THE DYNAMIC SIGNIFICANCE OF THE GRAIN SIZE OF SEDIMENTS TRANSPORTED AND DEPOSITED BY THE DANUBE

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Abstract. The paper is based on grain size analyses as well as on the macroscopic lithologic description of a large number of samples collected from the bottom of the Danube. Unlike previous papers on sedimentology, which were limited to the textural characterisation of sediments from the various sectors of the Danube, this paper attempts a new approach of the sediment dynamics. The interpretation of histograms, of cumulative curves or of the Passega diagram is used in the attempt to explain the dynamic and genetic reasons for the presence of a particular type of sediment in locations characterised by different environmental energy conditions.

Key words: bimodal character, cumulative curve, mean size, standard deviation, skewness, Passega Diagram

1. INTRODUCTION

The grain size of the alluvia transported and deposited in the Danube as bottom sediments differs from one sector to another and at the level of each sector from one point to another, generally depending on the grain size of the material taken in the alluvia (material available from various sources), on the one hand, and on environment energy (current velocity) on the other.

Through its tributaries the Danube takes from the reception basin material particles of a great dimensional and lithologic diversity, resulting from the erosion of geological formations the water comes in contact with. Particles covering the entire dimensional spectre possible are also introduced in the Danube by various means of transport, from rolling down slopes to aeolian transport.

From a grain size point of view particles introduced by anthropic means can be placed in various textural categories, from the boulders used in hydrotechnical constructions to clay-size particles resulted from the decantation of used water.

A relatively large dimensional variation can result following the biotic activity of some organisms. Thus, the death of molluscs leaves shells which disaggregate turning into particles of all possible sizes and most organisms (including molluscs) introduce into the fluvial system fine matters resulting from their biotic activities which can change the grain size of sediments.

All these particles are taken over by the water masses, complicating to a large extent the grain size of alluvia. During transportation, particles are preferentially directed on certain trajectories, characterised by certain flowing speeds according to size, as well as to other physical characteristics (mainly grain shape and specific gravity). Coarser particles (having the maximum size that can be driven by means of traction) are thus preferentially transported to maximum depth areas with maximum current velocity, and smaller particles are moved to smaller depths with reduced current velocity.

2. THE GENERAL CHARACTERISATION OF THE RIVER DANUBE SEDIMENTS

A comparative analysis of sediment grain size along the Danube reveals the existence of several sectors (Panin *et. al.* 1997) in which sediments with different textural features are deposited or transported in specific geomorphological, geological and anthropic conditions. Thus, in the place where the Danube enters the Romanian territory (*i.e.* km 1075) the sediments are coarser than along the rest of its course, with much more frequent gravel elements.

Between km 1072 – Baziaş and km 1047 – Moldova Veche in the waterway sediments consist mainly of fine and medium gravel elements (near the fine / medium gravel border), and secondarily of shells and fragments, caught in a matrix made of sand or silty sand. Gravel elements have a rounded to sub-rounded shape and a heterogeneous lithological composition. A significant part of the matrix is organogeneous, consisting of a shell derived detritus which can be mistaken for sand. In the vicinity of the banks the percentage of gravel in the structure of sediments decreases progressively and the matrix gets richer in silt, clay and organic matter. In the limited sector between km 1047 and km 1040 (the entry into the Danube gorge) sediments consisting mainly of gravel are gradually replaced by sediments consisting of fine to coarse sand. Starting from km 1040 until km 1015 (Drencova), where the Danube has a maximum width and depth of 30-40 metres respectively, the river bed consists of medium (94-64mm) or coarse (>64mm) gravel which, from a lithological point of view, is mainly composed of limestone elements.

At km 999 the grain size of bottom sediments starts to change, coarser sediments being gradually replaced by finer sandy or silty sediments. In the sector between km 995 (Sviniţa) and the Iron Gates 1 Barrage, bottom sediments have similar textures, consisting mainly of silt and clay. Between km 943 (Iron Gates 1 Barrage) and 931 (Drobeta-Tr. Severin) the river bed consists of coarse gravel with a maximum diameter of 150 mm. From a lithological point of view gravel elements have different genesis with limestone predominating. Further downstream gravel elements have smaller sizes, a greater rounding degree and a higher sand content. Down the river after km 932 until approximately km 876 sediments consist of coarse sand, medium fine sand with rounded elements with different geneses in the waterway which turn into sand or silty sand towards the banks. At km 858.4, in the vicinity of Iron Gates 2 Barrage (km 864), as opposed to the situation in the vicinity of Iron Gates 1 Barrage, sediments in the waterway mainly consist of rounded elements of medium gravel, whereas in the vicinity of the banks where water depth is comparable (approximately 9 metres) sediments consist of coarse sand with elements of sand and shells. In the first 2 kilometres following Iron Gates 2, the river bed consists of angular or sub-angular elements of medium and coarse gravel, similar to those downstream Iron Gates 1. Between km 862 and 804 sediments consist of coarse sand with elements of medium and fine gravel, whose participation percentage decreases downstream. In the interval between km 804 and 167 (Brăila) sediments consist of medium sand and fine gravel dimensionally situated at the borderline between sand and gravel. Sediments consisting of coarse sand turn towards the banks into finer sediments consisting of fine sand, clayey sand or silt. Between km 167 and Mile 44 (the entry into the Danube Delta territory) sediments mainly consist of fine or medium sand in the waterway which turn towards the banks into clayey-silty sediments.

In the Danube Delta sector sediments become increasingly fine having characteristics specific to each distributary. Thus on Chilia distributary sediments mainly consist of fine sand which becomes siltier towards the banks, but it must be mentioned that in the vicinity of the sea sediments consist of sandy silt or clayey silt down to maximum depth. On Tulcea distributary sediments mainly consist of coarse sand in the waterway and medium sand or silt towards the banks. On Sf. Gheorghe distributary bottom sediments are coarser than those on Chilia branch, mainly consisting of coarse sand at the maximum depth, which turns into fine sand or silt towards the banks. Along the Sulina channel the river bed is mostly characterised by sediments consisting of fine sand and silt (only black silt at Km 72) and in the areas where the water current is strong sediments can be absent (in the river bed at Mile 33.5 compact hard clays appear).

3. FEATURES OF SEDIMENT GRAIN SIZE WITH DYNAMIC SIGNIFICANCE

3.1. The nature of grain size distribution

An initial step in reconstituting the environmental conditions in which fluvial sediments are transported and deposited and to study their genesis is the examination of grain size distributions. Each sediment sample is characterised by its own grain size distribution, which can be gathered by analysing the frequency and cumulative curves and by calculating and analysing textural parameters.

In the interpretation of grain size distributions we have accepted the classical sedimentology concept according to which cumulative curves consist of several line segments, each segment symbolising categories of particles (populations) (Visher, 1969) moved by different means of transport. In the fluvial domain, the most typical cumulative curves are those consisting of three line segments, with the middle segment representing particles transported by salting, the lower segment representing particles transported by traction (sliding or rolling) and the upper segment representing fine particles transported by means of suspension. The absence of some populations from the constitution of a grain size distribution have hydrodynamic implications. Thus, the absence of very fine particles from the composition of fluvial sediments indicates energetic sedimentation conditions which prevented these particles from depositing.

In the case of Danube alluvia this model of the materialisation of the various means of transport through line segments must be used as a set of guidelines rather than for a clear distinction between the sizes of particles transported through traction, salting or suspension. Particles of similar sizes can be carried through various means of transport, due to the variation in the course of limited time intervals of the parameters of turbulent flow, a very likely phenomenon in the fluvial domain. The analysis of a large number of cumulative curves representing various types of sediments along the Danube confirms the existence of line segments which stand for categories of particles (populations) transported through traction, salting or suspension. Sediments collected from various points along the Danube which can have different textural compositions display curves consisting of 1, 2 or 3 segments.

Sandy sediments from the waterway are very frequently characterised by curves consisting of only one segment (Fig. 1). In this case the existence of a single segment and the curve inclination which is usually higher than in the case of other Danube sediments suggest the existence of a single means of transport (usually transport through salting) and the removal of finer particles. In a large number of cases the main segment of the curve displays an inflexion or a very short segment, indicating the presence of particles transported through traction (Anastasiu, Jipa, 1983). In the case of sediments which contain coarser grains the cumulative curves consist of two line segments (Fig. 2), suggesting the existence of the two means of transport (traction and salting). The cumulative curves of sediments deposited upstream lake barrages usually consist of a single segment, which suggests deposits from suspensions (Fig. 3). Curves consisting of three line segments (Fig. 4) specific to silty sand or sandy silt type sediments, very frequent on the Danube, suggest the existence in the same point of particles transported through traction, salting or suspension or the combination of sediment sequences deposited in different hydrodynamic conditions.

3.2. The textural parameters variation of sediments along the Danube course

The most significant of the textural parameters used to interpret the grain size of Danube sediments are the median diameter, standard deviation and skewness.

Mean grain diameter in Φ units

Mean grain diameter, the most widely used distribution parameter, is regarded by most authors (Folk, Ward, 1957; Passega, 1964) as an indicator of the average energy of the transport and as sedimentation agent. Taking into account the fact that most sediments consist of particles of various sizes, mean diameter represents the easiest way to provide a granulometric characterisation of a sediment through a single value. In interpreting the results of grain size analyses of Danube sediments we mainly used the median diameter Md which is one of the parameters on which the Passega diagram is based, one of the reasons being the absence of significant differences between the median and the graphical mean.

Standard deviation (Sorting) (Folk &Ward, 1957)

Hydraulic sorting is done through the selective sedimentation of the material, which is in movement. As a result of a reduced current competence, fractions which are coarser or have a higher specific weight are deposited, and the material which is transported further has an improved dimensional sorting. Grain sorting is also influenced by the morphological characteristics; particles with similar shapes accumulate together, being moved through the same means of transport (rolling, traction). At the level of cumulative curves the high inclination of some segments can indicate a good sorting of particles belonging to a population, and almost horizontal segments a poor sorting.

Skewness (Folk &Ward, 1957)

The usually positive skewness of fluvial deposits results from suspension material overlapping the sediment transported on the bottom through traction and salting, due to the reduced turbulence of fluvial current. The phenomenon is very obvious on the Danube in barrage lakes, as well as in other areas with reduced current velocity.

The variation of the mean grain diameter of particles along the Danube course

The reduction of the mean grain diameter of bed load particles according to the transport distance, a widely used concept in sedimentology (Parker, 1991; Paola, Parker, Seal, Wilcock, 1992; Pizzuto, 1995; Gasparini, Tucker, Bras, 1999 etc.) is to a certain extent also valid along the course of the Danube.

The mean diameter of particles in the first part of the sector under study, that is km 1072 Baziaş - km 1049 Moldova Veche, is higher than the mean diameter of the particles in the last part, that is the Danube Delta, but between these two extremes there are several oscillations which conceal the decreasing tendency. The most important disturbing factor of the definite decreasing tendency of particle diameter consists in the countless sources, mainly tributary rivers, which introduce into the system particles whose sizes frequently differ from those in the Danube's riverbed upstream the point of confluence. Moreover, the building of hydropower station barrages on the Danube segments the course under study, blocking the free circulation of particles and limiting the length of the routes along which one can study changes in sediment texture.

Variations in sorting degree and skewness values

In specialised literature (Parker, 1991; Pizzuto, 1995) fluvial deposits are regarded as poorly sorted deposits and their skewness is usually positive since the material is introduced through deposits of solid suspensions. The analyses of textural parameters values of Danube sediments reveals that in many sediment samples standard deviation values indicate a poor to very poor sorting, normal for a fluvial environment, and that skewness is slightly positive. There are however numerous standard deviation values which place them in the good (very rarely very good) to moderate sorting categories and skewness values that place them in the negative skewness to symmetry categories.

Analyses of standard deviation and skewness values along the course of the Danube reveal that the bottom sediments from the waterway have good and very good sorting

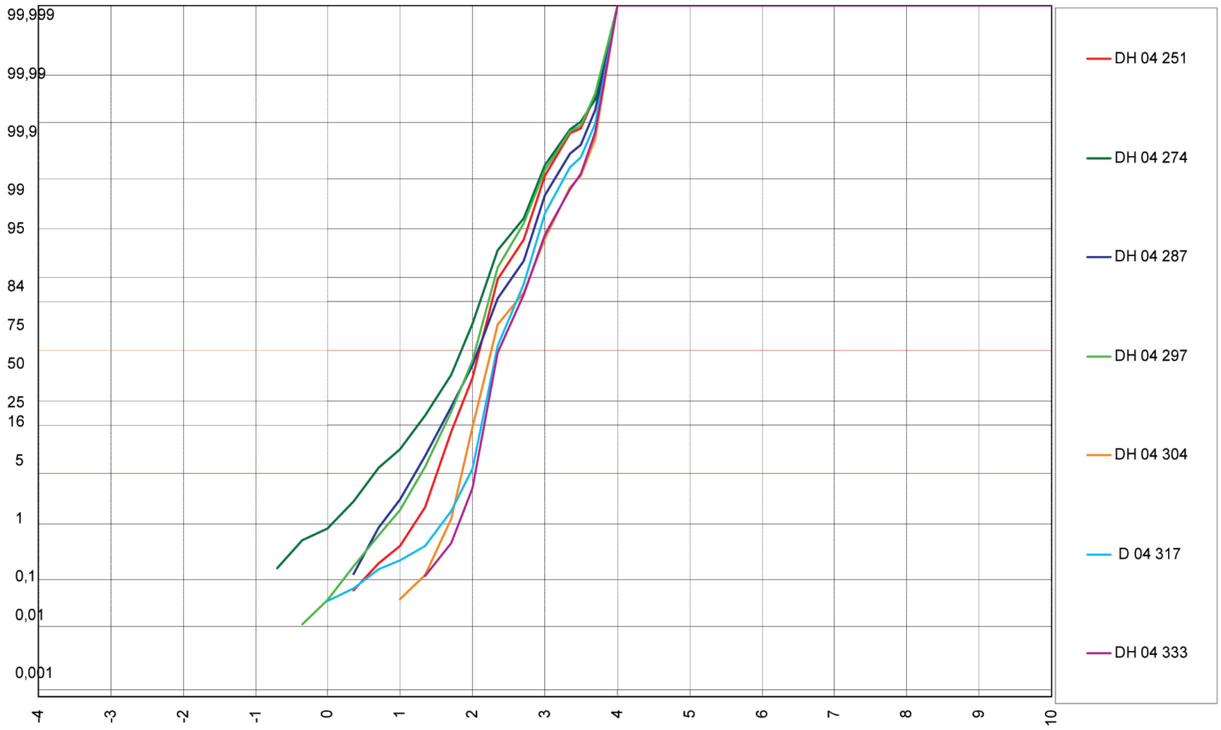

Fig.1 Cumulative curves of sorted sand consisting of only one segment

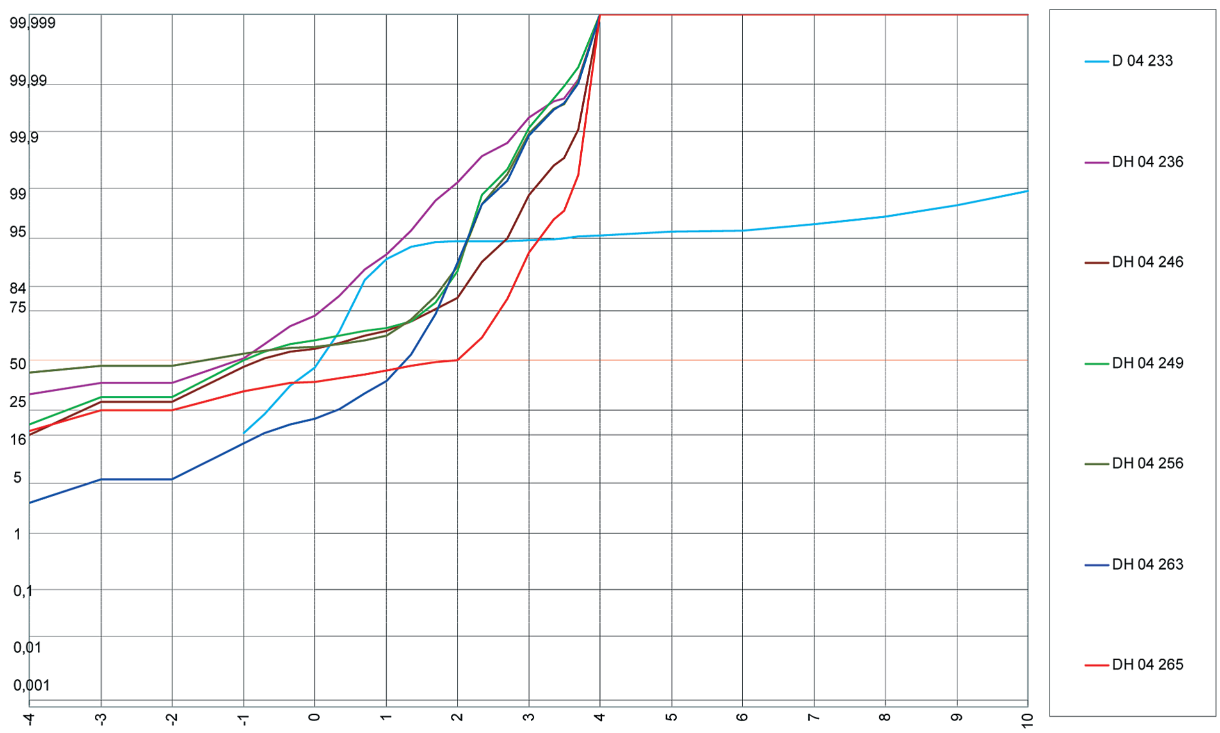

Fig. 2 Cumulative curves of coarse sands consisting of two segments

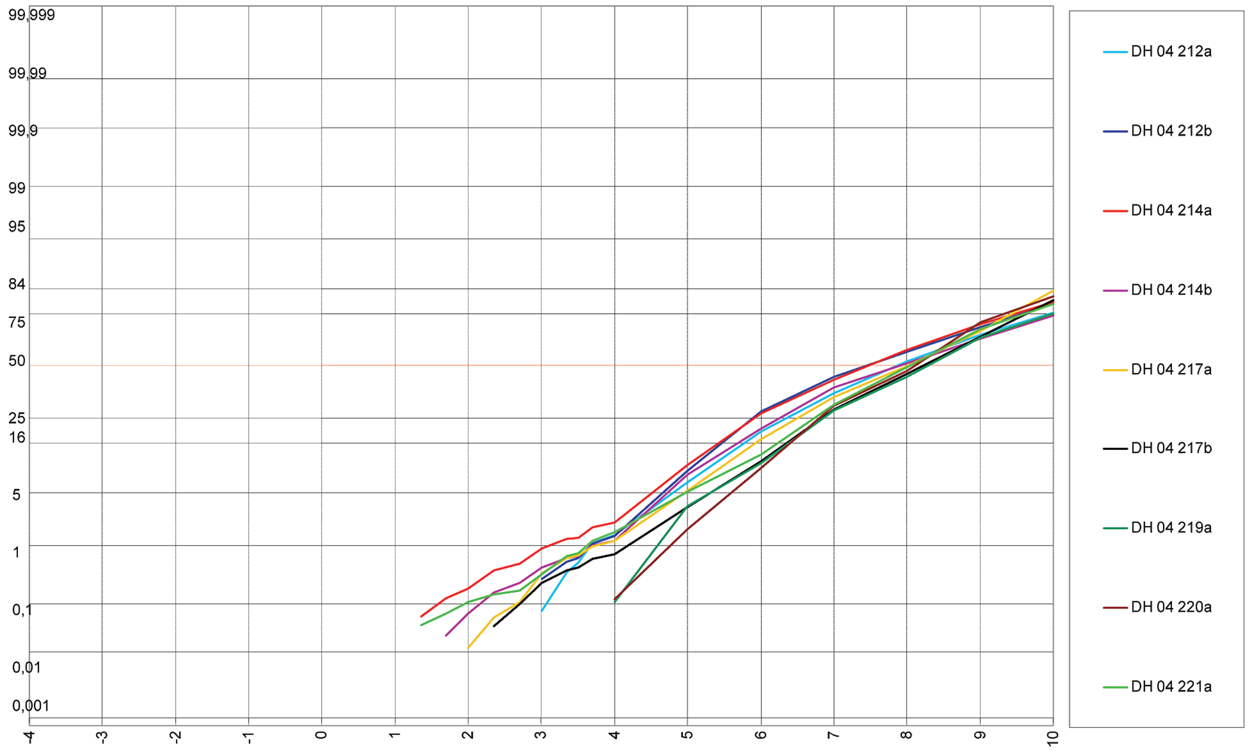

Fig. 3 Cumulative curves of fine sediments deposited upstream lake barrages

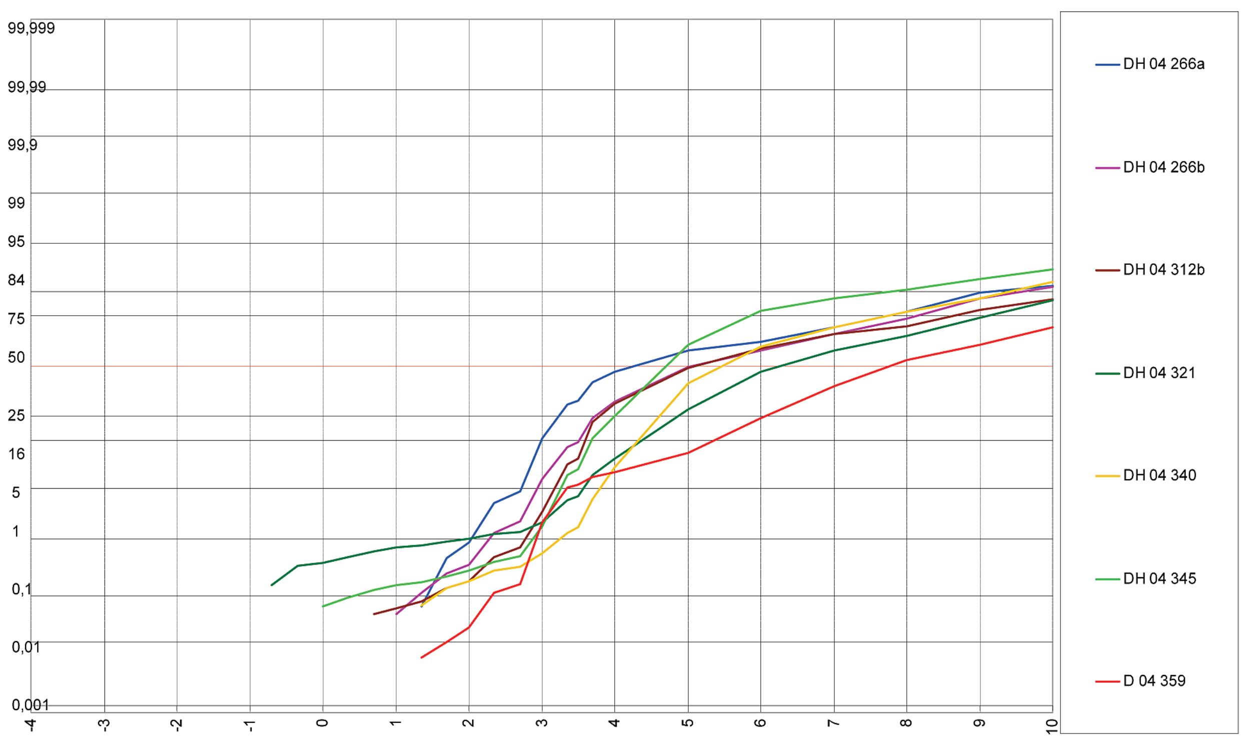

Fig. 4 Cumulative curves consisting of two or three segments specific to silty sand or sandy silt type sediments

(σ = 0,30 -0,45) between km 864 and km 0 and that skewness values are negative, being generally comprised in the interval –0.10 and –0.30, and less frequently outside this interval between km 864 and Mile 78. Starting from Mile 78 and continuing with the Danube Delta until it flows into the sea skewness values are usually positive. Along the entire course of the Danube with rare exceptions at smaller water depths sediment sorting decreases reaching values that situate them in the poor - very poor sorting domains, and their skewness is positive or very positive. The distribution of standard deviation and skewness values differs from km 1072 to km 845 but especially in the gorge and along the Danube course it is influenced, in one way or another, by Iron Gates 1 and Iron Gates 2 barrages, as compared to the distribution of values along the free course.

Starting from km 1072 at the entrance of the Danube on Romanian territory, until km 1049 - Moldova Veche, sediment sorting is very poor (σ = 3,07-3,12) at maximum water depths, where the sediments consist of sand, gravel elements and lower percentages of silt and clay. In the vicinity of the banks standard deviation has lower values due to the disappearance of gravel elements, but sorting still remains in the "very poor" domain. In the Danube gorge, where the riverbed consists of medium and coarse gravel elements, the sorting is good. In the Iron Gates 1 barrage lake sector the sorting is from poor to very poor (1.75-2.49), with the smaller values appearing in the vicinity of the barrage. In the Iron Gates 2 barrage lake sediment sorting is better than in Iron Gates 1 barrage lake, with values ranging from 1.13 – 1.18, situated in the poor sorting domain, as sediments mainly consist of sand. Sediments in the vicinity of the banks in Iron Gates 2 barrage lake are more poorly sorted than those in the waterway, due to the higher percentage of finer particles in their composition.

3.3. The Passega Diagram

The easiest way to determine the environmental conditions in which a sediment was deposited is to use the CM Diagram or the Passega diagram based on the 1% percentage and on the 50% percentage or the Median (Md), regarded by numerous authors as useful in the hydrodynamic interpretation of grain size data. The Passega diagram (Fig. 5) features several fields (pelagic suspension-T, uniform suspension-SR, gradual suspension-RQ, suspension and rolling-QP, rolling and suspension-PO, rolling-ON) corresponding to the various transport and sedimentation conditions in the marine, littoral or fluvial domains.

Although the latest theories of sediment transport no longer accept the absolute validity of the phenomenon of particle deposit according to the decrease in current competency, in the case of Danube alluvia most samples rigorously respect the fields in the Passega diagram (Fig. 5). The angle between the fields in which Danube sediment samples projections are grouped and the C=Md line have comparable values to the standard diagram. Thus the majority of samples collected in the Iron Gates 1 barrage lake are projected in the T field (named pelagic suspensions by Passega) and secondarily in the SR (uniform suspension) field, samples collected from the rest of the course, in the vicinity of the banks, usually continue to be projected in the SR, RQ (uniform suspension and gradual suspension) fields, and the coarser samples collected from the waterway are projected in the last three fields RQ, QP and PO (gradual suspension, suspension and rolling, rolling and suspension). Samples from Iron Gates 2 barrage lake, being poorer in material deposited in suspension as compared to Iron Gates 2, and richer in coarser particles, can be confused with samples collected from the free course of the Danube.

When projecting on the Passega diagram the samples corresponding to the maximum depth locations of each profile along the free course (Fig. 6), excluding those from the barrage lakes, it can be noted that samples collected from the Danube Delta distributaries are arranged in a group in the S-R fields (gradual suspension) and the samples from the greatest part of the Danube course follow in the next fields, being more concentrated in the vertical Q-P field (rolling and suspension).

The dynamic interpretation of the Passega diagram for sediments from the Danube's solid discharge, although unable to clearly separate transport and sedimentation domains, can provide informations concerning the predominance of one of the means of transport and sedimentation (that is bottom transport in the vicinity of the bottom or in suspension) in the case of each sample. Thus in the case of sediments deposited in reservoirs, especially in Iron Gates 1, exclusive deposit from solid suspensions has been clearly proved. In the case of Danube course sediments from the waterway where current velocity, including the velocity of solid particles, is maximum, there is the suggestion of transport through rolling, which is more intense in locations projected on the upper side of the diagram. Between the extreme fields, where suspension deposit and transport through rolling predominate, there are projections of sediments for which both processes are valid, what differs being the relations between these processes.

4. INTERPRETATION OF DYNAMIC PROCESSES OF SEDIMENT TEXTURAL FEATURES

In interpreting the significance of the grain size composition of sediments from various Danube sectors use has been made of the Passega diagram, as well as of all the data obtained from macroscopic description and the results of interpretation of grain size analyses, including textural parameters and cumulative curves. We have also taken into account any kind of information concerning the availability of certain soils or rocks to provide alluvial material, data concerning the biotic processes that can influence sediment grain size and, not least, data concerning anthropic influences on the texture of sediments.

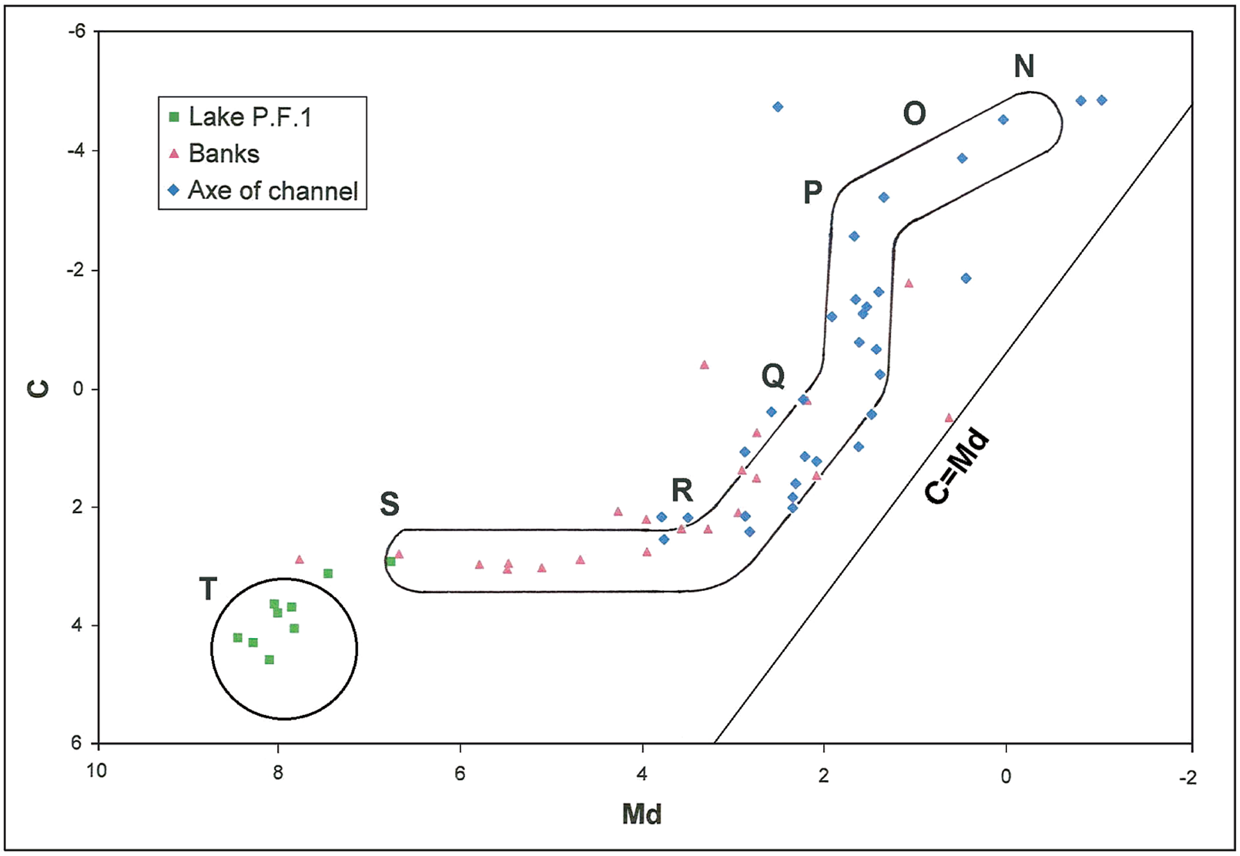

Fig. 5 The Passega diagram for all samples

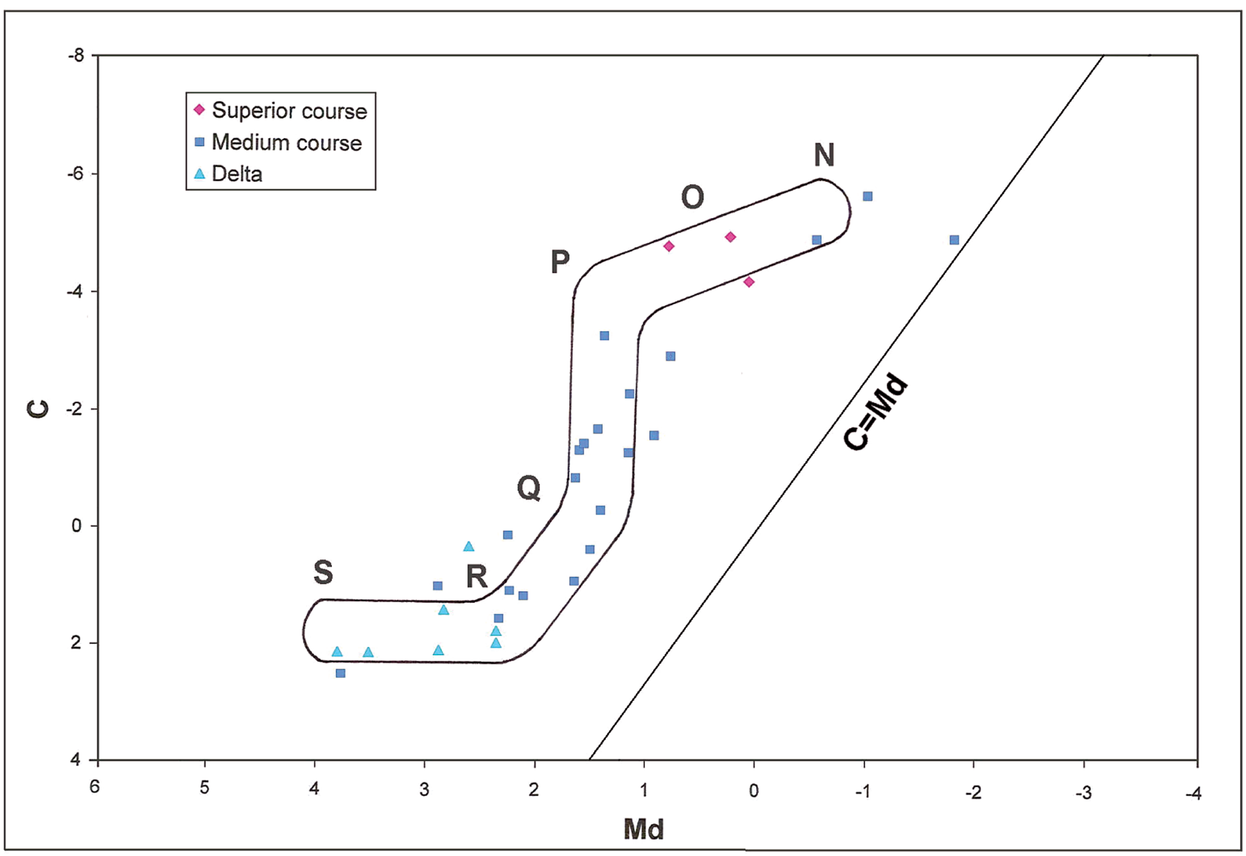

Fig.6 The Passega diagram for the samples selected from the maximum depth locations of each profile along the free course of the Danube

The presence of gravels in sediments at the entrance of River Danube into Romanian territory is thus due to the availability of these components in the sources feeding the solid discharge. Rounded gravel elements indicate a lengthy processing. The relative high frequency of shell detritus in sediments is due to the abundance of bivalves in this sector. The high percentages of gravel elements in the composition of sediments determine the negative skewness. On the other hand the presence of gravel elements next to sand, silt and clay particles are the cause of very poor sorting.

Grain size distribution curves are usually complete (consisting of three segments) in this case, indicating the presence of particles transported by all possible means (traction, salting or suspension). The enrichment in the sand fraction of sediments downstream Moldova Veche is determined by the discharge of material resulted from grinding certain rocks in the mining industry (Oaie *et al*. 2005). The introduction of certain amounts of sand in the Danube bed is also proved by the increased sorting degree of sediments and the reduction in skewness values.

The angular character and large sizes of gravel elements in the Danube gorge are clear indication of the very reduced source distance. The greatest part of these elements (many of which can only be moved for very short distances by the current) derive from the disintegration of geological basement. The sizes of these gravel elements do not vary according to depth, confirming the very near source and the fact that they are static or move very little.

The absence or reduced percentage of finer fractions is due to the lack of other sources apart from those already mentioned as well as to the high current velocity in the gorge, which easily removes finer particles. The only fine particles of sand dimensions are formed through solid rocks and shell abrasion. The appearance of finer silt particles, starting from km 999, is due to changes in hydrodynamic conditions with the widening of the bed, the reduced current velocity and gradual passage to a *sensu stricto* lacustrine sedimentation environment respectively. In these conditions few fine sand and coarse sand particles are deposited, and finer silt particles start to deposit with the decreased current velocity.

Deposit skewness passes from the negative to the positive domain due to the predominance of fine particles, but does not greatly exceed 0 value. Sorting is poor due to the increasingly reduced presence of coarser particles and the depositing of fine particles.

In the vicinity of Iron Gates 1 barrage fine sediments predominate due to the depositing of clayey-silty particles from suspensions following the formation of aggregates (through flocculency) as well as the release of biotic activity products. Sediment skewness is positive, due to the elimination of the greatest part of coarse particles and the poor sorting degree is determined by the depositing of particles of various sizes, including very fine ones due to the formation of aggregates. Significant percentages of the fine material in clayey-silty sediments are the result of the biotic activity of certain organisms.

The similar hydrodynamic conditions (reduced current velocity) in all points of the riverbed section are the cause of the almost identical grain size of sediments from the waterway compared to those towards the banks. Coarse gravel elements downstream Iron Gates 1 barrage, whose diameter is much higher compared to the maximum size that can be driven by the waters, move on very short distances suggesting source vicinity. It is highly likely that these elements result from materials used in the construction of barrages or the consolidation of the riverbed in the immediate vicinity of the barrage, this idea being also confirmed by their subangular character, which explains the lack of processing through transport. The presence of large size elements in the immediate vicinity of barrages is due to the removal of fine material through erosion in high environment energy conditions rather than to fluvial transport.

The transport and depositing of sediments in the Iron Gates 2 barrage lake differ from Iron Gates 1 due to the particular aspects of sediment circulation and especially the reduction of solid debit. Iron Gates 1 barrage blocks the free circulation of the sediments moved on the bottom as well as of a large part of the solid suspensions deposited in Iron Gates 2 lake. The coarser sediments circulating in the sector Iron Gates 1 – Iron Gates 2 come from tributaries or from riverbed erosion in this sector. For this reason sediments from Iron Gates 2 barrage lake are much poorer in the clayey-silty fraction and much richer in gravels. The grain size features (textural parameters included) of the deposits upstream Iron Gates 2 are not typical of deposits deposited in lacustrine but rather in fluvial conditions. Thus the deposits consisting of sand from the waterway and silt from the banks 15 km upstream Iron Gates 2 do not differ considerably from the deposits along the free course of the Danube. Downstream Iron Gates 2 the presence of angular gravel elements of extreme sizes suggests the existence of hydrodynamic conditions comparable to those from downstream Iron Gates 1 barrage.

The deficit of typically fluvial sediments materialised in the excessive presence of coarse gravel elements is maintained between Iron Gates 2 and Timok River (km 845) which has a more significant solid discharge. Starting from downstream Timok River and until the discharge of Danube distributaries into the sea, the existence in the waterway of sand sediments, turning towards the banks into predominantly silty sediments, suggests the lack of essential changes in the sediment transport and depositing process. The deficit of typically fluvial sediments is to a small extent compensated by the Danube tributaries which introduce into the system sedimentary material in the shape of bed-load or suspensions.

The bioclastes in the sediment mass are very frequently produced by a mollusc fauna which, although limited in number of species, is abundant in terms of individuals.

The presence of coarse gravel elements together with the lack of finer particles in the same areas are an indicator or the high environment energy as well as of their availability. The deficit of coarse sediments which usually form the riverbed is proved by the existence of hard and compact greyish-green clays, especially in several points in the waterway (Mile 43, Mile 33 etc.). The presence of clay basement in this area is determined by the high environment energy which removes present coarse sediments and erodes the riverbed. The obviously higher percentages of silts and clays in the sediments, near the place where the Danube flows into the sea, can be interpreted as an effect of the change in the hydrodynamic conditions of the fluvial environment (reduced current velocity) at the borderline with the littoral marine environment. The increased percentage of fine material in profiles in the vicinity of the sea is due on the one hand to a decrease in current velocity but also to the deposition of fine particles due to changes in the physico-chemical water parameters stimulating the formation of particle aggregates. The excess of fine material in the composition of sediments determines in this case the "very positive" skewness values.

CONCLUSIONS

The grain size of Danube River sediments varies according to geomorphologic and hydrodynamic conditions and to the availability of materials that can constitute sediment sources.

Sediments with specific textural characteristics are transported and deposited in each sector with distinct geomorphologic, geodynamic and hydrologic features. Thus, in the areas with high environment energy, as Danube gorge, downstream barrages or in other sectors with a narrow riverbed, at considerable water depths where current velocity is high, there usually are boulder or gravel elements. The frequency of large size coarse and very coarse gravel elements depends on the availability of geological basement which is the main source, being higher in the vicinity of mountains, and on the high energy of the environment which tends to eliminate the other particles from the system.

Areas with reduced environment energy (upstream barrages) are characterised by fine clayey-silty sediments. Between Iron Gates 2 Barrage and the Danube distributaries' river-mouths into the sea downstream Iron Gates 2 Barrage, the typical fluvial model with coarser sediments in the waterway and finer sediments towards the banks characterises most profiles. Tributary rivers with less important discharges influence the grain size of sediments in the Danube river bed. Sorting and skewness values depend on environment energy. Thus, sediments deposited along the Danube in points with high environment energy have a better sorting and negative skewness whereas the sediments deposited in points with low environment energy have poorer sorting and positive skewness.

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