

High Field Strength Elements distribution in river sediments of Nile (Egypt) and Zarafshon (Tajikistan) as investigated by Instrumental Neutron Activation Analysis

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Abstract

The High Field Strength Elements (HFSE), due to their relatively low mobility in the majority of sedimentary processes, are among the most suitable elements for provenance studies, as they permit collecting information on the parent material. Therefore, the distribution of the mass fractions of two incompatible elements (Co and Ni) and 13 HFSE (Sc, Zr, La, Ce, Nd, Sm, Eu, Tb, Tm, Yb, Hf, Th, and U) in unconsolidated sediments belonging to two different river systems, i.e., the Egyptian sector of the Nile River and the Tadjik sector of the Zarafshon River, evidences similarities and dissimilarities between the sedimentary materials and their correlation with the local geochemistry. The Instrumental Neutron Activation Analysis (INAA) in its Epithermal variant was used. In total, 38 and 29 samples of unconsolidated sediments were collected along the Nile and the Zarafshon rivers. In the great majority, the distribution functions of the mass fractions were not normal, as Shapiro–Wilk, Anderson–Darling, Lilliefors, and Jarque–Bera ANOVA tests proved. More discriminating bi-plots and ternary diagrams permitted a better comparison between the distribution functions of the considered elements. All of them showed, for both types of sedimentary material, a relative similarity with the less recycled felsic type of rocks. Despite this, a further detailed analysis revealed systematic differences between the two sediment categories, suggesting that the Nile sediments have been influenced by the mafic material transported from the basalt-rich plateaus of Ethiopia via the Blue Nile.

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1. Introduction

The High Field Strength Elements (HFSE) are a group of incompatible elements, i.e., those that, due to their ionic radii or electric charge, are poorly accommodated in the crystal structures of common minerals. Among the incompatible elements, HFSE are characterized by the charge (atomic number) Z over the ionic radius r , i.e., Z/r generally greater than two [1]. Consequently, HFSE comprise all three and tetravalent elements, including platinum group, the Lanthanides (Ls), as well as Thorium and Uranium.

The behavior of incompatible elements, including the HFSE ones, provides insights into the processes of magma generation and evolution, including the extent of partial melting and the composition of mantle and crust. At the same time, the reduced mobility in most geological processes increases their tendency to concentrate in the last portions to solidify or in the first ones to melt, making them valuable tracers of these processes, or classifying a diverse category of rocks [2]. In this regard, Sc, the Lanthanides, Zr, Hf, Th, and U are usually included in the 38 elements most commonly used in geological studies.

Sediment is a solid material that occurs naturally through the processes of weathering and erosion of rocks, being dismantled and later transported by the action of wind, water, ice or by the gravity acting on its particles. For this reason, sediments transport the information concerning the parent rocks as well as the different factors that act during transport and final deposition. Therefore, sediment analysis proved to help understand magmatic processes and rock genesis [3].

These types of studies need high-performance analytical techniques of investigation, able to determine the mass fraction of a multitude of individual elements with an accuracy better than 0.5 mg/kg. In this respect, the Instrumental Neutron Activation Analysis (INAA) proved to be one of the most appropriate as it permits determining the mass fraction of more than 40 elements, including an appreciable number of HFSE [4]. Specific to INAA is its capability to analyze small amounts of material, less than 50 mg, without any preliminary treatment such as acid digestion, prone to inducing systematic errors [5]. It is also worth mentioning that INAA allows determining the mass fraction of all HFSE mentioned before, which makes this method indispensable in provenance studies of a diverse category of sediments and rocks [6–12]. In addition to them, two other trace elements, Co and Ni, which could not be considered HFSE, are useful in characterizing the nature of sediments.

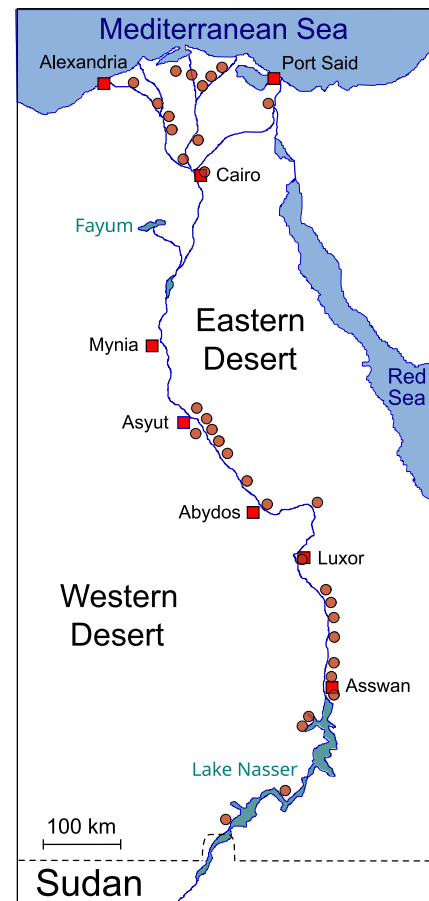


Figure 1. The Egyptian sector of the Nile River showing the location of sampling points which are marked by red circles [10].

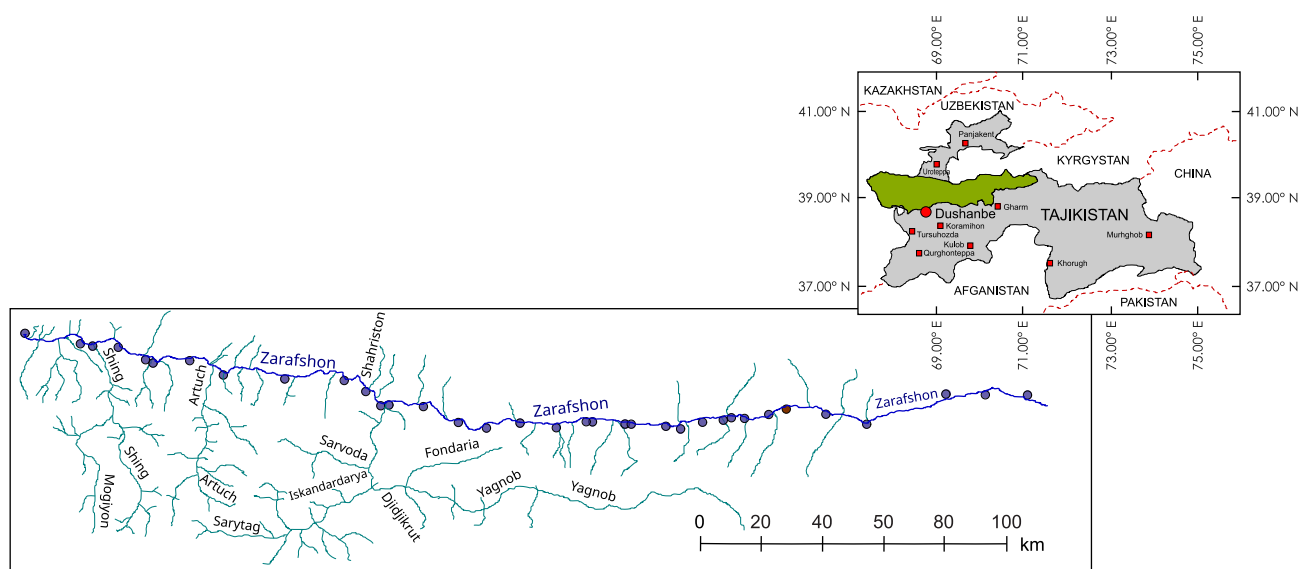


Figure 2. The Tadjik sector of the Zarafshon River showing the location of sampling points marked by blue circles. The most representative tributaries are also illustrated. The inset shows the position of the Zarafshon catchment basin (green colour) on the Tajikistan territory [15].

During the years 2015–2019, many field studies were focused on the investigation of the geochemical features of the Nile (Egypt) (Figure 1) and the Zarafshon (Tajikistan) (Figure 2) riverbeds. These rivers [13–15] play a significant role in the geology and economics of Egypt and Tajikistan, but, while the Nile River is the longest in the world having a length of 6650 km and a catchment basin of $3.35 \cdot 10^6 \text{ km}^2$ [16], the Zarafshon has more modest dimensions with a length of 877 km and a catchment basin of $1.17 \cdot 10^4 \text{ km}^2$ [17].

Concerning the Zarafshon River, it should be mentioned that it rises at an altitude of 2775 m, flows through a 300 km narrow and deep valley, reaches the city of Panjakent, crosses the Tajikistan–Uzbekistan border, passes the cities of Samarkand and Bukhara, and finally is lost in the Kyzylkum Desert.

Both rivers are located on two distinct continents, with different geomorphology and geochemical backgrounds, which are expected to influence sediment chemistry. Indeed, while the Blue Nile, the main tributary of the Nile River, is responsible for about 80% of Nile debit springs from Lake Tana at the high Ethiopian plateaus, rich in the Oligocene and late Miocene basalts [18], the Zarafshon River catchment basin spreads over various geological formations of Oligocene age located between the Turkestan and Zarafshon mountain ranges, both belonging to the Pamir-Alay mountain system [19].

At the same time, it is important to note that the Nile River crosses the Great Egyptian Desert with a total lack of tributaries (Figure 1), and the Zarafshon River, due to its position between two mountain ranges, has a significant number of tributaries, mainly distributed along its Tadjik sector (Figure 2).

As the investigated systems belong to totally different geological formations, albeit somewhat coeval, a comparative analysis of the presence of HFSE in river sediments could reveal similarities as well as differences in their distribution, all of them finally being related to local conditions, and providing a better understanding of the regional geological background.

2. Materials and methods

2.1. Sediments

For this study, 38 [10] and 29 [15] unconsolidated sediments samples were collected from the Nile and Zarafshon rivers (Figures 1 and 2). At all locations, the upper layer of sediments, e.g., 20 to 30 cm depth, was handpicked from the riverbeds during the high-water period. Further, three samples covering an area of about 10 m² were collected and mixed at each sampling point, resulting in an average composite material. After being collected, each sample was placed in glass containers or plastic bags, kept at low temperatures until transported to the laboratory, where they were completely dried at room temperature.

In the end, dried sedimentary material was sieved with a 0.425 mm (42 mesh) sieve, uniformed, and sent to the Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) for further INAA.

2.2. Instrumental Neutron Activation Analysis and the quality assurance

At the Sector of Neutron Activation Analysis and Applied Research (SNAA&AR) of FLNP JINR, 10 g of each sample were homogenized again for 15 min in a PULVERISETTE 6 planetary ball mill [25] at 400 rpm. Finally, six aliquots of about 0.3 g were selected from each sample and independently irradiated at the IBR-2 nuclear reactor using the REGATA facility [26, 27]. It is worth mentioning that all investigated elements belong to the “long half-life time” category, so all irradiations were performed in a Cd-lined channel using epithermal neutrons.

In this regard, it should be noted that to get a higher accuracy and precision, special attention was paid to quality assurance experimental determinations. This was done by using different Standard Reference Materials (SRM) irradiated together with the investigated sedimentary material. Accordingly, the following NIST (National Institute of Standards and Technology) SRM were used: 690CC — Calcareous soil, 1632c — Trace elements in coal, 2709 — Trace elements in soil, 2709a — San Joaquin soil, and AGV2 — Andesite. All SRM were chosen to be closer to the mineral nature of the investigated sediments. More details concerning the INAA measurements are provided in [15].

Under these circumstances, the total uncertainties in determining the mass fractions of the considered elements never exceeded 7%.

2.3. Statistical analysis

For more efficient processing of experimental data on the distribution of mass fractions of the studied elements, such as incompatible Co and Ni, as well as the HFSE Sc, Zr, La, Ce, Sm, Th, U, and Hf, more informative bi- and ternary discriminating diagrams were employed. Additionally, to characterize the degree of singularity between their distribution in the Nile and Zarafshon recent unconsolidated sediments, more ANOVA tests were chosen, by considering *a priori* a non-normal distribution [28]. LibreOffice 25.2 Calc, OriginLab[®] Origin 10, and PAST 5.2 free software [29] were used.

It is worth mentioning that for better understanding of the geochemistry of the investigated sedimentary material, the Upper Continental Crust (UCC) [20] and North American Shale Composite (NASC) [21], Average World Suspended Sediments (AWSS) [22], Mid-Ocean Ridge Basalt (MORB) [23] as well as Dobrogea Loess (DL) [24] (the last one as example of sedimentary sorting process) were considered as the most appropriate references.

3. Results and discussion

One of the main aims of the present study consisted in evidencing the extent to which the presence of all the 15 chosen elements can serve as an indicator of how similar the two categories of sediments (Table 1), the average values of their mass fractions together with the Combined Uncertainties (CU) [30], median, and the Coefficient of Variation (CV) are reproduced. Further, for a better characterization, the corresponding values for the UCC, NASC, AWSS, DL, and MORB are also reproduced.

Table 1. The average mass fractions of the investigated elements, together with the corresponding CU, median, and CV. For comparison, the mass fractions of the same elements in the UCC, NASC, AWSS, DL, and MORB are reproduced as well. Mass fractions are expressed in mg/kg, CV – in %.

Nile									
Element	Average	CU	Median	CV	UCC	NASC	AWSS	DL	MORB
Sc	13.5	6.7	14.7	49	14	14.9	18.2	10.1	38.8
Co	21.3	11.2	25.6	51	17.3	25.7	22.5	15	43
Ni	48	26.3	53	54	47	58	74.5	58	92
Zr	317	276	219	87	193	200	160	394	116.9
La	18.7	9	18.6	48	31	31.1	37.4	32	5.21
Ce	37.1	20.1	38.7	54	63	66.7	73.6	61.0	14.86
Nd	18.7	7.3	18.7	39	27	27.4	32.2	29.8	12.03
Sm	3.9	2.65	4.28	67	4.7	5.59	6.12	4.3	3.82
Eu	1.7	0.61	1.7	36	1	1.18	1.29	0.9	1.36
Tb	0.6	0.28	0.71	43	0.7	0.85	0.82	0.6	0.82
Tm	0.47	0.19	0.46	40	0.3	—	0.3	0.2	—
Yb	1.89	0.76	1.7	40	1.96	2.97	2.11	1.9	3.63
Hf	6.2	6.5	5.30	105	5.3	6.3	4.04	14.3	2.79
Th	3.6	2.6	3.45	73	10.5	12.3	12.1	11.6	0.4
U	1.07	0.68	0.94	65	2.7	2.66	3.3	3.1	0.12
Zarafshon									
Element	Average	CU	Median	CV	UCC	NASC	AWSS	DL	MORB
Sc	10.3	2.54	10	25	14	14.9	18.2	10.1	38.8
Co	11.2	4.11	10	37	17.3	25.7	22.5	15	40
Ni	35.2	10.3	32.1	32	47	58	74.5	58	92
Zr	206	42.6	3	21	193	200	160	394	116.9
La	29.1	7	29	24	31	31.1	37.4	32	5.21
Ce	57.1	15	5	26	63	66.7	73.6	61.4	14.86
Nd	23.4	15	22.8	56	27	27.4	32.2	29.8	12.03
Sm	8.8	2.8	9.2	32	4.7	5.59	6.12	4.3	3.82
Eu	0.9	0.6	1.1	67	1	1.18	1.29	0.9	1.36
Tb	1.01	0.41	0.96	38	0.7	0.85	0.82	0.6	0.82
Tm	0.3	0.3	0.3	100	0.3	—	0.3	0.2	—
Yb	1.9	1.2	17	63	1.96	2.97	2.11	1.9	3.63
Hf	4.8	1.19	5	24	5.3	6.3	4.04	14.3	2.79
Th	8.5	3	8.6	30	10.5	12.3	12.1	11.6	0.4
U	3.5	0.6	3.5	17	2.7	2.66	3.30	3.10	0.12

On this point, it is worth noting that there is a greater dispersion of the mass fractions values of Nile sediments, confirmed by the corresponding CV, the values of which in the case of the Nile exceeded the Zarafshon ones by a factor of 1.6 (Table 1).

However, and this was the second aim of the present study, the distribution of considered HFSE as well as Co and Ni in the Nile and Zarafshon sediments, appears close to the UCC, NASC, AWSS and even DL, but is completely different from the MORB, indicating a continental origin for the sedimentary material (Table 1). To reach a conclusion about the contribution of individual elements, a more detailed analysis is necessary, for which various types of discriminant bi-plots and ternary diagrams have proven their versatility. At the same time, when interpreting these data, it should be taken into account that the present study concerns unconsolidated sediments, the source of which may be located at a great distance from the sampling sites, so, in essence, the sediments carried not only information about their sources, but also on local geochemistry.

Of all the elements considered, Scandium (Sc) is one of the most appropriate in discriminating against the felsic rocks from the mafic ones, as Sc mass fraction which is less than 20 mg/kg in the felsic rocks reaches values between 20 and 40 mg/kg in the case of the mafic ones [31]. In the framework of the present study, Sc mass fractions varied from (13.5 ± 6.3) mg/kg in case of Nile sediments to (10.2 ± 2.5) mg/kg for the Zarafshon ones (Table 1), apparently slightly higher in the case of Nile sediments, but in both cases lower than the conventional threshold of 20 mg/kg. That is why Sc is frequently used in evidencing the reciprocal affinity of different types of rocks [32–34].

A similar discriminating trend was reported for Co and Ni on the one hand, and Th and U on the other, as the felsic rocks are depleted in Co and Ni and enriched in Th and U, contrary to the mafic rocks which present an opposite tendency [35]. Accordingly, the Nile sediments presented for Co a mass fraction of (21.3 ± 11.2) mg/kg, significantly higher than the value of (11.2 ± 0.17) mg/kg found in the case of Zarafshon sediments, but in the case of Ni, both types of sediments showed relatively closer values of (48 ± 26.3) and (35.2 ± 0.2) mg/kg (Table 1). On the contrary, Th showed an average mass fraction of 3.6 ± 2.6 in the Nile sediments, smaller than those found in the Zarafshon River of (8.5 ± 0.2) mg/kg (Table 1). A comparable behaviour was noticed for Th and U, mass fractions of which were significantly lower in the case of Nile sediments than in the case of the Zarafshon ones, the same discriminating tendency existing in the case of felsic UCC and mafic MORB (Table 1).

Another peculiarity, evidenced by the discriminating Th/Ni vs. Zr/Ni bi-plot (see Figure 3, *b*) [34], ternary Sc–La–Th diagram (Figure 3, *c*) [36, 37], and Th/Co vs. La/Sc bi-plot (Figure 3, *d*) [37], suggests a certain presence of the mafic material in the Nile sediments. At a careful examination, the Zarafshon data are closely grouped on the felsic subdivision of these diagrams, while the corresponding Nile data present a small tendency towards the mafic subdivision.

On this point, the La/Th mass fraction ratio could be useful in understanding the nature and provenance of depositional material. Although, for each sediment, there is a good linear correlation between La and Th, the corresponding La/Th ratio values differ quite significantly since a *t*-test value of 0.967 suggests a probability of 0.336 that the slopes will be similar (Figure 3, *e*). These values should be compared with the corresponding ones for the UCC of 2.95, 2.53 in the case of NASC, 3.09 for the AWSS, and 13.03 for the MORB, suggesting again a certain difference of Nile sediments from the UCC, mainly a slight displacement towards more mafic material.

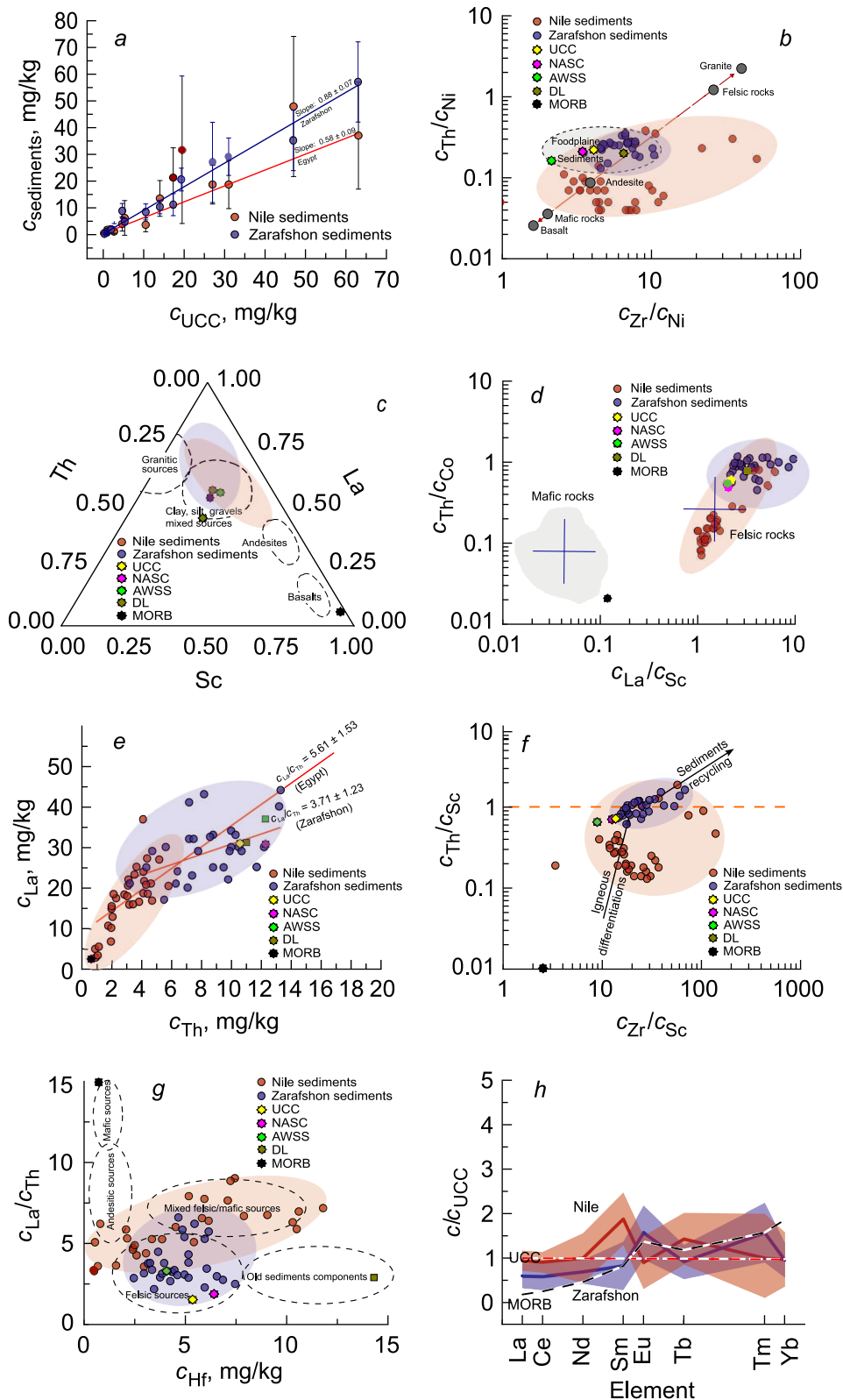


Figure 3. Discriminating bi-plots (a, b, d, e, f, g, h) and Sc–La–Th ternary diagram (c) illustrating the relative position of Nile (red circles) and Zarafshon (blue circles) sediments with respect to the UCC, NASC, AWSS, DL, and MORB. Although closer, the data corresponding to the Nile and Zarafshon sediments form always two clusters partially overlapping. NB in Figure (a), the mass fraction of Zr was divided by 10.

Two other HFSE, Zr and Hf, behave almost similar in sedimentary material. Zr is the main constituent of the mineral zircon ZrSiO_4 which, due to its higher hardness of 7.5, poses an increase resilience to abrasion so that the higher the Zr mass fraction, the larger the sedimentary material sorting and recycling [38]. Hf, in turn, due to the fact it is always bound up with Zirconium compound which usually has about 1–4% of Zr replaced by Hf [39], shows the same tendency to be enriched during the erosion of sedimentary rocks.

The discriminating Th/Sc vs. Zr/Sc (Figure 3, *f*) [33] and La/Th vs. Hf (Figure 3, *g*) [40, 41] diagrams help understand the past evolution of the sedimentary materials as well as their compatibility with respect to the main category of rocks. Accordingly, the Th/Sc vs. Zr/Sc bi-plot suggests a reduced cycle of erosion and recycling, as the majority of points are grouped around the UCC, NASC or AWSS, and far away from the MORB, and at a certain measure from the DL (Figure 3, *f*). In turn, the La/Th vs Hf bi-plot points to a felsic origin of the sedimentary material, but, as in previous cases, the Nile data form a cluster whose position seems slightly shifted toward the andesitic source (Figure 3, *g*). On both bi-plots, the DL points suggest the presence of either sediment recycling (Figure 3, *f*) or of the old sedimentary components (Figure 3, *g*), normal for loess.

The Lanthanides (Ln) are a subdivision of the Rare Earth Elements (REE) consisting of 14 elements, from Lanthanum to Ytterbium, monotonously filling the 4f orbitals. This fact determined all of them to have closer chemical properties, making this group of HFSE very useful in getting confidence information on the origin of host rocks.

In the framework of the present study, the INAA permitted determining the mass fractions of only eight REE, e.g., La, Ce, Nd, Sm, Eu, Tb, Tm, and Yb. By comparing their mass fractions with the UCC one (Figure 3, *h*), in spite of a great dispersion of the mass fractions of the investigated Ln, their distribution rather followed the UCC one, different from the opposite mafic MORB.

Regrettably, the INAA does not allow one to determine with sufficient accuracy the mass fraction of Gd, the value of which, together with Sm, is indispensable for the quantitative determination of the Eu anomaly, one of the most important parameters in establishing the nature of depositional material [42].

4. Concluding remarks

The Instrumental Neutron Activation Analysis represents a powerful analytical method in determining the mass fractions of a great number of incompatible and High Field Strength Elements, the presence and distribution of which are important for understanding the provenance and evolution of various geological formation, including recent sediments, regardless of their locations.

Under such circumstances, the INAA was used to determine the mass fractions of incompatible Co and Ni as well as of the other 13 HFSE, i.e., Sc, Zr, La, Ce, Nd, Sm, Eu, Tb, Tm, Yb, Hf, Th, and U, with an accuracy of 7% in sedimentary material of the Egyptian sector of the Nile River as well as the Tajik sector of the Zarafshon River, both of them coeval, but belonging to two different systems, and located on different continents. All these elements play a significant role in providing reliable information about the geochemistry of sedimentary materials and their sources.

To evidence this, the mass fractions of all analyzed elements were compared with the mass fractions of the same elements in more universal sedimentary media such as the Upper Continental Crust, North American Shale Composite, Average World Suspended Sediments, and particularly Dobrogea Loess as a model of recirculated sedimentary material. This comparison

was performed by means of different methods of statistical analysis, including the graphic ones, which consisted of different types of discriminating bi- and ternary plots.

This study demonstrates that both categories of sediments share a common acidic, felsic background, while Egyptian sediments present also some basic, mafic features, most probably due to the Blue Nile, the main tributary of the Nile River which springs from the high Ethiopian plateaus rich in basalt.

Such kind of investigations are important because they highlight the extent to which the systematic study of the distribution of HFSE in recent river sediments provides information not only on the source geochemistry, but also on the formations that these rivers cross. The study becomes even more interesting if the investigated formations are on different continents.

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Author contributions

O. G. Dului: Conceptualization; W. M. Badawy, D. Abdusamadzoda, O. G. Dului, P. S. Nekhoroshkov: Methodology; O. G. Dului: Software; W. M. Badawy, D. Abdusamadzoda, I. Zinicovscaia, P. S. Nekhoroshkov: Data curation; O. G. Dului: Original draft preparation; W. M. Badawy, D. Abdusamadzoda, D. A. Abdushukurov, M. V. Frontasyeva, I. Zinicovscaia, P. S. Nekhoroshkov, H. El-Samman: Investigation; O. G. Dului, W. M. Badawy, D. Abdusamadzoda: Supervision; W. M. Badawy, D. Abdusamadzoda, D. A. Abdushukurov, M. V. Frontasyeva, I. Zinicovscaia, P. S. Nekhoroshkov, H. El-Samman: Validation; O. G. Dului, P. S. Nekhoroshkov: Writing, Reviewing, and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

References

- [1] H. Rowlinson, *Using Geochemical Data: Evaluation, Presentation, Interpretation*, Longman Scientific and Technical Publishers, New York, 1993, p. 352, ISBN 978-0582067011.
- [2] S. M. McLennan, S. R. Taylor, A. Kröner, *Geochemical evolution of Archean shales from South Africa I. The Swaziland and Pongola Supergroups*, *Precambrian Research* 22 (1983) 93–124. [https://doi.org/10.1016/0301-9268\(83\)90060-8](https://doi.org/10.1016/0301-9268(83)90060-8).
- [3] S. Boggs, *Principles of Sedimentology and Stratigraphy*, 5th edition, Pearson, Chennai, India, 2016, p. 174, ISBN 978-0321745767.

- [4] S. J. Parry, Handbook of Neutron Activation Analysis, Viridian Publishing, Surrey, UK, 2003, p. 243, ISBN 978-0954489113.
- [5] M. V. Frontasyeva, Neutron Activation Analysis in the life sciences, Physics of Particles and Nuclei 42 (2011) 332–378. <https://doi.org/10.1134/S1063779611020043>.
- [6] Y. L. Wang, Y.-G. Liu, R. A. Schmitt, Rare earth element geochemistry of South Atlantic deep sea sediments: Ce anomaly change at ~ 54 My, Geochimica et Cosmochimica Acta 50 (1986) 1337–1355. [https://doi.org/10.1016/0016-7037\(86\)90310-8](https://doi.org/10.1016/0016-7037(86)90310-8).
- [7] N. Aota, Y. Miyamoto, S. Kosanda et al., Neutron Activation Analysis of nine GSJ sedimentary rock reference samples, Geostandard Newsletter 18 (1994) 185–193. <https://doi.org/10.1111/j.1751-908X.1994.tb00516.x>.
- [8] M. J. Marqués, A. Salvador, A. E. Morales-Rubio et al., Trace element determination in sediments: A comparative study between Neutron Activation Analysis (NAA) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), Microchemical Journal 65 (2000) 177–187. [https://doi.org/10.1016/S0026-265X\(00\)00051-5](https://doi.org/10.1016/S0026-265X(00)00051-5).
- [9] Y. Yao, C. Xiao, P. Wang et al. Instrumental Neutron Activation Analysis of Chang'E-5 lunar regolith samples, Journal of American Chemical Society 144 (2022) 5478–5484. <https://doi.org/10.1021/jacs.1c13604>.
- [10] W. M. Arafa, W. M. Badawy, N. M. Fahmi, Geochemistry of sediments and surface soils from the Nile Delta and lower Nile Valley studied by Epithermal Neutron Activation Analysis, Journal of African Earth Sciences 107 (2015) 57–64. <http://dx.doi.org/10.1016/j.jafrearsci.2015.04.004>.
- [11] W. M. Badawy, M. Mitwalli, A. Y. Dmitriev et al., Neutron Activation Analysis for geochemical characterization of rocks from gold mines in Egypt, Applied Sciences 13 (2023) 4564. <https://doi.org/10.3390/app13074564>.
- [12] C. Bueno, C. J. Sanders, D. I. T. Favaro et al., Accumulation patterns of rare earths and other elements in coastal lake sediments under different land uses, Journal of South American Earth Sciences 161 (2025) 105576. <https://doi.org/10.1016/j.jsames.2025.105576>.
- [13] W. M. Badawy, E. H. Ghanim, O. G. Dului et al., Major and trace element distribution in soil and sediments from the Egyptian central Nile Valley, Journal of African Earth Sciences 131 (2017) 53–61. <https://doi.org/10.1016/j.jafrearsci.2017.03.029>, WOS:000403515600005.
- [14] W. M. Badawy, O. G. Dului, H. El Samman et al., A review of major and trace elements in Nile River and Western Red Sea sediments: An approach of geochemistry, pollution, and associated hazards, Applied Radiation and Isotopes 170 (2021) 109595. <https://doi.org/10.1016/j.apradiso.2021.109595>, WOS:000637950400017.
- [15] D. A. Abdushukurov, D. Abdusamadzoda, O. G. Dului et al., On the geochemistry of major and trace elements distribution in sediments and soils of Zarafshon River Valley, Western Tajikistan, Applied Sciences 12 (2022) 2763. <https://doi.org/10.3390/app12062763>.
- [16] R. O. Collins, The Nile, Yale University Press, Yale, CT, US, 2002, ISBN 978-0300097641.
- [17] A. M. Prokhorov, Zarafshon (River in Central Asia), in: Great Soviet Encyclopedia, Vol. 30, Moscow, Russia, 1968–1978 (in Russian).
- [18] K. Verner, J. Síma, L. Megerssa et al., A Synopsis of the Regional Geology and Hydrogeology of Ethiopia, Czech Geological Survey, Prague, 2025, ISBN 978-8076731134.
- [19] M. G. Leonov, A. K. Rybin, V. Y. Batalev et al., Tectonic structure and evolution of the Hissar–Alay Mountain Domain and the Pamirs, Geotectonics 51 (2017) 566–583. <https://doi.org/10.1134/S001685211706005X>.
- [20] R. L. Rudnic, S. Gao, Composition of the Continental Crust, in: H. D. Holland, K. K. Turekian (Eds.), Treatise on Geochemistry, Vol. 3, Elsevier-Pergamon, Oxford-London, 2003, pp. 1–64, ISBN 978-0080548074.

- [21] L. P. Gromet, R. F. Dymek, L. A. Haskin et al., The ‘North American Shale Composite’: Its compilation, major and trace element characteristics, *Geochimica et Cosmochimica Acta* 48 (1984) 2469–2482. [https://doi.org/10.1016/0016-7037\(84\)90298-9](https://doi.org/10.1016/0016-7037(84)90298-9).
- [22] J. Viers, B. Dupré, J. Gaillardet, Chemical composition of suspended sediments in World Rivers: New insights from a new database, *Science of the Total Environment* 407 (2009) 853–868. <https://doi.org/10.1016/j.scitotenv.2008.09.053>.
- [23] A. Gale, C. A. Dalton, C. H. Langmuir et al., The mean composition of ocean ridge basalts, *Geochemistry, Geophysics, Geosystems* 14 (2013) 489–518. <https://doi.org/10.1029/2012GC004334>.
- [24] L. C. Tugulan, O. G. Dulu, A.-V. Bojar et al., On the geochemistry of the Late Quaternary loess deposits of Dobrogea (Romania), *Quaternary International* 399 (2016) 100–110. <https://doi.org/10.1016/j.quaint.2015.06.062>.
- [25] <https://www.fritsch-international.com/sample-preparation/milling/planetary-mills/details/product/pulverisette-6-classic-line/>.
- [26] D. Grozdov, V. Galustov, I. Zinicovscaia, Modernization on the REGATA facility (IBR-2 reactor) designed for Instrumental Neutron Activation Analysis, *Journal of Radioanalytical and Nuclear Chemistry* 334 (2025) 2435–2442. <https://doi.org/10.1007/s10967-025-10014-4>.
- [27] I. Zinicovscaia, O. G. Dulu, O. A. Culicov et al., Major and trace elements distribution in Moldavian soils, *Romanian Reports in Physics* 70 (2018) 701. <https://rrp.nipne.ro/2018/AN70701.pdf>
- [28] C. Reimann, P. Filzmoser, Normal and lognormal data distribution in geochemistry: Death of a myth. Consequences for the statistical treatment of geochemical and environmental data, *Environmental Geology* 39 (2000) 1001–1014. <https://doi.org/10.1007/s002549900081>.
- [29] Ø. Hammer, D. A. T. Herper, P. D. Ryan, PAST: Paleontological Statistics software package for education and data analysis, *Palaeontologia Electronica* 4 (2001) 1–9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm.
- [30] I. Farrance, R. Frenkel, Uncertainty of measurement: A review of the rules for calculating uncertainty components through functional relationships, *The Clinical Biochemist Review* 33 (2012) 49–75, PMID: 22896744, PMCID: PMC3387884.
- [31] J. C. Norman, L. A. Haskin, The geochemistry of Sc: A comparison to the rare earths and Fe, *Geochimica and Cosmochimica Acta* 32 (1968) 93–108. [https://doi.org/10.1016/0016-7037\(68\)90089-6](https://doi.org/10.1016/0016-7037(68)90089-6).
- [32] M. R. Bhatia, K. A. W. Crook, Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins, *Contribution to Mineralogy and Petrology* 92 (1986) 181–193. <https://doi.org/10.1007/BF00375292>.
- [33] P. A. Floyd, B. E. Leveridge, Tectonic environment of the Devonian Gramscatho basin, south Cornwall: Framework mode and geochemical evidence from turbiditic sandstones, *Journal of the Geological Society* 144 (1987) 531–542. <https://doi.org/10.1144/gsjgs.144.4.0531>.
- [34] G. Újvari, A. Varga, Z. Balogh-Brunstad, Origin, weathering, and geochemical composition of loess in southwestern Hungary, *Quaternary Research* 69 (2008) 421–437. <https://doi.org/10.1016/j.yqres.2008.02.001>.
- [35] S. Marshak, *Essentials of Geology*, 6th edition, W. W. Norton & Company, NY, USA, 2019, ISBN 978-0393667523.
- [36] S. R. Taylor, S. M. McLennan, *The Continental Crust: Its Composition and Evolution: An Examination of the Geochemical Record Preserved in Sedimentary Rocks*, Blackwell Scientific Publications, 1991, ISBN 978-0632011483.
- [37] R. L. Cullers, Implications of elemental concentrations for provenance, redox conditions, and metamorphic studies of shales and limestones near Pueblo, CO, USA, *Chemical Geology* 191 (2002) 305–327. [https://doi.org/10.1016/S0009-2541\(02\)00133-X](https://doi.org/10.1016/S0009-2541(02)00133-X).

- [38] S. M. McLennan, S. Hemming, C. K. McDaniel et al., Geochemical Approaches to Sedimentation, Provenance, and Tectonics, in: M. J. Johnsson, A. Basu (Eds.), Processes Controlling the Composition of Clastic Sediments, Geological Society of America Special Papers, Vol. 284, 1993, pp. 21–40. <https://doi.org/10.1130/SPE284-p21>.
- [39] W. A. Deer, R. A. Howie, J. Zussmann, Rock-Forming Minerals: Orthosilicates, Vol. 1A, Geological Society of London, 1982, pp. 418–442, ISBN 978-0-582-46526-8.
- [40] Y. I. Lee, Geochemistry of shales of the Upper Cretaceous Hayang Group, SE Korea: Implications for provenance and source weathering at an active continental margin, *Sedimentary Geology* 215 (2009) 1–12. <https://doi.org/10.1016/j.sedgeo.2008.12.004>.
- [41] R. Nagarajan, J. S. Armstrong-Altrin, F. L. Kessler et al., Provenance and tectonic setting of Miocene siliciclastic sediments, Sibuti Formation, northwestern Borneo, *Arab Journal of Geosciences* 8 (2015) 8549–8565. <https://doi.org/10.1007/s12517-015-1833-4>.
- [42] P. Henderson (Ed.), Rare Earth Elements Geochemistry, in: *Developments in Geochemistry*, Vol. 2, Elsevier, 2013, ISBN 978-1483289779.