THE GENERAL CIRCULATION OF WATER IN THE BLACK SEA

by

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The study of the Black Sea and of the circulation of its waters is of particular importance for the solution of a number of problems connected with navigation, biology, geology and economics. In order to find an immediate solution of these problems, I initiated in 1932 a series of oceanographic expeditions on board vessels of the Royal Navy : *Lt. Comandor Stihi Eugeniu* and *Sblt. Ghiculescu*, as well as on board the schooner *Boz Burnu* of Constantinople. I wish to express here my thanks to the Commanders of these vessels of the Royal Navy for their solicitude and for the assistance which they rendered to me.

In this article I propose to examine the circulation of the waters in the Black Sea and, in particular, that in the region of the Rumanian Coast ; I should like to study as well the influences exerted by the marine elements on the silting of the Delta of the Danube, since the economic problem of the "access to the Danube" — at present accomplished through the Sulina — is a function of these elements.

HISTORICAL.

Certain authors, among whom are men of indisputable authority such as HARTLEY, ANDROUSOV, WOEIKOFF, and later Dr. Gr. ANTIPA, all assume, when dealing with the currents in the Black Sea, the existence of a single current flowing along the west coast in a N-S direction. Those who have worked in this region of the mouth of the Danube, Engineer VIDRASCU, Ionescu DOBROGEANU, and Engineer G. VASILESCU, also concede the existence of this current. With regard to the origin of this current, Sir Charles HARTLEY and CORRÉARD maintain that it arises in the Sea of Azov as a result of the great influx of fluvial waters. Others are of the opinion that this current is a result of the northerly winds 1) or, that it is due to the great difference in density which exists between the waters of the Black Sea and those of the Mediterranean. 2) Observations in the Bosphorus have actually proven the existence of an exchange of waters which supposedly takes place between the Black Sea and the Mediterranean by means of two currents : one on the surface flowing into the Black Sea from the Sea of Marmara ; the other a deep current flowing in the inverse direction. 3) The waters of the surface current are sweetened by the river waters from the north-west section of the Black Sea while the submarine current transports waters which are strongly saline.

Recent investigations have proven that this current is simply a complement of the circular current flowing along Anatolia, Sinope, Trebizond, Sebastopol, Odessa, Coast of Rumelia, Bosphorus. 4) From the point of view of circulation, one has even compared the waters of the Polar mediterranean to those of the Black Sea, given the fact that on our hemisphere, currents are deviated towards the right in such a manner that this mass of saline waters should be *a priori* directed towards the east of the mouth of the Bosphorus and should consequently enter into the general circulation in the sense of a right to left movement comparable to that of the Arctic mediterranean sea (S. MEHEDINTI).

Between 1922 and 1926 a Russian Expedition under the direction of Professor N.M. KNIPOVITSCH was able to establish the fact that, outside the known circular current, there were two other circuits, on each side of the Crimea, (Knipovitsch Chart annexed to the work entitled : *Abhandlungen der wissenschaftlichen Fisherei Expedition im Asowischen und Schwarzen Meer*). Another observation — unique up to 1926 — mentioned by Dr. Gr. ANTIPA in a work dating

(1) S. MEHEDINTI : *România*, p. 176.
(2) Em. DE MARTONNE : *Géographie Physique*, p. 313.
Alfred MERZ : *Hydrographische Untersuchungen in Bosphorus und Dardanellen*, 1928.
Pilote de la Mer Noire, Ed. 1865.
G. VASILESCU : *Contribution à la Formation du Delta du Danube.*
(3) S. O. MAKAROFF : *L'Echange d'eaux entre la Mer Noire et la Méditerranée*, 1883.
Alfred MERZ : *Hydrographische Untersuchungen in Bosphorus und Dardanellen*, 1928.
Em. DE MARTONNE : *Géographie physique.*
(4) CORRÉARD : *Guide Maritime et stratégique de la Mer Noire.*
S. MEHEDINTI : *România.*
Camille VALLAUX : *Géographie générale des Mers.*
Em. DE MARTONNE : *Géographie physique.*
G. VASILESCU : *Contribution à la Formation du Delta du Danube.*
KNIPOVITSCH, N. M. : *Abhandlung der wissenschaftlichen Fisherei*, Exp. 1932.

from 1916, indicated in the vicinity of the Rumanian Coast between Sf. Gheorghe and Zàton the presence of a band of froth — whence the hypothesis of two currents flowing in contrary directions.

From the above discussion it appears that there exists in the Black Sea a circular marine current which is supplemented by two other currents on each side of the Crimea, the direction of the general movement being from right to left. As far as the vicinity of the Rumanian coast is concerned, everyone up to 1926 (except for the above-cited observation of Dr. ANTIPA), assumed the existence of one sole coastal current flowing in a N-S direction. After 1927, however, the Current Chart of the Rumanian Coast area changed its aspect thanks to the studies made by the Hydrographic Service of the Royal Navy. These studies have been further supplemented by others made in 1934 and 1935 by Drs N. GAVRILESCU and Z. POPOVICI. All these agree on the existence of another current in a reverse direction flowing along the entire coast and outside of the N-S current.

CIRCULATION OF WATERS IN THE BLACK SEA.

Research work in the Black Sea between the years 1932-1937 justifies the following conclusions :

a) There exists in the Black Sea a circular marine current flowing along the coast of Anatolia, Sinope, Trebizond, Bacou, Sebastopol, the Island of Serpents, Coast of Rumalia, Bosphorus; to this current should be added three other circular currents, one on each side of the Crimea and a third, which supplements the water circulation in the north-west basin of this sea, comprised between the Crimea, the coast of Bessarabia, and the Island of Serpents. (See Current Chart accompanying this article). All of these currents have a movement in the same sense, i.e. from right to left and a mean velocity of five-tenths of a nautical mile per hour. Their mass and velocity reach a maximum in the Spring during the great discharge of river waters into the north-west region of this sea.

b) This great circulation is determined by a multiplicity of causes :

The first is the appreciable difference in density between the waters of the Black Sea and those of the Mediterranean. It is a well-known fact that liquids held in two containers which are reciprocally in communication will assume levels which are in inverse relation to their respective densities; from this fact we can deduce that the level of two seas which are unequal in salinity must necessarily stand in inverse relation to the densities of their waters. Consequently the Black Sea, whose composition on the whole is of lesser density, should show a slightly higher level with respect to the Mediterranean waters which are of greater density. From this arises an exchange of waters between these two seas : a surface current which is slightly saline flowing from the Black Sea through the Bosphorus and the Dardanelles into the Aegean Sea — while from the Aegean Sea another current, submarine, transports into the Black Sea the salt waters of the Mediterranean which are borne along the coast of Anatolia by that portion of the surface current flowing N-S which cannot completely drain through the Bosphorus. A similar exchange has been established by us between the waters, almost fresh, of the Sea of Azov and those, higher in salinity, of the Black Sea.

The second cause is the great influx of fluvial waters from the north-western area of this sea. These waters enter into the general circulation by a right to left movement determined by the shape of the basin of this sea and by the position of the Bosphorus which aspirates the waters on the west coast.

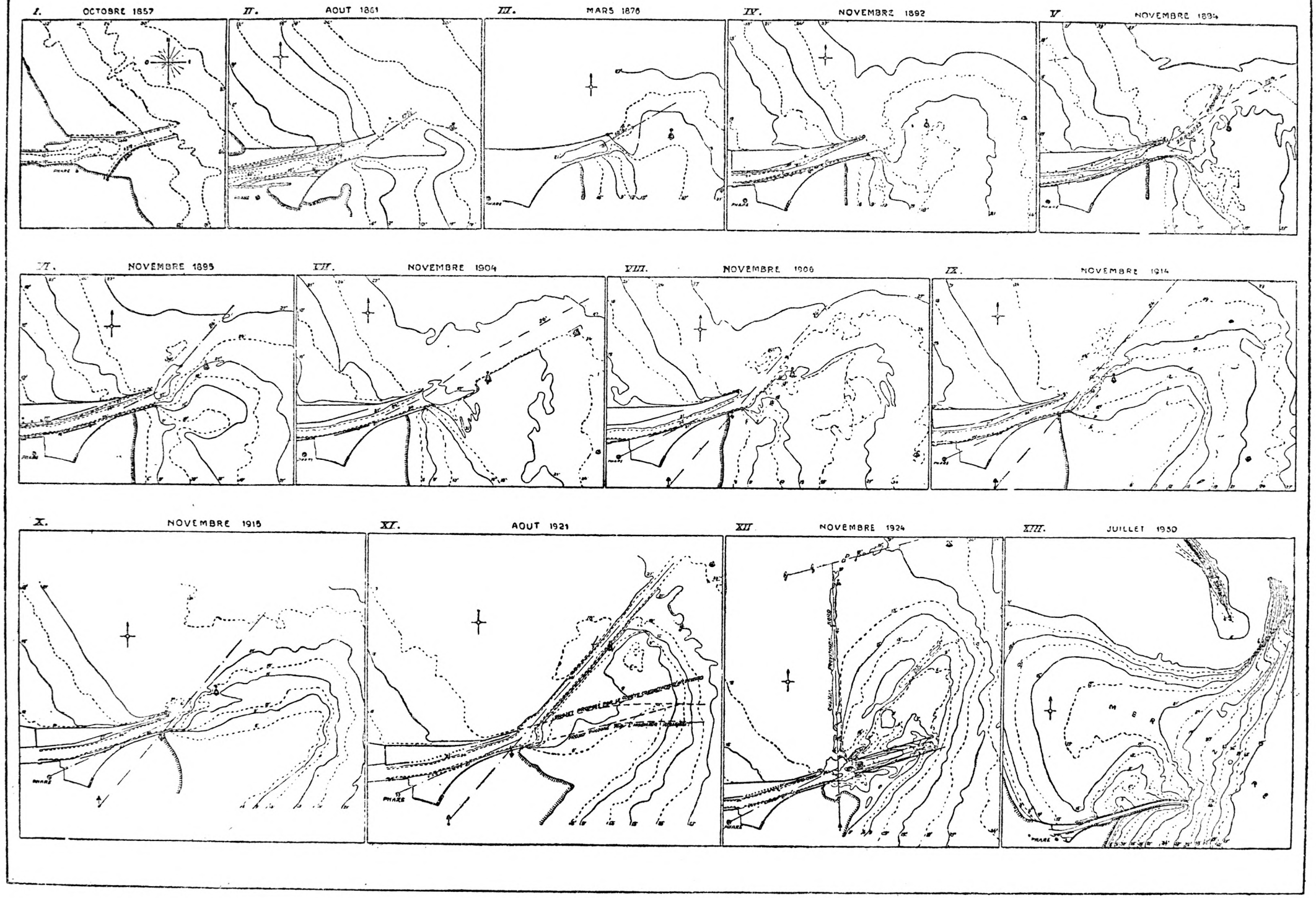
A third cause, which explains the movement of these currents, is that in all the marine basins in the Northern hemisphere, the waters are deviated from right to left as a result of the Earth's rotation.

Certains authors attribute the currents in the Black Sea to the prevailing North winds (5). Our observations have established the fact that these winds actually do succeed in increasing and diminishing the speed of those currents and even in bringing about their deviation ; on the other hand, however, we cannot concede that such a complex phenomenon as that of the general circulation of the waters in the Black Sea could be due entirely to the winds. Very weak surface currents originate solely in the region of the Delta of the Danube; their action helps to bring about alluvial deposits in the Delta of this river (6). One fact, due entirely to the winds and observed on the west coast at a period of strong winds from the north-west, is the process of lowering of water level registered also at the port of Constanza by the *Service des Ports* tide-gauge; these reductions in sea level are a phenomenon due to the transporting effect exerted by air currents on liquid molecules, and not to differences in atmospheric pressure. This phenomenon is observed almost exclusively in winter and solely during the period of very violent

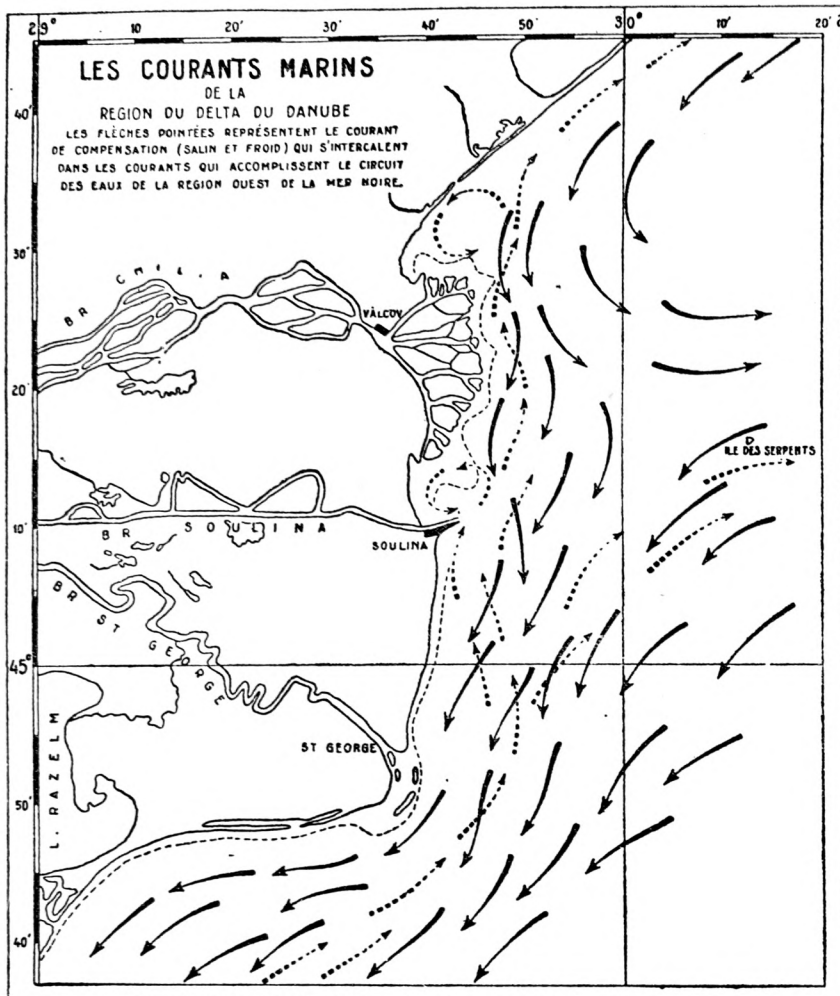
(5) S. MEHEDINTI : *România.*
(6) R. CIOCARDEL : *Influence des Vents sur l'Evolution du Delta du Danube*, Académie des Sciences, T. I., 1937.

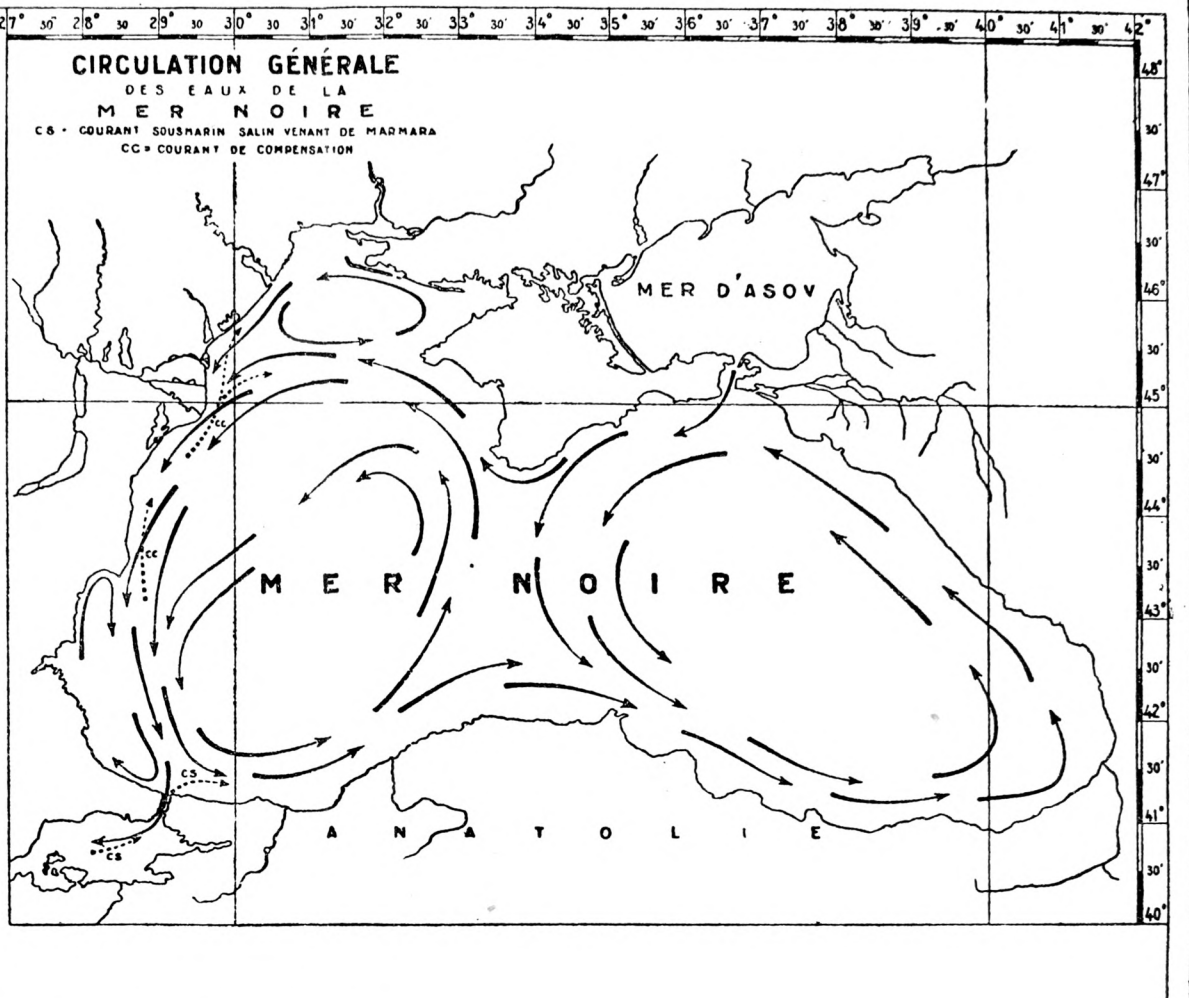
ENBOUCHURE DE SOULINA

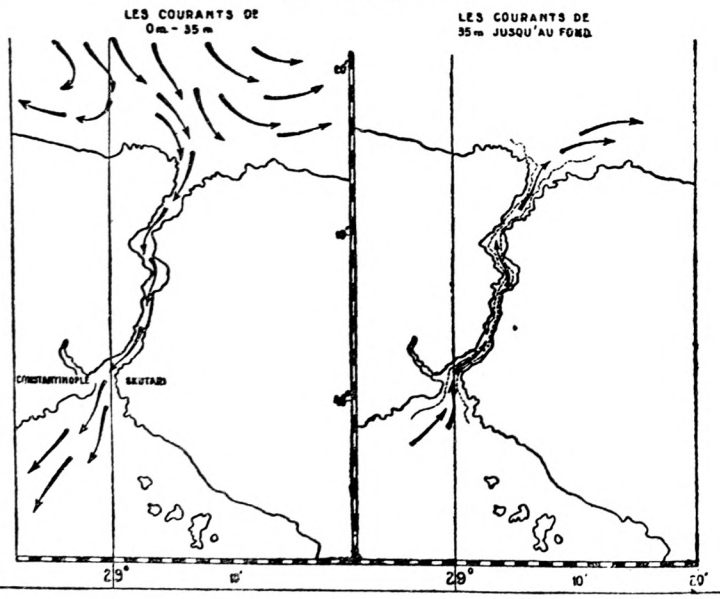
LES CARTES COMPARATIVES MONTRANT LA SEDIMENTATION PROGRESSIVE DEPUIS 1856 - 1930



Mouth of the Soulina.
Comparative Charts showing the progressive sedimentation from 1856 to 1930.





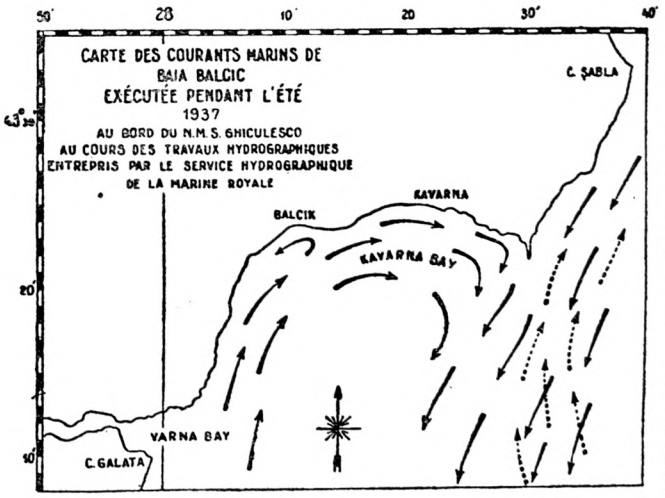


LES COURANTS MARINS DE LA MER NOIRE

TRAVAUX EXECUTÉES PENDANT LES ANNÉES 1932-1937

PAR

RADU CIOCÂRDEL



The Currents in the Black Sea.

winds blowing off this coast; the observed reductions in level reached a maximum of about 60 centimetres.

c) At the Bosphorus, the impossibility of the mass of water contributed by the current which flows along the western coast completely draining through the strait, has been determined; this necessitates a part of the waters following the coast of Anatolia with the waters of the saline submarine current coming from the Bosphorus, while another part follows the coast of Rumalia, Burgas, Varna, Balcic, Caliacra. In the Bosphorus and in the Dardanelles we find two superposed currents, one a surface current of 0 to 30-35 m. depth flowing from the Black Sea into the Aegean Sea and the other in depths from 35 m. downwards to the bottom. The first transports into the Mediterranean the fresh waters of the north-western basin of the Black Sea, and the second transports into the Black Sea the saline waters of the Mediterranean. The density of the waters of the surface current vary between 1.0128/1.0135 and that of the deep current waters between 1.019/1.025. The velocity of the surface current reaches 0.8 to 1.5 miles an hour, but it may increase at the period of strong North winds to 7 nautical miles an hour. (Data supplied by the Turkish *Service des Ports* in the Bosphorus). The velocity of the submarine saline current reaches as much as 0.7 to 1.2 nautical miles an hour.

d) Along the Rumanian coast we find two currents: The first, in a N-S direction, follows the coast except for a few points in the region of the mouths of the Danube. In the vicinity of the Sf. Gheorghe arm, this current unites with a surface current coming from the Island of Serpents and the Crimea. Along the coast of Bessarabia, the width of this current does not exceed 2 to 3 miles; but southward of the mouths of the Danube, owing to the waters which this river transports into the sea and its consequent fusion with the circular current coming from the Crimea, the width reaches as much as 10 to 15 and even 20 miles. The waters of this N-S current have a yellowish-green colour as a result of the alluvia transported by the waters of the Danube. In the vicinity of the delta, the density is from 1.003/1.004 (or almost fresh water); a little to the southward, in the vicinity of Constanza, this density increases to 1.005/1.008. The temperature varies with the season (in summer 22°-26°; in winter 3°-4° and even lower). Velocity is from 0.5 to 0.7 miles an hour.

The second current flows in a S-N direction. It first becomes appreciable a little to the southward of Cape Caliacra (represented on the Current Chart of the Black Sea by dotted arrows). In our idea this is a "compensation" current resulting from the displacement towards the Bosphorus of the enormous water masses of the N-S current. This current continues towards the North, intercalating in a very irregular manner in the mass of the N-S current. Frequently it flows in depths below the N-S surface current; at other times it flows on the surface showing clearly a band of froth at the line of friction between the two currents; occasionally it is not simply one band but two bands at a distance apart of 200-300 metres, showing very clearly the difference in colour of the two waters. In the vicinity of Sf. Gheorghe, the current divides into two branches; one is directed towards the Island of Serpents, where we have identified it as a deep current; the other branch continues along the Delta, crossing over and intersecting the N-S current. This current, which acts on the accretions in the mouths of the Danube, has a greater density (1.012/1.013); its temperature is lower (7°-9°). With regard to intensity and direction it is very inconstant.

In the region of the mouths of the Danube, some very weak surface currents originate as a result of the winds. The prevailing winds in the vicinity of the Delta of the Danube are NNE-NE and SE (See annexed plate showing diagrams of the winds in the region of Sulina).

Their velocity varies from 3 to 5 metres per second, but this velocity is often exceeded. The friction which occurs between the water and the air currents gives rise to marine currents, the direction of which is the same as that of the winds which gave them birth. When this current elicited by the winds encounters a marine current, it takes the direction of their resultant. The depth of the current generated by the wind is proportional to its velocity, and the latter varies from 1 to 2 metres; but during the season of the strong winds from the north-east, it may attain as much as 3 m.

As a result of the winds the currents are subjected to deviations and accelerations. Winds blowing from west to east often drive the N-S current towards the open sea; its place is then taken by the S-N current — a fact which is manifested by the sudden change in colour and temperature of the waters (a phenomenon which is observed also at the port of Constanza).

In the vicinity of Balcic we find a circular current coming from the south and following the coast. After having made the circuit of the gulf, it unites in the region of Caliacra with the great surface current flowing N-S along the coast of Dobroudja. The current in this bay is simply a continuation of the eddy current from the region of the Bosphorus which, as we have seen, originates owing to the impossibility of all the water masses transported by the N-S current completely escaping through the Bosphorus. Considerable importance must be attributed to

the transporting force exerted by the N-S current on the waters of the current in this bay. The velocity of the circular current varies between 0.3 and 0.5 nautical miles an hour. It has been established, however, that during the period of great floods and when as a consequence of this fact the velocity as well as the volume of the N-S current is greatly increased, the speed of the circular current in the bay is also augmented as a result of this transporting force, sometimes attaining a velocity as great as one mile per hour. The density is 1.011 and the temperature varies with the seasons. The width of the current is from three to four miles — sometimes greater.

e) The density of the waters of the Black Sea varies at the surface between 1.011 and 1.0139. In the North-west basin of this sea, the density of the waters becomes lower as a result of the great influx of fluvial waters. In depths the density increases and reaches as much as 1.022-1.025. (On the chart showing the densities of water in the Black Sea there has been shown by mistake, at Long. 29° and Lat. 41°40' a density of 1.028 instead of 1.0128).

THE INFLUENCE OF MARINE CURRENTS ON THE EVOLUTION OF THE DELTA OF THE DANUBE.

In order to solve the problem of access to the sea, which is at present accomplished through the Sulina arm, it is absolutely indispensable to have direct and accurate knowledge of the phases and rate of silting in the Delta.

In 1856, as a result of political and financial conjunctures, the *Commission Européenne du Danube* was compelled to choose the Sulina arm. If, in the choice of this branch, no consideration was given to the natural agents which exert their influence on the sedimentation, and if the importance of the latter was not sufficiently appreciated, this is only a striking illustration of the fact that the work of man should never contend against that of nature but should, on the contrary, adapt itself to it. In order to understand the phases in the evolution of the Delta and the silting of its branches, it would have been necessary to carry out systematic research long before undertaking to regulate the Sulina. Such studies would necessarily have revealed the nature of the marine agents which exert an influence on the alluvia and that of the natural evolution of the Delta and its arms.

In order to determine those marine agents it was necessary to study the currents which are found along the entire shoreline and particularly in the region of the Delta; to establish in an accurate manner the currents in the bays and the causes which bring about their variations in velocity; and to record during several consecutive years the regime of the winds and, at the same time, their natural consequences (shape, depth, speed, impetus of the waves).

In order to establish the phases in the development of the Delta and its arms, it would have been necessary to measure accurately the debit in each arm; to have a continuous record of the direction of its advance, because this bears a direct relation to the principal marine agent; and finally to measure each year the quantity of alluvia by units in order to obtain as accurately as possible their variations with respect to the clearing of the growth.

Of all the investigations mentioned above the most important are those which relate to the currents playing a preponderant rôle in the process of sedimentation — and for this reason we will examine the influence which the marine currents exert on the process of silting in the mouth of the Danube and the manner in which they influence the evolution of the Delta in general.

In treating the historical aspects of the problem, we have seen that with a few exceptions everyone concedes the existence of a single coastal N-S current which is the unique and principal agent influencing the alluvia in the mouth of the Danube, and which is considered at the same time as an unfavourable circumstance for the advance of the Delta.

The studies undertaken by us in this region have permitted us to arrive at the following conclusions:

Two currents having different chemical and physical properties are acting in the region of the Delta. The current from the North is a cleansing agent transporting towards the South the alluvial material in suspension, while, on the contrary, the current from the South has a tendency to annihilate the action of the current from the North, by speeding up precipitation of the alluvia as a result of its salinity.

If we commence our study of the Delta at the North, we notice that one branch of the current from the South acts upon the Polunojnoe, Sabos and Rupturi arms, which discharge into the Bay of Jibrieni, and precipitate a part of the alluvia in the mouth itself. Alluvia transported by the waters of the circular current in the bay are deposited where this current crosses the N-S current on the south bank of the Oceacoff mouth. Alluvia from the Bistra,

Otnojno and Ancadinov arms still further enlarge this bank, due to the activity of the S-N current. The rapid heaping-up of the South bank of the Oceacoff mouth and the orientation of the latter show that the advance of the northern part of the Chilia Delta takes place in a north-easterly direction.

The Bistra region constitutes a new zone of increase; to the right of this arm, the N-S current crosses the S-N current and forms with the latter a line of dead points. Along this line precipitations occur in an intensified manner which has given rise to a "strand" along the coast, extending from the Bistra to the outlet of the Serion channel. As a result of currents acting in contrary directions, the increase in the banks situated to S. and N. of the Bistra mouth is very rapid.

The southern part of the Chilia Delta advances by means of deposits which occur at the Stari-Stambul mouth due to the S-N current which obliges the waters to discharge on the banks and principally on the bar of this arm. Non-precipitated alluvia are transported by the water mass of the circular current in the bay and deposited farther along its course; alluvia which succeed in reaching the Sulina are deposited in the shelter of the north dyke without, however, influencing the deposits which occur opposite this mouth. Progression towards the South is very rapid and its tendency is to close the bay which exists between this arm and the Sulina mouth.

In conclusion, the Chilia Delta advances in three principal directions: Oceacoff, Bistra, and Stari-Stambul. Examination of the charts of the annual advance of the Chilia Delta from 1894 to 1935 shows that progression does not occur simultaneously but alternatively, so that the Stari-Stambul advances towards the East when the zone of the Bistra is extended, while Oceacoff remains stationary; on the other hand, when Oceacoff progresses, the zone of the Bistra remains stationary and the Stari-Stambul advances towards the South. Intermediate zones between those arms also increase, but only after the creation of shelter, and if progression is retarded, bays are often formed.

If we now pass to the problem of the silting of the Sulina mouth, we find that the alluvial-mass is not due solely to the activity of this arm but, to a great extent, to that of the S-N current. Owing to this current, deposits commenced to occur under the South dyke immediately after its construction. The waters of the current, in contact with the fluvial waters, precipitate a large part of the alluvia at the mouth itself, and this is why the navigable channel is continuously deviated towards the North, a fact which may also be ascertained in examining the charts established each year by the *Commission Européenne du Danube*. As the alluvial mass constantly increased from South to North, the channel being constantly deviated, it was decided in 1924 to cut the bank opposite the mouth. As a result of this undertaking it was found that the deposits occurred at an increasing rate under the South dyke, while the bank remaining to the North extended only very slowly in the West, where the effects of the circular current in the Sulina Bay are felt. It is evident from the above that the alluvial mass of the Sulina mouth is due to the S-N current, the existence of which has been neglected because one was convinced that the greater part of the alluvia came from the adjoining Stari-Stambul arm. If it had been possible to avoid the construction of dykes which favour those deposits, it would have been possible by simple dredging operations to maintain the depth of the navigable channel; this is confirmed by the fact that before the regulation of the Sulina arm, constant depths were maintained.

Contrary to what occurs in the other regions, to the South of the Delta the deposits take place solely under the action of the N-S current. This falls perpendicularly on the mass of fluvial waters of the Sf. Gheorghe arm and compels the deposits to form-up to the southward of the mouth, which has given rise to the Sakalin Island. It appears that this island forms an attraction for the long strand off the shore, which has a tendency to block up the sea from Sf. Gheorghe as far as Cape Midia. If we take into consideration that the tendency of the bar to increase opposite this arm is very small, and that the depths are greater than opposite the other mouths, the making of a new exit to the sea by Sf. Gheorghe appears in a very much more favourable light: on one condition, however, that sea dykes should not be constructed, thus leaving the mouth open to the liberating action of the N-S current; otherwise a phenomenon analogous to that of the Sulina, but in an inverse direction, would be encountered.

A phenomenon determined at all the mouths of the Danube is that the winds exert an influence on the sedimentation; not by direct action, but due to the waves and the surface currents which they produce. It is thus we observe that by the action of the winds in general the fluvial waters remain in the vicinity of the coast and the velocity of the river currents is thereby greatly diminished; a fact which brings about a considerable increase in the rate of sedimentation. This produces a deformation in the general mode of advance of the arms of the

Delta towards the sea. Instead of taking place by means of elongated banks in the direction of the river currents after the manner described by Dr. Gr. ANTIPA in his work entitled: *Wissenschaftliche und wirtschaftliche Probleme des Donau Deltas*, page 27, the advance occurs by deformed banks, as can be seen on the accompanying plate (Diagram of the mode of progression of the arms of the Delta of the Danube towards the sea).

A Study of the charts showing the evolution of the Delta of the Danube and particularly that of the Chilia Delta, leads us to observe the existence of several zones; thus we distinguish the zones of normal progression (described by Dr. Gr. ANTIPA) and the zones of abnormal progression (deformed by the winds). Zones A, C and E show the regions of normal progression while zones B and D are those of abnormal progression.

However, these zones are subjected to very large deformations as a result of the continuous action of the marine currents.

There is another factor which intervenes successfully in the process of sedimentation in the mouths of the Danube, namely, the cycloïdal waves. These waves retain the fluvial waters on the banks, the increase of which they accelerate. They are further of great importance in the increase of the bars and also of the "grindes".

In general, NE winds favour the increase of the north region of the Delta (Oceacoff), while SE winds favour that of the Sf. Gheorghe and Stambulul Nou regions. It may therefore be stated that, in the physico-chemical phenomena which occur in the sedimentation process at the mouths of the Danube, as a whole, it seems to us the winds play an important rôle by means of the waves and the surface marine currents which they produce, and not by direct action.

CONCLUSIONS.

In the region of the Delta of the Danube, there are two currents which have a different direction, temperature and salinity. The principal agents acting on the progression of the Delta are the marine currents and winds with their natural consequences. The channels which escape the influence of those currents are condemned to be blocked (as in the case of the Musura, Ananache, Bielgorodsk, Ancandinov, etc. channels). The Delta progresses alternatively as a result of the states of equilibrium established between the zones of progression.