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MAPPING OF REDOX ZONES AND THEIR RELATION TO URANIUM MINERALISATION IN THE ARTOIS NE SECTOR OF THE TIM MERSOI SUB-BASIN. NIGER REPUBLIC

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ABSTRACT

Ditch cutting and well logging data were used to analyze the uranium mineralized Tarat Formation in Artois NE sector of the Tim Mersoi Basin in the Niger Republic. The research subdivided Tarat into three lithological subunits: Tarat-Madaouela. Upper Tarat. and Lower Tarat. and produced maps indicating oxyhydroxide accumulation and radiometry. These results show a relationship between oxidized and reduced zones. crucial for understanding the uranium mineralization process. with oxyhydroxides indicative of oxidizing environments driven by oxidizing fluid circulation. Notably. Tarat-Madaouela is more oxidized yet mineralized in its reduced parts. while Upper Tarat is largely reduced without significant mineralization. Lower Tarat is predominantly reduced and mineralized. The study also highlights that the observed mineralization correlates with redox processes. influenced by structural. lithological. stratigraphic. and hydrogeological factors.

Keywords: Uranium, Redox, Tarat, Tim Mersoi, Niger

1 INTRODUCTION

Uranium mineralization in Niger Republic occurred in the Tim Mersoi sub-basin in 3 major deposits namely Arlit. Akouta and Imouraren (Figure 1). In the first two deposits. it is hosted as U^{4+} phase in the reduced Carboniferous Tarat and Guézouman Formations respectively. while in the third deposit. it is hosted by the oxidized Tchirezrine 2 Jurassic Formation as U^{6+} silicate and vanadate minerals (Billon & Patrier. 2019) ; Mamadou et al.. 2022). The Artois NE sector. where the present study focuses. is part of the Arlit uranium deposit.

The Tim Mersoi sub-basin in Niger and the Tin Séririne syncline in Algeria constitute the northern part of the regional intracontinental Iullemmeden Basin. This tectonically sag-type depression is bordered to the north by the Tuareg Shield made of the Adrar des Iforas. the Hoggar and Air Mountains; to the south by the Nigerian-Benin Basement Complex; to the east by the Damagaram Mounio and to the west by the Liptako Gourma. The basin communicates with the Taoudeni Basin trough the Gao Trough. It extends for about 1000 km from north to south and 800 km from east to west and filled of 1.500 to 2.000 meters of Cambrian to Pleistocene sediments of alternating marine and continental origin (Kogbe. 1991; LeBlanc. 2022).

The present research used ditch cutting and well logging data to subdivide and map the oxyhydroxide accumulation and radiometry of the mineralized Tarat Formation to understand the uranium mineralization process in the basin.

1.1 Geological setting

The Tim Mersoi is made of 4 stratigraphic groups namely: (1) the Terada. constituted of mudstones. sandstones. and siltstones; (2) the Tagora. containing continental sandstones. marine sandstones. arkoses. and mudstones; (3) the Izégouandane. composed of arkoses. mudstones. and analcimolite; and (4) the Agadez. made of sandstones. arkoses. and significant amounts of volcanic material (LeBlanc. 2022)

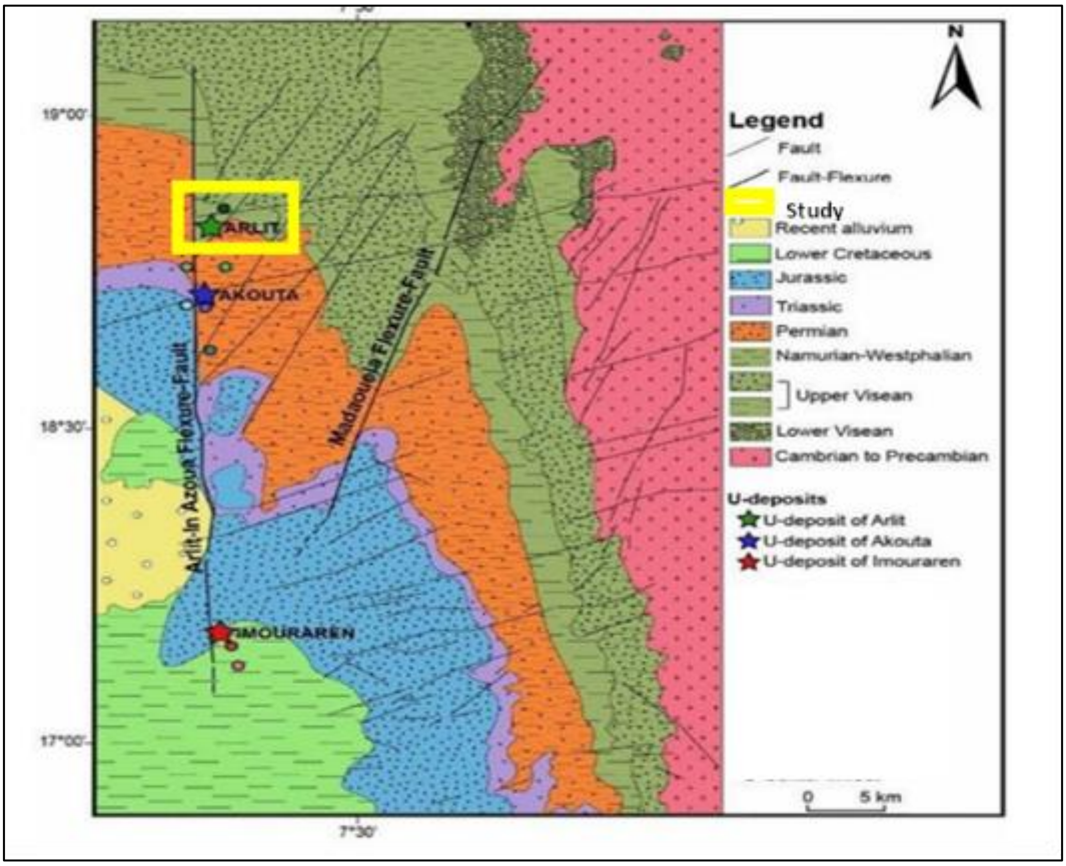

Figure 1: Geological and structural map of part of the Tim Mersoï Sub-Basin showing the location of Niger Uranium deposits of Arlit. Akouta and Imouraren (modified from Mamadou. 2016).

Structurally. the Tim Mersoi is composed of 3 compartments: A collapsed Western compartment. located west of the Arlit-In Azaoua Fault. in a half-graben. showing flexed or stretched layers; a triangular compartment in the middle called "Quart de Brie" between the Arlit In Azaoua and Madaouela Faults. in horst position. displaying an alternation of anticline domes and syncline troughs. associated with the Mouron and Izéretagen thrust-fault and an Eastern compartment. East of the Madaouela Fault. displaying an asymmetrical synclinal half-graben (Fig. 1). There are 3 principal fault-trends. namely NNE-SSW. NW-SE and WSW-ENE. The major one is the NNE-SSW trend. which is responsible for the existence of the two depressions within the basin. The NW-SE trending faults mark the western limit of the basin and display a downthrow of about 500 m (Konate *et al..* 2007; Yahaya et Lang. 2000; Clermont et *al.*. 1991; Kogbe. 1991).

The sediments within the Tim Mersoï sub-basin have been shaped by the reactivation of these tectonic structures. most of which were initiated during the Panafrican orogenesis and reactivated later during the Carboniferous and Cretaceous. These alterations played a major role in the current lithology and in the Uranium migration and mineralization (Le Blanc. 2022).

The basin can be described as an N30-trending syncline that has been divided into several blocks by N30-trending faults. However. the larger structure impacting is the NS-trending Arlit-In-Azaoua fault which seems to be the main metallotect of uraniferous mineralization. Extensive hydrothermal alterations related to fluid circulations along the fault are described in several studies such as Mamadou (2016). Billon and Patrier (2019) and Ahmed Elmola et al. (2020).

Uranium mineralization in the Tim Mersoi Basin is associated with sandstone and was considered syngenetic with sedimentary structures (Sempéré. 1981; Elhamet. 1983).

2 MATERIALS AND METHODS

Ditch cuttings samples. well logging probes (caliper. resistivity. radioactivity and SP) as well as Wellcad. Sermine. and ArcGIS softwares were used firstly to subdivide the mineralised Tarat formation into 3 lithological sub units and then to produce maps of oxyhydroxide accumulation and radiometry of each mineralized sub unit.

A total of 24 exploratory boreholes were drilled in the Artois NE sector. Ditch cutting samples (Fig. 2) at the site of drilling were carefully and systematically described according to their lithological facies on a log sheet. The lithological description includes. the colour of the facies. the lithology. the cement. the nature of the grains (rounded. angular. poorly sorted. homogeneous. dull. clear. etc.). the grain size. the redox degree. the content of pyrite. the content of organic matter. the carbonate content and any other additional observation such as the sedimentary structure. tectonic object. etc.

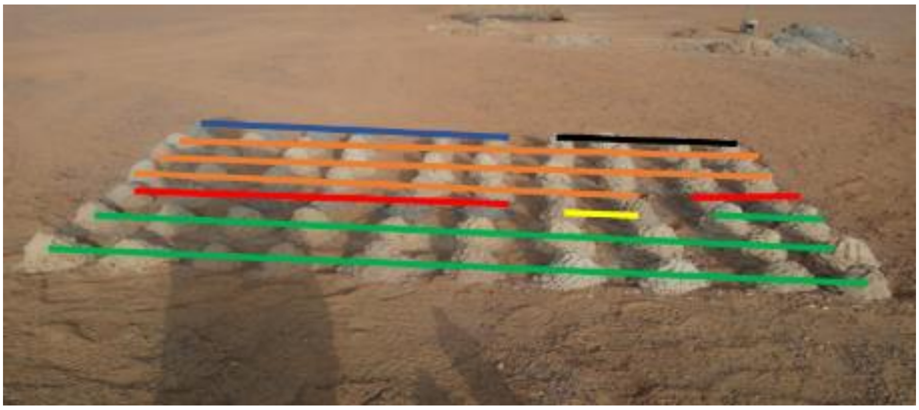

Fig. Ditch cutting samples from the NE Artois

Figure 2: Dictch cutting samples displaced on the NE Artois site

The well logging is carried out using a technical gadget made of two types of stacks or combinations of probes as follows:

2.1 Stack1: Caliper_GM28

This is made up of two different probes: a first probe. or caliper. with three arms. hence the name CAL3. which allows measuring the diameter of the hole. A second probe. called GM28. is an economical one used to detect mineralized zones. The probes are connected by a digital adapter. The whole setup is powered at 70V and forms a 3.11m stack (Fig. 3).

2.2 Stack2: DLL3_VERT_NGRS_SP

This setup has three probes instead of the two in Stack1 (Fig.3). The first probe is a resistivity probe called DLL3. which measures the resistivity of the rocks; the second probe. called VERT or verticality. measures the tilt of the hole relative to horizontal; and the third probe. called NGRS. measures the natural radioactivity of geological formations. The setup also includes the SP. which measures the chargeability in the geological formations it passes through. Stack2 is connected to a flange that carries the current to the probes. The stack is 3.55 m long and the flange is 5.23 m long.

The Well logging consisted of sending the two stacks one by one using a steel cable suspended from a tripod with a winch to measure various parameters. The results are displayed directly on a computer located in the diagraph operator's vehicle. Using software called Geovista. the results are presented as graphs in different colors depending on the parameter measured.

Before starting the logging. a test of the probes and probe stacks was performed using the test rule for the Caliper_GM28 stack and the housing and its cables for the Resistivity_Verticality_Gamma_SP stack. When lowering the stack. a reference point is set as the start of the recording. On the way back up. when the stack returns to its initial point. it can happen that the Logger shows a difference of a few centimetres compared to the zero set at the beginning of the recording. This difference was corrected using the "Operating Conditions" box on the logging sheet. Note here that all parameters are measured on the way up. except for SP. which is measured on the way down.

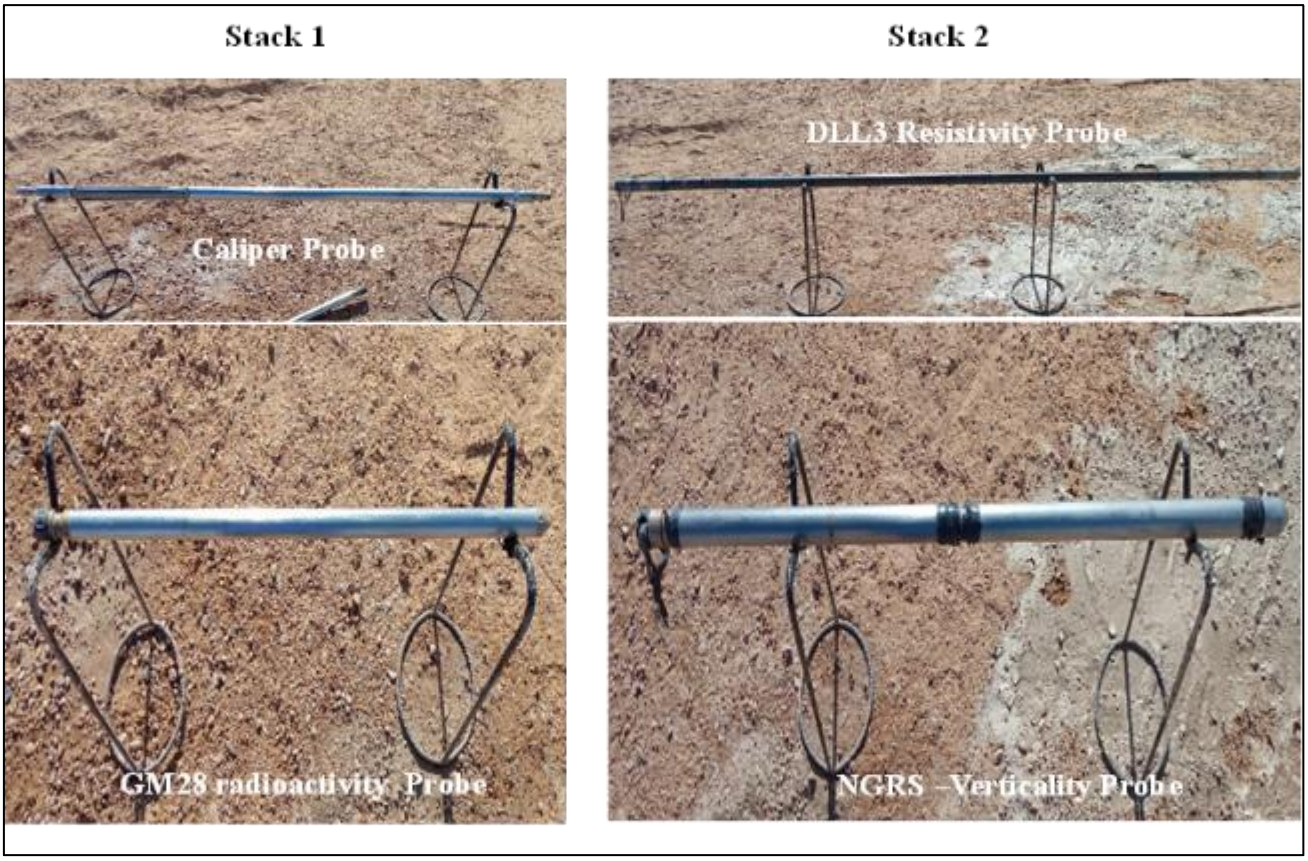

Figure : Stack 1 and Stack 2 equipment; **Figure: Stack 1 and 2 equipment**

Figure 3: Well logging Probes. Stack 1 & Stack 2

For the production of geological logs. Wellcad and Sermine softwares were used following the procedure chart below (Fig.4).

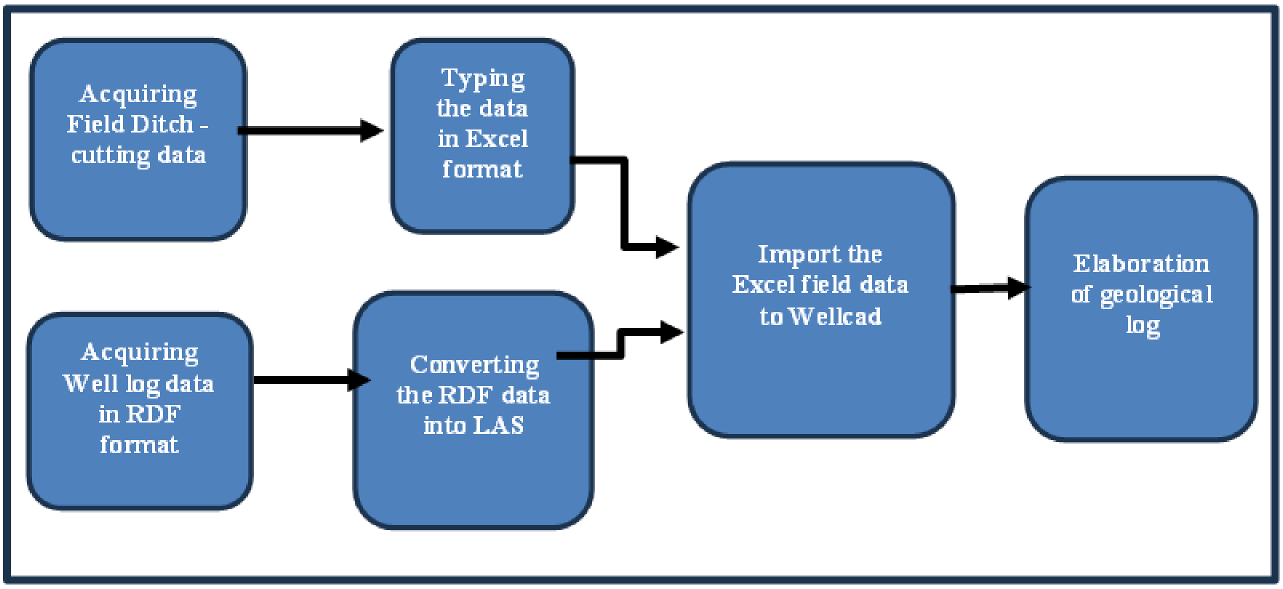

Figure 4: Procedure for geological log elaboration

3 RESULTS

3.1 Lithostratigraphy of the study area

Ditch cutting description and well logging data were combined to obtain an intra-Tarat stratigraphic subdivision. This layout takes into consideration the sequence stratigraphy as well as the elements of the paleogeography and depositional environment of the area. Hence the Tarat was split into three (3) sub units from top to bottom (Figs.):

- **The Tarat-Madaouela** sub unit: is made up of alternating medium sandstones with layers of clayey silts and fine sandstones. and coarse sandstone with layers of fine sandstone.
- **The Upper Tarat:** consists of coarse to very coarse grains. It is characterized by high resistivity values and can be fairly easily distinguished from the Madaouela. It is locally conglomeratic and sometimes contains pyrite.
- **The Lower Tarat:** is made up of light-gray medium sandstone and coarse sandstone. Silty layers or alternating silt-clay layers can appear between the coarse to very coarse sandstones. Small fine layers rich in organic matter (OM) and pyrite.

A geologic cross section of the Artois NE is also drawn from the boreholes and well log data (Fig. 5).

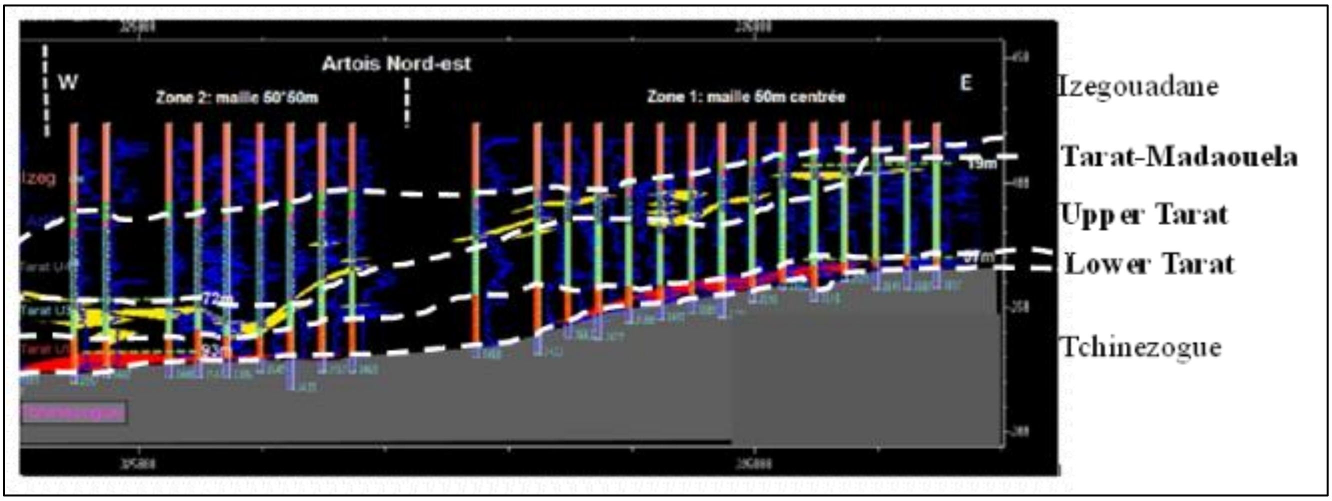

Figure 5: Geologic cross section of Artois Nord-Est

3.2 Mapping of redox zones in the North-East Artois area

Many studies conducted by earlier authors. such as the work of Grégoire (2006) have shown that redox phenomena are at the basis of the formation of the Arlit deposits. The promising results obtained in the Arlit fault area (Grégoire. 2006) encourage us to test the same method in other areas. despite very different structural contexts and highly variable Tarat thicknesses. Thus. the redox state is used as a metallotect (a structure that promotes the concentration of metallic minerals) in exploration. Characterizing and mapping the redox state of the Tarat formation in the North-East Artois area is a means of understanding how mineralization occurred and. in some cases. a guide for exploration. The redox mapping parameters used in this study are: oxyhydroxides (OXY) and radiometry (RA). Oxyhydroxides are compounds formed by the combination of metallic elements with oxygen. They mainly result from the weathering of ferrous minerals. The colour of the facies is the most commonly used indicator to assign the oxyhydroxide index which ranges from 0 to 3 as follows:

- ✓ 0: reduced facies;
- ✓ 1: slightly oxidized and leached facies;
- ✓ 2: oxidized facies;
- ✓ 3: highly oxidized facies.

The table 1 below describe the facies and their corresponding oxyhydroxide indices.

Table 1: Sedimentary facies and their corresponding oxyhydroxide indices

Facies Color	Oxyhydroxide Index	Type of Facies
Black. light gray. gray-green. green. yellow-green	0 à 1	Reduced. weakly oxidized. and washed-out appearance
Yellow. yellow-brown. brown. red. pink	2	Oxidized
Brownish red. reddish orange. purple	3	Very Oxidized

Hence. the oxyhydroxides values of the whole mineralised Tarat (Tarat – Madaouela. Upper Tarat. and Lower Tarat) can be computed from each borehole. As a case study. we use the borehole AT_3420_1 (Table 2).

Table 2: Oxyhydroxides values of Tarat in the borehole AT_3420_1

From (m)	To (m)	Oxy	Thickness (m)
13.65	14.69	2	1.04
14.69	16.14	2	1.45
16.14	19.15	0	3.01
19.15	21.41	0	2.26
21.41	25.3	0	3.89
25.3	27.81	0	2.51
27.81	29.83	0	2.02
29.83	35.54	1	5.71
35.54	36.51	0	0.97
36.51	38.54	0	2.03
38.54	39.9	1	1.36
39.9	41.36	0	1.46
41.36	44.11	1	2.75
44.11	46.98	0	2.87
46.98	49.36	0	2.38
49.36	51	0	1.64
51	55.08	0	4.08
55.08	56.22	0	1.14
56.22	57.5	0	1.28
57.5	60	0	2.5
60	60.35	0	0.35

3.3 Computation of the Redox accumulations in the Northeast Artois sector

The method for calculating the redox accumulation of a given index for a particular formation. and for any borehole. remains the same for both parameters and is calculated as follows

$Accus_{/s} = \{ \sum Accus_{/p} \ / \ \sum P \}$ with $Accus_{/p} = V \times P$ and $P = Cf - Ci$ (SOMAÏR. 2018).

- **Accus/s**: accumulation for a considered borehole;
- **Accus/p**: accumulation per pass;

- **V**: index value;
- **P**: Thickness;
- **Ci**: the roof;
- **Cf**: the wall.

Using this equation. the values of redox accumulations were computed and maps of the oxyhydroxide accumulation and radiometry of the whole Tarat. the Tarat – Madaouela. the Upper Tarat. and that the Lower Tarat were plotted as followed:

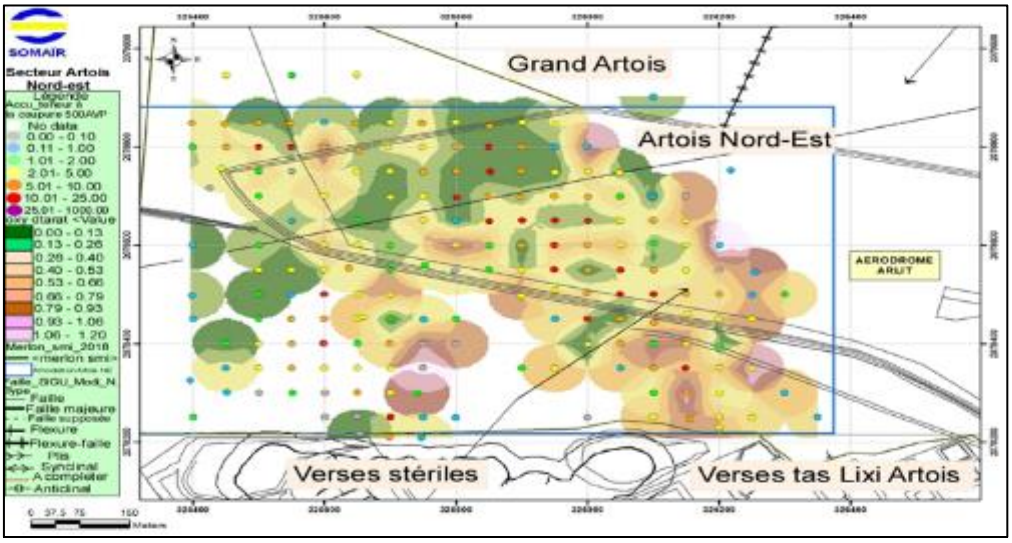

Figure 6: Map of oxyhydroxide accumulation and radiometry of the whole Tarat

From Fig. 6 above. the overall Tarat is moderately oxidized in the south and east with a maximum index of 1.06. In the north. parts of the west. and in the center. the Tarat is reduced or even leached. It is noticeable that the radiometric potential is higher in areas where the Tarat is reduced and slightly oxidized. and it is almost zero in the oxidized zones.

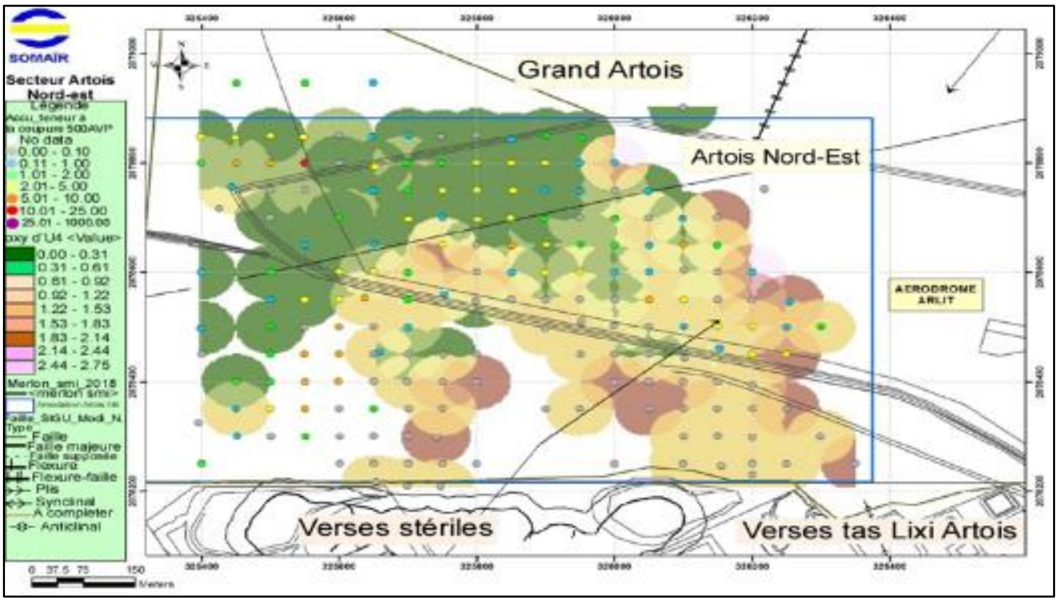

Figure 7: Map of oxyhydroxide accumulations and radiometry in the Tarat-Madaouela

The Tarat-Madaouela is reduced in the Northwest. It is oxidized in the Southeast and in the center. with a maximum accumulation of 2.14. It is noted that in the Tarat-Madaouela. the radiometric potential is higher in the reduced areas (Fig.7).

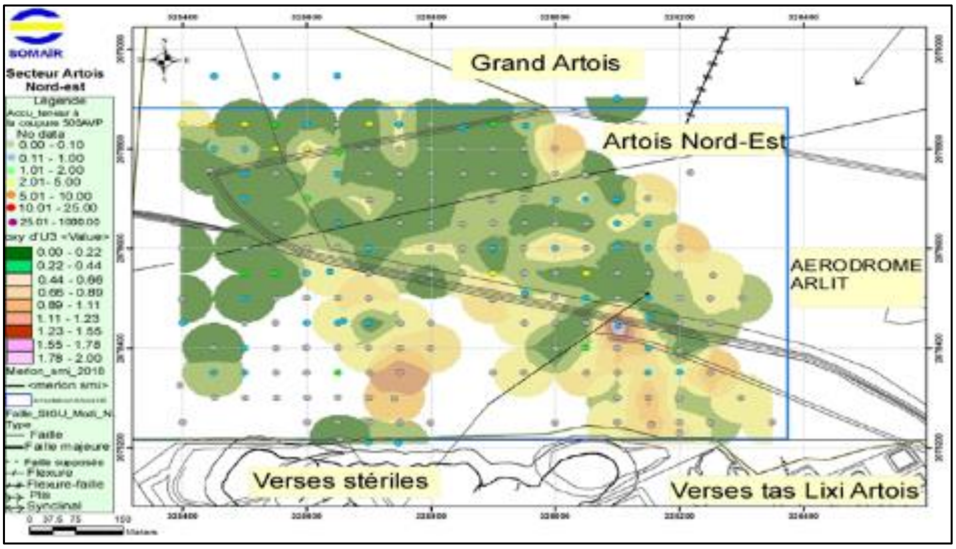

Figure 8: Accumulation map of oxyhydroxides and radiometry in the Upper Tarat

Overall. the Upper Tarat is reduced (about ¾ of the whole) and the indices range between 0.00 and 0.41. Only the extreme South and East are oxidized. with indices ranging from 0.44 to 1.11. It is noted that the Upper Tarat is not mineralized as a whole (Fig.8).

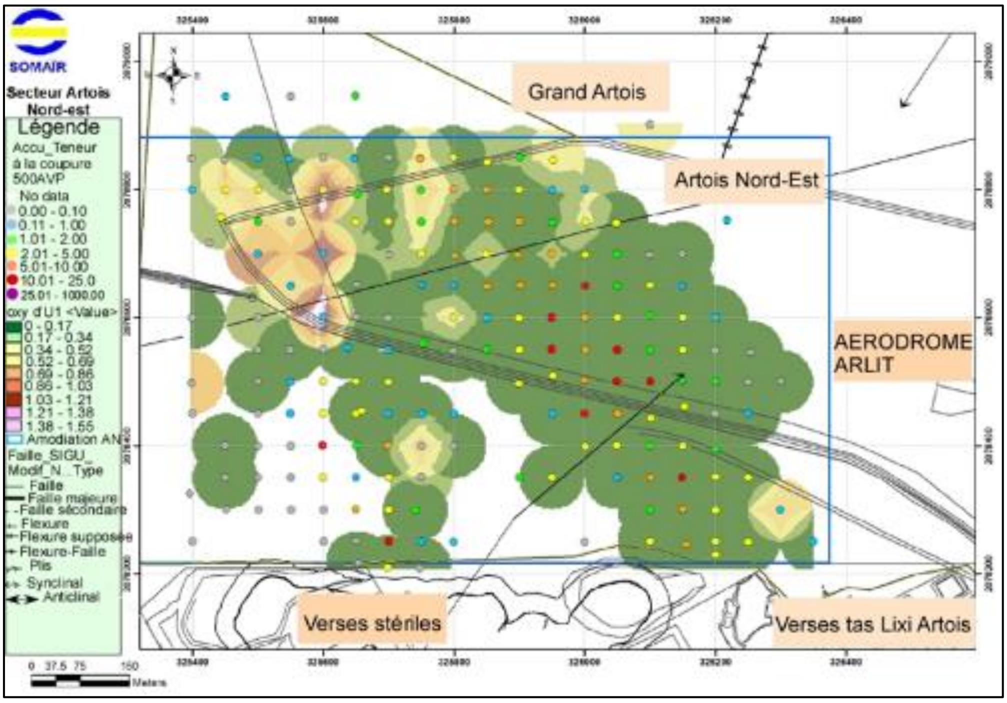

Figure 9: Accumulation map of oxyhydroxides and radiometry in the Lower Tarat

The Lower Tarat is largely reduced overall. These areas have indices ranging from 0.00 to 0.34. Part of its far Northwest is oxidized with a maximum accumulation of 1.21. The radiometric potential is very high in the reduced zones (Fig.9).

4 DISCUSSIONS

The distribution of oxidized and reduced areas. and more generally the spread of different redox indicators. is complex. It's probably controlled by a multiphase interaction between tectono-sedimentary factors on one hand. and fluid circulation mechanisms on the other. especially triggered during tectonic pulses linked to the activity of the Arlit fault. Interpreting the distribution of redox parameters gives us information about the type of facies. Oxyhydroxides indicate oxidized environments due to fluid circulations.

Precipitation and mobility of uranium in sandstone-type uranium deposits are influenced by redox potential (Eh). pH. and composition (Hongliang Dang et al.. 2025; Cumberland et al.. 2016; Szecsody et al.. 2013).

4.1 Interpretation of the distribution of reduced elements

In the North-East Artois area. identifying zones favorable for uranium trapping is based on the type of facies. Overall. the reduced elements are concentrated in medium to very coarse sandstone facies. As a result. they are found throughout the lower Tarat (U1). the upper Tarat. and in the Tarat-Madaouela. Like all deposits prior to the formation of Arlit. the Tarat belongs to the gray series of the Tim Mersoï basin. These correspond to primary reduced deposits. The Tarat was deposited in a fluvio-deltaic environment. which explains the plant origin of the organic matter abundantly found in these gray formations.

4.2 Interpretation of the oxidation distribution

The identification of oxidized zones is based on oxyhydroxides. which give characteristic colors depending on the oxidation state. Since the Tarat formation is a primary reduced formation. any oxidation of this formation would logically occur after the formation was laid down. A first hypothesis. according to Forbes (1989). is linked to the circulation of oxidizing fluids coming from the east through the Arlit fault. The abundance of certain minerals like U. Mo. V. Zr. Zn. Pb found in the area indicates the magmatic origin of the sediments carrying the oxidizing fluids. which are also mineralizing.

Another hypothesis according to Valsardieu (1971) involves fluid circulations drained from the basement. This last hypothesis seems to be the most obvious in the northeastern Artois area since most of the oxidation is located to the east and south. and not to the west. The fluid circulations completely or partially carried away the Tarat-Madaouela during their passage. mainly through the channe ls draining these fluids. The oxyhydroxides are strongly represented in the coarse formations. The colours observed come from certain minerals that. when changing their redox state. change colour—particularly iron. which. when oxidized. it colours the primary gray rocks to yellow. orange. pink. or red depending on the degree of oxidation.

4.3 Uranium and redox relationship in Tarat

The relationship between uranium/oxyhydroxides is quite clear in the Northeast Artois area. Analysis of the distribution maps of oxyhydroxides and radiometry shows that in Tarat-Madaouela and Lower Tarat. mineralization is concentrated in areas that are weakly oxidized (Figs. 7 and 9). The broader Tarat distribution map of oxyhydroxides and radiometry indicates that mineralization is concentrated in weakly and moderately oxidized areas. Not all oxidized zones were favorable for uranium deposits. The more intense the oxidation. the more absent the mineralization. But areas with weak oxidation are conducive to mineralization. These areas correspond to medium oxidation of the facies. mainly situated at the interface between oxidized and reduced facies. corresponding to redox fronts. This is in line with the findings of Akhtar et al.. (2017). Hu et al.. (2024) who stated that sandstone-type uranium deposits primarily form due to the interaction between oxidized ore-forming fluids and reductants in permeable sandstones. Uranium precipitates at the redox interfaces. where soluble U^{6+} is reduced to insoluble U^{4+}.

5 CONCLUSION

The maps showing accumulations of oxyhydroxide and radiometric indices reveal a connection between oxidized zones. reduced zones. and mineralization. Oxyhydroxides characterize oxidizing environments formed during the circulation of oxidizing fluids. which are also responsible for mineralization. The study of the Tarat stratigraphic units in the Northeast Artois area led to the identification of three (3) subunits. Tarat-Madaouela. Upper Tarat and Lower Tarat and the locations of facies containing mineralization. The Tarat-Madaouela is more oxidized but mineralized in its reduced part. Upper Tarat is reduced but not mineralized overall. Lower Tarat is generally reduced and mineralized as a whole. In the Northeast Artois area. reduced environments appear gray. while oxidized areas range from pink to red. The study of the relationship between uranium and redox phenomena clearly confirms that mineralization is controlled by redox processes. However. it should be noted that this phenomenon is linked to several factors. including structural control. lithological control. stratigraphic control. and hydrogeological control.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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