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Geomorphological evolution of longitudinal river profiles in the Carpathians

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Abstract

The main rivers which drain the east and southeast side of the Eastern Carpathians and those that drain the Southern Carpathians have been analysed regarding the sediment transit, the change of the riverbeds and the type of channel deposits. In this paper, attention is focused on the concavity of the stream profile. On this basis, we tried to determine the evolution of some Carpathian rivers and thus estimate their long-term evolutionary tendencies.

The concavity index of the east-Carpathian rivers shows a trend to increase from north to south from the Eastern Carpathians to the Carpathian Bend and the Bucegi Mountains. The explanation of this situation required a review of the evolutionary stages of the Eastern Carpathians, in order to establish the age and the evolutionary tendencies of the river network in our study area: the Rivers Suceava, Moldova and Bistriţa have followed the same courses since the Sarmathian (approximately 13.5 million years ago); the Trotuş River, between 10 million and 5.4 million years ago); the Rivers Putna, Buzău, Prahova, and Ialomiţa suffered the most important changes, so the age of their present course is about 2.5 million years.

The rivers could be grouped according to the mathematical model which fits best: the exponential, exponential–logarithmic, and logarithmic model. Finally, we tried to correlate the age of the river with the form of its longitudinal profile. The customary theoretical models require that: the older a river is, the more its concavity should increase in the headwater area and should asymptotically approach a longitudinal equilibrium profile or "grade" as Davis calls it. However, the Carpathian rivers do not follow this general tendency. What we have demonstrated is that age had no influence on the form of the longitudinal profiles for the rivers on the exterior side of the Carpathians. This is because tectonic uplift was important, and this phenomenon is still present today with values of over 6 mm/year.

Keywords: Longitudinal profiles; Concavity index; Mathematical model; Geomorphological evolution; Carpathians

1. Introduction

Longitudinal profiles have interested many authors especially with regard to understanding their evolution and finding the most pertinent ways to predict their development. We could say that the most prolific period in the study of the longitudinal profiles was during the fifth and sixth decades of the 20th century, when many problems related to the form of longitudinal profiles and to the causes of their development were explained and researchers even tackled the

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problem of a rational description for them (Shulits, 1941; Yatsu, 1955; Hack, 1957; Brush, 1961; Roşu, 1967; Grumăzescu, 1975). After a relatively "calmer" period, the study of longitudinal river profiles was resumed, with new arguments and new research methods in the 1990s (Snow and Slingerland, 1987; Ohmori, 1991; Scheidegger, 1991; Rhea, 1993; Morris and Williams, 1999).

The most striking phenomenon related to longitudinal profiles is their form. The plotting of these profiles shows altitude against distance downstream. The resulting form is a curve, more or less regular, the concavity of which increases towards the headwater area. This is their most obvious and persistent feature regardless of the climatic conditions, the length of the river or the rock cut by the riverbed. The attention here is focussed on stream profile concavity, partly because it is assumed to be "...so common as to be almost universal" (Rubey, 1933, quoted by Wheeler, 1979). So it is only natural that this largely generalized observation be a fascinating subject for research of geologists, geomorphologists, and geographers everywhere.

We owe the first pertinent explanation of the form of the longitudinal profile to Gilbert (1877) who, on the basis of numerous laboratory experiments, showed that: *the slope of the longitudinal profile is inversely proportional to the discharge*. Further studies were concerned with an even greater number of variables which could explain the form of the profile as well as its evolutionary tendencies. Special attention is paid to the effect that the discharge, the characteristics of the riverbed material, the sediment discharge (suspended or bedload), and the type of rock in situ have on the form of the stream bed profile. The conclusion was that the variation of the discharge (Q), the riverbed material diameter (D_{mm}), and the sediment load (Q_s) are the most important in explaining the shape of the profile. All other factors such as rocks of different hardness, tributaries, neotectonic movements, and discontinuities caused by the different stages in the evolution of the profile, account for deviations from the general form of the profile, without fundamentally modifying it.

A steady preoccupation for researchers was to find a mathematical function describing the form of longitudinal profiles as precisely as possible, so that there could be a rational basis for palaeomorphological reconstructions and estimates of future evolution tendencies. The most relevant progress was made by referring to equilibrium profiles (so-called *graded profiles*), which have a smooth curve, without important discontinuities. This is related to an equilibrium in sediment transport without steep morphological changes in the direction of the riverbed. Referring to these types of profiles, a variety of mathematical functions have been suggested.

Further researchers tried to fit one or other of these functions to the real situation in the field but had little success. Many rivers, although they have profiles with no discontinuities (*graded profiles*), deviate strongly from the supposed equilibrium curve, because of local influences of the tributaries, changes in the calibre of the riverbed material, the influence of vegetation, and so on.

The entire field of models of longitudinal profiles was thoroughly reviewed by Snow and Slingerland (1987). A great number of experiments and different combinations of control factors led them to results which could be generalized. Further studies (Ohmori, 1991; Ohmori and Saito, 1993) verified in the field the results of numerical and laboratory experiments.

Related to the experience accumulated thus far in the study of longitudinal profiles, we investigated profiles of the main rivers which drain the east and southeastern side of the Eastern Carpathians. Our main objective was to define the present evolution of the Eastern Carpathian rivers, based on an analysis of the longitudinal profile form, and thus estimate their long-term evolutionary tendencies. The evolutionary estimates refer to both prediction and postdiction of profiles.

In order to attain this objective, we are taking the following steps: (1) to define the research area and the data basis; (2) to characterize the form of the longitudinal profiles by the method of unit profiles; (3) to present the mathematical model of the profiles; (4) to study geomorphological evolution of the longitudinal profiles.

2. The study area

Our study refers to 13 rivers of Romania, nine of them drain the exterior side of the Eastern Carphatians, the Carpathian Bend, and the Bucegi Mountains and

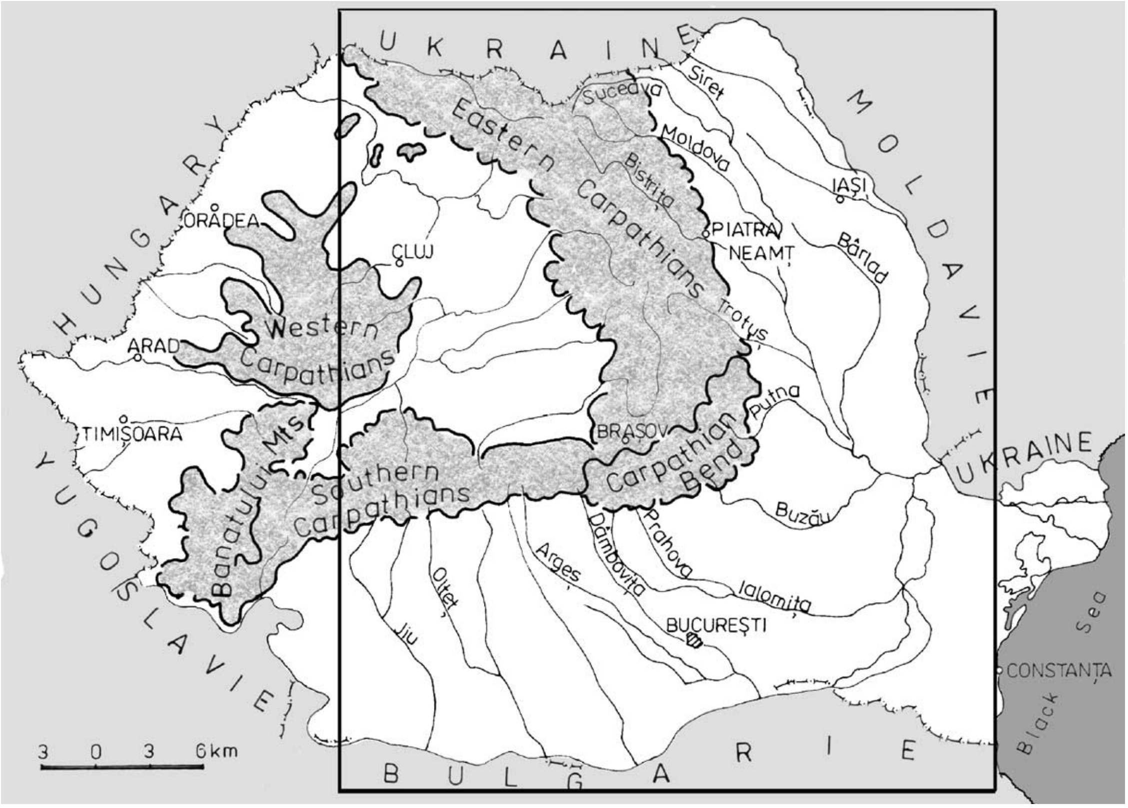

Fig. 1. Location of the studied streams. The marked area is detailed in Fig. 3.

the others drain the Southern Carphatians (Fig. 1 and Table 1). These rivers have been analysed by our team for several years, thus, we have an important database concerning sediment transport, the change of the riverbeds, and the type of channel deposits. We consider them representative for the morphodynamic

Table 1
Data on the studied rivers

No.	River	Drainage basin, A (km^2)	Network order (Ω)	Relief ratio, RR (m/km)	Average discharge, Q (m^3/s)	Peak discharge, Q_{max} (m^3/s)	Suspended load, Q_s (kg/s)
1	Suceava	2616	8	7.88	14.1	1385	5.90
2	Moldova	4299	8	8.19	26.2	1830	14.70
3	Bistriţa	6974	8	7.44	52.0	2200	8.30
4	Trotuş	4456	8	8.95	33.0	1700	38.45
5	Putna	2480	7	11.00	13.4	1400	91.80
6	Buzău	5264	8	6.44	25.7	1800	80.30
7	Ialomiţa	10,430	8	5.94	45.7	1440	95.00
8	Siret	42,274	9	4.17	254.0	3168	221.00
9	Teleajen	1656	7	14.4	9.35	–	–
10	Dâmbovita	2837	7	10.5	13.3	1420	21.30
11	Argeş	12,590	8	7.28	49.7	1700	45.20
12	Olteţ	2474	7	11.02	8.6	1190	39.40
13	Jiu	10,070	8	5.20	86.8	2200	114.00

conditions in the area, with reference both to the natural conditions and to the anthropogenic impact, especially to the presence of man-made lakes and extraction of sand and gravel (Ichim et al., 1989, 1996).

Concerning the position of these rivers (Fig. 1), it should be noted that over 50% of their length is outside the Carpathian area, but the deposits reflect the characteristics of the mountain area. The Siret and the southern rivers have long courses outside the Carpathians, but from the point of view of their sedimentary facies, their longitudinal profiles, and stream bed dynamics, they are Carpathian rivers for almost 85% of their total length.

Referring to the natural conditions, a few preliminary remarks are necessary for our study, namely: (i) The Carpathians imposed the main drainage directions to the streams in Romania, with a relief of approximately 2500 m. (ii) The main rivers from the east side of Eastern Carpathians (Suceava, Moldova, Bistriţa, etc.) have had an evolutionary continuity in their present courses since the Miocene (Donisă, 1968). (iii) The range of petrography in the hydrographic basins we studied is very large (metamorphic rocks, Neogene volcanic rocks, Mesozoic–Neogene flysch deposits, molasse deposits, and Quaternary–Holocene deposits). (iv) From a tectonic point of view, the area is still very active, at the present day. In the northern part of Eastern Carpathians (the drainage basins of Moldova, Suceava, and Bistriţa rivers), constant vertical movements of up to 5–6 mm/year are registered (Cornea et al., 1979), and the southern part of the Eastern Carpathians and Subcarpathians (for example, the basins of Buzău and Putna rivers) is affected by three to four earthquakes every century, with a magnitude of 7 on the Richter scale). (v) The rivers are mostly torrential. About 70% of the annual flow occurs in spring, and summer average discharges, with few exceptions, are under 6 m^3/s. On the other hand, maximum flows of over 1000 m^3/s have been registered on some rivers with hydrographic basins larger than 1000 km^2. (vi) There is a high mobility of the riverbeds in a vertical plane, with an amplitude that sometimes becomes more than 3 m in 35 years (for example, Moldova River in the Tupilati cross-section) and in a horizontal plane up to 11 m/year (Trotuş River), estimated for a 100-year period (1898–1986) (Radoane and Ichim, 1991).

3. The database and the method of work

The database for analysis of the form of longitudinal profiles consisted in the measurements of the river altitude against distance downstream, having as a result the following general table (Table 2).

Processing of the measurement data has the objectives:

(1) *To obtain a "unit" profile* in order to make comparisons between all the studied profiles on the same grounds. The data have been used for plotting and calculations of the parameters of the longitudinal profile form.

Table 2
Parameters of longitudinal profiles of the studied rivers

No.	River	Junction with	River length, *L* (km)	Max. altitude a.s.l., *H* (m)	Observations (*n*)	Concavity index, Ca	Median diameter of bed material (mm)
1	Suceava	Siret	156.0	1100	79	0.494	52.4
2	Moldova	Siret	205.0	1110	57	0.431	37.5
3	Bistriţa	Siret	292.5	1850	111	0.503	
4	Trotuş	Siret	160.6	1420	105	0.488	88.6
5	Putna	Siret	146.3	1460	99	0.651	83.1
6	Buzău	Siret	313.5	1800	86	0.765	66.9
7	Siret	Danube	657.3	1385	66	0.672	11.1
8	Teleajen	Prahova	116.7	1740	120	0.634	
9	Ialomiţa	Danube	416.5	2400	132	0.866	32.1
10	Dâmbovita	Arges	261.7	2469	113	0.685	
11	Argeş	Danube	338.3	2544	96	0.765	
12	Olteţ	Olt	189.0	2000	40	0.781	70.9
13	Jiu	Danube	416.1	2030	122	0.800	

(2) *To calculate the parameters of the form of the longitudinal profile*: the concavity index, the gradient, the gradient index, the hypsometric pseudointegral (Snow and Slingerland, 1987; Rhea, 1993). The concavity of the profile was determined as a ratio of the measured areas on the profile graphic, $Ca = A_1/A_2$, where A_1 is the numerically integrated area between the curve of the profile and a straight line uniting its ends and A_2 is the triangular area created by that straight line, the horizontal axis traversing the head of the profile. This parameter permits the quantitative estimation of the folding degree of the longitudinal profile.

(3) *Models of the longitudinal profiles using simple mathematical functions* were made considering four functions for describing the form of longitudinal profiles:

- the linear function $Y = a - bX$
- the exponential function $Y = ae^{bX}$
- the power function $Y = ax^{b}$
- the logarithmic function $Y = a\log X$

where Y is elevation (H/H_0); X is the length of the river (L/L_0), and a, b are coefficients independently determined for each profile.

4. Results

The rivers chosen for our study have been included for many years in our programme of measurements and surveys concerning morphodynamics, channel deposits, and the analysis of the sediment system (Ichim and Rădoane, 1990; Radoane et al., 1992; Ichim et al., 1998). We were concerned first with the rivers which drain the east side of Eastern Carpathians as direct tributaries of the Siret River. This area has been a point of interest for researchers because of the numerous palaeo-evolutionary problems and of development present dynamics.

4.1. Discussion of longitudinal unit profile forms

When the data are plotted, a first observation on the longitudinal profiles in dimensionless form is that it is immediately clear that the studied streams, all between 116 and 660 km long, have forms which differ from one river to another. The concavity in the upstream area is extremely reduced for Moldova, Suceava, and Trotuş Rivers and very obvious for Siret and Ialomiţa Rivers. Certain profiles present slope discontinuities, like, for example, Buzău and Ialomiţa, which show precisely the different stages in the river evolution. On the Bistriţa River, the Izvoru Muntelui Dam provides a threshold of anthropogenic origin, which must be considered for the general evolution of the river in the future. There are numerous secondary thresholds on all the rivers, caused by the interference of rocks with different hardness (Suceava and Moldova Rivers), the effect of neotectonic movements (especially, Teleajen River), the morphologic contact alluvial fan-plain (Putna and Buzău Rivers), and the deformation of the profile because of the tributaries (Siret River).

The general forms of longitudinal profiles can be compared more easily if the dimensionless curves are superposed, by reducing all the studied profiles to the same dimensions. For example, rivers of similar dimensions but of different ages, like Suceava, Moldova, and Trotuş have approximately the same form of their longitudinal profiles. The Putna River and Buzău River have a middle position, while the Ialomiţa River is at the opposite end. The lower the extra-Carpathian courses, the more L-shaped the profiles are.

Beside the qualitative observations of the form of the longitudinal profiles, we also have a series of quantitative measures, such as the concavity index. The concavity index Ca allows the following interpretation: if its value is close to 0.0, the form of the profile is close to a straight line; if its value is close to 1.0, the profile is L-shaped. A general analysis of this index shows indeed that there is a large variation in the form of the studied profiles. The most interesting observation is related to the variation of the concavity index for the east-Carpathian rivers. If we considered the position from north to south of each river from the Eastern Carpathians, the Carpathian Bend, and the Bucegi Mountains, we would see that the concavity index tends to increase (Table 2). The lowest Ca values are for the northern rivers, the Suceava, Moldova, Bistriţa, and Trotuş Rivers, between 0.431 and 0.503, followed by the Rivers Putna, Buzău, Teleajen, and Siret, with values between 0.651 and 0.765. The Ialomiţa River has the highest concavity index, very close to 1.00. Still, the other rivers which drain the south side of Southern Carpathians (Dâmboviţa, Argeş, Jiu, Olteţ Rivers) are also characterized by a high concavity of the longitudinal profiles (see also Figs. 4 and 5).

We have noticed that, at least for the right side tributaries of the Siret River, this tendency is exactly the opposite of the general opinion, which states that the older the river is, the more concave its longitudinal profile becomes, since it has a concavity index very close to 1.00. An explanation of this situation requires a review of studies of the evolutionary stages in the Eastern Carpathians, in order to determine the age and the tendencies of the river network in our study area.

4.2. The palaeogeographic evolution of the river system on the east side of the Eastern Carpathians

In this part of our work, we will review the main contributions to the understanding of the palaeogeomorphological evolution of the hydrographic system in our study area by Martiniuc (1948a,b), Niculescu (1963), Barbu et al. (1964, 1966), Posea (1967), Orghidan (1969), Donisă (1965, 1966, 1968, 1972), Lupu et al. (1970), Donisă et al. (1973), Posea et al. (1974), Ielenicz (1973, 1984), Donisă and Martiniuc (1980), Brânduş (1976, 1979), and Bandrabur (1981).

The most recent synthesis regarding the geotectonic evolution of the foreland basin of Eastern Carpathians is Grasu et al. (1999). We are interested in the emergence of the land, its vertical dynamics and the incision of the rivers, that is why we consider the picture based on Artyushkov et al. (1996) (Fig. 2) to be very suggestive. These authors point out the relation between tectogenetic stages, the Carpathian uplifting, and the subsidence of the Pre-Carpathian Basin (north and south of the Trotuş River). The tectogenetic stages, with their duration and their load under the nappes, are indicated from 1 to 6, from Oligocene up to Pleistocene (Fig. 2).

The time of events of convergence is indicated by inclined straight dashed lines. The height of solid vertical bars equals a load increase ΔP in the shortened region. The left-hand side of each bar is placed at the end of convergence. Crustal subsidence and uplift are shown by solid lines, which are labelled according to the place of occurrence. In this diagram, the crustal subsidence, uplift, and convergence, which took place in different parts of the East Carpathians, are shown together in order to compare the epochs of the occurrence. It appears that most of the crustal subsidence in the foreland regions, past and present, and the major uplift in the Carpathians, took place at the times when there was no convergence.

We can say that the most defining tectonic stages for the uplifting of the Carpathians were the Moldavian stage (marked 5 in Fig. 2, with a charge of $\Delta P\, 2 \times 10^9$ t/m) during the Volhynian, and the Vallachian stage (marked 6 in Fig. 2, with a charge of $\Delta P\, 0.5 \times 10^9$ t/m), during the Romanian. During the first stage, the Carpathians were uplifted approximately 500 m, and about 1000 m during the second stage. The huge load of the tectonic nappes had an effect upon the subsidence of the Pre-Carpathian Basin, which was lowered by >5 km north of Trotuş and by >10 km in the south, in Focşani Basin (for the latter, the subsidence had other causes, too). The uplifting of the Carpathians is still active in today; the last surveys give values of more than 6 mm/year north of Trotuş (Cornea et al., 1979). Thus, we want to emphasize the obvious phenomenon of isostatic adjustments in the study area and we will give many reasons for believing that the isostatic phenomenon is one of the factors which influenced the form of the longitudinal profiles. But first we need to review the evolutionary stages of the drainage system as seen by those who have studied this phenomenon for a long time.

The main features of the Eastern Carpathian drainage network (Fig. 3) are determined by the mainly transverse or diagonal–transverse character of the main river directions; none of them succeeded in crossing the Carpathian branch on its entire width. On the basis of rich material concerning the evolution of valleys on both sides of the Eastern Carpathians, the researchers determined two more stages in the evolution of the drainage network: the Pre-Sarmathian and Sarmathian–Pliocene–Quaternary stages.

The Pre-Sarmathian stage was long and confused owing to the succession of numerous phases of the Alpine orogenesis (Austroalpine, Mediteranean, Subhercynian, Laramic, Pireneean, Helvetian, Savic, and Styric phases). Under these conditions, it is difficult to identify any trace of pre-Miocene relief surface or of old hydrographic network in the present relief.

The Sarmathian–Pliocene–Quaternary stage corresponds to the final phase of the Alpine cycle, when

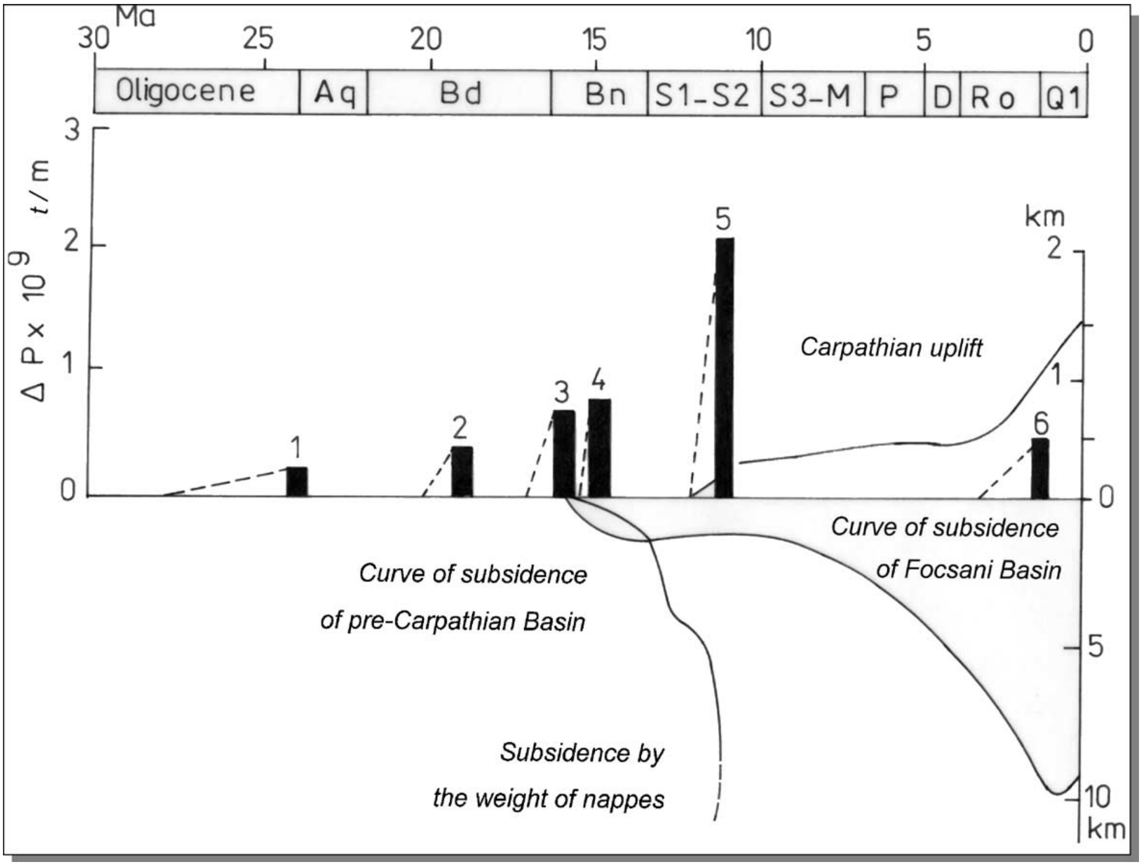

Fig. 2. The subsidence evolution of the foreland basin of East Carpathians together with the main convergence events and nappe fronts development in Oligocene–Pleistocene. 1 → 6 is the time of convergence events and load ΔP of thrust folds (nappes) (Artyushkov et al., 1996).

the landforms of Eastern Carpathians are relatively stable, except for some interior depressions, and the orogenic movements were vertical rather than horizontal. The even drainage network, which appeared then, had great stability and many of its features can be seen today. This is the period (the last 10 Ma) we are particularly interested in for the analysis of the longitudinal profiles and we shall discuss it in more detail. Considering events which had an influence on hydrographic network evolution, this stage may be divided in to three: *Sarmathian–Upper Pliocene*; *Upper Pliocene–Lower Pleistocene*; *Lower Pleistocene–Holocene*.

The Sarmathian–Upper Pliocene period is characterized by a rather long apparent tectonic calm. Almost the entire area of the Eastern Carpathians was emerged, except for the Comăneşti Basin and part of the Subcarpathian Bend. As today, the crystalline-Mesozoic axis was the water parting between west and east sides of Carpathians. On the east side, starting from Volhynian, transverse rivers appeared, flowing into the sea which was occupying the territory of the Moldavian Tableland. The deltas formed in this sea attest to the existence in that period of several palaeo-rivers such as the palaeo-Suceava and the palaeo-Moldova, which particularly interest us. These two long rivers have survived showing approximately the same direction until today.

During the Bassarabian, the Bistriţa surely existed in its present position, draining even then the axial side of the crystalline-Mesozoic area, the Dorna Depression, and with tributaries from the Bârgău and Călimani Mountains. The same can be said about the Siret River at least for its upstream part, as its age

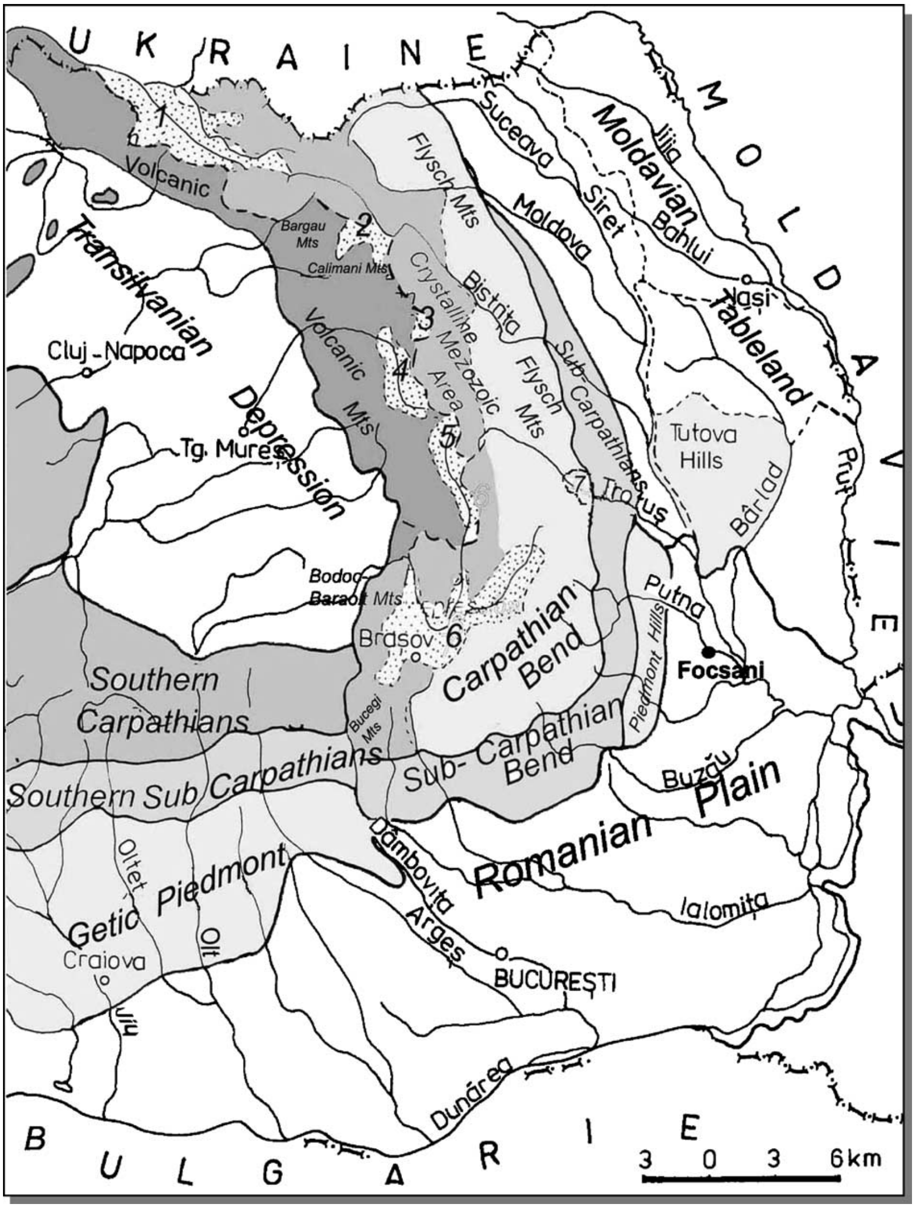

Fig. 3. Location of different areas discussed in the text: 1, Maramures Depression; 2, Dorna Depression; 3, Borsec Depression; 4, Giurgeu Depression; 5, Ciuc Depression; 6, Brasov Depression; 7, Comăneşti Basin.

is comparable to that of the other Carpathian rivers. In the Platform area, it is younger as it was formed gradually when the Sarmathian Sea withdrew towards the southeast; the other rivers became tributaries to the extended Siret. The Siret River remains a Carpathian river by sediment and the channel morphology, so that it makes an important contribution to the big gravel deposits in the Tutova Hills area (Hârjoabă, 1968).

The evolution of the Trotus¸ valley is related to the existence of an aquatic basin in the Comăneşti Depression. The upper Trotuş might have formed since the Sarmathian. In the Comăneşti Depression the marine conditions lasted until the Lower Pliocene; it was then traversed by the Trotuş while the Pliocene seas withdrew south from the Moldavian Plateau.

It is difficult to reconstitute the aspect of the drainage network at the Carpathian Bend in the Lower Pleistocene because the Braşov Depression did not exist then and the rivers from the exterior side had their source further to the northwest, in the Interior Curvature Mountains (Bodoc–Baraolt). Also, they advanced less to the southeast where the Sarmathian and Pliocene seas filled the entire Subcarpathian area. Further tectonic movements caused important changes in the aspect of the drainage network from this region, but certain parts of the old main courses survived, including those of the Putna, Buzău, Prahova, and Ialomiţa Rivers.

The Upper Pliocene–Lower Pleistocene Period did not bring important changes in the drainage system on the east side (Suceava, Moldova, Bistriţa, Trotuş Rivers) where the main rivers resisted the Vallachian uplifts and became antecedent. The Vallachian movements had their highest intensity in the Carpathian Bend. There was a general uplift of this group of mountains on the one hand and folding and an obvious raising of the exterior Sarmathian–Pliocene sediments, while the Braşov Depression sank. These processes caused the cutting of the upper watercourses of the Putna, Buzău, Prahova, and Ialomiţa Rivers and the prolongation of their lower watercourses towards the shore of the Levantine–Quaternary lake of the Romanian Plain.

The Lower Pleistocene–Holocene Period is the period when the present drainage network of the Eastern Carpathians stabilised. Tectonic movements of the Vallachian phase continued, causing uplift of the whole mountain group. Towards the end of the Pleistocene, new movements of the Pasadene phase determined the present altitudes. At the same time, because of the general raising of the Carpathians, subsidence movements appear in certain depression basins (we are especially interested in the area Intorsura Buzăului, which influenced the longitudinal profile of the Buzău). On the exterior part of the Carpathian Bend, the centre of subsidence gradually moved eastward towards Siret watercourse, and the Quaternary lake withdrew from the Romanian Plain allowing the drainage network to extend south and southeast. Upper Pleistocene climatic changes in the Riss and Würm glacials, led to periglacial conditions throughout the Carpathians, culminating in glacial conditions on the highest peaks (at over 1800 m altitude) and temperate climates during the intergla-

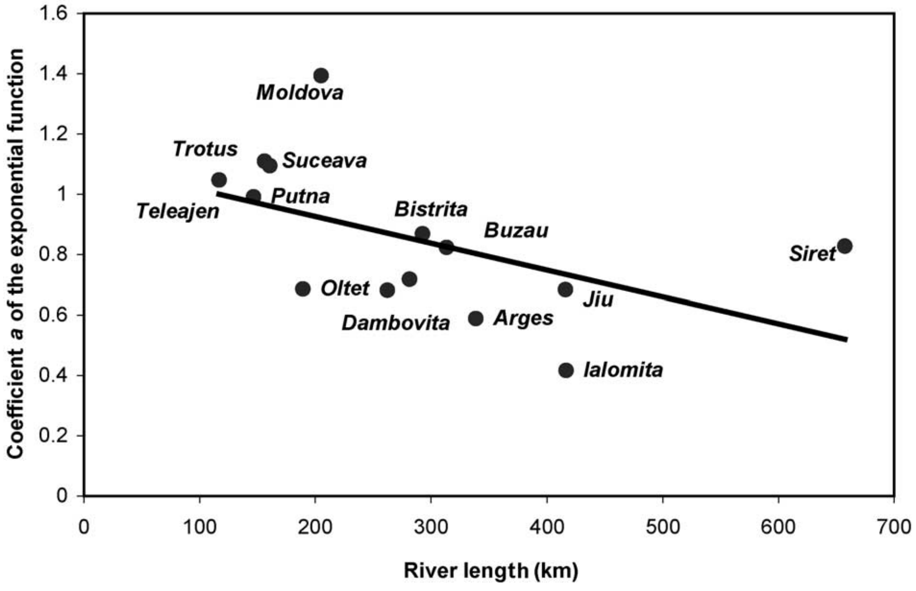

Fig. 4. Relationship between the river length and the coefficient *a* of the exponential function for the longitudinal profile.

cials. After the last glaciation, a temperate climate reappeared during Holocene, with certain thermal and pluvial variations. Valleys were deepened for about 100–200 m and the drainage system received its present aspect by capture, especially from the secondary tributaries.

We could conclude that:

– the Suceava, Moldova, and Bistriţa Rivers have followed the same courses since the Sarmathian (approximately 13.5 million years);

– Before entering the Comăneşti Depression, the Trotuş River has the same age as the rivers from the north; downstream, it is much younger (Lower Pliocene in Comăneşti Depression and Pliocene downstream of Târgu Ocna, that is 10 million and 5.4 million years);

– the Putna, Buzău, Prahova, and Ialomiţa Rivers suffered the most important changes, especially because of the Vallachian movements so their age in their present courses is Upper Pliocene–Pleistocene (about 2.5 million years);

– the Siret River is a special case. If we consider the deposits from its riverbed, it is a Carpathian river, but much younger than the rivers flowing into it, the age of its course being related to withdrawal of the Sarmathian Sea. Throughout its evolution, it processed a large amount of coarse Carpathian sediments and produced the deposits of Romanian age from the Tutova Hills;

– Once formed in their present courses, the longitudinal profiles of the rivers were affected by tectonic uplift and subsidence and by the great climatic changes of the Quaternary. From the Volhynian to the present day, the Carpathians rose 1500 m, and the Pre-Carpathian Basin sank over 5000 m. North of Trotuş River, the Carpathians continue to rise about 6 mm/year.

4.3. *Mathematical modelling of the longitudinal profiles*

Four simple functions (linear, exponential, logarithmic, and power), frequently used in previous studies of longitudinal profiles, were fitted to our data (Fig. 4). The results are presented in Table 3. The best fit is defined by the function which minimises the sum of squares of residuals and gives a minimum standard deviation of residuals. The closer a correlation or a

Table 3
Mathematical models applied to longitudinal profile data of the studied streams

River	Function	*a*	*b*	(*r*)	(r^2)	(*n*)
Suceava	Linear	0.659	− 0.845	0.919	0.846	51
	Exponential	1.100	− 3.939	0.987	0.976	51
	Logarithmic	0.014	− 0.258	0.979	0.960	51
	Power	0.073	− 0.949	0.829	0.688	51
Moldova	Linear	0.747	− 0.905	0.952	0.908	57
	Exponential	1.394	− 4.594	0.927	0.860	57
	Logarithmic	0.100	− 0.175	0.924	0.854	57
	Power	0.071	− 0.658	0.664	0.441	57
Bistriţa	Linear	0.683	− 0.808	0.904	0.818	111
	Exponential	0.869	− 3.366	0.904	0.818	111
	Logarithmic	0.147	− 0.118	0.966	0.935	111
	Power	0.129	− 0.348	0.682	0.466	111
Trotuş	Linear	0.693	− 0.917	0.937	0.878	105
	Exponential	1.095	− 4.154	0.923	0.853	105
	Logarithmic	0.107	− 0.165	0.939	0.882	105
	Power	0.106	− 0.541	0.666	0.444	105
Putna	Linear	0.629	− 0.889	0.895	0.802	99
	Exponential	0.991	− 5.771	0.951	0.906	99
	Logarithmic	0.029	− 0.156	0.981	0.964	99
	Power	0.039	− 0.701	0.719	0.518	99
Buzău	Linear	0.507	− 0.762	0.824	0.680	86
	Exponential	0.823	− 6.393	0.974	0.951	86
	Logarithmic	0.0002	− 0.137	0.978	0.956	86
	Power	0.029	− 0.715	0.716	0.451	86
Siret	Linear	0.457	− 0.571	0.775	0.602	66
	Exponential	0.829	− 4.672	0.903	0.817	66
	Logarithmic	− 0.029	− 0.197	0.964	0.930	66
	Power	0.027	− 1.096	0.763	0.583	66
Teleajen	Linear	0.679	− 1.002	0.894	0.801	120
	Exponential	0.883	− 4.688	0.974	0.950	120
	Logarithmic	0.042	− 0.162	0.963	0.928	120
	Power	0.069	− 0.562	0.775	0.602	120
Ialomiţa	Linear	0.427	− 0.627	0.659	0.435	132
	Exponential	0.417	− 5.299	0.963	0.928	132
	Logarithmic	− 0.092	− 0.152	0.962	0.926	132
	Power	0.015	− 0.817	0.893	0.798	132
Dâmboviţa	Linear	0.489	− 0.686	0.822	0.676	113
	Exponential	0.682	− 4.786	0.976	0.952	113
	Logarithmic	− 0.012	− 0.149	0.997	0.995	113
	Power	0.038	− 0.702	0.794	0.636	113
Argeş	Linear	0.433	− 0.608	0.728	0.530	96
	Exponential	0.540	− 5.284	0.947	0.898	96
	Logarithmic	− 0.055	− 0.132	0.968	0.983	96
	Power	0.025	− 0.695	0.782	0.612	96
Olteţ	Linear	0.412	− 0.558	0.695	0.484	40
	Exponential	0.686	− 4.874	0.936	0.876	40
	Logarithmic	− 0.055	− 0.342	0.979	0.958	40
	Power	− 1.648	− 0.793	0.804	0.647	40
Jiu	Linear	0.482	− 0.859	0.790	0.625	122
	Exponential	0.547	− 5.370	0.978	0.957	122
	Logarithmic	− 0.052	− 0.143	0.987	0.975	122
	Power	0.035	− 0.630	0.858	0.737	122

determination coefficient is to 1.0, the lower the dimensionless value of estimated standard error (i.e. the smaller the errors between the real and the theoretic a profiles). We have also presented in the table the number of survey points for each profile, spaced between 1 and 9 km apart. On basis of the analysis of this table, we can make the following observations:

• From a statistical point of view, *all four functions show that the degree of fit is generally high*. The correlation coefficients have values higher than 0.5. This means that we were right to choose these four functions to describe the form of these longitudinal profiles.

• The best fit for each profile is the *logarithmic model.* The power function model often provides an even poorer fit than a straight line.

• The Siret River presents a special situation, which we have already described before (Ichim and Rădoane, 1990). Although this river flows mostly over a plateau, it has all the features of a Carpathian river, because of the granulometric and petrographic nature of the deposits from the riverbed (Schumm, 1960). The large amount of coarse sediments brought by the right bank tributaries from the Carpathians caused much aggradation of the riverbed and consequently, distorted the longitudinal profile (Knighton, 1980).

4.4. Morphological development of longitudinal profiles of rivers

In order to analyse this problem, we also took into consideration the progress that other authors have made in the study of longitudinal profiles. A number of recent studies (such as: Snow and Slingerland, 1987; Ohmori, 1991; Ohmori and Saito, 1993; Morris and Williams, 1999) induced their conclusions based on numerous data from all physico-geographical regions of the world. They showed that longitudinal profile gradient forms result from the action of three major controlling factors: the liquid flow, the solid flow, the type of deposit over which the river flows and tectonic conditions. The numerical experiments showed the following statistics:

• If the water discharge changes four times, the slope of the longitudinal profile changes 114%.

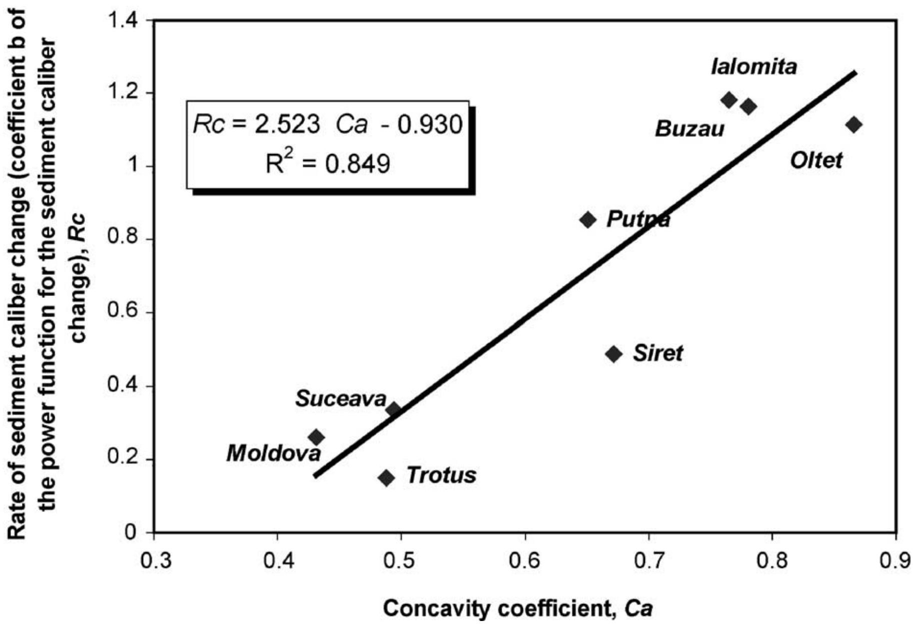

Fig. 5. The concavity coefficient, Ca, in relation with the rate of sediment caliber change of bed material, Rc. The streams with a low concavity coefficient (Suceava, Moldova, Trotuş) are characterized by a low rate of sediment calibre change; contrarily, streams with a high concavity (Ialomiţa, Olteţ) have a high rate of bed material diminution.

- If the sediment load changes four times, the slope of the longitudinal profile changes by 88%.
- If the calibre of the riverbed material changes four times, the sensitivity of modifying the slope of the longitudinal profile is 58%.

These numbers represent only approximate results. It is possible to obtain distinct influences of the major controlling factor for each river (for example, Roşu, 1967, calculated the influence of discharge and lithology of over 80% for the Rivers Motru and Gilort). Consequently, generally speaking, the power, exponential, and logarithmic models can indicate the most important factor to influence the form of the longitudinal profile. So, *if the dimension of the riverbed material is approximately uniform along the river and there is a large increase of discharge and load*, the longitudinal profile tends to have a form with a high concavity and is defined by a *power function*. From all the rivers we studied, Siret River approaches this condition the most, if we do not take into account the coarse allochtonous material, as we have already shown above. The longitudinal profile of the Siret River has a high concavity upstream and this makes it similar to the rivers which drain the southern part of the Southern Carpathians. However, the power function is not the right mathematical model for this river, because the weak transporting power of the river causes the middle profile to be relatively high.

The rivers with high calibre materials in the riverbed (cobbles, gravels) are dominated by transport processes, with an equilibrium between erosion and accumulation. These rivers have longitudinal profiles of small concavity, almost straight, and they are

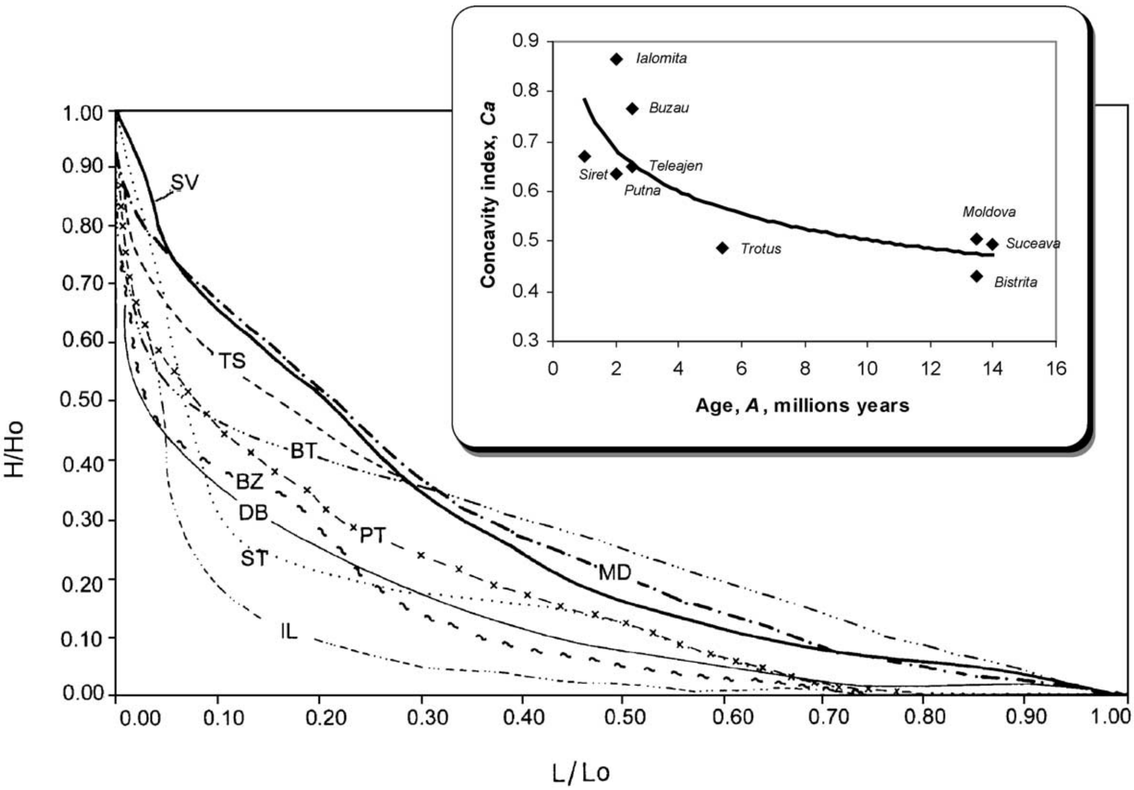

Fig. 6. Illustration of the relationship between longitudinal profile shapes and their ages. Discussions in the text. H/H_o ratio of altitude, where H is the stream altitude at the point of measurement, H_o is the stream altitude from the river mouth at the headwaters; L/L_o ratio of distance, where L is the stream distance from the river mouth at the point of measurement, L_o is the stream distance from the river mouth at the headwaters. SV—Suceava River; MD—Moldova River; BT—Bistriţa River; TS—Trotuş River; PT—Putna River; BZ—Buzău River; ST—Siret River; DB—Dambovita River; IL – Ialomiţa River.

described by linear and exponential functions. In our case, the rivers from north of the Trotus, River are typical, as they have an obvious slope of transportation with coarse bed deposits along their courses (Fig. 5). For rivers with an obvious decrease of bed-material size, from boulders, cobbles, and gravels in the upper course, to fine sand in the lower course, the logarithmic model offers the best fit of the curve of the longitudinal profile. This is the most important characteristic of most of the rivers south of the Trotuş River.

One of most important conclusions of our work refers to the relation between the age of the river and the form of its longitudinal profile. The theoretical models starting with Davis (1909) and up to the numerical simulation of Snow and Slingerland (1987) show that the older a river is, the more its concavity increases in the upstream area and asymptotically approaches the equilibrium longitudinal profile or grade as Davis called it.

However, the Carpathian rivers do not follow this general tendency. The tectonic predesign in geomorphology has been contended by Hantke and Scheidegger (1999) with regard to the Nile, Jaldhaka and other rivers. What we have demonstrated so far and shown in the synthetic image in Fig. 6 proves that age has no influence on the form of the longitudinal profiles for the rivers on the exterior side of the Carpathians. The rivers from the north of Trotuş River, which followed the same courses for 13–14 million years (a period long enough to realize an erosion cycle, as Davis says), have the least concave longitudinal profiles. On the other hand, the rivers south of the Trotuş River (Putna, Buzău, Ialomiţa, and Dambovita Rivers), the watercourses which suffered important changes, blockage, uplift, and subsidence, flowing for about 2.5 million years on their ancient courses, are characterized by longitudinal profiles with a high concavity, that is "evolved".

If we consider that a period of 2.5 million years was long enough to create an equilibrium longitudinal profile of high concavity, we cannot but wonder why this did not happen during a period six times longer? Based on our results, the answer might be that:

- The equilibrium profile of a river can also be a profile of small concavity, with a high slope, described by a theoretical, linear–exponential curve.
- The linear–exponential equilibrium profile is also a profile of the equilibrium between erosion and accumulation, a transport profile, a feature which characterizes the northern rivers (north of Trotuş River). Tectonic uplift was important, and this phenomenon is still present with values nowadays of over 6 mm/year. Tectonic uplift has been more important than river erosion, so that the northern rivers were not able to develop an equilibrium profile with a high concavity. In other words, the actual form of the longitudinal profiles of the rivers from north of Trotuş River is the result of continuous adjustment since the Volhynian until the present day (C. Grasu, personal observation).

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