HEAVY MINERAL ABUNDANCES IN THE LOWER DANUBE TRIBUTARIES

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Abstract. The sediments brought by several left tributaries of the Lower Danube, such as Cerna, Topolnița, Jiu, Olt, Argeș, Ialomița and Siret were sampled close to their confluence. An overview of the rock provenance is presented, taking into account the identified mineralogical feature based on the mineralogical observations, two heavy mineral associations were identified, having, in general, a clearly provenance signature from lower to medium grade metamorphic units. Other sources of the sampled sediments are represented by the igneous bodies, high grade metamorphics, as well the sedimentary rocks of the external nappes from the Carpathian belt. Besides, the Carpathian surrounding platforms, such as Moesian and Moldavian ones, contribute to the sedimentary input of Danube River. Additional to the mineralogical data, geochemical analysis show a medium maturity grade of the sampled sediments.

Key words: Heavy mineral associations, Romanian Danube tributaries, provenance.

1. INTRODUCTION

Connecting the Western Europe and the Black Sea, the Danube River is known as a key waterway in Europe. Consequently, the Danube has a great significance for both EU member states official and private sectors, for maintaining it as a safe fluvial pass between the western and eastern parts of the Europe. Because the Danube is the second largest river in Europe, there is a continuous awareness regarding its ecological state.

Having a total length of 2,826 km, the main course of the Danube River was divided into three segments: (i) the Upper Danube, defined by a typical river course, from the confluence of Brigach and Breg rivers up to the Austrian border; (ii) the Middle Danube, which the beginning is marked by the Devin Gate, located at the Austrian - Slovakian border up to the Iron Gate I, having a wider riverbed and (iii) the Lower Danube, located between the Iron Gate I and Sulina Town, at the Black Sea shore. This classification is made based on the basin geomorphologic features. With a surface of 240,000 km^2, the Lower Danube basin covers several important tributaries of this river, most of them situated on the Romanian territory. The tributaries are discharging an important volume of terrigenous material from the Carpathians belt.

Since the industrializing period, the whole Danube River channel, including the Lower one, was modified for the navigation. On the Danube course, many hydro-electrical plants were built. In this way, a high percentage of sediments were distributed in the river channel instead discharging into the Black Sea basin.

The distribution of the Danube sediments plays an important role for a safe navigation system. Therefore, any change raises issues of the environmental state along the river, especially downstream the Iron Gates dams, located at the beginning of the Romanian Lower Danube. After the construction of the Iron Gates and other several smaller dams on the Danube tributaries (e.g. Jiu and Olt rivers), the discharged sediment decreased by more than 50% (Panin, 1996) comparing with the seven decade of the 20th Century. The new lakes became traps for the sediments.

This paper presents the results of our researches carried out on the provenance of sediments identified in several Danube confluences with left tributaries Romanian rivers.

The results of various analyses, such as mineralogical, granulometric and X-ray fluorescence spectrometry are interpreted herein.

2. MATERIALS AND METHODS

To identify features of the discharged material in the Danube River, several major left tributaries (approx. 0.5 km upstream for each river), close to their confluence with the Danube River (Fig. 1), have been sampled. The targeted rivers are, from West to East: Cerna, Topolnița, Jiu, Olt, Argeș, Ialomița and Siret; another location, situated in the Danube channel, near the Isaccea town, was sampled for an overview of the total Danube sedimentary input.

For the provenance determination, one of the most widely-used techniques represents the heavy mineral (HM) analysis, with the consideration of HM associations that allows the reconstruction of a source to sink path of the sediments, due to their chemical and physical high resistance. Moreover, many HM have specific association and therefore they offer information regarding the source area and lithological features of various rocks. Additionally, the grain morphology is an important indicator of the distance from the source area, providing supplementary information for estimating the minerals provenance area.

Sediment sampling was done using a Van Veen bodengreiffer from the middle part of the Danube River channel and its tributaries. Sample analysis preparation consisted in drying the sediment, sieving for the 0.063 - 1mm fraction extraction, treated with HCl (approx. 15%) for organic matter and carbonate digestion and, finally, a gravitational separation in glass separating funnels, using a heavy liquid, sodium polytungstate ($Na_6(H_2W_{12}O_{40})$ * H_2O^x), with 2,82 g/ cm^3 density.

Quantitative analysis was performed by identifying over 1000 HM grains from each sample and observing the grain morphology, using stereomicroscope (Olympus SZ61). Additionally, a magnetic separation was employed (Franz Magnetic Separator L1), allowing a better mineralogical separation, due to the magnetic properties of the minerals. These analyses were performed in the laboratories of the National Institute of Marine Geology and Geo-ecology. Supplementary analyses have been made in the laboratory of the Faculty of Geology and Geophysics, Dept. of Mineralogy (University of Bucharest), by using a Zeiss microscope for volumetric estimations of each mineralogical species (Plate). The procedure of the mineralogical observation also includes the identification of phyllosilicate crystals as biotite (Cascalho & Fradique, 2007; Wang *et al.*, 2019) and chlorite (Dill & Skoda, 2019).

Geochemical investigation was performed in order to obtain strontium (Sr) and rubidium (Rb) concentrations. The analyses were achieved by using X-ray fluorescence spectrometer (XRF). Having the values for Sr and Rb elements, the Sr/Rb ratio was calculated. This ratio is generally used for indicating the relative maturity of the sediments (Plimer & Elliott, 1979).

It is certainly that since their entrance in the sedimentary system, every heavy mineral grain is affected by different altering processes, along with selective sorting factors (e.g. hydraulic sorting and selective accumulation of grains). Due to the natural factors that occur in fluvial environments, in many cases the provenance information given by the heavy mineral grains may affect an accurate interpretation (Morton, 1985). Therefore, the user must consider the inaccuracy of data as a natural deviation for inexact grain morphology or heavy mineral percentages.

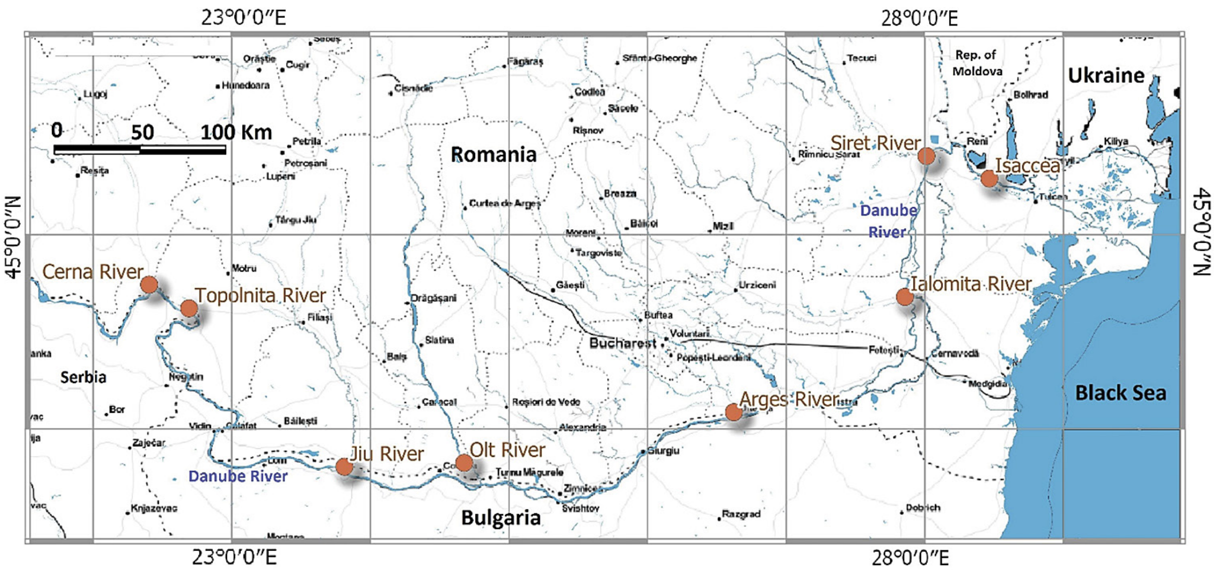

Fig. 1. The Lower Danube course and the location of the studied samples (from https://www.openstreetmap.org)

3. GEOLOGICAL SETTING OF THE DANUBE RIVER MAJOR ROMANIAN TRIBUTARIES BASINS

On the Romanian territory, several left tributaries of the Lower Danube drain the regions of the Apuseni Mountains, Eastern and Southern Carpathians (Fig. 2). Consequently, a high amount of terrigenous material discharges, generally from North to South, into the Danube River. For describing the sediment generating rocks, we are presenting the geomorphological units, the Alpine and pre-Alpine geotectonics and the petrography.

The westernmost Romanian tributary is the Cerna River, which discharges into the Danube River sediments originated from Godeanu, Culmea Cernei, Mehedinti, Bahna and Almaj Massifs. In these areas the Danubian (Upper and Lower) and Getic domains, included in the Marginal Dacides and, respectively, the Median Dacides (Săndulescu, 1984), as well as the Severin Nappe of the Outer Dacides (Fig. 2) occur (Săndulescu, 1984, Berza *et al*., 1994, Iancu *et al.,* 2005a).

The lithology encountered by the Cerna River course is mainly represented by metamorphic-magmatic basement: granites of different ages, low-grade (different type of schists) and medium-grade metamorphic rocks, mainly represented by quartz-feldspars, eclogites, gneisses, amphibolites, marbles and micaschists (Săbău & Massonne, 2003; Iancu *et al*., 2005b; Balintoni *et al.,* 2011, Duchesne *et al.,* 2017).

Towards East, the Topolniţa River has a small basin (Fig. 2) that covers the Mehedinţi Massif, which consists of the Getic outliers and Lower Danubian tectonical units (Săndulescu, 1984; Iancu *et al.,* 1997). From the lithological point of view, the Topolniţa River crosses gneisses, amphibolites, metasedimentary rocks and quartzites, while a subordinate input is generated by high-pressure rocks, such as eclogites and garnet peridotites (Medaris *et al*., 2003, Săbău & Massonne, 2003).

The Jiu River has its spring in the Sebeş Massif, while its basin covers areas from the Parâng, Căpăţânii and Vâlcan Massives, traversing, also, a large part of the Romanian Plain towards its confluence. Its sedimentary input is generated by the Upper and Lower Danubian tectonic units represented by Mesozoic cover and Neoproterozoic basement of Drăgăşan and Lainici-Păiuş Groups and associated pre-alpine granites (Berza *et al*., 1994; Duchesne *et al.,* 2017), as well as the Getic basement (Iancu & Seghedi, 2017). The aforementioned authors indicate that, before entering the Tertiary sedimentary cover, the Jiu River discharges material from sandstones of the Mesozoic cover and Neoproterozoic gneisses, amphibolites, schists and granites. Towards south, the Olt River traverses the Moesian Platform including the Pleistocene to Quaternary deposits (Săndulescu, 1996).

One of the most important Romanian tributaries of the Danube River, the Olt River, has a significant discharge volume

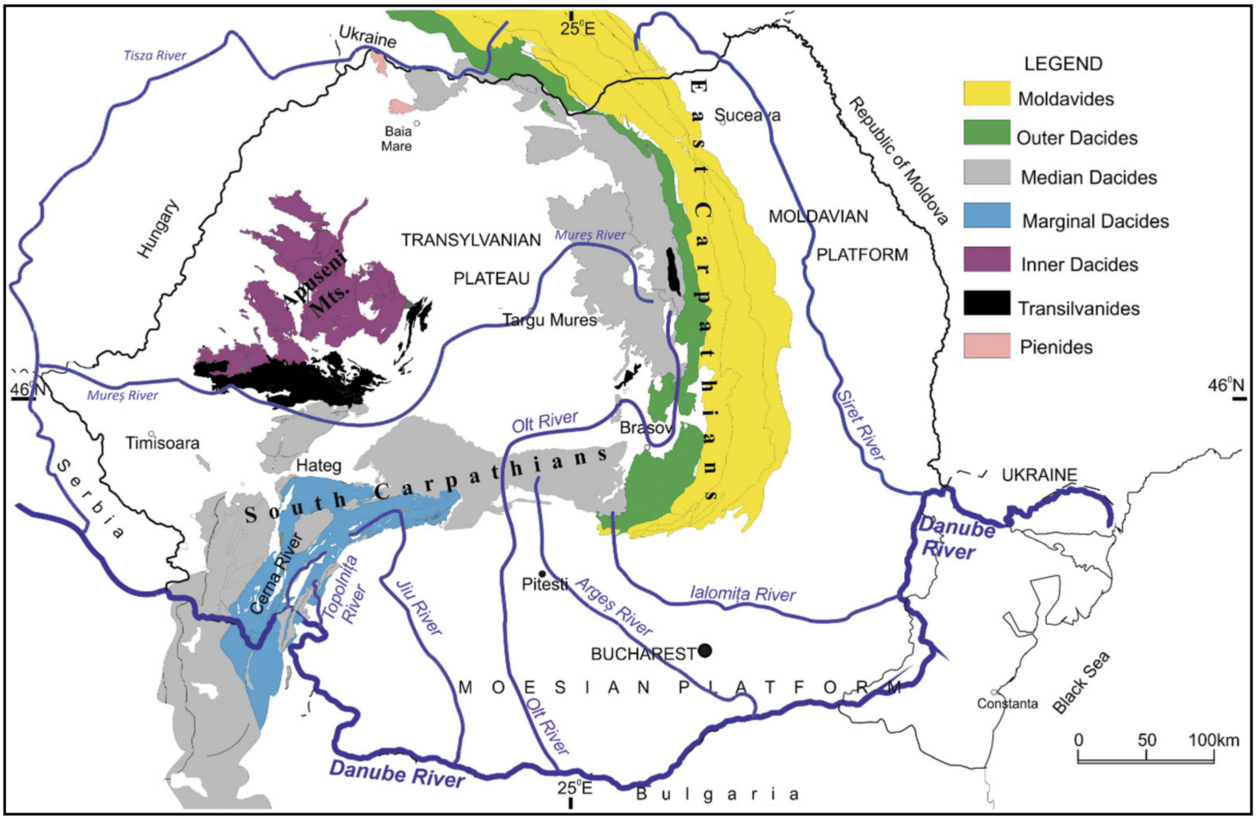

Fig. 2. Tectonic map of Romania (from Melinte-Dobrinescu et al., 2009 modified after Săndulescu, 1984; Bădescu, 2005) and the sampled Danube River left tributaries.

of sediments from both Eastern and Southern Carpathians. This river crosses the Harghita and Perşani massives in its upper course, and the northern Făgăraş, the Cibin, Lotru, Căpăţânii and Cozia massifs in its lower course, traversing also a large part of the Romanian Plain towards its confluence. This river crosses immediately south of its spring, located in the central Eastern Carpathians, several units, such as: the Supragetic and Bucovinian nappes of the Getic Domain, the Neogene Magmatic arc and some nappes belonging to the Outer Dacides, such as Baraolt and Ceahlău (Săndulescu, 1984; Balintoni & Balica, 2013). The crossed vulcanoclastic and sedimentary rocks are located in the Harghita and Perşani Massives, while the Supragetic metamorphic units are encountered in the north Făgăraş Massif. The Getic nappe basement and its mainly Cretaceous to Paleogene post-tectonic cover occur in the Cibin, Lotru, Căpăţânii and Cozia massives (Săndulescu, 1984; Iancu *et al.,* 1997 and references there in). The basement lithology is represented by metamorphic rocks, such as gneisses, metagranites, micaschists, quartzites, marbles and amphibolites (Hann & Szasz, 1984; Gheuca, 1988; Hann & Balintoni, 1988; Iancu *et al.,* 1997; Medaris *et al.,* 2003; Seghedi *et al.,* 2005; Balintoni *et al.,* 2009). The Upper Cretaceous to Paleogene sediments of the Getic sedimentary post-tectonic cover traversed by the Olt River are represented mainly by conglomerates, massive sandstones, and thick marly and clayey successions (Ştefănescu *et al.,* 1982). Towards south, the Olt River traverses the Moesian Platform including the Pleistocene to Quaternary deposits (Săndulescu, 1996).

The Argeş River and its tributaries crosses the southern part of the Făgăraş Massif and a large part of the Romanian Plain towards its confluence with the Danube (Fig. 2). Concerning the traversed tectonic units, these are: the Median Dacides, represented by the Getic Domain, Supragetic nappes; several Variscan metamorphic units (Iancu et al., 2005b), such as Cumpăna, Holbav, Voineşti, Lereşti and Căluşu-Tămăşel series are encountered by the Argeş River. This river basin covers areas described by Săndulescu (1984) as being representative for the prehercinic medium-grade and hercinic lower-grade metamorphism. The rocks crossed by the Argeş River are represented by gneisses, greenschists and amphibolites (Iancu & Seghedi, 2017).

Next to the East, the Ialomiţa River basin drains areas from the Iezer and Leaota Massive. This river traverses the Median Dacides (Sandulescu, 1984), composed by Mesosoic sedimentary cover and a basement of gneissic rocks (Cumpana-Voinesti medium-high grade metamorphics), including the low-grade metamorphic (Lereşti and Caluşu) formations. The main source rocks of the sediments are different types of gneisses (garnet bearing micaschists and gneisses, metagranites, metagabbros, eclogites, amphibolites. Greenschists and albite-epidote-garnet bearing schists and quartz-chlorite mica schists (Dimitrescu, 1978; Gheuca & Dinica, 1986; Iancu *et al.,* 1997; Sabau & Negulescu, 2006). Isotopic ages on zircon crystals give Lower Paleozoic (Ordovician) to Middle Paleozoic (Upper Devonian-Carboniferous) ages of different basement protholiths (Balintoni *et al.,* 2009, Balintoni *et al.,* 2014). The isotopic ages on metamorphic rocks indicate Variscan and Carboniferous events (Medaris *et al.,* 2003, Iancu & Seghedi, 2017 and references). In this area, greenschists and amphibolites occur (Balintoni *et al.,* 2009), along with volcanoclastic rocks can be encountered in this area (Iancu *et al.,* 1997). South of the metamorphic rocks, the river penetrated the common post-tectonic cover of the Getic and Supragenetic tectonic units and Outer Dacides, i.e. the Ceahlău Nappe (Săndulescu *et al.,* 1981; Ştefănescu, 1995; Melinte & Jipa, 2009); afterwards, towards south, as the western rivers, such as Argeş, Olt and Jiu, it crosses the Moesian Platform.

The easternmost sampled tributary of the Danube River, the Siret River, discharges into the Danube River high volumes of sediments generated from the Moldavide nappe system of the Eastern Carpathians, as well from the Moldavian and Scythian platforms (Săndulescu, 1984; Bădescu, 2005).

Several tributaries of the Siret River (i.e., Moldova and Bistriţa rivers) cross both the Marginal Dacides (Bucovinian and Sub-bucovinain nappes) and Outer Dacides and Moldavide nappe systems (Maţenco & Bertotti, 2000; Maţenco *et al.,* 2003). The crossed rocks are sedimentary successions, mainly turbidites, along with crystalline rocks, i.e., schists, quartzites and rhyolitic volcano-sedimentary association (Săndulescu, 1988; Săndulescu & Visarion, 1988; Balintoni *et al.,* 2014). Another tributary, the Trotuş River, brings also a significant input from the metamorphic and sedimentary units described above, as well from the granitoids of the Hăghimaş Syncline (Bancilă, 1958) located in the Bucovian units, as well as from the Outer Dacides and Moldavide nappes of the Eastern Carpathians (Săndulescu *et al.,* 1981; Dinu, 1985).

It is worth mentioning that the Tisza River, discharging into the Danube River on the Hungarian territory, collects a mixed input from its tributary, the Mureş River. Having its spring nearby the Olt River, the Mureş basin covers large areas from Eastern and Southern Carpathians, as well as the Apuseni Mountains. The river discharges indirectly into the Danube River an Eastern Carpathians input from low- to medium-grade metamorphic rocks and porphyroids from the Ordovician Rebra unit, along with the Triassic porphyroids from the Ditrău Masiff (Balintoni *et al.,* 2014). From the Southern Carpathians, the Mureş River collects, through its tributaries, inputs from the Sebeş-Lotru and Făgăraş Massives, where Getic tectonic units occur (Săndulescu, 1994). Crossing through the Apuseni Mountains, the Mureş River and its main tributary, the Arieş River, have an input from the Transylvanides Alpine ophiolites, the Baia de Arieş, Biharia metamorphic units, the Permian cover and igneous intrusions (Balintoni & Balica, 2012).

To summarize, the Danube River has a significant input from the Getic and Danubian domains belonging to the Median and Marginal Dacides, traversed by its course in the area located upstream the Iron Gates Dam. Thereby, a direct discharge is generated by the Caraş, Sebeş-Lotru, Tişoviţa and Lainici-Păiuş metamorphic units (Dumitrescu & Săndulescu 1968; Balintoni *et al.,* 2014). These are represented by alternating orthogneisses, amphibolites, micaschists, and mica-rich quartzites (Iancu *et al.,* 2005a and 2005b). In this area, other igneous units are represented by granites and granitoides (Balintoni *et al.,* 2014). An important discharge in the central Southern Carpathians is brought from the Marginal Dacides, and less from the Outer Dacides and the Neogene magmatic arc. To the East, the Danube River course flows through the Moesian Platform, from which drain an important volume of allochthonous sediments (Oaie *et al.,* 2005), including rocks from the outer structures of the Eastern Carpathians, i.e. the Outer Dacides, the Inner and Outer Moldavides (*sensu* Săndulescu, 1984). Before discharging into the Black Sea, the Danube River encounters the North Dobrogea Orogen with a pre-Triassic basement and mainly Upper Cretaceous sediments (Seghedi & Oaie, 1995; Seghedi, 2012).

4. RESULTS AND DISCUSSIONS

4.1. Mineralogical data of the Lower Danube major tributaries

The light minerals average proportion for the studied samples is approx. 93.5% (Fig. 3), with a lowest concentration identified in the Danube River sample, near the Isaccea town (83.2%). The highest concentration samples in light minerals were found in the Olt and Jiu rivers (98.4 % and, respectively, 98.35 %). The most common low-density minerals identified are quartz, feldspar and phyllosilicates (mostly micas).

The carbonates, mostly represented by the shell fragments, along with the organic matter were identified with the highest proportions in the samples collected from the Ialomiţa and Siret rivers (10% and, respectively, 5,4%), Fig. 3. Showing an average abundance of 3.5% (Fig. 3), the heavy minerals concentration varies between 13% (near Isaccea town) and 1% (in the Jiu and Ialomiţa rivers). Overall, the heavy mineral abundances are identified with a considerably homogeneity. Heavy minerals with the highest average participation are garnets with 22.6%, green hornblende with 20.3%, opaque minerals (e.g. magnetite, hematite and chromite) with 15.3% and, epidote with 13.9% (Fig. 4).

The garnet abundance varies between 11.9% and 32.9% (Fig. 4). Being the most common heavy mineral that occurs in the Danube River sediments, the garnet grains show a variable morphology, from angular to rounded, but mostly a medium angularity (Table 1). This aspect possibly confirms a proximal source of this mineral, taking into account that usually it might be linked to metamorphic and magmatic source rocks (Mange & Maurier, 1992).

The green hornblende was found with a high abundance that varies from 7% to 30% (Fig. 4), while the sediments sampled from the Ialomiţa River (7%) contain the lowest observed value of this mineral. The identified grains reveal a diverse morphology (Table 1), mainly due to the various physical and chemical resistances, in generally low (Plate).

The epidote grains show high values (up to 26.8%), with two exceptions: the samples from the Ialomiţa and Siret rivers (6%) - Fig. 4. In general, the grain morphology was identified as angular to sub-angular (Table 1, Plate).

The opaque minerals, represented by grains of magnetite, hematite and chromite were observed in various concentrations (from 3.5 up to 20.9 %), with a minimum value in the Olt River (Fig. 4). The morphology of the opaque minerals varies from rounded (Jiu and Olt rivers) to angular, as observed in the Ialomiţa and Siret rivers (Table 1).

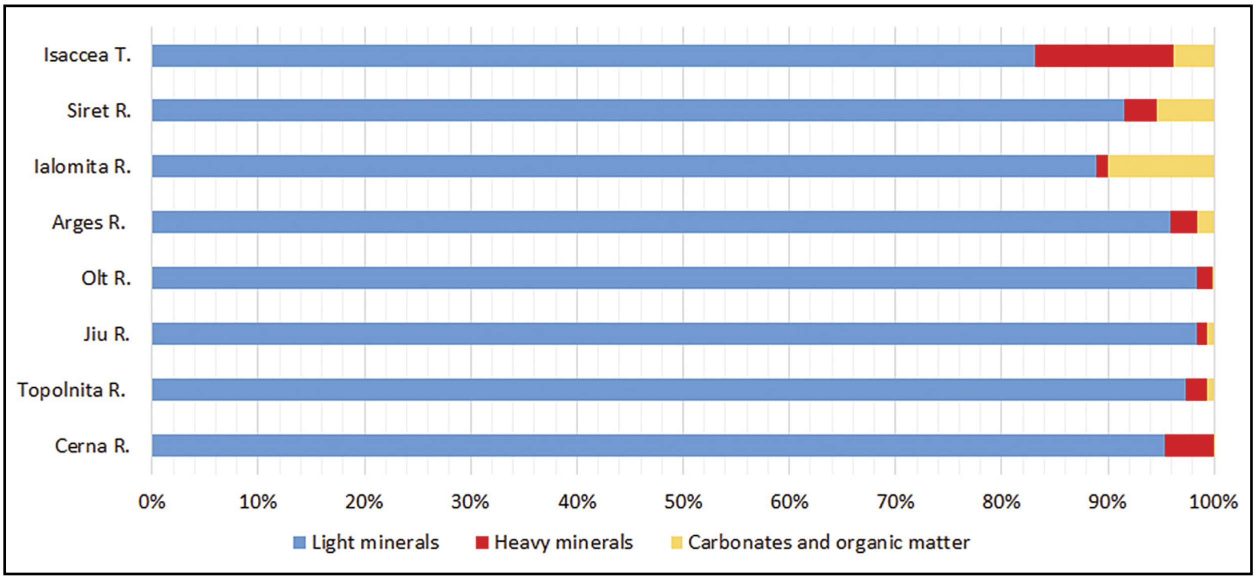

Fig. 3. Concentration of the light and heavy minerals and of the carbonates and organic matter.

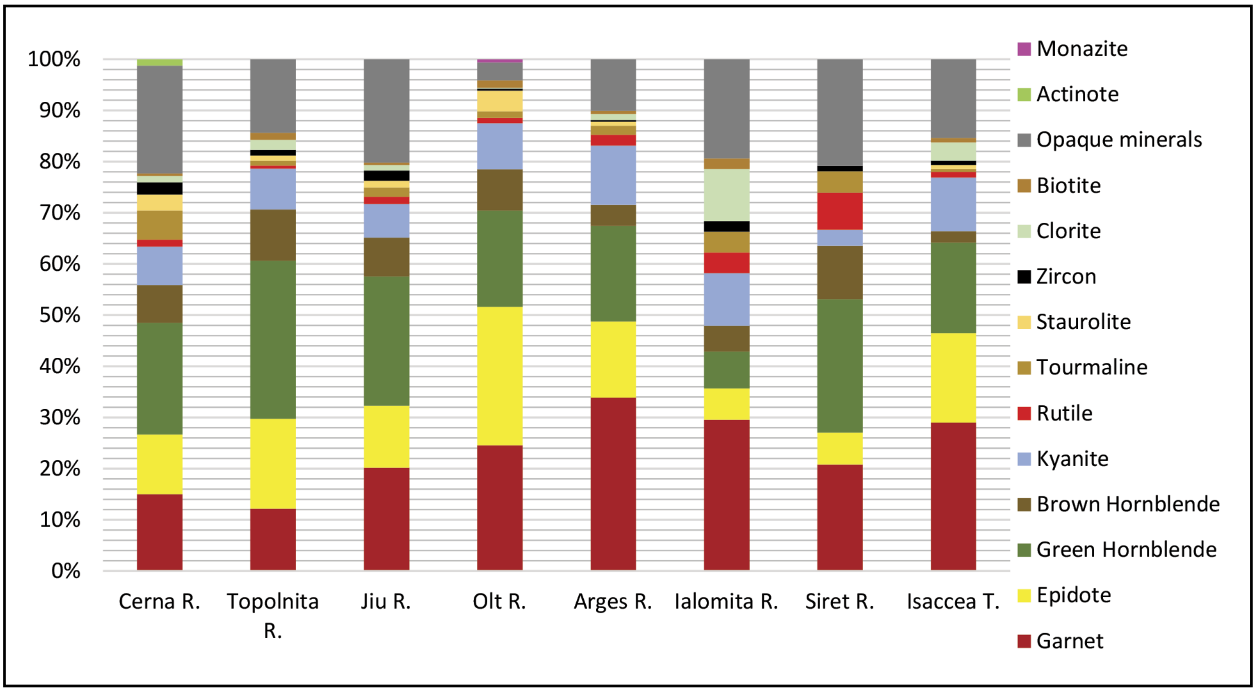

Fig. 4. Heavy mineral abundances of the sampled locations.

Table 1. The morphology of the identified heavy minerals from the sampled locations.

	Cerna	Topolniţa	Jiu	Olt	Arges	Ialomiţa	Siret	Isaccea
Garnet	SA-SR-R	SR-SA-R	A-SA-SR-R	A-SA-SR	A-SA-SR	A-SA-SR-R	SR-SA-R	SA-SR-R
Epidote	SR-R-SA	SA-A	A-SA-SR	A-SA-SR	A-SA	SA	SR-R-SA	SA-SR
Green Hornblende	A-SA	SA-SR-R-A	R-SR-SA	A-SA	SA-SR	SA-SR	SR-R-SA	SA-A-SR
Brown Hornblende	SA-SR	SR-SA	SA-SR	SR-SA	SA-SR	SR-SA	SA-SR	R-SR-SA-A
Kyanite	SA-SR	A-SA-SR	R-SR-SA	A-SA	A-SA-SR	A-SA-SR	SA-SR-A	SA-A-SR
Rutile	SR-SA	R-SR	SA-SR	SA-SR	A-SA	A-SA	SA-SR	SR-SA
Tourmaline	SA	A-SA	A-SA	SA	A-SA	A-SA	A-SA	SA-SR-A
Staurolite	SR-SA	SA- SR	SA-SR	SA-SR	SA-SR			SA-SR
Zircon	A	A	A-SA	SA-A	A-SA	SA-SR	SA	SA-A
Chlorite	SA-SR-R	SA-SR-R	R-SR-SA	SR-R-SA	SR-SA-R	SR-SA		SR-SA
Biotite	SA-SR	SA- SR	SA-SR	SA- SR-R	SA-SR	SA- SR		SR-R
Opaque minerals	A-SA-SR	SA-SR	SA-SR-R	SA-SR-R	A-SA	A-SA	A-SA-SR	SR-SA

A – angular; SA – sub-angular; SR – sub-rounded; R – rounded

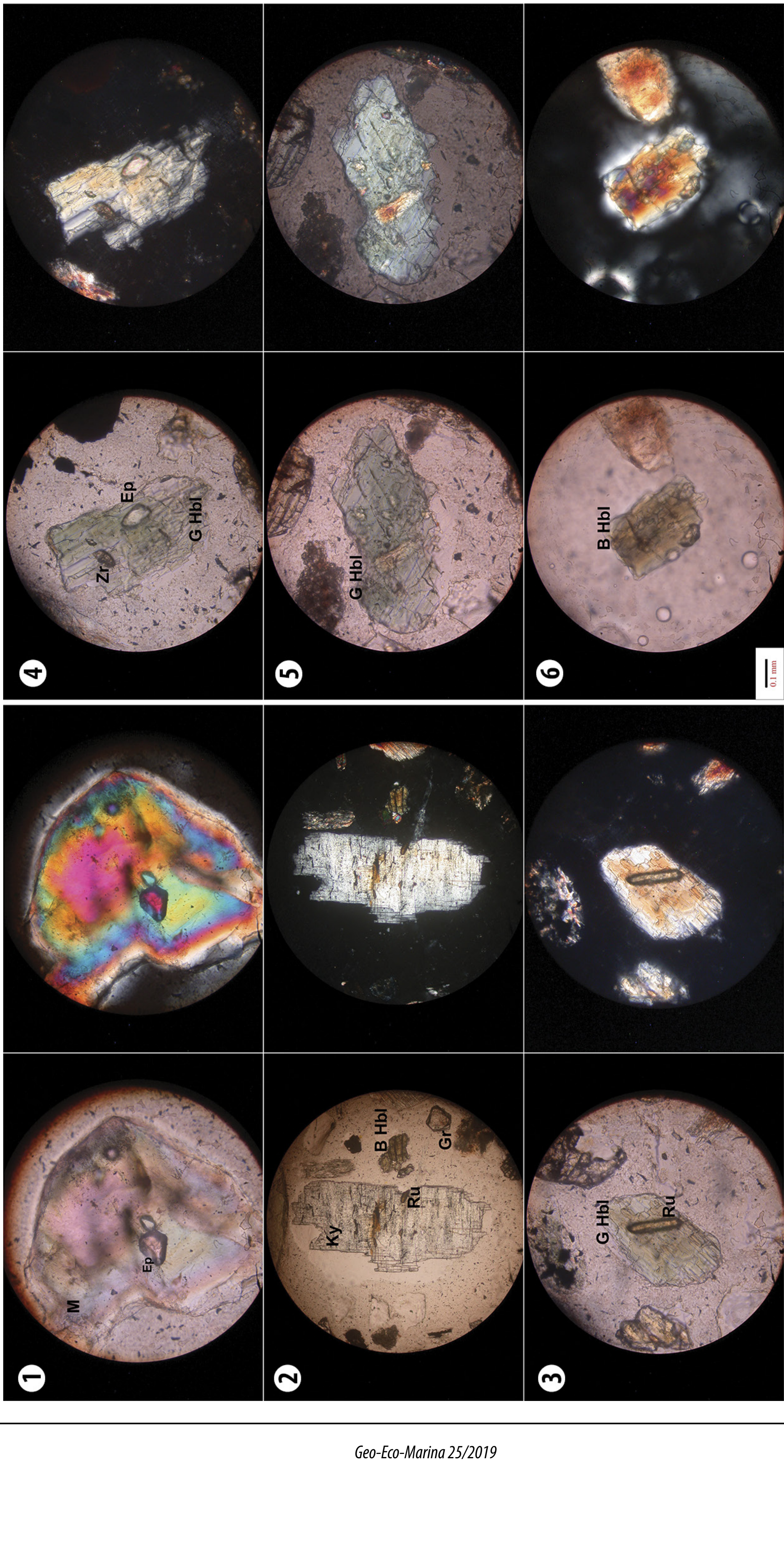

Plate. Heavy minerals identified in the studied samples; left images in plain light, right images in crossed-polarized light; **M** – muscovite; **Ky** – kyanite; **Ru** – rutile; **Gr** – garnet; **B, G Hbl** – brown, green hornblende; **Zr** – zircon.

The chlorite crystals were identified in most studied samples, with one exception - the one from the Siret River (Fig. 4). The highest concentration of this mineral was observed in the Ialomiţa River (10%). Due to their poor physical and chemical resistance, the chlorite grains were identified with a variable morphology, however most of the crystals are sub-rounded to sub-angular (Table 1).

The ZTR (zircon, tourmaline, rutile) group represents the most resistant heavy minerals to physical and chemical factors (Schuller & Frisch, 2006). Although these minerals were identified in low concentrations, their presence allow, in addition of the identification of the source rocks, to estimate the maturity of the sediment through the ZTR index (Hubert, 1962). As mentioned above, the average abundances of zircon, tourmaline and rutile are 1.24%, 2.5% and, respectively, 2.3%, with a relative homogeneous concentration in the sampled sediments (Fig. 4). The grains morphology is generally angular to sub-angular (Table 1, Plate), as it was expected.

4.2. Major associations of heavy minerals from tributaries

Taking into account the highest abundances of the identified heavy minerals *versus* their presence into the most probable rocks, as primary parageneses of minerals (i.e., granites, gneisses, amphibolites and green schists), generating the input discharged into the Danube River, we may state that two main associations are present in the sampled locations (Fig. 5):

- Garnet + Epidote + green amphiboles + Kyanite (Gr+Ep+Am+Ky), association that occurs in the magmatic rocks (such as granites and gabbros) and medium to high grade metamorphic rocks, i.e., eclogites, ultramafics, gneisses and amphibolites; the provenance of epidote can be related to prograde green schist to epidote-amphibolite facies rocks (Iancu *et al*., 2005b), as well as to retrograde gneisses and amphibolites.
- Chlorite + opaque minerals (Chl+OM), heavy minerals occurring in retrograde gneisses and green schists facies rocks (chlorite) and different gneisses or magmatic rocks (opaque minerals).

Hence, similarities among the South Carpathian crossing studied rivers (Topolniţa, Jiu, Olt and Argeş), showing a high concentration of the Gr+Ep+Am+Ky association, is observed. Taking into account these results, several sources of the sediments may be inferred: gneisses, amphibolites and micaschists from the Upper and Lower Danubian tectonic units occurring along the Jiu Valley and, the Getic-Supragetic tectonic units (crossed by Topolniţa, Olt and Argeş valleys); a small input from the Olt River (monazite and some of the garnet grains) is believed to have a magmatic origin, presumably from the Neogene volcanic or volcanoclastic rocks, both located in the Eastern Carpathians.

The correlation between each heavy mineral association and the grain roundness degree confirm a proximal to medium length sources. The determined associations, displayed in Fig. 5, are showing foremost the signature of the source area.

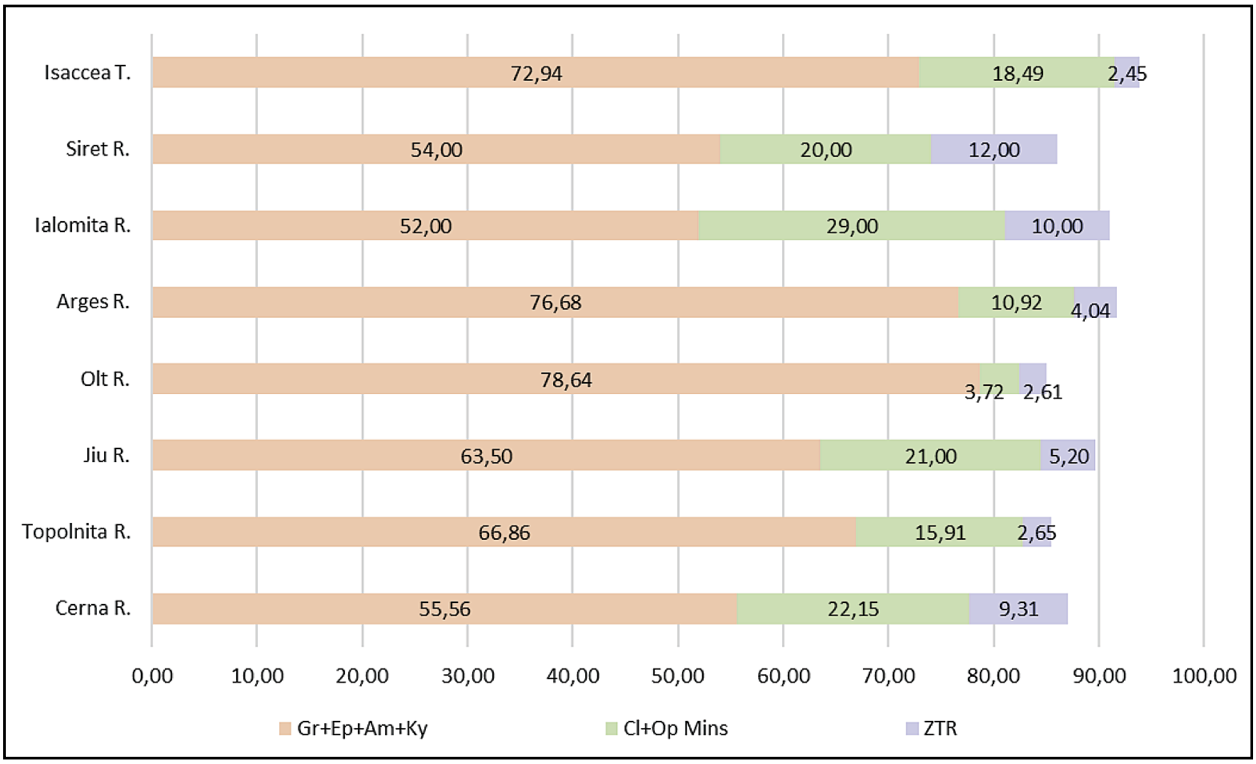

Fig. 5. HM association concentration and ZTR index (zircon + tourmaline + rutile) values in the sampled river confluence with the Danube

The Chl + OM association may be associated mainly with the green schists and retrograde gneisses from the Getic and Danubian tectonic units; the aforementioned rocks have also a significant occurrence as clasts in the sediments of the Moesian and Moldavian platforms. This association is most representative in the eastern samples, collected from the Ialomiţa and Siret rivers. Besides the sources already mentioned, the North Dobrogean Orogen might be considered, especially for the sample content identified in Isaccea location. Concerning the sample from the Cerna River, a mixture between the two above-mentioned associations was observed, as a combined input from the aforementioned sources.

An interesting feature was remarked on the correlation among the two pointed out association and the ZTR (zircon + tourmaline + rutile) values. Therefore, the ZTR index shows a negative correlation with the Gr+Ep+Am+Ky association and a positive one with the Chl+OM association. This correlation can be presumed as a consequence of a similar provenance from magmatic rocks as granitoids and gabbros.

4.3. ZTR index *versus* Sr/Rb ratio

The Sr/Rb ratio plot collected from the Danube River tributaries in comparison to the ZTR index chart is presented in Fig. 6. Although the Sr/Rb ratio was plotted from the geo-chemical analysis of the bulk samples, the proportions resulted could be considered as a confirmation for the ZTR index. Moreover, the differences between the two plots are the resulted surplus of the measured elements (strontium and rubidium) from the < 0.063 mm fraction.

The maturity degree of the studied sediments attests a partially connection between the two graphs, showing a modest proportion of the concerned heavy minerals (zircon, tourmaline, rutile) into the whole sample. However, the highest analogy between ZTR and Sr/Rb could be seen in the samples from Ialomiţa and Siret rivers, both showing values that indicate a long exposure of the sediments (since they entered the sedimentary system). Contrary, Topolniţa, Jiu and Argeş rivers retain younger sediments than the eastern Danube effluents, probably due to their short source-to-sink distance and their high velocity currents.

Due to the sedimentary variety observed in the Isaccea sample, we suppose that the maturity level should be higher than it is visible on the graphs. Although, we must take into account the possible deviation that appears due to the natural factors (e.g. selective sedimentary accumulation and annually and seasonally variation of the flow discharge).

Concerning the Cerna and Olt rivers, these bring a mixed input, as mentioned above. The samples from these rivers confluence with the Danube show a high concentration of ZTR crystals, but also a high amount of coarse fraction (low value of Sr/Rb) used for extracting HM.

5. CONCLUSIONS

The Danube River receive a high amount of sediments from the Romanian tributaries, which drain the entire Carpathian area represented by all type of rocks, from sedimentary, represented by the numerous flysch nappes to metamorphic ones, such as amphibolites, gneisses (i.e. garnet bearing micaschists and plagiogneisses, quartz-feldspar gneisses and meta-granites) and schists to igneous rocks (i.e. granites and gabbros). The input of each tributary has an unique mineralogical signature that could be studied

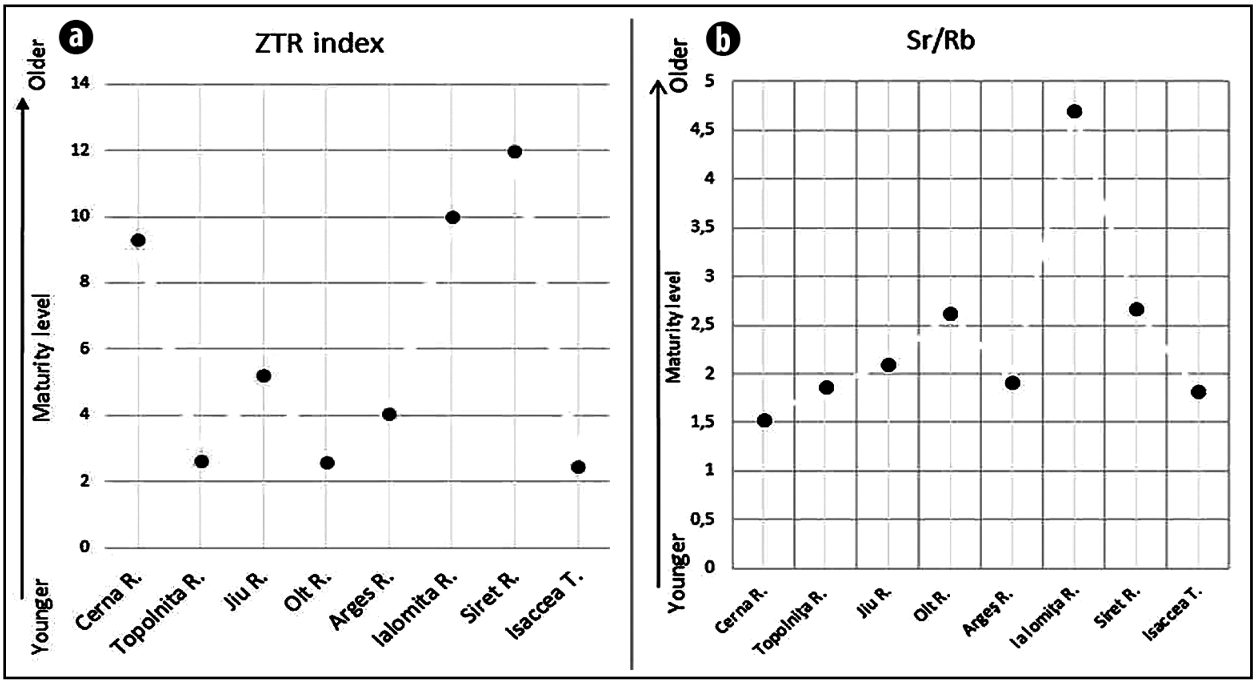

Fig. 6. Diagrams showing relative maturity of the studied samples (this study): **(a)** ZTR (zircon + tourmaline + rutile) index; **(b)** Sr/Rb ratio.

for the determination of the heavy minerals source contained in the discharged material. The average concentration of heavy minerals is approximately 3.5% of the entire sampled material; concurrently, the light minerals have a proportion of 93.6%, while the rest of the sample is represented by organic matter and shell fragments.

The most frequent heavy minerals identified in the studied samples are garnets, green hornblende, opaque minerals and epidote. Therefore, these minerals form two associations: Garnet + Epidote + green Hornblende + Kyanite (1) and Chlorite + Opaque minerals (2); these are mainly representative for metamorphic rock sources, especially for the amphibolitic facies, and subjacent for the retrograde gneisses and green schists, including chlorite bearing rocks. Additionally, an input from the nappes of the Eastern Carpathians made by sedimentary deposits, along with sediments from the platforms situated in the outer Carpathian areas (i.e. Moldavian and Moesian ones) is present.

ZTR index and Sr/Rb ratio indicate a high maturity for the eastern Danube tributaries (Ialomiţa and Siret), while the western ones, such as Topolniţa, Jiu and Argeş show a low maturity degree of the discharged material. The samples from the Olt and Cerna tributaries, as well that from the Isaccea sample, a moderate maturity level may be emphasized.

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