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Morpho-Geochemical Analysis of Detrital Zircons from Carboniferous Formations in the Tim-Mersoï Basin (Niger) and Implications for Uranium Potential

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ABSTRACT

Detrital zircons are robust tracers widely used to reconstruct sediment provenance and evaluate the metallogenic potential of sedimentary basins. This study focuses on the morphological and geochemical characterization of zircons from the Carboniferous formations of the Tim-Mersoï Basin (Niger) in order to identify sedimentary sources and assess their contribution to uranium mineralization. Optical microscopy, scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS), and geochemical analyses revealed two dominant zircon morphologies: elongated prismatic zircons and ovoid zircons. The elongated zircons are euhedral, transparent, and enriched in uranium (U), vanadium (V), and molybdenum (Mo), displaying signatures typical of evolved felsic magmatic systems. Their morphology and chemical composition indicate primary crystallization in differentiated granito-volcanic magmas enriched in incompatible elements, likely related to the magmatic complexes of the Aïr Massif. In contrast, the ovoid zircons, commonly rounded and associated with clay and sulfide minerals, reflect sedimentary recycling and prolonged transport processes while preserving inherited magmatic geochemical signatures. Geochemical data reveal high UO_2 contents (average ≈ 54.79 %) associated with relatively low ZrO_2 concentrations, suggesting significant isomorphic substitution of uranium for zirconium as well as metamictization processes induced by radioactive decay. TiO_2 concentrations indicate high crystallization temperatures consistent with deep magmatic environments. Altogether, the results point to a dominantly evolved magmatic origin subsequently modified by sedimentary recycling, diagenetic alteration, and hydrothermal processes. This study demonstrates that the combined use of zircon morphology and geochemistry provides an effective tool for constraining sediment provenance and identifying potential uranium-bearing source rocks. The results confirm the major contribution of the granito-volcanic complexes of the Aïr Massif to the Tim-Mersoï Basin sediments and provide significant insights into the genesis of uranium mineralization. This approach also offers valuable perspectives for uranium exploration in detrital basins of Niger.

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KEYWORDS: *Detrital zircon; Tim-Mersoï Basin; SEM-EDS; metallogeny; Aïr Massif; Niger.*

1. INTRODUCTION

Sandstone uranium deposits constitute one of the world's main sources of uranium production due to their abundance, accessibility, and relatively low operating cost. They generally develop within medium- to coarse-grained detrital formations deposited in continental fluvio-continental or marine marginal environments, where the circulation of oxidizing and reducing fluids promotes the mobilization, transport, and precipitation of uranium (Cuney, 2009; Yang et al., 2009; Fayek, 2013; Bonnetti et al., 2015; Chu et al., 2015; Cumberland et al., 2016). In these systems, volcanic inputs, particularly in the form of ash, constitute a significant potential source of uranium (Kache, 2013; Hou et al., 2017; Bohari et al., 2018; Salze et al., 2018; Xu, 2020), while redox conditions control its fixation within detrital formations via organic matter, sulfides, or ferromagnesian minerals (Scholtz, 2009; René, 2017; Wang, 2017). In this context, resistant detrital minerals, especially zircons, play a fundamental role in the study of uranium-bearing sedimentary systems. Thanks to their high physical and chemical stability, detrital zircons are excellent tracers of crustal sources and sedimentary processes. They record essential information on sediment origin, transport conditions, magmatic and tectonic events, and sedimentary recycling processes (Fedo et al., 2003; Cawood et al., 2012). Furthermore, their geochemical composition allows for the identification of uranium-fertile magmatic environments and the assessment of the role of volcanic and granitoid inputs in feeding sedimentary basins. The Tim-Mersoï Basin, located in the western part of the Iullemmeden Basin in Niger, is one of Africa's major uranium-bearing districts. It contains most of the country's uranium resources, mainly embedded in Carboniferous detrital formations resulting from the erosion of the Aïr massif and its granito-volcanic complexes (Crawley et al., 1985; Areva, 2005; Nicholls and Vincent, 2007; Salze et al., 2018). The tectonic structure of the basin, combined with significant fluid circulation, has favored the emplacement of numerous economically exploitable uranium mineralizations. Despite the economic and scientific importance of this basin, the relationships between sediment origin, the characteristics of detrital zircons, and uranium concentration processes remain insufficiently documented. In this context, the morphological and geochemical study of detrital zircons appears to be a relevant approach for better understanding the origin of sedimentary materials and the associated metallogenic mechanisms. The main objective of this work is to identify the sources of Carboniferous sediments in the Tim-Mersoi Basin and to assess their contribution to the basin's uranium potential through the study of detrital zircons. More specifically, this study aims to:

- characterize the main morphologies of detrital zircons;
- determine their geochemical signatures using SEM-EDS analyses;
- Identify crystallization environments and potential magmatic sources;
- Evaluate the transport, recycling, and alteration processes that have affected the zircons;
- Establish the relationships between zircon characteristics and the uranium metallogenic potential of the basin.

In order to achieve these objectives, an integrated morpho-geochemical approach was adopted. The zircons were studied using optical microscopy and scanning electron microscopy (SEM) to analyze their morphology, textural relationships, and state of preservation. Chemical analyses were performed using an EDS system coupled to SEM to determine the uranium and associated element contents, such as zirconium, titanium, vanadium, and molybdenum. The comparison of morphological and geochemical data made it possible to interpret the origin of zircons, the post-magmatic evolution processes as well as the metallogenic implications for the uranium formations of the Tim-Mersoï basin.

1.1. Location of the study area

The study area is located in northern Niger, in the Agadez region, near the city of Arlit. It lies within the Aïr Massif, in a desert environment characterized by an arid climate and uranium-rich geological formations. The area includes the main mining infrastructure of the Société des Mines de l'Aïr (SOMAÏR), as well as the surrounding areas affected by mining activities. It is situated between 18° and 19° North latitude and between 7° and 8° East longitude (Figure 1).

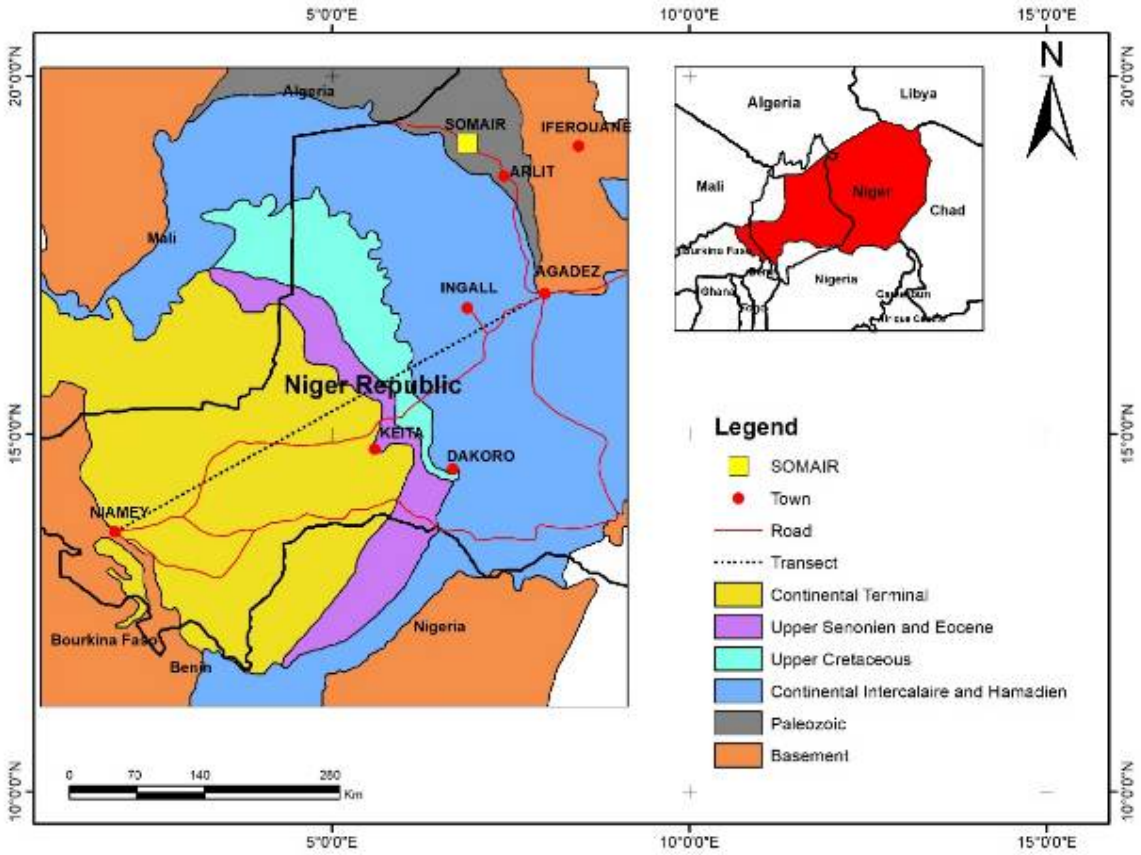

Figure 1 : Map of Niger showing the geographical location of the study area

2. Materials and methods

2.1. Geological setting

The geology of Niger is dominated by the Proterozoic basement of the Aïr Massif and the intracratonic Tim-Mersoï sedimentary basin. The basement, formed during the Pan-African orogeny, consists of metamorphic rocks (gneiss, schist, quartzite, and amphibolite) intruded by syntectonic granites. Magmatic activity continued from the Proterozoic to the Jurassic, with Tertiary to Quaternary volcanism (Bowden, 1981; Nicholls and Vincent, 2007; Kogbe, 1991; Navez et al., 1999). The Tim-Mersoï Basin, covering approximately 600,000 km², contains all of Niger's main uranium deposits, particularly in the Arlit-Akokan, Madaouela, Imouraren and Azelik regions (Scholtz, 2009). Its stratigraphy includes, from base to top: the Lower Visean formations of the Terada Group, the Upper Visean formations of the Tagora Group, a continental Permo-Jurassic sequence ("Continental Intercalary") and the Lower Cretaceous deposits (Beaudoin, 1984; Crawley et al., 1985; Konate et al., 2007; Nicholls and Vincent, 2007). The basin's structure is dominated by the north-south oriented Arlit fault (In Azawa lineament), which controls sedimentation and the formation of structural traps favorable to uranium mineralization (Konate et al., 2007). The economic deposits are mainly located east of this fault and hosted in the Visean Carboniferous formations (Tarat and Guezouman), rich in organic matter (Forbes et al., 1988; Salze, 2008; Salze et al., 2018) (Figure 2). These deposits have grades ranging from 0.2 to 0.5%, at depths of up to 220 m, while the lower-grade Imouraren deposit is located in Jurassic formations (Crawley et al., 1985; Areva, 2005; Kache, 2013). Isotopic dating (U-Pb, K-Ar and Sm-Nd) indicates that the mineralization was primarily emplacement during the Jurassic period, between approximately 190 and 150 Ma (Pagel, 2000; Cavellec, 2006; Gerbeaud, 2007; Salze et al., 2018).

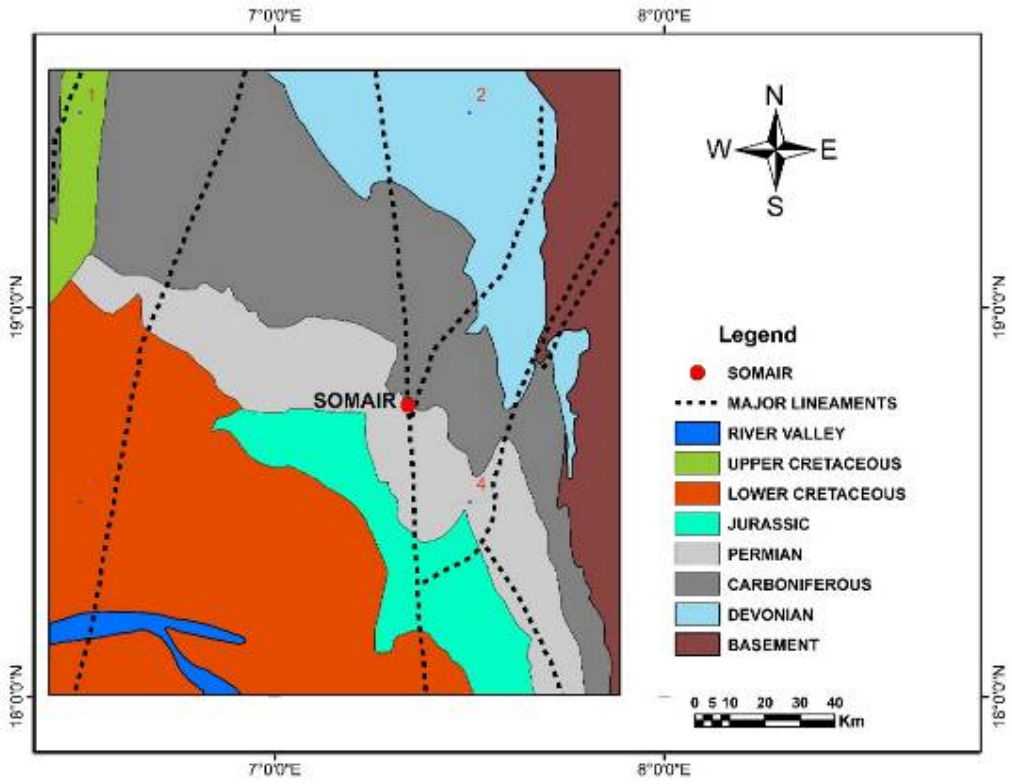

Figure 2 : geological context of the Tim-mersoi basin, northern Niger

2.2. Sampling and analytical technique

Sampling was carried out using an AVP threshold of 300 c/s, targeting the main mineralization peaks identified by SPPY gamma measurements. A total of 31 samples, ranging in thickness from 0.5 to 1.5 m in homogeneous facies, were collected, indexed, photographed, checked by SPPY, and then packaged. Petrographic analysis was performed using optical microscopy (transmitted, polarized, and reflected light) on 30 µm thin sections and polished sections to characterize zircon morphology. Complementary analyses using a ZEISS Merlin SEM (IIT Roorkee), coupled with an EDS detector, enabled the characterization of minerals and uranium oxides in secondary and backscattered electron modes, with elemental mapping. The analyses were performed at 10 kV, 1 nA and acquisition times of 56 to 124 s (Figure 3).

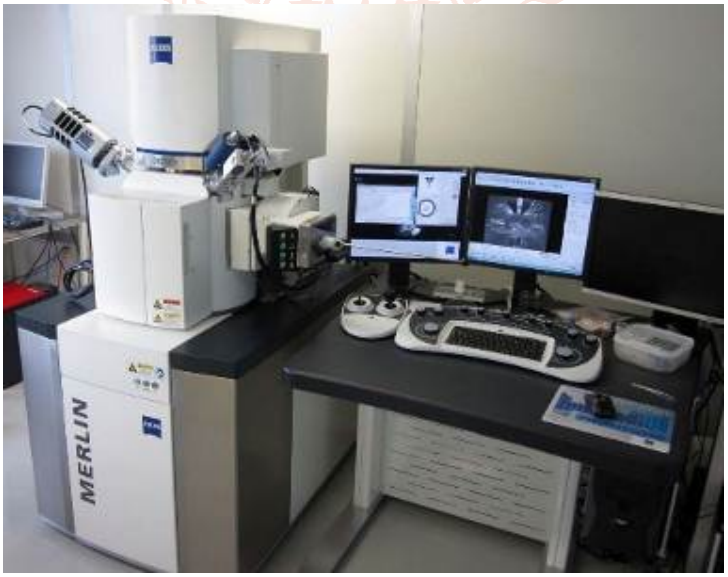

Figure 3 : Merlin-type scanning electron microscope

3. Results and discussion

3.1. Morphology of detrital zircons

Morphological analysis of zircons under optical and electron microscopy reveals a notable diversity of shapes, dominated mainly by elongated zircons and ovoid zircons.

3.1.1. Elongated zircons

The combined analysis of the morphological characteristics and geochemical data of the studied zircons reveals a close relationship between their crystallization mode and the evolution of the magmatic system from which they originated. Morphologically (Figure 4), the zircons exhibit elongated, prismatic, and euhedral forms with remarkable clarity. This crystalline facies reflects free growth in a magmatic liquid under relatively stable and high-temperature conditions. According to the work of Pupin (1976, 1980), zircon morphology is directly controlled by the temperature and composition of the magma. Elongated prismatic zircons are typically associated with differentiated magmas, often of volcanic or subvolcanic origin. This interpretation is reinforced by the absence of obvious traces of reworking or alteration, which largely rules out a detrital or metamorphic origin.

From a geochemical perspective, EDS analyses (**Figure 5**) reveal enrichment in uranium (U), vanadium (V), and molybdenum (Mo). Uranium, an incompatible element, readily integrates into the zircon structure by substituting for zirconium, and its concentration generally increases with the degree of magma differentiation (Hoskin and Schaltegger, 2003). Thus, a high uranium content is a reliable indicator of an evolved magmatic environment.

Furthermore, Belousova et al. (2002, 2006) showed that magmatic zircons are often enriched in trace elements such as U, Th, and certain transition metals, reflecting the composition of the residual fluid. The presence of V and Mo, although less typical, suggests enrichment of the system in metalliferous elements, which could be linked either to strong magmatic differentiation or to the involvement of late-stage fluids. Chemical mapping also reveals a close association of zircons with silicate phases, as well as the distribution of aluminum in their immediate environment. This textural relationship indicates syn-magmatic crystallization within an evolving silicate liquid. Taken together, these observations highlight a consistent magmatic signature: the euhedral and prismatic morphology indicates free growth within a magma; the uranium enrichment reflects an advanced degree of differentiation; the presence of vanadium and molybdenum suggests a system enriched in incompatible elements; and the association with silicates confirms primary crystallization within a magmatic matrix. Nevertheless, certain limitations must be considered. The presence of molybdenum and vanadium could also reflect a late hydrothermal influence, capable of modifying the chemical composition without significantly altering the zircon morphology.

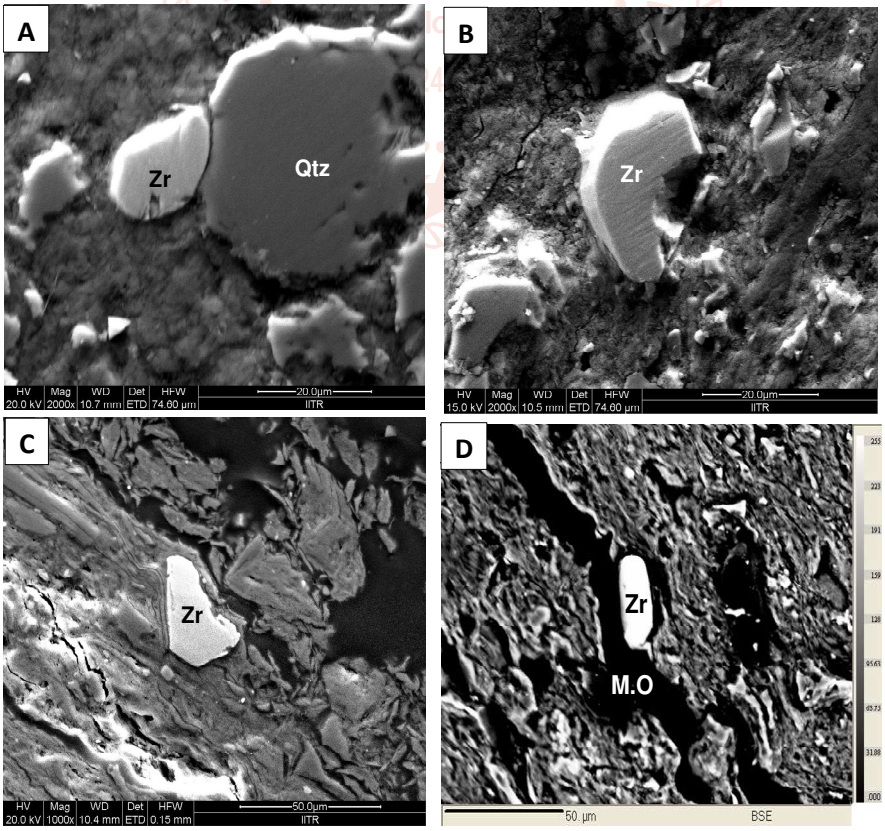

Figure 4: A : Observation of elongated zircon (Zr) by SEM: A – zircon in corrosion with detrital quartz grain (Qtz); B- elongated zircon; C- elongated zircon associated with clay phase; D- detrital zircon epigenized by organic matter.

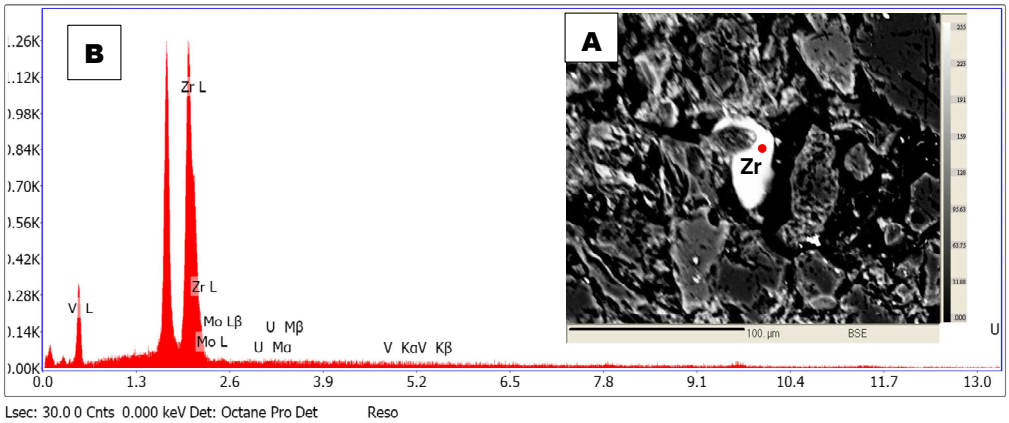

Figure 5. : A: Elongated zircon associated with the clay phase; B: EDS spectrum on detrital zircon (Zr) grain showing the enrichment of the latter in U, V and Mo.

3.1.2. Ovoid-shaped zircons

The studied zircons, ovoid in shape (Figure 6), exhibit subhedral to euhedral crystals and a significant size, reaching approximately 400 µm. This morphology contrasts with that of elongated prismatic zircons and reflects different crystallization conditions, typically associated with alkaline granitic masses or anorogenic felsic magmas. Large ovoid zircons are generally considered to be residual or accumulated crystals from plutonic rocks or the erosion of such rocks (Pupin, 1976; Forbes, 1989). Geochemically, EDS analyses (Figure 7) also reveal significant enrichment in U, V, and Mo. The high uranium contents indicate, as with the prismatic zircons, an evolved magmatic environment, typical of anorogenic alkaline and rhyolitic granitic systems (Hoskin and Schaltegger, 2003). The presence of V and Mo suggests an environment enriched in incompatible elements, consistent with the alkaline and aluminous nature of these rocks. Chemical mapping shows the distribution of Si, Zr, and U, confirming that these zircons are closely associated with the silicate matrix and that uranium is concentrated within the crystal, indicating primary magmatic crystallization. This spatial distribution of elements supports the hypothesis of crystallization in a felsic liquid rich in silicates and incompatible elements. The combination of the ovoid morphology and chemical composition thus allows us to infer a secondary origin derived from the erosion of alkali granites or alkaline rhyolitic volcanic rocks. These zircons bear witness to erosion and sedimentary transport processes while retaining their primary magmatic signature.

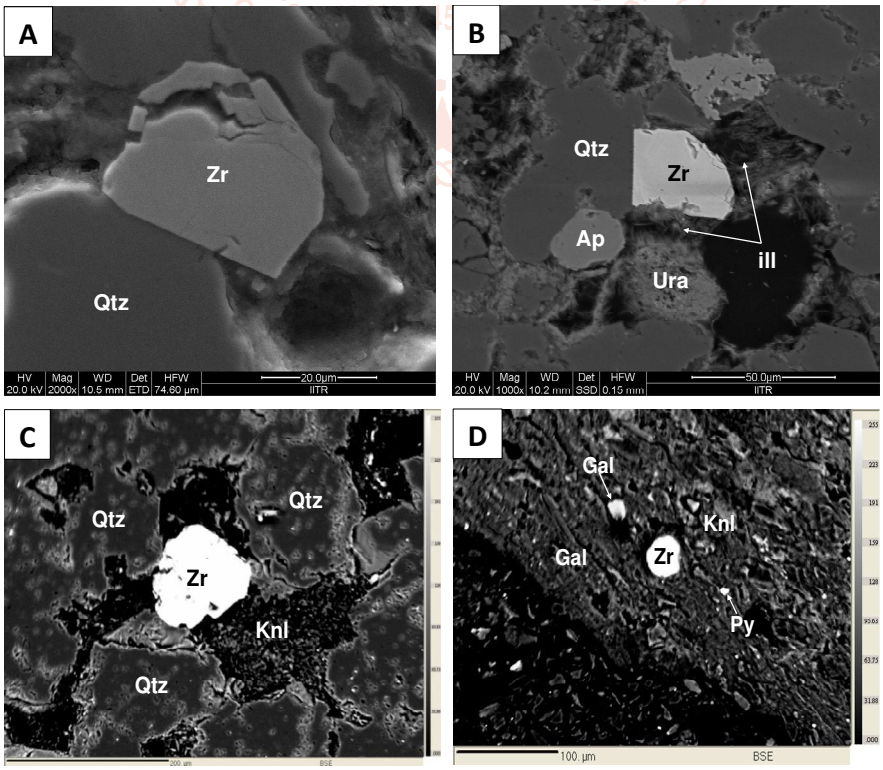

Figure 6 : Observation of ovoid zircon (Zr) in SEM: A- zircon in corrosion on detrital quartz grain (Qtz); B- zircon associated with illites, quartz, uraninite and apatite; C- zircon in epigenesis in kaolinite; D- zircon associated with kaolinite, galena and pyrite.

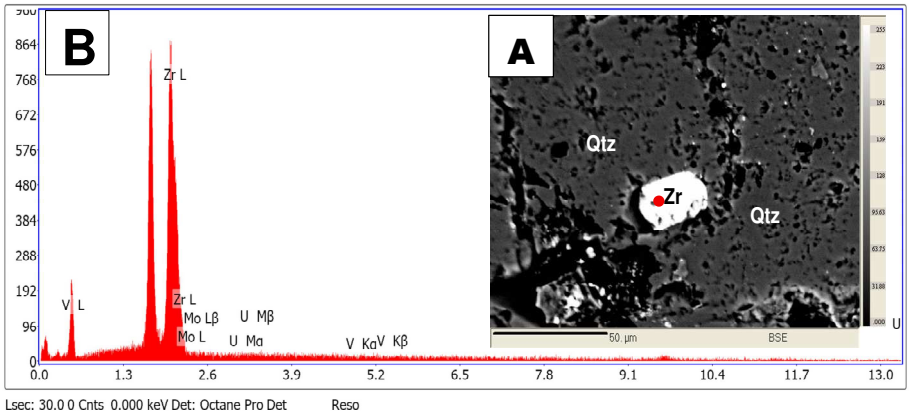

Figure 7. A : zircon in corrosion on quartz detrital grain (Qtz); B: EDS spectrum on zircon detrital grain (Zr) showing enrichment in U, V and Mo.

3.2. Geochemical signatures of zircons

The analyzed zircons (Table 1) exhibit a geochemical signature marked by significant uranium enrichment (UO_2 ≈ 54.79%) and relatively low ZrO_2 contents (≈ 15.28%) compared to the theoretical zircon composition ($ZrSiO_4$). This anomaly reflects the existence of isomorphic substitution mechanisms in which U^{4+} ions replace Zr^{4+} ions in the crystal lattice. This type of substitution is favored in environments rich in incompatible elements, particularly during the late stages of magmatic crystallization. Uranium, a lithophilic element with a large ionic radius, tends to concentrate in residual liquids during magmatic differentiation. Thus, the observed enrichment is a robust indicator of an evolved magmatic origin, typical of highly differentiated felsic magmas (Hoskin and Schaltegger, 2003). The relative decrease in ZrO_2 content can also be interpreted as a consequence of structural alteration processes, particularly metamictization. This phenomenon results from the accumulation of damage in the crystal lattice due to the radioactive decay of uranium and thorium, leading to partial disorganization of the zircon structure. This disorganization promotes fluid circulation and the incorporation of foreign elements, explaining the presence of minor elements such as Ca, Fe, and Mn. The TiO_2 content, at approximately 2%, places significant constraints on the thermal conditions of crystallization. According to the "Ti-in-zircon" thermometer proposed by Watson and Harrison (2005), these values correspond to relatively high crystallization temperatures, generally between 700 and 900 °C. These conditions are consistent with deep magmatic environments or high-grade metamorphic settings, thus confirming the primary origin of the zircons in an energetic thermal system. Furthermore, the ovoid morphology observed in some grains provides additional evidence for secondary processes. This type of morphology is generally interpreted as the result of mechanical wear related to sedimentary transport or recrystallization in a metamorphic setting. According to Corfu et al. (2003), zircons exhibiting such shapes may correspond to inherited grains that have undergone several geological cycles, including erosion, transport, deposition, and recrystallization. Thus, the combination of geochemical and morphological characteristics suggests not only an evolved magmatic origin but also a complex geological history involving processes of remobilization, alteration, and recycling.

Table 1 : Chemical composition of ovoid and elongated zircons by electron microprobe

Minéraux	SiO2	SO2	Al2O3	MnO	FeO	TiO2	MgO	CaO	ZrO2	PbO	UO2
Zircon ovoïde	13.28	0.36	0.92	0.69	0.29	2.01	0.51	1.95	16.33	0.01	53.44
Zircon allongé	12.87	0.33	0.89	0.65	0.27	2.03	0.49	1.89	15.99	0.04	53.66
Zircon ovoïde	13.91	0.36	0.87	0.71	0.34	2.11	0.52	1.77	16.29	0.02	54.02
Zircon allongé	13.27	0.32	0.91	0.73	0.32	1.99	0.48	2.51	16.35	0	55.67
Zircon ovoïde	13.28	0.14	0.93	0.71	0.33	2.04	0.5	2.55	13.95	0.01	55.88
Zircon allongé	11.47	0.16	0.85	0.77	0.31	2.13	0.49	2.57	14.06	0	54.99
Zircon allongé	11.51	0.17	0.9	0.78	0.31	2.13	0.49	2.49	14.01	0.02	55.91
Moyenne	**12.79**	**0.26**	**0.89**	**0.72**	**0.31**	**2.06**	**0.49**	**2.24**	**15.28**	**0.01**	**54.79**

4. Conclusion

The morphological and geochemical study of detrital zircons from Carboniferous formations in the Tim-Mersoï Basin reveals a signature dominated by inputs from evolved magmatic sources, particularly the granitic-volcanic complexes of the Aïr Massif. The coexistence of euhedral prismatic zircons and ovoid zircons suggests both primary magmatic crystallization and sedimentary reworking of inherited grains. Geochemical analyses reveal a significant enrichment in uranium, associated with

trace elements such as vegetum and molybdenum, indicating crystallization in differentiated magmatic liquids rich in incompatible elements. Titanium content indicates high formation temperatures, consistent with deep magmatic environments. Furthermore, the observed chemical anomalies, notably the substitution of zirconium by uranium and the presence of secondary elements, point to post-magmatic processes such as metamictization and hydrothermal interactions. These results highlight a dual contribution to the genesis of uranium mineralization: a primary magmatic source enriched in uranium, followed by sedimentary and diagenetic processes responsible for its mobilization, transport, and concentration in detrital layers. Thus, detrital zircons constitute reliable tracers of sediment provenance and the metallogenic potential of the Tim-Mersoi Basin. This approach offers significant prospects for uranium exploration, although further analyses, particularly isotopic analyses, are needed to better constrain the temporal and genetic evolution of the system.

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