THE DANUBE DELTA EVOLUTION DURING THE HOLOCENE: RECONSTRUCTION ATTEMPT USING GEOMORPHOLOGICAL AND GEOLOGICAL DATA, AND SOME OF THE EXISTING CARTOGRAPHIC DOCUMENTS

Nicolae PANIN[(1)], Willem OVERMARS[(2)]

[(1)] National Institute of Marine Geology and Geoecology – GeoEcoMar, Romania, Dimitrie Onciul Street No.23-25, Bucharest, RO 024053, panin@geoecomar.ro

[(2)] WWF consultant, historian and landscape architect: Rombus films / Wildernis consultancy, Jan de Jagerlaan 2A, 6998AN Laag Keppel, The Netherlands, willem.overmars@wildernis.eu

Abstract. The paper presents the Danube delta evolution during the Holocene with an emphasis on the last three centuries. Detailed descriptions of the physiographic evolution and depositional characteristics of the delta are given on the basis of detailed sedimentological and geomorphological studies. For the recent period (last three centuries) the physiographical changes are highlighted using the most interesting cartographic documents stored in different archives and libraries of European countries and the USA. The main documents used are: the maps of 1771 and 1778, the maps of 1856-1857 made by the Danube European Commission (HMSV *Medina* under the direction of Captain Spratt), the Austrian map of 1918, the Royal Navy Chart of 1926/1936, the German map of 1944, the Soviet map of 1983, the Romanian map of 1985, the British Sea Chart of 1999 and the most recent satellite images offered by Google (2004, 2006). Some conclusions on the delta development and on the hydrodynamic and sedimentological laws governing the processes in the delta area, especially at the distributary mouth zones and on the coastal area are given.

Key words: Danube Delta, main distributaries, meander loops, river water and sediment discharges, wave-dominated delta – cuspate delta, river-dominated delta – lobate delta, delta front platform, beach ridge, barrier beach, river levee, mouth bar

INTRODUCTION

The Danube River – Danube Delta – Black Sea is the most important river – sea system in Europe; it represents a backbone of more than a half of the European continent and influences the physiography, hydrography and environment of Central and Eastern Europe, as well as its socio-economic development. The Danube Delta is the middle component of this system and is the largest delta in the European Union (Fig. 1).

Many investigations have been carried out on the Danube Delta since the middle of the XIX century, which improved our understanding of the genesis, structure and evolution of this major coastal accumulative feature. Particularly important are the studies of A.C.Hartley (1867), Gr. Antipa (1915, 1941), C. Brătescu (1922, 1942), G. Vîlsan (1934, 1935), I. Lepsi (1942), H. Slanar (1945), M. Pfannenstiel (1950), I.G.

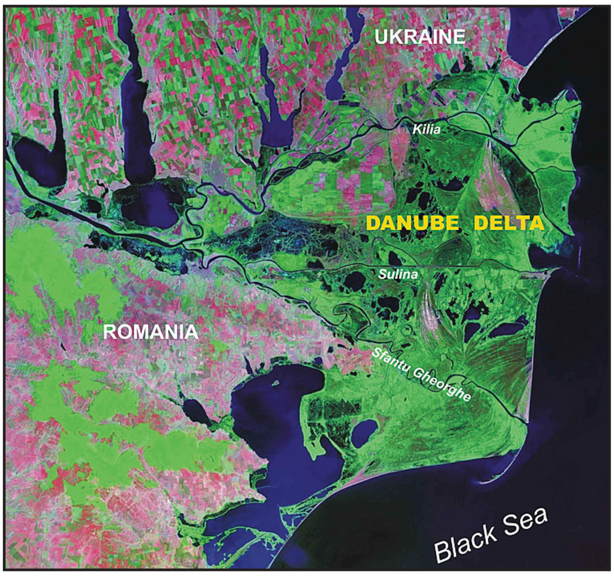

Fig. 1 Danube Delta general view. Satellite Landsat image

Petrescu (1957), V.P. Zenkovich (1956, 1960, 1962), P. Coteț (1960), M. Bleahu (1963), H. Grumăzescu *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), C. Bondar (1972, 1989, 1992, 1993, 1994), C. Bondar *et al.* (1991), C. Bondar and N. Panin (2000), N. Panin (1974, 1976, 1983, 1989, 1996, 1997, 2001, 2003, 2009), N. Panin and D. Jipa (2002), N. Panin and Irina Popescu (2002, 2004) N. Panin *et al.* (1983, 2005), P. Gâstescu and B. Driga (1981, 1985, 2009), A. Stancik, S. Jovanovic *et al.* (1988), Giosan *et al.* (1997, 2005, 2006).

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. During the last lowstand (the Last Glacial Maximum, about 20 kyr. ago) the coastline was located at the shelf-break (after Popescu *et al.*, 2004, Lericolais *et al.*, 2005) (Fig. 2). The coastline was identified in the neighbourhood of the Paleo-Danube Canyon (Viteaz Canyon) head and is represented by paleo-beaches and wave-cut terraces. After the lowstand period, the coastline migrated with the sea-level rise towards the present-day position. There are morphological features that show intermediate locations of the coasts. The studies showed that the highstand Danube Delta edifice was therefore formed mainly during the Upper Pleistocene (Karangatian, Surozhian, Neoeuxinian) and mainly in the Holocene (Panin, 1989). The present geomorphology of the delta plain records the interaction of the river and the sea during the Holocene.

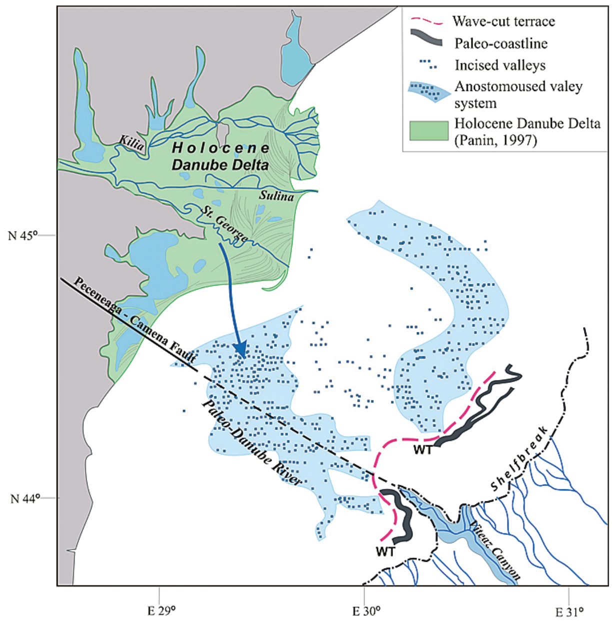

Fig. 2 The coastline location close to the shelf-break during the Last Glacial Maximum (after Popescu *et al.*, 2004; Lericolais *et al.*, 2005)

The present paper aims to analyse and highlight the changes in the coastline position and in delta morphology during the Holocene, with an emphasis for the last three centuries when cartographic documents can be used for this purpose.

1. THE HOLOCENE EVOLUTION OF THE DANUBE DELTA

General discussion

The main phases of the Danube Delta evolution during the Holocene have been evidenced and dated by corroboration of geomorphologic, structural, textural, geochemical, mineralogical, and faunal analyses and, mainly, by ^{14}C dating.

The ages of delta evolution phases are presently under discussion. The older ^{14}C age determinations (Panin *et al.*, 1983) gave the following timing and succession of evolution 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 yr. BP; (3) the Sulina Delta, 7 200-2 000 yr. BP; (4) the St. George II and Kilia Deltas, 2 800 yr. BP - present; (5) the Cosna-Sinoie Delta, 3 500-1 500 yr. BP (not calibrated ages) (Table 1, Fig. 3).

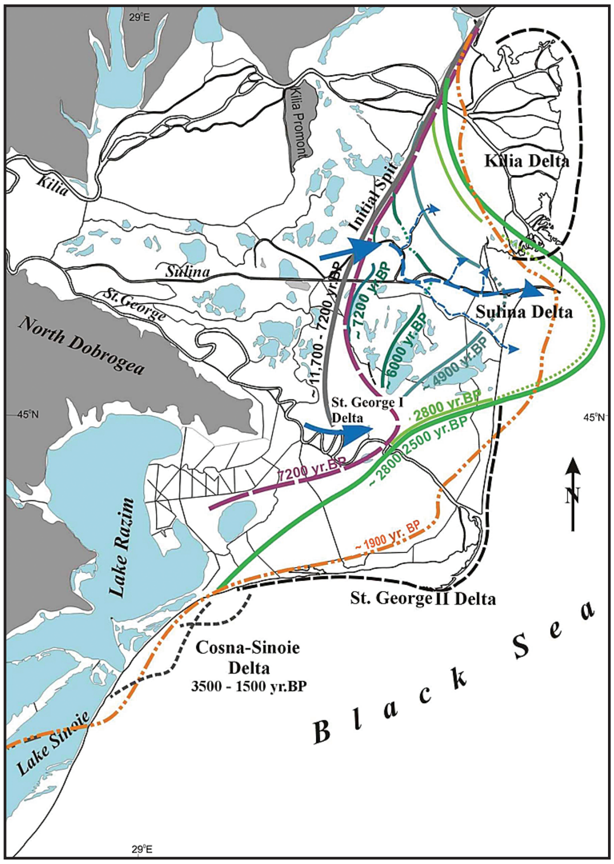

Fig. 3 Main phases of the Danube Delta development during the Holocene (after Panin, 1983)

Table 1 Danube Delta lobes chronology (after Panin *et al.*, 1983)

Nr.	Main lobe	Relative dating	Absolute dating years BP	Number of channels	Number of mouths	Progradation speed
1	Initial Spit	1	11,700 - 7200	1	1	
1	Blocked Delta	1	11,700 - 7200	1	1	
2	St.George I Delta	2	~9000 - 7200	1	1	3-5 m/yr
3	Sulina	3	~7200 - 2 000	1	1	3-5 m/yr
3a	Sulina Delta – phase 1	3a	7200	1	1	6-9 m/yr
3b	Sulina Delta – phase 2	3b	~ 6000	3	3	
3c	Sulina Delta – phase 3	3c	~ 4900	5	5	
3d	Sulina Delta – phase 4	3d	~ 2800 - 2000	2	2	
4	Cosna – Sinoie Delta		3500 - 1500	1	1	?
5a	Kilia Delta	4	2500 - present	1 to 19	1 to 19	8-10 m/yr
5b	St. George II Delta	4	~ 2800 - present	1 to 3	1 to 3	8-9 m/yr

Giosan *et al.*, 2005 suggest younger ages for the initial stages of delta development (for example, in their view, the St. George I Phase could not be much older than ~5,500 – 6,000 yr. BP). This hypothesis seems to better correlate with the present-day understanding of water-level changes in the Black Sea during the Pleistocene – Holocene time.

New age determinations are now in progress and, probably, they will give a new understanding of the Danube Delta development timing during the Holocene.

In the present paper we shall avoid the discussion about the Holocene timing of the delta development, and taking into account that the succession of main phases of development are not contested we shall restrict ourselves to describe mainly the physiographic changes of the delta.

The evolution of the delta coastline was a continuous process, and was materialised by the position of successive single beach-ridges or sets of such ridges. The following description will highlight the position of the beach-ridges marking the maximum progradation for different lobes (phases) of the delta.

1.1 The Coastal Zone Changes

The "Blocked Danube Delta" and the Letea-Caraorman initial spit

At the beginning of the Holocene the present area of the Danube Delta was transformed into a large marine bay - the *Danube Gulf* (Fig. 5). All the 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.

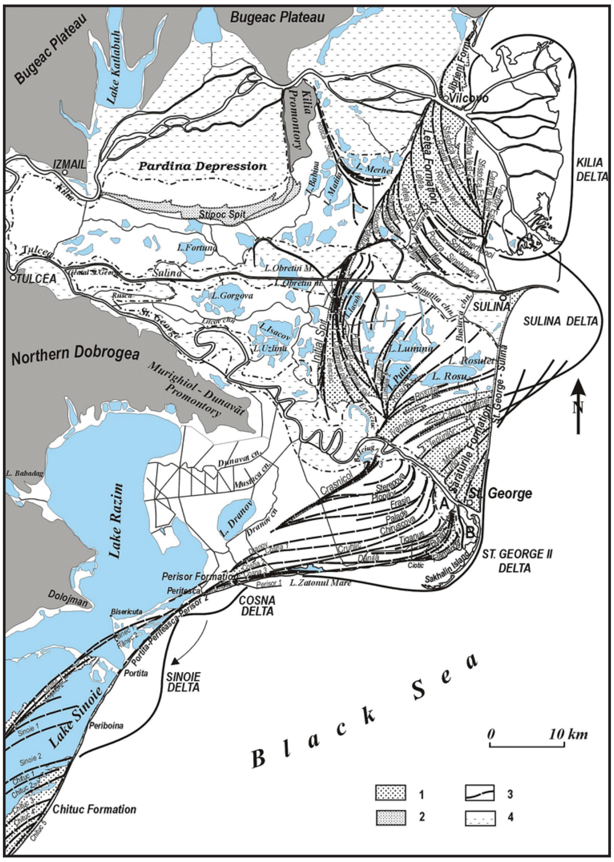

Fig. 4 The Danube Delta geomorphologic-sedimentologic structure (after Panin, 1974, 1989).
The map outlines the main sets of beach ridges and the phases of delta development during the Holocene. 1: marine beach ridges; 2: lacustrine spit; 3: directions of main beach ridges and beach ridge sets; 4: river meandering zone.

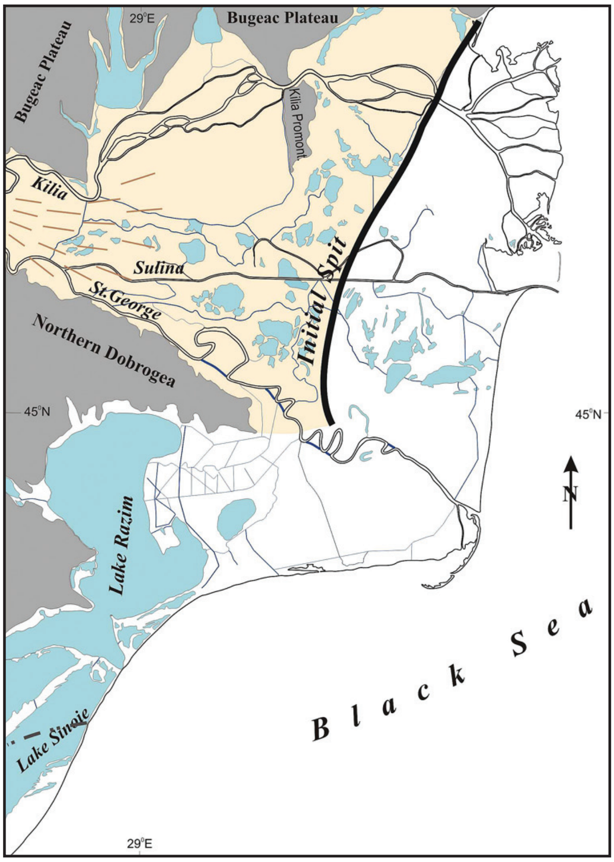

Fig. 5 Danube Delta coastline position during the "Blocked Danube Delta"

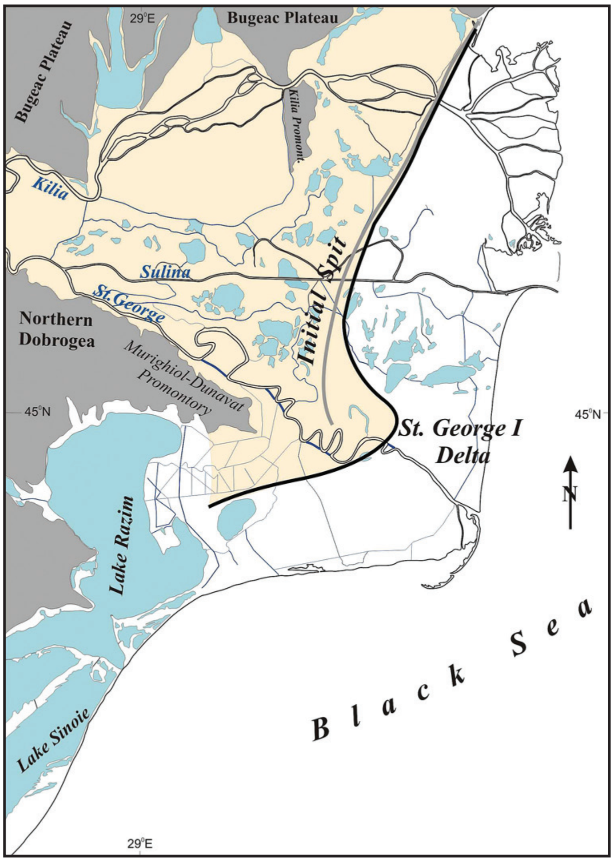

Fig. 6 Danube Delta coastline position at the maximum progradation of the St. George I Delta phase

At the mouth of the Danube Gulf, between the *Jebriani promontory* to the north and *Murighiol-Dunavăţ promontory* of Dobrogea to the south, a spit was formed by the littoral sediment drift fed by Ukrainian rivers (Dniester, Dnieper and Southern Bug).

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 coastline for this period of time.

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 F (~11,000 - 9,000 yr. BP) (Fig. 5).

The St. George I Delta

A pass existed between the southern end of the *Initial Spit* and the Murighiol-Dunavăţ 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. 6) and its development lasted for about 2 000 years (~ 9,000 - 7,000 yr. BP).

Only the northern wing of this delta is nowadays preserved. This wing is represented by the *Caraorman Accumulative Formation*, built by juxtaposition of a large number of paleo-beach ridges. These ridges were formed exclusively of sandy sediments from Ukrainian rivers transported along the seashore by littoral drift. The progradation of the St. George I Delta coastline was of some 10 km in about two thousand years. At the end of this phase the Paleo-St. George distributary was partially clogged and a new distributary named Sulina was formed.

The Sulina Delta

The newly formed distributary had broken the Initial Spit at some 20 km north of the Paleo-St. George mouth zone and started to build its own delta – the *Sulina Delta*. The development of the Sulina Delta lasted about 5 000 years (after Panin *et al.*, 1983, from 7 200 to 2 000 yr. BP). Initially, its evolution was slow and its shape was controlled by waves and littoral drift. The progressive increase of sediment discharge of the Sulina distributary caused a significant progradation of the Sulina Delta front, which became lobate over time with three and then five distributaries.

The maximum progradation of the Sulina Delta into the sea (Fig. 7) (the Sulina Delta front was 10-15 km offshore from the present shoreline), coincides with the Phanagorian regression when the sea level was at -2 to -4 m elevation. The total progradation of the Sulina Delta front during these 5,000 yr. was of about 30 km.

Detailed descriptions of the structure of the two wings of the Sulina Delta are given in previous papers (Panin, 1989, 1996, 1997).

At the end of the Sulina Delta Phase, at about 3,000 yr. BP the Sulina distributary was partially clogged and lost its prevalent importance in the delta system and this determined a gradual erosion and retreat of the Sulina delta front. At that time, the St. George distributary was reactivated in the south and a new distributary, the Kilia one, in the north, was formed. Both these distributaries started to build their deltas.

The Saint George II Delta

The formation and the development of the St. George II Delta took place during the past ~3,000 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 progradation of the delta shoreline (Fig. 8).

The *Sărăturile Formation* has a divergent structure composed of numerous beach-ridge sets. The divergent structure is due to the coastline regression in the north as the Sulina Delta was subject to continuous erosion, while in the south the coast was prograding with the development of the St. George II Delta. The southern wing 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. 3,000 yr. BP. The latest ridge is the arcuate lateral mouth bar *Sakhalin (Island Sakhalin)* that appeared in the 19th century and is rapidly developing nowadays.

The overall progradation over 3,000 yr. was of about 16-20 km, the average rate of progradation being of 8-9 m/yr.

The Kilia delta

When the Kilia distributary reached and broke the Initial Spit (about 2,500 yr. ago), a new depocentre, the Kilia Delta, began to develop. At the beginning the progradation was very slow as the Kilia sediment supply was small. During this period the Kilia delta was of a wave-dominated type. About 1,000 yr. ago the Kilia distributary reached a predominant importance in the delta system, its sediment supply gradually increased and the Kilia Delta became lobated (Fig. 8). The most rapid progradation occurred in the last five centuries and will be discussed further. The sandy sediments supplied by the littoral drift system from the Ukrainian rivers stops north of the Kilia Delta forming the Jebriani Formation ridges. The total progradation of the Kilia delta in 2,500 yr. is of about 18 km.

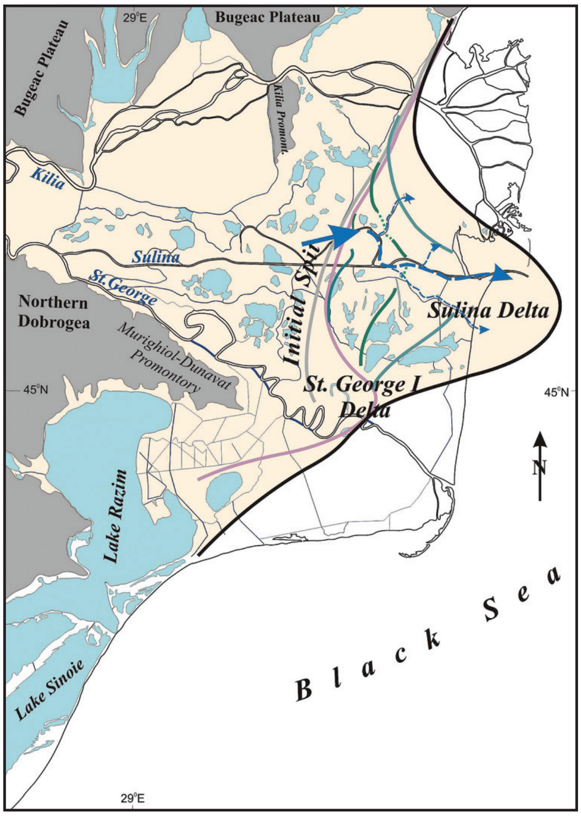

Fig. 7 Danube Delta coastline position at the maximum progradation of the Sulina Delta phase

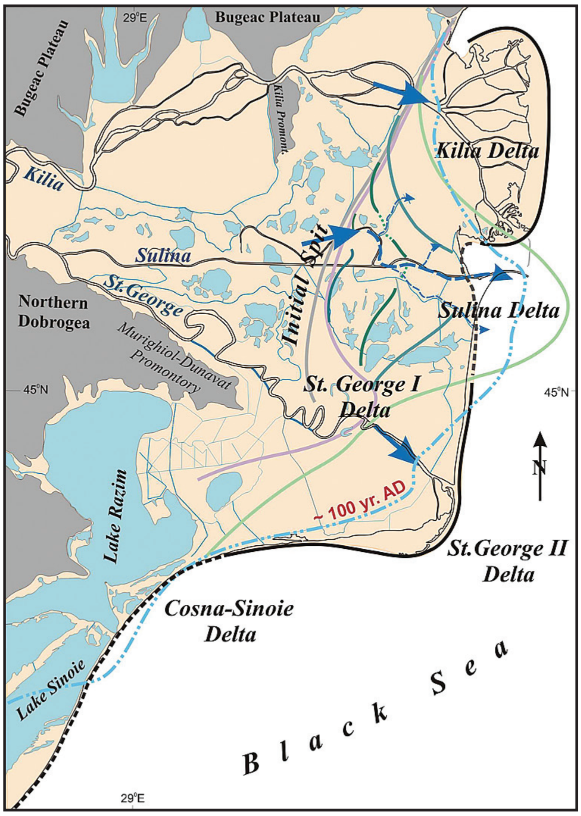

Fig. 8 Danube Delta coastline position at the present-day progradation of the Kilia and St. George II Deltas

Sinoie Delta

In the southern Danube Delta territory, during the period from 3 500 to 1 500 yr. BP, there was a secondary delta, the Sinoie Delta (Fig. 9). Two successive development stages could be evidenced: *Cosna* and *Sinoie* Deltas. These two deltas are, in fact, formed by a secondary distributary, the *Dunavăţ*. 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* sets of beach ridges were synchronous with the existence of the Istria Greek and Roman colony (~VII century BC to ~VII century A.D.) on the western coast of the Black Sea. The sediments eroded from the *Sinoie Delta* and drifted southwards caused the decline and, at the end, the collapse of the town of Istria at about 700 yr. A.D.

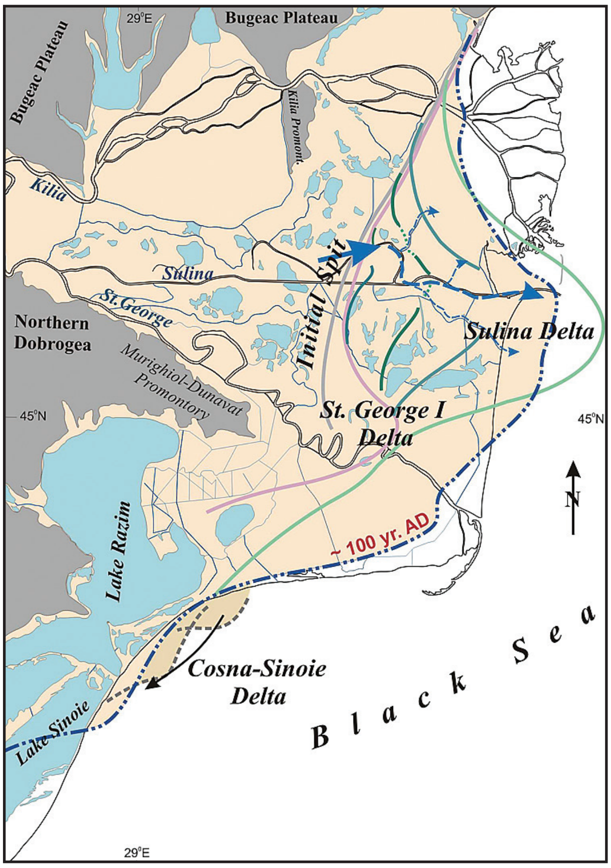

Fig. 9 Danube Delta coastline position during the Cosna-Sinoie Delta phase. The coastline at ~ 100 yr.AD is also shown.

1.2 Hydrographical Network Changes

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

Main distributaries of the Danube Delta – short description

The delta starts at the first bifurcation of the Danube – Ceatal Izmail (Mile 43 from the mouth zone, measured along the Sulina distributary). The river forks into the *Kilia distributary* to the North and the *Tulcea distributary* to the South.

At present, 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 two depressions occur: they are named *Pardina* and *Babina-Cerneovca*. Here the distributary becomes braided and then anostomoused. At its mouth zone 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.

The *Tulcea distributary* stretches from the Ceatal Izmail knot 17 km to the east 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* flows eastward 71.7 km (present-day length, including the 8 km of jetties at the mouth of the arm) towards the Black Sea. The Sulina distributary present-day physiography results from a large cut-off programme carried out during the 1868-1902 interval by the European Danube Commission and will be discussed below. 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 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* starting from the hydrographic knot at Ceatal Sfântu Gheorghe has 108.8 km until the sea. The distributary flows some 15-20 km along the North Dobrogean unit formed of old geological formations that represent a hard to erode "wall" and influence the river physiography. The course of the St.George branch can be subdivided into three sections (Panin, 1976): (1) the Dobrogean section of limited meandering (between km 104 and km 90), (2) 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 (3) the downstream section of limited meandering (between km 22 and km 0).

The St. George meander loops were rectified in the 1981-1992 interval; these cut-offs lead to a shortening of the distributary by about 31 km and, consequently, increased the free water surface slope and waterflow 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. 10) with two secondary branches that fork at km 5: the prolongation of the main St. George channel (also called in historical documents *Kedrilles*) and the *Olinca* branch on the right. This latter branch bifurcates into two small branches: the *Seredne* on the left, about 3.5 km long (already clogged today), and the *Turetzkii (or Gârla Turcului)* on the right, some 4.5 km in length. There were two periods when the St. George distributary formed secondary lobate deltas (Fig. 10): 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 has been growing until now.

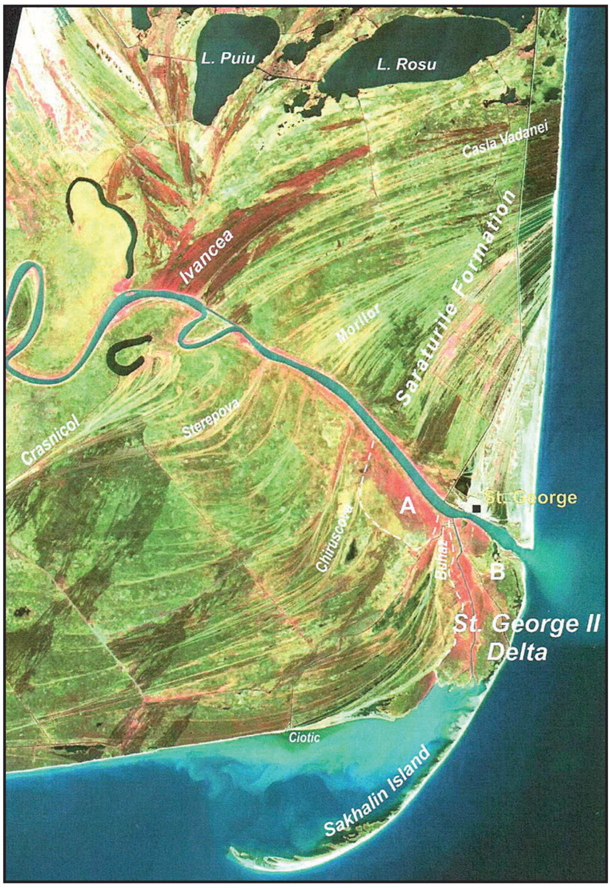

Fig. 10 The secondary delta of the St. George distributary. The two successive secondary deltas "A" and "B" are shown. Landsat Satellite image.

The evolution of the hydrographic network in Holocene

The bifurcation of the Danube River at the first hydrographic knot occurred probably during the "Danube Blocked Delta". The northern distributary - Paleo-Kilia, during this period appears to have been less important, with a smaller discharge than the southern one - Paleo-Tulcea branch. The southern branch evolution was influenced by the land of the northern Dobrogea: there were four impingements against Dobrogea - the first at Tulcea, the second, at about 7 km downstream, at Nufăru (Preslav or Periaslavetz), followed by Carasuhat and Mahmudia impingements (Panin, 1976). After the impingement at Preslav, (km.104 upstream the mouth zone of St. George arm) the distributary divided into two distributaries - Paleo-St. George (southern branch) and Paleo-Sulina (northern branch) as a result of disturbed flow conditions that occurred immediately after the impingement. Consequently, initially the second hydrographical knot (Ceatal St. George) was located few kilometre downstream the present-day bifurcation point, immediately after Preslav. The Paleo-St.George branch became the most important and active distributary for a long period and was responsible for the formation of the first Danube Delta, the St. George I Delta.

The Kilia distributary flowed northwards, stroke against the Bugeac Plateau in the Izmail area, where it changed the flow direction towards east, probably, along the Stipoc lacustrine spit and then followed the present-day course of the Sontea channel to join 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 wavelength (λ), amplitudes (α) of 5-7 km and curvature indices r_m/w exceeding 2.0 (Panin, 1976) (Fig. 11).

Only by the end of Phanagorian regression, when the sea level lowered by few meters (-2 ÷ -4 m) and the relief energy increased, the *St. George* distributary 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. 11). Then the excessive length of the distributary channel and associated low relief energy led to a partial clogging of the *Paleo-St.George* which lost its major role in the hydrographic system of the delta during the following period. The Paleo-Sulina branch gradually became the most important distributary (for a period of almost 5 000 yr.) and some 6 000 – 7 000 yr. BP broke the initial spit in the Răducu area, starting to build the "Sulina Delta" (Fig.11). 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).

The Kilia distributary may have derived its present course at 3 000 – 3 500 years BP. The area north of Stipoc spit, the Pardina Depression, was occupied by the Lake Thiagola, mentioned by the ancients *(among them Ptolemy or Claudios Ptolemaios* - ~90-168 AD), that was a lagoon formed in the drowned valleys coming from the Bugeac Plateau (Panin, 1983) (Fig. 12). The Kilia arm entered the Pardina Depression, probably, after exceptionally high water in the Danube River and Gulf. 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.

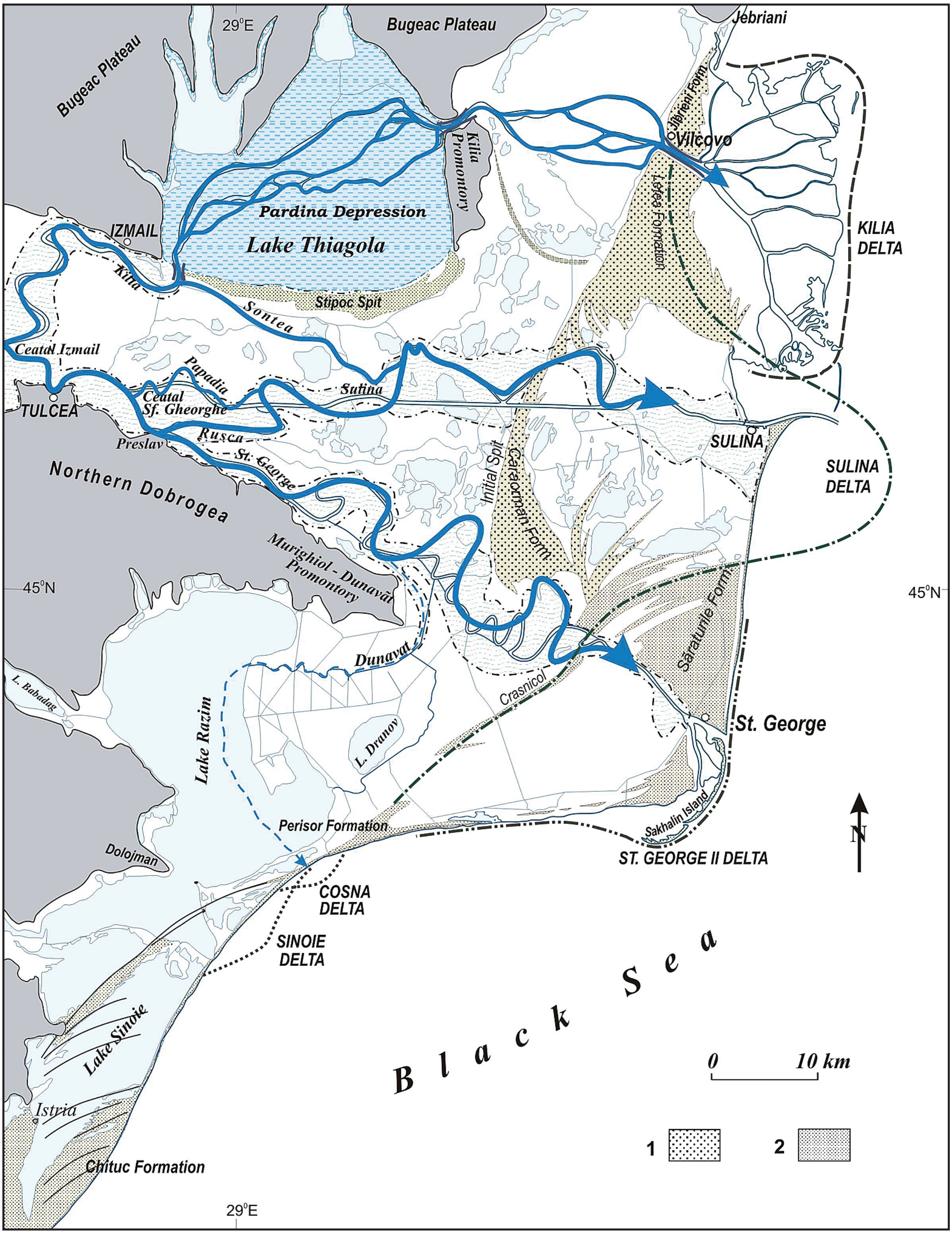

Fig. 11 Hypothetical courses of Paleo – St. George, Paleo – Sulina and Paleo-Kilia distributaries (after Panin, 1976 with completions)

Legend: **1**. Dnieper and Dniester - born sandy deposits transported by the longshore sediment drift; **2.** Danube - born sediments redistributed along shore.

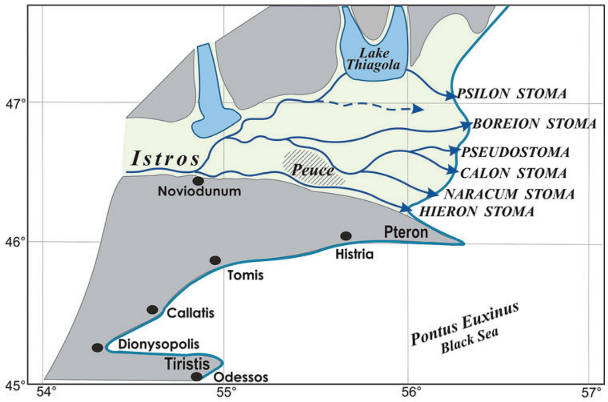

Fig. 12 Sketch of the Danube Delta as Ptolemy described it (from Panin, 1983)

2. ANTHROPOGENIC CHANGES OF THE MAIN HYDROGRAPHIC SYSTEM OF THE DELTA

The man-made changes of the Danube Delta can be precisely evaluated using cartographic documents stored in different libraries and archives. The most relevant cartographic documents are dated from the middle of the 19th century. Few maps of the 18th century are also available, but the accuracy of referencing system is not good enough. Consequently we shall present the main phases of delta front modern development based on the 19th and 20th centuries documents.

Short historical overview

The ancients visited, described and mapped the Danube Delta and neighbouring regions quite in detail. There are attempts to evaluate and reconsider these ancient geographic descriptions and their accuracy especially in measuring distances among distributaries existing at that time (Panin, 1983). The ancient data are remarkable; neverthless, it is difficult to make a referenced evaluation of the coastline position migration since that time.

The maps of the Dark Ages give us some information but it is very difficult to evaluate the changes in the morphology of the delta. There are maps that are not very precise copies of older ancient maps. We have considered that the maps of 1771 and 1778 can be taken as a departure point of the assessment.

After the Crimean War, the Paris Peace Treaty of 1856 stipulated that the Black Sea became an Open Sea and also the free international navigation on the Danube. Since 1856 two international bodies were created – the *Danube European Commission* for improving the navigation at the Danube River mouth zone and along the lower course of the river and the *Commission of river riparian countries* for working out the legal aspects of the Danube international waterway and for ensuring the control of all the economic activities related to the Danube. Sir Charles Hartley was nominated chief engineer of the International Commission. The most important task of the Commission and of Sir Hartley was to improve the navigation along the Lower Danube, especially to open one of the Danube Delta distributaries for vessels coming from the sea. Extensive research and mapping works were performed in 1856 by a British ship, H.M.S.V. *Medina*, under the command of Captain Spratt assisted by Lieutenant Wilkinson and Master Millard.

The International Danube Commission went into detailed discussion about the choice of the river mouth that would be used for sea-river navigation and about what should be done for improving it. The Kilia delta distributaries, with their large and shallow delta front platform, many sandbanks and very active sedimentation were immediately rejected. Sir Hartley was in favour of St. George distributary mouth where the underwater slope of the coast was steep enough and the littoral drift current very strong and consequently the river-borne sediments would easily be transported away alongshore southwards. Nevertheless a provisional and compromise solution was accepted: in 1857, Sir Hartley was commissioned to make a first and cheapest step to improve navigation at the Danube mouth by dredging the Sulina mouth bar and by building funnel-like jetties on both sides of the mouth for increasing the current velocity and washing out the sediments supplied by the river from the mouth bar (Fig. 13). As these works were successful, in 1864, the Commission decided to continue the works for improving the navigation along Sulina distributary. A large programme of Sulina distributary meander belts cut-off have been performed that resulted in almost 25 km shortening of the waterway and in more than 10% increasing of the Sulina's water and sediment discharge. Additionally, the Commission decided to build at the delta apex (Ceatal Izmail bifurcation), a longitudinal embankment of some 430 m for protecting the left bank of the Tulcea distributary. The embankment had also the role to divert a part of the Danube water flux towards the Tulcea – Sulina waterways (Fig. 15).

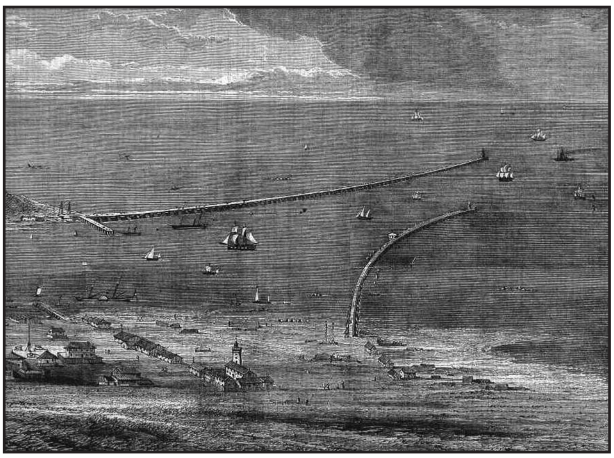

Fig. 13 The first phase of Sulina mouth jetties building (engraving, 1857)

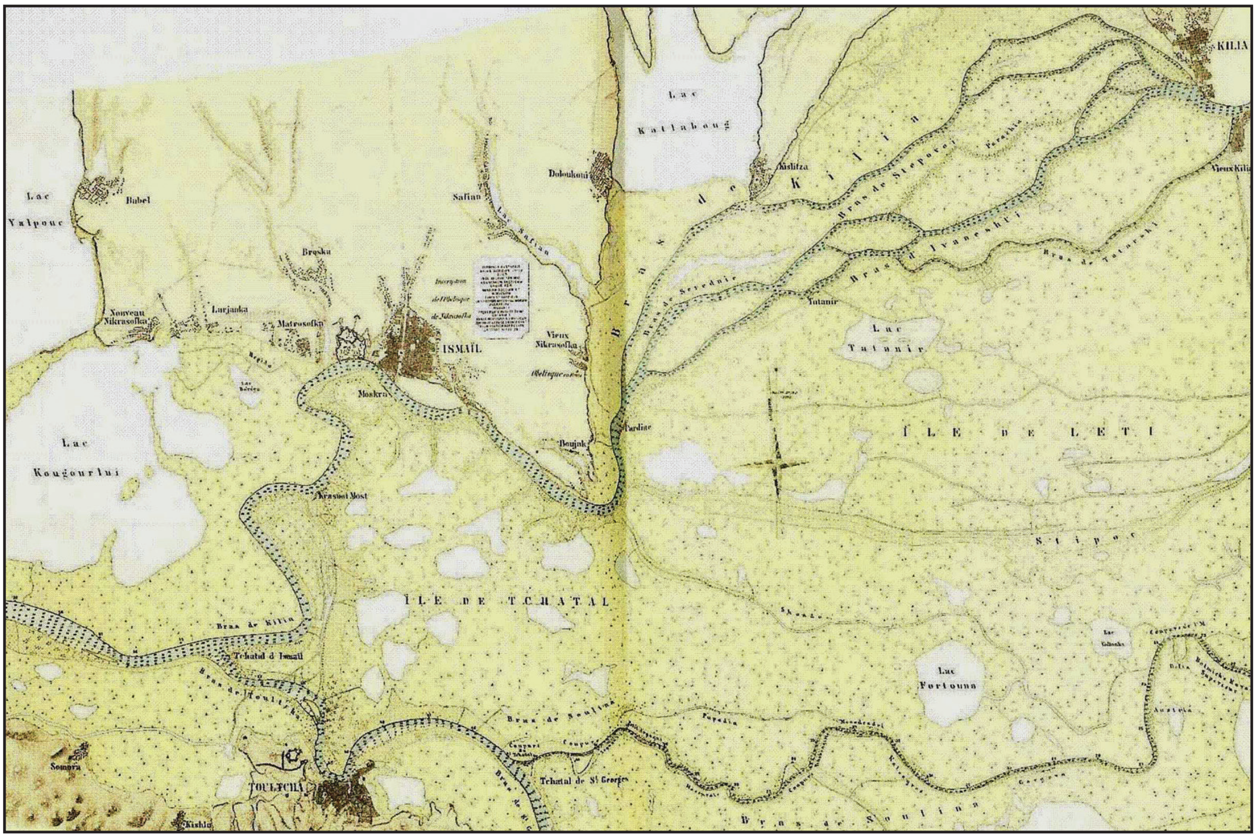

Fig. 14 The map of the upper part of the delta and the two main hydrographic knots Ceatal Izmail (the delta apex) and the Ceatal St.George (Danube European Commission, 1870–1871, with completions in 1886)

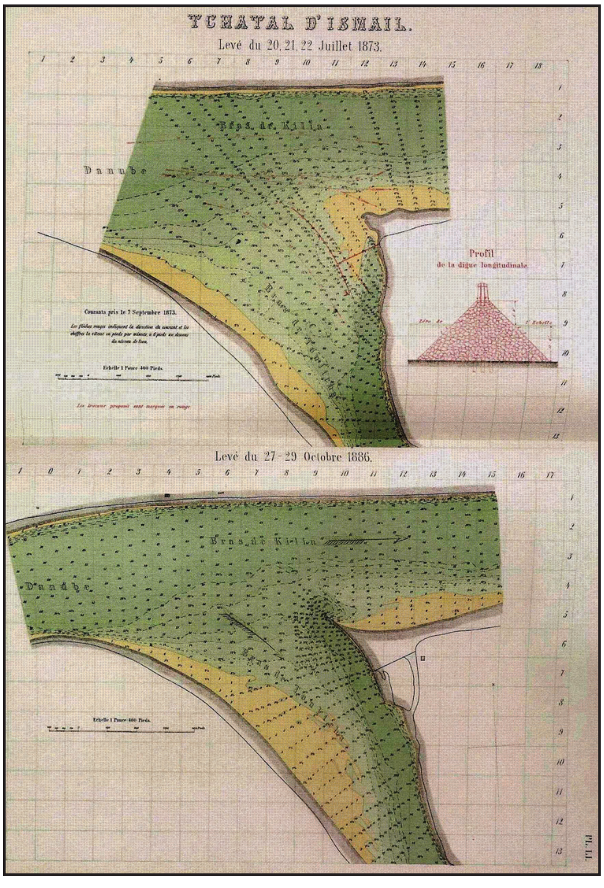

Fig. 15 The longitudinal embankment built by the Danube Commission by 1886 at Ceatal Izmail for protecting the left bank and diverting more water towards Tulcea - Sulina distributaries. Drawing by Danube International Commission.

We shall present below some maps and drawings resulted from Sir Hartley's studies illustrating how large were the works fulfilled under the coordination of the Danube European Commission (Figs. 14, 16, 17). The anthropogenic changes of the main hydrographic system of the Danube Delta can be summarised as follows.

A. Sulina distributary

The Sulina meander belt cut-off programme was fulfilled during 1858-1902 period. This programme shortened the Sulina branch by about 25% (83.8 km before the cut-offs and only 71 km nowadays) and this induced an enlargement of the water discharge of the distributary from about 7-9 % of the total Danube discharge around 1860 to almost 15% in 1928 and about 20% nowadays. Some of these cut-offs are illustrated in Figs. 18, 19, 20, 21 (see also Table 2).

The hydrotechnical works carried out along the Sulina distributary determined the deepening in time of the river channel from less than 2.5 m as it was in 1857 to at least 9.5 m in the 1959. The shortening (that caused a steeper slope of the distributary) and deepening of the river channel radically changed the hydrological regime of the Danube Delta by increasing the water discharge of the Sulina arm.

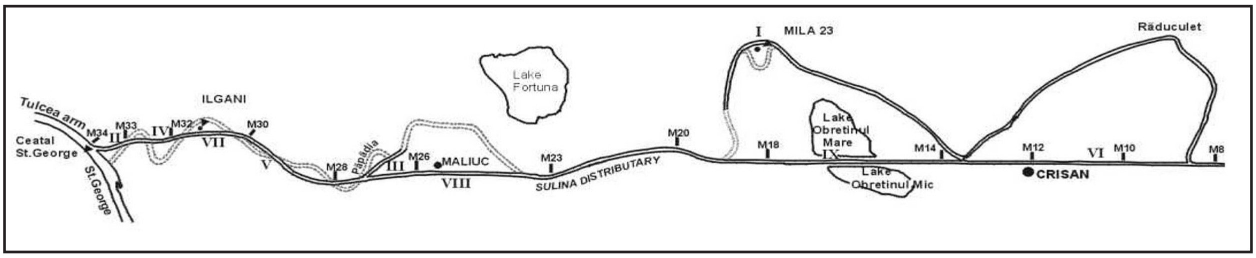

Fig. 16 Cut-off works of the Sulina distributary meander belts in 1868-1902 period.

Table 2 European Danube Commission cut-off works carried out along the Sulina distributary

Succession of works	Period	Length of cut-off (km)	Channel location
I	1868 - 1869	0.6	"Little M" meander bend, nearby the village "Mila 23" (Fig. 18)
II	1880 - 1882	1.0	Ceatal St. George (Fig. 19)
III	1883 - 1884	0.9	"Păpădia" meander bend (Fig. 20)
IV	1885 - 1886	2.0	Miles 32 – 33
V	1886 - 1889	2.1	Miles 28 – 30
VI	1890 - 1893	9.7	Downstream half of the "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 the "Big M" meander bend

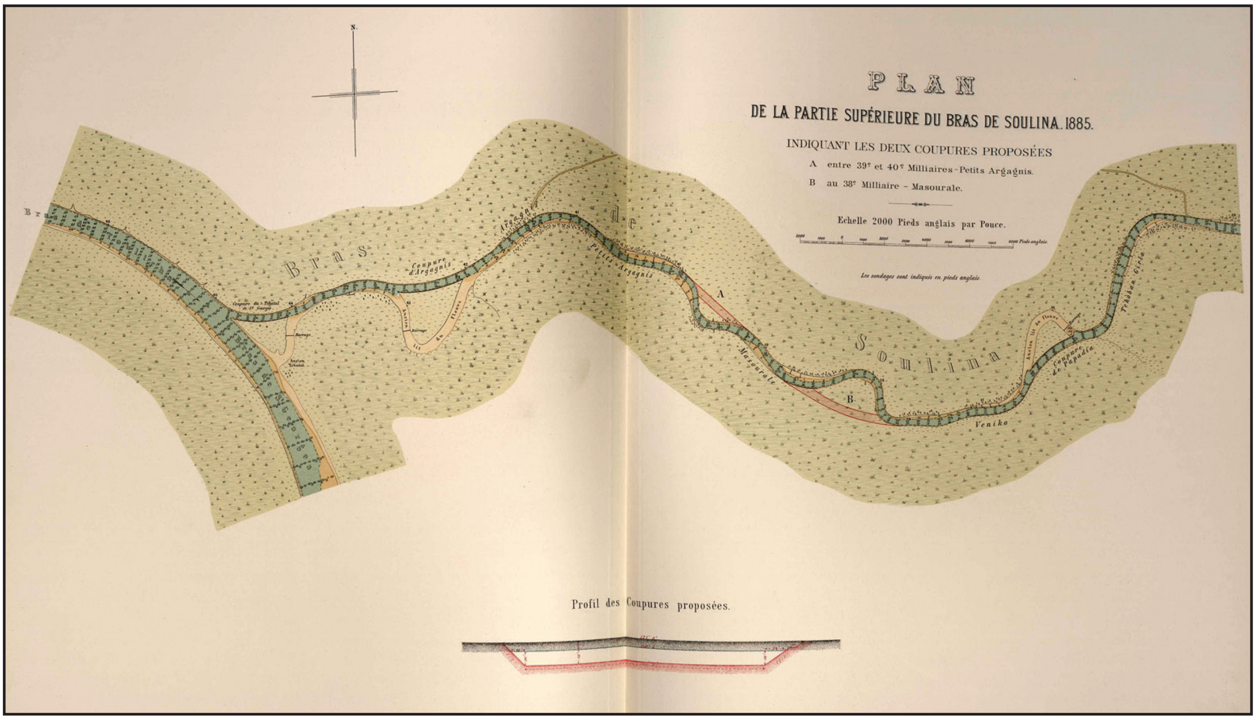

Fig. 17 The upstream part of the Sulina distributary and the cut-offs performed by the European Danube Commission (map of 1885)

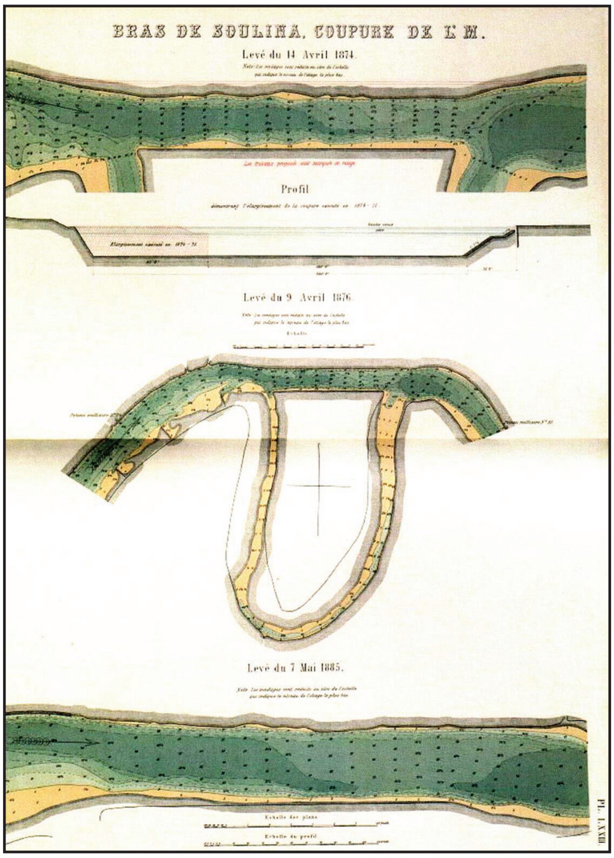

Fig. 18 The "Little M" meander belt cut-off

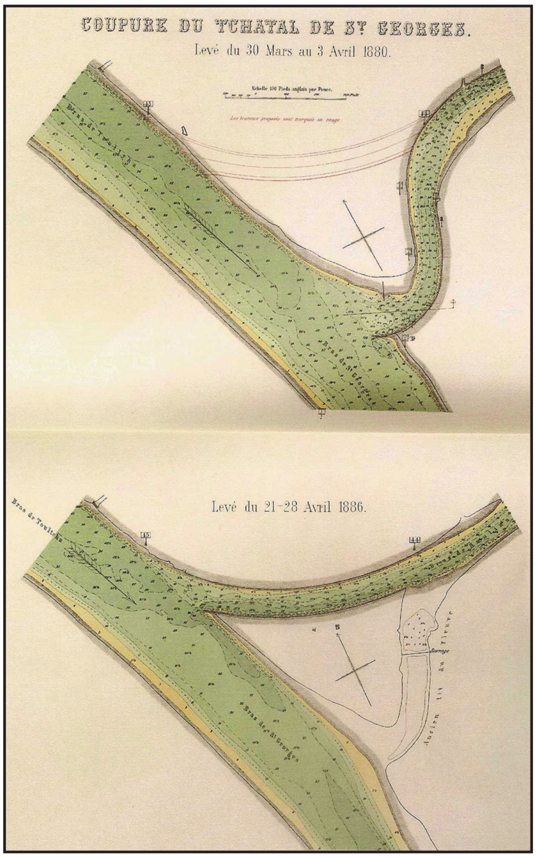

Fig. 19 The cut-off at the Ceatal St. George (1880)

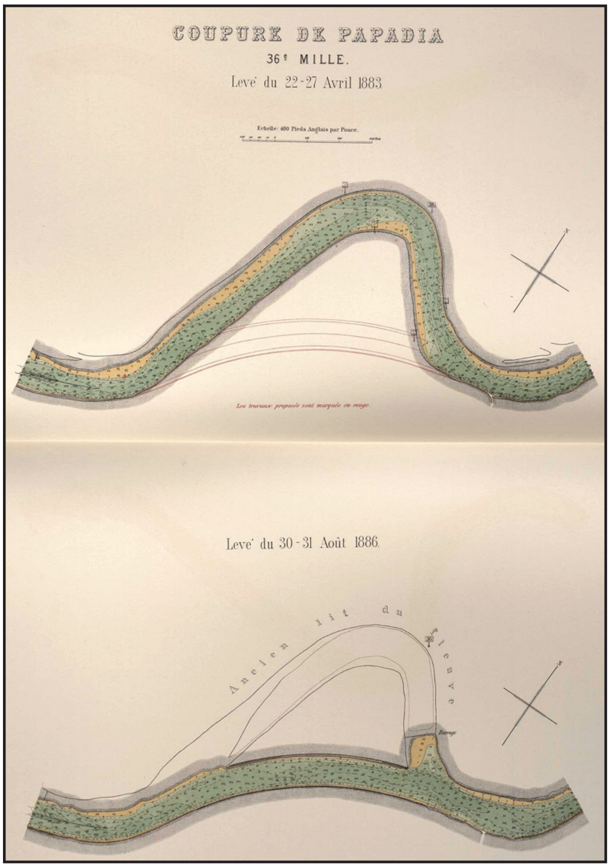

Fig. 20 The "Păpădia" meander belt cut-off

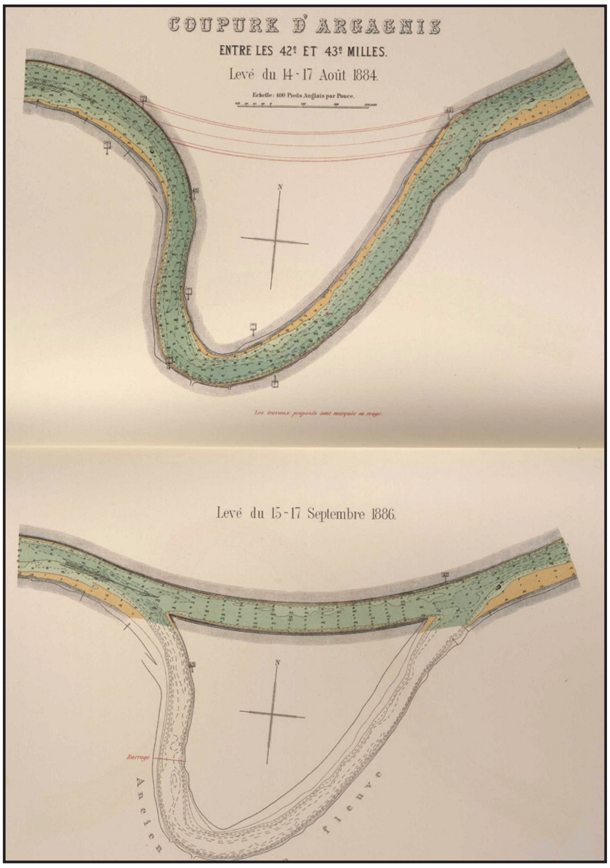

Fig. 21 The "Argagnis" (Ilgani) meander belt cut-off

Most of the meander belts of the former Sulina distributary were closed by dams. Only few remained connected to the main Sulina branch channel; among these are to be noticed the Maliuc meander, connected to Sulina channel at Mile 23.7 and the "Great M" meander belt, called "Dunarea Veche" (The Old Danube), connected at Mile 13.5 and at Mile 8.4.

B. St. George distributary

In the 1981-1992 interval another important meander cut-off programme was carried out on the St. George arm. The table 3 shows the succession of cut-off works.

These works lead to the distributary shortening by about 32 km and, consequently, the water and sediment discharges of the distributary started to increase (until now, the St. Georges discharge value has increased by 5-10%, being about 30% of the total Danube discharge). The table below (Table 3) shows the phases of works and the lengths of the cut-off.

C. Major canals cut in the Danube Delta

The Danube Delta was affected by different works in order to open the fresh water supply to different zones of the territory or to facilitate the navigation and access to other areas. Among these canals the following had an important impact on the environment:

- The canal "King Charles I" (canalul "Regele Carol I") was dredged in 1906 on 23 km for rectifying a small, secondary, distributary Dunavăţ that at that time was almost completely clogged. The works were done in order to increase the fresh water supply to the Razelm lagoon and,

Table 3 The cut-off programme for rectifying the St. Georges distributary meander belts (C. Bondar, personal communication)

Phases of works	Period of work	Name of the meander belt: location (km from the distributary mouth) of the upstream and downstream ends of the meanders	Length of water course (km)		Course shortening (km)
			Natural course	Cut-offs	
1	1981-1992	Ivancea: 19.75-16.05	3.70	1.50	2.20
2	1984-1988	Mahmudia: 84.0-64.0	20.00	4.50	15.50
3	1985-1989	Dunavăţ: 58.1-54.7	3.40	1.65	1.75
4	1986-1989	Perivolovca: 53.85-49.5	4.35	1.67	2.68
5	1987-1991	Dranov: 43.8-38.3	5.50	2.40	3.10
6	1988-1992	km 37: 37.8-29.25	8.55	1.20	7.35
Total	**1981-1992**		**45.5**	**12.92**	**32.58**

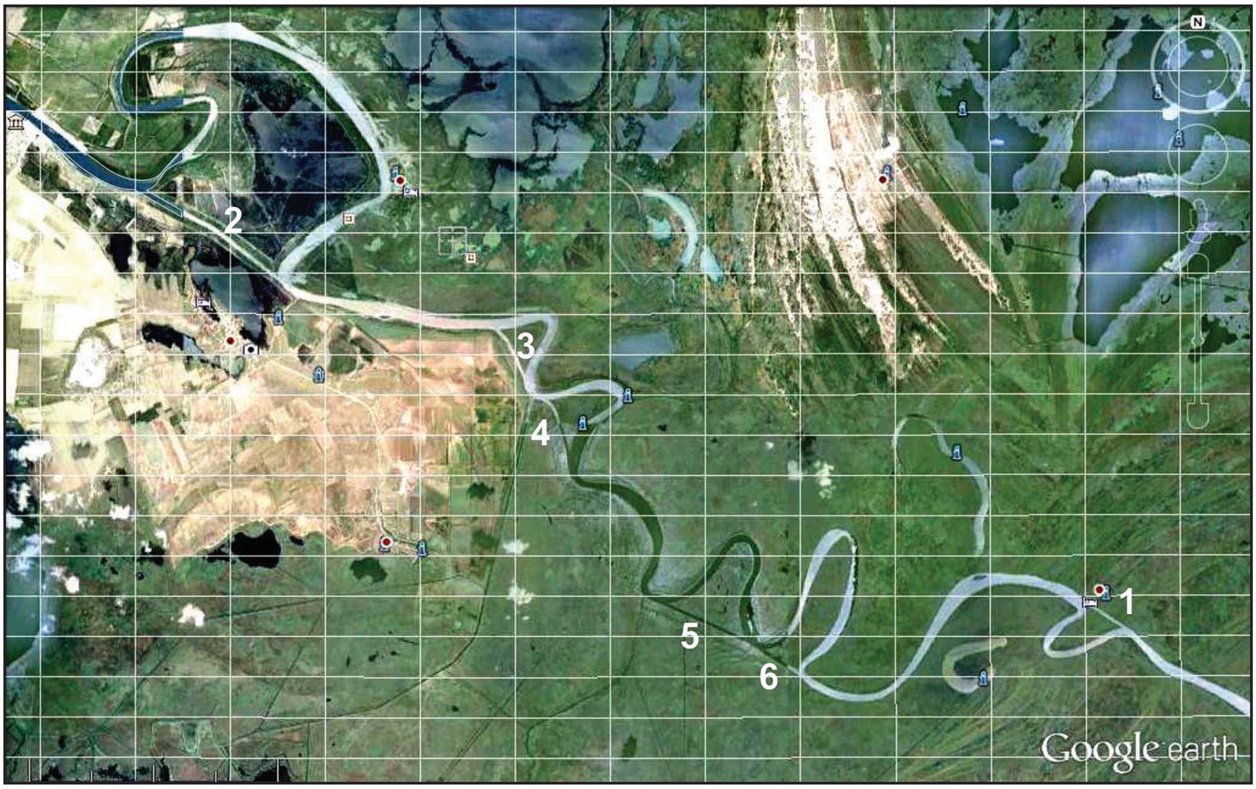

Fig. 22 The St. George distributary – the meander belts cut-off programme (1981 – 1992). Google Earth image

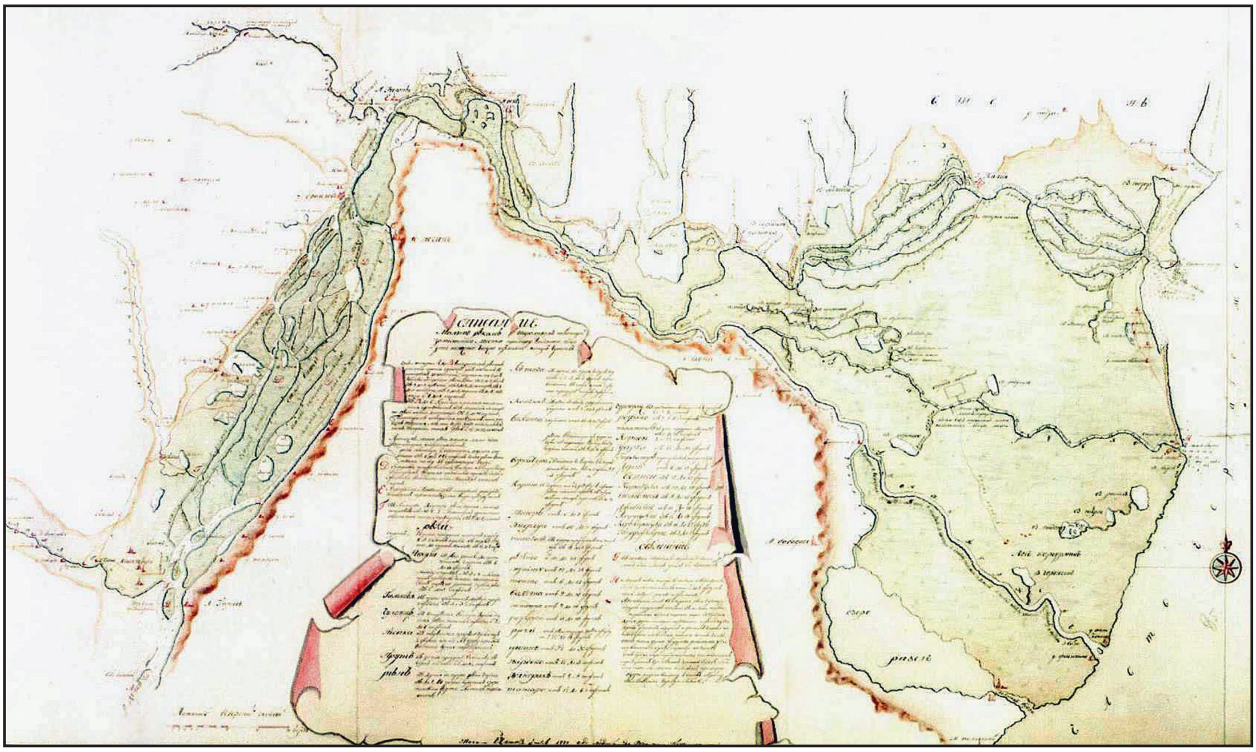

Fig. 23 The Russian map of 1771. The lower course of the Danube River and the Danube Delta are shown.

consequently, improve the environmental condition for fish farming. After digging this canal the water discharge of the Dunavăț increased to 100 – 150 m^3/s.

- The canal "King Ferdinand" was cut in 1911 – 1914 along 28 km for opening a waterway to the Lake Dranov area and finally, to the Razelm lagoon.
- The canal "Mila 36" was cut in 1983-1985 for facilitating the access from the Tulcea distributary (Tulcea city) to the Kilia distributary (Kilia Veche – Old Kilia village).

D. Other man-made works that had influenced the Danube River – Black Sea system

In 1970 and 1983 the Danube River was dammed two times at Iron Gates I and Iron Gates II and consequently the total river sediment supply decreased by about 40%. This had an adverse impact on the sedimentary budget of the delta coastal zone that became unbalanced and strong erosion of delta front started.

There are many other anthropogenic structures along the lower course of the Danube that have influenced the environmental state of the region but to pass in review these works is not the aim of the present paper.

3. THE COASTAL ZONE CHANGES OVER THE LAST THREE CENTURIES

The Coastal Zone changes in the last three centuries, can be studied using the cartographic documents stored in different archives and libraries of European countries and USA. The main maps that have been used in the present paper are: the maps of 1771 and 1778, the maps of 1856-1857 made by the Danube European Commission (sea campaigns of HMSV *Medina* under the direction of Captain Spratt), the Austrian map of 1918, the Royal Navy Chart of 1926/1936, the German map of 1944, the Soviet map of 1983, the Romanian map of 1985, the British Sea Chart of 1999 and the most recent satellite images offered by Google.

The Russian map of 1771 (University of Leiden, The Netherlands) gives information about the mouth zones of the three main distributaries of the delta as well as for the general shape of the delta coastline (Fig. 23).

This map shows that the St. George distributary mouth was already, at that time, divided into two arms by a middle ground bar (transformed into an island, called later Olinka). The mouth was marked by two signposts (Fig. 24).

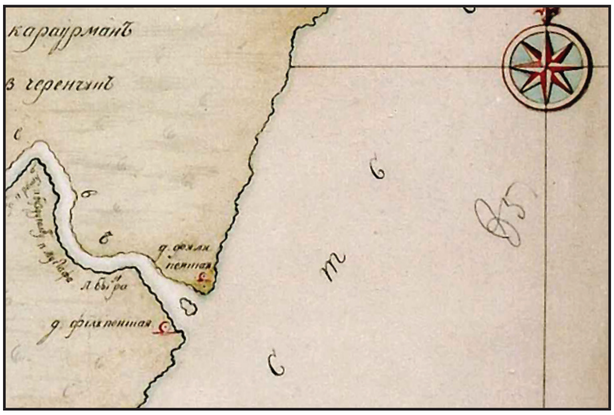

Fig. 24 The St. George distributary mouth – detail from the Russian map of 1771. (Source: University Library, Leiden NL)

The mouth of the Sulina distributary was a simple outlet towards the sea. Two signposts on both sides of the distributary mouth were in place, but, at a certain moment, were blown away by a storm. The soundings mark the two deepest passages of the river current to the sea.

The Kilia distributary entered the Black Sea some 3 000 – 2 800 yr. BP. At that time Kilia was a very small distributary and it started to build a small wave-dominated secondary delta, with a single river channel. The northern wing was constituted by the Jibriany Littoral Accumulative Formation, made

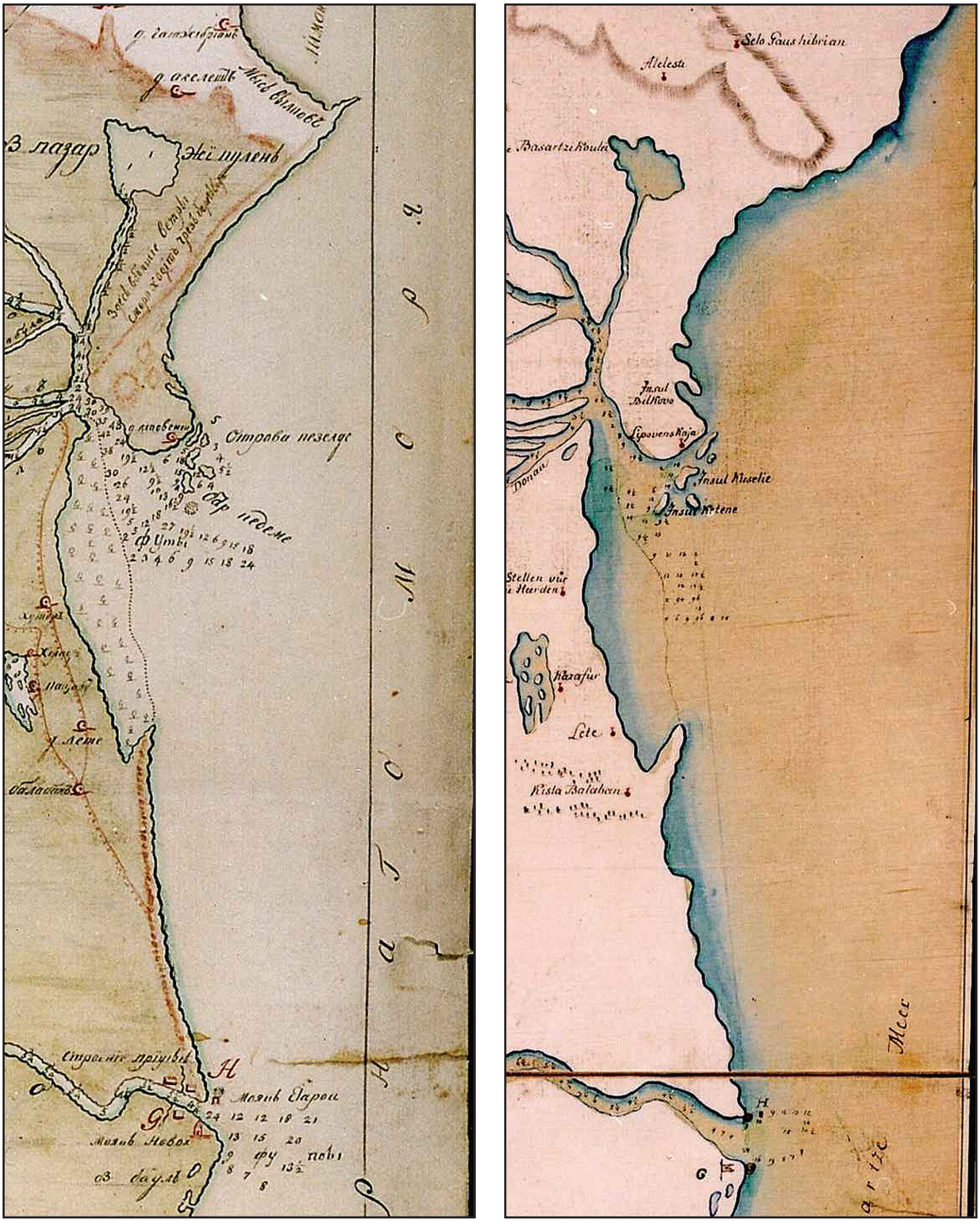

Fig. 25 Details from the maps of 1771 (left) and 1778 (right): the Kilia and Sulina distributaries mouth zones

of a large number of successive beach ridges with Dniester and Dnieper born sands drifted along the shoreline. This early wave-dominated delta developed quite rapidly into a lobate Kilia delta that continued to prograde very quickly after 1800. The map of 1771 shows the beginning of this stage of the Kilia Delta quick development. The Kilia distributary is still not divided but it seems that two main channels can already be evidenced. In front of the Kilia mouth there were a number of islands (probably mid-ground bars) that will be points of bifurcation of different secondary distributaries in the next phases of delta development. The Kilia distributary on its right side had a marshy area next to the Letea Formation. The map shows also the "Lipovenskaya" village (the village of Lipovens), later Vilkovo. There is a warning written on the map, north of Jibriany Formation, saying that when very strong winds are blowing the beach barrier is over-washed by stormy waves (Fig. 25, figure at the left).

In the Austrian National Archive in Wien, there is another map in German language, edited in 1778, which seems to be a quite rough copy of the 1771 map (Fig. 25, figure at the right).

The map of 1778 gives a quite complicated and distorted image of the two zones where the Kilia distributary becomes braided and then anostomoused – the Pardina depression and the Babina-Cerneovca area (Fig. 26).

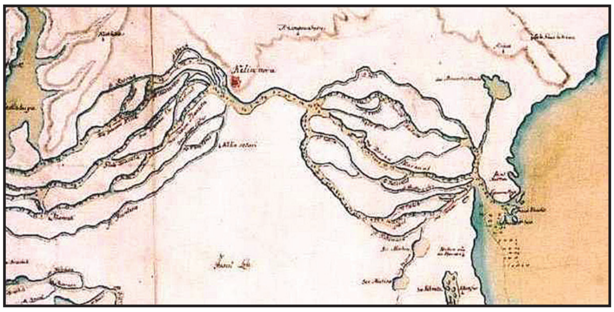

Fig. 26 Braided and anostomoused course of the Kilia distributary in the Pardina Depression and in the Babina – Cerneovca area. Detail from the German map of 1778.

After about a century (1856 – 1886), the maps realised by the European Danube Commission are very detailed and precise. The bathymetric data for the mouth zones of the delta distributaries are very dense and offer an excellent image of the delta front and of the St. George, Sulina and Kilia distributaries mouth zones morphology.

On these maps, the St. George arm appears divided in two branches with a middle ground bar (Olinka Island) and a sand-bank inbetween (Fig. 27). The southernmost branch (Olinka) has a narrow main channel of about 13 feet water depth (3.96 m), surrounded by shallows of 1 – 4 feet (0.30 – 1.21 m). At about 1.5 km from the bifurcation point, the Olinka channel divides again in two smaller channels by a middle ground bar, developed later in an island, where the Commission will build a lighthouse. In front of the mouth zone of this distributary there is a wide and very shallow (1 – 3 feet, ~ 0.3 ÷ 0.9 m) delta front platform.

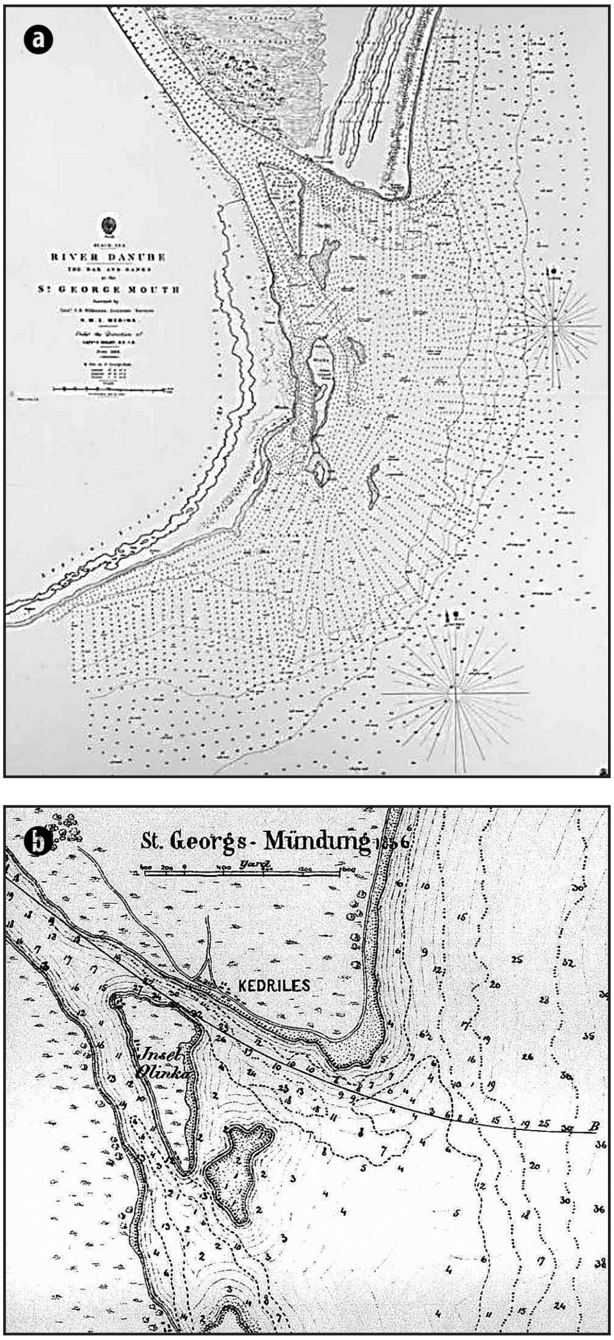

Fig. 27 The St. George mouth zone on the British map of 1856 (Sources: **a** - National Maritime Museum, London; **b** - Medina chart, Nationalbibliothek, Wien).

On the cross section (Fig. 28) through the mouth bar the dotted line of 16 feet (4.80 m) represents the needed depth for navigation. Although the St. George distributary itself is deep enough, the mouth was blocked by a massive mouth bar and by the delta front platform mentioned above with a very active sediment accumulation.

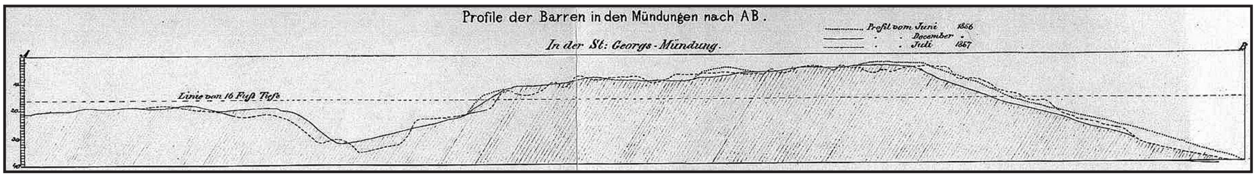

Fig. 28 The cross-section through the St. George distributary's mouth bar

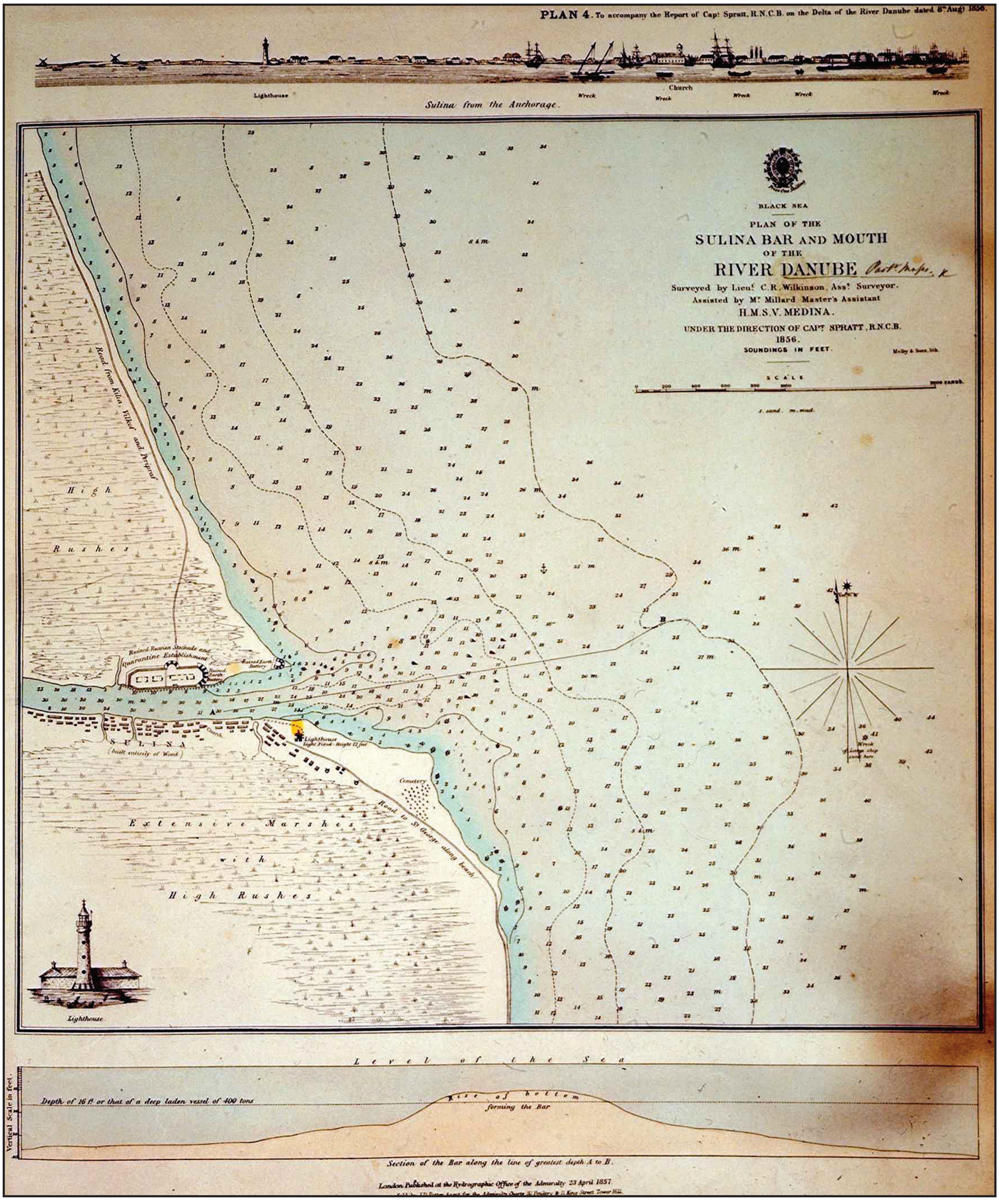

Fig. 29 The 1856 HMSV Medina map of the Sulina distributary mouth zone (British Library - London)

The CED's map of 1856 is remarkably precise and gives valuable information about the Sulina distributary mouth zone (Fig. 29). At that time the discharge of Sulina was about 7 – 9% of the Danube total discharge and the mouth zone continued to be a simple outlet with a small mouth bar. At the mouth of Sulina there were a small town of wooden houses, and a 22 feet high lighthouse located close to the mouth on the right bank.

As already mentioned, after long debates, the Danube Commission decided to choose the Sulina as a temporary solution for the navigation on the Danube River. The first action was to build inexpensive jetties that should last for a period of five years. The jetties were intended to keep the velocity of the river flow as high as possible, in order to maintain its sediment transport capacity and push the location of the mouth bar outside the river channel to greater water depth offshore. This solution was quite innovative for 1858. The construction was finished in 1861, and was very successful. The river maintained the depth over the mouth bar at 6 m without the need for dredging. In 1865, additional money became available, and the decision was taken to build new and permanent jetties at the Sulina mouth. On the CED's maps the Kilia delta appears already well developed: its morphological form is quite different from the other deltas of the Danube. This delta is a lobate one, showing that it was controlled by the river with large sediment supply – at that time Kilia was the main distributary in the delta, with water and sediment discharge close to 70 % of the total Danube discharge. The delta front had a large development with a wide delta front platform. Earlier deltas (St. George I and Sulina) (Fig. 3) and even the other contemporary delta (St. George II) are cuspate deltas, wave-controlled, built up by juxtaposition of a large number of old beach ridges where the sediments brought by the river were redistributed along the seashore.

On the British map of 1856 numerous Kilia delta distributaries are clearly seen (Fig. 30). Two of them are particularly important: the Ocheakov branch to the north, and the Stary Stambulsky branch to the southeast. Along the river branches, on the riverbanks, an alluvial gallery-forest is indicated. Within the areas between the river branches large areas are occupied by marshes and lakes. At the west side, the area between the Stary Stambulsky branch and Letea Forest, mentioned in the 1771 map description, in 1856 is already almost filled with sediments. Offshore the Kilia delta a shallow wide delta front platform is visible (with water depth of only 1 - 2 feet and up to 2 km width). At several places, exposed sandbanks are indicated as well. All these features show that in 1856 the Kilia delta was in full expansion seawards.

The newer maps are more and more precise and give an excellent image of the delta front evolution during the XXth century. Development phases of the distributary mouth zone bar and accumulative platform are clearly visible.

Though the Austrian map of 1918 (Fig. 31) that was probably drawn after the map of the Romanian Department of Fisheries of 1909 is much more elaborated showing numerous details and morphological features, including old beach ridges, littoral accumulative formations (Sărăturile, Caraorman), inter-ridge swales, natural channels, old almost abandoned distributaries, ox-bows, inter-ridge depressions and lakes etc. The St. George distributary has already built a small secondary delta with three arms – the northern one, the St. George *sensu stricto* or Kedrilles, then the Olinka that bifurcated into Seredne to the left (north) and Turcului arms to the right (south). In front of this secondary delta the same very large delta front platform and slope are present. On the platform, at its offshore limit, an exposed arcuated lateral mouth bar appeared after the exceptional centennial flood of 1897.

The bar developed into an arcuated spit, called Sakhalin Island, that had grown in about 10 years (from 1897 to 1909) some 7 km. Southwards of St. George distributary a large number of beach ridges with similar origin and development as the present-day Sakhalin spit were formed during the last about 3 000 yr.

The coastline between Sulina and St. George is, on this map, still convex, and the Imputita channel has, not far from the coast, a change of direction from NW-SE to W-E, towards the sea. On later maps this inflexion disappears as all the area was eroded.

The 1936 map of the Royal Navy (with successive corrections until 1956) shows how the St. George's mouth zone evolved in about 20 years (Fig. 32).

First the secondary delta grew into a real delta with three branches already described above. Then, the delta front platform narrowed and the platform in front the Sakhalin spit became very narrow and the front slope very steep. The Sakhalin spit lengthened to some 12 km and migrated closer to the secondary delta front.

The coastline north of St. George mouth became strait, the convexity seen on the map of 1918 between St George and Sulina disappeared.

The Romanian map of 1985 (Gâştescu and Driga, 1985) (Fig. 33) beautifully shows the morphology of the St. George II Delta: the divergent old beach ridges forming the Sărăturile Littoral Accumulative Formation on the northern side of the St. George distributary and a series of Sakhalin-like beach ridges on the southern side. The secondary delta of this distributary grew and the Sakhalin Island lengthened to about 17 km. The coastline between Sulina and St. George straightened and stepped back visibly – the Imputita channel shortened and the turn to the east described above disappeared.

The Google Earth satellite image of 2006 gives an excellent view of the St. George secondary delta evolution (Fig. 34). The Sakhalin Island lengthened over 18 km (the average yearly rate of lengthening is over 200 m). At the same time the island migrated westward by over-washing some 30 – 70 m/year. The front of the secondary delta prograded rapidly. The northern end of the Sakhalin Island entered into contact with the front of the delta and closed the Seredne branch mouth, which is nowadays almost completely clogged.

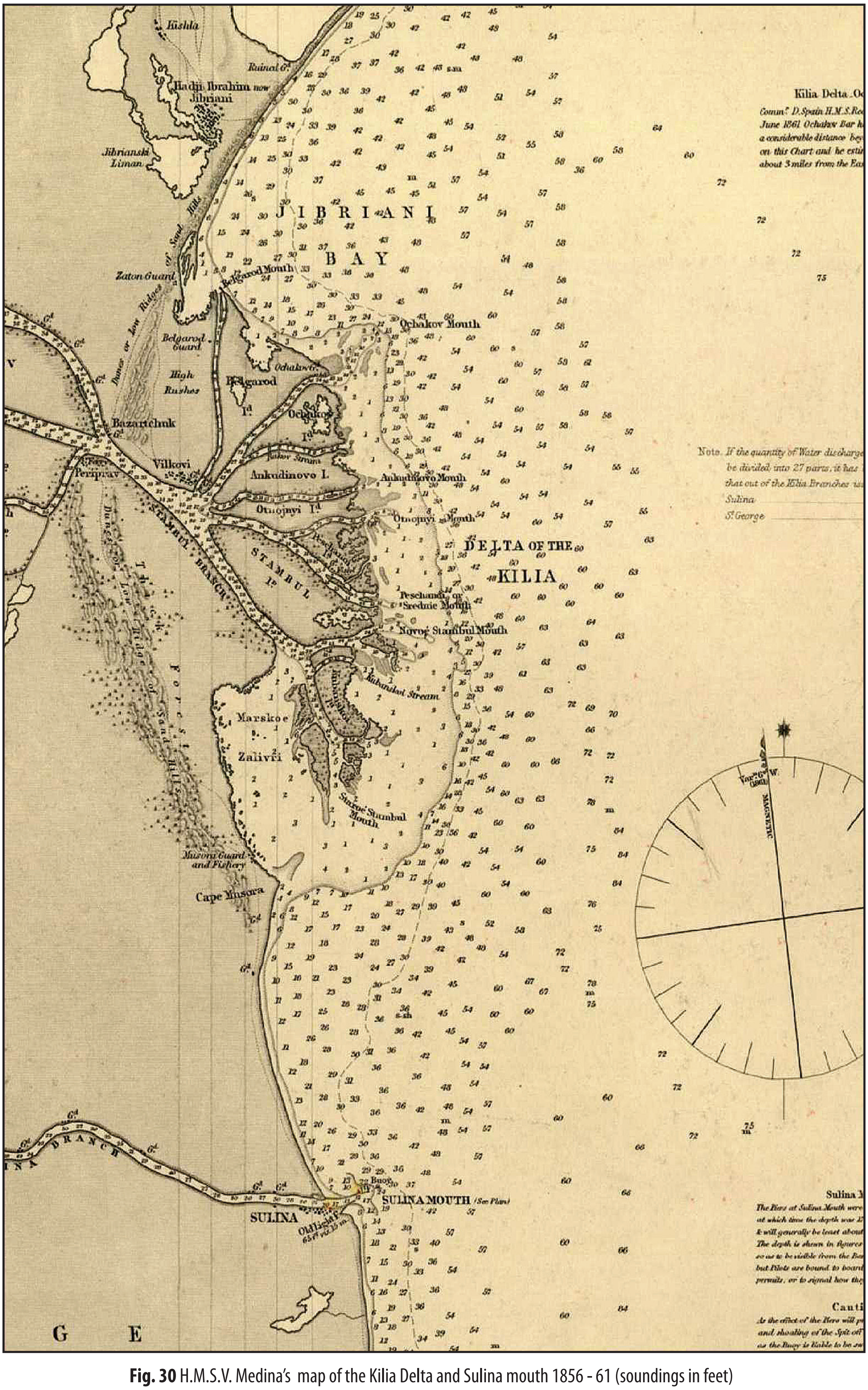

Fig. 30 H.M.S.V. Medina's map of the Kilia Delta and Sulina mouth 1856 - 61 (soundings in feet)

Fig. 31 The coastline between Sulina and St. George and the secondary St. George delta in 1918 (Austrian map)

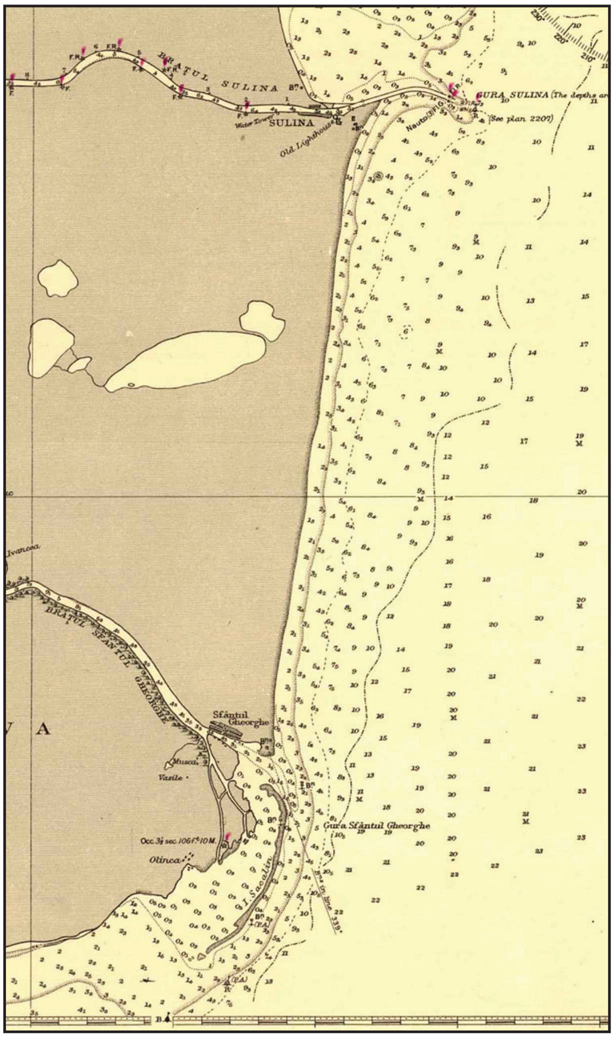

Fig. 32 The Sulina – St. George coastline in 1936 (Royal Navy Chart).

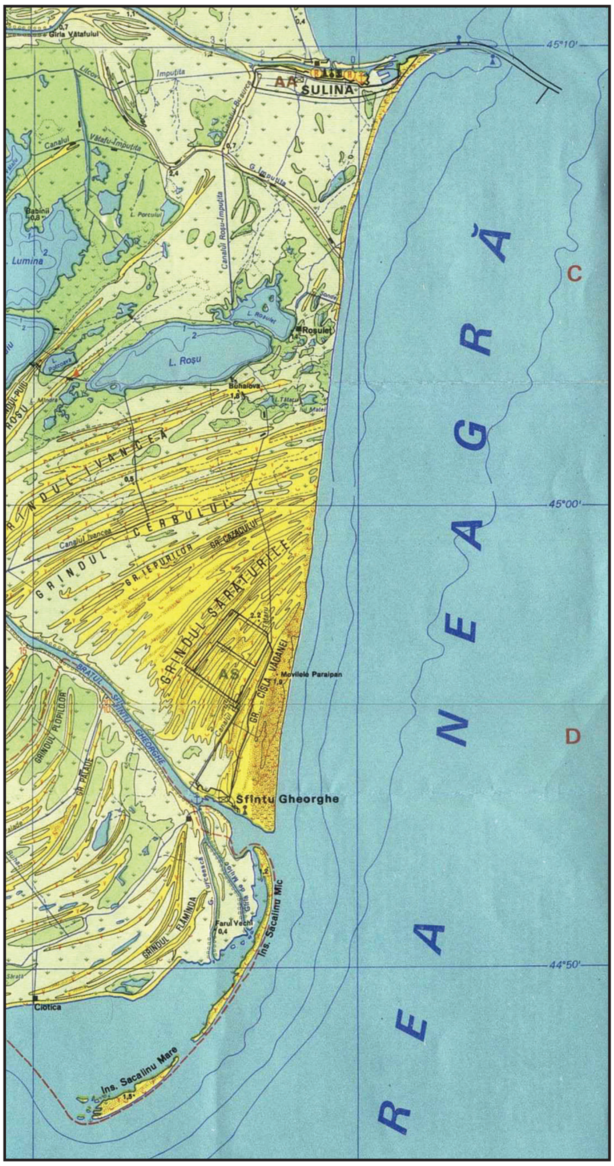

Fig. 33 The coastline between Sulina and St. George in 1985 (Romanian map, Gâștescu and Driga, 1985)

The St. George meander loops cut-offs described above triggered an increase of about 6 – 8 % in the distributary water and sediment discharge and the sedimentary budget of the coastal zone became more stable and the Sakhalin Island development became faster.

The map of 1918 shows that the old jetties at the Sulina's mouth have functioned well, but they had to be prolonged offshore every year. To the south of the mouth a considerable accumulation of sediments takes place. The area between the continuously developing Kilia Delta in the north and the Sulina jetties becomes gradually clogged. On the British Sea Chart of 1926 (Fig. 35) the Kilia delta front platform and its slope are clearly visible (there is a well marked step from water depth of 1-2 feet to 18 feet). South of the Sulina jetties an eddy-like current occurs and brings sediments to the coast.

After this first phase of jetties building the Sulina distributary mouth zone was under the influence of three sources of sediments: (1) the sedimentary load of the Sulina, (2) the Kilia-borne sediments transferred southwards by the littoral drift system and (3) the sediments brought back to Sulina's mouth by the eddy-like current generated by the jetties. This situation forced the European Danube Commission to decide the periodic lengthening of the jetties. 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. The jetties reaching such a length are influencing the dynamics of the delta front area.

The following maps (Figs. 36, 37, 38) show the elongation of jetties and changes in the location of sediment depocentres in this area.

Fig. 34 The St. George distributary mouth zone, 2006. Google Earth.

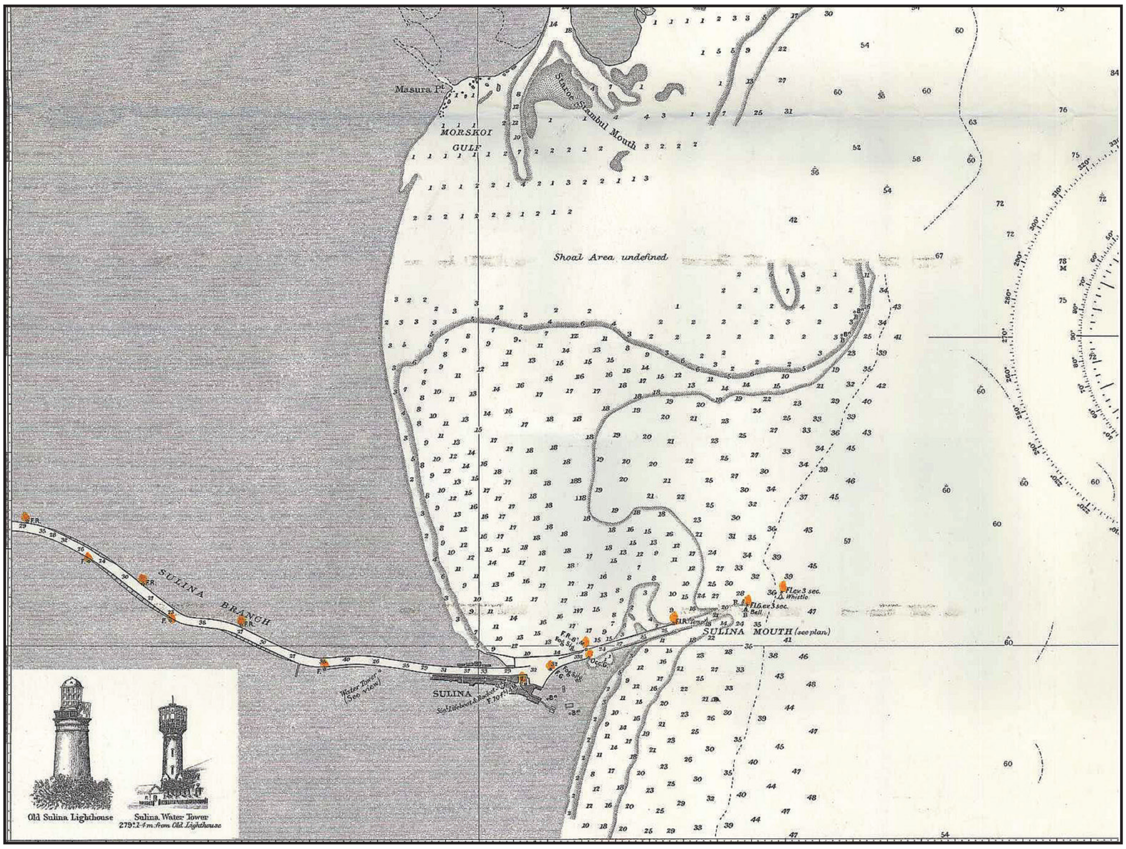

Fig. 35 Sulina mouth (jetties and harbour) and the Kilia delta front platform and slope, British Sea Chart, 1926.

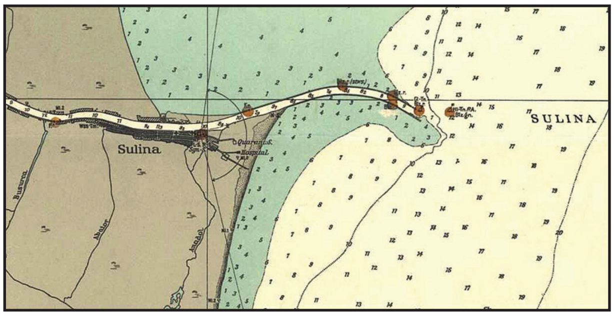

Fig. 36 The Sulina distributary mouth and Sulina harbour in 1944 (German map).

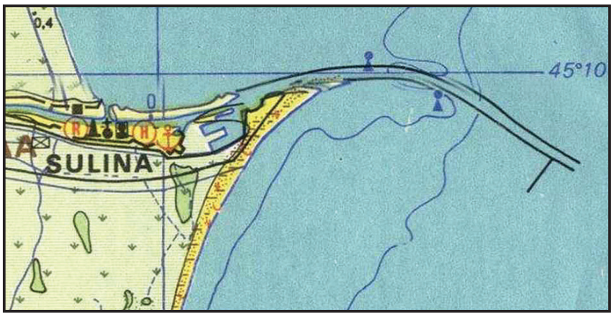

Fig. 37 The Sulina distributary mouth and Sulina harbour in 1985 (Romanian map)

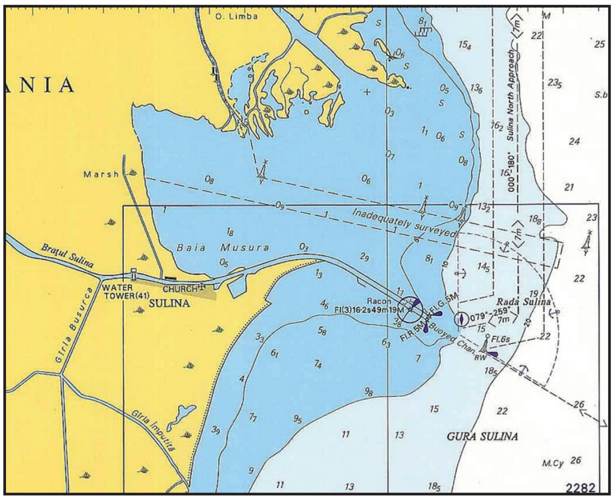

Fig. 38 The Sulina distributary mouth and Sulina harbour in 1999 (British Sea Chart).

The British sea chart of 1999 (Fig. 38) shows the final development of the Sulina jetties (about 8 km long). South of them there is a new groin built on the town beach for stopping the littoral sediment drift towards north generated by the eddy-like current at Sulina mouth. In the North, the Bay of Musura became shallower because of the constant supply of sediments by southern branches of the Kilia Delta – Stary Stambulsky, Musura, Lebedinoe and other smaller distributaries.

The satellite image (Google Earth, 2006) shows the present-day situation of the Sulina mouth and the neighbouring areas on both sides of the jetties (Fig. 39).

The Musura Bay appears to be almost closed by a lateral mouth spit of the Stary Stambulsky distributary. The location of the sandbar has been influenced by an underwater jetty built in 1943 for directing the water and sediment flux of the Stary Stambulsky distributary to the east. The spit is lengthen-

Fig. 39 Satellite image of the Sulina distributary, the Musura Bay and the southernmost part of Kilia Delta. 2006

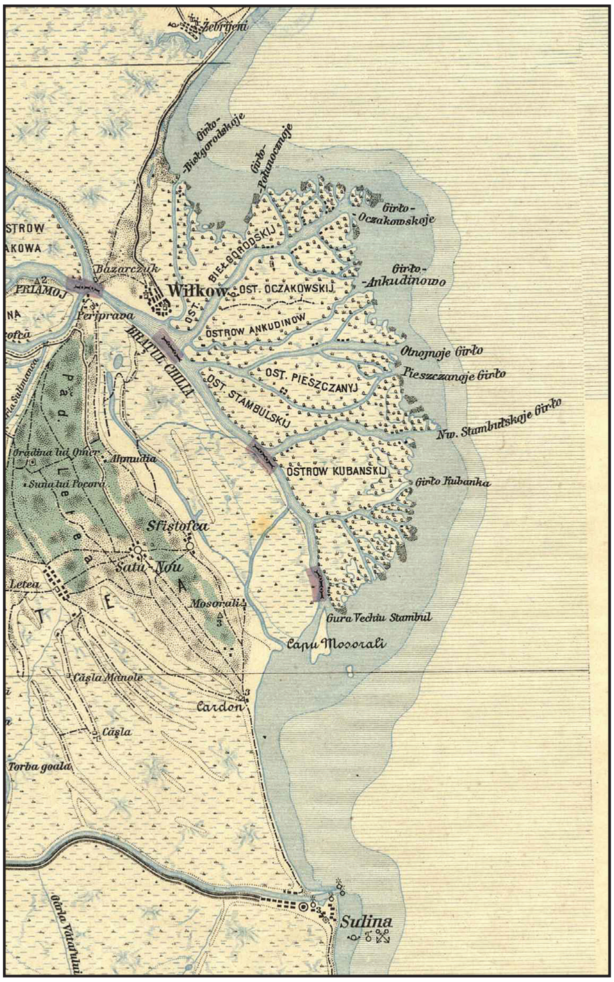

Fig. 40 Kilia Delta in 1918, Austrian map

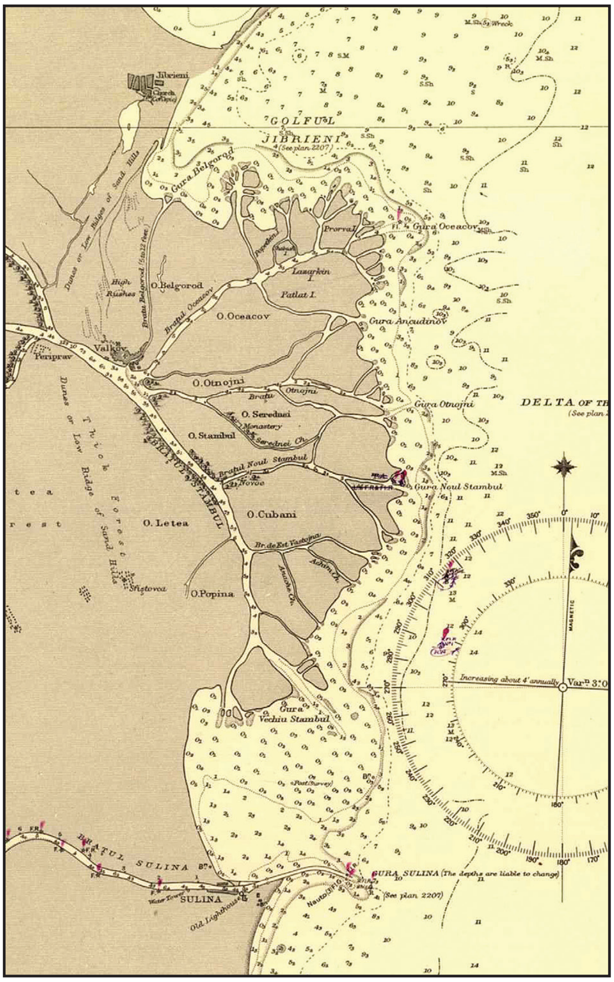

Fig. 41 British map of 1936. Soundings in feet.

ing rapidly (200 – 300 m/year) and nowadays only very few hundreds of metres remain from the southern end of the spit to the northern Sulina jetty. The littoral sediment drift along the spit is quite important and the Stary Stambulsky distributary is supplying continuously this drift with sandy material.

The southwards coastal flux of sediments influences the Sulina mouth adding more and more sediments to those brought by the Sulina distributary as sedimentary load on the mouth bar.

As already described above on the British map of 1856 numerous Kilia delta distributaries can be clearly seen. Among them, two are particularly important: the Ocheakov branch to the north, and the Stary Stambulsky branch to the southeast. Along the river branches, on the riverbanks, alluvial gallery-forest is indicated. Within the areas between the river branches larges areas are occupied by marshes and lakes. At the west side, the area between the Stary Stambulsky branch and Letea Forest, mentioned in the 1771 map description, was already almost filled with sediments in 1856. Offshore the Kilia delta, a shallow wide delta-front platform is visible (with water depth of only 1 - 2 feet and up to 2 km width). At several places, exposed sandbanks are indicated as well. All these features show that in 1856 the Kilia delta was in full expansion seawards.

The Austrian map of 1918 at 1:125.000 scale (Österreichische Nationalbibliothek, Wien) (Fig. 40) shows that the strong development of the Kilia Delta continued. The marshy area or the bay between Letea and the Stary Stambulsky distributary was completely filled up during the 1856 – 1918 interval. The river distributaries expanded seawards. The river side levees were covered by forest, and the delta front shallow platform has developed to the east and to the south. The progradation towards north was slower and the delta became more and more asymmetrical under the influence of southwards oriented littoral drift of sediments. The progradation rate for the period 1856 – 1926 (70 years) was comparable with the rate for the previous 80 years period (1771 – 1856). As already mentioned, the map of the Royal Navy of 1856 has been revised many times. Large revisions were made in 1936 (Fig.41), and minor ones in 1947 and 1956. On this map the soundings extend far offshore. The delta front platform is narrower than on the earlier maps. The delta front slope has small valleys continuing the delta distributaries and representing the pathways of the turbid denser water during river flooding pe-

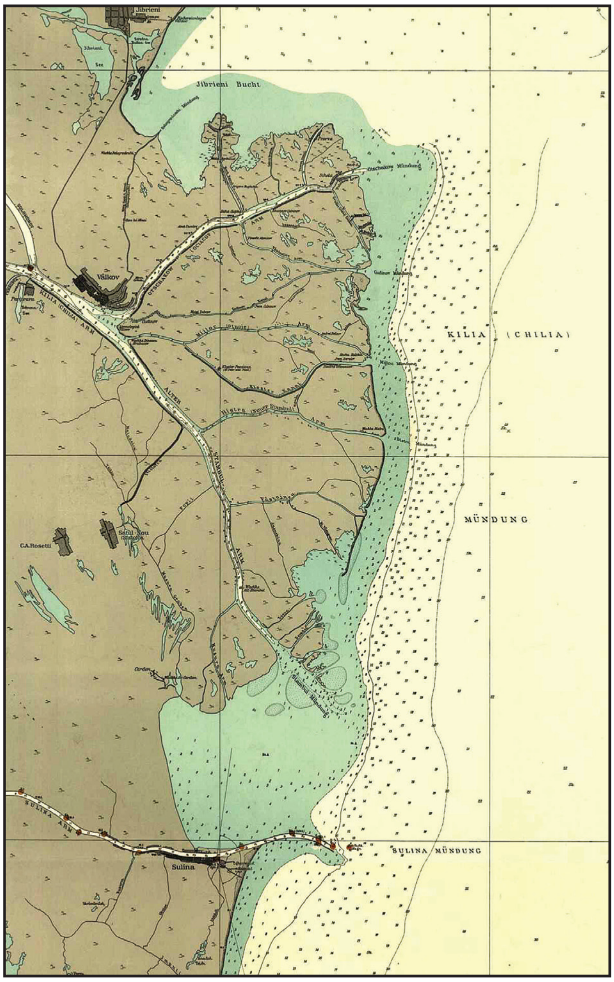

Fig. 42 The Kilia Delta and the Sulina mouth, 1944 (German map, soundings in meters)

Fig. 43 Kilia Delta in 1983 (Soviet Union map).

riods. Especially the line of 10 fathom (~18.29 m) is strongly sinuous. The marshy area on the right of Stary Stambulsky distributary is now completely silted and exposed.

On a German map of 1944 from the Österreichische National-bibliothek, Wien (Fig. 42), the shallow Musura Bay between the Stary Stambulsky distributary mouth zone and the Sulina distributary jetties appears to be actively silted. The most interesting feature on this map is, however, the Kilia Delta coastline itself. At both sides of the Bystroe distributary mouth the coastline changed into a strong, almost uninterrupted sandy barrier beach. In its southern end, a sandy spit is developing. This means that the seawards progradation of the delta controlled by the river as seen until this moment has changed into a wave controlled system, with the river-born sandy sediments redistributed into beach ridges along the shoreline by the waves and by the littoral drift systems. The eastern delta front platform became narrower.

In the north, not much has changed as the sea energy is dissipated on a wide shallow sea bottom in front of the delta. In the south, the Stary Stambulsky distributary mouth zone is still river-dominated as its supply of sediments is enough large for prograding into the sea as a lobate secondary deltaic body. The change of the delta morphology was caused, probably, by the diminishing of the water and sediment supply of the Kilia distributary as the resistance to waterflow increased because the branch became too long and the water was distributed through too many branches. The change of delta morphology into a wave-dominated cuspate in the vicinity of the distributary mouth zones will continue until nowadays.

A Soviet map of 1983 (Fig. 43) shows that the morphological changes continue and accelerate. In the northern part of the Kilia delta, the two main branches Prorva and Potapovskoye Girlo, that fork at the sea-end of Ochakov distributary are lengthening visibly and the delta bodies formed by them are of cuspate, wave-dominated shape. The southern part of the Ochakov mouth zone is represented by a newly formed spit – Potapovskaya Kosa. All along the eastern coastline of the delta barrier beaches have developed. The spit south of the Bystroe distributary mouth almost closed the Anokin Kut bay; the mouth of Vostochnoye distributary is also almost closed by the Bystroe-born sandy sediments. Only at the Stary Stambulsky branch mouth, in the south, the progradation is still very active.

At the end of the river channel, a beginning of a middle ground bar and a new bifurcation of the channel are visible.

In the 1970 – 1990 interval, the Soviet Union developed harbour facilities, called Ust' Dunaisk, on the left side of Prorva distributary, close to its mouth.

The British sea chart of 2005 (Fig. 44) doesn't offer many details about the coastline of the Kilia delta. However, the Ochakov mouth zone appears developing as sea dominated secondary delta bodies formed by Prorva and Potapovskoe Girlo.

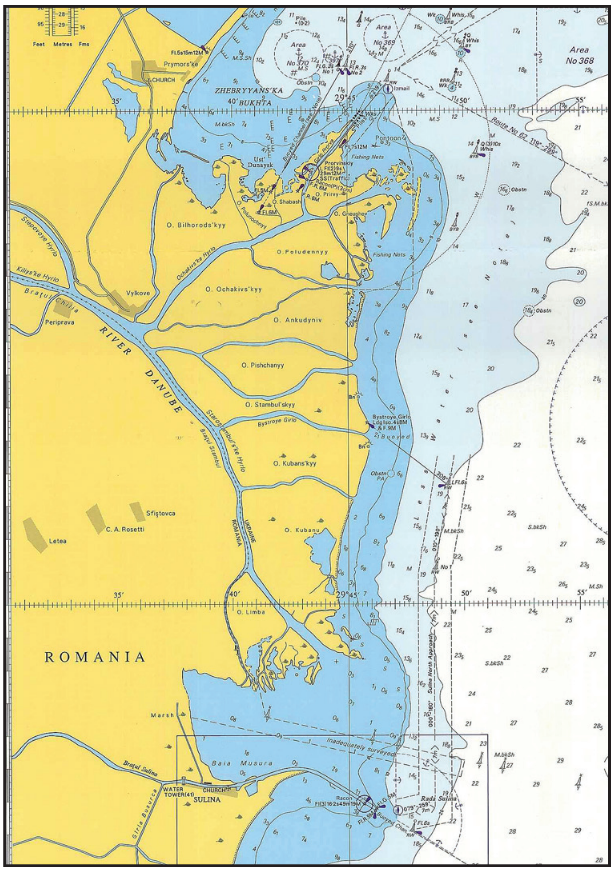

Fig. 44 British Sea Chart for the Kilia Delta zone, 2005.

West and north of the Ochakov distributary mouth lays the Zhebrianskaya bay. Here a small amount of sediments are supplied mainly by the littoral drift along the coast from the Dniestr and Dnieper rivers mouth zones. The flux of the littoral drift is not very important and the barrier beach limiting the Sasyk lagoon (*liman*, as it is called locally) towards the sea is quite narrow and with a relatively steep underwater beach slope. In the south, the map doesn't offer enough details for assessing changes at the Stary Stambulsky distributary. The situation seems to change quite rapidly and the Musura Bay, situated between the southern Kilia delta front and the Sulina jetties is silting up actively.

In the satellite image published by Google Earth in 2013, the further development of the Kilia Delta is clearly visible (Fig. 45). Figure 46 shows the progradation phases of this delta (Overmars, 2007).

Fig. 45 Kilia Delta satellite image published by Google Earth in 2013.

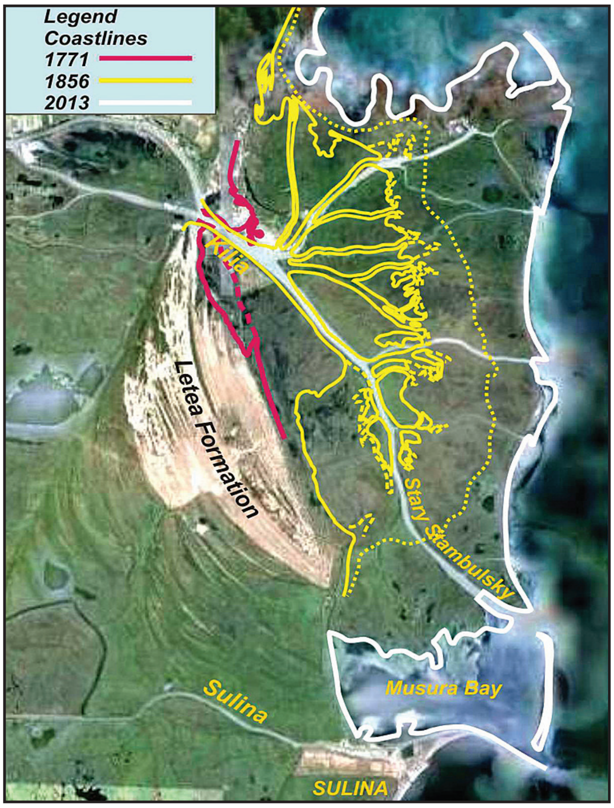

Fig. 46 Phases of the Kilia delta progradation since 1771 until 2013.

At the Ochakow distributary mouth zone, north of Potapovskoye Girlo mouth a new sandy spit has developed and almost closed the area between the mentioned arm and the Prorva distributary. Here the change of delta morphology to a wave-dominated delta is clearly visible. South of the Bystroe distributary mouth, a new spit has been formed – Ptychyi island (Fig. 46). The sandy load of the Bystroe distributary is reworked on this spit.

In the south, only the Stary Stambulsky mouth still shows an active progradation. However, even here there is an evidence of the sea controlled redistribution of the sedimentary load supplied by the distributary. In 1943 an underwater jetty was built on the right side of the distributary mouth for directing the river jet flow towards east. At the end of this jetty a lateral mouth bar was formed and very rapidly (during the eighties) was transformed in a lateral spit with a dynamic development. Nowadays the spit almost closes the Musura bay and facilitates the clogging of this area.

DISCUSSIONS AND CONCLUSIONS

The morphology of deltas depends on one hand on the river water and especially sediment input and on the other hand on the marine factors, mainly the wave power and currents. For the same wave power regime, when the sediment supply will be very high the morphology of the delta will be river-dominated - lobate or even finger-like, on the contrary, when the supply will be lower, the shape of the delta will be cuspate, wave-dominated, marked by successive beach ridges of river-borne sediments reworked by the waves and littoral currents along the shore. Many other factors play an important role in shaping a deltaic body: among them can be mentioned the difference between the river water density (fresh water plus sedimentary load) and the density of the receiving water body (in the case of the sea the water is salty and, consequently, denser than the river fresh water), the salt-water wedge that enters the river mouth beneath the fresh river outflow, the shape of the receiving water body, the subsidence etc. *Vice versa*, changes in the morphology of a deltaic lobe can give information about the distributary sediment discharge changes – *e.g.* a lobate delta attests of large river sediment supply, if the delta shape starts to change in a wave-dominated it means that the discharge is diminishing and the marine factors prevailed.

When the river sediment discharge is large, the first step in the development of a mouth zone is represented by the building of a large shallow (1-4 feet) frontal platform limited offshore by a quite steep slope deeping to 12 – 15 m water depth. Sometimes on the external side of such a platform low sandy ridges can form and develop into lateral mouth bars and spits (*e.g.* the Sakhalin Island at the St. George mouth and the Musura Spit at the Stary Stambulsky distributary mouth).

During the Holocene development of the Danube Delta one can identify a number of phases when the main river discharge has switched from one distributary to another with formation of corresponding deltaic lobe. The main phases are the following: St. George I Delta, Sulina Delta, St. George II and Kilia Deltas and Cosna-Sinoie Delta (Fig. 8). The most prograding lobe was the Sulina Delta – over 30 km in about 5 000 years (average progradation rate of 6 – 10 m/yr). Kilia distributary was also very active in the last three centuries, when the rate of progradation was very high (8 – 10 m/yr).

The present-day Danube Delta lobes differ substantially – the Kilia delta is lobate while the St.George II delta is cuspate. These differences in morphology indicate that the Kilia branch was for a period of time (about 2 – 3 centuries) the main delta distributary, with the largest water and sediment discharges. In the last time the Kilia distributary sediment supply diminished considerably (from 70 % of the total Danube sedimentary discharge to about 50%) (Fig. 47) and this has induced changes in morphological pattern of the lobe. The river-dominated lobate delta starts to change into a wave controlled one (with cuspate shape close to main distributar-

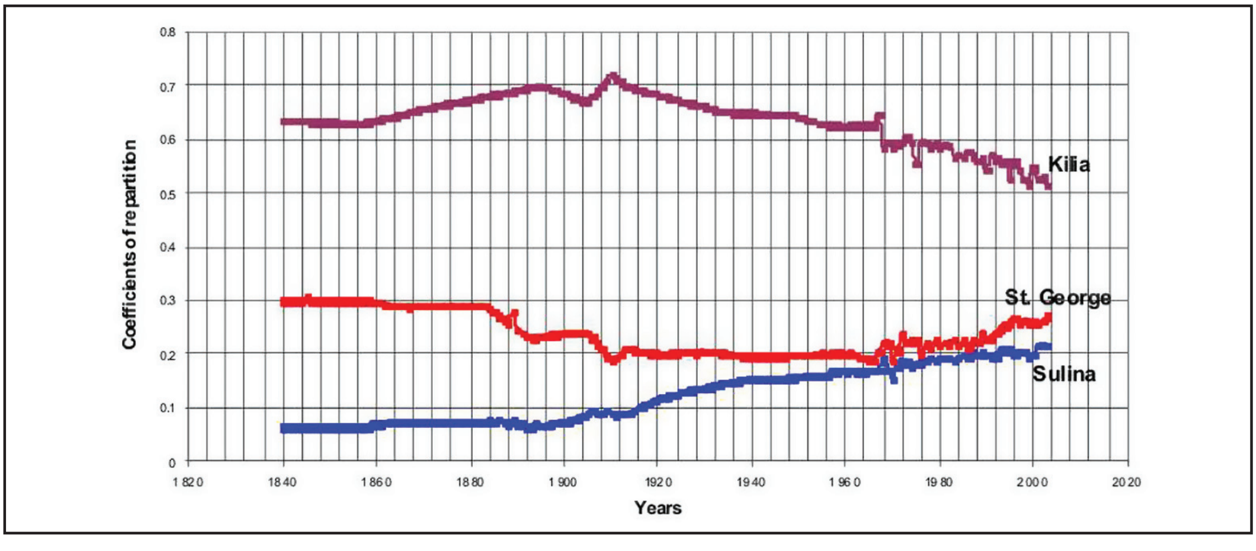

Fig. 47 Changes of water discharge repartition among the Danube Delta main distributaries in the 1840 – 2003 period (from Bondar *et al.*, 2000)

ies mouth zones), the delta-front platform became narrower and the delta-front slope steeper.

The partition of the sediment discharge between the main distributaries at the delta entrance is almost similar to the distribution of the water discharge.

The diminishing of the Kilia distributary water and sediment discharges is due to natural and anthropogenic causes.

The main natural factor playing an important role in diminishing water and sediment discharges is the constantly increasing resistance to the waterflow by over-lengthening of the Kilia natural course and consequently diminishing the free water slope as well as the dispersal of the water outflow to the sea through a large number of relatively small distributaries.

The anthropogenic influence is multiple and can be summarised as follows:

- The Sulina meander belt cut-off programme performed by the European Danube Commission during the 1858-1902 period, in order to improve the navigation along this distributary shortened the branch by about 25% inducing thus an enlargement of the water discharge of the Sulina distributary from about 7% of total Danube discharge around 1860 to ~ 15% in 1928 and about 20% nowadays, and, implicitly, decreasing the Kilia discharges (see Fig. 47);
- In 1970 and 1983 the Danube River was dammed twice at Iron Gates and consequently the total river sediment supply decreased by about 40 %. This had a negative impact on the sedimentary budget of the delta coastal zone that became unbalanced and strong erosion of delta front started;
- In 1981-1992 another meander cut-off programme was carried out on the St. George arm. These works lead to the distributary shortening by about 31 km and, consequently, to the increasing of its water and sediment discharges while the Kilia discharges went down again.

The existing cartographic documents for the last three centuries give an excellent basis for studying and scaling the development and the behaviour of the Danube delta edifice. This is also a good base for documenting all kind of projects regarding sustainable and adaptable management systems in such sensitive areas as deltas are.

ACKNOWLEDGEMENTS

The authors express their thanks to the archives and libraries of European Union and USA (British Library - London, Nationalbibliothek - Wien, National Maritime Museum - London, University of Leiden Library - The Netherlands, the Library of Congress of the US and many others) from where the use of different maps for illustrating the Danube Delta changes in time was possible.

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