Analele Universităţii din Oradea – Seria Geografie Year **XXI**, no. **2/2011** (**December**), pp. **181-191**
ISSN **1454-2749**, E-ISSN **2065-1619** Article no. **212103-528**

PERSPECTIVES IN THE ANALYSIS OF THE TERRACES OF THE DANUBE WITHIN THE OLTENIA PLAIN (ROMANIA)

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Abstract: The present paper aims at rendering the evolution of the morphologic, climatic, and hydrographical events registered starting with the end of the Romanian till the Holocene. All the aforementioned events led to the formation of the terraces of the Danube along the sector Gura Văii - the mouth of the Olt River. By the end of the Romanian, within the Oltenia Plain, the continental phase that brought to the formation of the present landforms began. The development of the terrace plain occurred on the background of the deterioration of the piedmont structure that was located along the Carpathian-Balkan curvature. The start of the destruction of the piedmont structure coincides with the formation of the Danube course and the development of its hydrographical system. The erosion of the piedmont structures and the development of a terrace plain functioning as a depression occurred on the background of the Pleistocene climatic oscillations, of the rightward deviation of the Danube, and of the lowering of the base level. Thus, it appeared the Danube Valley the width of which reached even 48 km and the depth 180 m, with a terrace system that corresponds to the main palaeogeographic coordinates. All these analysed events and transformations that are rendered by means of GIS lead to the reconstruction of the formation stages and allow a synchronization of the morphologic, climatic, and hydrographic stages.

Key words: Terraces, GIS, Oltenia Plain

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INTRODUCTION

The South of Romania is crossed by the Danube River. The paleogeographic evolution led to the development of a wide plain on the left of the river, called the Romanian Plain or the Lower Danube Plain. There can be noticed the following genetic types of plains - piedmont plains, subsidence plains, terrace plains, and tabular plains, which are generally distributed on longitudinal alignments. The western side, starting with the area where the Danube River flows out of the Defile, at the Iron Gates up to the Olt River, is called the Oltenia Plain (figure 1). It presents 75% terrace

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plains (Geografia României, 2005) and only 25% of its surface was not modelled by the river still displaying the features of the piedmont plain (Leu - Rotunda and Drănic - Sălcuța Fields).

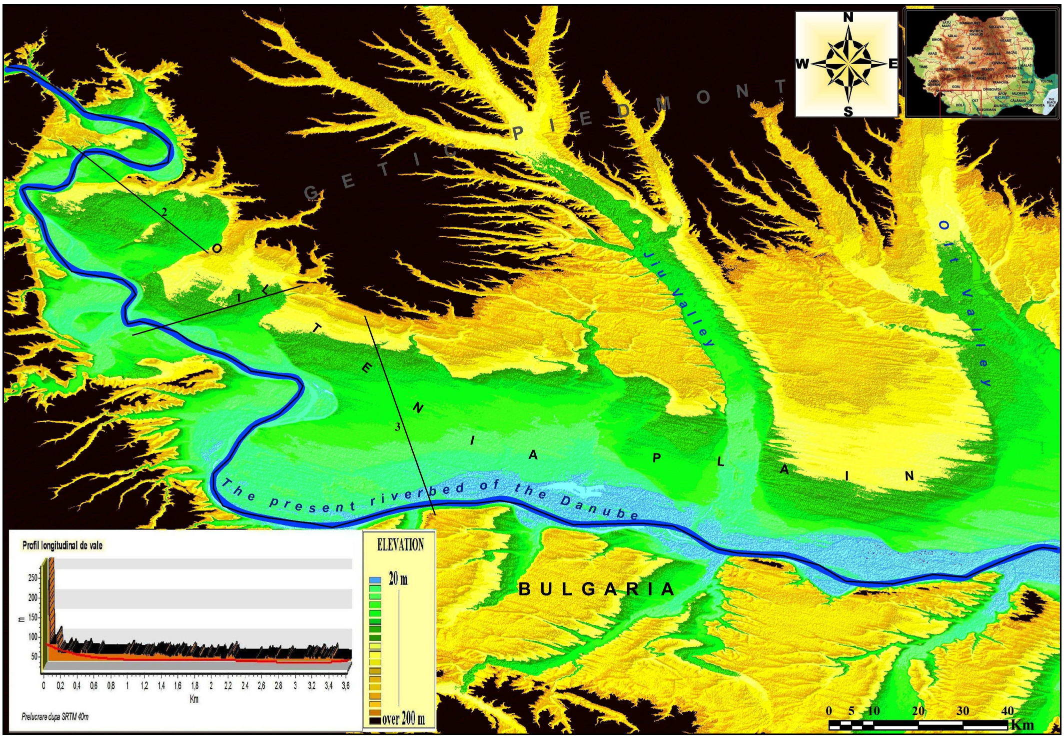

Figure 1. The hypsometrical map of the Oltenia plain

The Oltenia terrace plain is an erosion and accumulation depression, entirely developed under the action of the Danube, the southern limit following its lowest part (Boengiu, 2000). The erosion of the piedmont structures and the formation of a terrace plain that functioned as a depression occurred on the background of the Pleistocene climatic oscillations, of the rightward deviation of the Danube, and of the lowering of the base level. Thus, presently, in Oltenia, it was proven the presence of eight discontinuously developed terraces (Geografia Văii Dunării Româneşti, 1969) (figure 2). Yellowish-reddish loess and loess-like deposits cover the upper terraces, while the lower terraces and the floodplains present sands and dunes.

The analysis of the position of the Danube terraces within Oltenia, their link to the terraces of the Jiu and the Olt rivers, made by many researchers brings us to the conclusion that the evolution of this river is, at least to a certain extend, determined not only by the neotectonic movements (which imposed the development of the terraces only on the left of the Jiu River and on the right of the Olt River), but also by the Quaternary eustatic modifications, induced by the succession of many glacial and interglacial stages.

The rising from Leu - Rotunda is due to the Passadena neotectonic phase, when 'the Riss-Wurm red clays located within Schiau anticline indicate a folding during the Middle Pleistocene' (Saulea, 1967), phase that has to be taken into account in the analysis of the terraces of the Danube, which can be correlated with the terraces of the Olt and of the Jiu rivers.

The Romanian research in the field continues to use the Alpine chronology (that referring to glaciations) in order to correlate the age of the terraces. The relative altitude of terraces, the characteristics of the sediments, and the age of fossils (paleonthological method) still represent the main methods for terrace dating. Absolute dating, based on paleomagnetic data, Th/U or luminescence dating, were used for establishing the age of the terraces of the Danube in Hungary (Pécsi, 1973, 1959).

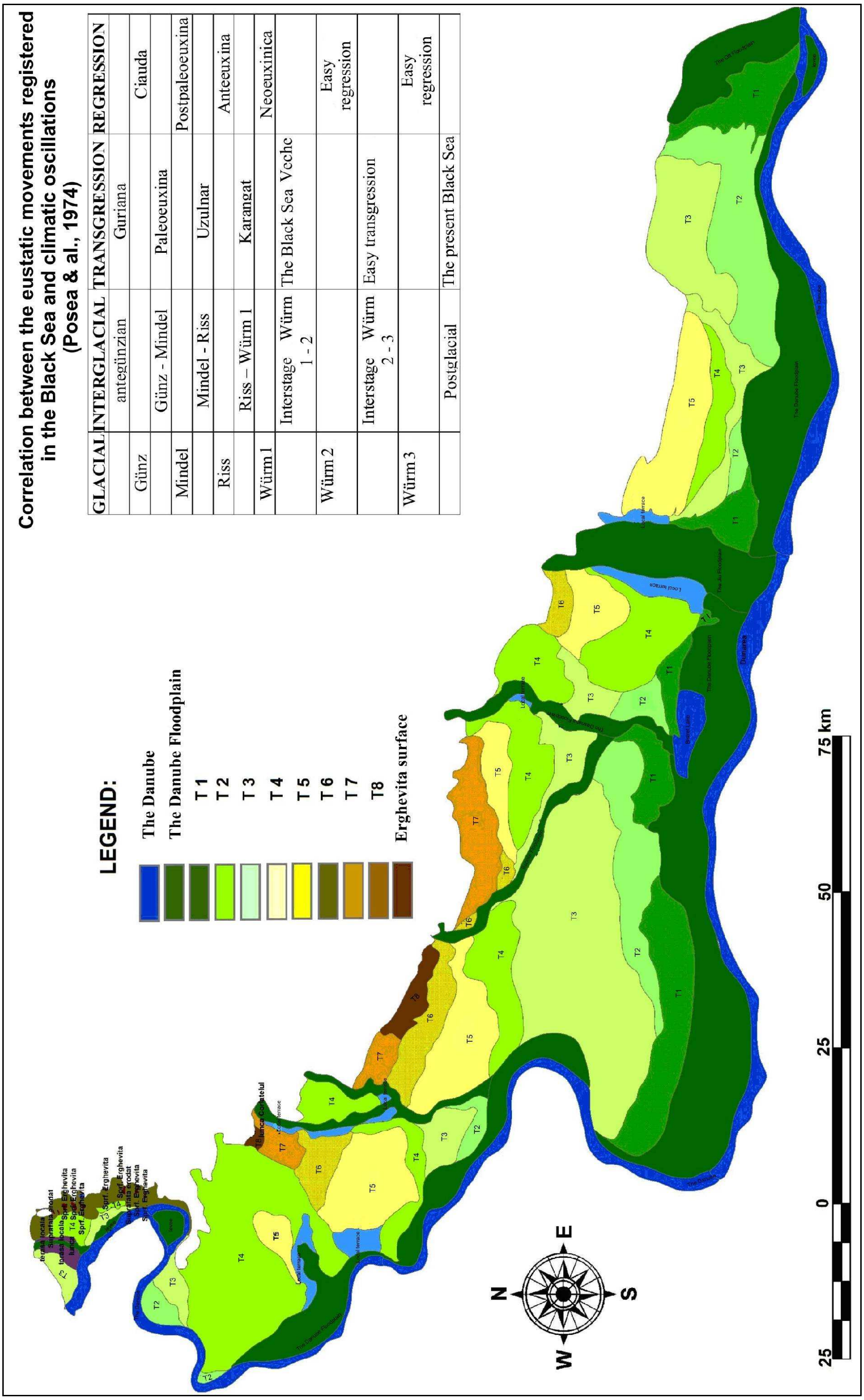

Figure 2. Map of the Danube terraces within the Oltenia Plain
(Source: after *Geografia Văii Dunării Româneşti*, 1969)

The dating of the terraces located within Wien basin was achieved according to the thickness of sediments, namely the depth of the lower horizon and the height of the terrace tops. From the granulometric point of view, older deposits are finer than the younger ones, which display larger dimensions of the sediments (Pfleiderer, 2008). The features of each terrace have also been analysed according to the local trend of geomorphologic modelling conditioned of not by tectonic faults, as well as by the base level.

In Vojvodina region, Serbia, in the sector Vukovar-Belgrade, sediments dating based on magnetic susceptibility (MS), which was also correlated with the stratigraphy of the marine isotope (Markovic et al, 2009). The thickness of the analysed deposits generally reached 40 m and there was noticed low concentration of magnetic minerals in loess and high concentration in paleosols. The interpretation by means of rubification index and rock magnetic record of these data allowed the reconstruction of the paleoclimatic fluctuations during five glacial and interglacial cycles.

The literature abunds in recent studies about the climatic and tectonic control for the formation of terraces, sediments analysis as well as dating of terrace or adjacent deposits (Gibbard, 2004; Ruszkiczay-Rüdiger, 2005; Jakab, 2007; Bridgland, 2007, 2008; Gábrisa, 2007; Buggle, 2009).

DATA AND METHODS

Starting from the evolution of the valleys developed in sedimentary deposits due to the rapid lowering of the base level, we used quantitative data, as well as verifications for the terraces developed on the background of the Quaternary climatic oscillations in analogous cases. The premises for the GIS analysis of the Danube Valley, located between the Defile and its confluence with the Olt River, are the linear and lateral erosion of the sediments of Carpathian-Balkan origin induced by certain neotectonic movements or by the change of the base level imposed by the climatic oscillations. The geological data indicated by the boreholes made along the Oltenia Plain correspond to Pelletier model only in the immediate proximity of the mountainous area, in all the other cases sedimentation being controlled by marine transgressions and regressions and by the alluvia discharge of the hydrographical systems from the region (Enache, 2008).

Thus, the complexity of the terraces genesis determined us to take into account many models and try to eliminate by means of analysis those models that are not adequate in the case of the Danube. For the sector located between the Danube Defile and Corbului Islet-Stîrmina Hill, the accepted model for the formation of the terraces is the one described by Pelletier (Pelletier, 2008). These terraces are induced by the alternance of the sedimentation - drainage process, which means that when the alluvial fan is under formation, the drainage is not concentrated, while during the periods characterized by climatic cooling and lowering of the base level, the flow is concentrated along certain channels (increase of the bottom erosion). Thus, it results lateral alluvia are no longer directly influenced by drainage becoming terraces; the process repeated as the base level oscillated. The channeling of the river along a single bed functioned as a local base level for the hydrographical systems installed on the newly formed terrace. Along the sector between Stîrmina and the confluence of the river with the Olt River, from Pelletier model, we must take into account only the relation between the slow flow, characterized by very wide meanders during warm periods when the base level raised, and the intensive bottom erosion registered during climatic cooling periods when the base level decreased.

The used satellite images are taken by Landsat 7, NASA for the Balkan region. We also used orthophotoplans at the scale 1:5,000 for the regions where the limits are not characterized by large variations of level. Thus, the first stage of the research was the georeferenciacion of the satellite images and of the aerophotograms, as well as of the lithological (scale 1:200,000), geomorphologic (Geografia Vaii Dunarii Romanesti, 1969), hydrogeological (scale 1:50,000), and topographical (scale 1:25,000) maps. The overlapping of the cartographic documents allowed the precise identification of the limits between the terraces and of the eventual contradictions, which were solved by means of local altitude determinations and boreholes. On the base of the satellite images, we worked according to Pelletier model when trying to correlate the terraces through the analysis of the torrent processes installed there and of the average altitude, they are located at.

DISCUSSIONS

The relation between the eustatic movements registered within the Black Sea and the glacial and interglacial stages is a starting point in the analysis of the period when the Danube River built its terraces in the south of Oltenia (Badea, 2000). This relation might be explained by the fact that when the eustatic level of the Black Sea raised and, of course, that of the lake located at the south of the Carpathians, due to the thawing of the glaciers and heavy rainfalls registered during the interglacial stages, the advancement of the river stopped and there occurred a more intense divagation within the floodplain (Boengiu, 2009). During the glacial stages, as the climate was dry and the surface flow diminished, there occurred an eustatic lowering of the Black Sea and of the extra-Carpathian lake, which affected the extension of the Danube's riverbed and led to the intensification of vertical erosion. Consequently, the Danube left the former floodplain that remained as a new terrace compared the new riverbed.

The classical dating of the terraces of the Danube in the studied sector made reference to the chronology of the Alpine glaciers. Thus, we used the correlation *Global Chronostratigraphical Correlation for the last 2.7 million years, 2010*, achieved by University of Cambridge, University of Utrecht, International Union for Quaternary Research (INQUA), Stratigraphy and Chronology, International Union of Geological Sciences.

Starting from the hypothesis that the 8th terrace (T_8) of the Danube, with a relative altitude of 140 - 170 m, represented the first floodplain of the Danube during the Pre-Günz stage (MIS 16, 620 - 680 ka) and then it was cut during Günz glacial stage (Marković et al, 2009), it results that the 7th terrace (T_7) with a relative altitude of 110 - 115 m functioned as a floodplain during Günz - Mindel interglacial stage, being cut in Mindel stage (MIS 13 - 15, ka 455 - 620). Günz glacial stage occurred by the end of the Upper Pleistocene (St. Prestian); in the South of Romania, there was registered a temperate continental climate and the Black Sea was in a lacustrine stage, its shore being located eastwards of its present position (Ciauda phase). The first formed terrace generally does not present alluvia. At the beginning of the Middle Pleistocene, there occurred Günz - Mindel interglacial stage; on the background of a warm and dry climate with seasonal differences, red clays formed. The Black Sea maintained its level (Post-Ceauda phase) and the Danube widened its floodplain. It followed Mindel glacial stage, when the climate got colder, the level of the Black Sea decreased (Paleo-Euxinic phase) allowing the deepening and the formation of a new terrace.

The 8th and 7th terraces are located only west of the Jiu River more precisely to the area were the Baboia Stream and the Desnățui River flow out of the piedmont (Geografia Văii Dunării Româneşti, 1969).

The 6th terrace (T_6), with a relative altitude of 90 m, functioned as a floodplain during Mindel - Riss interglacial stage and developed during Riss glacial stage (MIS 6, ka 130 - 200). In the second part of the Middle Pleistocene, there occurred Mindel - Riss interglacial stage, when climate acquired Mediterranean aspects and the basin of the Black Sea was subject to a transgression (Uzulnar phase). Under these circumstances, lateral erosion exerted by the Danube increased and the river extended its floodplain. By the end of the Middle Pleistocene, it occurred Riss glaciation, climate got colder and the line of the shore withdrew due to the regression registered during the Middle Euxinic period. Consequently, the Danube increased its vertical erosion.

The 5th terrace (T_5), with a relative altitude of 70 - 75 m, appeared as a large floodplain during Riss-Würm interglacial stage. It formed during Würm 1 glacial stage (MIS 5e [7, 9?], ka 110 - 130). The Upper Pleistocene starts with Riss - Würm interglacial stage; on the background of a temperate climate, there occurred a new transgression of the Black Sea (Karangat phase), the Danube carried huge amounts of alluvia and increased its lateral erosion. The last glacial stage, Würm 1, when the climate got periglacial, is characterized by the occurrence of a new regression registered during the Neo-Euxinic phase; the river deepened its course.

The 4th terrace (T_4), with a relative altitude of 50 m, functioned as a floodplain during the warm Würm 1 - Würm 2 interglacial stage. It developed through the deepening of the riverbed during Wurm 2 glacial stage (MIS 4 - 5 a - d, ka 40 - 110). By the middle of the Upper Pleistocene, it started the old Black Sea phase, characterized by a general transgression with slow stagnation periods (Coteț, 1957). During Würm 1 - Würm 2 stage, climate became temperate there occurred a transgression, and implicitly a divagation, while during Würm 2 climate became periglacial.

The 6^{th}, the 5^{th}, and the 4^{th} terraces appear along all the sectors of the Oltenia Plain, but not after the confluence of the Danube River with the Argeş River.

The 3^{rd} terrace (T_3), with a relative altitude of 27 - 35 m, formed the Danube floodplain in Würm 2 - Würm 3 interstage; it was left as the riverbed lowered during Würm 3 glacial stage (MIS 2 - 3, ka 12 - 40). The 2^{nd} terrace (T_2) of 13 - 27 m and the 1^{st} terrace (T_1) of 8 - 13 m, which are wider and continue east of the Olt River, appeared during the post-glacial stage (MIS 1, ka present day - 12). By the end of the Upper Pleistocene, the Black Sea evolved towards the present features; the anaglacial and cataglacial stages Würm 2 - Würm 3 and Würm 3 induced slow regressions and transgressions, while during the tardiglacial and postglacial, the shoreline evolved from -35 (-80) m towards the present position.

RESULTS

In the case of old terraces, geomorphologic processes display an increased intensity, while in the case of very old terraces, these processes led to their total destruction; the action of erosion on terraces can be noticed in the satellite image from figure 3, where T4 appears more fragmented than T3 within Severin Depression, which comes to support this theory. As the age of the terraces decreases, from the Middle Pleistocene (T5, T4) till the Upper Pleistocene or even Holocene (T3, T2, T1), the tops of the terraces get more intact (Enciu, 2007). Using the method of relative dating of the terraces age proposed by Hsu and Pelletier, one may correlate the succession of the terraces, especially of those that are more recent, as they preserve, in most of the cases, their top intact. Surface and altitude are the data necessary to apply the calculation formula (Pelletier, 2004):

$$h(x, t) = \frac{4h_0}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}$$

Considering the solution of the data series and replacing $h(x, t) = h_0$, we have in the formula:
$H(x, t)$ = extension of the degradation of the terrace top within the surface (x) and in time (t)
h_o = initial surface

The facility of obtaining the data necessary for the determination of the relative age with the help of the aforementioned formula, in GIS system, is easily identifiable as the measurement of the surface of the terrace tops and of the extension of the surface affected by torrents may be achieved on satellite images, orthophotoplans, as well as by local mapping with the total station (equipped with a GPS); then, the acquired data are also evaluated in the same geographic information system.

Thus, through regressive erosion, the torrent fragments the scarp of the terrace and penetrate towards its top. The surface of the terrace tops in the case of the Danube along the analysed sector and the data introduced in the model for kt are 40, 60, 100... 3,200 sqm, and the length of the terrace 2L = 200 m. The threshold when the extension of the torrent determines the complete destruction of the terrace is kt≈200 sqm; thus, in the integral $\int \cos x\, dx = \sin x + C$ if we consider cos de x = decrease of the altitude of the top/ decrease of the surface of the terrace top and sin de x = time increase, then one may notice that the height of the terrace laniary decreases in time, relation expressed by means of the integral cos x dx + sin x + C, where cosx represents the decrease of the terrace altitude according to sin x, which represents time. Thus, in the case of T4 and T3 within Severin Depression, according to the torrents installed on T4, kt presents a value of 200 sqm for kt, while for T3, kt is 60 sqm. Consequently, T4 is at least twice older than T3. Once kt values are established for the representative samples for each of the 8 terraces, we may achieve their correlation also by taking into account the length of the torrents according to the formula $\alpha = \sqrt{kt}$.

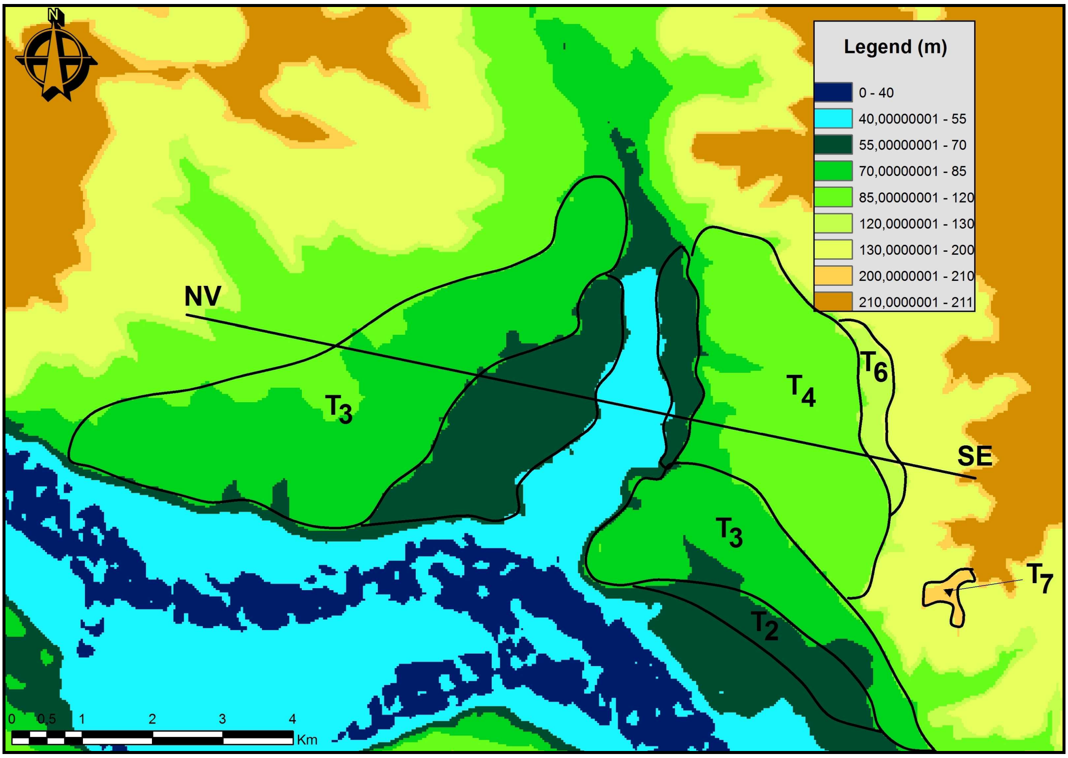

Figure 3. Reconstruction of the terraces of the Danube within Severin Depression according to the altitude of the terrace tops

Analysing the numerical model (SRTM, 90 m, from 2004), it comes out that the situation is even more complex; for example, in Severin Depression, according to the map rendered in Geografia Vaii Dunarii Romanesti, on the left of the Topolnita River, there is located T 4, which presents an extended and less fragmented top, while on the right, after the local terrace of the river that crosses this depression there appears only T 3, T4 being absent.

The altitude from the numerical model (figure 4) indicates that T4 is fragmented. In this case as well, there might be some discussions-the fragmentation might have been achieved by the Danube through meanders and, thus, T4 would be separated to the level T3 from the river course or the fragmentation might be of later origin induced by different erosion processes. With regard to the right side of the Topolnita River, where we should have had two terrace levels (local and T3 of the Danube), the situation rendered by the numerical model indicates that T3 is more withdrawn from the axe of the valley, due to the Topolnita River, which replaced the scarp of T3 through its local terrace (the upper level) (figure 4).

As we have mentioned before, Severin Depression also rises a series of correlation problems. According to the achieved profile, it comes out that on the left of the river, besides T4, there also develops a level that might be attributed to T3 (using the altitude correlation), as the difference of altitude between the Topolnita Flood plain and the top of the terrace that might be generated by the Danube River reaches 30 m.

Of course, there cannot be excluded the possibility that this local terrace of the river, would have been induced by the change of the base level or climatic oscillations. Regarding the right side, the correlation of the altitudes with the possible T3 located on the left of the Topolnita emphasizes the fact that this is more withdrawn and that the floodplain of the Topolnita River appears at a lower level (figure 4).

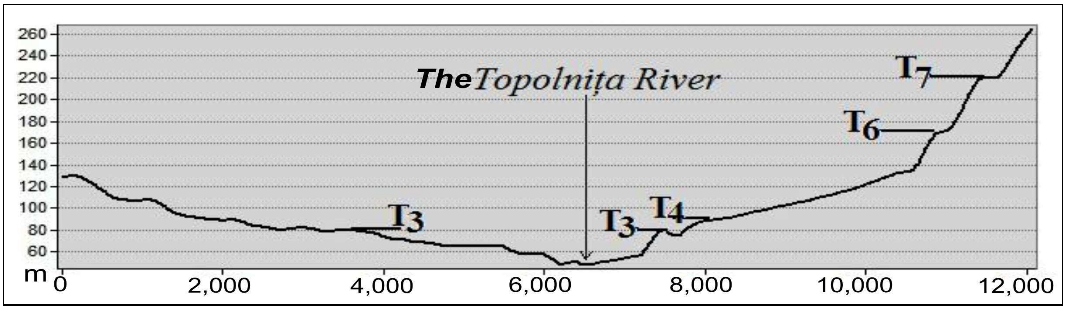

Figure 4. Topographical profile within Severin Depression, achieved after SRTM 40 m

The utilization of GIS, besides helping us create the models of erosion and correlation of the terraces according to the torrents installed on the terraces of the Danube, also allowed the achievement of a series of profiles within the areas that displayed certain problems with regard to the location of the limits. We also achieved transversal profiles, which, on the base of the extensions of the program ArcGis (Spatial Analyst, 3D Analyst), may render the succession of the terraces or, if it is the case, their lack in the established succession. Thus, through the option of creating the graphs according to the elevation model achieved by Shuttle Radar Topography Mission in 2004, the profile line was modelled in steps for each modification of altitude in order to obtain a better correlation of the terraces (figure 5).

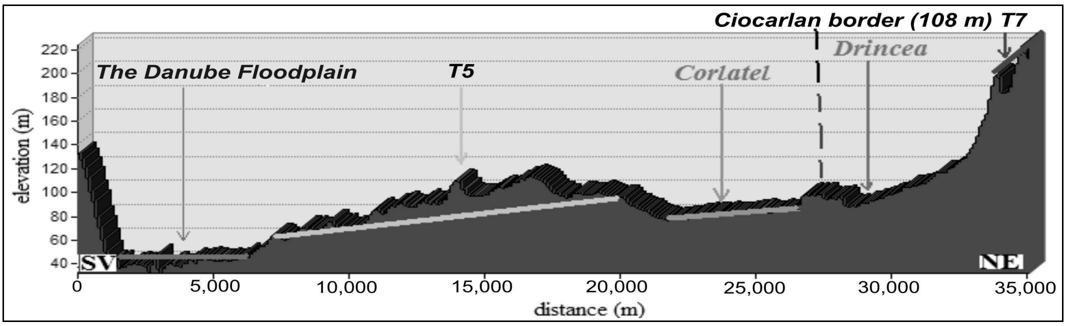

Figure 5. Topographical profile no. 1

By correlating the data obtained on the base of the profiles, satellite images, and the main cartographic product in terms of the Danube terraces (Geografia Văii Dunării Româneşti, 1969), we noticed a series of non-concordances.

Thus, as we may notice from figure 5, the succession of the levels in the analysed sector is T5 and, according to the aforementioned volume, there would follow T6 on the same alignment. However, the altitude of the area indicates that there should be a terrace lower than T5 or that on T5 (from this sector) the level of the sediments (at the level of the lateral levee) is much higher than on T6 or that there appears a series of dunes.

The west-east succession of the terraces is rendered in figure 6, which present an erosion outlier (T5) that has on its both sides T4; it is thus obvious that the meanders of the river eroded the material and the continuity of T5 was no longer preserved.

Figure 7 renders a new succession of the Danube terraces within a perimeter of the Oltenia Plain where the floodplain destroyed T1; T2 remained due to the aeolian sediments carried in the area. T3 and T4 are reduced and fragmented by the hydrographical system installed on subsequent valleys (Boengiu, S., 2000). Within this sector, T7 appears for the last time on the Danube Valley, at the contact with the northern piedmont region (Stroe, 2003).

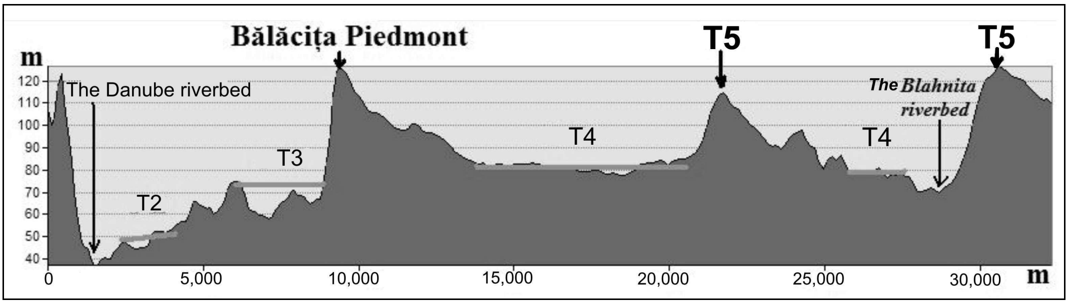

Figure 6. Topographical profile no. 2

The creation of the digital product DEM, using ArcGis 9.2 on the base of the topographical maps and GPS surveys, allowed us a better determination of the elevation that helped us correlate the terraces according to the relative and absolute altitudes of the terrace tops. DEM-s also enabled us to analyse these terraces from the morphologic point of view as, according to the sedimentary deposits, it resulted that certain terraces present a higher altitude mainly due to the eolian deposits, which formed after their initial development.

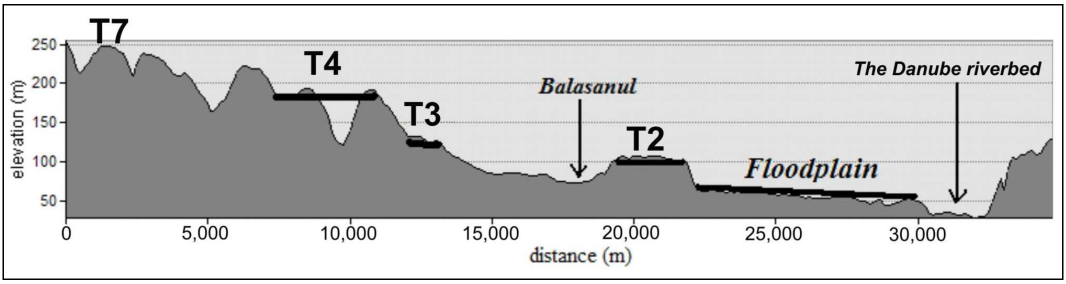

Figure 7. Topographical profile no. 3

The interpolation between the altitude (altitudes determined by means of GPS) and the piezometric level (the hydrogeological maps 1:50,000) DEM-s allowed us to locate the contact area between two successive terraces. In this contact area, in most of the cases, there also appear springs, the presence of which was also certified in the field. We mention that the GPS measurement were achieved by means of a NAUTIZ X7 device, which supplies values in real time and has an error of 2 - 3 cm both on vertical and horizontal directions. The measurements were made in WGS84 projection system and then the values were transformed such that they matched the projection system Stereografic 70, as the Romanian maps are achieved in this last system.

On the base of the correlation between the phreatic level and the altitudes/depths they are located at, numerical modeling (figure 8) allows us notice that, in most of the cases, the discontinuity of the morphologic slope and sometimes even of the phreatic aquifers at the limit between terrace levels and, on certain sectors, between terraces and floodplains, is induced by the presence of some impermeable layers below the aquifers, which are former erosion levels of the Danube (Badea, 2000). Thus, the isopieses map, as equipotentials of the piezometric surface, expresses the morphology of a phreatic horizon and indicate the slope and the flow direction emphasizing the level of the impermeable layer, the flow altitude at the moment when the respective terrace developed.

The results obtained for the interpretation of the chronology of terraces on the base of the geomorphologic, lithological, and pedological aspects may be further used in case there are no possibilities of absolute dating. There are some problems that may appear when using traditional methods, as Ruszkiczay-Rudiger et al. observed (Ruszkiczay-Rudiger et al, 2005). The deepening of the longitudinal profile may be induced by a continuous tectonic rising or / and the influence of the climatic fluctuations upon rainfall amounts and sedimentation rate. The depositing of sediments may be considered a consequence of the increase of the solid flow or of the decrease of the flow speed (Burbank and Anderson, 2001). The deterioration of the terraces due to meander formation / lateral erosion make the determination of their age be quite imprecise if we resume only to altitudes. The granulometry of the sedimentary deposits is not identical for the same horizon and making correlations among lithostratigraphical columns is difficult.

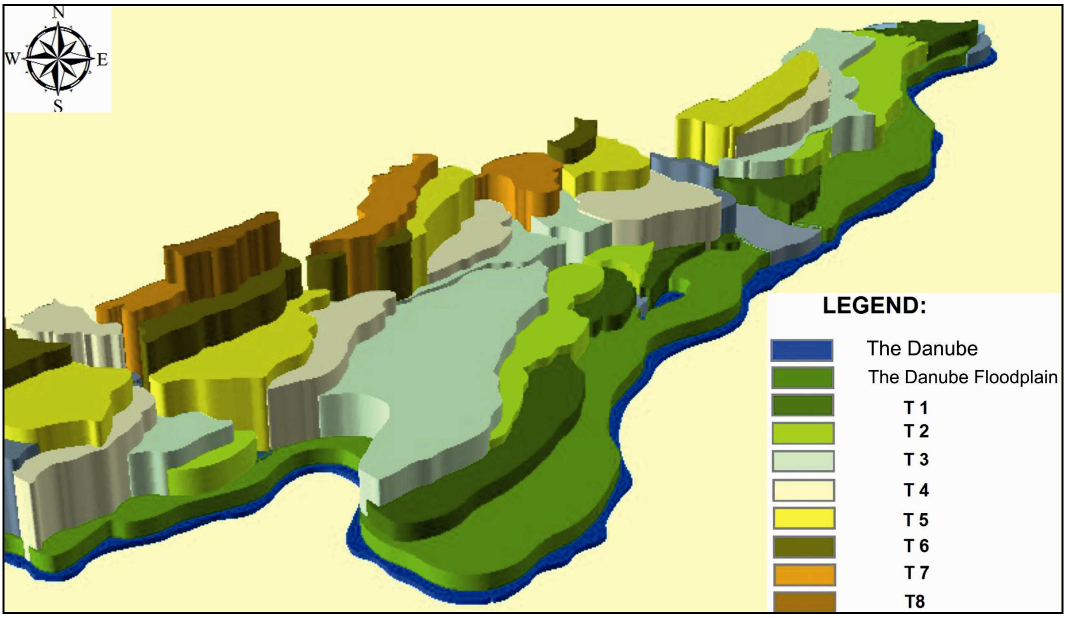

Figure 8. Modelling of the terraces of the Danube according to the average altitude of the terrace tops (Source: Geografia Văii Dunării Românești)

CONCLUSIONS

By analysing the dependence of the terraces of the Danube between Gura Vaii and the Olt River, it results a good correlation between climatic oscillations and the formation of the respective terraces, if we admit that, during the interglacial stages the river got slower, formed meanders within a large floodplain (Pleniceanu and Boengiu, 2001), while during the glacial stages, due to the severe reduction of the surface flow and of the base level, vertical erosion intensified and the riverbed deepened. The main idea resulting from the studies achieved at international level is that the number of terraces did not exclusively conditioned by interglacial periods. There should be also taken into consideration the oscillations of the base level and neotectonic movements.

Through the digitization of the map published in Geografia Vaii Dunarii Romanesti we could start the reconstruction of the genesis of the terraces by correlating this cartographic product with the other models and interpolations in order to obtain the most accurate product possible. The digitization of the map achieved in Stereo 70 projection and then the introduction of the attributes for the relative altitude of the terrace tops allowed their block modelling enabling an optimal visualization of the succession of terraces. The evaluation of the extension of torrents within the terrace tops may also be considered a method for estimating terrace age (we consider that a terrace is older if the torrential valleys as more extended, both in terms of length and surface)

The reconstruction and exact correlation according to the altitude of the terraces could be achieved on the base of the extension Spatial Analyst and ArcScene of 3D interpolation, by means of which we were able to model the terraces in 3D, as blocks. We also were able to follow the southwards withdrawal of the riverbed according to the altitude the former riverbeds of the Danube used to be located at.

The cartographical and geomorphologic interpretation of the terraces of the Danube along the analysed sector allowed us to get aware of the fact that the methods used so far for dating and classifying terraces are empirical. Consequently, it is quite necessary to start using absolute dating methods, such as TH/U and luminescence, paleomagmatic dating etc.

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Submitted:	Revised:	Accepted and published online
May 23, 2011	July 27, 2011	August 22, 2011