CONTRIBUTIONS TO THE STUDY OF THE SEDIMENT SINK PROCESSES WITHIN THE DANUBE – BLACK SEA SYSTEM

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Abstract. The paper analyses the sediment sink processes at the end of a large river sea system as the Danube – Black Sea is. It tries to evaluate the amount of sediments accumulated within the high stand depocentre, represented by the present-day Danube Delta, and the low stand one – the Danube deep sea fan complex. The deep-sea fan complex mobilised over 40,000 km^3 of sediments with an accumulation rate that ranges between 88×106 t/a and 302×106 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 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 80x106 m^3/a that is consistent with the Danube sediment discharge before the Iron Gate barrage was completed (about 70 to 80×106 m^3/a). These evaluations are of large approximation but even in such conditions they give an apercu on the sediment sink processes at the end of a large river sea system.

Key words: river-sea system; sediment sink, depocentre, high stand, low stand, Danube Delta, Danube deep-sea fan complex.

INTRODUCTION

The development of the Danube Delta is closely dependent of the evolution of the Black Sea water level on one hand and to the development of the Danube River, of its sediment and water discharge on another.

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 Bosporous 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 high-stands: during the Karangatian phase of the Black Sea (~125 – ~65 ka BP), during the Surozhian phase (~40–25 ka BP) and after the melting of Würmian icecap (the melting occurred after ~16-15 ka BP). Another low stand is documented during the Younger Dryas, followed by a quite rapid transgression of the sea up to the present-day water level.

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. 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 between the Black and the Mediterranean seas.

These high stands 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 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.

The purpose of this paper is to try to define the volume of sediments deposited during the Quaternary on the territory of the Danube Delta Plain, especially on its marine part. The volume of coastal sandy deposits that form the Holocene successive delta lobes have been also estimated and consequently some conclusions about the past Danube River sediment discharges have been proposed.

The information regarding the thickness, composition and texture of these sediments is given by geological (drillings and complex sedimentological studies) and geophysical investigations that have been carried out in 3-4 decades period of time.

For investigating the first hundreds of metres of sedimentary formations the refraction and reflection seismic technique with frequencies higher than 100Hz 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.

The seismic investigations spread almost all over the Danube Delta territory. The seismic profiles (Fig. 1) were located on steady ground as old beach ridges, littoral accumulative formations, river levees, flood-protection dams etc. The investigations allowed to:

- establish the succession of 3-4 refraction horizons in the upper 30-40 m of the geological section;
- evidence and correlating, in certain area, 2-3 reflection-seismic sequences in between the depth of about 40 m and 100m. These reflecting horizons are at - -40m, -58m and –72m;
- locate the bottom of the Quaternary where is situated a very characteristic reflection.

A detailed description of the seismic investigations carried out, their limits and difficulties to be applied within the deltaic deposits and the main results has been given by Spânoche and Panin (1997).

THE REFLECTION AT THE BOTTOM OF THE QUATERNARY

The deposits at the bottom of the Quaternary, mainly clayey, give a well-characterised reflection (signal shape and frequency of about 30-50 Hz) and it make easy to identify and correlate this reflection. The depth of this horizon varies from few tens of metres to -220 m in the lowest zones.

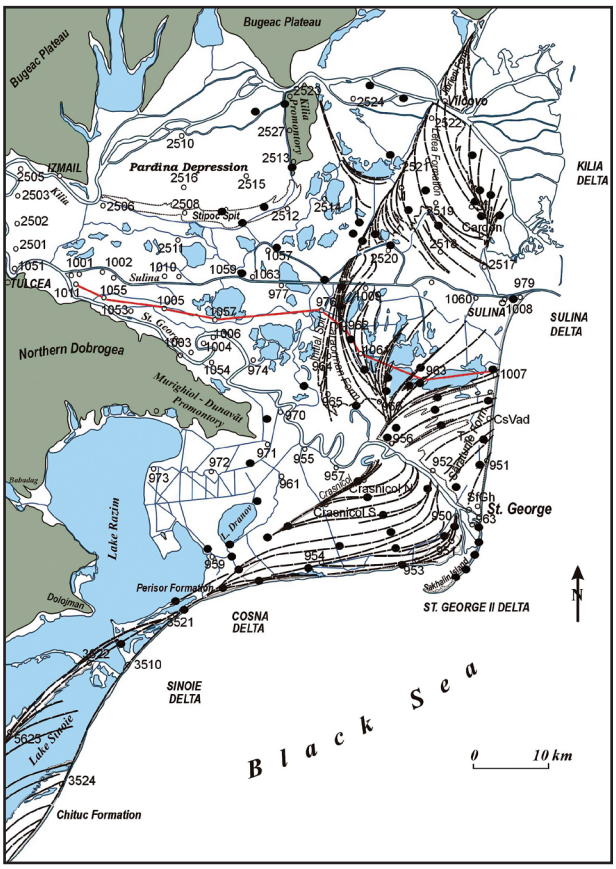

Fig.1 Location of boreholes and of seismic profiles within the Danube Delta territory (empty circles – boreholes, black circles – seismic lines)

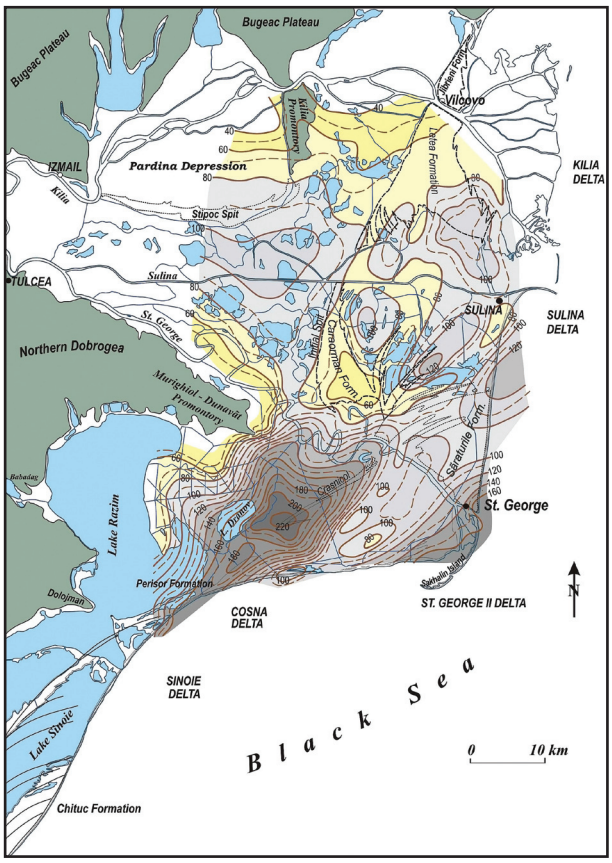

Fig. 2 Contour lines at the bottom of Quaternary deposits within the Danube Delta territory

Taking into account this reflection all over the Danube Delta territory, as well as the data from boreholes, it was possible to draw up a map with isobaths, which shows the morphology of the Quaternary formation bottom or the relief of the Pre-Quaternary formations and brings about new information on the Quaternary deposits thickness (Fig. 2).

The general analysis of the Pre-Quaternary relief shows that the most important old littoral accumulative formations – Letea and Caraorman, are located above the relict highs of this relief.

The depression zones of the Pre-Quaternary relief represent, probably, the morphological elements, which influenced the orientation of the oldest Quaternary delta hydrographic network.

The most significant of such possible paleo-valleys is located between the southern end of the Initial Spit and the Murighiol-Dunavăţ Promontory, being oriented towards the present-day Dranov-Perişor area. Such orientation of the Paleo-Danube valley corresponds very well to the paleo-valley traced by seismo-acoustic investigations on the continental shelf that continued the river course towards the shelf-break when the Black Sea water level was at -120 m during the last glacial some 18 ka BP (Fig. 3) (Popescu *et al*., 2004).

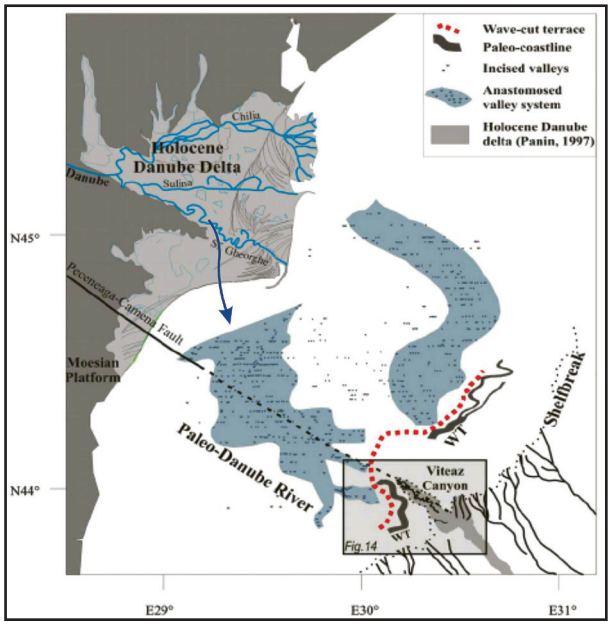

Fig. 3 Paleo-geographic map of the northwestern Black Sea margin during the last sea-level lowstand. **WT** - Location of the submerged wave-cut terrace (Popescu *et al*., 2004; Lericolais *et al*., 2005)

SEDIMENT VOLUMES MOBILISED WITHIN THE HIGH STAND DEPOCENTRE

Taking the map of the Pre-Quaternary relief isobaths as basis of calculation, the Quaternary sediments volume within the Marine Danube Delta Plain, limited to the West by the line of the Initial Spit and to the East by the present-day coastline, represents some 150 – 200 Km^3. Taking into account the surface of the Delta Front unit that is similar with the Marine Delta Plain surface the volume of sediments within the marine part of the Danube Delta (the Marine Delta Plain and the Delta Front) should be considered at least of 400 – 500 Km^3.

Offshore the delta front unit there are over 6,000 Km^2 of Prodelta Unit (Fig.4), with a sediment blanket over 20 – 30 m thick, representing about 150 km^3 of sediments.

Considering the Danube Delta Fluvial Plain that lies westward the Initial Spit line at least till the delta apex at Ceatal Izmail hydrographic knot, the volume of Quaternary sediments settled within this unit can be appreciated to other 400 – 500 Km^3.

Adding the estimated Quaternary sediments volumes from all the morphogenetic delta units (Fluvial and Marine Delta Plains, Delta Front and Prodelta) we shall obtain a figure over 1,200 Km^3.

SEDIMENT VOLUMES MOBILISED WITHIN THE LOW STAND DEPOCENTRES

But the main volume of sediments brought by the Danube River during the Quaternary is placed within the deep-sea fan complex and some intermediary depo-centres on the con-

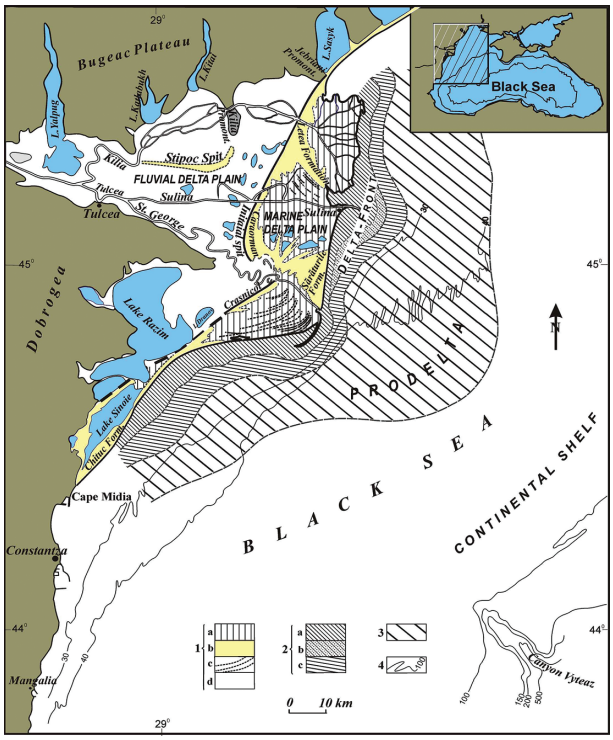

Fig. 4 The Danube Delta major morphological and depositional units (Panin, 1989). **1** – delta plain: "marine" delta plain (**1a**) spits and littoral accumulative formations built up by juxtaposition of beach ridges (**1b**); fossil and modern beach-ridges (**1c**); fluvial delta plain (**1d**); **2** – delta-front: delta-front platform (**2a**), relics of the Sulina Delta and it delta-front (**2b**), delta-front slope (**2c**); **3** – Danube Prodelta; **4** – depth contour lines in metres

tinental shelf when the Black Sea water level migrated according to the glacial and interglacial ice melting phases. Wong *et al*. (1997) and Winguth *et al*. (1997, 2000) have proposed sediment accumulation rates for all the sedimentary sequences within the deep-sea Danube fan of 68 – 302 × 10^6 t/a. The overall volume of sediments accumulated within the Danube fan system during the low stands along some 480 ka (since the Danube River flew into the Black Sea) is estimated at over 40,000 Km^3 (Wong *et al*., 1997, Winguth *et al*., 1997, 2000).

It is much more difficult to estimate the volume of sediments accumulated within the intermediary depocentres on the continental shelf when the water level migrated up or down between the extreme values of low and high stands.

A comparison of the sediment volumes settled at high stands and low stands depocentres shows that the low stand accumulation is some 30 times higher than the high stand one.

SEDIMENT VOLUMES MOBILISED WITHIN THE HOLOCENE DANUBE DELTA

A short aperçu of sediment amounts settled in different lobes of the Holocene Danube Delta was given already in Panin *et al*. (2005).

We shall present the main results of this evaluation and for this reason a short description of the Holocene Danube Delta structure and its evolution is needed.

The Holocene evolution of the Delta includes the following main phases (N. Panin *et al*., 1983; N. Panin, 1989) (Fig.5): (1) the formation of the Letea-Caraorman initial spit and of the "Danube Blocked Delta", 9,700-5,500 yr. BC; (2) the St. George I Delta, 7,000-5,200 years BC; (3) the Sulina Delta, 5,200-~0 years BC; (4) the St. George II and Kilia Deltas, 800 years BC to present and (5) the Cosna-Sinoie Delta, 1,500 BC-500 years AC.

The Danube Delta marine plain displays two types of coastal deposits: (1) marine littoral deposits of type **„a"**, formed by longshore drift from the north (from mouths of the Southern Bug, Dniester and Dnieper rivers) and (2) littoral deposits of type **„b"**, of Danube origin (fig.6).

The structure of the Danube Delta was deciphered by interpreting the data from boreholes of over hundred meters deep (fig.1, 7). Unfortunately the 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 the Prodelta and Delta-Front areas is limited by the presence of gases in sediments and this make not possible to recognise 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.

As already mentioned above, the deposits of Holocene Danube Delta Plain are of two origins: sandy deposits of Ukrainian rivers origin drifted longshore to the delta area and the Danube River born sediments. It is necessary to distinguish these different sources of material for having an idea of the past Danube River sediment supply and its contribution to the delta progradation.

The volume of sediments forming different delta lobes was estimated taking into consideration the area of lobes, the thickness of the coastal sandy progradational sheet and the source of sediments (the Ukrainian rivers – type "a" or the Danube River – type "b") (fig.8, Table 1).

The volumes mentioned above represent the coastal sandy deposits supplied by the littoral drift from different sources (Ukrainian rivers-borne "a" deposits, Danube-borne "b" deposits and reworked by the coastal erosion "r" deposits). The estimation of the paleo-littoral drift fluxes is given below (Table 2).

The Danube-borne sandy coastal sediments represent mostly the amount of sediments trapped in the mouth-bar zone, reworked and redistributed long-shore. Considering that the mouth bar deposits represents only ~20 % of the to-

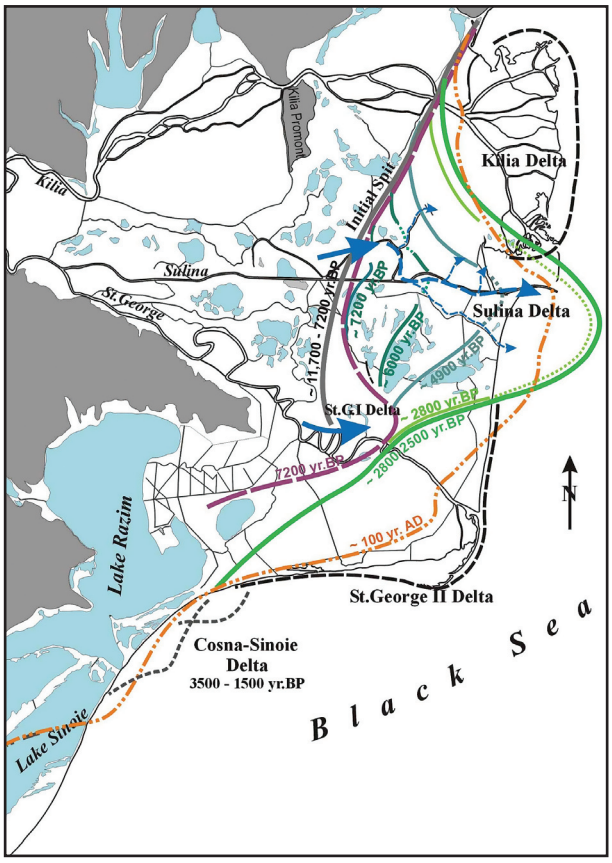

Fig.5 The Danube Delta evolution during the Holocene and correspondent coastline position changes (after Panin, 1997). **1**: initial spit 11.7-7.5 K yr.BP; **2**: St. George I Delta 9.0-7.2 Kyr.BP; **3**: Sulina Delta 7.2-2.0 K yr.BP; **4**: Coastline position at ~ 100 yr AD; **5**: St.George II Delta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

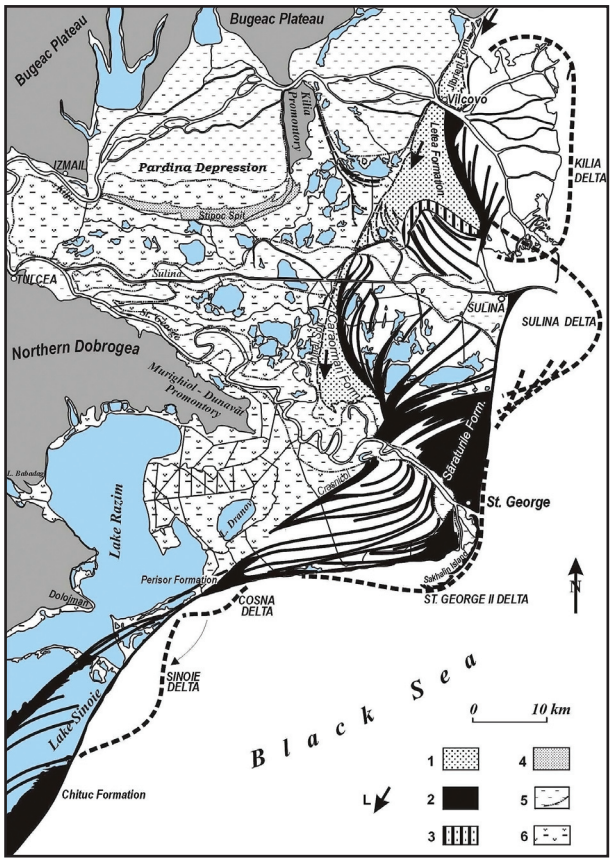

Fig. 6 Areal distribution of the main types of deposits within the Danube Delta territory (after Panin 1989). **1**: marine littoral deposits of type "a", formed by the littoral drift from the rivers Dniester and Dnieper mouths; **2**: marine littoral deposits of type "b", of Danubian origin; **3**: 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

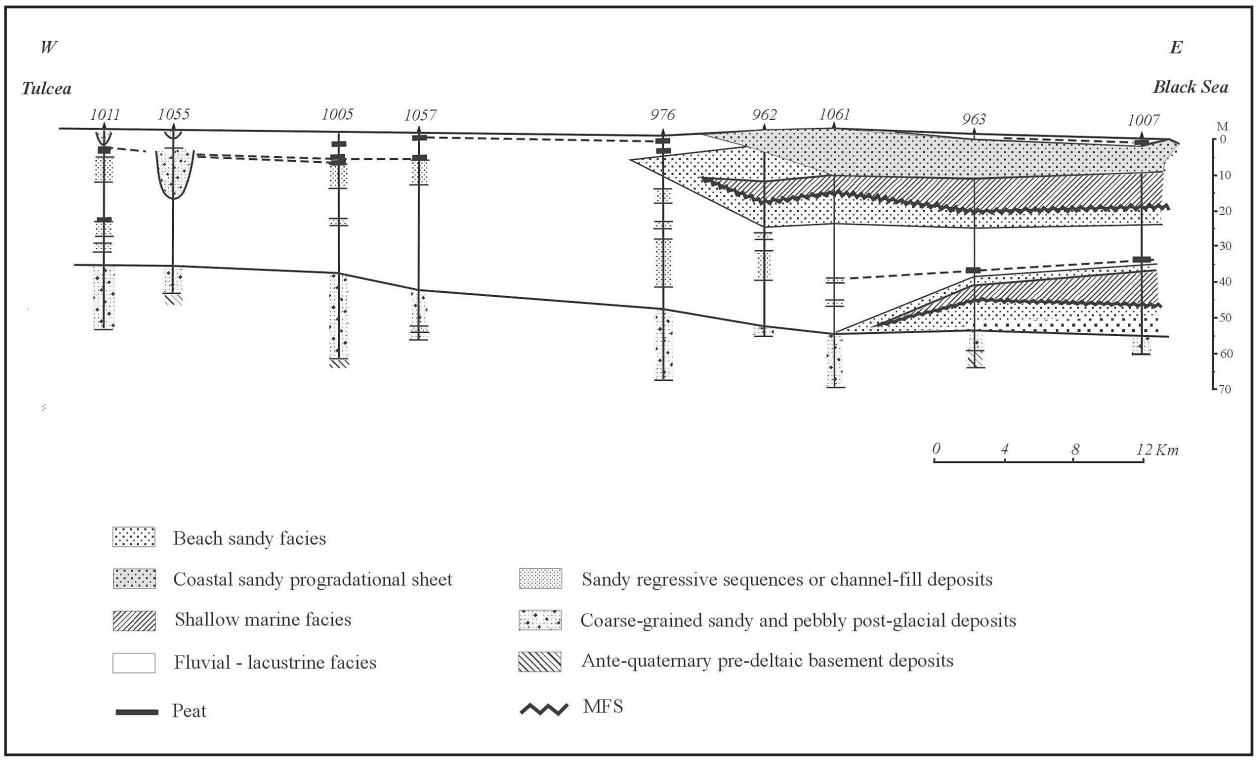

Fig. 7 Geological section through the Danube Delta oriented west – east (red line on the Fig.1)

Table 1 The Danube Delta lobes – the volume of deposits mobilised in different lobes

Lobe name and their time of development	Total Volume of deposits (m^3)	Volume of type "a" deposits (Ukrainian) or "r" (reworked) (m^3)	Volume of type "b" deposits (Danubian) (m^3)	Average rate of deposition (on total volume) (m^3/yr)	Rate of deposition for Danubian sediments (m^3/yr)
St. George I/ 2200 yr.	2,105,342,923	"a"-1,262,603,707	842,739,216	956,974	383,063
Sulina Delta/ 4500 yr.	9,236,857,413	"a"-1,797,681,322	7,439,176,091	2,052,635	1,653,150
St. George II/2800 yr.	5,294,475,401	"r"-1,271,199,243	4,023,276,158	1,890,884	1,436,884
Kilia/ 2500 yr.	3,982,737,489	-	3,982,737,489	1,593,095	1,593,095
Jebriani Formation	~ 400,000,000	"a" ~400,000,000	-	120,000	-
Cosna-Sinoie Delta	~1,320,000,000	-	~1,320,000,000	660,000	660,000
Total	~22,339,413,226				

Table 2 Estimated average paleo-fluxes of the littoral drift during different phases of delta development

Fluxes of littoral drift (m^3/yr) for type "a" or "r" deposits	St.George I Delta ("a")	Sulina Delta ("a")	St. George II Delta ("r")
	~574,000 m^3/yr	~400,000m^3/yr	~454,000 m^3/yr

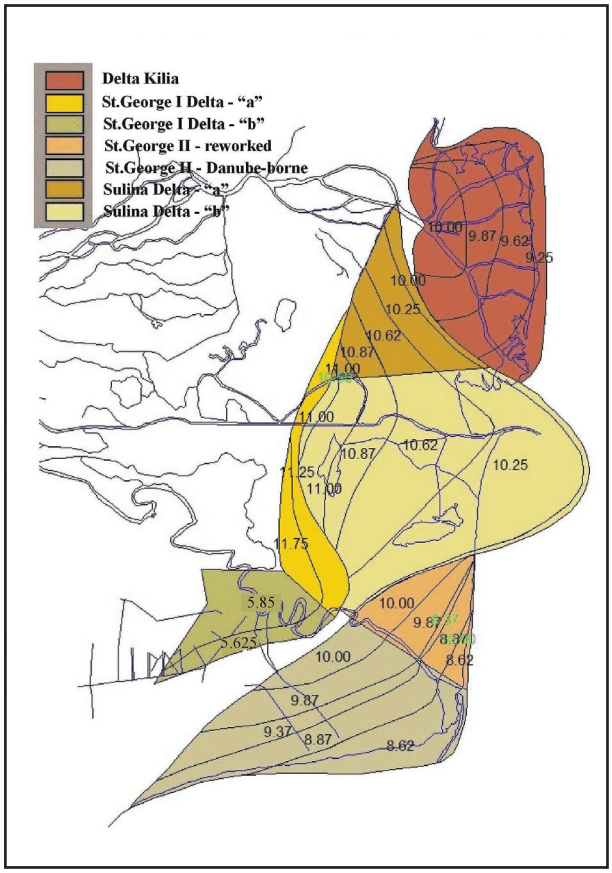

Fig. 8 The main lobes of the Danube Delta – their surface and the thickness of the coastal sandy progradational deposits forming these lobes (basis for the calculation of volumes of sandy deposits of the Holocene delta)

tal sediment discharge of the river, one could approximate the total sediment supply for a period of 11 k yr to about 80 – 100 billion cubic meters (average annual sediment discharge of about 80 million cubic meters).

CONCLUSIONS

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.

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 (Popescu *et al*., 2004).

The sediment volumes accumulated within the high stands depocentre (the present-day delta) and low stand ones are very different:

During the low stands the deep-sea fan complex mobilised some 40,000 km3 of sediments, structured in at least 6 sequences. The computed accumulation rate range between 88×10^6 t/a and 302×10^6 t/a (Wong *et al*., 1997; Winguth *et al*., 1997, 2000).

The high stand 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 80×10^6 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).

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