THE DANUBE DELTA – THE MID TERM OF THE GEO-SYSTEM DANUBE RIVER – DANUBE DELTA – BLACK SEA.

GEOLOGICAL SETTING, SEDIMENTOLOGY AND HOLOCENE TO PRESENT-DAY EVOLUTION

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Abstract. The Danube Delta is part of the largest European river – sea geo-system consisting of the Danube River, the Danube Delta and the Black Sea. Each component of the system is described and the main characteristics are given: the Danube River – total length – 2,860 km, mean water discharge at delta apex ~ 6,280 m^3a^{-1}, mean sediment discharge ~ 40 $Mt.a^{-1}$; the Black Sea ~ 420,000 km^2, total water volume ~534,000 km^3, salinity ~17‰ at surface and ~ 22‰ in the deep sea, anoxic conditions and H_2S contamination occur below ~180–200 m water depth. The Danube Delta is described extensively. The geomorphologic and sedimentary units of the delta are: the exposed delta plain – over 5,800 km^2, of which the marine delta plain – 1,800 km^2, the delta-front unit of ca. 1,300 km^2 is divided into Delta-front platform (800 km^2) and Delta-front slope (ca. 500 km^2), the Prodelta – more than 6,000 km^2. On the outer shelf incised valleys of the Paleo-Danube River can be evidenced and in the deep-sea zone a large Danube fan system occurs. A detailed presentation of the delta structure and evolution is given. Delta formation was initiated in the Quaternary, when the Danube started flowing into the Black Sea basin. During this time the Danube River brought into the Black Sea important volumes of sediments that were accumulated in depocentres according to the sea water level. The depocentres migrated from the extreme highstand position, represented by the present-day location of the Danube Delta, to the lowstand ones, beyond the shelf break, forming the deep-sea Danube fan complex. The sediment volumes accumulated within the lowstand depocentres and highstands ones are very different: the lowstand depocentre – the Danube deep sea fan complex, stored over 40,000 km^3 of sediments structured in at least 6 sequences corresponding to the main glaciations with an accumulation rate that ranges between 88×10^6 t/a and 302×10^6 t/a (Wong *et al*., 1997; Winguth *et al*., 1997, 2000), while the amount of sediments accumulated in the present-day Danube Delta, including all the morphologic and depositional units, as Fluvial and Marine Delta Plains, the Delta-front unit and the Prodelta, is only of some 1,200 km^3. The present-day Delta is formed of a sequence of detrital deposits ranging from tens to 200–300 meters thick that accumulated during the Upper Pleistocene (Karangatian, Surozhian, Neoeuxinian) and mainly in the Holocene. The Holocene evolution of the Delta records the following main phases: (1) the "blocked Danube Delta" and formation of the Letea-Caraorman initial spit, 11,700–7,500 years BP; (2) the St. George I Delta, 9,000–7,200 years BP; (3) the Sulina Delta, 7,200–2,000 years BP; (4) the St. George II and Kilia Deltas, 2,800 years BP – present; (5) the Cosna-Sinoie Delta, 3,500–1,500 years BP. These ages are presently under discussion. Giosan *et al*., 2005, proposed younger ages for the initial stages of delta development (in their scenario, the St. George I phase could not be much older than ~5,500–6,000 yr. BP). The modern time delta evolution is presented starting with the descriptions given by ancients, continuing with the evolution recorded in the last two-three centuries until nowadays. The anthropogenic factors (river damming, meander belts cut-offs, dykes and groins etc.) influencing the development of the delta are analysed.

Key words: river-sea geo-system, Danube River, Black Sea, Danube Delta, delta evolution, sediment sink, depocentre, highstand, lowstand, Danube deep-sea fan complex.

Résumé. Le Delta du Danube fait partie du géo-système fleuve-mer le plus important de l'Europe qui est constitué par le Fleuve Danube, le Delta du Danube et la Mer Noire. Chaque terme du système est sommairement décrit et les principales caractéristiques sont données: le Fleuve Danube – longueur totale – 2860 km, le débit multi-annuel à l'apex du delta ~ 6280 m^3a^{-1}, le débit moyen de sédiments ~ 40 Mt. a^{-1}; la Mer Noire – ~420.000 km^2, le volume total de l'eau ~534,000 km^3, salinité ~17‰ à la surface et ~22‰ dans la partie profonde, des conditions anoxiques et contamination au H_2S à partir de ~180 – 200 m de profondeur d'eau jusqu'au fond. Le Delta du

Danube est décrit en détail. Les unités géomorphologique et sédimentaires du delta sont les suivantes: la plaine deltaïque exondée – plus de 5800 km^2, dont la plaine deltaïque marine – 1800 km^2, le front du delta ~ 1300 km^2 desquels la plateforme ~ 800 km^2 et le talus du front ~ 500 km^2 et le Prodelta – plus de 6000 km^2. Sur le plateau continental externe en rencontre des vallées incisées du Paléo-Danube et au large l'éventail profond du Danube. Suit une présentation détaillée de la structure et de l'évolution du delta. La formation du delta a commencée au Quaternaire quand le Danube soit arrivé à déboucher dans la Mer Noire. Pendant ce temps le fleuve a transporté vers la Mer Noire des volumes importants de sédiments qui se sont accumulés dans des dépôt-centres en fonction de la position du niveau de la mer. Les dépôt-centres ont migrés de la position extrême du highstand (haut niveau), représentée par la position actuelle du delta du Danube vers l'emplacement de lowstand (niveau bas), au dèlà de la flexure continentale, en formant l'éventail profond du Danube. Les volumes de sédiments accumulés pendant les lowstands diffèrent largement de ceux accumulés pendant les highstands: le dépôt-centre de lowstand, l'éventail profond du Danube, a mobilisé plus de 40.000 km^3 de sédiments, structurés en au moins 6 séquences qui correspondent aux principales phases de glaciation avec un taux de sédimentation compris entre 88×10^6 t/a et 302×10^6 t/a (Wong *et al*., 1997; Winguth *et al.*, 1997, 2000), tandis que la quantité de sédiments accumulée dans l'édifice actuel du Delta du Danube (dans toutes les unités comme la plaine deltaïque, le front du delta et le Prodelta) ne dépasse pas 1200 km^3. Le delta actuel est formé par une séquence de dépôts détritiques qui a comme épaisseur entre quelques dizaines et 200–300 m et qui s'est accumulée pendant le Pléistocène Supérieur (Karangatien, Surozhien, Néoeuxinien) et surtout pendant le Holocène. L'évolution holocène du delta comprends les phases suivantes: (1) le «delta bloqué» et formation de la flèche initiale Letea-Caraorman, 11.700–7500 ans av.p; (2) le Delta St. Georges I, 9000–7200 ans av.p; (3) le Delta Sulina, 7200–2000 ans av.p; (4) les deltas St. Georges II et Kilia, 2800 ans av.p – présent; (5) le delta Cosna-Sinoie, 3500–1500 ans av.p. Les datations ci-dessus sont à présent en discussion. Giosan et al., 2005, a proposé des âges plus jeunes pour les phases initiales du développement du delta (dans leur scénario le delta St. Georges I, par exemple, ne peut pas être plus ancien que ~5500–6000 ans av.p). L'analyse de l'évolution du delta dans les temps modernes commence par les descriptions des anciens Grecques et Romains, continue avec les enregistrements cartographiques des derniers deux-trois siècles jusqu'à présent. Les facteurs anthropogéniques (barrages des rivières, recoupements des méandres, digues, épis etc.) qui influencent le développement du delta sont aussi analysés.

Mots-clés: géo-système fleuve–mer, le Fleuve Danube, la Mer Noire, le Delta du Danube, l'évolution du delta, accumulation des sédiments, dépôt-centre, niveau haut (highstand), niveau bas (lowstand), l'éventail profond du Danube.

INTRODUCTION

The Danube Delta is part of the largest European river – sea geo-system consisting of the Danube River, the Danube Delta and the Black Sea. The Danube River flows into the northwestern Black Sea and forms one of the largest deltas in Europe. The Danube Delta (Fig. 1) is situated between 44°25' and 45°30' N and between 28°45' and 29°46' E, being bordered by the Bugeac Plateau to the north and by the Dobrogean Orogenic Unit to the south. The main part of the delta area (about 90%) is located in Romania, while the remaining area (especially the secondary delta of Kilia distributary) is on Ukrainian territory.

Many investigations have been carried out on the Danube Delta since the middle of the XIX^{th} century, which improved our understanding of the genesis, structure and evolution of this major European river – sea system. Particularly important are the studies of A.C. Hartley (1867), Gr. Antipa (1915, 1941), C. Brătescu (1922, 1942), G. Vâlsan (1934, 1935), I. Lepsi (1942), H. Slanar (1945), M. Pfannenstiel (1950), I.G. Petrescu (1957), V.P. Zenkovich (1956, 1960, 1962), P. Cotet (1960), M. Bleahu (1963), H. Grumazescu *et al.* (1963), E. Liteanu *et al*. (1961), E. Liteanu and A. Pricăjan (1963), A.A. Almazov *et al.* (1963), A.C. Banu (1965), A.C. Banu and L. Rudescu (1965), N. Panin (1974, 1976, 1983, 1989, 1996, 1997, 2001), N. Panin *et al.* (1983, 2004), P. Gâstescu and B. Driga (1985), C. Bondar (1972, 1989, 1992, 1993, 1994), C. Bondar *et al.* (1991, 2000), A. Stancik, S. Jovanovic *et al.* (1988), Giosan *et al.* (1997, 2005).

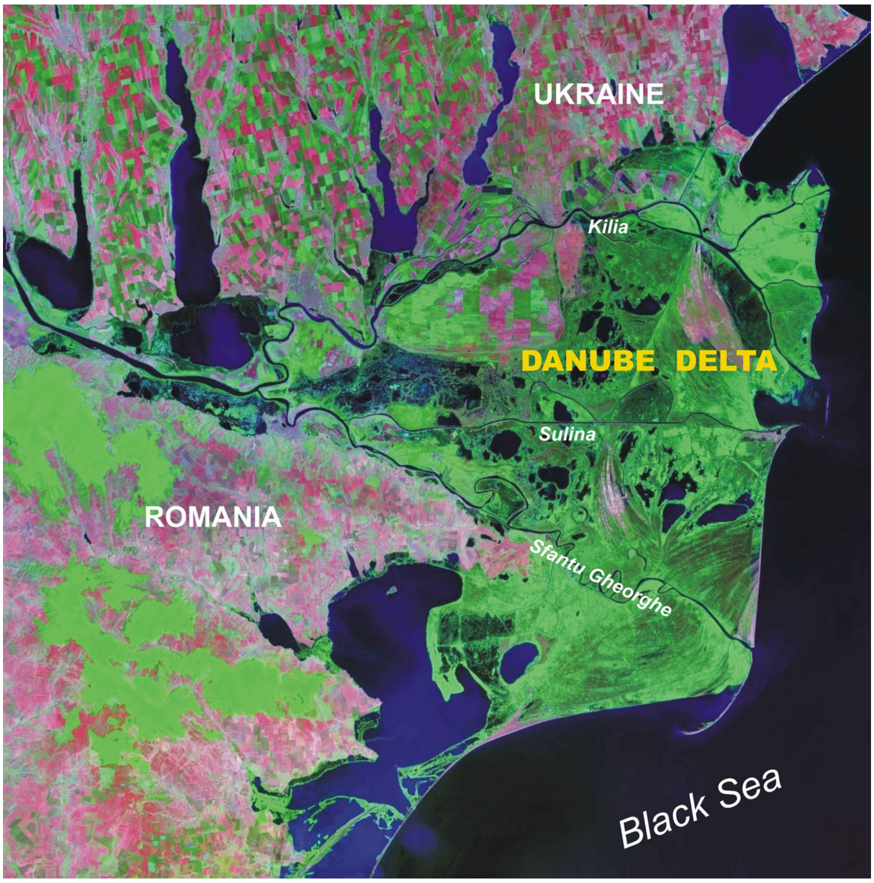

Fig. 1 – The Danube Delta – Landsat image.

THE DANUBE RIVER – DANUBE DELTA – BLACK SEA GEO-SYSTEM

The three components of the system, the River Danube, the Black Sea and the Danube Delta as river-sea interface will be shortly presented below.

DANUBE RIVER

The main hydrological and meteorological characteristics of the Danube fluvial system, which are of primary importance for delta formation and development, are listed in Table 1 (Almazov *et al*., 1963; Stançik *et al*., 1988; Bondar, 1991, 1993; Bondar and Panin, 2000).

Table 1

Main meteorological and hydrological characteristics of the Danube River (Almazov *et al*., 1963; Stançik *et al*., 1988; Bondar, 1991, 1993; Bondar and Panin, 2000)

Meteorological and hydrological characteristics	Location of station	Value	Date/period of record
Danube River total length		2,860 km	
Area of the drainage basin		817,000 km^2	
Mean annual rainfall for the Danube drainage basin		816 mm	
Mean annual evaporation for Danube drainage basin		547 mm	
Mean annual runoff for the Danube drainage basin		246 mm	

Table 1 (continued)

Average annual water discharge		6,050–6,550 $m^3.s^{-1}$	1840–1990
Maximum mean annual water discharge	Ceatal Izmail M. 43	9,420 $m^3.s^{-1}$	1941
Minimum mean annual water discharge	Ceatal Izmail M. 43	3,160 $m^3.s^{-1}$	1863
Maximum daily water discharge	Ceatal Izmail M. 43	20,940 $m^3.s^{-1}$	July 1897
Minimum daily water discharge	Ceatal Izmail M. 43	1,350 $m^3.s^{-1}$	October 1921
Annual average sediment discharge before damming at Iron Gates	Danube mouth zone	51.7 million t/a	Before 1970
Annual average sediment discharge after damming	Danube mouth zone	35–40 million t/a	After 1983
Mean multiannual annual water discharge at Danube Delta apex	Ceatal Izmail M. 43	6,283 $m^3.s^{-1}$	1840–1990
Mean annual rainfall at the delta sea-side	Sulina M.0	367.7 mm	1840-1990
Distribution (frequency) and average speed of winds at delta-front zone	Winds from N+NE+NW	43.8 %; V_m = 4.96 $m.s^{-1}$	
	From S+SE+SW	35.7 %; V_m = 3.37 $m.s^{-1}$	
	From E	7.2 %; V_m = 3.1 $m.s^{-1}$	
	From W	4.7 %; V_m = 2.5 $m.s^{-1}$	
	Calm	8.6 %	

Among the most important present-day changes in the Danube River hydrology (especially in its sediment discharge) are determined by the building of the Iron Gates dams in 1970 (Iron Gates I, at Km. 942.95 from the Black Sea) and in 1983 (Iron Gates II at Ostrovul Mare, Km. 864). Consequently, the sediment discharge decreased by ca. 30–40% (Fig. 24) and, at present, the Danube total average sediment discharge into the Black Sea is not larger than 35–40 million t/yr., out of which 4–6 million t/year sandy material (Panin, 1996; Bondar *et al.* 2000). This is the only amount of sandy sediments contributing yearly to the littoral zone sedimentary budget, which since 1970 has been strongly uncompensated. It is also obvious that the present day sediment load of the Danube originates mainly in the eroded bottom sediments of the river course. Only the suspended sediments and a very small part of the sandy material could be supplied by the tributaries and by the direct soil erosion on the river borders.

THE BLACK SEA

The Black Sea (Fig. 2) is one of the largest enclosed seas in the world: its area is about 4.2×10^5 km^2, the maximum water depth is 2.212 m, the total water volume is 534,000 km^3, and the volume of anoxic deep water contaminated with H_2S (below a depth of 150–200 m) is 423,000 km^3. The salinity of the Black Sea water is about 17‰ at the surface and 22 ‰ at the bottom. The salinity decreases to 10–12 ‰ in the neighbourhood of the Danube Delta front.

The northwestern Black Sea is characterised by a very large shallow continental shelf, representing about 25 % of the total area of the sea. This part of the sea receives the discharge of largest rivers from the Central and Eastern Europe – the Danube with a water discharge of about 200 km^3/yr. and the Ukrainian rivers (Dnieper, Southern Bug and Dniester) contributing about 66 km^3/yr. These northwestern river-sea systems correspond to low relief energy areas, and they differ completely from the high energy systems characterizing the eastern and the southern sides of the Black Sea where the shelf is very narrow and the coastline is flanked by high mountain ranges. Correspondingly, the present-day sedimentary systems are different as well.

The high energy river-sea systems that flow into zones with a very narrow continental shelf discharge their almost entire sediment supply into the deep-sea zone of the Black Sea through a network of canyons. The sedimentary systems in these areas are turbidity type with much coarse-grained sediments. The deep-sea fans related to them are located in the slope and apron zones, and even in the deep-sea zone close to the apron. Flushes of density currents and slumped sediment masses affect large areas of the deep-sea. In many cases, normal sediment units I and II (Coccolith ooze and Sapropel mud layers) are washed out, and relatively coarse-grained turbidity-born sediments lay there.

The high energy systems of the eastern and southern margins are permanently active, at highstands as well as during lowstands when they were even more active.

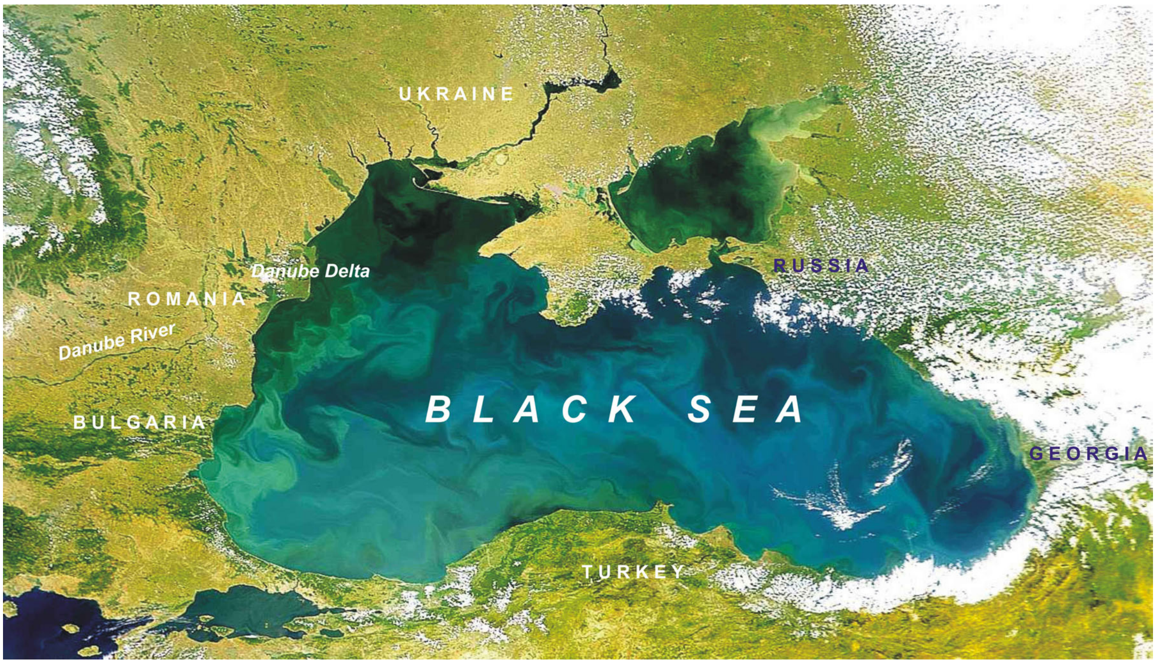

Fig. 2 – The Black Sea. Landsat image 2002.

In the low relief energy areas as in the northwestern Black Sea, the sedimentary systems are of a different type. The main sediment supplier is the Danube River. The dispersal pattern of the Danube sediment supply indicates the existence of two main areas on the continental shelf with different depositional processes (Panin *et al.*, 1998, 2002): the Danube sediment-fed internal shelf and the sediment starving, external shelf (Fig. 3).

The sediment-fed area in the neighbourhood of the Danube Delta includes the Delta Front unit and, towards off-shore, the Prodelta unit. During the Upper Quaternary, in correlation with the sea-level fluctuations of this period, very large sediment accumulations were formed in the deep-sea zone of the northwestern Black Sea, mainly on the continental slope and apron areas. These accumulations are represented by two distinct but inter-fingering fans (Fig. 3): the Danube fan fed by the River Danube during lowstands when fan accretion occurred and the Dnieper fan built up by the Ukrainian rivers Dnieper, Dniester, and Bug almost contemporarily with the first one. The Danube and Dnieper fans are nowadays inactive. The only supply in the fan area is represented by hemipelagic sediments and by extremely fine-grained sediments brought by nepheloid currents at the shelf break.

The present-day longshore sediment drift system off the Danube Delta area is directed toward the south. It is induced by the predominant winds (see Table 1), which are from the north and northeast and the most frequent wind waves recorded also from NE corresponding to the prevailing wind direction. The mean maximum heights of wind waves in front of the Danube Delta reach 7.0 m. The energy of storm waves reaches important values (to 12,242 kWh/m, recorded on February 17, 1979), but generally the energy value is about 2,000 kWh/m (Spătaru, 1984). The storm surges from N, NE, E and SE direction induce water level rises to 1.2–1.5 m. The tide in the Black Sea has an average period of 12h 25' and amplitudes of only 7–11 cm (Bondar *et al.*, 1973; Sorokin, 1982). The general relative sea-level rise in the delta-front area (at Sulina gauge) is estimated at 3.7 mm/a, of which subsidence accounts for 1.5–1.8 mm/a (Bondar, 1989).

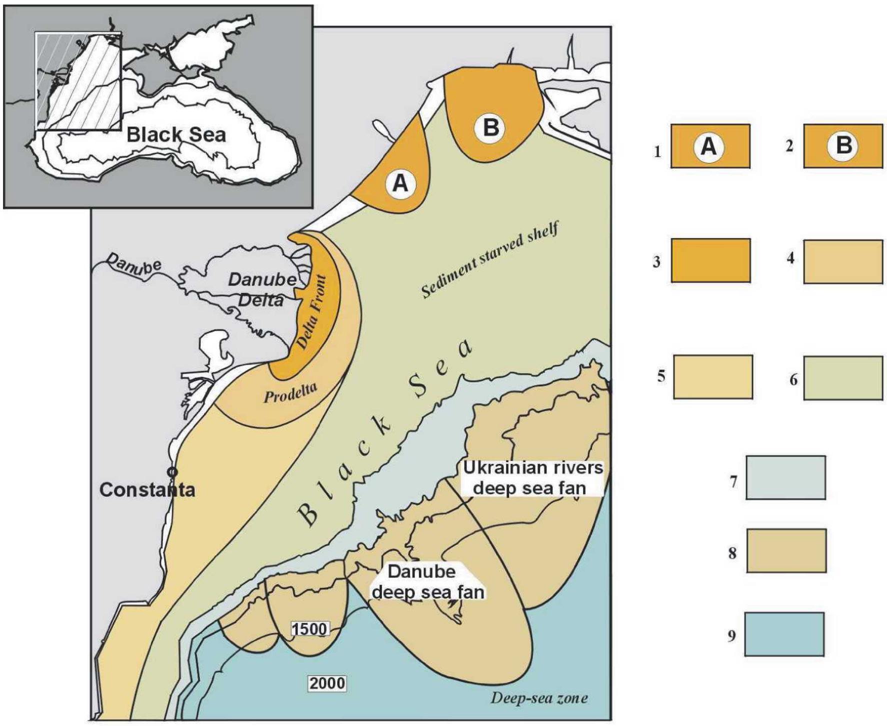

Fig. 3 – Main sedimentary environments in the northwestern Black Sea (after Panin *et al*., 1998, 2002). Legend: 1–2 – Areas under the influence of Ukrainian rivers sediment discharge (A – Dniester, and B – Dnieper); 3 – Danube Delta Front area; 4 – Danube Prodelta area; 5–6 – Western Black Sea continental shelf areas; 5 – under the influence of the Danube-borne sediment drift; 6 – sediment starved area; 7 – shelf break and uppermost continental slope zone; 8 – Deep-sea fan area; 9 – Deep-sea floor area.

It is well known that during the Quaternary the Black Sea water level changed many times, in accordance with drastic climatic changes (glaciations and inter-glaciations). The Bosphorous strait with its sill placed at about –34 m had determined a specific regional behaviour of the Black Sea when the water level was lower the sill depth as the connection with the Mediterranean Sea was interrupted and the Black Sea water level varied under the local hydrological and climatic conditions.

In the last 100 ka there were at least three highstands: during the Karangatian phase of the Black Sea (~125 – ~65 ka BP) (Fig. 4), during the Surozhian phase (~40–25 ka BP) and after the melting of Würmian icecap (the melting occurred at ~16–15 ka BP).

The low stands are documented during the Neoeuxinian (Fig. 5) and the Younger Drias, followed by a quite rapid transgression of the sea up to the present-day water level (See also Table 2).

During the Karangatian the water level was by few metres higher than the present-day one and this meant that the Mediterranean water entered the Black Sea and the water covered the lowlands such as the present-day delta territory (Fig. 4). The Surozhian high-stand brought the water level to a slightly lower mark as today, and consequently the water didn't cover the entire delta area, but it seems that at least the eastern part of the delta was submerged. The Würmian icecap melting brought again the water level to a stand that allowed the water to cover the delta territory and restored the connection of the Black and the Mediterranean seas.

These highstands are the periods when the Danube River sediment load is settled within the present-day delta territory. On the contrary, during low stands the river continued to flow down towards the Black Sea water body, to the low-stand coastal zones situated at or even beyond the shelf break. On the present-day delta territory the low stands are marked by important incisions of river valley and by strong erosions when the older deposits were washed out almost completely. The following transgressions filled up the incisions and covered the area with new blankets of sediments.

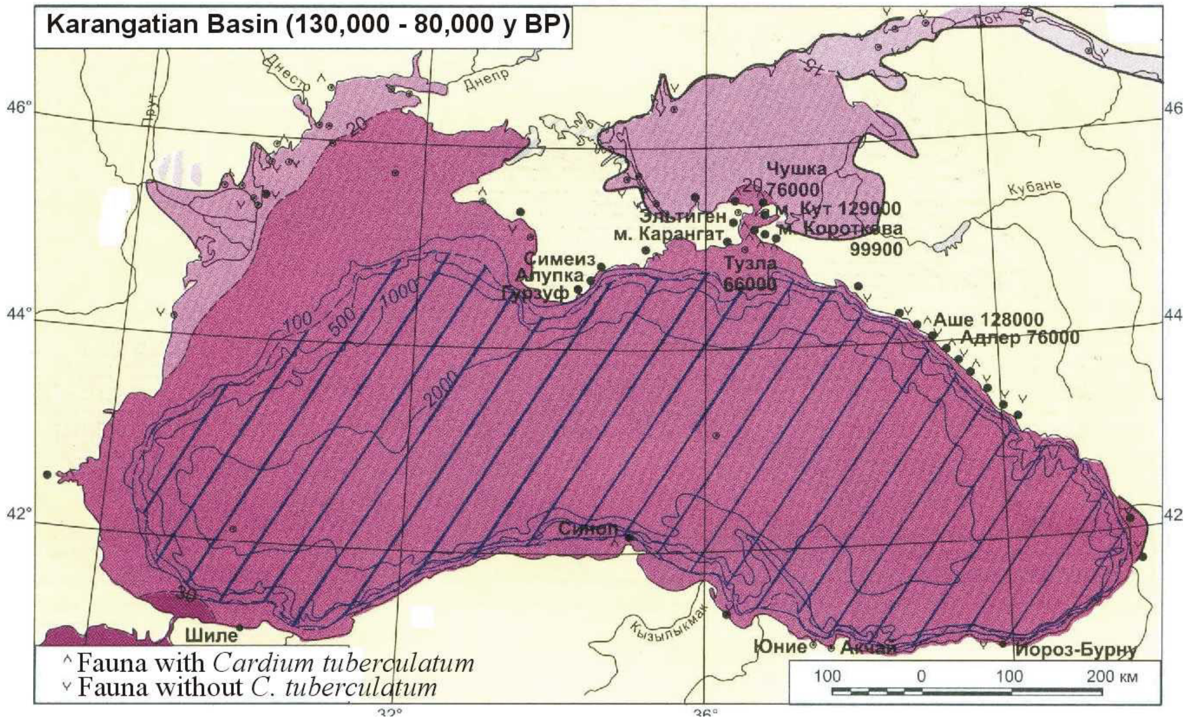

Fig. 4 – The extension of the Karangatian Basin (~ 125–65 ky BP). The water level was at ~ +8 – +12 m and the salinity between 20 and 30 ‰. (from Tchepalyga, 1984).

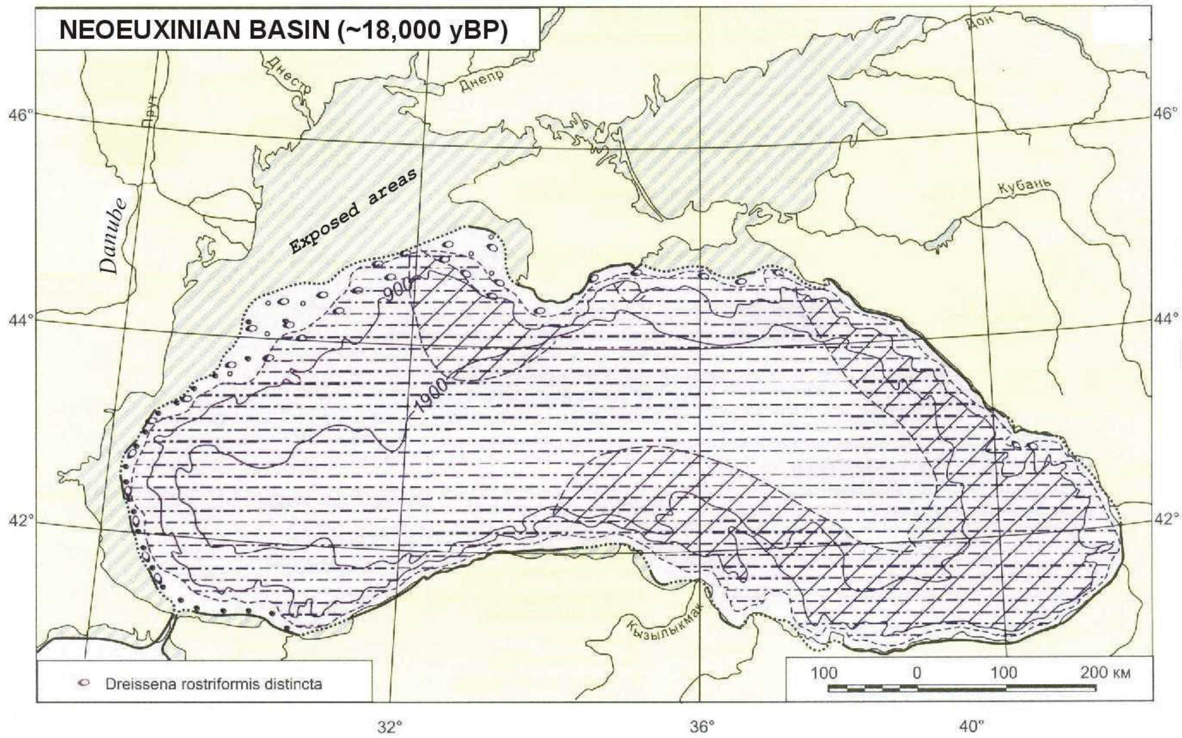

Fig. 5 – The extension of the Neoeuxinian Basin (~ 18 ky BP).
The water level was at ~ -100m (from Tchepalyga, 1984).

Table 2

Stratigraphy and correlations of Upper Quaternary phases for the shelf and bathyal zones (after Scherbakov *et al.*, 1979, with slight adaptations)
Abbreviations: M-S.ig. = Mologo-Sheksnian interglacial; K.g. = Kalininian glacial

Northern Europe				*B L A C K S E A*				
Stratigraphic subdivisions				Bathymetric zone 0–50 m		Bathymetric zone 50–200 m		
				Layers	Molluscs	Horizon	Molluscs	Diatomaea
Holocene		Upper	Subatlantic - 2,800 Sub-boreal	**Dzhemetinian**	*Divaricella divaricata; Gafrarium minimum; Pitar rudis; Cardium papillosum*	**Phaseolinus muds**	*Modiolus phaseolinus*	*Coscinodiscus radiatus; Thalassiosira excentrica Actinocyclus ehrenbergii; Cyclotella kutzingiana Cyclotella aceolata*
		Middle	- 4,800 Atlantic	**Kalamitian**	*Chione gallina; Spisula subtruncata; Mytilus galloprovincialis*	**Mytilus muds**	*Mytilus galloprovincialis; Cardium edule*	*Coscinodiscus radiatus; Thalassiosira excentrica; Asteromphalus robustus*
			- 7,800 Boreal - 9,400	**Bugazian-Viteazian**	*Cardium edule; Abra ovata; Corbula mediterranea;Mytilaster lineatus; Monodacna caspia; Dreissena polymorpha*	**6,800 ± 140**	*Mytilus galloprovincialis; Cardium edule; Monodacna caspia; Dreissena polymorpha*	*Thalassiosira excentrica; Stephanodiscus astraea Synedra buculus; Navicula palpebralis var. semiplena*
		Lower	Pre-boreal - 10,200	**Neoeuxinian**	*Monodacna caspia; Dreissena polymorpha*	**8,550 ± 130**	*Monodacna caspia; Dreissena rostriformis bugensis*	
Upper Pleistocene	Würm (Valdai)	Upper, Ostashkovian gl.	Younger Dryas Allerød Lower Dryas Bølling Gothiglacial Pomeranian Frankfurtian Brandenburgian		*Dreissena polymorpha; Viviparus fasciatus Unio sp.*	**13,500± 1,500**	*Dreissena rostriformis distincta* *Dreissena rostriformis distincta*	
				Karkinitian	*Dreissena polymorpha; Cardium edule*	**17,760 ± 200**	*Dreissena rostriformis distincta*	
			- 25,000	**Tarkhankutian**	*Cardium edule; Abra ovata; Dreissena polymorpha*	**~ 22,000** **~ 25,000**		
		Middle, M-S.ig	Paudorf Arcy Gotweig - 40,000	**Surozhian**				
		Lower, K.g.		**Regression**				
			- ~ 65,000	**Post-Karangatian**				
	Riss – Würm	Mikulinian interglacial	Eemian - ~125,000	**Karangatian**				

THE DANUBE DELTA

1. Geological setting

The Danube Delta overlaps the Pre-Dobrogean Depression, which, in its turn, lies mainly on the Scythian Platform (Fig. 6). The sequence of the Scythian Platform cover deposits, which constitute the fill material of the Pre-Dobrogean Depression, displays six sedimentation cycles: Palaeozoic calcareous–dolomitic; Lower Triassic of considerable thickness (400–2,500 m), slightly unconformable over subjacent deposits and consisting of red continental detrital deposits with interlayered volcanic rocks; Middle-Upper Triassic transgressive, marine, built up of carbonate rocks in the lower part (350–450 m limestones, and 500–600 m dolomites) and of detrital rocks (450 m) in the upper part; Jurassic transgressive marine, consisting of detrital deposits at the base (Middle Jurassic, 500–1700 m thick) and carbonate ones at the top (Upper Jurassic, 1000 m thick in the southern area); Lower Cretaceous overlying Jurassic deposits, consisting of red continental deposits of varying thickness (ca. 500 m) and Sarmatian-Pliocene overlying different Mesozoic deposits and consisting of alternating clay, sand and sandstone (200–350 m thick) (Pătrut *et al.*, 1983).

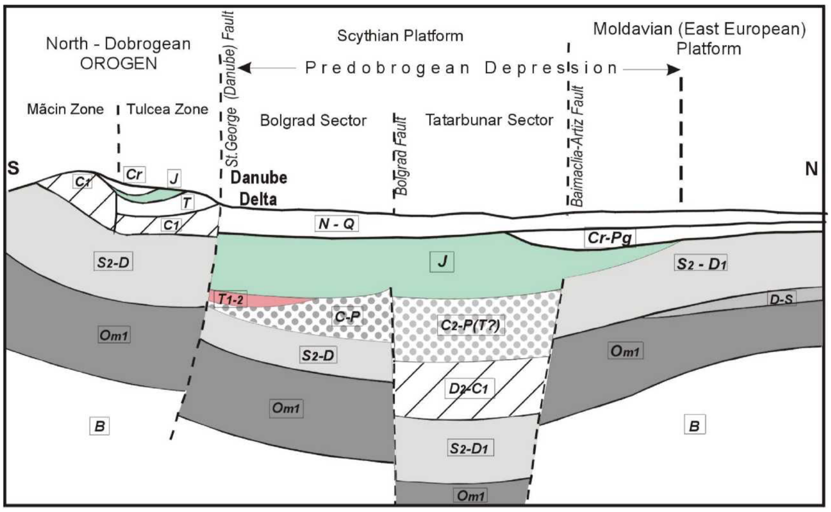

Fig. 6 – Simplified sketch of a geologic section showing the location of the Danube Delta within the major structural units of the region.
Legend: B: Basement; O: Ordovician; S: Silurian; D: Devonian; C: Carboniferous; P: Permian; T: Triasic; J: Jurassic; Cr: Cretaceous; Pg: Paleogene; N: Neogene; Q: Quaternary

The Delta is situated in an area of high structural mobility, repeatedly affected by strong subsidence and important sediment accumulation. The deltaic conditions developed here during the Quaternary, when the Danube started flowing into the Black Sea basin.

2. Geomorphological and depositional units of the Danube Delta

The Danube Delta can be divided into three major depositional systems (Panin, 1989): *the delta plain* with a total area of about 5,800 km^2, of which the marine delta plain area is 1,800 km^2; *the delta-front*, with an area of ca. 1,300 km^2, is divided into delta-front platform (800 km^2) and delta-front slope (ca. 500 km^2) and extends offshore to a water depth of 30–40 m; *the prodelta* lies offshore, at the base of the delta-front slope to a depth of 50–60 m, covers an area over 6,000 km^2 (Fig. 7). To the proximal and Holocene depositional system should be added *the Danube deep-sea fan system* that occurs off Romania, Bulgaria and Ukraine in the northwestern Black Sea and reaches from a depth of several hundred meters to the abyssal plain (over 2,200 m).

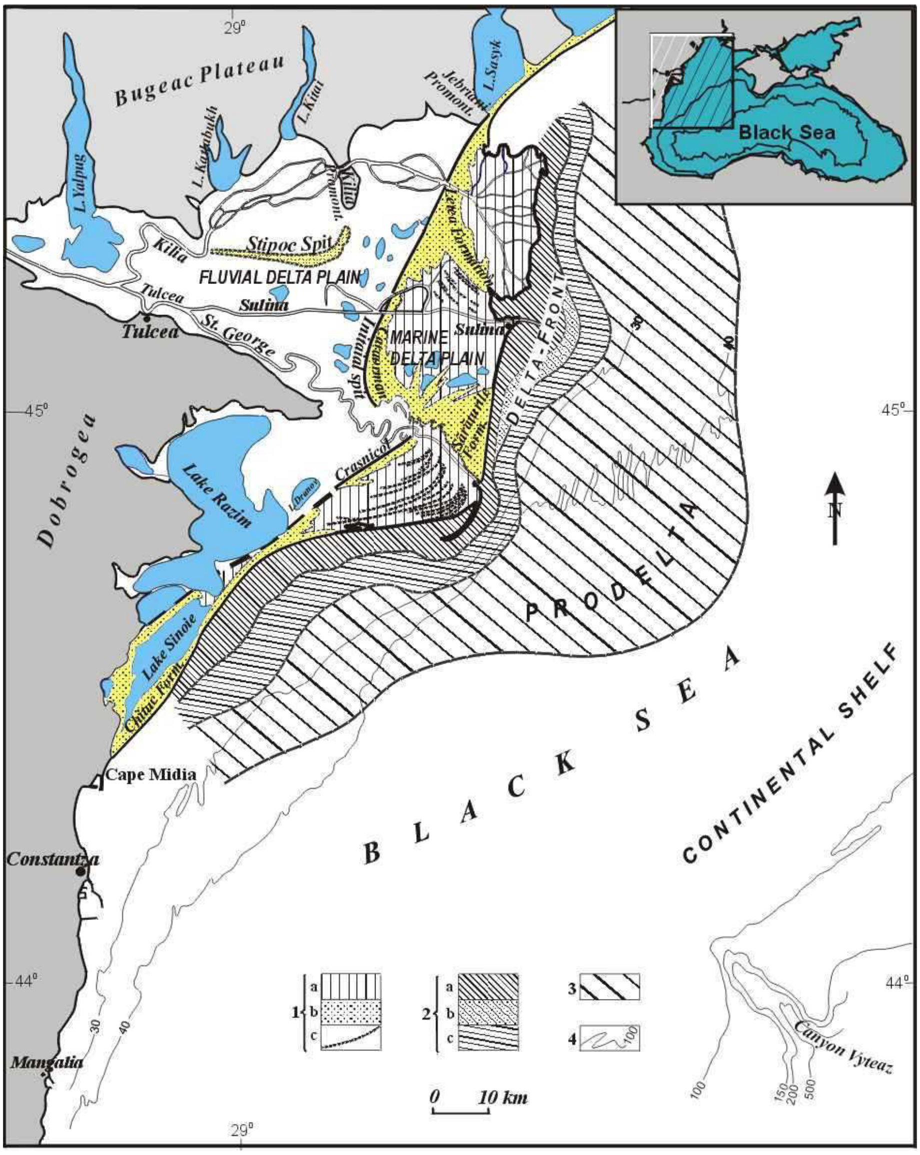

Fig. 7 – The Danube Delta major morphological and depositional units (after Panin, 1989).

1: delta plain; fluvial delta plain (1a); "marine" delta plain (1b); fossil and modern beach-ridges and littoral accumulative formations built up by juxtaposition of beach ridges (1c); 2: delta-front; delta front platform (2a); relics of the "Sulina Delta" and its delta-front (2b); delta front slope (2c); 3: Danube prodelta; 4: depth contour lines in meters.

The delta plain starts from the first bifurcation of the Danube, called Ceatal Izmail (the apex of the delta); here the river divides into two distributaries: a northern one, the Chilia (Kilia), and a southern one, the Tulcea. The Tulcea distributary, 17 km farther downstream, again divides into other two branches: Sulina and Sfântu Gheorghe (St. George). The delta plain is roughly triangular in shape, with a strong southward asymmetry. The average altitude of the Delta relief is about 0.52 m with a mean inclination of ca. 0.0428%. The present-day morphology of the Delta highlights 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 to the east. With regards to the hypsometry, the delta plain contains different elements of positive and negative relief. Among the positive relief are listed continental relics (e.g. Stipoc remnants) and promontories (e.g. Kilia) entering the delta territory, fluvial sub-aerial levees, old and present-day marine beach ridges and littoral accumulative formations formed by the juxtaposition of numerous ridges (among these formations the most important are: *Jibrieni* – on Ukraine territory, *Letea, Caraorman*, Sărăturile, *Perisor, Chituc* etc.), lacustrian spits (*e.g.* Stipoc spit) (Fig. 8). Negative relief areas are covered by water and form the Delta hydrographic network.

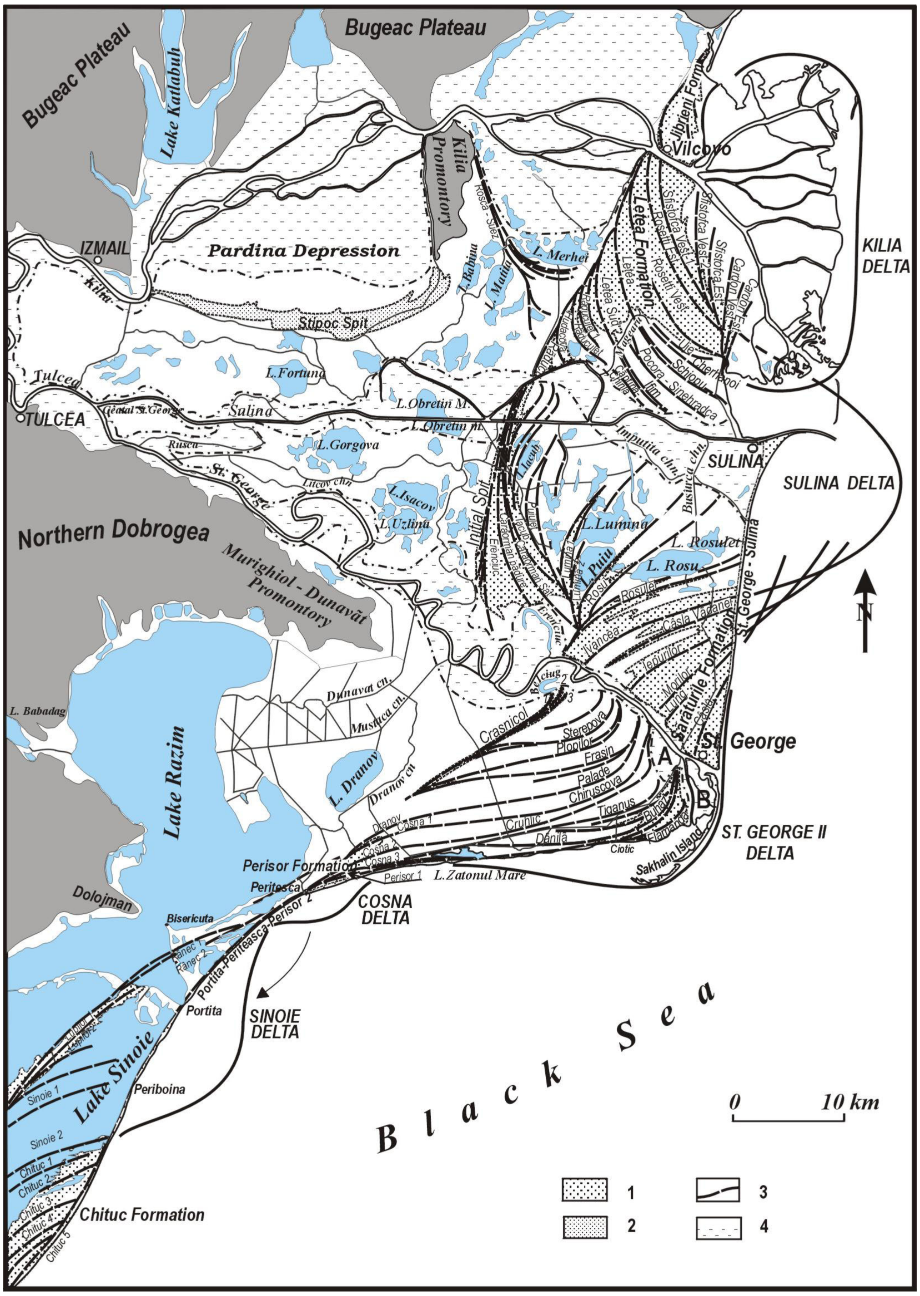

Fig. 8 – The Danube Delta geomorphologic-sedimentologic structure (after Panin, 1989).
The map outlines the main sets of beach ridges and the phases of delta development during the Holocene. Legend: 1: marine beach ridges; 2: lacustrine spit; 3: directions of main beach ridges and beach ridge sets; 4: river meandering zone.

About 54.5 % of the Danube Delta plain consists of areas having altitudes between 0 and 1 m above the Black Sea – Sulina reference system, and 18 % with altitudes between 1 and 2 m. Among the positive relief with a higher altitude are: Kilia Promontory – an extension of the Bugeac loess plateau into the delta territory, Stipoc lacustrine spit and the old Littoral Letea and Caraorman Accumulative Formations. The highest altitudes can be found in the dunes of the cited formations (+12.4 m in the Letea Formation, and +7 m in the Caraorman Formation).

About 20.5 % of the Danube Delta – plain represents areas with negative relief, i.e. those with an average level below that of the Black Sea. In these areas, the water depths in different lacustrine depressions do not exceed 3 m. Exceptions are the Belciug and the Erenciuc abandoned meander bends, where the maximum depth is 7 m, and respectively ~ 4–5 m, and different sections with limited extension along the main Danube Delta distributaries where depths reach to 35 m (especially in concave sectors of meander belts).

Hydrographical Network

The following information gives only a general overview of the delta hydrographical "skeleton" and a simplified idea about the importance of Danube water and sediment input into the western Black Sea.

Main distributaries of the Danube Delta

The *Kilia distributary*, the largest of the delta system, is 117 km long and forms the border between Ukraine and Romania. Along the Kilia course there are two depressions where the distributary becomes braided: *Pardina Depression* and *Babina-Cerneovca Depression*, east of Kilia loess promontory. At its mouth Kilia forms a secondary lobate delta with numerous distributaries (the main ones are the Oceacov flowing to NE, and Stary Stambul oriented towards S-SE); this secondary delta has an area of 24,400 ha and lies within Ukrainian territory.

Forking to the right at Ceatal Izmail (Mile 43), the *Tulcea distributary* stretches further to the east 17 km to the second main hydrographic knot Ceatal Sfântu Gheorghe (St. George) at Mile 33.84 (km 62.2). Here, the Tulcea branch divides into two main distributaries: Sulina on the left and Sfântu Gheorghe (St. George) on the right.

From the Ceatal St. George, the Sulina distributary stretches eastward 71.7 km (present-day length, including the 8 km of dykes at the mouth of the arm) towards the Black Sea. The present branch physiography of the Sulina distributary results from a large cut-off programme carried out during the 1868–1902 period by the European Danube Commission. This project shortened the branch by 24% (83.8 km before the cut-offs, and now only 63.7 km), and induced the deepening of the river channel in time, from less than 2.5 m in 1857 to at least 9.5 m in 1959. The shortening (steeper slope) and deepening of the river channel radically changed the hydrological regime of the Delta by increasing the water discharge of the Sulina distributary from 7–9 % to about 19 % of total Danube discharge.

The *St. George distributary* starts at the hydrographic knot at Ceatal Sfântu Gheorghe (km 108.8 from the sea). A major fault system (called St. George fracture zone), which northward borders the North Dobrogean orogenic unit, controls the general orientation of the distributary. The North Dobrogean unit represents a hard to erode "wall" that influences the river physiography, and results in the course of the St.George arm subdividing into three sections (Panin, 1976): the Dobrogean section of limited meandering (between km 104 and km 90), the free meandering segment of the St. George arm (between km 90, where the Dobrogean unit ends, and km 22) with a succession of 6 meander loops, and the downstream section of limited meandering (between km 22 and km 0).

The St. George meander loops have been rectified in 1984–1988 period; these cut-offs lead to a shortening of the distributary by about 31 km and, consequently, increased the free water surface slope and water flow velocity. As a result, the St. George distributary water and sediment discharges have also slowly increased.

At its mouth, the St. George distributary forms a small secondary delta (Fig. 16) with two secondary branches, which fork at km 5: the prolongation of the main St.George channel (also called in historical documents *Kedrilles*); the *Olinca* branch on the right. This latter branch bifurcates to two small branches: the *Seredne* on the left, about 3.5 km long, and the *Turetzkii* (*or Gârla Turcului*) on the right, 4.5 km in length.

Danube water discharge distribution among the main delta branches

The Danube River water discharge distribution among the main delta branches varied in time mainly as a result of anthropic intervention: cut-off projects, damming, canal construction. Table 3 and Fig. 9 show the approximate variation of the water discharge distribution in the last century (Bondar and Panin, 2000). The tendency of Kilia distributary discharge to decrease is continuing at present, especially after the cut-off of St.George distributary meander loops discussed above.

Table 3

Danube River water discharge distribution (after Bondar and Panin, 2000)

Danube distributaries	Distribution of Danube water discharge among the delta distributaries (%)					
	1857	1902	1921	1960	1990	2003
Kilia distributary		72.0–73.0		62.0–63.0	57.0–58.0	~ 52
Tulcea		~ 28.0		~ 38.0	~ 42.0	~48
Sulina	7.4	9.0	12		18.0–19.0	~ 20
St. George		~ 19.0	~ 18.0		~ 23.0	~ 28

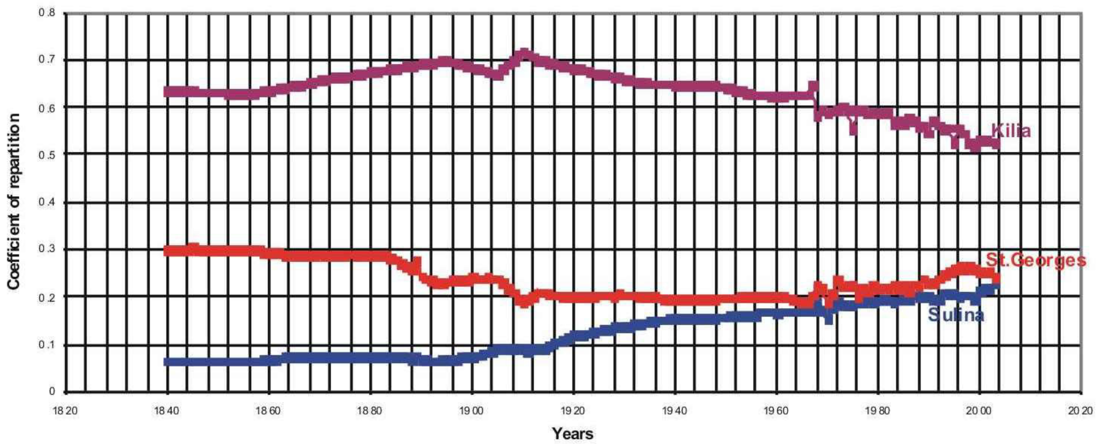

Fig. 9 – Changes of water discharge repartition among the Danube Delta main distributaries in the 1840–2003 period.

Interdistributary depressions and related network of lakes and channels

The interdistributary depressions of the Danube Delta (*Kilia-Sulina* – 160,700 ha, *Sulina-St. George* – 101,850 ha and *St. George-Razim* unit or *Dranov* Depression – 73,325 ha) are large areas covered by water and vegetation, playing the role of buffer and filtering reservoirs. They store water during the high water periods of the Danube River and release water when the level is low. The residence time of the water in these depressions are 3–4 months.

The *Razim-Sinoie lagoon complex* is located in the southernmost part of the delta, at the site of an old marine gulf, called Halmyris by the ancient Greeks, and is isolated from the sea by beach barriers. The system comprises a series of lagoons and lakes the more important of which are *Razim* (39,160 ha), *Golovitza* (9,160 ha), *Zmeica* (4,960 ha) and *Sinoie* (17,580 ha). In certain zones, the bottom of these lagoons is to –3 m below the Sulina-Black Sea reference system.

Network of main and secondary channels

To the main hydrographic units described above one should add the dense network of natural main and secondary channels as well as artificially dug canals which allow a permanent water and sediment inflow into the interdistributary depressions.

Ialpug-Catlabug-Kitaï lacustrine unit

The *Ialpug-Catlabug-Kitaï* lacustrine unit is located in Ukraine; it does not represent a true delta unit but, by its genesis, is nevertheless closely related to the delta development. The lakes of this unit (Fig. 6), *Ialpug* (14,000 ha, maximum water depth ~ 10 m), *Cogurlui* (8,000 ha, water depth of 0.8 m), *Catlabug* (6,400 ha, water depth of 1.5 m), *Kitaï* (5,000 ha, water depth of 5.0 m) and *Sofianaï* (600 ha, water depth of 1.0 m), represent submerged valleys of Danube River tributaries separated from the river by spits and fluvial levees. At present, most of the lakes are connected by channels to the Kilia distributary.

To the units above one can add the polders and dammed enclosures built for different economic uses (agriculture, fish farming, reed exploitation) and their associated network of water draining canals and specific hydrology.

3. The evolution of the Danube Delta during the last Upper Pleistocene and Holocene highstand

The Danube Delta is formed by a sequence of deposits of tens to over 200 meters thick (Liteanu *et al.* 1961; Liteanu and Pricăjan, 1962; Spânoche and Panin, 1997). Important Quaternary changes of sea level have strongly influenced Danube Delta evolution. Würmian regressions, and especially that of the Neoeuxinian stage of the Black Sea (about 20,000–18,000 years BP), when the sea level lowered to about -100 – -120 m and induced intense erosion of earlier delta deposits. Probably considerable sections of older Quaternary deposits were thus removed. One can still recognise deposits assigned to the Karangatian and Surozhian stages (Würmian interstadial – Table 2), located eastward of the Letea – Ceamurlia – Caraorman line and preserved behind some erosion relics of the predeltaic relief.

The present-day Danube Delta edifice was therefore formed mainly during the Upper Pleistocene (Karangatian, Surozhian, Neoeuxinian) and especially in the Holocene (Panin, 1989). The present geomorphology of the delta plain records the interaction of the river and sea during the Holocene.

The main phases of the Danube Delta evolution during the Holocene have been indicated and dated by the corroboration of geomorphologic, structural, textural, geochemical, mineralogical, and faunal analyses and in large part by ^{14}C dating (Panin *et al.*, 1983; Panin, 1974, 1983, 1989, 1996, 1997) as follows: (1) the "blocked Danube Delta" and formation of the Letea-Caraorman initial spit, 11,700–7,500 yr. BP; (2) the St. George I Delta, 9,000–7,200 years BP; (3) the Sulina Delta, 7,200–2,000 years BP; (4) the St. George II and Kilia Deltas, 2,800 years BP – present; (5) the Cosna-Sinoie Delta, 3,500-1,500 years BP (Fig. 8) (Table 4, Fig. 10).

Table 4

Danube Delta lobes chronology

Nr.	Main lobe	Relative dating	Absolute dating years BP	Number of channels	Number of mouths	Progradation speed
1a	**Initial Spit**	*1*	*11,700–7,200*	*1*	*1*	
1b	*Blocked Delta*	*1*	*11,700–7,200*	*1*	*1*	
2	*St.George I Delta*	*2*	*~9,000–7,200*	*1*	*1*	*3–5 m/yr*
3	*Sulina*	*3*	*~7,200–2,000*	*1*	*1*	*3–5 m/yr*
3a	*Sulina Delta – phase 1*	*3a*	*7,200*	*1*	*1*	*6–9 m/yr*
3b	*Sulina Delta – phase 2*	*3b*	*~ 6,000*	*3*	*3*	
3c	*Sulina Delta – phase 3*	*3c*	*~ 4,900*	*5*	*5*	
3d	*Sulina Delta – phase 4*	*3d*	*~ 2,800–2,000*	*2*	*2*	
4	**Cosna – Sinoie Delta**		*3,500–1,500*	*1*	*1*	*?*
5a	*Kilia Delta*	*4*	*2,500 – present*	*1 to 19*	*1 to 19*	*8–10 m/yr*
5b	*St. George II Delta*	*4*	*~ 2,800 – present*	*1 to 3*	*1 to 3*	*8–9 m/yr*

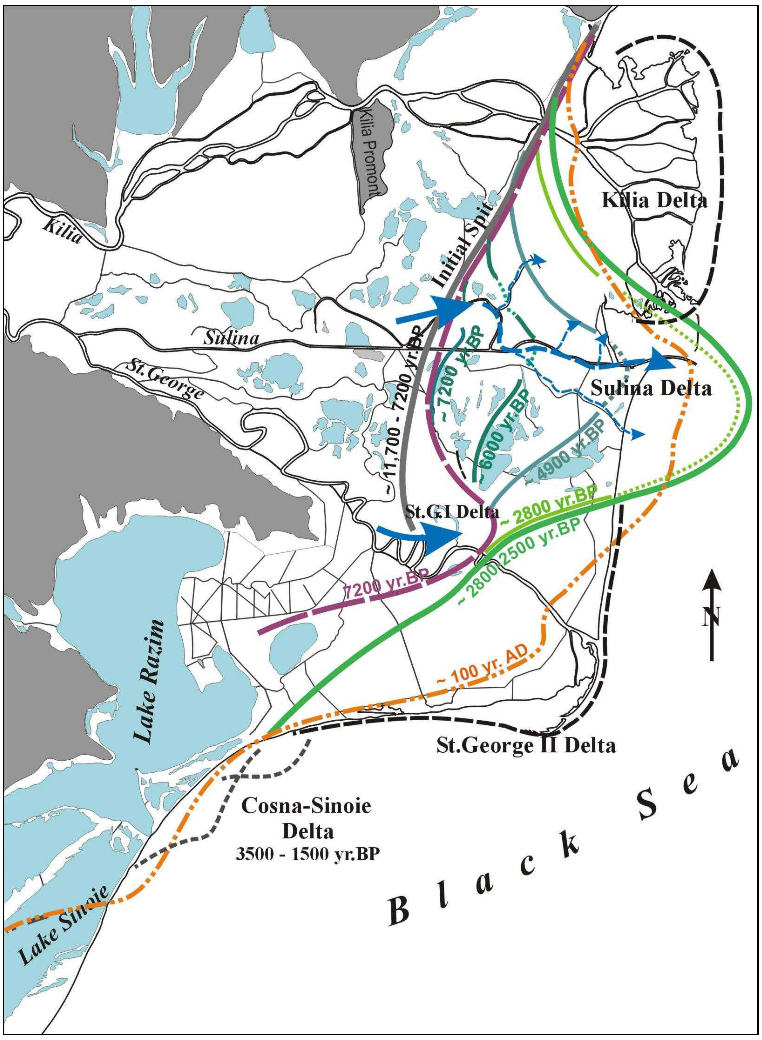

Fig. 10 – The Danube Delta evolution during the Holocene
and correspondent coastline position changes (after Panin, 1997)
1: initial spit 11.7–7.5 K yr.BP; 2: St. George I Delta 9.0–7.2 Kyr.BP; 3: Sulina Delta 7.2–2.0 K yr.BP; 4: Coastline position at ~ 100 yr AD; 5: St.George II Delta and Kilia Delta 2.8 K yr.BP – Present; 6: Cosna-Sinoie Delta 3.5–1.5 K yr.BP.

These ages are presently under discussion. Giosan *et al*., 2005, has proposed younger ages for the initial stages of delta development (for exemple in their hypothesis, the St. George I phase could not be much older than ~5,500–6,000 yr.BP. A new atempt of age determining is ongoing and, probably, it will give a new understanding of the Danube Delta development timing during the Holocene. Anyway, in the present paper we shall use the ^{14}C dating of 1983 as the succession of phases doesn't change even if their age will be somehow different.

4. 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 present-day beach-ridges which generated by juxtaposition the littoral accumulative formations *Caraorman, Letea, Sărăturile, Istria, Chituc, Jebriani, Perisor* etc. (enumeration in the genesis order) (Figs. 8, 11).

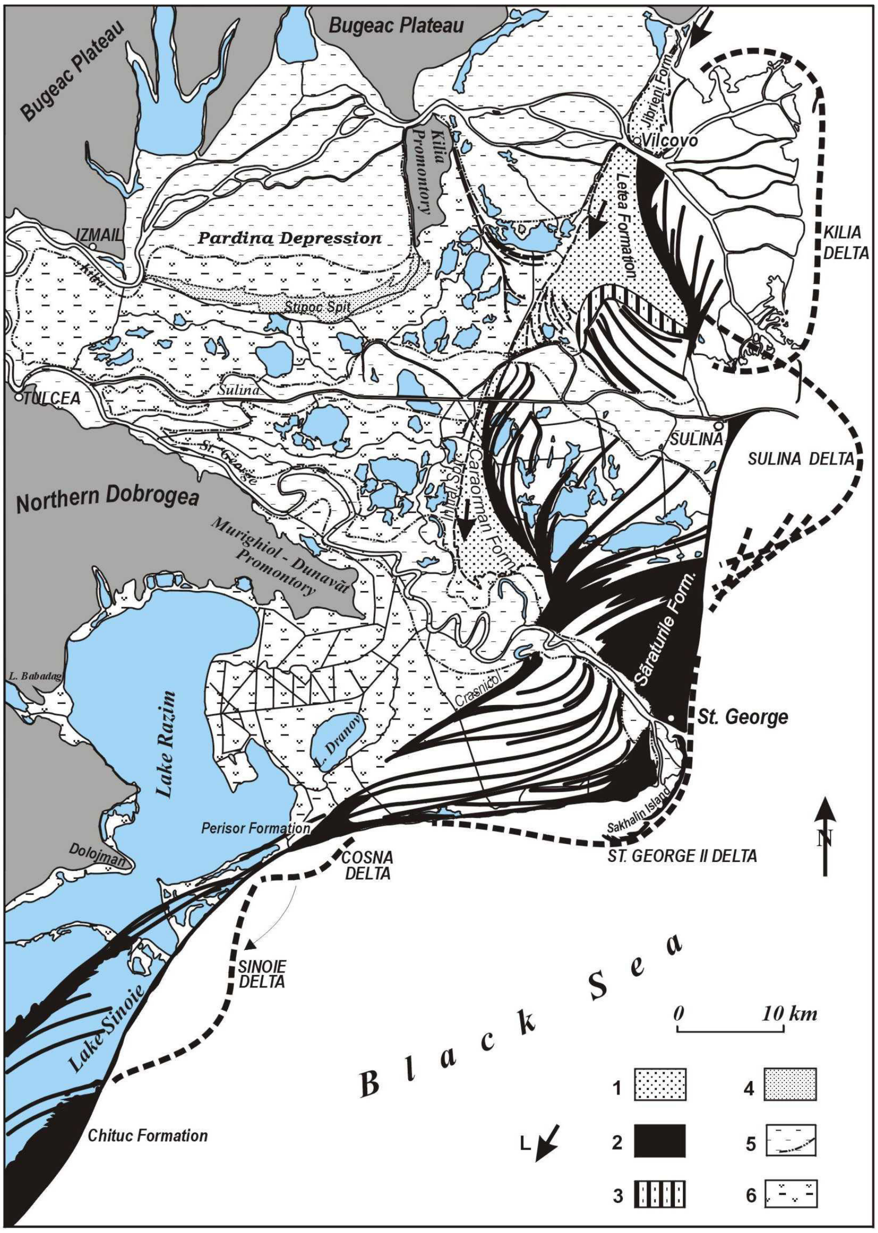

Fig. 11 – Areal distribution of the main types of deposits within the Danube Delta territory (after Panin 1989). 1: marine littoral deposits of type "a", formed by the littoral drift from the rivers Dniester and Dnieper mouths; 2: marine littoral deposits of type "b", of Danubian origin; 3: deposits of littoral diffusion, formed by mixing of "a" and "b" types; 4: lacustrine littoral deposits; 5: fluvial meander belt deposits; 6: inter-distributary depression deposits; L: direction of the longshore sediment drift.

There are two basic types of littoral deposits:

– 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"** (Fig. 10). 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”**)(Fig. 10), 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: the subtype **“b_{dif}”** of littoral diffusion, marked by mixing with type **“a”** material and the 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 lacustrine littoral deposits*** formed in the *“Danube gulf”* behind the initial spit, more precisely in the fluvial delta plain. These deposits constitute the lacustrine spits *Stipoc* and *Rosca-Suez* (Figs. 8, 11). 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 lacustrine 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.

* ***Lœss like 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 Kilia Promontory, which is the southward prolongation of the Bugeac Plateau (Figs. 7, 8, 11).

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-Răducu*.

5. The Danube Delta evolution phases (description)

“Blocked Danube Delta”

Radiocarbon dating performed in the seventies (Panin *et al*., 1983) showed that at 12–11 k.yr. BP the level of the Black Sea had almost reached the present elevation and even exceeded it by a few meters. Even if these dates are presently under discussion we have to admit that there was a moment when the present area of the Danube Delta was transformed into a large marine bay – the *Danube Gulf* (Fig. 12). All tributary valleys coming from the north, from the Bugeac Plateau (*Kitai, Catlabug, Ialpug, Kahul*) had been partially invaded by the sea and then transformed into lakes (lagoons, local name limans) by closing them off with spits at their mouths.

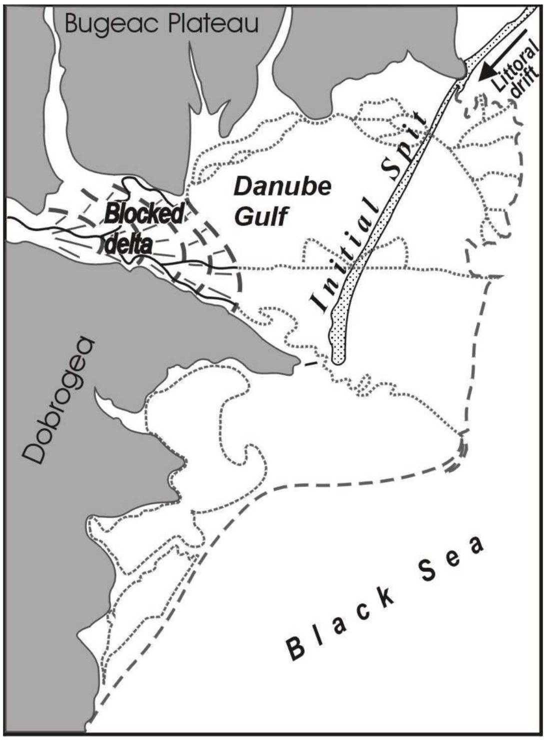

Fig. 12 – The "Blocked Danube Delta" phase and the "Initial Spit" (after Panin, 1996).

At the mouth of the Danube Gulf, between the *Jebriani promontory* to the north and *Murighiol-Dunavăt promontory* of Dobrogea to the south, a spit was formed by the sediment littoral drift fed by Ukrainian rivers (Dniester, Dnieper and Southern Bug). The sediments of Ukrainian river origin are assigned to the type **"a"** (Fig. 10). The spit was named, in accordance with other predecessors, the *"Jebriani – Letea – Caraorman Initial Spit"* It closed almost entirely the access into the Danube Gulf and represented the limit between the two main units of the Danube deltaic plain: the fluvial delta plain westward the spit and the marine delta plain eastward of it (Fig. 7). During the existence of the Danube Gulf, almost the entire solid discharge of the Danube River was deposited inside the gulf sheltered by the initial spit, and formed a deltaic body called the *"Blocked Danube Delta"* phase (Fig. 12).

"Saint George I Delta"

A pass existed between the southern end of the *Initial Spit* and the Murighiol-Dunavăt Promontory through which the first Danube distributary, *Paleo–St. George*, flowed into the sea. It is here that the first delta of the Danube was formed, the *"St. George I Delta"* (Fig. 10) during a period of about 2,000 years (9,000–7,200 yr. BP).

At present, only the northern part of this delta can be recognised. This part is represented by the *Littoral Accumulative Caraorman Formation*, built by juxtaposition of an impressive number of paleo-beach ridges, formed exclusively of sandy sediments from Ukrainian rivers (type **"a"** deposits) transported along the seashore by the littoral drift. Four phases of St. George I Delta development are suggested (Fig. 13), starting with the *Initial Spit* as base for the further development, followed by the *Erenciuc*, the *Caraorman-pădure* and *Caraorman-sat phases*. Each of these phases is defined by a set of fossil beach ridges. Finally, the overall progradation of this delta was about 10 km during the period of about two thousand years.

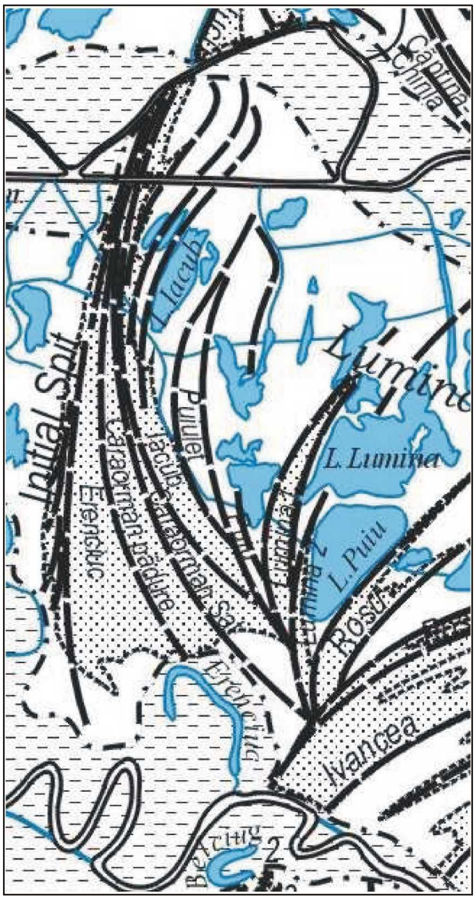

Fig. 13 – The structure of the northern wing of the “Saint George I Delta” (after Panin, 1989).

Only in the extreme eastern and youngest part of the *Caraorman-sat set* can one identify a few beach ridges formed of different origin sediments. This is the first, still reduced part of Danube alluvial load introduced into the littoral area by the second branch of the river, the *Sulina distributary*; it marks the transition to the next phase (the “Sulina Delta”) of Danube Delta development.

The Paleo-St. George, Paleo-Sulina and Paleo-Kilia distributaries evolution

It is difficult to confirm when and how the bifurcations of the Danube River at Ceatal Izmail and Ceatal St.George formed. The forking into Paleo-Tulcea and Paleo-Kilia at Ceatal Izmail (Mile 44 upstream from the present Sulina distributary mouth) may have occurred when the front of the Danube “Blocked Delta” reached this area.

The southern branch, the Paleo-Tulcea joined land of northern Dobrogea: the first impingement point was at Tulcea, then at about 7 km downstream the Nufăru (Preslav or Periaslavetz) impingement, followed by Carasuhat and Mahmudia ones (Panin, 1976). After the contact at Preslav, the Paleo-Tulcea branch divided into Paleo-St.George and Paleo-Sulina distributaries. However, as a result of Coriolis force, the Paleo-St.George branch became the most important and active distributary for a long period; its flow (as described above) was responsible for the formation of the first Danube Delta, the St. George I Delta.

During the “Blocked Delta” phase, the Paleo-Kilia distributary appears to have been less important (smaller discharge) than the Paleo-Tulcea branch. At a certain distance, the Kilia distributary flowed northward, against the Bugeac Plateau in the Izmail area, where it changed direction toward the east, probably along the present course of Sontea channel and joined the Paleo-Sulina distributary at Mile 25 – Mile 24 area (on the so-called Old Danube) (Panin, 1976, 1997).

During the phase of maximum progradation of the St. George I Delta, the *paleo-distributary St. George* formed meanders of 10–14 Km wave-length, amplitudes of 5–7 Km and curvature indices r_m/w exceeding 2.0 (Panin, 1976) (Fig. 14). Then the excessive length of the distributary channel and associated low relief energy led to a partial filling of the *Paleo-St.George* which lost the major role in the hydrographic system of the delta during the following period. A new distributary formed – the Paleo-Sulina branch (Figs. 12, 14). The initial bifurcation point of the Paleo-Tulcea branch into Paleo-St.George and Paleo-Sulina distributaries was located immediately after the impingement against the “Dobrogean wall” at Preslav (Nufăru) (Km.104 upstream the mouth zone of St. George distributary). The Paleo-Sulina distributary meander system (composed of Maliuc and “Big M” meander bends), had wavelength and amplitudes very similar to those of the *Paleo-St.George* branch (λ = 14–16 Km; α = 5–7 Km; r_m/w = 2.67–2.78) (Panin, 1976).

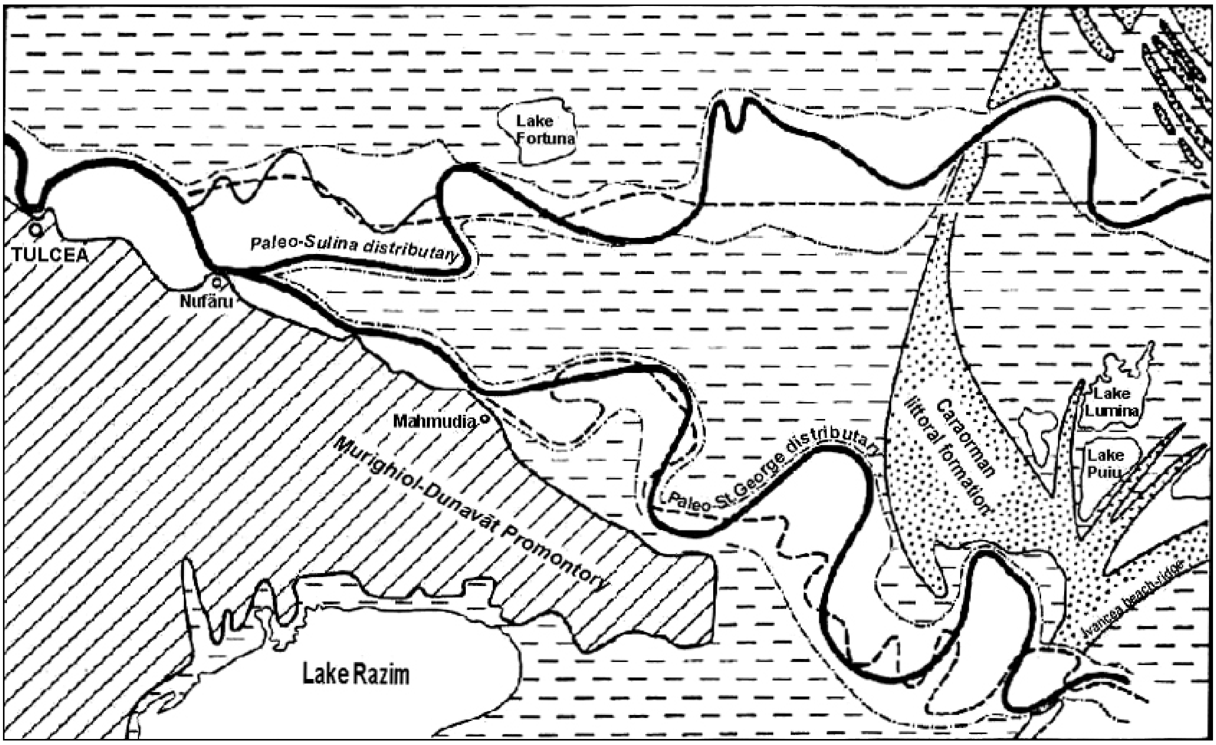

Fig. 14 – Hypothetical courses of Paleo-St. George and Paleo-Sulina distributaries (after Panin, 1976).

At about 7,200 yr. BP the *Paleo-Sulina* distributary reached and penetrated the *Initial Spit*. Since that time it gradually became the main branch of the entire Danube Delta hydrographic system for almost 5,000 yr. and began forming its own delta, Sulina Delta (the next subchapter).

The subsequent increase of water and sediment discharges of the Sulina distributary system determined a rapid progradation of the Sulina Delta and it became lobated with three and then five distributaries. The maximum progradation of the Sulina Delta into the sea (its front surpassed by 10–15 km the present-day shore line), coincides with the Phanagorian regression when the sea level was at -2 – -4 m mark.

By the end of Phanagorian regression, when the sea level lowered by few meters (-2 ÷ -4 m) and the relief energy increased, the *intial St. George* distributary meander loops system was drained and a new generation of meander bands characterised 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 (Panin, 1976) (Fig. 14).

The Kilia distributary may have derived its present course at 3,000–3,500 years BP. The distributary probably found a way out to the sea through the *Initial Spit* at almost the same time. Since then, the Kilia distributary began introducing into the littoral area an increasing quantity of sediment and building up its own depocentre, the Kilia Delta.

The next phase, which took place during the following 2,800–2,000 years, coincides with present sea level rise. By then the Sulina distributary was partly clogged, and the Sulina Delta began to undergo gradual erosion. At the same time, the new Kilia distributary in the north and St. George in the south prevailed and built up their own depocentres, the Kilia Delta and the St. George II Delta, respectively.

"Sulina Delta"

The development of the Sulina Delta took place from 7,200 to 2,000 yr. BP (Panin *et al.*, 1983). Initially, its evolution was slow and its shape was controlled by waves and littoral drift. The progressive increase of sediment discharge from the Sulina distributary system caused a rapid progradation of the Sulina Delta that over time became lobate with three and then five distributaries. The maximum progradation of the Sulina Delta into the sea (Fig. 9) (its front was 10–15 km offshore of the present shore line), coincides with the Phanagorian regression when the sea level was at -2 to -4 m elevation.

The Sulina Delta's northern flank, represented by the Letea Accumulative Formation, was formed of a very large number of fossil beach ridges and sets of beach ridges. Most of these are composed of type **"a"** sandy sediments, with only a small contribution of Danube sediments brought by Sulina Delta secondary distributaries flowing on the left side of the main Paleo-Sulina branch. The southern flank of the Sulina Delta is composed by fossil beach ridges formed exclusively of Danube-borne material (type **"b"**) (Fig. 11). Some of these beach ridges are attached to the Caraorman Littoral Formation mentioned earlier. Thus, to describe the evolution phases of Sulina Delta it's necessary to present the structure of the two main Littoral Accumulative Formations, the Letea and Caraorman, representing the northern and the southern parts of the delta, respectively (Panin, 1989, 1996, 1997).

Structure of the Northern Part of the Sulina Delta (Letea Littoral Accumulative Formation)

The Letea Formation is formed by the following fossil beach ridges sets (Fig. 15), which at the same time, represent important phases of the Sulina Delta evolution (Figs. 8, 10). The beginning of progradation is represented by *Răducu, Hudacova, Răduculet I, Răduculet II and Răduculet III* phases of the Sulina Delta development. All the beach ridges constituting afore mentioned sets comprise type "a" sandy sediments. These are followed by the *Letea-South Megaset* and *Letea-North Megaset* which represent quick progradation phases of the Sulina Delta involving important supply of type **"a"** sands. Subsequently the *Rosetti West* and *Rosetti East Magasets* correspond to the maximum development of the Sulina Delta, when its front extended the present delta shoreline by more than 10 km. During the first five or six phases of development, three secondary distributaries flowed on the left side of the main Sulina branch: *Magearu, Movilă* and *Sinehradca*, and one on its right side, the *Imputita*. These distributaries supplied Danube-borne fine-grained sandy material (type **"b"**) that forms a number of beach ridges, including the *Căpătână-Chirilă, Ifim, Pocora-Sinehradca, Schiopu, Cherhanoi, Uje* and *Sulina* (Fig. 15).

Following the *East Rosetti* phase, the Sulina Delta began to undergo erosion and, in the north, the initial development of the Kilia Delta began (Sfistofca West, Sfistofca East, Cardon West, Cardon East sets) (Fig. 15).

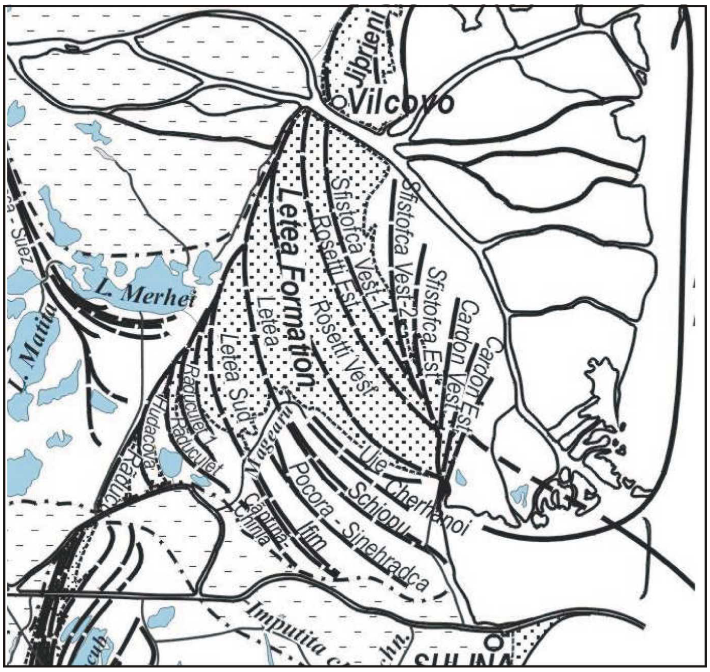

Fig.15 – The structure of the northern wing of the "Sulina Delta" (Letea Littoral Accumulative Formation) (from Panin, 1989).

Structure of the Southern Part of the Sulina Delta (Caraorman Littoral Accumulative Formation)

As indicated earlier, the western and central parts of the *Caraorman Formation* represent the northern flank of the St. George I Delta and the four first (western) sets (*Initial Spit, Erenciuc, Caraorman-pădure* and *Caraorman-sat*) record the development phases of this first delta. These beach ridges are formed exclusively of type **"a"** sediments. The eastern part of the *Caraorman Formation* consists of some additional sets of fossil beach ridges including the *Iacob, Puiulet I* and *Puiulet II, Lumina I* and *Lumina II, Rosu, Rosulet* and, finally, the *Ivancea*; these form the southern part of the Sulina Delta (Fig. 8, 13). These southern sets are formed of Danube-borne (type**"b"**) sediments (Fig. 11) and correspond to successive evolution phases. The inter-ridge depressions are occupied by lakes: Iacob, Puiu, Lumina, Rosu, Rosulet a.o. The *Ivancea set* represents the maximal progradational phase of the Sulina Delta, which took place approximately 3,000–2,800 yr. BP. Paleoerosion occurred at the southern end of different beach ridge sets, where the youngest truncate the older ones.

Table 5 outlines the Sulina Delta development phases, their timing and geomorphologic characteristics. There is a very good correlation between the main sets of beach ridges within the northern and southern delta flanks.

Table 5

Sulina Delta evolution phases and geomorphologic characteristics (after Panin, 1997)

Evolution Phases	Main sets of fossil beach ridges		Age ^{14}C yr. BP	Geomorphologic Characteristics
	Northern wing	Southern wing		
I	Răducu	Iacob	7,200	cuspate delta, 1 distributary
II	Hudacova	Puiulet I		cuspate delta, 1 distributary
III	Răduculet I	Puiulet II		cuspate delta, 1 distributary
IV	Răduculet III + Căpătână-Chirilă	Lumina I	6,000	lobate delta, 3 distributaries

Table 5 (Continued)

V	Letea South + Pocora-Sinehradca	Rosu A		lobate delta, 5 distributaries
VI	Letea North + Schiopu-Movilă	Rosu B	4,900	lobate delta, 5 distributaries
VII	Letea North + Sulina	Rosulet		lobate delta, 5 distributaries
VIII	Rosetti East	Ivancea	2,800–2,500	cuspate delta, 4 distributaries

"Saint George II Delta"

The formation and the development of the St. George II Delta are due to reactivation of the St. George distributary, and took place during the past ~ 2,800 yr. (Panin *et al.*, 1983; Panin, 1989, 1997).

The *St. George II Delta*'s northern part is represented by the *Sărăturile Littoral Accumulative Formation*, while its southern flank comprises an impressive number of fossil beach ridges and beach ridges sets that record successive delta shoreline progradation (Fig. 8).

The *Sărăturile Formation* has a divergent structure composed of the following beach ridge sets: *Câsla Vădanei, Iepurilor, Morilor, Lung, Câsla* and *St. George* (Fig. 16). This structure is due to coastline regression in the north, where the Sulina Delta was subject to continuous erosion, while in the south, the coast prograded with development of the *St. George II Delta*. The *Sărăturile Formation* comprises sediments eroded from the Sulina Delta, most of which were supplied by the Paleo-Sulina distributary (type **"b"**).

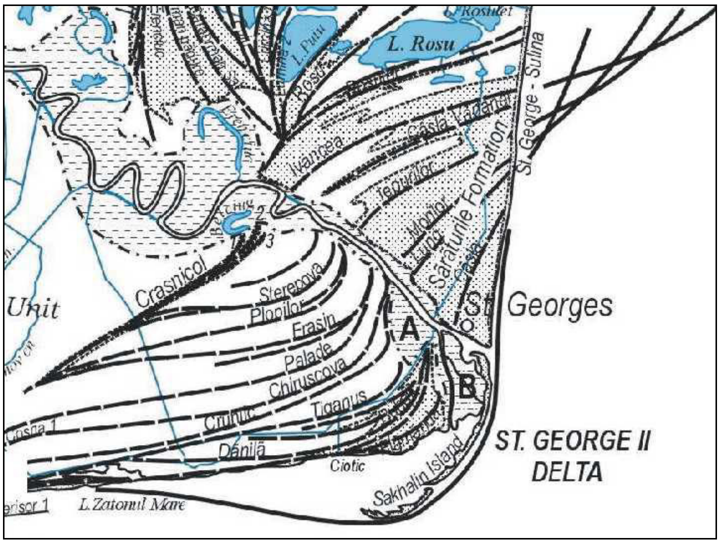

Fig. 16 – The structure of the St.George II Delta (after Panin, 1989).

The southern part of the St. George II Delta is formed of multiple fossil beach ridges and beach ridge sets, recording successive steps of delta development and progradation during the last ca. 2,800 yr. BP (by ^{14}C dating). The main sets of beach ridges in the southern part are (from oldest to youngest) (Fig. 16): *Crasnicol, Frasin, Grindac, Plopilor, Uncu* and *Strajina, Palade-Cretu, Chiruscova-Cruhlic, Tigănus-Crucea-Călugăru, Buhaz* and, finally, the arcuate lateral mouth bar *Sakhalin* (*Island Sakhalin*). These are composed exclusively of type **"b"** sediments supplied by St. George distributary (Fig. 11).

Apparently, progradation of the St. George II Delta did not occur uniformy in time. The *Crasnicol* set is the oldest in this delta: it was formed about 2,800 yr. BP. At the beginning, progradation was slow: 1.0–1.5 km in ca. 800 yr. Then, progradation accelerated to about 6 km in ca. 1,000 yr., after which delta-front advancement went on even more rapidly (more than 10 km in the last 800 yr.). The overall average rate of progradation is 8–9 m/yr.

Beach ridges and sets of beach ridges constituting the southern part of the St. George II Delta and recording the development of this delta had a similar genesis and evolution as the *Sakhalin Island* arcuate lateral bar. The end parts of these fossil beach ridges reached out the former, already stabilised, shoreline. The same evolution has the end of the *Sakhalin Island*, advancing towards WSW and joining, in the future, the present delta coastline in the Zătoane section.

There were two periods when the St. George distributary formed secondary lobate deltas (Fig. 16): the first, "*St.George secondary delta A*" formed about 2,000 yr. ago, and the second, "*St.George secondary delta B",* which began to develop 200 yr. ago and develops until now.

The present phase of St. George II Delta evolution, represented by the *Sakhalin* lateral arcuate mouth bar, began after an exceptionally high flood in 1897. Sakhalin Island developed during a century, and now reaches a length of ca. 17 km (Figs. 16, 26). As a result of wash-over, the shoreline shifted inward, while the front of the secondary "B"delta of St. George distributary, sheltered by the island, prograded continuously. Consequently, in the 1980's the island joined the front of the secondary delta near the mouth of Seredne branch. The south-western end of the island is still free, tending to approach the shore in the Ciotic – Zătoane area of the Danube Delta coast.

"Kilia Delta"

Since the period of time when the Kilia distributary reached and broke the Initial Spit, a new depocentre, the Kilia Delta, began to develop.

The Kilia Delta is situated north and east of the *Letea Littoral Accumulative Formation*, whose west side represents the northern part of the *Sulina Delta*. The earliest beach ridges of the Kilia Delta are juxtaposed to this body, while the eastern ridges correspond to further development of the Kilia Delta (fig.8, 15). The following phases of development are recorded:

The Sfistofca West I set (~3,000–2,500 yr. BP) is divergent pursuing the earliest Kilia Delta progradation. The beach ridges are made especially of type **"b"** sand and, subordinately, of type **"a"** brought by the littoral drift (Fig. 11). *The Sfistofca West II set* corresponds to Kilia Delta development from 2,500 to 1,000 years BP. During this period, the delta developed a lobate shape, which demonstrates that the Kilia distributary became the main distributary of the deltaic system, with major water and sediment discharge. The depositional material is exclusively of type **"b"**. The material from the Ukrainian rivers stops north of the Kilia Delta, forming the beach ridges of the *Jebriani Formation*. To the south, the Sulina Delta started to erod. *The Sfistofca East set* is strongly divergent to the northeast, corresponding to quick advancement of the Kilia Delta between 1,000 and 500 years ago. *The Cardon West set* follows the ever more rapid progradation of the Kilia lobate delta. *The Cardon East set* developed probably in the 16^{th}–17^{th} A.D. centuries. After formation of the *Cardon East set*, the *Kilia Delta* prograded so quickly that it covered entirely the previously formed beach ridges.

"Sinoie Delta"

In the southern Danube Delta territory, during the period from 3,500 to 1,500 yr. BP, existed a secondary delta, the Sinoie Delta (Figs. 8, 10). Two main successive development stages are recorded: Cosna and Sinoie Deltas. These two deltas are, in fact, formed by a secondary distributary, the *Dunavăt*. During the first centuries A.D. the Sinoie Delta was eroded and its material redeposited into beach ridges forming the *Lupilor*, *Istria and Chituc* accumulative formations.

The *Lupilor Formation* comprises two main sets of beach ridges, the *Lupilor I* and *Lupilor II* (Fig. 8), which can be correlated with the southern flank of the Cosna Delta. The *Istria Formation* is formed by the *Nuntasi* and *Istria sets* of beach ridges. These, as well as the *Lupilor sets*, may be synchronous with the most prosperous time of the Istria Greek and Roman colony (700 yr. BC to 300–400 yr. A.D.). The *Chituc Formation*, at the beginning the southern part of the Sinoie Delta stage, and then the product of this delta's erosion. Thus, the first period is represented by the *Sinoie I* and *Sinoie II* sets, and the second period by *Chituc I to V* sets (Fig. 8). Starting with the *Chituc I set*, the port of

Istria was clogged by sandy sediments eroded from the *Sinoie Delta* and their southward drift. This caused the decline and, at the end, the death of the town of Istria at about 700 yr. A.D.

6. 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. 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 in natural discharge conditions. This tendency of progradation has changed, as mentioned before, after the River Danube damming at Iron Gates.

The dynamic factors and processes, described 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 characterised 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 shoreline 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 characterise 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**):

$$\mathbf{I_{pr} = L_m/W} \quad \text{(I)}$$

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

$$\mathbf{I_{cr} = L_s/W} \quad \text{(II)}$$

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):

$$\mathbf{V_t} = \int_{-12.5}^{0} a.dz \quad \text{(III)}$$

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 (for the Danube Delta case on the North) of the protrusion axis and the sediment volume on the right (on the South) of this axis:

$$\mathbf{Sk = V_N/V_S} \quad \text{(IV)}$$

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 6 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 reported in the table point to a strong asymmetry of the Danube Delta caused by a very intense southward longshore sediment drift oriented to the south, which is obviously increased in front of St. George II Delta. However, the presented Sk index values do not show wholly the magnitude of this drift, which is, in the Danube Delta case, much higher (Panin, 1996).

Table 6

Morphometric Indices of the Danube Delta (Panin, 1996)

Delta	$\mathbf{I_{pr}}$ =L_m/W	$\mathbf{I_{cr}}$ =L_s/W	Sk=V_N/V_S
Kilia Delta	0.56	2.84	0.44
Sulina Delta	0.55	1.34	0.57
St. George 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 assertion is based on the fact that the sediment volume located to the north of the delta protrusion axis is supplied mainly by different northern sources (other sedimentary bodies or the littoral drift of the Ukrainian rivers – Bug, Dniester, Dnieper sediment input) and only subsidiaryly by the Danube distributary which had formed the delta under discussion. Thus, in the case of the St. George 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 the crenulation indices show the relative prevalence of fluvial or marine factors. It is obvious that the Kilia distributary is, as described above, the most active and its sediment discharge is superior to the capacity of dispersion and redistribution of marine processes.

7. Geological structure of the Danube Delta and sediment volumes stored within the Danube Delta

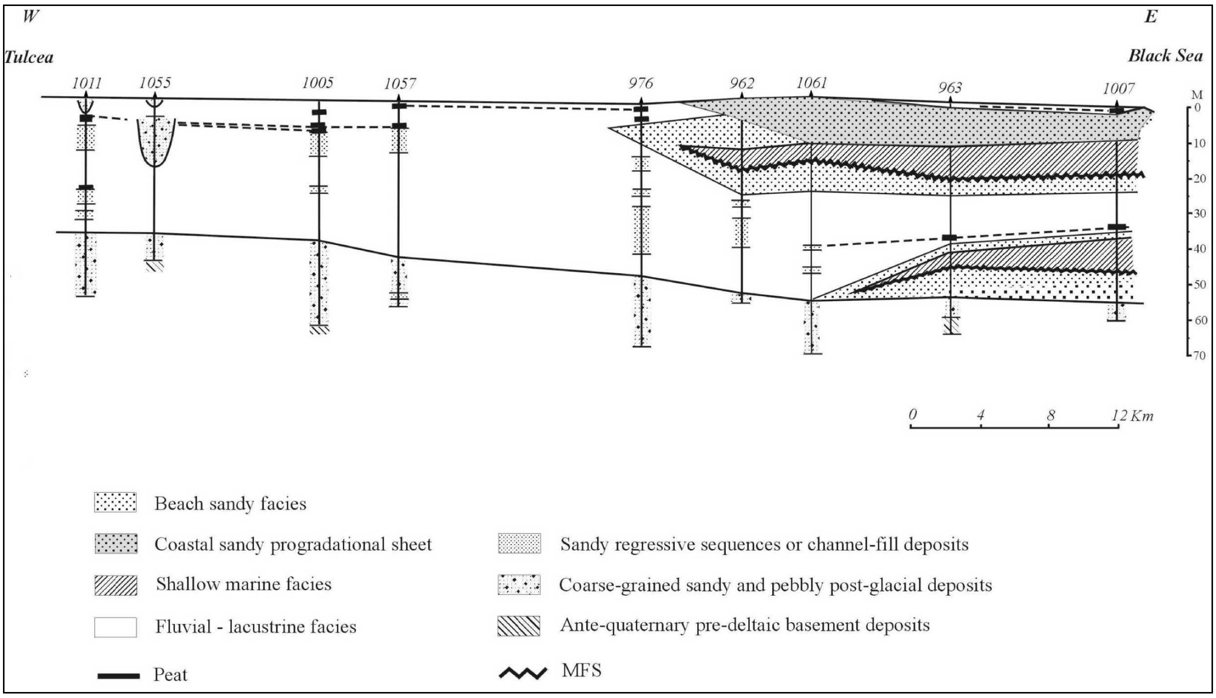

Fig.17 – Sketch of the geological section through the Danube Delta (from Panin, 1972).

The structure of the Danube Delta plain was deciphered by interpreting the data from bore-holes of over hundred meters deep (Liteanu *et al.*, 1961, 1963; Panin, 1972). Unfortunately high-resolution seismic data from the Danube Prodelta and Delta Front zone are not available. The only data available for this zone are the 3.5 kHz sub-bottom profiler in quite dense network of lines. The penetration in these areas is limited by the presence of gases in sediments and this makes not possible the recognising the MFS. This surface was recognised on land based on the data from boreholes; the progradational beach ridge sandy deposits that form different delta lobes during the Holocene high stand were defined (Fig. 17).

For investigating the first hundreds of metres of sedimentary formations the refraction and reflection seismic technique with frequencies higher than 100 Hz was used. A portable multi-channel equipment with non-explosive sources allowing summing up the weak seismic signals gave the first data on the bottom of Quaternary deposits within the delta territory. A isobath map at the bottom of Quaternary deposits was realised (Fig. 18) (Spânoche and Panin, 1997). During the Quaternary the Danube River brought into the Black Sea important volumes of sediments that were accumulated in depocentres according to the water level of the sea. The depocentres migrated from the extreme high-stand position, represented by the present-day location of the Danube Delta, to the low-stand ones, beyond the shelf break, forming the deep-sea Danube fan complex.

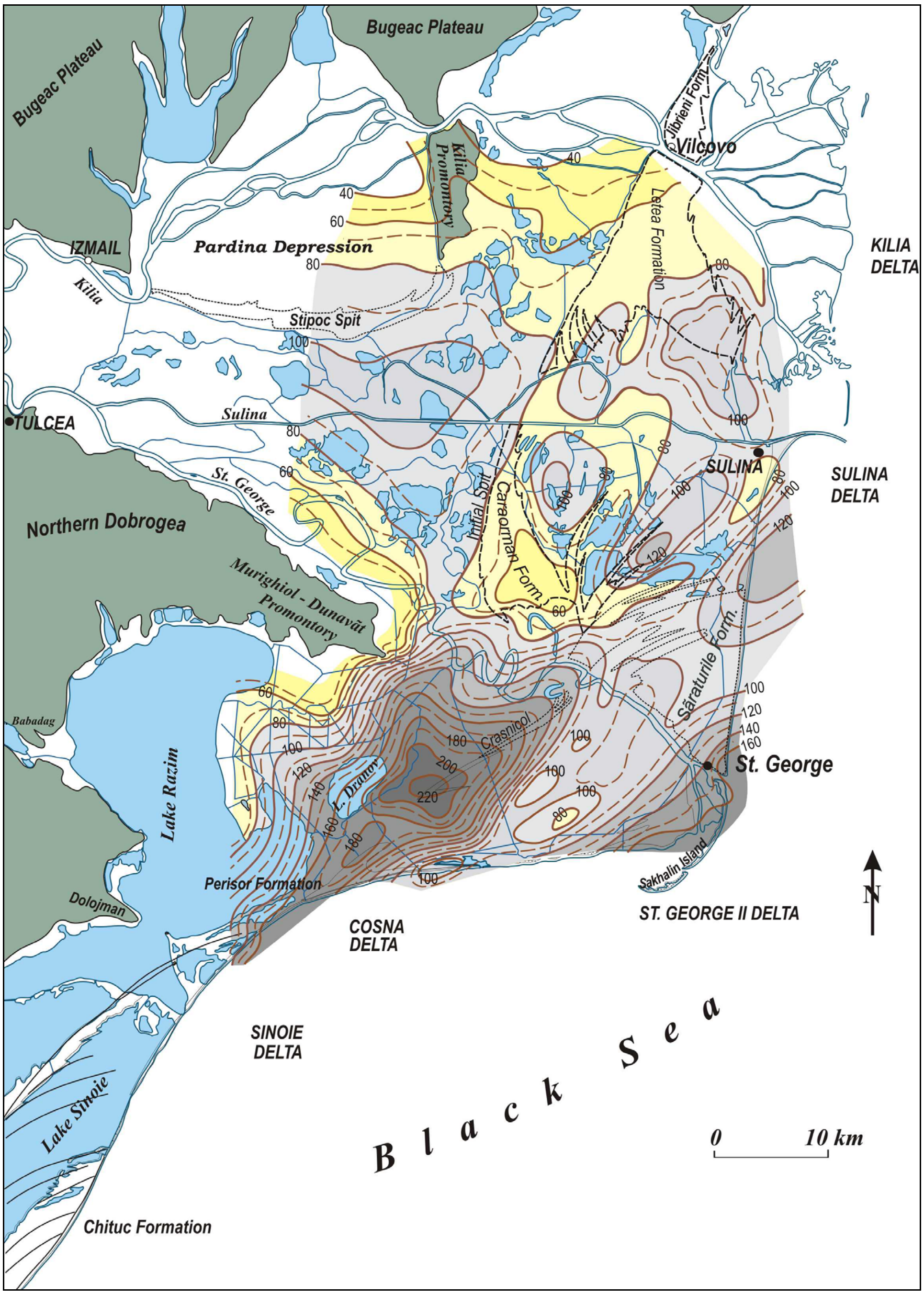

Fig. 18 – The isobaths at the base of Quaternary deposits within the Danube Delta (from Spânoche and Panin, 1997).

The isobath lines at the bottom of the Quaternary deposits within the present-day Danube Delta show a basement relief high separating the marine and fluvial delta plains – the initial spit was formed having as support this relief. Between this high and the Murighiol-Dunavăt Promontory of the North-Dobrogean unit there is a depression, which probably determined the orientation of the Paleo-Danube (paleo-St. George arm) towards SE, towards the Dranov depression. This direction corresponds with the Danube paleo-valley traced by seismo-acoustic investigations on the continental shelf that continued the river course towards the shelf-brake when the Black Sea water level was at about –120 m during the last glacial some 18 ka BP (Figs. 19, 20) (Popescu *et al*., 2004).

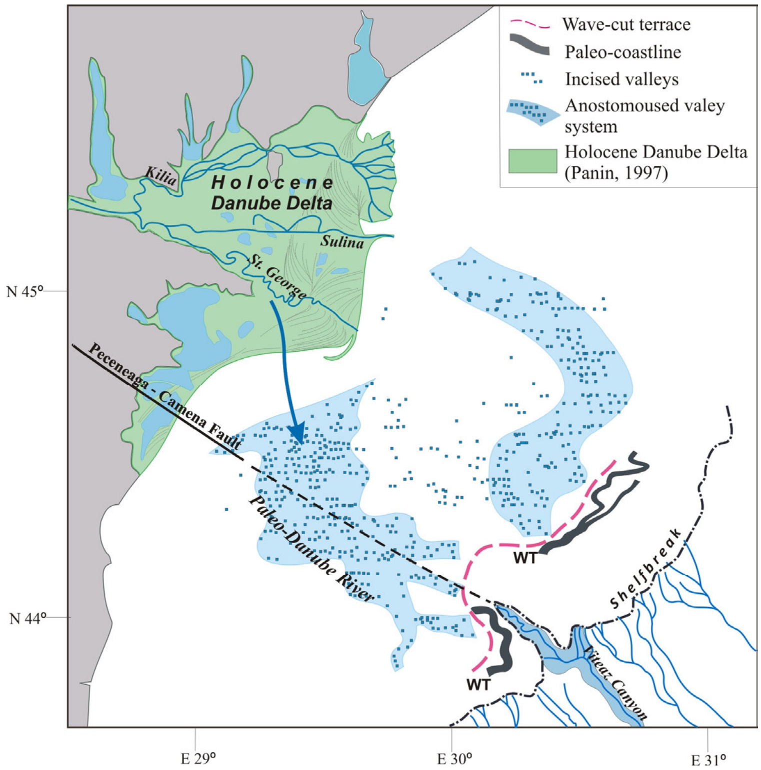

Fig.19 – The lowstand Paleo-Danube valley and its correspondence with the low relief determined from the seismic investigation on the Danube Delta territory (compiled from Spânoche *et al*., 1993 and Popescu *et al*., 2004).

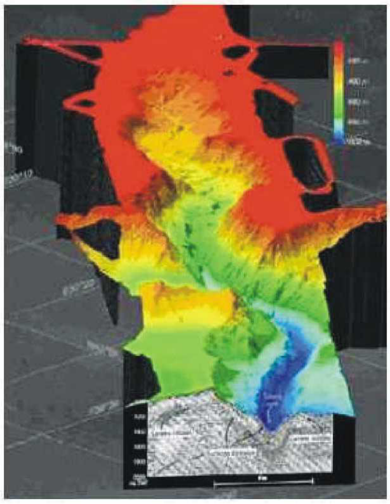

Fig. 20 – The Viteaz Canyon (the Danube canyon) – a multibeam image (from French- Romanian BLASON expedition, Popescu *et al*., 2004).

The sediment volumes accumulated within the highsands depocentre (the present-day delta) and lowstand ones are very different.

During the low stands the deep-sea fan complex mobilised some 40,000 km^3 of sediments, structured in at least 6 sequences corresponding to glaciation stages of Quaternary (Fig. 21). The computed accumulation rate ranges between 88×10^6 t/a and 302×10^6 t/a (Wong *et al*., 1997; Winguth *et al*., 1997, 2000).

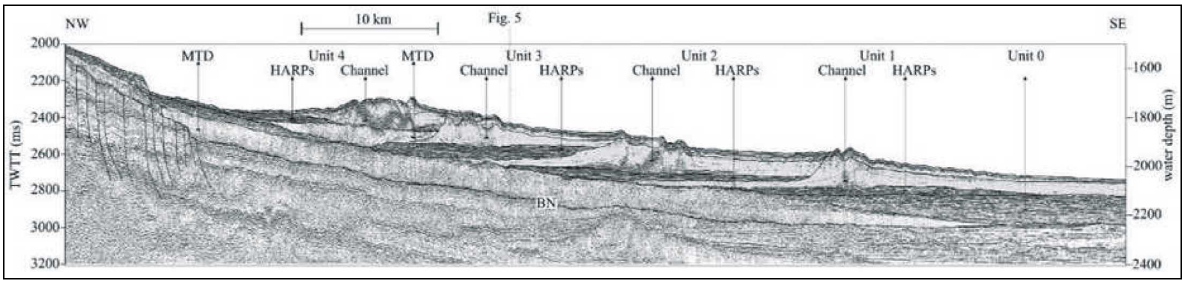

Fig. 21 – High resolution seismic section along the deep-sea Danube fan complex. French-Romanian BLASON cruise in the NW Black Sea (from Popescu *et al*., 2004).

The highstand depocentre represented by the present-day Danube Delta, including all the morphologic and depositional units, as Fluvial and Marine Delta Plains, the Delta-front unit and the Prodelta, accumulated some 1,200 km^3. As the Quaternary deposits were repeatedly eroded during the low stands there is no possibility to compute the average rate of sediment accumulation on the present day delta territory. Such computation can be done only for the last Holocene high-stand delta progradation.

The last (Holocene) progradational littoral sandy sheet is formed of about 22 km^3 of sediments. The Danube River average annual sediment discharge during the Holocene was estimated to about $80x10^6$ m^3/a that is consistent with the Danube sediment discharge before the Iron Gate barrage was completed (about 70 to 80×10^6 m^3/a).

8. The Danube Delta in ancient time. Description of the Delta according to the ancient authors

In the first millennium BC the regions around the Black Sea, the River Danube plain and its Delta were inhabited by the Scythians, Thracians, Getae and Dacians, Sarmatians and other ancient populations. By the middle of 8^{th} century BC (about 750 yr. BC) the great Greek colonisation started towards north-east (Hellespont, Pontus Euxinus), west (Italy, Sicily) and south (Egypt). This process of expansion brought about the formation of colonies all along the sea-shores of the mentioned regions. On the western and north-western Black Sea shore were established a number of colonies, as: Odessos (nowadays Varna), Callatis (present-day Mangalia), Tomis (Constantza), Histros and Argamo on the coast of Danube Delta lagoons Sinoie and Razim, Tyras on the coast of Dniestr estuary-lagoon, Olbia not far from the present-day Odessa, on the coast of Southern Bug estuary, and many others. The town of Histros was founded, for example, in 657 BC, by the Milesians.

Since the first and second centuries AD the former Greek colonies on the Black Sea coast were occupied by the Romans and these centres of Roman influence, civilisation and culture lasted up to the seventh century AD.

The ancient philosophers and geographers travelled along the coasts and even lived for different periods of time in these colonies. They gave us additional and valuable information about the development of the sea coast zone and the Danube Delta since the first millennium BC, up to the 7^{th} century AD when almost all the colonies on the Black Sea shore declined, some of them being destroyed (Panin, 1983).

The first information on the River Danube (Istros) springs, course and the five mouths at the Black Sea (Pontus Euxinus) is provided by *Herodotus* (484–425 yr. BC) in his Histories after visiting the region and living a certain period of time at Olbia.

Polybius (~203–120 yr. BC) in his Histories described Istros which was flowing into the Pontus by several mouths and its alluvia was forming a sand bank almost 1,000 stadia long, situated at a day sailing off the shore (probably from Histria colony).

In Geographia, *Strabon* (63 BC–19 AD), using old information or quoting his contemporaries (*Poseidonios, Hipparchos, Polybios, Artemidorus, Applodorus* and especially *Eratosthenes*) describes the Istros and Pontus Euxinus coasts. According to his descriptions the Pontus water was full of alluvia, the river had 7 mouths, the largest one being Hieron Stoma. Here from upstream the river, at a distance of 120 stadia, lies Peuce Island. Between Hieron Stoma and the last, the seventh mouth of the Istros there are 300 stadia. "At a distance of 500 stadia from Hieron Stoma of the Istros, going all the time along the coast – having it always on the right hand – there lies the small town of Istros (Istria), a colony of Milesians. Then follows Tomi, another town – also small – situated at a distance of 250 stadia from the first one. Then, at a distance of 280 stadia, we can see the town of Callatis, a colony of Heracleoton" (VII, 6,1 – C.319).

According to *Pomponius Mela* (first half of the I[st] century AD) "Among the mouths of the Istros there are six islands: Peuce is the best known and the largest one (De Chorographia – Description of the Earth).

Plinius Secundus (23–79 AC), known as Pliny the Elder, describes accurately the Pontus Euxinus and the Danube River in his Natural History (Naturalis Historia). He wrote that the Danube had 60 tributaries and flowed into the sea through six arms. "The first arm is called Peuce, after the island of Peuce, from which it is the nearest; it is absorbed by a marsh of 19,000 steps. From its bed, upstream Histropolis, there is developing a lake with a circumference of 63,000 steps, called Halmyris. The second arm is called Narakustoma; the third – Kallonstoma, next to the Sarmatic Island; the fourth – Pseudostomon, with the Conopon Diabasis Island, then Boreion Stoma and Psilon Stoma (IV, 12 (24), 79). The Leuce Island is 10,000 steps in circumference and lies 120,000 steps away from Thyras (Dniester) and 50,000 steps from Peuce Island (IV, 13 (27), 93).

Flavius Arrianus (Arrian) (~95–175 AD) offers valuable information on the Danube and Pontus Euxinus in his Travel Round the Pontus Euxinus (Periplus Ponti Euxini):

24.1. "From the Istros mouth, called Psilon, to its second mouth there are 60 stadia. Here from to the mouth called Kalon there are 40 stadia. And from Kalon to the fourth mouth, called Narakon, there are another 60 stadia.

24.2. From here to the fifth mouth there are 120 stadia. From this point to the town of Istria there are 500 stadia and from Istria to the town of Tomis, 300 stadia.

24.3. From Tomis to Callatis town there is another 300 stadia. Here is a place for anchoring".

The most detailed information is given by *Ptolemy (Claudios Ptolemaios)* (~90–168 AD) who wrote among other works the Geographic Guidebook or Geographia. It is an improved version of the ancient Greek geographers, especially of Marinus of Tyrus, information about the region of Pontus Euxinus and Danube Delta. The Ptolemy's description of the Danube Delta is reproduced below:

III, 10,2 "The succession of the river mouths from now on is the following:

The first separation of the mouths at the fortress Noviodunum has 54º50' and 46º30' degrees, while there from the southernmost arm which surrounds the island called Peuce, having the position: 55º20'; 46º30', flows into the Pontus through Hieron Stoma (Sacred Mouth) or Peuce, being at: 56º; 46º15'.

The northernmost part is divided into two and is situated at 55º; 46º45'. The northern part of this separation is divided in its turn into two at the position 55º30'; 47º. Then the southern part of this separation stops its course just before flowing into the Pontus. The northernmost arm which forms a pool called Thiagola, which lies at 55º40'; 47º15', flows into the Pontus through the mouth called also Thiagola or Psilon, situated at 56º15'; 47º. The southern part of the second division is, in its turn, divided into two at the position 55º20'; 46º45'. The northern part of this separation flows into the Pontus through the mouth called Boreic, situated at 56º20'; 46º50 degrees, and the southern arm is also divided into two at the position 55º40'; 46º30'. The southernmost arm of this separation flows into the Pontus through the mouth called Narakion, situated at 56º10'; 46º20'. The northern arm is also divided into two at the position 56º; 46º40'. The northernmost arm of this separation flows into the sea through Pseudostomos mouth, which lies at 56º15'; 46º40'. The southernmost arm flows through the mouth called Kalon, situated at 56º15'; 46º30'."

And farther:

III, 10, 3. ". . . The position of this coast is the following. After Hieron Stoma of the river Istros, Pteron Promontory 56º20'; 46º, the town of Istros – 55º40'; 46º , Tomi – 55º; 45º50', Callatis – 54º40'; 45º30', Dionysopolis – 54º20'; 45º15', Tiristis Promontory – 55º; 45º10', Odessos – 54º50'; 45º, the mouth of the river Panysos – 54º45'; 44º50', Mesembria – 55º; 44º40'."

In view of a better understanding the apparently confusing description of the Danube Delta, Fig. 22 outlines the Danube arms and the localities mentioned in Ptolemy's text (Panin, 1983).

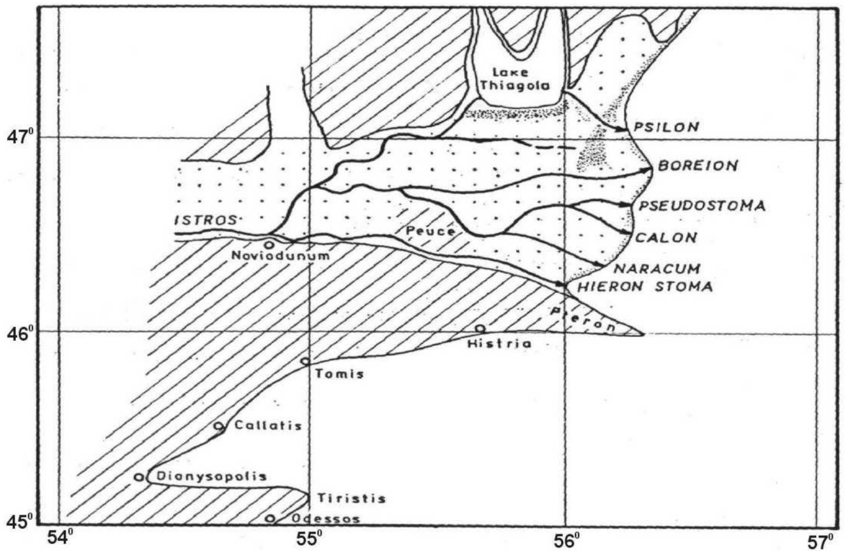

Fig. 22 – Scketch of the Danube Delta as Ptolemy described it (from Panin, 1983).

Although there are other studies which round up the image of this region in ancient times (such as Pseudo-Scymnos, Pausanias, Maximus of Tyr, Claudius Aelianus, Solinus, Dexippos, Tabula Peutingerianna etc.), we confine ourselves to the information given above regarding the River Danube and its Delta.

Briefly, between the 5th century BC and the 2nd century AD, the Danube Delta exhibited five (after Herodotus and Arrianus), six (after Ptolemy) or seven (after Strabo) arms. According to Pliny, the delta had six arms, while the seventh flowed into a marsh and then into a lake – Halmyris. The main arms debouching directly into the sea, from south to north, were: Hieron or Peuce Stoma (Sacred Mouth), Naraku or Narakion Stoma (Narrow Mouth), Kalon Stoma (Nice Mouth), Pseudostomon (False Mouth), Boreion Stoma (Northern Mouth) and Thiagola or Psilon Stoma (Barren Arm, without willows).

The distances between the mouths were given as follows (from north to south): from Psilon Stoma to Boreion Stoma – 60 stadia, Boreion to Kalon Stoma – 40 stadia, Kalon to Naraku Stoma – 60 stadia, between Naraku and Hieron Stoma – 120 stadia. Between Hieron Stoma and the town of Histria there were 500 stadia according to Arrianus and Strabo, or 425 stadia according to Ptolemy. From Histria to Tomis there was a distance of 300 stadia, according to Arrianus, or 250 stadia, according to Strabo (see Table 7).

Ptolemy mentioned that south of Hieron Stoma lay the Pteron Promontory and the northernmost arm of the Danube flowed formerly into the Lake Thiagola and then into the sea.

Herodotus, Strabo and Pliny mentioned that south of Hieron Stoma lay a gulf, several pools and marshes and the Lake Halmyris, the circumference of which was reported by Pliny of 63,000 steps (pasus).

The geological and geomorphological reconstruction as well as the radiocarbon dating demonstrate that the period 5th century BC – 2nd century AD corresponds to the final stage of the "Sulina Delta" phase and the beginning of the next phase of "St.George II" and "Kilia" Deltas described above. The reconstruction showed that within this interval of time there existed the following distributaries (from south to north) (Panin, 1983):

St. George, which at that moment (2,800–2,000 yr. BP) was reactivated and started to build up the "St. George II Delta". A secondary distributary, Dunavăt, forks from the St. George arm at about 55 Km upstream the present-day mouth of the arm and flows southwards into the Razim lagoon.

The main distributary of the Sulina Delta was the Sulina arm. On its right side, to the south there was a secondary distributary – Imputita arm, while on the left, to the north, remained during that final stage of Sulina Delta only one arm (called Movilă arm), the other two, Sinehradca and Magearu, which existed at the maximum development moment of the Delta, being already clogged.

North of the Sulina Delta, the Kilia arm started advancing and generating its own delta. At that time the Kilia Delta was of cuspate type, with a single distributary, and the surrounding landscape, was probably, limited to the Initial Spit and the few sandy beach ridges just formed on both sides of the river mouth.

So the geological reconstruction shows that during the period 500 yr. BC – 200 yr. AD the Danube Delta had six active distributaries and two already clogged.

Having as the main support the radiocarbon dating and the detailed aero-photogrammetric, geomorphologic and sedimentologic study of the Delta, we are able to join many predecessors (Ionescu, 1909; Brătescu, 1912; Lepsi, 1942; Petrescu, 1957 and many others) trying to identify the Danube mouth as described by the Ancients.

Our reconstruction leads to following correspondence with the data provided by the Ancients (Panin, 1983):

- *Hieron Stoma* corresponds to the St. George distributary; the secondary arm which forked from the St. George one and flew into a lake corresponds to the Dunavăt arm;
- The Lake Halmyris is the present-day Lake Razim.
- The *Pteron Promontory*, described by Ptolemy, is the Murighiol-Dunavăt Promontory, and the "breasts" of alluvia mentioned by Polybius and Strabo, seem to correspond to the beach ridges of the secondary Cosna-Sinoie Delta;
- *Naraku Stoma* corresponds to the Imputita arm, *Kalon Stoma* is the present-day Sulina distributary, *Pseudostomon* corresponds to the clogged secondary distributary north of Sulina called Sinehradca and *Boreion Stoma* to the Movilă arm, the only active secondary distributary during the considered interval north of Sulina;
- *Psilon* or *Thiagola Stoma* corresponds to the Kilia distributary;
- *Peuce Island* probably corresponds to the Caraorman accumulative formation and the *Leuce Island*, where the ships leaving the Psilon Stoma were arriving when the north-western winds blew, seems to correspond to the Snake Island (Insula Serpilor) in front of Kilia Delta;
- The *Lake Thiagola*, crossed by the northernmost arm of the Danube (Kilia) on its way to the sea, corresponds to the Pardina depression, bordered to the south by the Stipoc spit and to the east by the Kilia Promontory.

It is surprising how well the real distances between different reconstituted elements are corresponding to those provided by the Ancients (Table 7). Our calculation is based on the following values: Roman stadium – 185 m; Phileterian stadium – 211 m, Step (pasus) – 1,4815 m.

The experiment presented above concerning the comparison of the ancient descriptions of the Black Sea coastal zone, the River Danube and its delta with the results obtained from the complex geomorphologic, geologic and sedimentologic analyses and paleo-geographic reconstruction is a valuable meaning for completing our knowledge about the Ancient time evolution of the region. The two categories of data are supporting each other for offering the most reliable image of the delta at that time.

Table 7

Correspondence between the distances given by the Ancients and those obtained from the paleo-geographic reconstruction (after Panin, 1983)
Legend: S – stadium; P – pasus (step) = 1.4815 m; Km R – transformation using the Roman stadium (185 m); Km Ph – transformation using the Phileterian stadium (211 m)

Described sections of littoral	Distances given by the Ancients								Distances from the recon-struction
	Arrianus		Strabo		Ptolemy		Plinius		
	S/P	Km R/Ph	S/P	Km R/ Ph	S/P	Km R/Ph	S/P	Km R/Ph	
Psilon Stoma – Boreion Stoma	60 stadia	R: 11.1 Ph: 12.7							13.0 Km
Boreion Stoma – Kalon Stoma	40 stadia	R: 7.4 Ph: 8.5							8.5 Km
Kalon Stoma – Narakum Stoma	60 stadia	R: 11.1 Ph: 12.7							13.0 Km
Narakum Stoma – Hieron Stoma	120 stadia	R: 22.2 Ph: 25.3							25.0 Km
Hieron Stoma – Istria town	500 stadia	R: 92.0 Ph: 105.0	500 stadia	R: 92.0 Ph: 105.0	425 stadia	R: 78.6 Ph: 89.7			80.0 Km
Hieron Stoma – Peuce Island	–	–	120 stadia	R: 22.2 Ph: 25.3					23.0 Km
Istria – Tomis	300 stadia	R: 55.5 Ph: 63.3	250 stadia	R: 46.2 Ph: 52.7					50.0 Km
Tomis – Callatis	300 stadia	R: 55.5 Ph: 63.3	280 stadia	R: 51.8 Ph: 59.1					45.0 Km
Peuce Island – Leuce Island							50,000 pasus	74.0	70.0 Km
Lake Halmyris – circumference							63,000 pasus	93.0	95.0 Km

9. Modern time evolution of the river Danube and its Delta

We have seen how dynamic was the sedimentary environment of the Danube Delta during the Holocene. 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), has prograded seaward by about 8 Km in a period of about 2,000 yr. During the next 5,000 yr. the depocentre migrated to the “Sulina Delta”, the 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 depocentres 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. Kilia Delta and St. George II Delta have been formed and 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.

This dynamic sedimentary environment depends mainly of river sediment discharge, longshore sediment drift, sea energy and sea level changes. For short periods of time only the sedimentary budget of the delta littoral zone could be taken into consideration, the variation of other factors being almost insignificant. We could easily admit that the most important factor for the modern time evolution of the Danube Delta is the change of the Danube water and sediment discharge occurring mainly under the anthropic activities impact.

We could mention the “Imperial Directory for Navigation” founded by Empress Maria Therese in 1773 as the first national Authority in charge with planning and execution of draining, damming, channelling works along the Austrian and Hungarian sections of the Danube in order to improve the navigation and the protection against floods.

At the beginning of 18th century there was an initiative for organising an International Commission for the River Danube but it failed rapidly. Only after the Crimean War, after acceptance of Peace Treaty terms, in Paris (March 1856), the Danube River was opened to the shipping of all nations. A Danube European Commission was established since 1856 based on several agreements concerning the international navigation and engineering works needed for a better management of the river.

After the Second World War, during the Danube Conference held in 1948 in Belgrade, a new "Danube Commission" was founded with headquarters in Budapest. Its objectives were to co-ordinate and solve all the common and international problems concerning navigation, water management, water resources development and water engineering works for the whole Danube course from Regensburg to the Black Sea.

The anthropic activities and engineering works having environmental impact include mainly building of embankments along the river course to confine flood waters, dredging and meander cut-offs for improving the navigation, barrages for hydropower plants and retention reservoirs as meaning of water discharge regulation and flood peaks cutting etc. All these anthropic activities and structures are significantly modifying the natural flow regime of the river, its sedimentary environment and consequently of the Danube Delta and of the littoral zone. The main and immediate alterations of natural conditions are the following: the flow regime is flatten out (the extreme peaks of high and low waters are cut), the bed load flux is practically completely broken and drastically decreased, the trends of riverbed scouring in the downstream reaches are considerably increased and the littoral sedimentary budget is totally unbalanced inducing destructive erosions of the delta coastal zones.

As already mentioned above the anthropic changes of the Lower Danube 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.

1. Cut-offs and dredging

The rectification of the Sulina arm was carried out in 1868–1902 period (Fig. 23, Table 8) and shortened this branch by about 24% (83.8 Km before the cut-offs and only 63,7 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.

Table 8

European Danube Commission cut-off programme along the Sulina distributary (after Panin, 1976)

Order of digging channels	Period	Length of cut-off channel (Km)	Channel location
I	1868–1869	0.6	"Little M" meander bend, nearby the village "Mila 23"
II	1880–1882	1.0	Ceatal St. George
III	1883–1884	0.9	"Păpădia" meander bend
IV	1885–1886	2.0	Miles 32–33
V	1886–1889	2.1	Miles 28–30
VI	1890–1893	9.7	Downstream half of "Big M" meander bend
VII	1894–1897	5.5	"Maliuc" meander bend
VIII	1897–1898	1.7	"Ilgani" meander bend
IX	1898–1902	9.2	Upstream half of "Big M" meander bend

The operations carried out at the mouth of the Sulina distributary, in accordance with the initial project of Sir Charles Hartley from the European Danube Commission for navigation purposes, represent the best-known case of Danube Delta environmental stressing. 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 facilitating the navigation at the mouth-bar zone (initially thought to concentrate the river flow for washing out mouth-bar deposits) and 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, nowadays – 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.

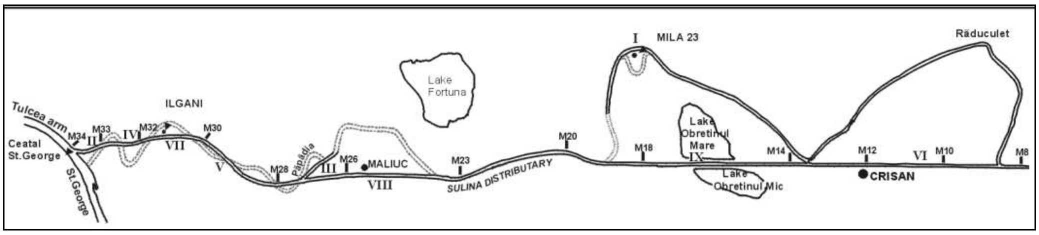

Fig. 23 – Cut-off works of the Sulina distributary meander belts in 1868–1902 period.

Sulina mouth bar is also continuously dredged in order to keep clear the navigation channel, the dredged sand being dumped away offshore removing it from the littoral sedimentary budget.

The combined effect of these two anthropogenic 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 25 years, the coast was permanently eroded, the coastline regression being of 5–30 m/yr (Fig. 27). As already mentioned, this section is situated in a zone with a tendency of recession lasting 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.

2. Damming of the river

The list of dams built up within the upper and middle sections of the River Danube is very impressive. Just to mention 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 hydro-power plant at Gabcikovo (Km 1842).

Within the Lower Danube two barrages (Iron Gates I and Iron Gates II or Ostrovul Mare) and the hydrotechnical amelioration works along the Danube tributaries have diminished dramatically the sediment flux of the Danube. The Iron Gates I barrage (Km 942.95) was built up in 1970 and the second one at Ostrovul Mare (Km 553) 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 could be partially restored along the downstream reaches by riverbed scouring and the sediments supplied by the tributaries. The sediment flux at the upper limit of Lower section of the River Danube is estimated at about 30 million tons per year. This amount of sediments is brought into the reservoir lake at Iron Gates forming a small delta in its upstream end. On the contrary, downstream the Iron Gates I and II barrages the sediment flux of the river dramatically dropped by about 40 % compared to the mean value of pre-damming values at the delta apex (Fig. 24).

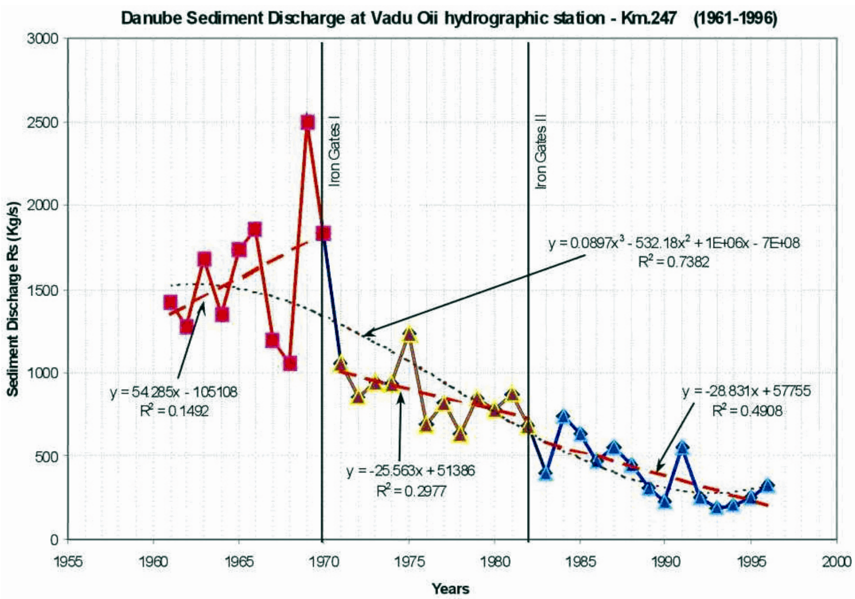

Fig. 24 – The Danube Sediment Discharge diminishing after the Danube River damming at the Iron Gate I (in 1970) and Iron Gate II (in 1983).

3. The present-day development of the Danube Delta

Presently the Danube deltaic system is active only within the Kilia Delta and the secondary modern Saint George 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. Moreover the diminishing of the water and sediment discharge of the Kilia distributary modifies the delta morphology from a lobate delta to a cuspate one, at least at the mouth zone of some of the Kilia delta distributaries (Fig. 25).

Fig. 25 – Kilia Delta – satellite image, 2006.

Due to its anthropic rectification at the beginning of the 20th century described above, Sulina distributary took away part of the sediment load from Saint George and Kilia distributaries. This practically produced the almost ceasing of the Saint George II Delta active progradation. The deltaic activity continued at small scale through secondary distributaries of the St. George branch since the end of 19th and the beginning of 20th centuries by the creation of a small secondary delta. After an exceptionally high flood (1897) a several hundred meters long sand bar was formed in front of this small delta. The bar – the Sakhalin Island – grew out (up to over 17 km long at present time) as a barrier island protecting the deltaic accumulation (Figs. 16, 26). During its evolution Sakhalin Island displayed backstepping migration through overwashing and lengthening (up to 200–500 m/year) due to a very active southward sediment littoral drift. The bar was attached to the secondary delta front and its southern end is approaching to the delta coast at Ciotic Zătoane section. The rest of the Danube Delta front is strongly eroded (in some sections up to 15–20 m per year) and the general sedimentary budget of the delta front is uncompensated (Fig. 27).

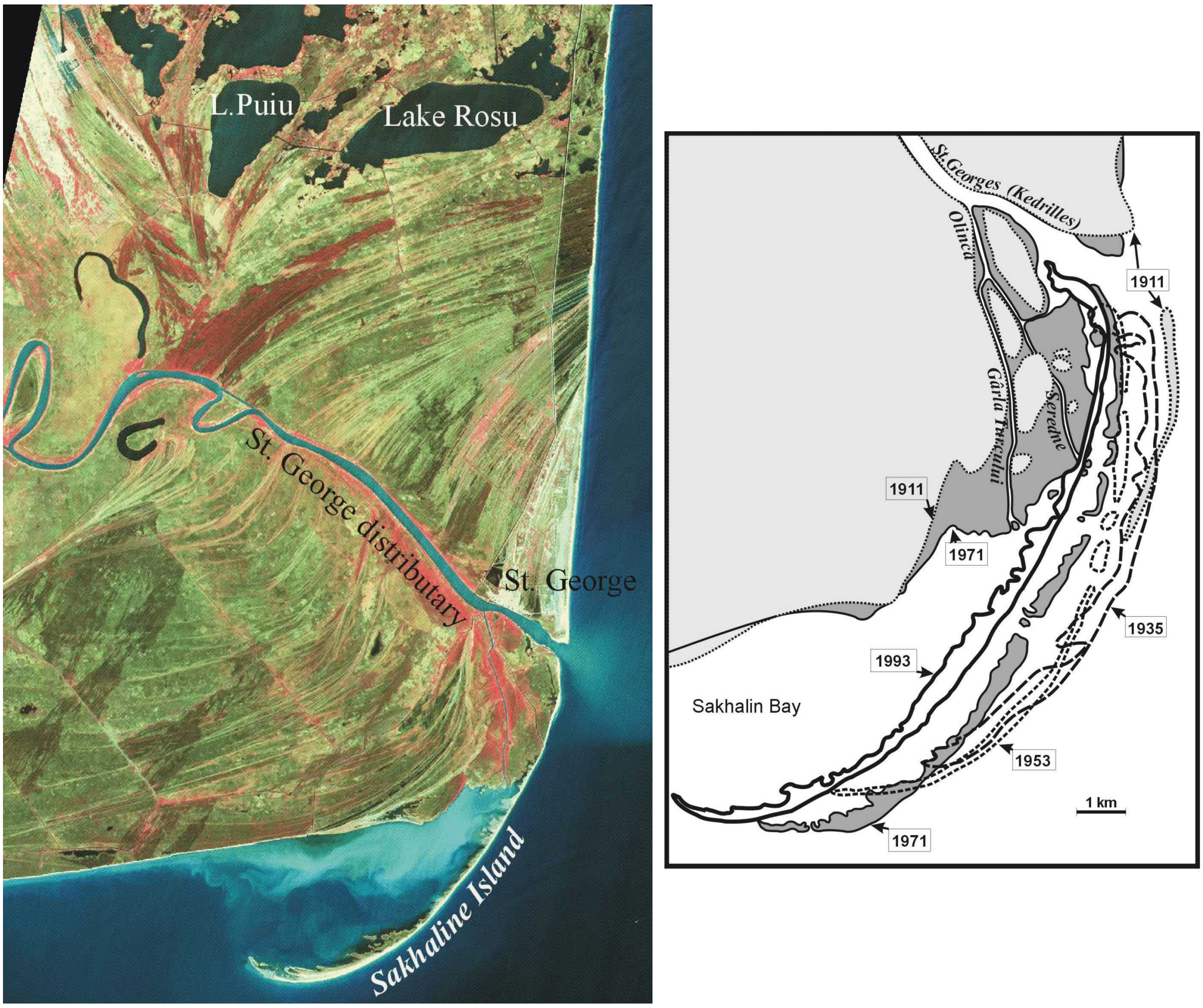

Fig. 26 – The Sakhalin Island and the St. George distributary mouth zone (Satellite image at the left and its morphological evolution after Giosan *et al*., 1993 at the right).

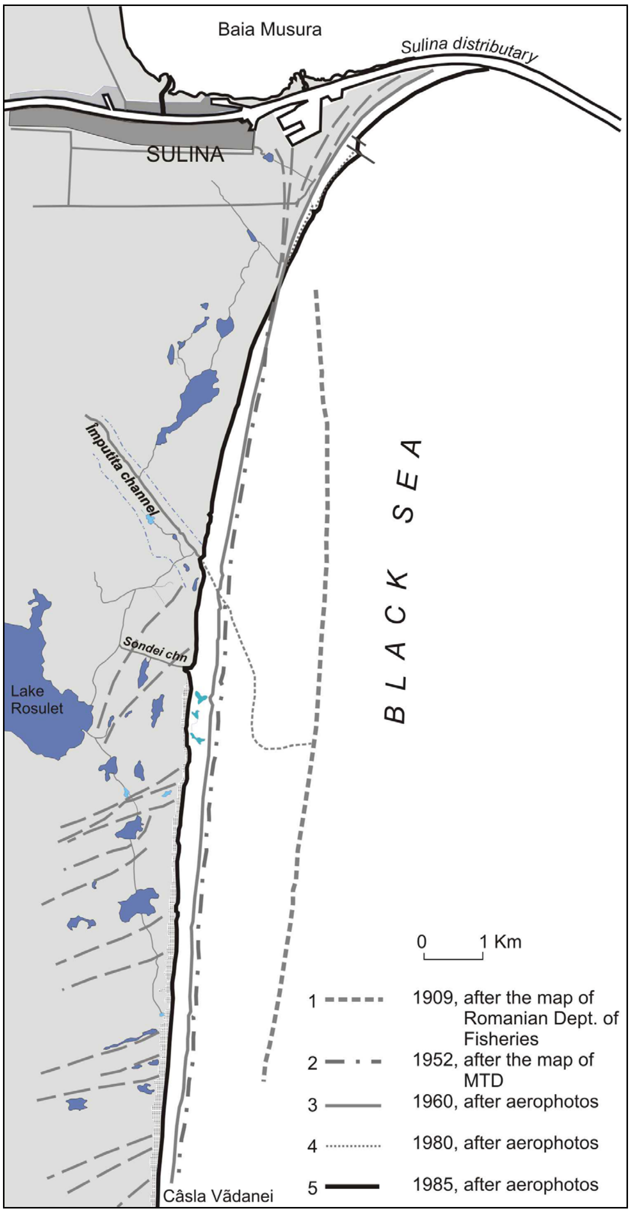

Fig. 27 – The coast-line regression in the last century in the Sulina – Câsla Vădanei section of the Danube Delta Coastal Zone (after Panin, 1996, 1997).

CONCLUSIONS

The geo-system River Danube – Danube Delta – Black Sea is the largest river-sea system in European Union. Its geological, hydrological, environmental and socio-economic importance is unique in Europe.

There are close interactions among the components of the system, interactions that played during the geological past and in modern time as well.

Each component of the system is described and the main characteristics are given: the Danube River – total length – 2,860 km, mean water discharge at delta apex ~ 6,280 m^3a^{-1}, mean sediment discharge ~ 40 Mt.a^{-1}; the Black Sea ~ 420,000 km^2, total water volume ~534,000 km^3, salinity ~17‰ at surface and ~22‰ in the deep sea, anoxic conditions and H_2S contamination below ~180–200 m water depth. The physiography of the Black Sea margins is characterized by an uneven extent of the continental shelf: very wide in the northwestern Black Sea (about 25% of the total area of the sea) and very narrow along the Crimean, Caucasian, and Pontic coasts. The sections with narrow shelf are flanked by high mountain chains – the Balkans and Pontic Mountains to the southwest and south, the Great and Little Caucasus to the East, and the Crimean Mountains to the north, and the river-sea systems are of high energy. The wide shelf corresponds to low-lying plateaus and the Danube delta lowland and the river-sea systems from this section are of low relief energy.

The Danube Delta is described extensively. The geomorphologic and sedimentary units of the delta are: the exposed delta plain – over 5,800 km^2, of which the marine delta plain – 1,800 km^2, the delta-front unit of ca. 1,300 km^2 is divided into delta-front platform (800 km^2) and delta-front slope (ca. 500 km^2), the Prodelta – more than 6,000 km^2. On the outer shelf incised valleys of the Paleo-Danube river can be evidenced and in the deep-sea zone a large Danube fan system occurs that extends from depths of several hundred meters to the abyssal plain (over 2,200 m water depth).

The present-day Delta is formed of a sequence of detrital deposits ranging from tens to 200–300 meters thick that accumulated during the Upper Pleistocene (Karangatian, Surozhian, Neoeuxinian) and mainly in the Holocene. The Holocene evolution of the Delta records the following main phases: (1) the "blocked Danube Delta" and formation of the Letea-Caraorman initial spit, 11,700-7 500 yr. BP; (2) the St. George I Delta, 9,000–7,200 years BP; (3) the Sulina Delta, 7,200–2,000 years BP; (4) the St. George II and Kilia Deltas, 2,800 years BP – present; (5) the Cosna-Sinoie Delta, 3,500–1,500 years BP. These ages are presently under discussion. Giosan *et al*., 2005, proposed younger ages for the initial stages of delta development (in their scenario, the St. George I phase could not be much older than ~5,500–6,000 yr. BP).

During the Quaternary the Danube River brought into the Black Sea important volumes of sediments that were accumulated in depocentres according to the water level of the sea. The depocentres migrated from the extreme highstand position, represented by the present-day location of the Danube Delta, to the lowstand ones, beyond the shelf break, forming the deep-sea Danube fan complex.

The sediment volumes accumulated within the highstands depocentre (the present-day delta) and lowstand ones are very different.

During the lowstands the deep-sea fan complex stored some 40,000 km^3 of sediments, structured in at least 6 sequences. The computed accumulation rate ranges between 88×10^6 t/a and 302×10^6 t/a (Wong *et al*., 1997; Winguth *et al*., 1997, 2000).

The highstand depocentre represented by the present-day Danube Delta, including all the morphologic and depositional units, as Fluvial and Marine Delta Plains, the Delta-front unit and the Prodelta, accumulated some 1,200 km^3. As the Quaternary deposits were repeatedly eroded during the lowstands there is no possibility to compute the average rate of sediment accumulation on the present day delta territory. Such computation can be done only for the last Holocene highstand delta progradation when the littoral sandy sheet is formed of about 22 km^{3}of sediments.

The Danube River average annual sediment discharge during the Holocene was estimated to about $80x10^6$ m^3/a that is consistent with the Danube sediment discharge before the Iron Gate barrage was completed (about 70 to 80×10^6 m^3/a).

The high energy river-sea systems that flow into zones with a very narrow continental shelf discharge almost their entire sediment supply into the deep-sea zone of the Black Sea through a network of canyons. The sedimentary systems in these areas are turbidity type with much coarse-grained sediments. The deep-sea fans related to them are located in the slope and apron zones, and even the near apron deep-sea zone. Flushes of density currents and slumped sediment masses affect large areas of the deep-sea. In many cases, normal sediment units I and II (Coccolith ooze and Sapropel mud layers) are washed out, and relatively coarse-grained turbidity-born sediments lay there. The high energy systems of the eastern and southern margins are active during both lowstands and highstands.

The deep-sea zones corresponding to the wide continental were very active during lowstands when the Danube and Dnieper fans complexes were formed. At highstands the fans are nowadays inactive. The only supply is represented by hemipelagic sediments and by extremely fine-grained sediments brought by nepheloid currents beyond the shelf break.

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