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GEOSTATISTICAL ANALYSIS OF GRAVEL SHAPE AND ROUNDNESS INDICES IN THE MOLDOVA RIVER

BY

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KEY WORDS: clast morphological analysis, fluvial gravel shape and roundness, variability in long profile, "optimum form" of gravels

1. Introduction

The morphology (form) of sedimentary particles proves an important source of information about provenance, transport and deposition of sediments. Sediments are the product of both heritage and environment (Pettijohn, 1957). To trace their lines of descent and to reconstruct the environment which gave rise to sedimentary rocks are difficult tasks. A knowledge of sedimentary processes, especially of those environmental factors that have had a major influence on the production, transportation, depositation and subsequent modification of the sediments is important. Therefore, the actual facies analysis of the rivers, especially of the East - Carpathian rivers, represents the study topic of Geomorphological Laboratory of "Stejaru" Research Station, topic which is part of an ample research objectiv on alluvial system in Romania.

This paper chose a restricted problem of above mentioned objectiv, namely: *shape and roundness indices variability of gravels along Moldova River and determining of its "optimum form"*.

Our interest in this problem is motived by obtaining expectation of a comparative term, in real world, of sedimentary deposits in Ciungi "Palaeodelta" which is concern that an outbuilding of "PalaeoMoldova" River in Lower Sarmatian (Martiniuc, 1948; Barbu et al., 1964; Barbu et al. 1966; Ionesi et al, 1971).

2. Data base and methods

2.1. Data base

The field sieving work was continuously accompanied by measurements of the axes of the clasts of selected rock type and size fraction. The final sum, adds up to 1381 clasts measured. The data was stored in the bank.

The grain size analyses of Moldova channel deposits was realised on bulk samples of 17 cross-sections (Lucina, Tatarca, Breaza, Colacu, Fundu Moldovei, immediately downstream of confluence with Putna River, Câmpulung Moldovenesc, Molid, Bucşoaia, Păltinoasa, Cornu Luncii, Praxia, Oniceni, Timişeşti, Tupilaţi, Gherăieşti and Roman) (Fig. 1), for surface and subsurface, respectively (Moesley and Tindale, 1985; Church et al., 1987; Ichim et al., 1992).

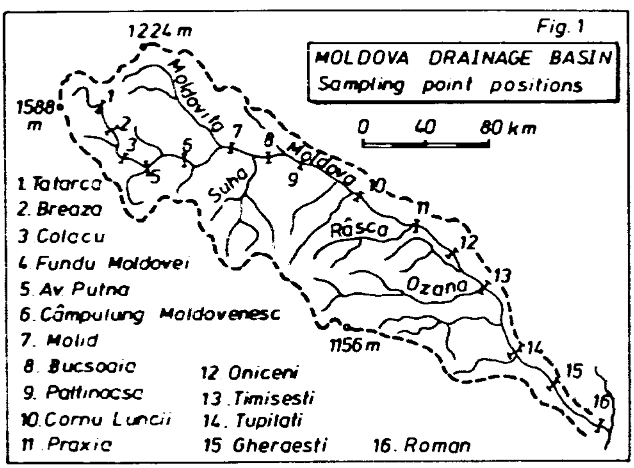


Fig. 1 MOLDOVA DRAINAGE BASIN Sampling point positions

Clast shape and roundness analyses was performed on 30 - 70 mm class of selected rock type. In this paper we focuse on shape and roundness analyses of gravels which proceed from carbonate rocks (limestones and dolomites) of Rarău Syncline (carbonate rocks are represented by 0,73 % in Moldova Drainage Basin which is 4.326 km^2, 205 km lenght and max. altitude is 1110 m). The clasts was sampling on the about 200 m^2 of each cross - section above mentioned. Samples was colected on the side or medial bars. Each sample consists of 50 to 130 clasts.

2. 2. Determining shape and roundness indices

Particle morphology or *form*, may be regarded as the sum of three - scale related properties: *shape*, or relative dimensions of a particle; *roundness*, or the overall smoothness of particle outline; and *texture* or surface roughness (Griffiths, 1967; Barret, 1980 cf. Benn and Ballantyne, 1993; Orford, 1981).

This paper is concerned with the description and representation of particle shape and roundness, defined in terms of the long (*a*), intermediate (*b*) and short (*c*) axes and at the same time the radius of the curvature of sharpest corner in the plane of maximum projection (the *ab* plane) (r) (Krumbein, 1941 cf. Pettijohn, 1957; Cailleux, 1945). We determined roundness and shape indices for each clast measured (Tab. 1).

Table 1.

	INDEX	FORMULA	REFERENCE
Roundness index	Cailleux roundness index	$R_0 = 2r_1 / a$	Cailleux 1947
Shape indices	Cailleux flatness index	$ApC = 100(a+b)/2c$	Cailleux 1945
	Cailleux dissymetry index	$As = AC / a$	Cailleux 1945
	c / a	c / a	Sneed & Folk 1958
	Elongation index	b / a	Zingg, 1935
	c / b	c / b	Zingg, 1935
	Oblate - prolate index	$OP = 10(((a-b)/(a-c)-0.5)/c/a)$	Dobkins & Folk, 1970
	Disc - rod index	$DC = (a-b)/(a-c)$	Sneed & Folk 1958
	Maximum projection sphericity	$MPS = \sqrt[3]{(c^2/ab)}$	Sneed & Folk 1958
	Krumbein sphericity	$Sf = \sqrt[3]{cb/a^2}$	Krumbein 1941
	Corey shape index	$CSI = c/\sqrt{(ab)}$	Corey 1949

2. 3. Data procesing

In this paper we had in view the aspects, as follows:
- obtaining of statistical parameters (median, standard error, standard deviation etc.), we used the *Excel* package for statistics;

- obtaining of the relationships between standard error and size sample for roundness and shape indices;
- using of 6 mathematical function types to characterize roundness and shape indices variability along Moldova River (linear, exponential, logarithmic, power, hyperbolic and polynominal function);
- obtaining of roundness and shape index histograms;
- evaluating of gravel "optimum form" features, in the given conditions.

3. Results

3. 1. On sample size

The sample size discussion it is an important problem because our observations and results depend on samples which were selected from very large but finite populations on the each cross section of Moldova River. The basis principle of sampling postulates that sample variable converge to population variable with a condition; sample size to be representative. In practice, 30 items it is considered to be an illustrative sample (this is especially statistics view).

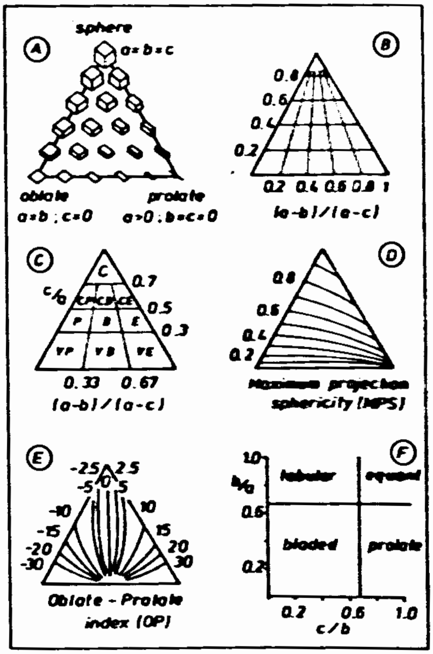


Fig. 2 The linear triangular shape continuum. All of the diagrams are exact geometrical equivalents

(A) Definition of the apices of the continuum and the positions of selected idealized shapes. (D. Benn and C. Ballantine, 1993)

(B) The scaling employed by Sneed and Folk (1958)

(C) The 10 descriptive classes defined by Sneed and Folk (1958)
C-compact ; CP-compact platy ; CB-compact bladed ; CE-compact elongated ; P-platy ; B-bladed ; E-elongate ; VP-very platy ; VB-very bladed ; VE-very elongate ;

(D) Isolines of the Maximum projection sphericity (MPS)

(E) Isolines of the oblate-prolate index (OP)

(F) The Zingg diagram. Definition of the shape classes

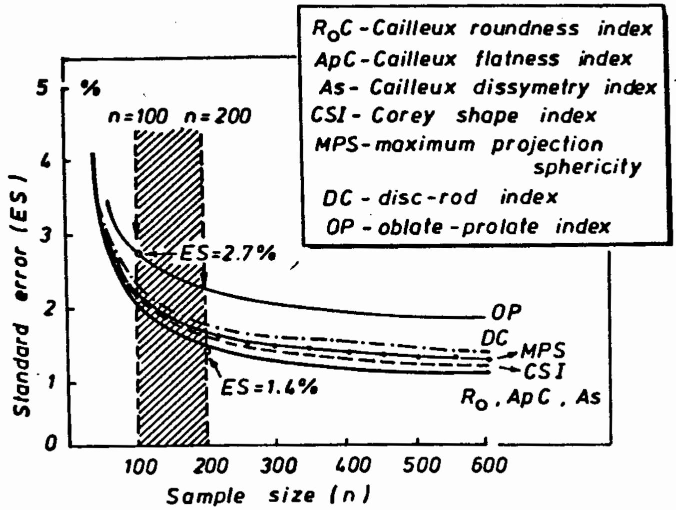


Fig. 3 Standard error versus sample size

As Fig. 4 shows the correlation coefficients (r) are sometimes the highest in polynominal function case, sometimes in hyperbolic or logarithmic function cases, but we can made some observations:

i). correlation coefficient, r, for polynominal function are very high for any significance level (95 %, 99 %, 99,9 %) (see Kirkby et al. 1987, Tab. 2. 1), this function it is not that which we need because it is a measure of local controls (e. g. confluences). Its representation is unique.

ii). exponential function has an important correlation coefficient (r) in some cases, but this function is an unlimited increasing function related of increasing x (in our case L, travel distance) and we think that this function cannot be used like forecasting function. In the same time this function is a good approach of any index variability in a given range of x (travel distance, L) values, but no for prediction (same problem for logarithmic and power functions). Linear function was given for comparison.

iii). we considered, because of limited variation domain of shape and roundness indices (y, in mathematical functions) in hyperbolic function case, this is that which we need for forecasting. This function has two asymptotes: first, is horizontal where $y = a$ (the intercept of each index) and the second is vertical, $x = 0$ (in our case $L = 0$ at river head). This function may be increase of decrease (related of b, regression coefficient). We justify this opinion by the fact that at one time a gravel reach an "optimum forum" (we said form because texture is same for a given rock type, in our case carbonate rocks) from which it do not support other modification related of travel distance. From this moment, sorting is the main process during of transport.

Standard error of sampling is very important in sampling theory. Its value is determined by sample size. There is a hyperbolic decrease trend of sampling error related of sample size (n) increase (Fig. 3). This hyperbolic curve have a high rate of decrease of error to 2 - 3 % for 100 items, then standard error become stabilized on 1,5 - 2 % level independently by doubling or tripling sample size. That is, doubling or tripling of sample size (number of items) does not double or triple precision of the estimate (Silk, 1979). The optimum number of gravel (hatched area), is between 100 - 200 gravels (Fig. 3), the same conclusion as Mihailescu (1965).

For 5 cross sections of Moldova River, the size sample is between 43 - 70 gravels. This is motived by low change to find carbonate gravels in these places. But this does not reduce representativeness of sample because the sampling error of each sample is below 5 %.

3. 2. Mathematical modeling of shape and roundness index variability

For mathematical modeling of shape and roundness index variability versus travel distance we used 6 mathematical function types:
linear function $y = a + bx$; exponential function $y = ae^{bx}$; power function $y = ax^{b}$; logarithmic function $y = a + b\ln x$; hyperbolic function $y = a + b\frac{1}{x}$; polynominal function $y = a + bx + cx^2 + dx^3 + ex^4$ where y is shape or roundness index to analyze; x is travel distance from river head (in km); a is intercept and b, c, d, e are regression coefficients.

Fig. 4 schematically shows mathematical curves of each function, regression coefficients (a, b, c, d, e), correlation (r) and determining (r^2) coefficients for eight shape and roundness indices of gravels. We can make the remarks that:

a) *travel distance is an effective control on clast shape and it roundness* (Pettijohn, 1957; Richards, 1982). That is, the channel facies supports transformations according to distance from the river head as a direct expression of river power and these transformations are mirrored in particle features.

b) *the reponse way of each shape and roundness index according to increasing travel distance*, is quantified on basis of the *values and signs of regression coeficients b, c, d, e*. There is an increase of roundness, flatness and elongation indices and a decrease of dissymetry, sphericity, disc-rod and oblate-prolate indices related to travel distance from the river head.

c) *the highest resolution of index variability there is in hyperbolic function case*.

3. 3. "Optimum form" of the carbonate gravels in Moldova River contemporary channel conditions

The shape of clasts may vary between theree end members, defined in terms of their three orthogonal axes (Fig. 2):

i) a prolate spheroid with one long and two shortes axes ("ideal prolate" conditions: $a > 0$; $b = c = 0$);

ii) an oblate spheroid with two long axes and one short axis ("ideal oblate" conditions; $a = b$; $c = 0$)

iii) a sphere with all axes equal (sphere conditions $a = b = c$).

The apices can also be defined in terms of ratios between two or more of particle axes, as follows (Ben and Ballantyne, 1993):

1). $b : a = c : a = 0$; 2). $b : a = 1$; $c : a = 0$; 3). $b : a = a = 1$.

Sneed and Folk (1958), utilized the ratios $c : a$ and $(a - b) : (a - c)$ (disc - rod index. Fig. 2), which together uniquely define any point within shape triangle. An alternative scaling was proposed by Hockey (1970) (cf. Benn and Ballantyne 1993) in which $b : a$ is plotted against $c : a$, but Hockey showed that this scaling system is the exact geometrical equivalent of that proposed by Sneed and Folk (1958). Ballantyne (1992) (cf. Benn and Ballantine, 1993) was proposed an other triangular diagram which is equivalent to that proposed by Hockey but reflected about the line $(a - b) : (a - c) = 0,5$ and rotated clockwise through 120 °.

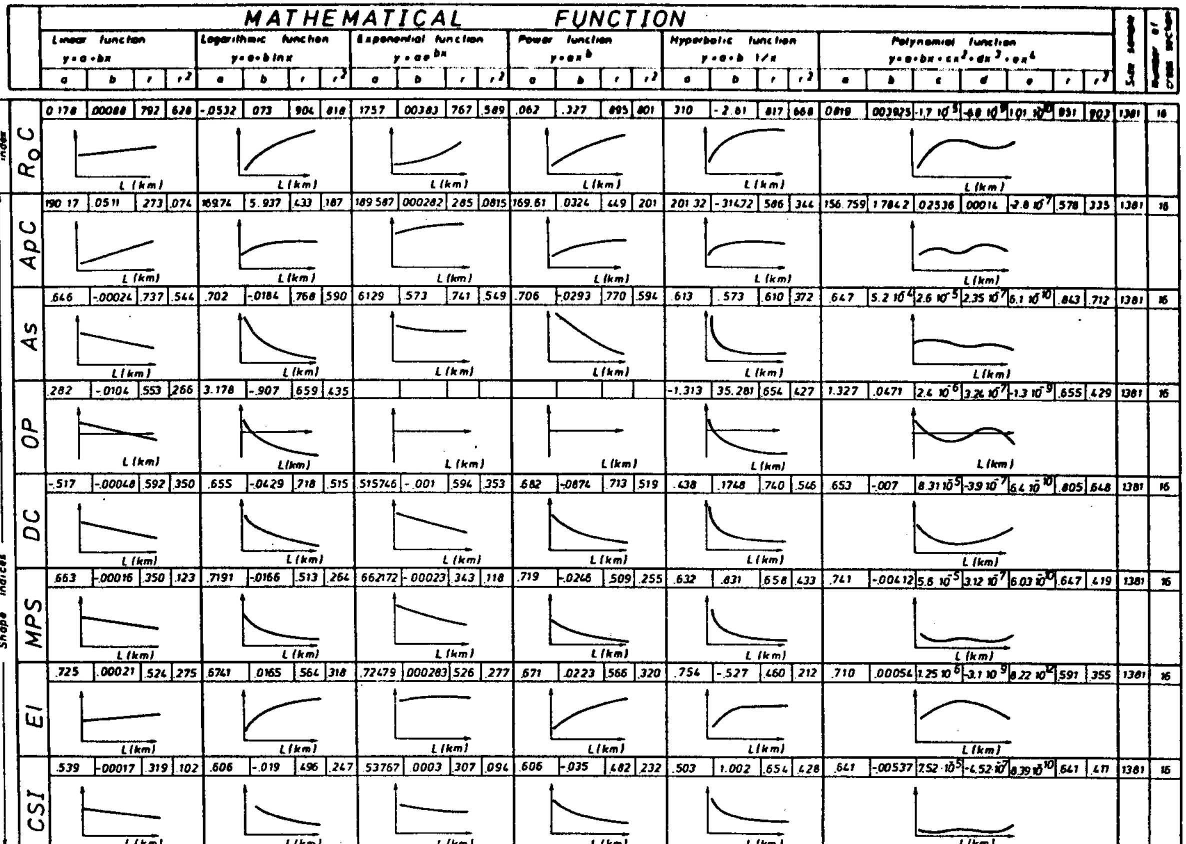
We used Sneed and Folk diagram and some varieties of it with isolines of maximum of projection sphericity (*MPS*) and oblate prolate (*OP*) indices and also we used Zingg diagram and we made histograms of frequency (Figs. 5, 6, 7, 8).

From Sneed and Folk shape diagram (Fig. 5) we obtained:

i) the *bladed class* frequency (25 - 30 %) is the most important both in upper and middle reaches (Carpathian and Subcarpathian areas) and in lower reach (Tableland area, see Fig. 10), exception in Tatarca cross section where compact - bladed class is the most important;

ii) values obtained of carbonate gravel axes ratios are: c/a ranges between 0,3 - 0,6 (more than 50 % of gravels analysed from each sampling cross - section); c/b ranges between 0,4 - 0,8 (more than 70 % of gravels of each cross - section;

iii) the ***maximum projection sphericity*** (*MPS*) (Fig. 6), is an important index of the behaviour of particles transported by or settling in water (Sneed and Folk, 1958). The *MPS* variation along Moldova River is useful only for hydraulic context of it. Maximum *MPS* frequency ranges between 0,6 - 0,8 in upper reach and between 0,5 - 0,7 in middle reach where it become stabilized (Fig. 10).



		MATHEMATICAL FUNCTION																										
		Linear function $y=a+bx$				Logarithmic function $y=a+b\ln x$				Exponential function $y=ae^{bx}$				Power function $y=ax^b$				Hyperbolic function $y=a+b\ 1/x$				Polynomial function $y=a+bx+cx^2+dx^3+ex^4$							Sum length	Number of cross section
		a	b	r	r^2	a	b	r	r^2	a	b	r	r^2	a	b	r	r^2	a	b	r	r^2	a	b	c	d	e	r	r^2		
Roundness index	R_oC	0.178	.00088	.792	.628	-.0532	.073	.904	.818	.1757	.00383	.767	.589	.062	.327	.895	.801	.310	-2.81	.817	.668	0.819	.003925	$-1.7\ 10^{-5}$	$-4.0\ 10^{-8}$	$1.01\ 10^{-10}$	.931	.903	1381	16
Shape indices	ApC	190.17	.0511	.273	.074	169.74	5.937	.433	.187	189.587	.000282	.285	.0815	169.61	.0324	.449	.201	201.32	-31.472	.586	.344	156.759	1.7842	.02536	.00014	$-2.8\ 10^{-7}$	.578	.335	1381	16
	As	.646	-.00024	.737	.544	.702	-.0184	.768	.590	.6129	.573	.741	.549	.706	-.0293	.770	.594	.613	.573	.610	.372	.647	$5.2\ 10^{-4}$	$2.6\ 10^{-5}$	$2.35\ 10^{-7}$	$6.1\ 10^{-10}$	.843	.712	1381	16
	OP	.282	-.0104	.553	.266	3.178	-.907	.659	.435									-1.313	35.281	.654	.427	1.327	.0471	$2.4\ 10^{-6}$	$3.24\ 10^{-7}$	$-1.3\ 10^{-9}$	.655	.429	1381	16
	DC	-.517	-.00048	.592	.350	.655	-.0429	.718	.515	.515746	-.001	.594	.353	.682	-.0874	.713	.519	.438	.1748	.740	.546	.653	-.007	$8.31\ 10^{-5}$	$-3.9\ 10^{-7}$	$6.4\ 10^{-10}$	.805	.648	1381	16
	MPS	.663	-.00016	.350	.123	.7191	-.0166	.513	.264	.662172	-.00023	.343	.118	.719	-.0246	.509	.255	.632	.831	.658	.433	.741	-.00412	$5.6\ 10^{-5}$	$3.12\ 10^{-7}$	$6.03\ 10^{-10}$	.647	.419	1381	16
	EI	.725	.00021	.524	.275	.6741	.0165	.564	.318	.72479	.000283	.526	.277	.671	.0223	.566	.320	.754	-.527	.460	.212	.710	.00054	$1.25\ 10^{-6}$	$-3.1\ 10^{-9}$	$8.22\ 10^{-12}$	.591	.355	1381	16
	CSI	.539	-.00017	.319	.102	.606	-.019	.496	.247	.53767	.0003	.307	.094	.606	-.035	.482	.232	.503	1.002	.654	.428	.641	-.00537	$7.52\ 10^{-5}$	$-4.52\ 10^{-7}$	$8.39\ 10^{-10}$	.641	.471	1381	16

Fig. 4 Relationships of roundness and shape indices versus transport distance on the Moldova River. (R_oC - Cailleux roundness index ; ApC - Cailleux flatness index ; As - Cailleux dissymetry index ; OP - oblate-prolate index ; DC - disc-rod index ; MPS - maximum projection sphericity ; EI - elongation index ; CSI - Corey shape index)

iv) the maximum *oblate - prolate* index frequency migrates from the 9 class (+ 5 - + 10) to 4 class (- 10 - -5) (Fig. 7.)

The mean shape class on Sneed and Folk diagram for all carbonate gravels analysed is bladed (Fig. 5), the mean shape class on shape triangle with isolines of oblate - prolate index of all carbonate gravels is between - 2,5 - + 2,5 (Fig. 7) and mean shape classes on diagram with isolines of *MPS* for all carbonte gravels are 6 - 7 (Fig. 6). As a general conclusion, the mean gravel shape analysed by us is *bladed*, bur concerning significance of the shape indices, there is not an unique conception. Ibbeken and Schleyer (1991) reviewed the contributions in this field and they conclude that shape indices it is not a provenance signals or is a very limited signals of it. They investigated Calabrian gravel shape indices and showed that the mean shape class of them is compact - bladed, sphericity class is 0,722 (class 7) and oblate - prolate class is between - 2,5 - + 2,5 but Calabrian rivers are very short and are steep gradients (mean river lengths are 20 km) (Ibbsken and Schleyer, 1986; Ibbeken and Schleyer, 1991).

Maximum shape class frequency on the Zingg diagramm (Fig. 8) migrates from the equant class to tabular class but we can observ that this classes are partly superposed on the bladed Sneed and Folk's class (Fig. 2).

For roundness we used Pettijohn (1949)'s roundness category (as defined in Fig. 9) and made a histogram.

In Fig. 9 the roundness categories are presented. Maximum roundness category frequency migrates from *A* (angular category; 0 - 0.150)to *SR* (subrounded category; 0.200 - 0.400). In fact the maximum roundness category in fluvial environment is 0.350 (Reineck and Singh, 1975).

The generalized trends of shape and roundness variability related of travel distance are approached by hyperbolic and logarithmic functions (Fig. 10). As the graphs of mathematical functions show, *there is a high variability of indices in upper part of Moldova River, first 40 Km in Carpathian area*, where the power of river is great. In this reach there is the highest gradient (from 1110 to 900 m).

Between 80 - 100 Km (from Paltinoasa to Cornu Luncii in Subcarpathian area) *mathematical function reach the maximum values each index, that is "optimum form" of gravels*, after this they do not support any transformatiom for next 100 km to confluence (maximum values of indices are follow: *roundness index = 0.300; flatness index = 180; dissymetry index = 0.62; disc - rod index = 0.46; MPS index = 0.64*). It seems that it is a consequence of power diminished of work environment on clasts, which is expressed in the longitudinal profile by decreasing gradient.

On the *next 100 km to confluence with Siret River, particle morphology of 30 - 70 mm class is close about "optimum form"*, as theoretical models show, obtained by forecasting equations (Fig. 10). In longitudinal profile this reach is characterized by lower gradient, then a low work environment of clasts. In this reach the dominant process is the sorting because of low river energy. This "optimum form" is only for Moldova River conditions.

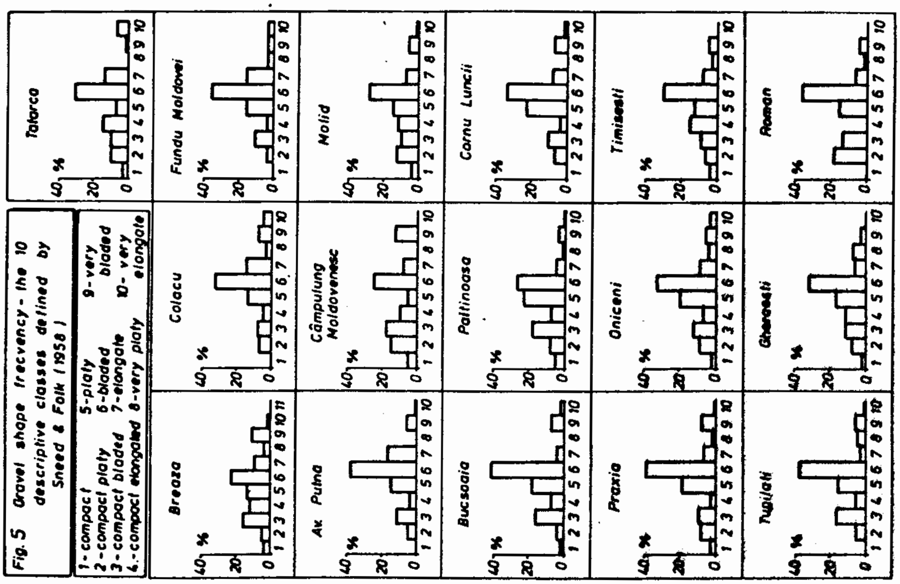


Fig. 5 Gravel shape frecvency - the 10 descriptive classes defined by Sneed & Folk (1958)

1 - compact; 2 - compact platy; 3 - compact bladed; 4 - compact elongated; 5 - platy; 6 - bladed; 7 - elongate; 8 - very platy; 9 - very bladed; 10 - very elongate

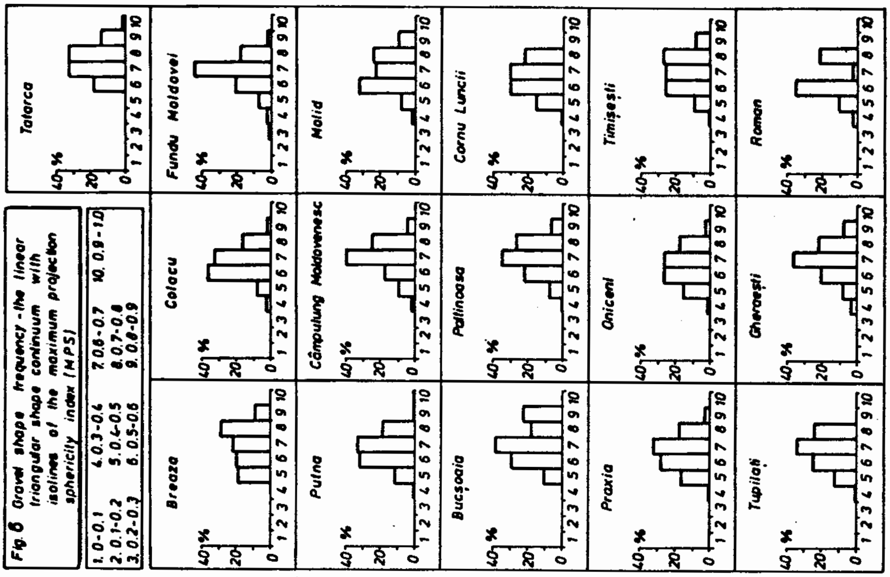


Fig. 6 Gravel shape frequency - the linear triangular shape continuum with isolines of the maximum projection sphericity index (MPS)

1. 0-0.1; 2. 0.1-0.2; 3. 0.2-0.3; 4. 0.3-0.4; 5. 0.4-0.5; 6. 0.5-0.6; 7. 0.6-0.7; 8. 0.7-0.8; 9. 0.8-0.9; 10. 0.9-1.0

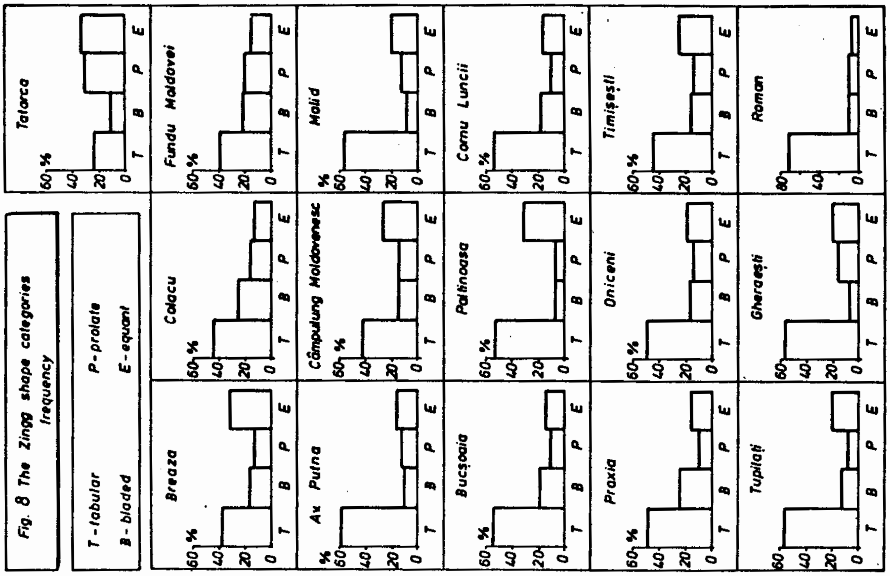


Fig. 8 The Zingg shape categories frequency

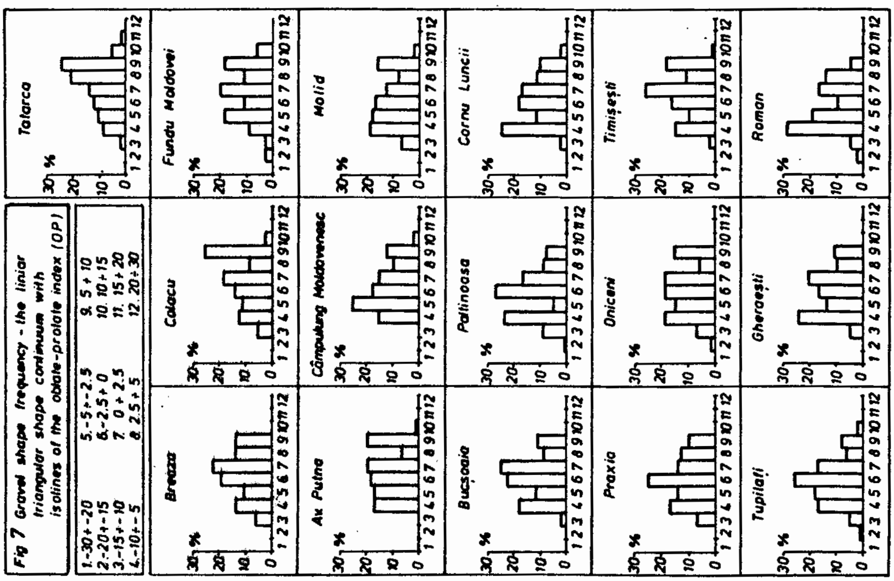


Fig 7 Gravel shape frequency - the liniar triangular shape continuum with isolines of the oblate-prolate index (OP)

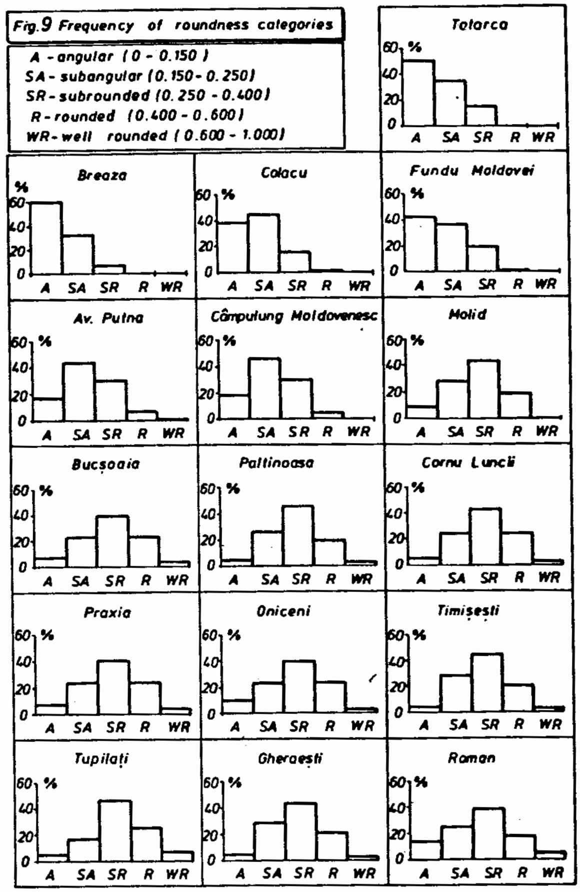


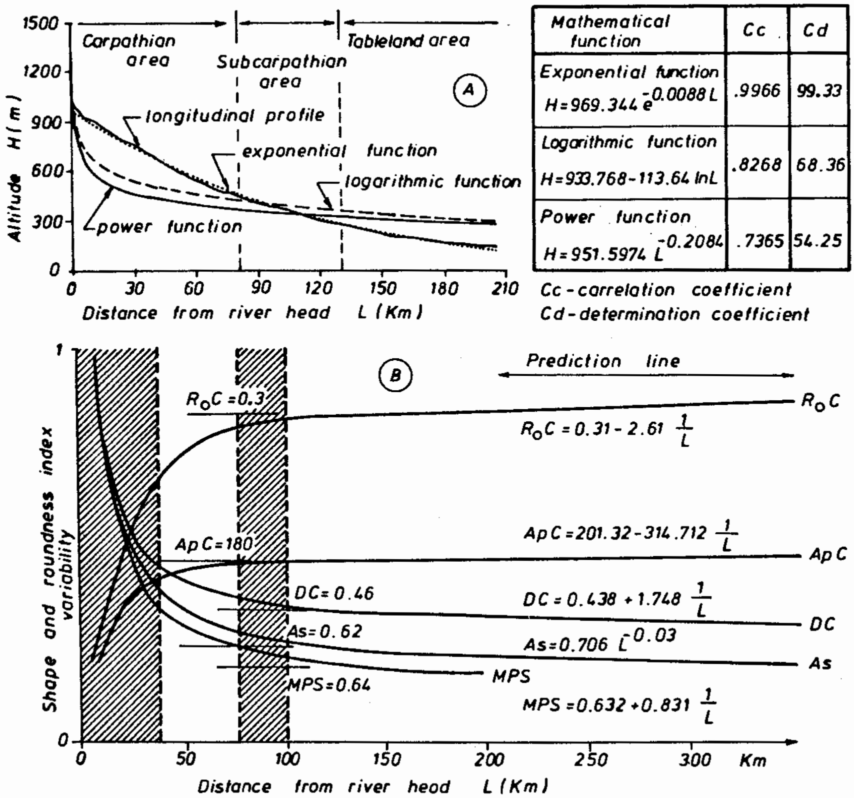
Fig. 9 Frequency of roundness categories

The roundness - flatness (Richter, 1959 diagram modified by Reineck and Singh, 1975) relationship is used by sedimentologists to distinguish transport and work environment. Fig. 11 shows our results on carbonate gravels in fluvial environment. As we can see there is a discrimination trend along Moldova River from head to mouth as follows:

i) *the angular - splitter area*, is proper of upper part of Moldova River (Tatarca and Breaza cross sections);

ii) *the rounded corners and edges - flat area*, is proper of next 6 cross sections (Carpathians area);

iii) *the subrounded - flat area*, is proper of Subcarpathian and Tableland areas (the next 8 cross section from Bucsoaia) exception in Campulung Moldovenesc cross section which is in this field too.



Mathematical function	Cc	Cd
Exponential function $H = 969.344\ e^{-0.0088\ L}$	.9966	99.33
Logarithmic function $H = 933.768 - 113.64 \ln L$	.8268	68.36
Power function $H = 951.5974\ L^{-0.2084}$	.7365	54.25

Cc - correlation coefficient
Cd - determination coefficient

Fig. 10 A. The longitudinal profile of the Moldova River and its mathematical modeling
B. The generalized trends of shape and roundness variability related of travel distance

We can conclude that a carbonate gravel support transformation since it reach an "optimum form" in the each river conditions. Form that moment it is transported without transformations, only by the sorting.

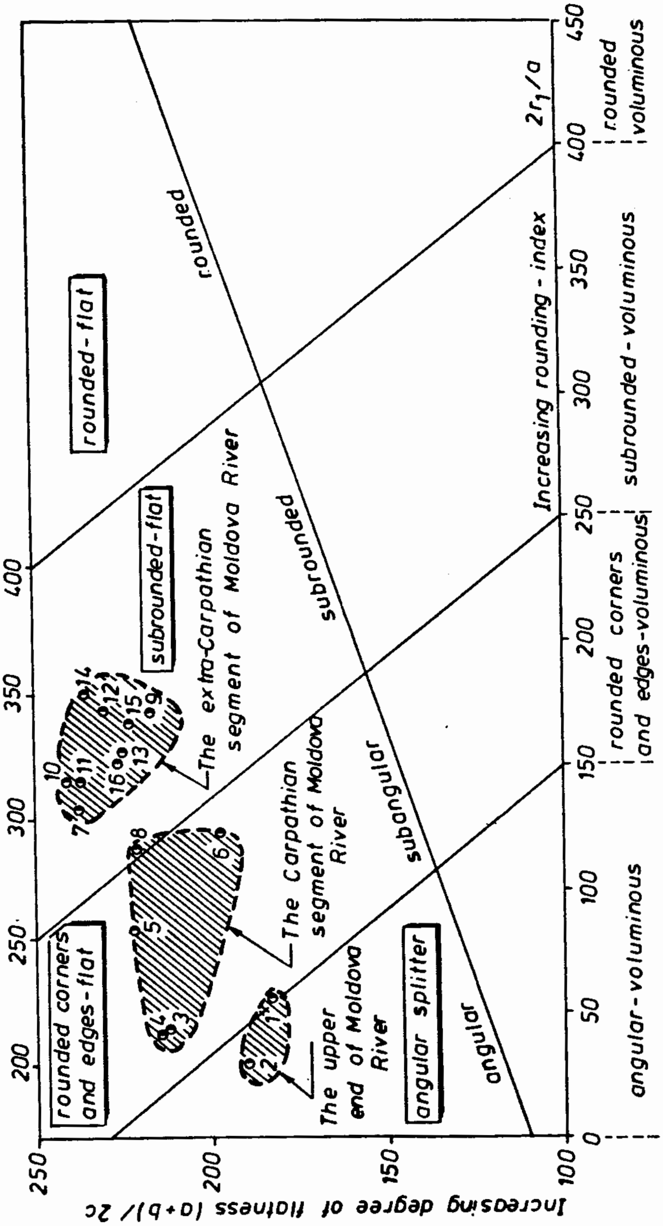


Fig. 11 Distribution of gravels based on flatness and roundness indices. This scheme is based on the measurements made on carbonate gravels (after Richter '59 modified by Reineck and Singh, 1975)

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