地形 第17巻第3号
135-157 頁 (1996)

Transactions, Japanese Geomorphological Union
17-3 p. 135-157 (1996)

Carpathian Gravel Bed Rivers in Recent Time —A Regional Approach—

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Abstract

The drainage network of the Romania's territory has a total length of 76,000 km, characterising an area of 237,500 km^2. A weight of 97.8% from this network is tributary to the Danube, the second river as size after Volga River from the Europe.

As geomorphologists, we approached gravel bed rivers in the context of relationships between channel deposits variability and some controlling factors characterising morphogenetically this region: i) longitudinal profile form related to the variation of bed material calibre; ii) grain size spectrum of bed material explained in relation with some drainage basin variables; iii) empirical evidence of the grain size modality in downstream direction; iv) petrographical variablity of bed material explained in relation with source area lithological composition. Our researches focused on the six rivers in Romania, whose drainage basins are 44,748 km^2, that is, 18.8 per cent Romania's surface.

The granulometrial spectrum of bed matеɹials is disturbed by the discontinuities in longitudinal profile, by lateral input of sediment, by intersection of some relict landforms. There is a tendency of *bed material segregation in the downstream direction* controlled by geological—geomorphological units cut by the streams. *Modality* of the granulometrical distributions is the best described by including of fractions of bedmaterial: sand, gravel and the fraction 1-20 mm. Bimodality is determined by *amouuts under about* 35% *of the fraction* 1-20 mm. The petrographical composition of fluvial gravel reflects, differently, the petrographical types of source areas. The *ratio river/source* is a measure of the river efficiency in different lithological clast abrasion. This measure shows, for example, that magmatic, metamorphic and carbonate rocks are of 10-30 time better represented in river channel than in source area. Contrarily, the gravel from sandstone rocks is of better represented in the source area than in river channel.

Key Words: *River bed gravel, Grain size distributions, Modality, Downstream variation, Petrographical composition, Eastern Carpathians, Romania*

Introduction

The drainage network of the Romania's territory has a total length of 76,000 km,

Received October 27, 1995; revised April 8, 1996.
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characterising an area of 237,500 km. A weight of 97.8% from this network is tributary to the Danube, the second river as size after Volga River from the Europe. The yearly mean discharge of the all drainage network is 1300 m^3/s and over 80% springs from the Carpathian Mountains. This last element is very important, because, although Carpathian Mountains represent 21% from the Romania's surface, they give 66% from the out-Carpathian yearly mean volume of the runoff. Therefore, except the streams which spring from the hill and plain regions, we consider that Romania has a Carpathian drainage network, both flow regime and channel deposits, in which prevalent feature is given by the gravel bed rivers.

In Romania, the interest for the gravel bed river studies is relatively recent. It was been imposed by the knowledge necessity of one very strong anthropical impact on the rivers: the arrangements of 260 reservoirs, the achievement of about 500 km branches and feed pipes; the river embankment and rectification of 16,000 km from the river length. All those induced dramatical changes at the level of sediment delivery ratio, of channel deposits variability and of river channel actual dynamics.

As geomorphologists, we approached this problem in the context of sediment budget analysis from a drainage basin, of sediment source identification, of identification of some peculiarities of the river development, of relationships between channel deposits and some controlling factors characterising morphogenetically this region. Seen as a whole, this study is deliberately empirical and data-oriented, but, in this stage, we preferred to present a reality from a region less known from this point of view, insisting less on the theoretical considerations. Concretely, we will refer at following: a) longitudinal profile form related to the variation of bed material calibre; b) grain size spectrum of bed material explained in relation with some drainage basin variables; c) empirical evidence of the grain size modality in the downstream direction; d) petrographical variability of bed material explained in relation with the source area lithological composition.

Study area

Our researches focused ou the six rivers in Romania (Fig. 1, Table 1), whose drainage basins are 44,748km^2, that is, 18.8 percentage of Romania's surface. We consider them representative cases for the morphodynamical condition from this region, both related to natural conditions and anthropical impact, especially dams and gravel exploitations. Concerning of the natural conditions, some specification can being made for the evaluating of the phenomenon approached by us, follows: i) The Carpathians imposed the main drainage directions of the Ramania's rivers, with a maximum relief of about 2500 m; ii) The main rivers on the eastern side of Eastern

Fig. 1. Drainage basins studied, sediment sample points, and bedrock geology. Inset map shows location of basins in Romania.

Table 1. General data on studied stream.

No	River	Drainage basin area (km²)	Strahler's network order	River lenght (km)	Relief ratio (m/km)	Mean annual flow (m³/s)	Maximum annual flow (m³/s)	Mean annual suspended sediment load (kg/s)
1	Siret	42,274	9	544	4.17	254	3,168	221
2	Suceava	2,616	8	172	7.88	14.1	1,385	5.9
3	Moldova	4,326	8	153	8.19	26.2	1,830	14.7
4	Putna	2,742	7	205	11.00	13.4	1,400	91.8
5	Buzau	5,264	8	302	6.44	25.4	1,800	80.3
6	Oltet	2,474	7	186	11.02	8.6	1,190	39.4

Carparthians (Suceava, Moldova, Bistrita, etc) have a development continuity on the contemporary paths since Miocene; iii) The petrographic composition of the studied drainage basins is very large: igneous, metamorphic and flysh sedimentary rocks (as nappes and imbrication), then, molasse, platform and quaternary deposits; iv) By tectonical point of view, the Eastern Carpathians are quite active in the present day, too. In the northern part of them (Suceava River, Moldova River) there are uplifits of about maximum 6 mm/year, and the southern part (Putna River, Buzau River) is affected by the earthquakes (3–4 earthqukes/100 years of 6–7 Richter magnitude); v) The river regime is dominantly torrential. About 70% of annual flow is realised in spring and summer, the average discharges (with few exceptions) are below 5–6 m³/s. In turn, some rivers with the drainage basins larger than 7,000 km² the maximum discharges more than 1,000 m³/s were recorded (Table 1); vi) There is a high vertical mobility of the river beds, which ranges up to 3 m in 35 years in some cases (e.g. Moldova River in the lower reach), and at the same time orizontal mobility ranges up to 11 m/year (Radoane and Ichim, 1985; 1991).

The studied rivers drain the eastern side of the Eastern Carpathians (Suceava, Moldova, Putna, Buzau, Siret Rivers) and southern side of the Southern Carpathians (Oltet River), (Fig. 1, Table 1). Concerning of these river settings, it can make observation that more than 50% channel lengths are developed apart from of Carpathian area, but their deposits preserved the characteristics given by mountainous area.

Data and methods

The data base related with the channel deposit analysis resulted wholly from the our surveys and measurements. The sampling was been realised on the river cross—sections spaced in average at 8–10 km apart. In all, we sampled about 160 cross—sections (Fig. 1), for which we measured the river gradient, too. Concerning of channel deposits, during the field research, we considered two aspects: the determining of clast petrography to identify the relationships with the source area and the determining of bed material grain size. As sampling method, the bulk sampling method was been used, that is, we have collected a quantity such that the largest particle accounts for less than about 5 per cent of the total sample volume. Sampling generally conforms with ISO-4346-1977 (cf. Mosley and Tindale, 1985). The surface and subsurface material, distinctly, were sampled. The fraction >6 mm was been sieved in the field using means of a transportable sieving and spliting device in 1 phi steps, and the fraction 64 mm was been measured individually with the vernier callipers. The largest clast was 130 kg and 54 cm in *b*-axis diameter. For the gravels larger than 256 mm we obtained a relation of *b*-axis diameter to measured stone weight, which was been applied to evaluate the cobbles and boulders position in the grain size spectrum of the bed material. The fractions <6 mm was been splited and taken to the lab, where the petrographical determinations and morphometrical measurements for 100 clasts from the 16–32 mm and, respectively, 32–64 mm interval were made. Field measurements and laboratory analyses produced a large amount of data, processing included: elements of descriptive statistics and empirical relationships among variables. Results obtained are approached in the following section clustered as: (1) grain size variability in the downstream direction; (2) on the modality of the grain size distributions; (3) changes in the petrographic distribution of the bed material.

The longitudinal profile form

The bed material analysis was been made in the idea from the source to the river-mouth sediment (Ibbeken and Schleyer, 1991), with the aim to identify certain properties through a sequence of environments that manifest in this direction. As geomorphologists, we consider that a such analysis must to be preceded of some observations on the longitudinal profile form of the studied rivers. This, because the longitudinal profiles, by their form, cumulate the effect of river development history and, in the same time, exprime, synthetically, the influence of all controlling factors from the drainage basin on the channel morphology and deposits.

The analysis of the longitudinal profile form of the studied rivers was been made on the basis the profile concavity coefficient and the best fit of the profile form using the simple mathematical functions.

The profile concavity: We have calculated values for profile concavity after Snow and Slingerland (1987)'s method, as ratios of areas measured on the profile graphs: $C=A_1/A_2$, where A_1 is numerically integrated area that lies between the profile curve and a straight line connecting the profile endpoints and A_2 is the triangular area below that straight line and above a horizontal axis connecting with the profile's

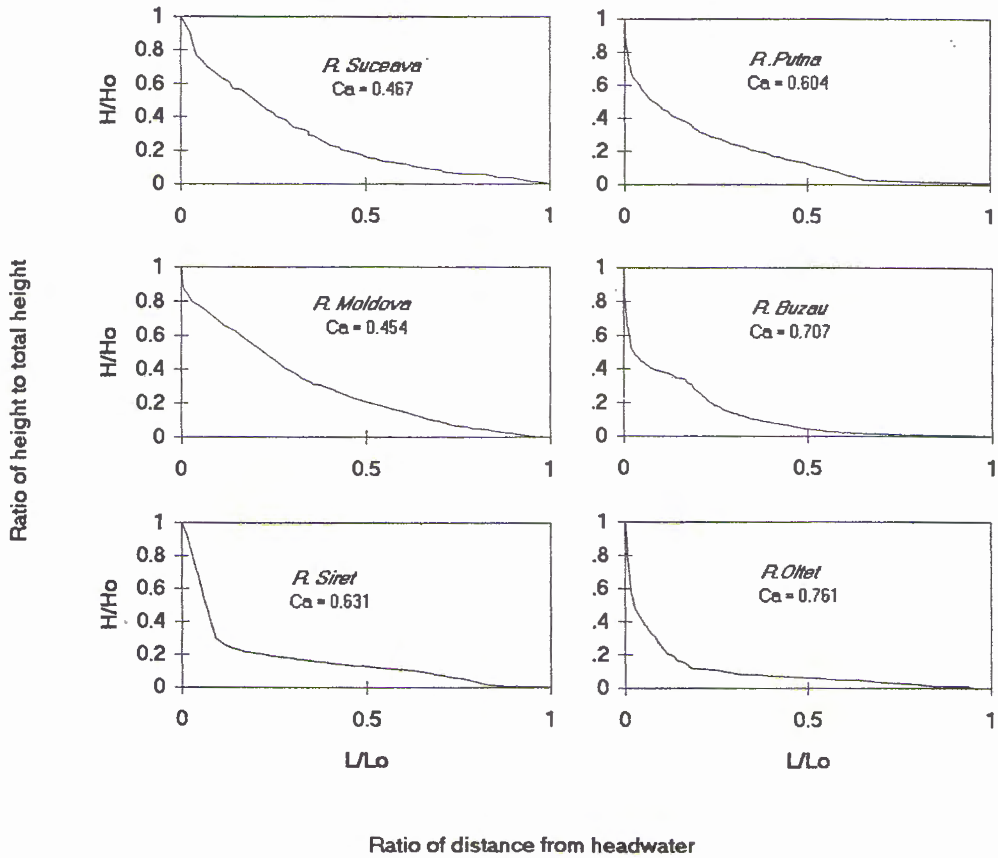

Fig. 2. The longitudinal profiles of studied rivers.

downstream endpoint.

The experience accumulated in the longitudinal profile study showed that the profile concavity is, semnificatively, modified by three main controlling variables: discharge, sediment load and bed material calibre. The highest degree of concavity is produced in those cases with a strong alongstream decrease of sediment calibre. Concavity is enhanced by a strong change in discharge downstream and weak change in sediment load. Finally, where sediment load increases downstream relative to discharge, profiles in gravel have reduced concavity and profiles sand become convex (Snow and Slingerland, 1987).

In our cases a concavity coefficient variation between 0.454 to 0.761 was been observed (Fig. 2), the main cause a high value being the dramatical change in bed material calibre. The way in which was been valued the change rate was on the basis of applying of a set of four simple mathematical functions, from which the

Table 2. Regression curves based on four simple functions for sediment calibre changes in the longitudinal profile.

River	Function	Regression coefficients		Correlation coefficients	Determination coefficient	Observations
		a	b	r	r^2	n
Suceava	linear	120.51	-0.716	0.862	0.742	17
	exponential	5.007	-0.0143	0.868	0.753	17
	logarithmic	162.71	-59.22	0.787	0.619	17
	power	2.422	-0.446	0.689	0.475	17
Moldova	linear	71.125	-0.332	0.785	0.617	18
	exponential	4.334	-0.0093	0.832	0.692	18
	logarithmic	103.84	-35.31	0.789	0.622	18
	power	2.188	-0.374	0.727	0.528	18
Putna	linear	472.36	-4.284	0.729	0.531	16
	exponentual	7.068	-0.049	0.887	0.787	16
	logarithmic	864.75	-415.23	0.866	0.749	16
	power	3.827	-1.369	0.689	0.476	16
Buzau	linear	126.02	-0.511	0.558	0.312	42
	exponential	6.083	-0.031	0.837	0.701	42
	logarithmic	153.18	-46.67	0.356	0.127	42
	power	3.279	-1.182	0.516	0.266	42
Siret	linear	13.566	-0.0066	0.108	0.012	53
	exponential	3.728	-0.0052	0.541	0.293	53
	logarithmic	1.619	-0.0022	0.541	0.293	53
	power	4.099	-1.313	0.422	0.178	53
Oltet	linear	287.49	-0.0296	0.691	0.478	16
	exponential	5.397	-0.0446	0.872	0.76	16
	logarithmic	612.08	-296.33	0.895	0.801	16
	power	3.933	-1.833	0.828	0.686	16

regression equation coefficients resulted (Table 2). The regression coefficients of power function were been used as a sensitive index of downstream change rate in and in relation from the Fig. 3 was been introduced. The last shows, suggestively, the way in which the rate of bed material calibre decrease is higher for the profiles whose the concavity is enhanced. For example, Suceava and Moldova Rivers, with a concavity coefficient of 0.45 and, respective, 0.47, have the less change rate of bed material size, too, given by the regression coefficient values of −0.374 and, respective, −0.446. Putna, Buzau and Siret Rivers, whose profile have a concavity of 0.6 to 0.7, are characterised by a much higher change rate of bed material, too, between −1.1 to −1.3, and Oltet River, with the highest concavity (=0.761), have the higher value of bed material decrease rate (−1.833).

The best fit functions of longitudinal profiles: The second way of analysis of the longitudinal profile form of studied rivers consisted in *profile fit by simple mathematical functions* (Table 3). Regression analyses between distance and altitude were been performed utilising linear, exponential, logarithmic and power function for all six rivers studied. Our results confirm the validity of the experimental researches made by Snow and Slingerland (1987) and, especially, they check up Ohmori and Saito (1993)'s observations, namely, that the differences in mathematical function best describing the profiles indicate the differences in fluvial processes. For a river, the

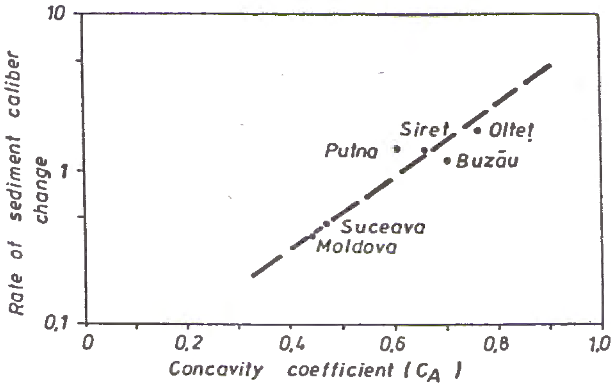

Fig. 3. Concavity coefficient in relation with the median diameter of bed material.

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

River	Function	Regression coefficients		Correlation coefficient	Determination coefficient	Observations
		a	b	r	r^2	n
Suceava	linear	0.684	-0.859	0.919	0.845	51
	exponential	0.102	-3.959	0.985	0.969	51
	logarithmic	0.018	-0.574	0.985	0.97	51
	power	-1.167	-0.902	0.829	0.687	51
Moldova	linear	0.747	-0.904	0.953	0.908	57
	exponential	0.264	-4.355	0.95	0.903	57
	logarithmic	0.108	-0.387	0.915	0.836	57
	power	-1.099	-0.605	0.681	0.464	57
Putna	linear	0.633	-0.881	0.896	0.802	99
	exponential	-0.212	-4.4	0.991	0.982	99
	logarithmic	0.052	-0.339	0.97	0.941	99
	power	-1.172	-0.544	0.793	0.629	99
Buzau	linear					
	exponential	-0.199	-6.393	0.975	0.951	86
	logarithmic	0.032	-0.275	0.943	0.889	86
	power	-1.444	-0.606	0.671	0.451	86
Siret	linear	0.459	-0.571	0.777	0.605	66
	exponential	-0.266	-4.37	0.918	0.843	66
	logarithmic	-0.011	-0.408	0.963	0.927	66
	power	-1.445	-0.897	0.752	0.565	66
Oltet	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

shape of longitudinal profile and the fluvial processes change with time through a feedback system between channel slope and discharge, and sediment calibre.

The best descriptors of the longitudinal profile form are the exponential, logarithmic and power functions, each having a certain significance concerning of downstream change in water discharge, sediment discharge, or bed material calibre. For example, the profiles of Siret River (partially) and of Oltet River are the best fit by a logarithmic function, as an expression of the downstream dramatical decrease in bed material calibre. Almost in the same degree the profiles are fit by an exponential function, especially, for the Suceava, Moldova, Putna, and Buzau Rivers. This points out a low rate of sediment transport, accompanying their grain size decrease. Concerning of power function, this better fits the river profiles which transport in equilibrium water+sediment, only the Suceava River is closed by this condition.

Development of river-bed sediment

The river bed material analyses were realised by the sediment sampling in three options: as *surface sample* (being represented only by hydraulic pavement layer, whose depth is equalled by the diameter of the largest grain exposed on the bed surface); as *subsurface sample* (being represented by the subjacent material to surface layer); as *full sample* (in which the two above categories are totalize). By the material sieving from the samples thus collected, we obtained 14 grain size classes in 1 phi steps. These classes were been clustered in five size steps, described in the following terms:

—silt and clay (<4 phi or 0.063 mm)
—sand (between 4 phi or 0.063 mm to—6 phi or 2 mm)
—pebble (between—1 phi or 2 mm to—6 phi or 64 mm)
—cobble (between—6 phi or 64 mm to—8 phi or 256 mm)
—boulder (over—8 phi or 256 mm)

The percents obtained were used in subsequent processings concerning of distribution type, trends in downstream direction, matrix of correlation, evaluating of distribution modality. Concerning of the cumulated percentage weight of grain size classes in downstream, it is know that an ideal distribution of bed material is that in which the more and more fine size classes succeed, uniformly, in flow direction. The rivers studied deviate from the ideal (Fig. 4), although there is a general tendency to preserve the expontential diminution, such how we saw in D50 decreasing (Table 2).

For the cases taken in the study, Suceava, Moldova and Oltet Rivers better approach of this tendency. For the Putna, Buzau and Siret Rivers occur a disturbance more enhanced of this tendency from the different reasons. Thus, for the Siret River is obvious the influence of main sediment input by the Carpathian rivers (Suceava, Moldova, Bistrita, Trotus Rivers). In Buzau River, the effect of a development discontinuity in the longitudinal profile is shown by the gradient diminution in the water head reach, where Intorsura Buzaului Depressions develops (about 40 km length), after which the stream cuts the mountainous mass of the flysch and a defile—valley appears (between 40-75 km); for the Putna River, an effect of a relict alluvial fan (perhaps

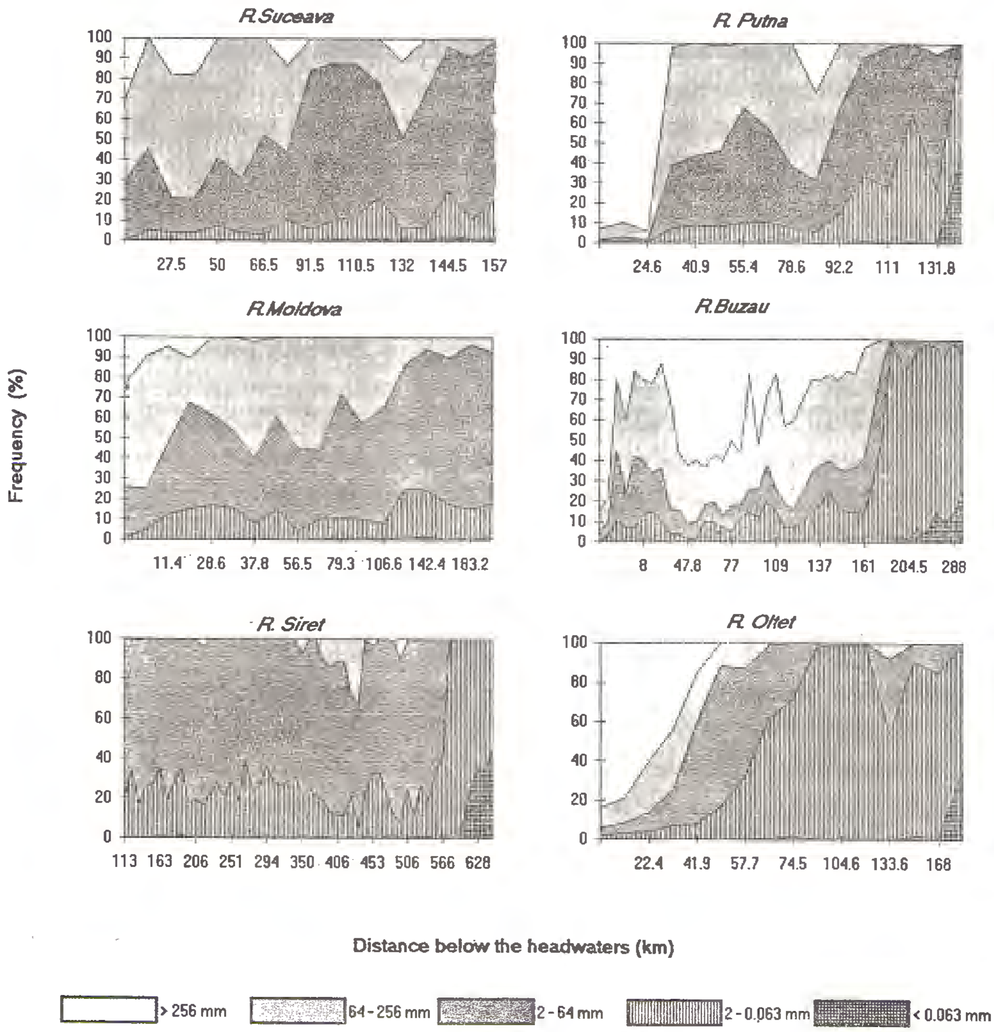

Fig. 4. Downstream variation in the grain size distribution of the channel deposits from the studied rivers.

Holocene) appears, whose apex is at 85 km below the spring.

Concerning of the cluster tendency of certain grain size classes related to the main landscape units cut by the stream, the triangular diagrams from the Fig. 5 show a selection of boulders and bobbles (>—6 phi), of pebbles (from—1 phi to—6 phi), and of the sands, silts and clays (<—1 phi). The clusters formed are of pebbles (from—1 phi to—6 phi), and of the sands, silts and clays (<—1 phi). The clusters formed are approximately according to the position of the following geomorphological

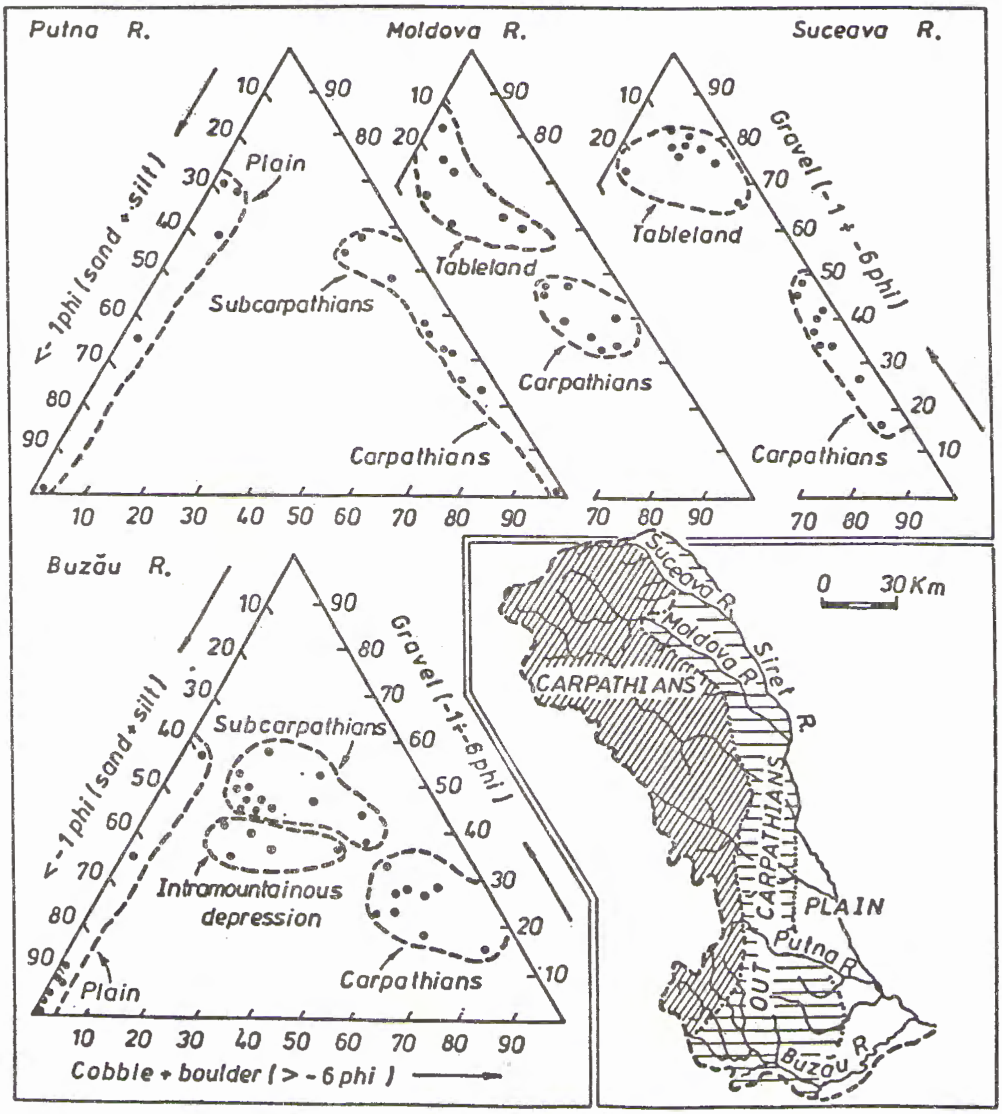

Fig. 5. Changes in the grain size composition of some Romanian rivers, related to geomorphological units.

units: i) *Carpathians' area,* where the river cross-sections with material from the boulder and block classes (60–80%) are clustered; ii) *Subcarpathian and Tableland area,* from which comes much skeleton-like material wlth the loam-sandy matrix because of landslide. This area is cut by the streams with the bed material given in main percentage of gravel classes; iii) *Plain area* clusters in the left corners of the diagrams, where are found the fine material class, under—1 phi.

This bed material segregation in relation with the geological-geomorphological units, by a long time process of competition between *sorting* and *abrasion* was been realised, in which the rock resistance, the river bed, the stream power interposed, finishing off the peculiarities of a river. Concerning of the importance of one or of other from the two processes (sorting or abrasion) in this granulometrical segregation, generally, of the fraction diminution in downstream, the opinions are being divided. Kodama (1991) reviews the studies that argue one or other from the two processes as being determinant in the bed material diminution. Among those which point out the particle abrasion importance, many are geologists-sedimentologists (Sneed and Folk, 1958; Ikeda, 1970, 1985; Adams, 1979; Ibbeken, 1983; McBride and Pickard, 1987). An other group of authors is formed, especially, by the hydraulicists, which asserts that the bed material decreasing in downstreams is a result of the sorting process: Knighton (1980, 1982); Brierley and Hickin (1985), Stih and Koman (1990, a, b); Koman and Karling (1941). Therefore, in either case, the points of view are the global expression of the approach field. The argnments are, alike, conclusive both on the one hand and the other hand and we consider the Plumley's solution expressed as far back in 1948 is preferably, namely: the downstream fining in river bed materal is result both of the selective tranport and of the abrasion effect. The proportion in which each process is responsible is different for each stream, the difficulty being in determining their ratio. For example, Plumley in 1948 concluded that selective transport accounts for 75% of the size reduction observed in Rapid Creek and abrasion for the remaining 25%; Bradley et al. (1972) concluded that 90-95% of the size reduction in Knik River gravels is caused by sorting processes, the balance being attributable to abrasion. Kodama (1991) showed that the bed material diminutation in rivers on alluvial fans in Japan can be explained by abrasion alone.

To evaluation the ratio between sorting and abrasion for the rivers in Romania we used the correlation intensity alongstream of the Folk-Ward sorting coefficient and, respectively, of the Cailleux roundness index (the last was determined for the clasts between 16-64 mm diameter, a characteristic group alongstream studied). The result is given below, the percentage values having an orientative character:

River	Sorting (%)	Abrasion (%)
Suceava	46	54
Moldova	73	27
Putna	72	28
Buzau	51	49
Siret	18	82
Oltet	79	21

The ratio of the two processes is variable, indeed, even for the rivers from physiographic conditions closed, similar to those above. For example, Suceava and Moldova Rivers, whose the drainage basin areas, the longitudinal profile forms, the drainage basin lithological compositions are very close, the proportion in which sorting and abrasion are responsible in downstream fining not at all is same. The same situation appears for the Putna and Buzau River is the single stream where the abrasion has a maximal weight, this not because it is longer, but because it is being supplied with well-rounded sediment by the Carpathian tributaries (Ichim and Radoane, 1991).

Modality of the grain size distributions

The interpretation of histograms represented another possibility of granulometrical distribution analysis in each sampling point alongstream. The more obvious observations related to the histogram form are on the *unimodal* character in some river reaches and *bimodal* in the others. Until now, researches (Pettijohn, 1949; Yatsu, 1955; Sundborg, 1956; Ibbeken, 1983; Kodama, 1991 etc) showed that unimodality is a characteristic of upper reaches of rivers, whilst bimodality is a characteristic of middle and lower reaches. Unfortunately, the causes of this tendency are being less understood, yet. Ibbeken and Schleyer (1991), explored many different possible causes in theirs research on gravels of Calabria. They removed from beginning an important set of supposed variables as those which are being characterised source areas (surface, petrography and granulometrical distribution of source area deposits) or variables of hydrodynamic conditions.

Our investigations on the river-sediment modality were have been approached, differently, for the surface layer, subsurface sediment and full sample, all these considered in the downstream direction. Modality was been quantified after the mode number of the distribution. Thus, if the distribution is unimodal, then the modality is 1.0; for the bimodal distribution, the modality is 2; for the polymodal distribution, the modality is $3, 4, \cdots, n$. It was possible the introduction of modality into a correlation matrix in which the following variables entered, too: the stream length below head waters, the river gradient, the median diameter of bed material, the percentages of silt, sand, gravel, boulder, block and 1–20 mm fraction. Correlation matrix was been assembled for 5 from the streams studied (Table 5). On its basis we will do the following general observations:

1. *Modality increases in the downstream direction* of the Suceava, Moldova, Putna Rivers and decreases for the Siret and Oltet Rivers. Tendency is different for these last streams because of in their low reaches the bed material is, dominantly, sand-silt, and, in consequence, here an unimodal distribution develops. A more general

Table 5. Matrix of the correlation coefficients of the some properties of the bed material.

A. *Siret River*

	L(km)	S(m/km)	D50(mm)	Silt(%)	Sand(%)	Gravel(%)	Cobble(%)	1-20 mm(%)	Modality
L(km)	1.000								
S(km/km)	-0.219	1.000							
D50(mm)	-0.108	0.140	1.000						
Silt(%)	0.519	-0.414	-0.346	1.000					
Sand(%)	0.482	-0.460	-0.615	0.493	1.000				
Gravel(%)	-0.610	0.511	0.419	-0.736	-0.914	1.000			
Cobble(%)	0.110	0.056	0.827	-0.121	-0.313	0.048	1.000		
1-20 mm(%)	-0.068	0.031	-0.665	-0.036	0.144	0.068	-0.687	1.000	
Modality	-0.522	0.502	0.437	-0.712	**-0.846**	**0.907**	0.162	0.019	1.000

B. *Suceava River*

	L(km)	S(m/km)	D50(mm)	Silt(%)	Sand(%)	Gravel(%)	Cobble(%)	1-20 mm(%)	Boulder(%)	Modality
L(km)	1.000									
S(km/km)	-0.501	1.000								
D50(mm)	-0.862	0.608	1.000							
Silt(%)	0.713	-0.301	-0.695	1.000						
Sand(%)	0.710	-0.388	-0.718	0.869	1.000					
Gravel(%)	0.785	-0.299	-0.895	0.651	0.559	1.000				
Cobble(%)	-0.793	0.140	0.805	-0.756	-0.691	-0.928	1.000			
1-20 mm(%)	-0.557	0.694	0.805	-0.445	-0.463	-0.650	0.396	1.000		
Boulder(%)	0.862	-0.411	-0.942	0.767	0.737	0.926	-0.900	-0.667	1.000	
Modality	0.244	-0.135	-0.403	0.615	**0.709**	0.247	-0.337	**-0.329**	0.476	1.000

C. *Moldova River*

	L(km)	S(m/km)	D50(mm)	Silt(%)	Sand(%)	Gravel(%)	Cobble(%)	1-20 mm(%)	Boulder(%)	Modality
L(km)	1.000									
S(km/km)	-0.883	1.000								
D50(mm)	-0.785	0.780	1.000							
Silt(%)	0.707	-0.681	-0.717	1.000						
Sand(%)	0.524	-0.539	-0.830	0.638	1.000					
Gravel(%)	0.902	-0.871	-0.902	0.662	0.649	1.000				
Cobble(%)	-0.818	0.738	0.883	-0.679	-0.745	-0.951	1.000			
1-20 mm(%)	-0.533	0.711	0.622	-0.417	-0.505	-0.507	0.283	1.000		
Boulder(%)	0.709	-0.563	-0.822	0.601	0.717	0.778	-0.845	-0.252	1.000	
Modality	0.337	-0.286	-0.712	0.350	**0.801**	**0.601**	-0.698	**-0.284**	0.608	1.000

D. *Putna River*

	L(km)	S(m/km)	D50(mm)	Silt(%)	Sand(%)	Gravel(%)	Cobble(%)	1-20 mm(%)	Boulder(%)	Modality
L(km)	1.000									
S(km/km)	-0.791	1.000								
D50(mm)	-0.729	0.856	1.000							
Silt(%)	0.460	-0.223	-0.179	1.000						
Sand(%)	0.830	-0.563	-0.528	0.554	1.000					
Gravel(%)	0.459	-0.577	-0.702	-0.376	0.181	1.000				
Cobble(%)	-0.309	-0.122	-0.280	-0.295	-0.506	0.113	1.000			
1-20 mm(%)	-0.670	0.817	0.971	-0.149	-0.477	-0.710	-0.371	1.000		
Boulder(%)	0.621	-0.580	-0.595	-0.281	0.495	0.837	-0.247	-0.576	1.000	
Modality	0.584	-0.509	-0.553	-0.279	0.278	**0.728**	-0.031	**-0.519**	0.680	1.000

E. *Oltet River*

	L(km)	S(m/km)	D50(mm)	Silt(%)	Sand(%)	Gravel(%)	Cobble(%)	1-20 mm(%)	Boulder(%)	Modality
L(km)	1.000									
S(km/km)	-0.644	1.000								
D50(mm)	-0.691	0.975	1.000							
Silt(%)	0.496	-0.192	-0.173	1.000						
Sand(%)	0.782	-0.582	-0.683	0.137	1.000					
Gravel(%)	-0.235	-0.343	-0.315	-0.260	-0.370	1.000				
Cobble(%)	-0.668	0.297	0.444	-0.249	-0.841	0.301	1.000			
1-20 mm(%)	-0.717	0.937	0.986	-0.182	-0.726	-0.309	0.556	1.000		
Boulder(%)	0.022	-0.438	-0.450	-0.248	-0.098	0.886	0.009	-0.467	1.000	
Modality	-0.152	-0.374	-0.385	-0.199	-0.192	**0.892**	0.083	**-0.394**	0.898	1.000

conclusion is being confirmed, moreover, namely: for the streams that are characterised by a sediment of very different diameters, the general feature has been unimodality in the upper reaches and bimodality in the lower reaches of the longitudinal profile. This feature was been given as rule for the streams from the different physiographic environments, as those from Italy (Ibbeken and Schleyer, 1991) or Japan (Kodama, 1991).

2. *Modality is in inverse relation with the river gradient* for all studied cases, except of the Siret River. That is, in so far as the river gradient is diminished there is a more probability to appear the bimodality, but this is valid only for the reaches where there is a mixture of gravel and sand. At very low gradients, where the stream transports only fine material, the unimodal distribution again appears. Exception given by the Siret River is explained by the massive lateral input of coarse sediment in the middle reach of this. The fact determines an increase of the gradient and, in consequence, of the bimodality. In the Siret River case, we add that it is possible as data base to be influenced by the fact that the channel material did not sample for the first 113 km of the stream, reach situated in Ukraine.

3. *Modality is in direct relation with variation D50*, except of the same stream, the Siret, which we ignored from the reasons showed above. From this relationship we obtained a conclusion that bimodality appears only in the case a certain mixture of the bed material in which large fractions are prevailing.

4. *Modality is the best described by including of three categories of fractions of bedmateriol: sand, gravel and the fraction 1-20 mm*. Thus, modality is directly related to the weight of sand and gravel in the full sample and inversely related to the weight of the fraction 1-20 mm. The explanation degree of the modality related to sand and gravel weight in global sample is different for studied rivers. It is higher for the Siret and Moldova Rivers where there is an equilibrium of mixing between sand and gravel, and it is lower for the others' cases studied, where the mixing equilibrium is less relevant. Instead, all the rivers reply to in same way concerning to the fraction 1-20 mm, that is, there is an increase of appearance chance of bimodality in so far as this fraction is decreasing.

5. *Modality of granulometrical distributions is different for the surface samples and subsurface samples* (Fig. 6); the firsts are, dominantly, unimodal, and the last are conspicuous bimodal. The sediment layer exposed by the river is, as rule, washed of finer material than 2 mm, what rests being in greatest proportion (90-95%) pebbles, cobbles and boulders. In this situations there are unimodal distributions lose their unimodal character because of 1-20 mm granulometrical interval has a very reduced weight instead the weight of under 2 mm interval is increasing. The result is a bimodality more marked than of the full sample and at closer of head waters is

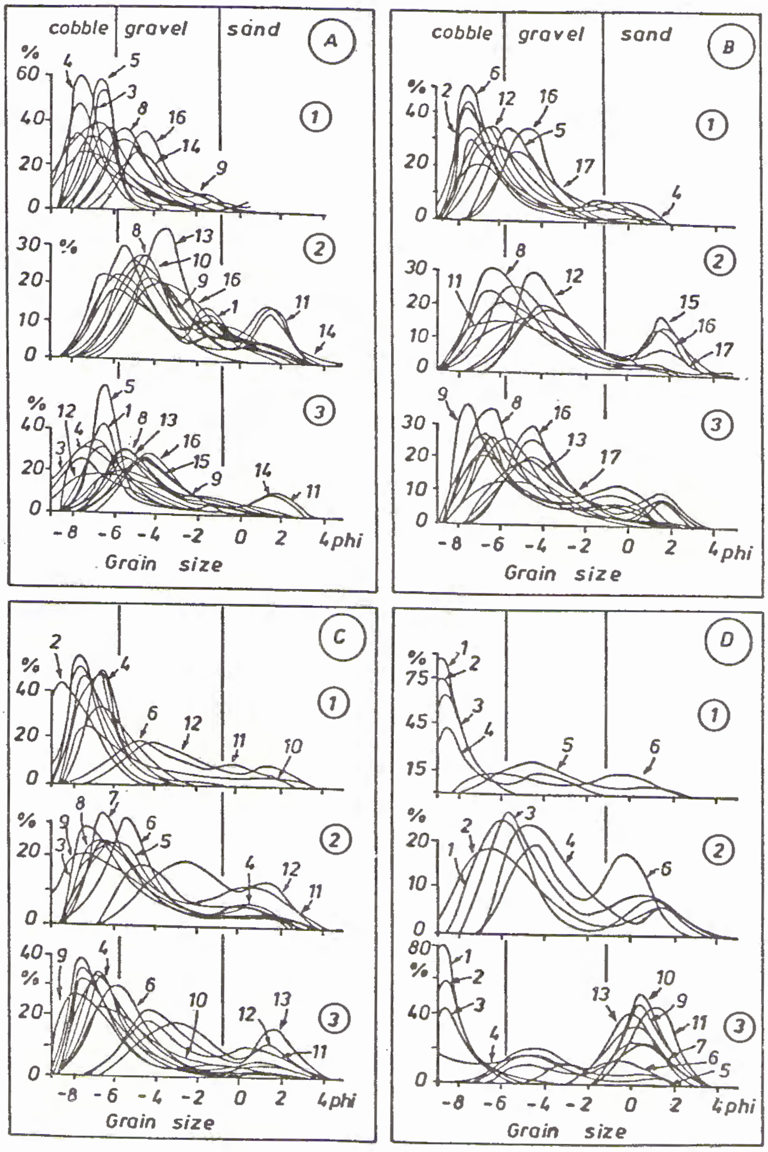

Fig. 6. Histograms of the grain size distribution along of the rivers, showing contribution of the subsurface sediments to bimodality of the full sample. A Suceava; B. Moldova; C. Putna; D. Oltet; 1, surface bed sample; 2, subsurface sample; 3, full sample.

manifested.

Consequently, the unimodalities of channel material distributions appear in those river cross-sections where the materials are, granulometrically, quasi-uniform, being

Table 5. Average values of the sand and gravel modes and of 1-20 mm fraction in the bed material.

River	Sand+silt+clay	Pebble+cobble+boulder (%)	1-20 mm fraction(%)
Suceava	9.99	90.01	20.87
Moldova	13.78	86.22	22.23
Putna	21.72	78.28	16.35
Buzau	30.58	69.42	
Siret	33.62	66.38	35.2
Oltet	55.23	44.77	12.6

only boulders+cobbles or only sands+silts+clays. Bimodality characterises those cross-sections where there are mixing sizes (gravels+fines). The averaged values for studied river mixtures are shown in Table 5.

From this table we can conclude that the percentages of mixtures are, generally, 73% gravels and 27% fines, which prove the ideal distribution proposed by Ibbeken (1984), 70% gravels and 30% fines, for the average Calabrian river-mouth sediments. Bimodality is determined by amounts under about 35% of the fraction 1-20 mm (in Calabria and in Romania), the element of first importance in defining fluvial sediment distributions. The question in what controls the appearance or disappearance of this grain-size interval. Interpretations made until now focuses attention on attrition and selective transport or deposition, as already proposed by Shea (1974, quoted by Ibbeken and Schleyer, 1991).

Petrographical variability of channel deposits

Petrographical composition of bed material for the studied rivers was approached in order to obtain further informations about source area-river-mouth sediment relationship, about abrasion degree of fluvial gravels related to their lithological composition. Consequently, the approached problem was been organised in following sections: (a) petrographical spectra of the drainage basins as sediment source areas; (b) petrographical spectra of fluvial gravels, emphasising on the relationship between source area lithological composition and river gravel lithological composition.

Source area lithological composition

The petrographical suite of the drainage basins was been evaluated, using 1/50,000—1/200,000 geological maps. Lithological entities with relative homogenous characteristics concerning of erosion resistance were emphasised. The percentage weights of different lithological entities, as well as tectonical-stratigraphical units to which the drainages belong, are shown in Table 6 and Fig. 1. These data were utilised to obtain the following petrographic characterisation of the basins:

Table 6. Petrographical composition of studied river drainage basins.

Drainage basin	Total area Km²	PETROGRAPHICAL GROUPS									
		Igneous rocks %	Metamorphic rocks %	Carbonate rocks %	FLYSCHS ROCKS (%) Audia Nappe	Tarcau Nappe	Vrancea Nappe	Other Nappes	Molassic rocks %	Plateforme rocks %	Quaternary deposits %
Suceava	2,890	-	-	-	7.12	28.14	-	0.89	2.09	40.56	21.20
Moldova	4,311	-	8.00	1.70	11.00	31.20	-	7.10	7.10	14.80	19.10
Putna	2,765	-	-	-	-	13.80	14.30	-	24.70	-	47.20
Buzau	5,240	-	-	-	3.40	29.70	-	9.10	27	20	30.60
Siret	42,274	0.80	4.90	0.60	28 70				15.90	26.30	22.80
Oltet	2,474	2.81	3.36	0.55	-	-		-	12.45	-	80.82

1. *Igneous rocks* occur in the upper part only of Oltet and Siert Rivers, with a limited extention. In the Oltet drainage basin, the magmatical intrusion (granite, granodiorite and diorite) are represented, and in the Siret drainage basin, the andezite and its varieties (Miocene-Pleistocene age) being exposed.

2. *Metamorphic rocks* (Upper Proterosoic-Palaeosoic age) occur limited areas in the upper drainage basins of Moldova and Siret Rivers. These are given by: gneisse, paragneisse, micaschistes, sericitous-chloritous schistes, quartzite, cristalline limestone and dolomite.

3. *Carbonate rocks* occur in percentage reduced (under 2%), being located in the upper drainage basins of Moldova and Siret Rivers. These rocks are of Triassic and Lower Cretacic age.

4. *Flysch rocks* occur in the drainage basins located on the eastern side of Easterns Carpathians (Suceava, Moldova, Putna, Buzau, and Siret Rivers). For the Easterns Carpathian rivers (Table 6, Fig. 1), a relative large surface occupied by flysch rocks (about 40%) explains the most important supply with clasts in the river channels. The flysch is represented by a great lithological variability: from weak shales and dysodiles to hard quartzarenites or limestones. From this reason, was been selected 4 lithologicat types: (a) *Cretaceous glauconotic quartzarenites* that are part of Audia Nappe, and is represented of about 6.5% from it in the startotype place. They crop-out in Siret, Moldova, Suceava, Buzau drainage basins; (b) *Paleocene-Eocene graywackes* with lihofeldspars and feldspatholithic varieties, that are parts of Tarcau and Audia Nappes. In stratotype places they are represented 52% from Audia Nappe and 50% from Tarcau Nappe, respective. They crop-out in all studied basins except of Oltet; (c) *Paleocene-Eocene limestones*, in fact varieties of limy-sandstone and biocalcarenite that are parts of Tarcau and Vrancea Nappes. In stratotype places they are represented under 5% of both nappes; (d) *Oligocene quartzarenites* appear only in the Tarcau and Vrancea Nappes, being under 15% in the extension maximal areas of the two nappes. They crop-out in the drainage basins: Suceava, Moldova, Buzau and Siret. For the other rock types identified in the basins we will use the name

of "miscellancous rocks", these being less characterised in the areas investigated.

5. *Molassic and Platform rocks* have variable extensions in the studied basins. These are represented of low resistance varieties at erosion, that belong to Subcarpathian Miocene and Platefom Miocene-Pliocene (shales, marls, brittle sandstone, gypsum, and weak conglomerates). In the out-corp areas neither relief energy is high nor secondary network river is developed, so that to do contamination of river bed material that is carry up to here.

6. *Quaternary deposits* that are, especially, extended in Oltet Drainage Basin, but they are customary in the other studied drainage basins, too. They contain Pliocene-Pleistocede terrace and Holocene floodplain deposits (loesses, gravels and sands).

Arrangement manner of these lithological entities in drainage basins is follows (Fig. 1): in upper parts which are the highest altitudes there are igneous and metamorphic rocks, in the middle parts are specific the flysch rocks, in lower parts, the molassic and platform rocks as well as quaternary deposits. This relative quasi-uniform distribution of sediment source areas facilitated the petrographical investigations of the three great rock categories (igneous, metamorphic and sedimentary rocks) which are rediscovered in bed river deposits from upper stream to lower stream of the studied rivers.

The petrographical spectrum of river gravels

Petrographical composition of the river gravels (32–64 mm) is showed in Fig. 7, for 5 studied rivers. Except of Oltet River, in channel deposits the greatest weight is given by sandstones (quartzarenites and graywackes) but, between the different types of it there is a competition related with relative erosion resistance. That is, because of quartzarenites from Audia, Tarcau and Vrancea Nappes are composed by quartz grains and siliceous cement (opal and calcedony), they have hardeness to impact and attrition whilst the graywackes that the grains are composed by feldspars, lithoclasts and quartz in different percents with argilous-detritical matrix (there are some varieties with calcitic cement) less resistant to impact, attrition and gelivation because of porosity and water absorption which are characteristics to matrix graywackes. Graywackes are being proves by Audia, Tarcau and Vrancea Nappes, but from the others Nappes, too.

Quartzarenites are being compose of 50–90% from river gravels in Suceava River, 30–40% in Moldova River and under 20% in Buzau River. To downstream, the weights of this kind of sandstones are being modify very low, that point out high fluvial abrasion resistance. Opposite, graywackes are being compose under 20% in Suceava River, 30–40% in Moldova River and 60–70% in Buzau River, there being a

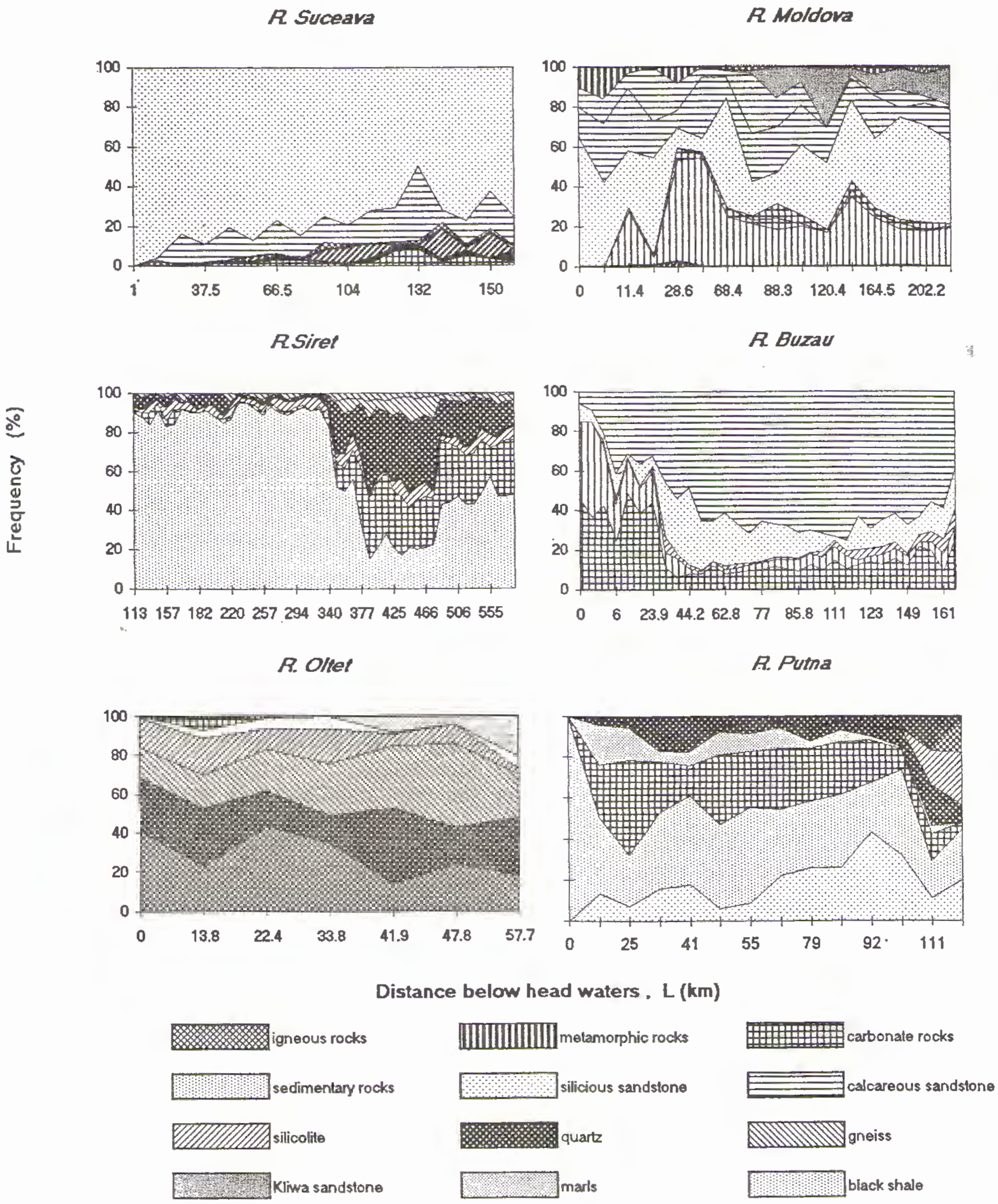

Fig. 7. Changes in the petrographic distribution of channel sediments.

slight tendency of weight diminution to downstream.

As concerns, the others rock categories (igneous and metamorphic), their weights in petrographical spectrum are important, especially, in Oltet River. In studied

Table 7. Petrographical composition change from the source to the river-mouth sediment.

River		Igneous rocks %	Metamorphic rocks %	Carbonate rocks %	Sandstones Quartzarenites %	Sandstones Greywackes %
Suceava	source (S)	-	-	-	4.68	14.00
	river (R)	-	-	-	70.00	10.00
	R/S	-	-	-	14.96	1.40
Moldova	source (S)	-	8.00	1.70	5.39	21.30
	river (R)	-	19.00	2.00	60.00	18.00
	R/S	-	2.37	1.18	11.13	0.84
Buzau	source (S)	-	2.00	2.00	14.80	4.72
	river (R)	-	6.00	26.00	20.00	38.00
	R/S	-	3.00	13.00	1.35	8.05
Siret	source (S)	0.80	5.00	2.60	28.70	
	river (R)	1.00	16.00	28.00	48.00	
	R/S	1.25	3.20	10.77	1.67	
Oltet	source (S)	2.60	3.80	1.00	10.00	
	river (R)	21.00	52.00	1.00	2.00	
	R/S	8.08	13.68	1.00	0.20	

drainage basins these kinds of rocks crop-out in very limitated surfaces. The higher fluvial abrasion resistance makes that their weights in gravel deposits to be maintain almost unchanging to downstream, although the source areas prove this kind of clasts only in upper parts of drainage basins. Excepts is the Siret River in which are confluent three main tributaries in it middle reach and which modify lithological composition of channel deposits. Conclusions obtained by reference of gravel lithological composition to source area lithological composition are shown in Table 7 for each studied river, namely:

1. *Igneous rocks*, andezites in Siret Drainage Basin and granitoides in Oltet Drainage Basin, respective, are being compose under 1% and 2%, respective, in surfaces of above mentioned drainage basins whilst the weights of these kind of rocks in channel are being compose 1% in Siret River and 21% in Oltet River, respective.

2. *Metamorphic rocks*, on the all studied basins, have a weight between 2 and 8%, but in the river bed of 2–4 times more numerous at about 150–200 km from the source and of 14 times at only 60 km from the source.

3. *Limestones and dolomites* are characterised by a more resistant strength against abrasion among all categories of rocks analysed by us, they being of 10 to of 30 times more numerous in the river bed at about 400 km from the source.

4. *Sandstone rocks* have the most dramatical shift, that is, they are important as area in the drainage basins, but in the river bed they decrease in the downstream direction. A certain differentiation there is concerning to the quartzarenites and graywackes; first category, with the siliceous cement, is hard and is from 4 to 15

times better represented in the Suceava, Moldova, and Buzau Rivers. For the second category, graywacke, the ratio river/source shows the inverse tendency for the Moldova River (that is, in the basin the weight is from 1 to 2 times more than in the river bed).

Acknowledgements

We would like to thank for the help in the field and laboratory of Vasile Frunzete and Dan Pipirigeanu. Special thanks are due to Professor Hiroo Ohmori who encouraged us in the publishing of this article.

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