghe was gradually filled, the Paleo-Sulina took over more and more water and sediment discharge and started forming its own delta edifice - **"Sulina Delta"** (Fig. 5). The development was slow at the beginning, its shape being controlled by waves and littoral drift; the later increase of water and sediment discharge as well as the discharge effectiveness index determined a rapid progradation and the lobated shape of the Sulina Delta, with three and then five distributaries. The development of the Sulina Delta took place during the 7,200-2,000 years BP period. The maximum progradation of the Sulina Delta into the sea, its front surpassing by 10-15 km the present-day shore line, coincides with the Phanagorian regression when the sea level was at -2 - -4 m mark. At the same time, in the southern part of the Delta area, a little secondary delta - the **"Cosna Delta"** - was formed by a secondary distributary - the Dunavăt.

The Sulina Delta has a complex constitution. Its southern wing is represented by the beach ridges sets: Iacub, Puiulet, Lumina, Rosu, Rosulet, Ivancea (Fig. 5) and consists of sedimentary material carried by the Danube, assigned by us to type **"b"** sediments. The northern wing consisted, at the beginning of the development of this delta, only of type **"a"** material, forming the Răducu, Hudacova and Răduculet sets. Then, the Letea South, Letea North, Rosetti West and partly Rosetti East sets consist, in their northern part, of type **"a"** material. The Sulina Delta distributaries streaming northward: Magearu, Movilă, Sinehradca, carry type **"b"** (Danubian) material, so that the beach ridges Capatâna-Ilarion and Mohammed, Ifim, Pocora, Sinehradca, Movilă, Schiopu, Cherhanoi, Uje, Sulina and the south-eastern part of the Rosetti-West set are built up of this type of material. To the NW of the Magearu distributary there is a limited area of littoral diffusion (Fig. 4, 5).

By the end of Phanagorian regression, when the sea level lowered by a few meters (-2 ÷ -4 m) and the relief energy increased, the Sf. Gheorghe distributary was drained and a new generation of meander bands characterized by λ = 2.4-5.0 Km , α = 1.5-4.0 Km and r_m/w values of 1.49-2.1 was formed. In the North, the initial spit was broken and a new distributary, Chilia, appeared.

The next stage, which took place during the following 2,000 years, coincides with the present-day sea level rising. By then the Sulina distributary was partly clogged, the Rusca meander bend was abandoned and Sulina continued to be supplied by the secondary, anastomosed, Păpădia channel, the Sulina Delta is gradually eroded, while the Chilia distributary in the North, and Sf. Gheorghe one, in the South, built up their own deltas - the **"Chilia Delta"** and respectively the **"Sf. Gheorghe II Delta"** These two deltas consist of Danube born material (type **"b"**). The type **"a"** material, supplied by the longshore drift, is accumulating North or the Chilia distributaries and constitutes the Jibrieni formation.

The northern side of the Sf. Gheorghe II Delta is represented by the Sărăturile formation, almost exclusively consisting of sedimentary material reworked by erosion of the Sulina Delta. The trending of the beach ridges of this formation is pointing to the shore retreat in the North (by the erosion of the Sulina Delta) and its advancement in the South (corresponding to the progradation of the Sf. Gheorghe II Delta front). The southern wing of Sf. Gheorghe II Delta consists mainly of the alluvia carried by the Sf. Gheorghe distributary (type **"b"** material) (Fig. 4, 5).

In the South, there was in that very time a secondary delta, named **"Sinoie Delta"** (Fig. 5). Cosna and Sinoie Delta are in fact successive development stages of the same secondary delta formed by a less important distributary - Dunavăt. During the first centuries AC the Sinoie Delta was eroded and its material was redeposited into beach ridges forming the Istria and Chituc accumulative formations. So, we can admit that the **Cosna-Sinoie Delta** existed during the 3,500-1,500 years BP period.

Additionally a very short information on the structure and evolution of the **Danube deep-sea fan complex** (Wong et al., 1994) Eight seismic sequences have been recognized by detailed continuous reflection seismic profiling. Each sequence consists of channel, levee and overbank sediments, as well as various mass transport deposits (slumps, slides, debris flows). The surficial channel-levee systems have been aggraded by the Danube. Downfan the main channel is bifurcating and diverging, and the volume of the levee deposits decreases. Towards NE there is another fan interlaping with the Danube one, related probably with the Ukrainian rivers.

The surficial main channel system have a low sinuosity which implies either young age, steep gradients and/or a limited sediment supply. Downfan channel sinuosity is considerably higher, the meander belts having amplitudes of several Km. Buried channel systems suggest that channel migration in the course of fan development may be significant.

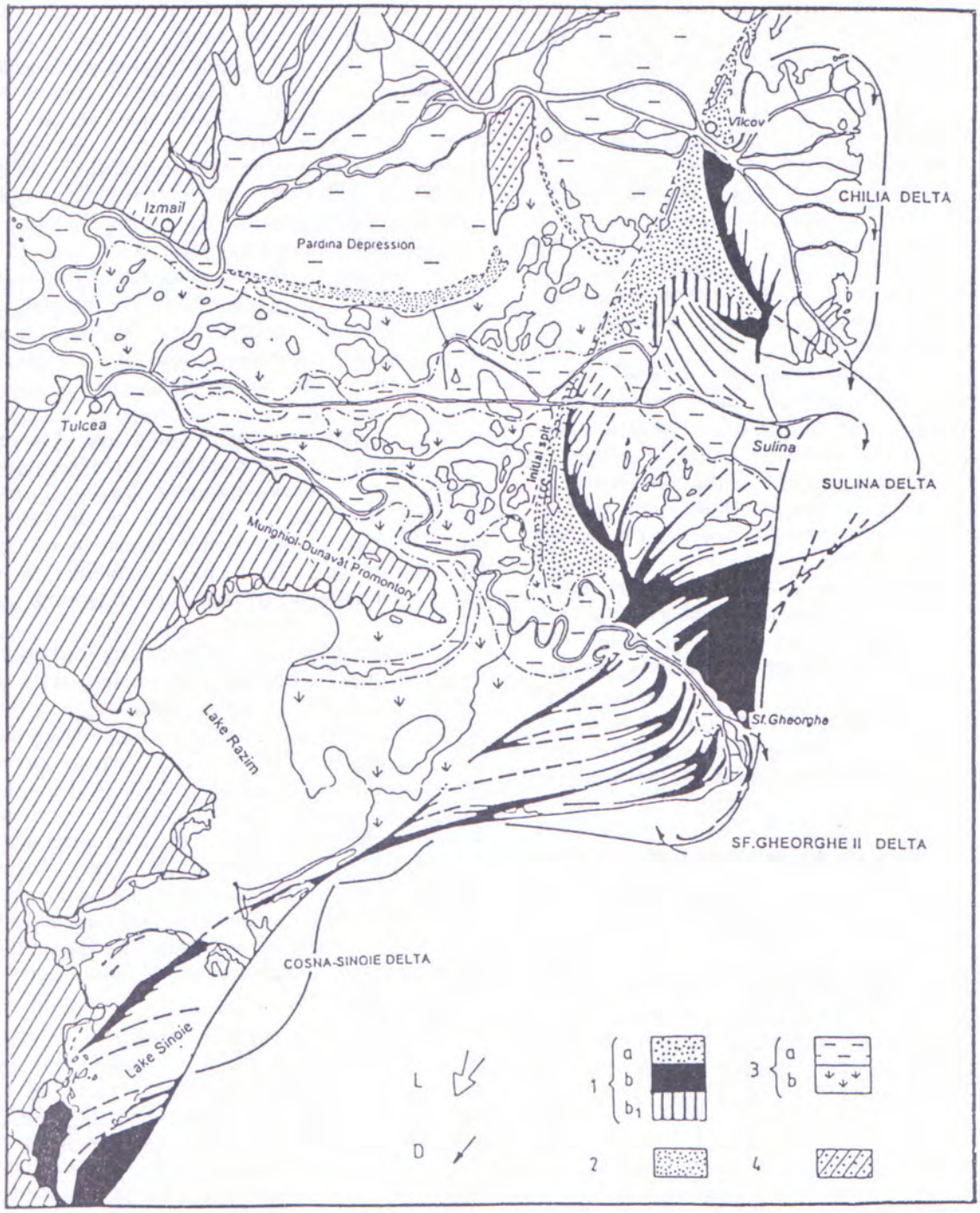


Fig.5 - Areal distribution of the main types of littoral deposits within the Danube Delta territory

Legend: 1. Marine littoral deposits: -type "a", formed by the littoral drift from the North, from the rivers Dniestr, Dniepr and Southern Bug; type "b", of Danubian origin; -type "b_1", of littoral diffusion, marked by mixing of types "a" and "b"; 2. Lacustrine littoral deposits; 3. Fluvial deposits: a-meander belt deposits; b-interdistributaries depression deposits; 4. Loess like deposits; L - Direction of the littoral sediment drift; D - Main sediment supplies.

The primary factor controlling fan development is relative sea-level changes and, implicitly, glaciation and deglaciation: fan aggradation would be most rapid during sea-level lowstands, while the fan system would be sediment-starved during highstands. Mass transport and the most important sediment supply would occur predominantly in the course of sea-level fall and during the beginning of interglacials. The seismic sequences 3 to 8 mapped may be correlated to the sea-level cycles from the post-Chaudian regression (Mindel, Elsterian) to today. Referring to the last two sequences for example one can evidence the following:

Sequence 7 corresponds to the Post-Karangatian regression (Early Würm, ca.100,000-72,000 BP) and the Surozhskian transgression. During this time, the river Danube found its way to the Black Sea and, together with the Ukrainian rivers, delivered the sediments that made up this sequence within the two fan complexes mentioned before.

Sequence 8 may be correlated with the Neo-Euxinian regression (Late Würm = Weichselian) and the subsequent Holocene transgression. The Neo-Euxinian started 23,000 BP with the lowest sea-level stand (at about - 100 m) occurring ca. 18,000 BP. From 15,000 - 12,000 BP to about 10,000 BP, sea level rose to its present stand and the area of sediment discharge of the Danube retreated towards the present coastline.

6. Sediment facies types of the Danube Delta

The Danube Delta plain displays a few main facies types of sediments, as follows:

* ***Marine littoral deposits***, occurring in the marine delta plain constitute fossil and actual beach-ridges which generated by juxtaposition the littoral accumulative formations Caraorman , Letea, Sărăturile, Istria, Chituc, Jibrieni, Perisor etc. (enumeration in the genesis order)(Fig. 5).

There are two basic types, as already mentioned:

- deposits formed by the longshore drift from the North (from the mouths of rivers Southern Bug, Dniester and Dnieper) called as mentioned before of **type "a".** They consist of quartz sands with very high silica contents (89-95%) and particularly reduced alumina (average value 1.5%) and iron oxides ones (mean value 0.12%). The heavy minerals content is very small (0.1-0.3%), while the characteristic mineral assemblage contains minerals highly resistant to transport and environment changes: garnets (50-60%) -ilmenite (12-18%)-tourmaline (6-10%).

- littoral deposits of Danubian origin (**type "b"**), represented by sands finer grained than those of type **"a"**, described above, yielding smaller SiO_2 contents (60-85%) and higher Al_2O_3 (1.7-8.0%), Fe_2O_3 (0.3-3.3%) and TiO_2 (0.1-1.6%) ones. The heavy mineral contents are important (2-3%), the characteristic assemblage including: amphiboles (15-35%) - garnets (5-35%) - opaque minerals, predominantly ilmenite (5-15%) - epidote (9-12%). The tourmaline ratio decreases to 0.5-1.5%. Two sub-types can be distinguished subtype **"b_{dif}"** of littoral diffusion, marked by mixing with type **"a"** material and subtype **"b_D"** , of normal littoral transfer, preserving obvious characteristics of the Danube born sediments.

One should also note a subfacies of present-day or fossil marine erosion, displaying deposits enriched in heavy minerals fraction residue reaching 35%(**"b_{hm}"**), as well as a subfacies related to terrigenous matter deficit, in which the terrigenous material is partly replaced by shell debris ($CaCO_3$ to 45-50%) named of type **"b_{Ca}"** .

* ***The lacustrian littoral deposits*** formed in the "Danube gulf" behind the initial spit, more precisely in the fluvial delta plain. These deposits constitute the lacustrian spits Stipoc and Rosca-Suez (Fig. 4). The following average contents are noted: SiO_2 - 66%, Al_2O_3 - 8.5%, Fe_2O_3 - 1.8%, TiO_2 - 0.8%, CaO - 7% and others. The heavy fraction occurs in reduced amounts (ca. 0.1%) being represented by the following assemblage: amphiboles-garnets-epidote-opaque minerals (prevalent ilmenite). The deposits of the Stipoc spit contain lacustrian manganese nodules. Mesolithic and Neolithic vestiges have been found here.

* ***The fluvial deposits***, genetically related to the Danube distributaries system, are to be assigned to several types: (a) bed-load and mouth-bar deposits, (b) subaqueous and subaerial natural levees deposits, (c) crevasse and crevasse-splay deposits, (d) point bar and meander belts, (e) decantation deposits in intradeltaic depressions or intradistributary areas. There is a transition from one type of deposits to another, depending on the transport competence of the water current.

From among the mentioned types, we pay attention to the former, the bed-load and the mouth-bar deposits. They consist of sands mixed up with finer grained sediments and plant debris and show the following chemical average composition: SiO_2 - 69%, Al_2O_3 - 7.5%, Fe_2O_3 -

1.15%, TiO_2 - 0.47%, CaO - 3.4% etc. The heavy fraction represents 1.8-4.7% and consists of the following assemblage: garnets (18-37%) - amphiboles (16-30%) - epidote (5-10%) - opaque minerals (4-7%). These are the sediments which contribute mostly to the delta front protrusion and supply the littoral area with sandy material (original material for the type **"b"** deltaic sediments).

* ***Marsh deposits***, mostly of organic origin, are formed in depression areas with marsh vegetation.

* ***Lœssoïde deposits*** (Upper Pleistocene) were formed in the delta area during its emergence by lowering of the sea level in the Quaternary. These deposits are exposed in the Northern part of the Delta, in the Chilia Promontory, which is the South ward prolongation of the Bugeac·Plateau (Fig. 5).

Lœss-like deposits also occur as erosion relief relics within the Stipoc lacustrian bar and in the basement of littoral accumulative formations Caraorman and Letea-Rãducu.

7. Conclusions

The Danube Delta can be divided into three major depositional systems (Fig. 1,2): the delta plain with a total area of about 5,800 km^2, from which the marine delta plain area is of 1,800 km^2; the delta front with an area of ca 1,300 km^2, divided into delta-front platform (800 km^2) and delta-front slope (ca. 500 km^2) expending off-shore to a water depth of 30-40 m; the prodelta lies off-shore, at the base of the delta-front slope to 50-60 m depth, covering an area of more than 5,500 km^2. The delta front and especially the prodelta displays a pattern of submarine channels, 4-10 m deep, bordered by lateral levees; these channels seem to constitute discharge ways of turbid flow yield by the river distributaries at high flood. It is also to notice the existence of some deformational processes of nonconsolidated sediments, such as: rotational slides, affecting the superficial layer of 10-30 m thickness, mass- or mud-flows, collapse depressions etc. To these depositional systems is to be added the Danube deep-sea fan occurring offshore Romania, Bulgaria and Ukraine in the northwestern Black Sea reaching from several hundred meters water depth down to the abyssal plain (over 2,200 m).

The delta development is controlled by: the river sediment input (the Danube average sediment discharge is ca. 40-50.10^6 t/y out of which 5-8.10^6 t/y sandy material); the prevalence of winds from the northern sector (40-50 % of instances); the predominance of southward trending of marine currents; the long-shore sediment drift directed also towards the South; the relatively important values of wave power etc. The interaction of these factors controls the delta morphological type, the geometry of the volumes of deltaic deposits, the asymmetry of the deltas of Danube distributaries and their development and evolution. In the end to characterize the delta sediment distribution and the magnitude of fluvial and marine process controlling the delta shape and development there have been used the indices of protrusion (I_{pr}), of crenulation (I_{cr}) and of sediment distribution or skewness (Sk) proposed by Wright and Coleman (1971).

The Danube Delta overlaps the Predobrogean Depression which, in its turn, lies mainly on the Scythian Platform. The sequence of the Scythian Platform cover deposits which constitute the filling material of the Predobrogean Depression display six sedimentation cycles (Paleozoic, Lower Triassic, Middle-Upper Triassic, Jurassic, Lower Cretaceous and Sarmatian-Pliocene) (Pãtrut et al., 1983). The Danube Delta is situated in a area of high mobility of the Earth crust, repeatedly affected by strong subsidences and important sediment accumulations. The deltaic conditions were settled here during the Quaternary, when the Danube started flowing into the Black Sea basin.

The Danube Delta edifice is build up of a sequence of detrital deposits of tens to 300-400 meters thickness formed mainly during the Upper Pleistocene (Karangatian, Surojskian, Neoeuxinian) and the Holocene. The Holocene evolution of the Danube Delta include the following main phases: (1) the formation of the Letea-Caraorman initial spit, 11,700-7,500 years BP; (2) the Sf. Gheorghe I Delta, 9,000-7,200 years BP; (3) the Sulina Delta, 7,200-2,000 years BP; (4) the Sf. Gheorghe II and Chilia Deltas, 2,000 years BP-present; (5) the Cosna-Sinoie Delta, 3,500-1,500 years BP. The Danube deep-sea fan consists of eight seismic sequences whose development was controlled primarily by the relative sea-level changes and therefore, implicitly, glaciations and deglaciations. The last 8-th sequence may be correlated with the Neo-Euxinian regression (Late Würm = Weichselian) and subsequent Holocene transgression.

The Danube Delta plain displays a few main facies types of sediments, as follows (Fig. 5):(I) marine littoral deposits of two types: type **"a"**, formed by the longshore drift from the North (from the mouths of rivers Southern Bug, Dniester and Dnieper) and type **"b"**, of Danubian origin; (II) lacustrian littoral deposits, forming the Stipoc and Rosca-Suez lacustrian spits; (III) fluvial deposits, genetically related to the Danube distributaries system, include several types: bed-load and

mouth-bar deposits, subaqueous and subaerial natural levees deposits, crevasse and crevasse-splay deposits, point bar and meander belts deposits, decantation deposits into intradeltaic depression and interdistributary area etc.; (IV) marsh deposits; (V) loess-like deposits.

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