The Study of the Methods of the Lower Danube Sector Limnological Evolution According to the Archaeological Sites and Remote Sensing Techniques

Studiul metodelor privind evoluția limnologică a sectorului inferior al Dunării pe baza siturilor arheologice și a tehnicilor de teledetecție

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Abstract

The purpose of this study was to develop a working method for analysing the natural environment according to the spatial distribution of archaeological data. In order to achieve these results, the data obtained from classical archaeological and historical studies were correlated with those obtained by field studies and remote sensing techniques. In this paper, the studies focused on the evolution of the Lower Danube, from Cotul Pisicii to Black Sea.

Data processing was based on free and open source applications. Through this, data from archaeological studies and satellite imagery was processed, thus obtaining a trace of the form and distribution of archaeological sites on vector strata. These were used to determine the evolution of Danube Delta area and the shape of the Danube fairway.

Preliminary data available at the moment revealed an intensive alluvial process of the Danube bank in the Cotul Pisicii-Crapina Lake area, *upstream of the Noviodunum Fortress (Isaccea) area, and in the sector* Revărsarea-Ceatalul Izmail. *The intense erosion process was found in the Noviodunum fortress (Isaccea) area.*

Within the Danube Delta area, four stages of its evolution, representing the three classic phases and the golf phase, have been identified. The correlation of these processes with data on the spatial distribution of the archaeological sites as well as on the historical periods that belong to them can provide a valuable indicator of the evolution of the lower sector of the Danube River.

Keywords: *Lower Danube, promontories, cluster, sub-cluster, historical periods*

Introduction

The purpose of this study was to develop a working method for analysing the natural environment according to archaeological data. In order to achieve these results, the data obtained from classical archaeological and historical studies were correlated with those obtained by field studies and remote sensing techniques. In this paper, the studies focused on the evolution of the Lower Danube (the Cotul Pisicii-Ceatalul Izmail Sector and Danube Delta). Data processing was based on free and open source applications.

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Many studies in the past have been carried out both on the natural environment and on the archaeological sites. Under these conditions, the present study is part of the current trend to determine the complex evolution of the natural environment through interdisciplinary research. Of course, from this point of view, the purpose of this study is to complete the data obtained by studying the stratigraphic sedimentary sequences.

Unfortunately, archaeological information is generally qualitative and, ironically, the more valuable information we have, the more difficult it is to identify the key information. From this point of view, it is more efficient to study the traces of human activities based on sedimentary stratigraphic sequences.

In order to use the archaeological information almost at the same level as the sedimentological ones, the data obtained through classical archaeological and historical studies were correlated with those obtained by field studies and remote sensing techniques. Based on this correlation, a number of key elements have been identified. Of these, the most important were: spatial distribution of archaeological sites over historical periods and classification of human settlements.

In this paper, the studies focused on the evolution of the Lower Danube area. Based on the spatial distribution of archaeological sites over historical periods, the evolution of this sector has been tracked over time. Data processing was based on cluster analysis, as well as free and open source applications. The analysis of the cluster was performed based on data obtained through historical and archaeological studies.

Based on the connectivity-based clustering (hierarchical grouping), observations made within the archaeological sites were grouped into classes (groups or clusters) of similar elements (historical periods). The evolution of the sector Cotul Pisicii-Ceatal Izmail and Danube Delta was tracked using the data obtained in the cluster analysis in relation to their spatial distribution.

Materials and Methods

The fact that the observations on the natural environment are generally punctual implies a degree of inconsistency in the data obtained.

To solve this problem, we can use the following solutions:

1. **Fill the gap between values** by statistical and mathematical methods (white box);
2. **Leaving blank the gap between values** and treating it as a black box;
3. **The mixed method** involves placing the variable containing the values in a known category but leaving blank the gap between them and treating it as a black box (gray box).

We can associate the last two solutions with the following data analysis techniques:

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1. Supervised classification, data analysis technique involving the processing of data sets by associating them with a particular class (label) whose identity is known (association of data with a certain known class is typical of grey boxes and black box);
2. Unsupervised classification (clustering) is an efficient way of dividing data into classes with a minimum amount of initial information about the identity of these classes (typical for the black box).

For historical and archaeological data analysis we used the method of hierarchical clustering the values of historical periods.

"Cluster analysis is a convenient method for identifying homogenous groups of objects called clusters. Objects (or cases, observations) in a specific cluster share many characteristics, but are very dissimilar to objects not belonging to that cluster" (SARSTEDT, MOOI, 2014).

The goal of data clustering, also known as cluster analysis, is to discover the natural grouping(s) of a set of patterns, points, or objects. Webster (MERRIAM-WEBSTER Online Dictionary, 2008) defines cluster analysis as ''*a statistical classification technique for discovering whether the individuals of a population fall into different groups by making quantitative comparisons of multiple characteristics*" (ANIL, 2010).

Many different types of clustering algorithms have been developed (SANTO, 2010; NEWMAN, 2012). Among these, hierarchical clustering methods play an important role in linking well-known scale-free and small-world network models as well as predicting the missing links (DUNCAN, STROGATZ, 1998; BARABÁSI, RÉKA, 1999; RAVASZ *et alii*, 2007; CLAUSET *et alii*, 2008; YU *et alii*, 2015)

In order to group the values of the historical periods into a hierarchy of classifiers, the intracluster correlation (*ICCor*) was used. „*The intracluster correlation coefficient, or ρ (the Greek rho), is a measure of the relatedness of clustered data. It accounts for the relatedness of clustered data by comparing the variance within clusters with the variance between clusters. Mathematically, it is the between-cluster variability divided by the sum of the within-cluster and between-cluster variabilities*" (KILLIP *et alii*, 2004).

The way in which historical periods measured in years (Val) are grouped in clusters was determined on the basis of their statistical deviation.

$$Dev = Val_i - \mathrm{m}(Val)$$

where,

Dev - statistical deviation;
m(Val) - the arithmetic mean value of historical periods (in years)
$Val_i \in Val$, $i = 1, 2, 3, \ldots, n$.

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Based on intracluster correlation (*ICCor*) the values of the historical periods were grouped into a hierarchy of classifiers by the following formula:

$$ICCor = \frac{\underset{i=1 \to n}{\mathrm{SUM}}(Val_i - \mathrm{m}(Val))^2 - (Val_i - \mathrm{m}(Val))^2}{\underset{i=1 \to n}{\mathrm{SUM}}(Val_i - \mathrm{m}(Val))^2}$$

This method is fully correct because it uses only *squared Euclidean distances* to compute centroids in Euclidean space.

The classifiers obtained by intracluster correlation (*ICCor*) were bring into the hierarchical structure through the linkage criterion. These criteria include the probability that candidate clusters spawn from the same distribution function (V-linkage).

Where,

$$Dis = 1 - abs(ICCor)$$

are the **complementary cumulative distribution function (tail distribution)** and

$$Dis = \frac{1}{\sqrt{2\pi}} \, e^{\frac{-ICCor^2}{2}}$$

the **standard normal distribution**.

For the analysis of the evolution of the lower sector of the Danube, the public cartographic materials and scientific information were generally used. These are either available in the Danube Delta Ecotourism Museum Center, on the Internet within the National Archaeological Register (http://ran.cimec.ro/) or on Google Earth Map (Google Hybrid, available under QGIS).

Results and Discussion

The cluster separation was performed based on a series of successive cuts performed at different levels of the dendrogram, as follows:

Cut1 = to_real(*substr* (*to_string* (*„disdiccor”*), *1,6*))
Cut2 = to_real(*substr* (*to_string* (*„disdiccor”*), *1,7*))
Cut3 = to_real(*substr* (*to_string* (*„disdiccor”*), *1,8*))
Cut4 = to_real(*substr* (*to_string* (*„disdiccor”*), *1,9*))
Cut5 = to_real(*substr* (*to_string* (*„disdiccor”*), *1,10*))

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The formula used for cluster separation is based on the observation that any attempt to reduce the number of decimals in a real number leads to the rounding of the last digits. Thus, to obtain a reduction in the number of decimals without rounding out the last digits, the values defining the clusters (disdiccor) have been converted to text (to_string()). The next step was to select the number of characters to be stored (substr()). Finally, the resulting values were converted from text format into numeric format with support for the decimal (to_real()).

The number of clusters per cutting varied as follows:

1. Cut1 = 2 clusters (0.4022 and 0.3989);
2. Cut2 = 4 clusters (0.40222, 0.39896, 0.39895 and 0.39894);
3. Cut3 = 6 clusters (0.402227, 0.398960, 0.398956, 0.398944, 0.398943 and 0.398942);
4. Cut4 = 8 clusters (0.4022278, 0.3989602, 0.3989561, 0.3989443, 0.3989430, 0.3989426, 0.3989424 and 0.3989422);
5. Cut5 = 8 clusters (0.40222789, 0.39896025, 0.39895619, 0.39894433, 0.39894304, 0.39894262, 0.39894240 and 0.39894228).

But the values in years of each period are grouped in the total number of nine clusters. This is due to the presence in cluster 0.39894228 of two subclusters 0.398942282 and 0.398942283. This is the explanation of the presence in Cut5 of only 8 clusters.

The Intracluster Correlation, performed in these works, was based on the removal of the *squared Euclidean distances* of a value to the arithmetic mean from the sum of the all *squared Euclidean distances* of the values to the arithmetic mean, and the result that remains, after we report everything to the sum of squared deviations, is the probability of associating the values in the clusters. For this reason, the resulting numerical values represent the likelihood that a particular event (cluster) occurs over one or more historical periods.

The distribution of the different stages of the evolution of the Lower Danube sector (sub-clusters) according to the historical periods in years is performed within the different sub-phases (sub-clusters) and time interval or phases (clusters), as can be seen in Table 1.

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Table 1. Stages and phases of the Lower Danube sector evolution
Tabel 1. Stadiile și fazele evoluției sectorului inferior al Dunării

Location	Cluster	Interval (Phase)	Sub-Cluster	Sub-Phase	Sub-Cluster	Period	Stage
Danube Lower Sector	0.4022	Paleolithic Period	0.40222	Gulf Phase	0.402227	Paleolithic Period	Initial Litoral Belt development begins on the area of Caraorman and Letea islands
Danube Lower Sector	0.3989	Neolithic - Present (Main Evolution)	0.39895	Sf. Gheorghe I Delta	0.398956	Neolithic Period	Initial Litoral Belt, Sf. Gheorghe Fluvial Delta and Sulina Fluvial Delta (partial)
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39895	Sf. Gheorghe I Delta	0.398956	Neolithic Period	Sf. Gheorghe I Fluvio-Maritime Delta
Danube Lower Sector	0.3989	Neolithic Present (Main Evolution)	0.39895	Sf. Gheorghe I Delta	0.398956	Neolithic Period	Danube River follows the main land shape
Danube Lower Sector	0.3989	Neolithic Present (Main Evolution)	0.39895	Sf. Gheorghe I Delta	0.398956	Neolithic Period	In the area Somova-Parcheş was a gulf of Danube
Danube Lower Sector	0.3989	Neolithic – Present (Main Evolution)	0.39895	Sf. Gheorghe I Delta	0.398956	Neolithic Period	Siret and Prut rivers flow into two gulfs
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398944	Early Bronze Period	Sulina Fluvial Delta
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398944	Early Bronze Period	Danube River follow the main land shape
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398944	Early Bronze Period	Siret and Prut rivers flow into two gulfs and the rivers deltas are started
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398944	Early Bronze Period	In the area Somova-Parcheş was a gulf of Danube

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Location	Cluster	Interval (Phase)	Sub-Cluster	Sub-Phase	Sub-Cluster	Period	Stage
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398942	Middle Bronze Period - Dacian Period	Sulina Delta (fluvial side and northern half of marine side)
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398942	Middle Bronze Period - Dacian Period	Chilia Delta (fluvial side - behind the Chilia Promontory)
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398942	Middle Bronze Period - Dacian Period	Danube River follows the main land shape
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398942	Middle Bronze Period - Dacian Period	In the area Somova-Parcheş was a gulf of Danube
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398942	Middle Bronze Period - Dacian Period	Siret and Prut rivers flow into two gulfs and the river deltas are in their early stages
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	Sulina Delta (fluvial and marine side)
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	Chilia Delta (fluvial side except the Thiagola Lack area)
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	The formation of the maritime sandbanks begins
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	Danube River follows the main land shape
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	In the area Somova-Parcheş was a gulf of Danube
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39894	Sulina Delta and Chilia Fluvial Delta	0.398943	Roman Period	Siret and Prut rivers flow into two gulfs and the river deltas are in their early stages

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Location	Cluster	Interval (Phase)	Sub-Cluster	Sub-Phase	Sub-Cluster	Period	Stage
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39896	Sulina Delta regression and Lagunar Complex development	0.39896	Byzantine Period	Sulina Delta erosion
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39896	Sulina Delta regression and Lagunar Complex development	0.39896	Byzantine Period	The development of the Lagunar Complex
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39896	Sulina Delta regression and Lagunar Complex development	0.39896	Byzantine Period	The Danube River begins the development of the sector Măcin-Grindu and the area Somova-Parches
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39896	Sulina Delta regression and Lagunar Complex development	0.39896	Byzantine Period	In the area Somova-Parcheş the Danube divides into two branches
Danube Lower Sector	0.3989	Neolithic-Present (Main Evolution)	0.39896	Sulina Delta regression and Lagunar Complex development	0.39896	Byzantine Period	Siret and Prut river deltas

Based on the method of hierarchical clustering proposed in this paper, a model of the evolution of the Lower Danube Sector was performed (see Figure 1).

Figure 1. The Lower Danube Sector.
Fig. 1. Sectorul inferior al Dunării

Figure 2. The sector between Ceatal Izmail and Cotul Pisicii
Fig. 2. Sectorul dintre Ceatal Izmail și Cotul Pisicii

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In order to understand the evolution of the Izmail Ceatal-Cotul Pisicii Sector (see Figure 2), the study had to be extended to a much larger area. Within this area, three obstacles that have influenced the Danube way have been identified. These points were named according to the archaeological sites existing in their area, such as: *Dinogetia* Promontory, *Noviodunum* Promontory and *Aegyssus* Promontory.

The whole Lower Danube Sector evolution can be divided into two phases (see Figure 3): Gulf Phase (0.4022) and Main Phase (0.3989).

These two phases are divided into four sub-phases: the sub-phase of the **Tulcea Gulf** (Palaeolithic Period), the sub-phase of the **Sf. Gheorghe I Delta** and the **Sulina Delta** (fluvial side) (Neolithic Period), the sub-phase of the **Sulina Delta** and the **Chilia Delta** (fluvial side) (Bronze Period – Roman Period) the sub-phase of the erosion of the Sulina Delta and the development of the **Lagunar Complex** (Byzantine Period).

The Gulf Phase is characterized by a single sub-phase (see Figure 4): the sub-phase of the Tulcea Gulf (Palaeolithic Period – sub-cluster 0.40222).

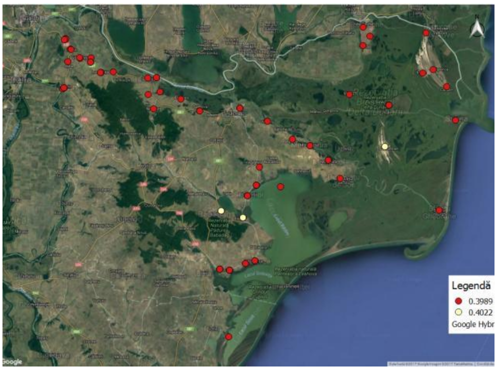

Figure 3. The two evolution phases of the Lower Danube Sector: main phase (red, 0.3989), gulf phase (white, 0.40222)

Fig. 3. Cele două faze de evoluție a Sectorului inferior al Dunării: faza principală (roșu, 0.3989), faza de golf (alb, 0.40222)

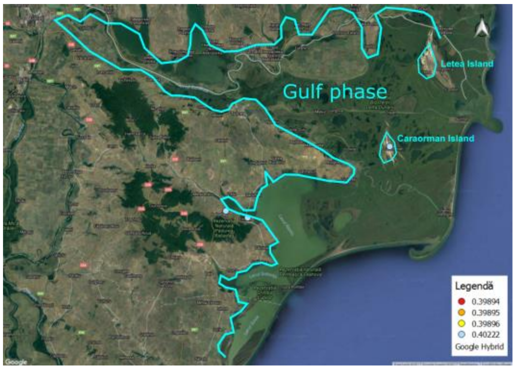

Figure 4. The sub-phase of the Tulcea Gulf (Paleolithic Period – sub-cluster 0.40222)

Fig. 4. Subfaza Golful Tulcea (Paleolitic – subcluster 0.40222)

Using these phases in the evolution of the Danube Delta to characterize the lower sector is not accidental. As suggested by the data on the fortifications in the *Noviodunum* Promontory area (see Figure 5), the Danube course was further north (about 45 m) and the water level 3 m below the

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current one. The presence of roman settlements in the south-eastern part of the fortifications from *Noviodunum* to the area Somova-Parcheş (after Gabriel Jugănaru, http://ran.cimec.ro), suggest a harbor existence in the East of *Noviodunum* Promontory. That suggests the existence of a gulf between *Noviodunum* Promontory and *Aegyssus* Promontory (see Figure 6). This means that the Danube River did not have enough power to develop the Delta and Izmail Ceatal-Cotul Pisicii sector at the same time. The sedimentation process between *Dinogetia* Promontory and *Aegyssus* Promontory was much lower than in the Delta area for a long period of time.

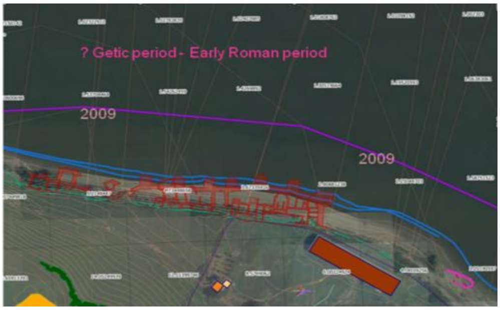

Figure 5. The fortifications in the *Noviodunum* Promontory area and probable limit to the first terrace of the Danube River (2009)
Fig. 5. Fortificațiile din zona promontoriului Noviodunum și probabil limita primei terase a Dunării

Figure 6. The potential presence of a Roman harbour in the East of *Noviodunum* Promontory
Fig. 6. Prezența ipotetică a unui port roman în partea de est a promontoriului Noviodunum

The Main Phase of the Lower Danube Sector (cluster - 0.3989) is characterized by three sub-phases: sub-cluster 0.39895 (the sub-phase of the Sf. Gheorghe I Delta and the Sulina Delta (fluvial side) (Neolithic Period)), sub-cluster 0.39894 (the sub-phase of the Sulina Delta and the Chilia Delta (fluvial side) (Bronze Period-Roman Period)), sub-cluster 0.39896 (the Sulina Delta erosion and the development of the Lagoon Complex (Byzantine Period)).

The sub-cluster 0.39895 (Neolithic Period) is the second important sub-cluster in the main phase of the Lower Danube sector. Towards the end of the Mesolithic Period and the beginning of the Neolithic, the Danube strikes the *Noviodunum* Promontory and is pushed to the north, where it hits another promontory and is pushed to the south-east. An intense sedimentation process in the northern part of the Palaeo-Danube course also occurs in the promontories *Dinogetia* and *Noviodunum*. This leads to an intensive process of deposition of the alluvium in the north and the formation of a bay in the

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south (the area Somova-Parcheş), between *Noviodunum* and *Aegyssus* promontories. During the Neolithic period, the Danube River follows the main shape of the land, and the Siret and Prut rivers have begun to create their own deltas (see Figure 7). In the Danube Delta area the fallows are formed: Initial Litoral Belt (Initial Spit – from geological point of view), Sf. Gheorghe I Delta and the Delta Sulina (fluvial side). The human settlements extending to the north and east suggest not only the extension of the Delta in the Neolithic, but also an interesting behaviour. Practically, after the formation of Initial Spit, Delta evolved in two directions simultaneously: along the Sulina Branch to the north and along St. Gheorghe Branch to the south (see Figure 7). This image recalls a fractal tree, which suggests the existence of a Paleo-Chilia Branch in the early phase.

Figure 7. Sub-cluster 0.39895 the situation of the Neolithic Period
Fig. 7. Sub-cluster 0.39895 situatia din perioada Neolitică

The sub-cluster 0.39894 is the most important cluster of Main Phase and contains three sub-clusters. The sub-cluster 0.398944 (Early Bronze Period) characterizes a dynamic stage in which the Danube River follow the main land shape as in the previous stage, but the settlements disappear along the Danube. If the restoration of the settlement in the following stages leads us to the conclusion that the form of the course has not changed, instead their disappearance in the Early Bronze Age signifies an increase of the level of the Danube (see Figure 8). In this period the river side of Sulina and Chilia Delta are developing. Delta continues to evolve in two directions at the same time. But the evolution of the Danube Delta is mainly on the direction of the Sulina Branch. The river side of Sulina Delta is fully formatted.

Within Sub-cluster 0.398942 (Middle Bronze Period-Dacian Period), the Danube River follows the main land shape and apparently during this period there are not major events. The Siret and Prut deltas continue their

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development (see Figure 9). In the Delta area, the Danube breaks the Initial Spit and develops the northern part of the fluvial-maritime delta of the Sulina branch. The fluvial side of Sulina Delta is in the process of consolidation and the river side of Chilia Delta is formed up to the Chilia Promontory.

If in sub-cluster 0.398943 (Roman Period) the Danube River follows the main land shape at the beginning of the period, when the Sulina Delta finishes its development, the Danube moves its course southwards. The water level is growing. Also, at this stage begins the clogging of the bay in the area Somova-Parcheş in its eastern part. Furthermore, the development of the sector behind the *Dinogetia* Promontory begins (see Figure 10). The river side of Chilia Delta is fully formed.

The sub-cluster 0.39896 (Byzantine Period) is the last as importance. The Danube River begins the development of the sector Măcin-Grindu and the area Somova-Parcheș. The Siret and Prut deltas are fully formed (see Figure 11). During this period, the first stages of the development of the Chilia Secondary Delta begin. The formation of the Sf. Gheorghe II Delta passes through the last stages. Sulina Delta is undergoing an intense erosion process. The formation of the Razim-Sinoie lagoon complex ends.

Conclusions

The preliminary data present at this moment revealed two major processes that were carried out within the main phase of evolution of the Danube Delta sector, namely: Delta formation and Cotul Pisicii-Ceatalul Izmail Sector formation. The first major process in the evolution of the Lower Danube Sector was the formation of the Danube Delta along the three branches. The training was based on a pattern that reminds of the fractal trees.

Figure 8. Sub-cluster 0.398944
the situation of the Early Bronze Period
Fig.8. Sub-cluster 0.398944 situația din Epoca Bronzului timpuriu

Figure 9. Sub-cluster 0.398945 the situation of the Middle Bronze Period-Dacian Period
Fig. 9 Sub-cluster 0.398945 situația din perioada Epoca Bronzului mijlociu și perioada Dacică

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Figure 10. Sub-cluster 0.398946 the situation of the Roman Period
Fig. 10. Sub-cluster 0.398946 situația din Epoca Romană

Figure 11. Sub-cluster 0.39896 the situation of the Byzantine Period
Fig. 11. Sub-cluster 0.39896 situația în Epoca Bizantină

For the sector Cotul Pisicii-Ceatalul Izmail formation, the data present at this moment revealed an intense alluvial process of the Danube River bank in the area of Cotul Pisicii-Crapina Lake (beginning in the Neolithic period, but having the greatest development during the Byzantine Period), upstream of the *Noviodunum* Fortress area (between *Dinogetia* and *Noviodunum* promontories) and in the sector Revărsarea-Ceatalul Izmail (beginning from the Roman Period – between the *Noviodunum* and *Aegyssus* promontories). The intense erosion process (beginning in the Roman Era) was found in the *Noviodunum* Fortress (Isaccea) area. During the medieval period, the Danube River takes control of the Prut and Siret deltas which are included in the main stream.

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