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Metallogeny and Emplacement Conditions of Continental Terminal 3 (Ct^3) Iron Formations of the Niamey Region (Western Niger)

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Abstract

This study aims to characterize the different lithofacies of the Ct^3 formation in the Niamey region, and to determine the distribution of major and trace elements, in order to highlight the conditions for the establishment of iron mineralization. A lithological column, synthesizing sections of selected outcrops in the vicinity of Niamey, was produced. The chemical compositions of the selected samples were determined by X-ray fluorescence (XRF) spectrometry. Microscopic analysis of the thin sections determined the gœthitic nature of the oolitic iron ore. The oolites show a quartz, limonitic or gœthitic nucleus. Sometimes the nucleus is absent. From a morphoscopic point of view, two types of oolites have been distinguished: spherical-shaped and ellipsoidal-shaped oolites. The oolites are either contiguous or disseminated, as the case may be, in a limonitic to goethitic cement or in a fine sandstone matrix. The larger oolites (pisolites) are relatively friable. They reflect the influence of a relatively turbulent to submerged environment. The hardground of the iron mineralized horizons are covered by quartz grains. They are indicative of a submerged or emergent environment. X-ray fluorescence analysis shows high Fe_2O_3 contents (50% to 80%) and variable contents of major elements SiO_2, Al_2O_3, TiO_2, MnO, MgO, CaO, K_2O and P_2O_5 associated with certain trace elements such as Th, U, V, Y, Zn, Zr and As. The results of the study are an important tool for decision-makers to adopt effective prevention/remediation measures for groundwater contamination in the Continental terminal aquifer systems.

Keywords

Continental Terminal, Iron Ore Mineralization, Sedimentation Conditions, Oolites, Gœthites, Hardground

1. Introduction

Niger is rich in mineral resources including iron ore [1]. Previous work across the country [2] [3] [4] and various subsequent works including those of [5] [6] [7] have shown that iron mineralization is present in many deposits of western part of Niger (in the Iullemmeden Basin) and in its eastern in its (Termit Basin).

According to Franconi *et al.* [1], it is in the Cenozoic deposits attributed to the Continental terminal (Ct) that the most important iron mineralization has been highlighted. The inventory of spores and pollens [8], supported by K/Ar radiometric dating on ferruginous sandstones from the Kandi basin [9], made it possible to assign an Oligo-Miocene age to the formation of the Continental terminal. For Issoufou-Fatiou *et al.* [8], the paleoclimatic and environmental conditions, which prevailed during the setting up of this formation, evoke an open environment under a hot and dry tropical climate. However, the undifferentiated nature of the Continental terminal formation in the Kandi basin does not allow them to be correlated with the ferruginous horizons of the Iullemmeden basin, further north [10].

The precursor works [1]-[7] and those of Guillon *et al.* [11] carried out on the iron mineralization of Niger did not focus on the conditions in which this mineralization was set up. This study aims to fill this gap. It concerns the Niamey area, which is straddling the southeastern border of the West African Craton and the southwestern edge of the Iullemmeden basin [12]. The choice to study the surroundings of Niamey to highlight the factors that originate from the mineralization of the Ct formations also follows three observations. First, in the western part of Niger, the importance of Ct lies in the influence and control it has on soil formation [13], and the erosion surfaces depend on the oolite beds very indurated ferruginous layers that shape the slopes [14]. Secondly, forming an interconnected or even phreatic aquifer complex [15], the Ct series (Ct^1, Ct^2, Ct^3) also constitute the support for several socio-economic activities in Western Niger [16]. In West Africa and other parts of Africa, the Continental terminal formation is the main source of water for millions of people [17] [18] [19]. Finally, in the current context of climate change and urbanization linked to economic progress, largely resulting from strong anthropogenic pressures [20], understanding the origins and mineralization processes of Ct groundwater resources is at the heart of sub-regional concerns [21] [22]. Based on this observation, the objective of this work is to specify the sedimentation conditions of the iron, and to contribute to the understanding of the links between geology and the different groundwater aquifers present in the study area. This will be done by polarizing microscopic analysis in transmitted and reflected light, and by X-ray fluorescence (XRF) spectrometry.

2. Geological Setting

The study area is Niamey, the capital of Niger (**Figure 1(a)**). It extends on both banks of the *Niger River* (**Figure 1(b)**). The Niamey region is made up of four major geological formations, namely: 1) the Paleoproterozoic basement formations; 2) the Infracambrian formations; 3) and those of the Continental terminal and 4) the Quaternary formations [23]. It is recently recalled by [24] that the Ct is characterized, from the base to the top, by three distinct series: 1) a siderolithic series from Ader Doutchi or Ct^1; 2) a clayey-sandy series with lignites corresponding to Ct^2; 3) and a series of argillaceous sandstones from the Middle Niger representing the Ct^3 formation.

The Continental terminal of the Niamey region, resting unconformably either on the Birimian basement or on the Infracambrian sandstones, is represented by the clayey sandstone series of the Middle Niger (Ct^3) [25]. Numerous laminated bodies of sandstones, clayey sandstone, levels of ferruginous oolitic sandstone, conglomerates and cuirasses are found as lenses across the outcrop sections of eight sectors of the Niamey area, namely: Goudel Gorou, Soudouré, Bulfouda,

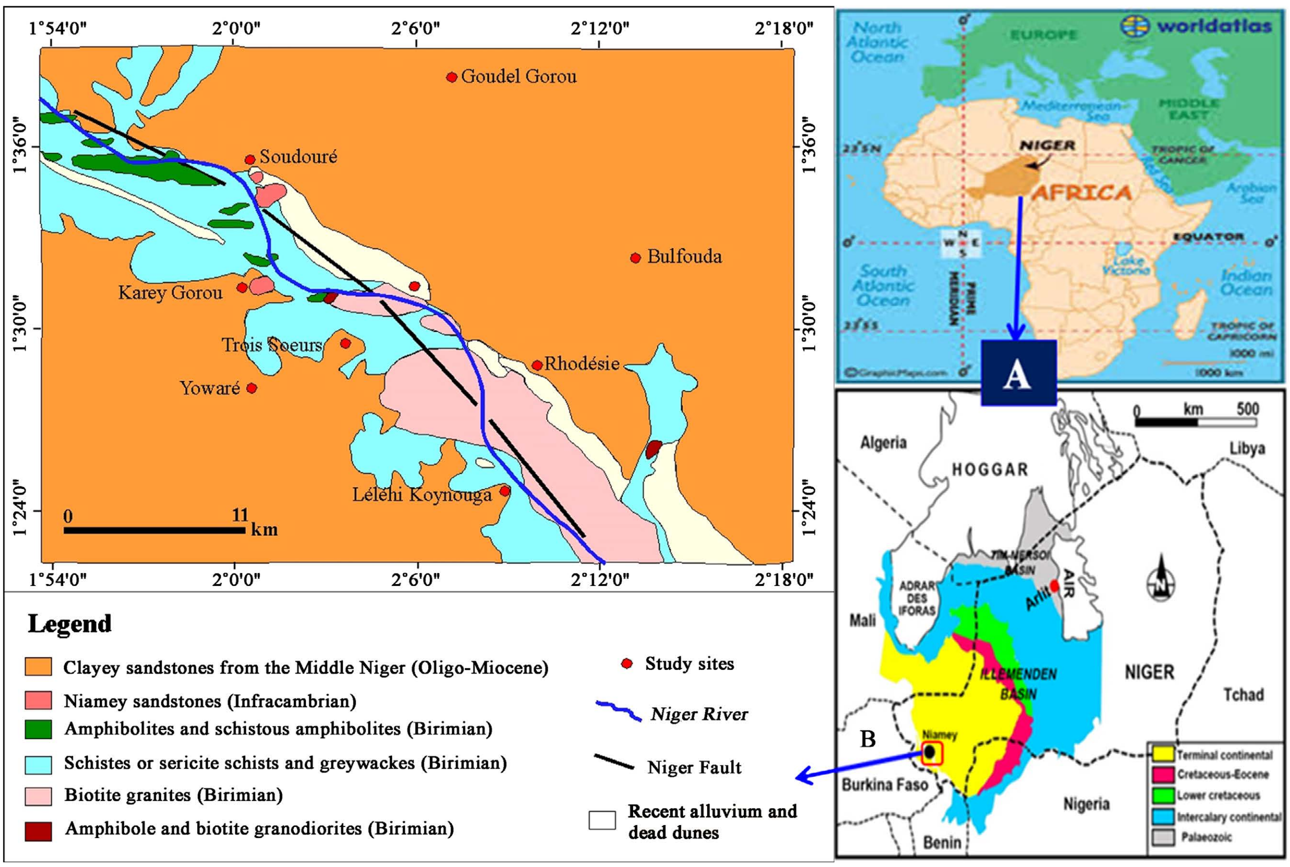

Figure 1. Location of the Niamey region. (a) Niger in Africa and Simplified geological map of the Iullemmeden basin (After [26]). (b) Simplified geological map of the study area ([24]).

"*Rhodésie*", Karey Gorou, Yowaré, the "*Trois Sœurs*", and Léléhi Koynouga (**Figure 1(b)**) [12] [24]. The ferruginous oolitic levels represent the iron ore deposit at the regional scale [25].

The sedimentological analysis [12] [24] made it possible to highlight the following levels, from bottom to top (**Figure 2**): 1) Level 1 consists of about 6 m of ferruginous oolitic to pisolithic sandstones, 2) Level 2, of about 25 m of thickness, is composed of two beds, namely bed 1 with alternating sandy argillites and ferruginous oolitic sandstone and bed 2 with alternating clayey sandstone and ferruginous oolitic sandstone, then 3) Level 3, about 7 m in thickness, begins at the base with a nodular facies and ended by a lateritic cuirass with pebbles of ferruginous oolitic sandstone. In order to characterize the stratified ferriferous lithofacies, and to define the composition in major and trace elements, and thus to identify their possible relationship with the conditions of occurrence of ironstone in the Ct^3 formation of Niamey area, this study was carried out.

3. Material and Analytical Method

3.1. Material

During the fieldwork, a total of 200 samples were taken and facies were identified within the three levels or members forming the synthetic sequence (**Figure 2**).

Among the rock samples taken, 42 are intended for making thin sections and six (6) for polished sections. A limited number of composite samples (n = 10) were subjected to geochemical analyses. Difficulties encountered during sampling and transportation are, among other things, linked to the lithological nature (soft facies) and to the heterogeneity of the facies (sometimes clayey, sometimes sandstone-clayey, sandstone-ferruginous, sometimes oolitic to pisolithic facies).

3.2. Analytical Method

The rock samples taken were first observed with a binocular magnifying glass at the Underground Water and Georesources Laboratory of the Faculty of Science and Techniques of the Abdou Moumouni University of Niamey (UAM). The samples observed were then sawed for the manufacturing of thin sections (n = 42) and polished sections (n = 6) at the laboratory of the Geological and Mining Research Center (CRGM) in Niamey (Niger). The thin sections and the polished sections were observed with a polarizing and metallographic microscope at the Laboratory of Underground Waters and Georesources of the Faculty of Sciences and Techniques of the UAM. The microphotographs obtained will make it possible to complete the description and the macroscopic analysis of the ferriferous facies in the study area. Finally, analyzes of elemental compositions using X-Ray Fluorence (XRF) were carried out on iron mineralization in the Niamey region. In total, a series of ten (10) composite samples, covering different sites (**Figure 1(b)**) and a wide range representative aliquots of each Ct^3 stratigraphic

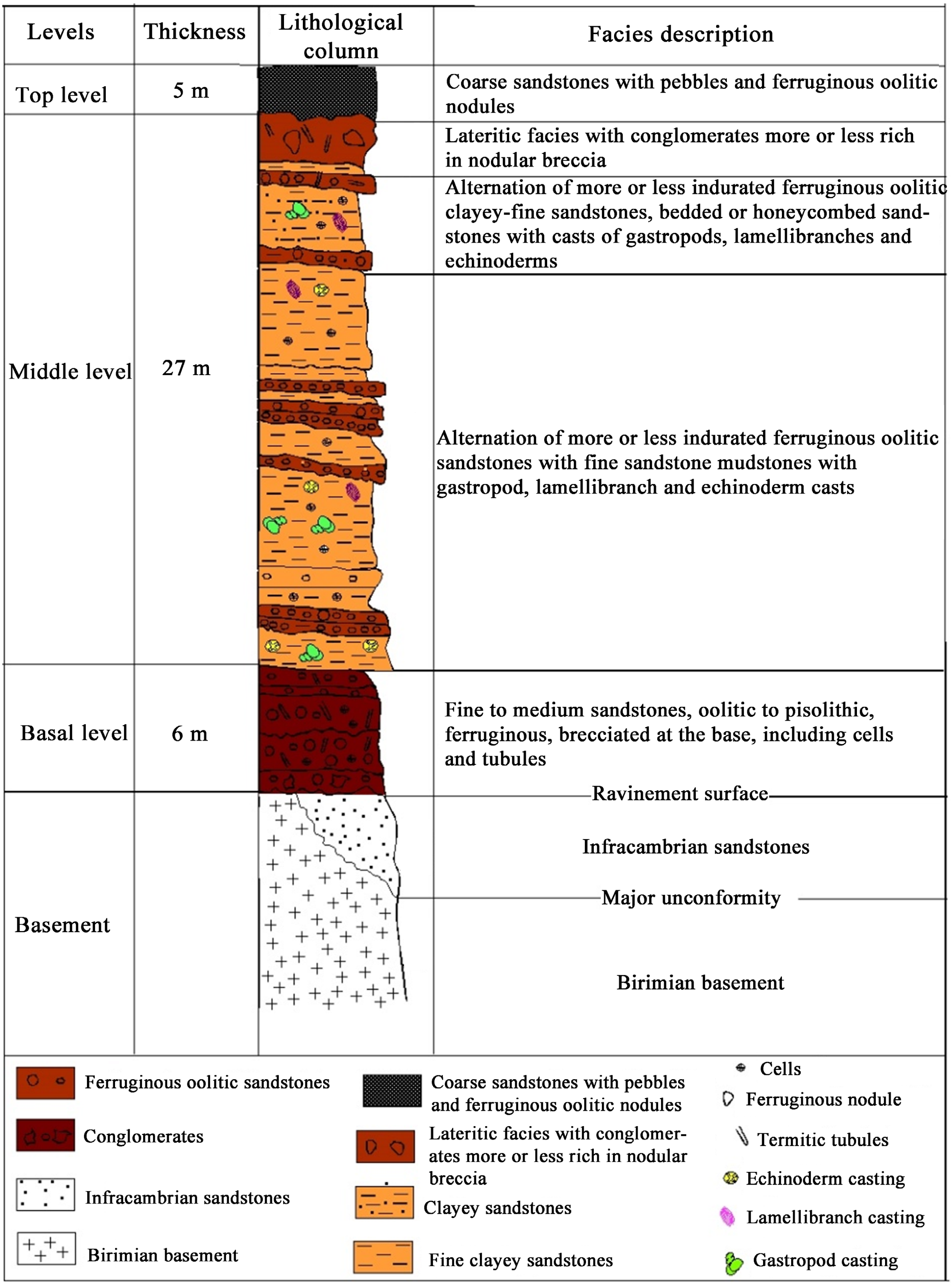

Figure 2. Synthetic lithological column of the Niamey area ([12] [24]).

level (**Figure 2**), were analyzed at the Laboratory of the Federal Institute for Geosciences and Natural Resources in Germany.

4. Results

4.1. Macroscopic Description of Iron Mineralized Facies

The base of the series (Level 1, **Figure 2**), overcoming a conglomeratic breccia, is represented by deposits of a sedimentary body increasingly rich in ferruginous oolites. This oolitic bed (6 m thick) is distinguished by an alternation of small levels of oolites of varying sizes (**Figure 3(a)**) which increasingly change to very fine-grained oolites (**Figure 3(a)**), fine, moderately coarse, and very coarse to pisolites (**Figure 3(b)**). The intermediate deposits of the Ct^3 formation (Level 2; **Figure 2**) are 27 m thick. The sequence contained several small levels (*circa* 8) of ferruginous oolitic sandstone. These small levels are sometimes more or less soft (**Figure 3(c)**, **Figure 3(d)**), hard to very hard and have a metallic sound. They are alternating with levels of clayey sandstone and sandstone argillites of metric to plurimetric thickness. In these argillites (sometimes kaolinized), there are also scattered ferruginous grains in the form of oolites, as well as freshwater molluscs and echinoids. The upper level, made up sometimes by a very dense ferruginous oolitic sandstone, is generally expressed in the form of a dark colored cuirass (**Figure 3(e)**), with pebbles of ferruginous oolitic sandstone in a clay matrix (**Figure 3(f)**). Thus, the eroded blocks of this level are found on the slopes or at the bottom of the outcrops, forming screes.

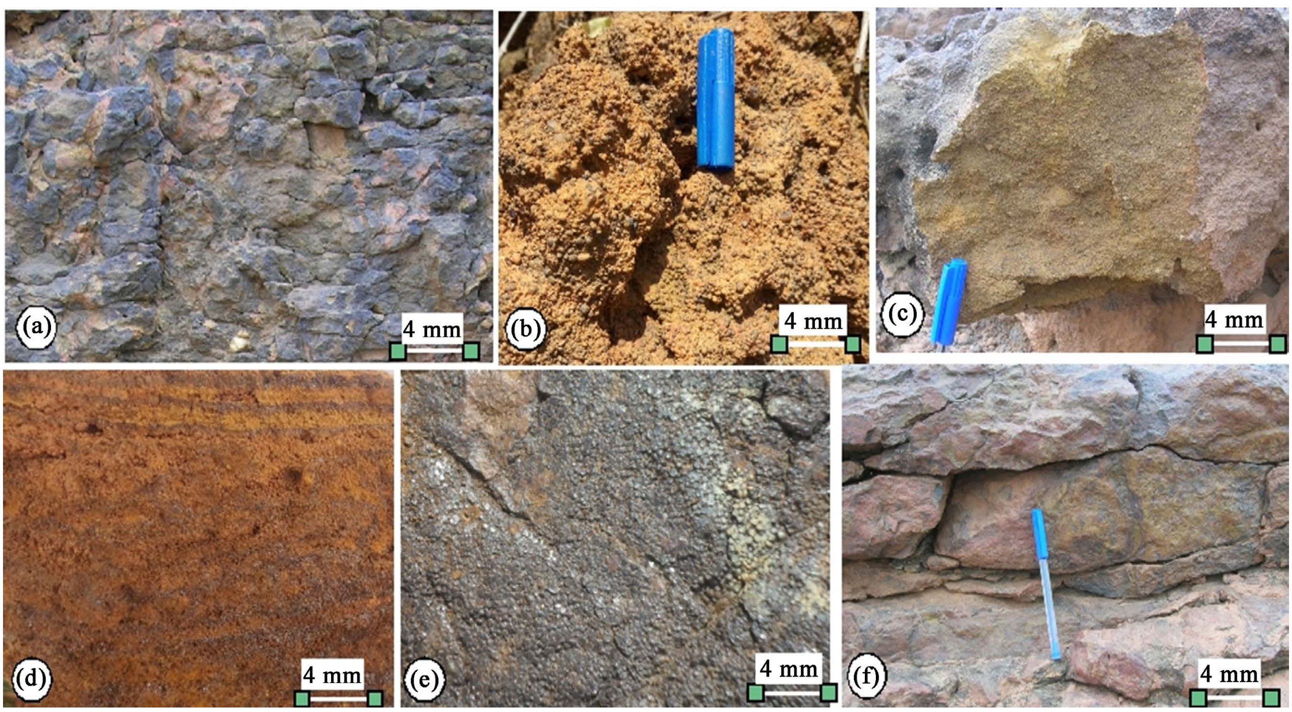

Figure 3. Photographs showing the different types of facies of the Continental terminal 3 oolitic ferruginous sandstone. (a) and (b) Oolitic ferruginous sandstone of the basal level. (c) and (d) Oolitic ferruginous sandstone of the intermediate level. (e) and (f) Oolitic ferruginous sandstone of the summit.

In general, the iron-mineralized facies, apart from a few rare flat horizontal or rough oblique bedding that stand out in certain levels (**Figure 3(d)**), present a massive structure. The oolites of these levels are of fine (**Figure 3(e)**) to very fine (**Figure 3(f)**) grain size. Also, the field analysis of the ferruginous facies shows the presence of very hard levels commonly called "indurated surfaces", "hardened surfaces", "hardened bottoms", or even "hard grounds". Most often mineralized in iron and lined with quartz grains, the indurated surfaces are located at the tops of the ferruginous facies and sometimes mark the limits of the beds (**Figure 4**).

Locally, ferruginous concretions in the form of an onchoid (**Figure 5**), whose

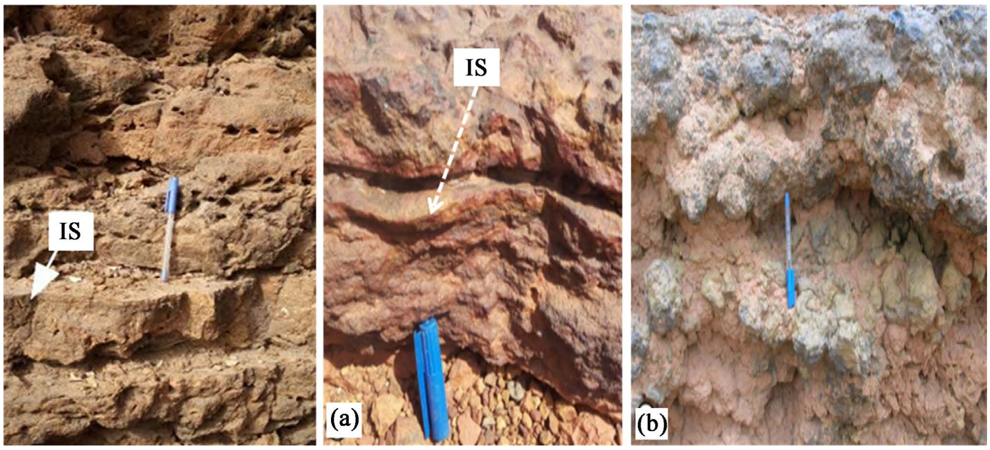

Figure 4. Photographs of the Ct^3 indurated surfaces (IS): alternation of benches more resistant to erosion and relatively soft interbeds in the base level (Léléhi Koynouga 1 sector). (a) Undisturbed indurated facies. (b) Reworked Indurated facies.

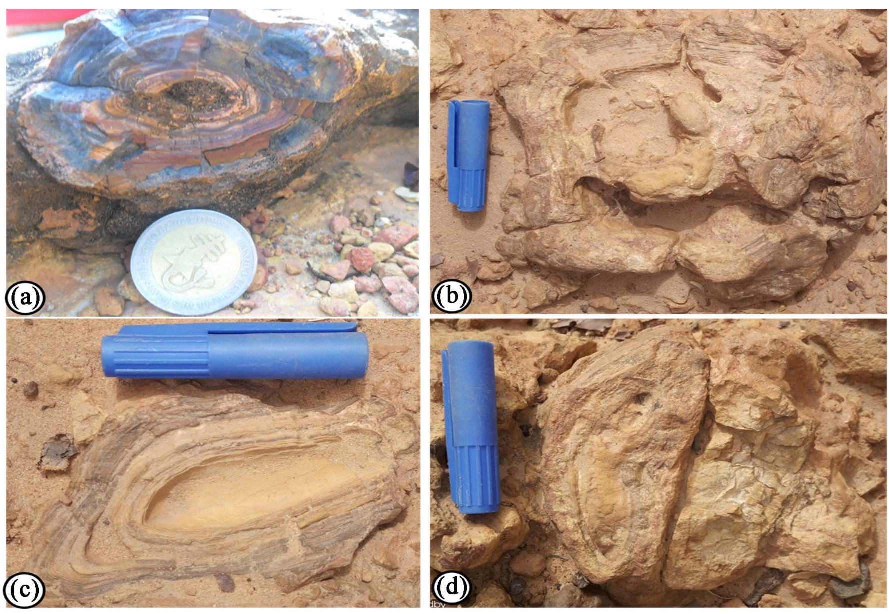

Figure 5. Macrophotograph showing ferruginous concretions (or coating banded ferruginous) of the intermediate level facies. (a) "*Trois Sœurs*" sector. (b)-(d) Léléhi Koynouga 1 sector.

central parts recall certain forms of life (**Figures 5(b)-(d)**), were identified. Depending on their shape and arrangement, however, two types of oolites can be distinguished: round (spherical) oolites and ellipsoidal oolites (**Figure 6**). In most facies, all these oolites are arranged in a contiguous manner (**Figure 6(a)** and **Figure 6(b)**). The binder is either clayey (**Figure 6(c)**), clayey-sandstone, clayey-ferruginous or silico-ferruginous for low-mineralized and ferruginous facies, or even ferrugino-siliceous (**Figure 6(d)**) for highly iron-mineralized facies.

4.2. Microscopic Analyzes of Ferruginous Oolitic Sandstones from Ct³

Microscopic analysis of thin sections of rock samples taken shows that iron mineralization is represented on the one hand by oolites with reddish to brownish

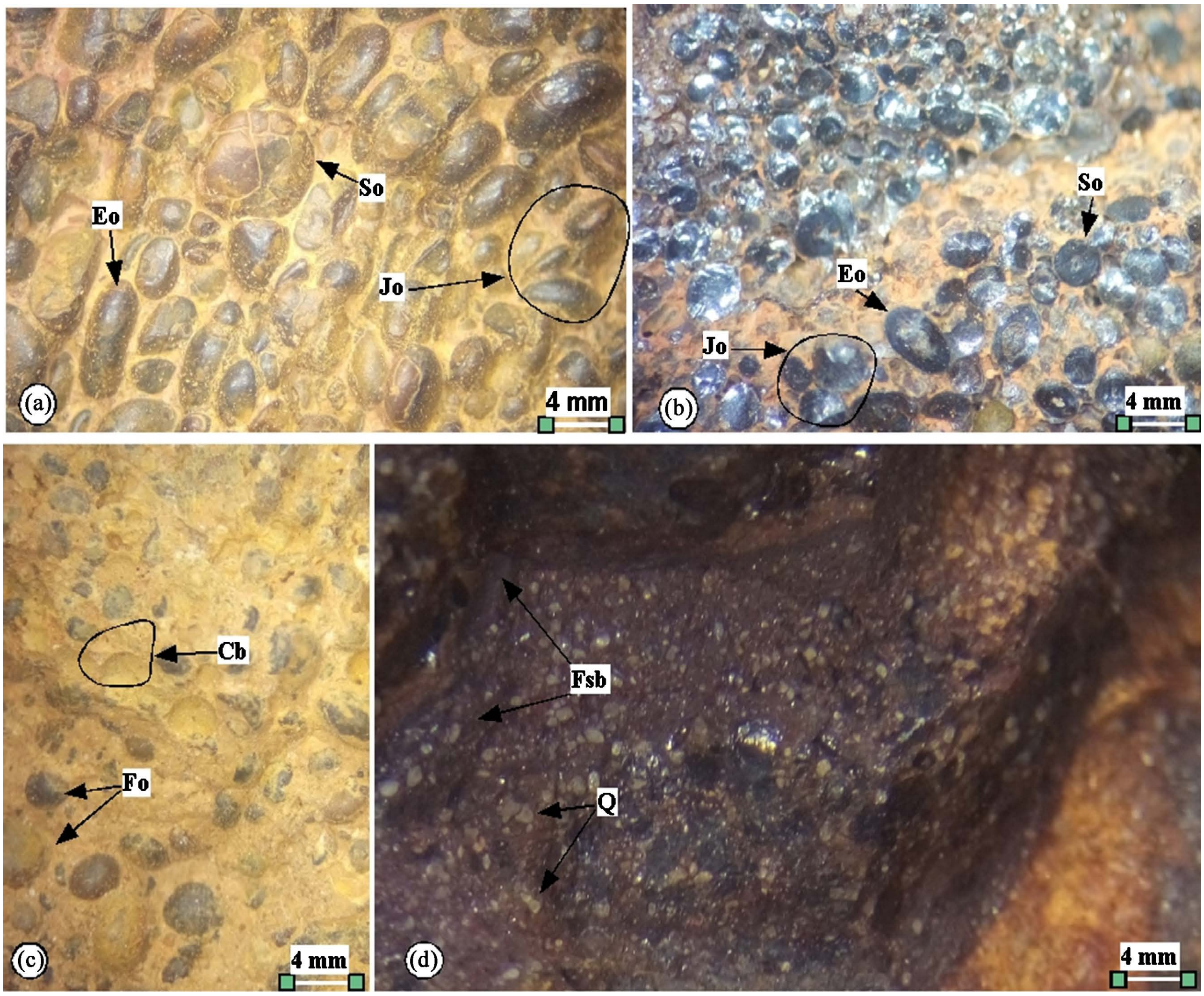

Figure 6. Photographs of some facies of the Ct³ oolitic ferruginous sandstones observed with a binocular magnifying glass. (a)-(c)—Magnifying glass view of the pisolithic facies of the first ferruginous level (**Figure 2** and **Figure 3(a)**) respectively of the sectors of: Léléhi Koynouga, Goudel Gorou and "*Trois Sœurs*". (d) Magnifying glass view of the summit facies, Goudel Gorou sector (**Figure 1**). Q—Quartz, JO—Contiguous oolites, Fo: floating oolites, Eo—Ellipsoid-shaped oolites, So—Spherical oolites, Fsb—Ferrugino-siliceous binder, Cb—Clayey binder.

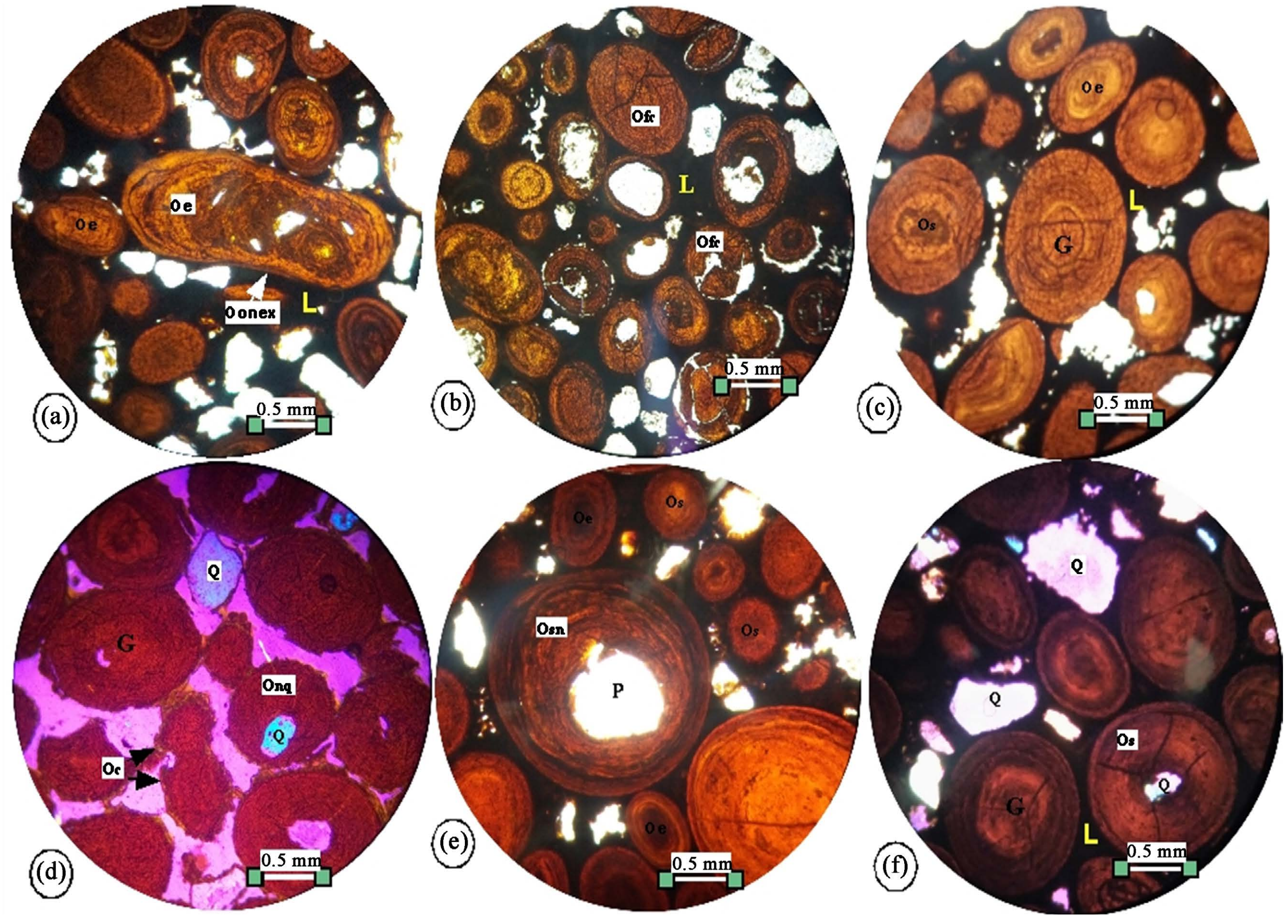

Figure 7. Microphotographs showing contiguous and non-contiguous ferruginous oolites from the Ct[3] formation in the Niamey region. (a)-(c) Observations in polarized light, (d)-(f) Observations in analyzed light, Onoex—Oolites with eccentric oolitic nucleus, Onq—Oolites with quartz nucleus; Osn—Oolites without nucleus, Ofc—Cracked ferruginous oolites; Oe—Ellipsoid-shaped oolite; Bones—Spherical oolites; Oc—Coalescent oolites; P—Pore; G—Goethite; L—Limonite; Q—Quartz

concentric zoning of goethite (**Figure 7**) and, on the other hand, by a relatively abundant brownish binder, consisting of a mixture iron oxides and hydroxides of a limonitic nature (**Figures 8(a)-(c)**, **Figure 8(e)** and **Figure 8(f)**). Textural (joining or floating) and morphological characteristics (spherical or ellipsoidal) oolites, observed macroscopically (**Figure 3** and **Figure 4**), can also be observed under a microscope (**Figure 7**).

The analysis of the internal environment of the oolites reveals the presence of three (3) types of oolites: one with oolitic cores (**Figure 7(a)**, **Figure 8(a)** and **Figure 8(b)**), the second with quartz core (**Figure 7(d)** and **Figure 7(f)**, **Figure 8(a)** and **Figure 8(b)**) and the third without nuclei (**Figure 7(e)**). Furthermore, some oolites are cracked or fragmented (**Figure 7(b)** and **Figure 8**).

The microphotographs of the binder phase (**Figure 9**) show that the matrix is essentially composed of sulphides represented by galena (PbS, (traces Ag, Zn, Fe)), sphalerite (ZnS), pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). These sulphides are still associated with other minerals such as: malachite ($Cu_2(OH)_3CO_3$) and gold (Au) as well as clays and quartz (Q).

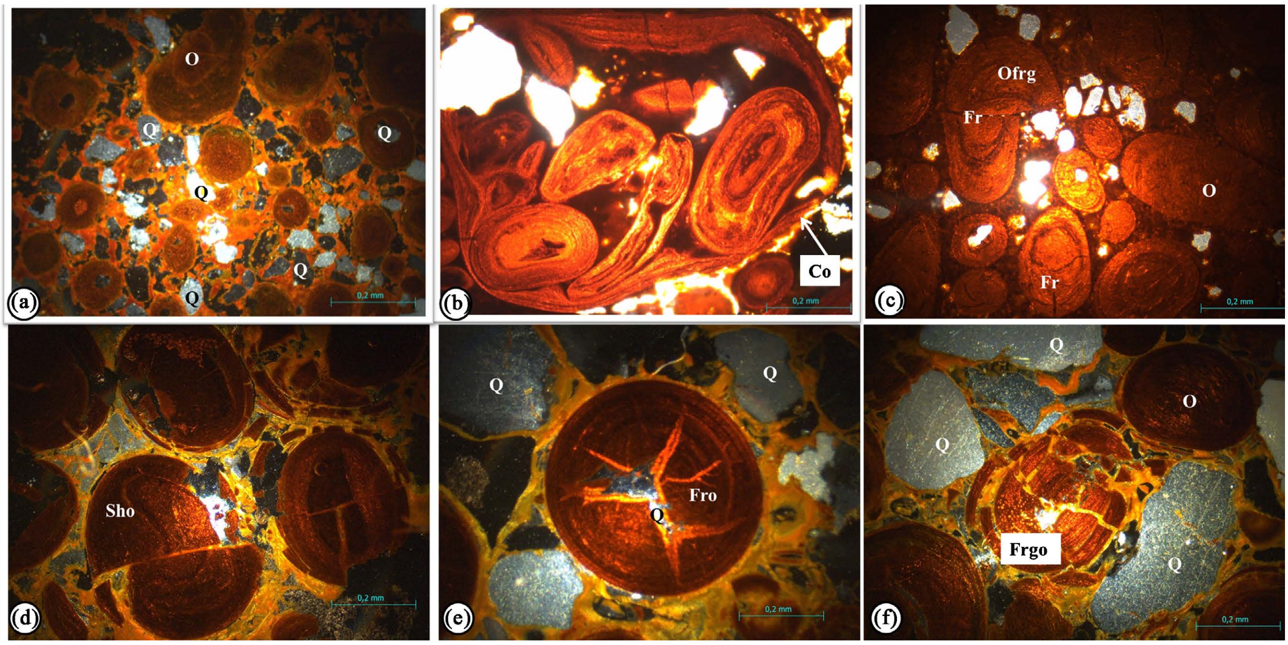

Figure 8. Microphotographs showing the different types of oolites and grains of quartz from ferruginous oolitic sandstones of Ct^3 from the Niamey region. (a) Oolites and quartz grains of variable size and shape in Ct^3 sandstones (Magnification ×40). (b) Large composite oolites, containing smaller oolites forming the nucleus of larger oolites (Magnification ×100). (c)-(f) (Magnification ×100)—Fractured ((c), (d)) and sheared (d) oolites. In D the shear is well marked, in F the oolite has a cataclastic appearance. Fractures are sealed with loamy or quartz-loamy or siliceous material. O—Oolite, Ofrg—Oolith fragment, Co—Composite Oolith, Sho—Sheared oolith, Fro—Fissured oolith, Frgo—Fragmented oolith, Fr—Fracture, Q—Quartz.

4.3. XRF Analysis of Ferruginous Oolitic Sandstones

The results of XRF analyzes of ferruginous oolitic sandstone samples from the Niamey region show three grade peaks (**Figure 10**). In addition, **Figure 10** makes it possible to oppose basal, intermediate and summit level, from right to left, respectively. A first triplet of Fe_2O_3 peaks with contents ranging from 50% to 80% can be distinguished, followed by a second of SiO_2 with compositions less than 40% and a third Al_2O_3 peak with contents less than 20%. Other major elements (Ti, Mn, Mg, Ca, K and P) are also associated with them, but their contents are generally low (**Figure 10**). Overall, the average contents of the major elements are distributed as follows: Fe_2O_3 (74.81%), SiO_2 (13.18%), Al_2O_3 (9.99%), TiO_2 (0.44%), MnO (0.29%), MgO (0.05%), CaO (0.09%), K_2O (0.01%) and P_2O_5 (1.09%). In regard to the Fe_2O_3 contents, note that the highest Fe_2O_3 concentrations are recorded in the top and bottom of the sequences (about 80% and 70%, respectively). On the other hand, the intermediate levels of the sequences show a clear enrichment in SiO_2 (approximately 35%) and in Al_2O_3 (approximately 15%).

The ferruginous oolitic facies of the three main levels contain other elements which, in trace amounts, include zircon, zinc, yttrium, vanadium, uranium, thorium, nickel, copper, chromium, cobalt and arsenic (**Table 1** and **Figure 11**).

The geochemical analysis shows that vanadium is the predominant element with averages of 331 ppm (at the base) to 460 ppm in the intermediate zone

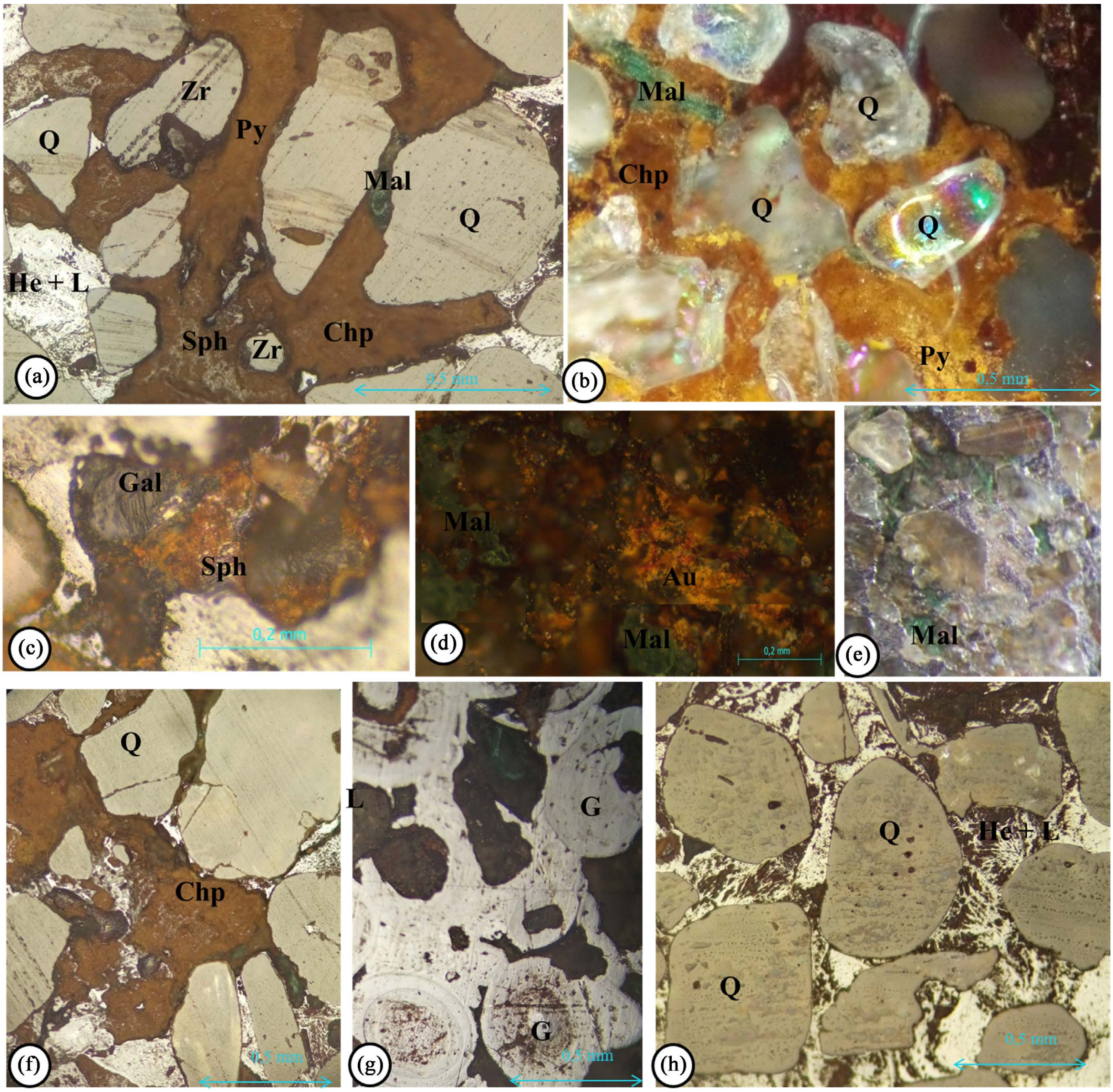

Figure 9. Microphotographs of polished thin sections of Ct^3 ferruginous oolitic sandstones from the Niamey region (40× magnification). Mal—Malachite, Au—Gold, Gal—Galena, G—Gœthite, Sph—Sphalerite, Chp—Chalcopyrite, Py—Pyrite, He—Hematite, L—Limonite, Q—Quartz, Zr—Zircon. View under a metallographic microscope in reflected light. ((a), (c), (f), (g)) and (h) without the polarizer. ((b), (d), (e)): Binocular magnifying glass observation of Ct^3 ferruginous oolitic sandstones showing prismatic malachite crystals occupying the intergranular space.

(**Figure 11**). With contents of 246 ppm, 106 ppm and 397 ppm (respectively at the base, intermediate and upper levels of Ct^3), zinc follows vanadium (**Figure 11**). There is also a tendency for zinc to mimic a systematic enrichment in both basal and top levels of the sequence, in addition to correlating fairly well with yttrium, uranium, nickel, cobalt, arsenic and the Fe_2O_3 (**Figure 10**). Arsenic concentrations vary in the range from 21 ppm to 74 ppm in the basal and top units respectively (**Figure 11**). The highest contents of Zr (323 ppm) and Cr (182

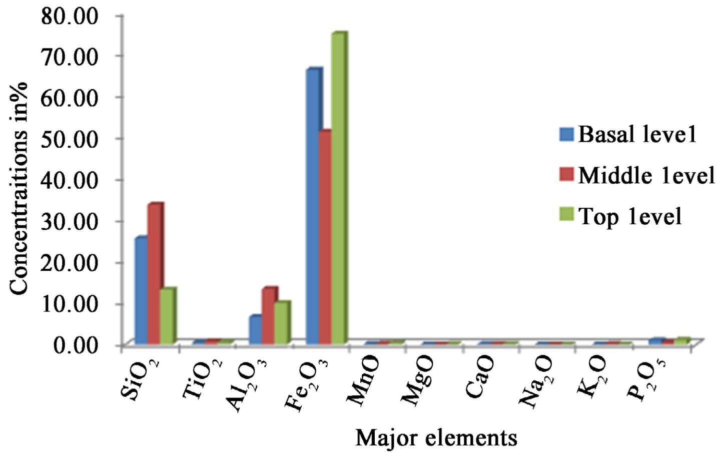

Figure 10. Major element compositions of the Niamey region Ct³ ferruginous oolitic sandstones.

Table 1. Distribution of trace elements of the Niamey region Ct³ ferruginous oolitic sandstone formation. The average grades per level (base, middle and summit) in the sequence are also calculated. ND—Not Detected.

	Trace Element (Concentration in ppm)										
	Zr	Zn	Y	V	U	Th	Ni	Cu	Cr	Co	As
Top Level	61	519	182	234	15	17	330	33	158	284	163
	219	384	23	458	16	12	57	20	51	59	42
	ND	287	49	391	19	24	164	42	109	63	17
Average content	**93**	**397**	**85**	**361**	**17**	**18**	**184**	**32**	**106**	**135**	**74**
Middle level	326	234	27	408	ND	18	52	28	103	32	9
	399	58	24	698	15	16	40	69	409	43	14
	162	111	17	325	ND	17	28	26	36	28	22
	404	16	15	410	ND	23	ND	33	178	ND	17
Average content	**323**	**105**	**21**	**460**	**4**	**19**	**30**	**39**	**182**	**26**	**16**
Basal Level	218	280	39	459	13	17	145	44	122	63	13
	46	261	31	322	13	12	116	42	27	65	34
	130	197	25	212	14	24	82	42	18	56	17
Average content	**131**	**246**	**32**	**331**	**13**	**19**	**114**	**43**	**56**	**61**	**21**

ppm) are observed in the intermediate units of the Ct³ sequence. This dispersion pattern remains the same with the vanadium (**Figure 11**) and the silicates (SiO_2 and Al_2O_3; **Figure 10**). The determination of uranium, thorium and copper revealed contents of between 4 ppm and 17 ppm in U for relatively constant values in Th (18 ppm to 19 ppm) and copper (32 ppm to 43 ppm).

5. Discussion

The vertical sequence of Ct³ facies in the Niamey region is marked, from the base to the top, by alternations (**Figure 2**): 1) sandstone-clay or clay-sandstone facies; 2) oolitic ferruginous to pisolithic facies; 3) hardened, altered or nodular

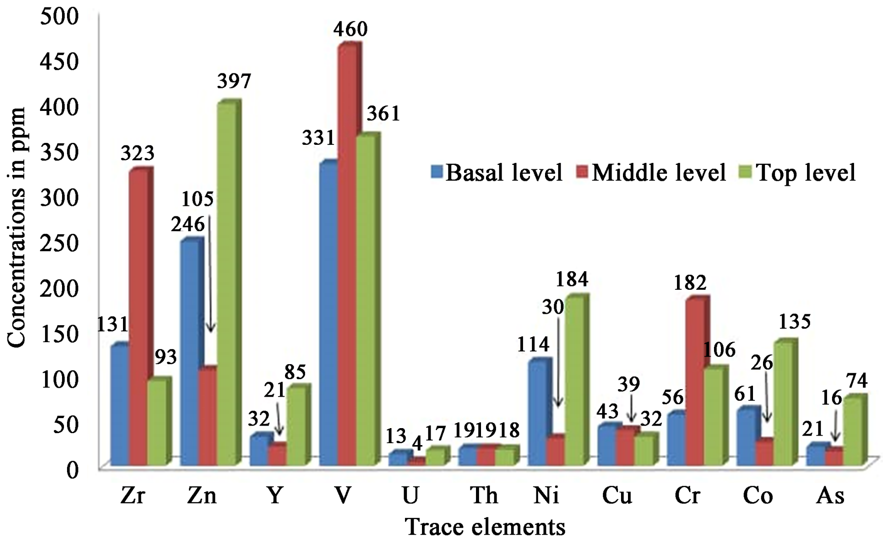

Figure 11. Trace elements average content in the three levels of the Ct³ ferruginous oolitic sandstones of the Niamey region.

facies. These facies variations are indicators of variations in the hydrodynamics of the sedimentation environment.

5.1. Synthesis on the Ferruginous Oolitic Facies

Ferruginous oolites form in several types of aquatic environment: marine, lacustrine or shallow but agitated fluvial [8] [27]. The different layers that make up the cortex take place in these conditions, while the oolite nuclei are in suspension [8]. These oolites, when sufficiently abundant, accumulate to form iron ores [27]. In addition, ferruginous oolites also form in the vicinity of shores where rivers flow, bringing iron oxides into solution from more or less iron-rich soils [8] [27]. For Issoufou-Fatiou *et al.* [8] and Faure [27], the genesis of these oolites is independent of the nature of the medium. However, to better understand their genesis, they must now be approached in terms of the characteristics of oolites formed in an aqueous medium and of oolites formed in non-aqueous medium.

The study of ferruginous oolites of the Ct³ formation in the Niamey region [24] revealed that the oolitic facies is mainly associated with an aqueous medium under various hydrodynamic conditions. The aqueous origin of the oolites in the Niamey region was demonstrated by the results of the geochemical analyses, where a very wide variety of chemical elements (**Figure 10** and **Figure 11**) were highlighted with high iron contents (average content of 74.81%). Fe_2O_3 contents close to those obtained in the context of this work were also obtained at Malbaza (76.15%) and in the Galmi sector (75.8%) by Dubois [5]. The average phosphate content (P_2O_5: 1.09%) obtained within the framework of this work is different from that obtained by Dubois [5] in the Galmi and Malbaza sectors and by Franconi *et al.* [1] and Machens [4] in the Say sector (the plateaus of Kolo, Say, Dyabou and Doguel Kaïna). In detail, however, it can be observed that this average remains closer to the value of the P_2O_5 contents obtained at Malbaza

(1.02%). Iron ore from the Niamey region has the same characteristics as that from the Say region. This could indicate the same placement conditions. According to Franconi *et al.* [1], the phosphorus found in Say iron ore is not expressed in mineral form. It occurs combined with gœthite by substitution of OH^- and PO_4^{3-} ions. Some compounds, which generally precipitate in place to give significant residual concentrations, could result from the hydrolysis of various minerals. In this case, the faults play an important role in guiding the massive subterranean weathering related to the prevailing hydrodynamic conditions in the Continental Terminal aquifer and in conditioning the final topography [28] [29].

According to Issoufou-Fatiou *et al.* [8], in addition to the presence of a nucleus facilitating the precipitation of the constituent of the envelopes and a physically agitated medium with a shallow depth of less than 2 m, the main condition necessary for the formation of oolites in an aqueous medium is a chemical supersaturation in ions entering the composition of oolites (Fe^{2+}, Fe^{3+}, CO_3^2, …). Saturation may be due to a high concentration of other constituents, resulting in lower relative solubility, or absolute saturation. We can remember that the cores are made up either of detrital particles (**Figure 7**) or fragments of fossils (**Figure 5**). Larger oolites are friable. They contain rare grains of quartz. Medium-sized oolites (e.g., ellipsoidal-shaped oolites) form in a low to medium energy environment, or they reflect a sheltered or rather quiet environment [30]. On the other hand, large oolites (1 to 2 mm) and pisolites (more than 2 mm) originate in agitated or very high-energy environments. This is the case of spherical oolites.

Thus, as they seem to be older than their binder, the ferruginous oolites of the Ct^3 formation in the Niamey region are for the most part ante-diagenetic. Indeed, these oolites show cracks and fragmentation that can be attributed either to tectonics or to the effect of compaction during diagenesis. When smaller oolites are sometimes coalescent (**Figure 5(d)**), they can be considered as syn-diagenetic. So the environment becomes more acidic and more reducing, it is obviously a zone of enrichment in CO_2 and in sulphurous or ammonia products. Finally, the oolite with oolitic cores corresponds in some cases to the composite type oolite [8] identified in the Continental terminal of the Kandi basin indicating at least two phases of suspension. For the oolite without nucleus, the nucleus is either unobservable or torn off during polishing [2].

In addition, the presence of fractured or cracked or even fragmented and sheared oolites shows that the agitation of the environment is sometimes associated with syndepositional tectonic activity. With lower iron enrichment and high phosphorus contents, the generalized oolitic textures under conditions of deposition in an agitated environment (elastic character) mainly relate to the mechanisms and indices genetically assimilable to Phanerozoic iron formations [1]. For Jullia [31], the oolitic horizon thus considered at the base of Ct^3 (**Figure 2**) defines a deposit of the transgressive type, as opposed to the regressive type (Ader Doutchi), concordant with the underlying units, materializing a withdrawal of the sea [24].

5.2. Synthesis about Indurated Surfaces

In the Niamey region, all the ferruginous oolitic sandstone deposits at the top of the Ct^3 sequence are locally exploited for the construction of houses and roads as well as for backfilling. The top of the sequence is considered to be a laterite by users and by several authors such as Chermette [32] and Du Preez [33]. On the other hand, for Tessier [2], the ferruginous oolite cannot be classified among the true laterites. Thus, the ferruginous oolite at the top of the sections, even if it is not a true laterite, must have evolved under certain laterization conditions. Thus, the formation of oolites and associated surfaces would be the product of a character deterioration of the hydrodynamics of the environment but also of the climatic context.

Indeed, if we accept that the indurated facies are characteristic of a stoppage of sedimentation or that they would indicate an exposed or emerged environment [34] [35], the climatic conditions would obviously be arid. Thus, in the hardened surfaces of iron-mineralized horizons, a significant amount of quartz grains is often observed. This was also reported by Machens [4] in the Say sector, to the south-east of the study area, on the Kolo plateau. Conversely, a resumption of sedimentation essentially involves an increase in the water layer and a significant reworking of indurated facies [24] (**Figure 4**). Thus, at the base of the "hard ground" there is always a formation of larger and relatively soft oolites with few or no quartz grains. This friable aspect of the oolite indicates a relatively agitated submerged environment.

The fact remains that the clayey facies (*i.e.* clayey-sandstone and sandstone-clayey; **Figure 2**) are indicators of the environments where the settling process prevails (low-energy or relatively calm environment) [24]. This is corroborated by the presence of casts of freshwater organism fossils, which militates in favor of a laguno-lacustrine type depositional environment (**Figure 2**). Throughout the Niamey region there are many types of sediments different from Ct^3 which come from the erosion of the rocks of the West African Craton, whose compositions are variable (alkaline, intermediate felsic or mafic). These source rocks have undergone strong weathering in a humid to arid climatic regime [24].

In fact, the evolution of the iron content at the top is not entirely due to the variations of the water layer, but to numerous (post-deposition) mechanisms of internal redistribution to the benefit of which are added, in certain cases, lateral contributions within the sequence [36]. The results obtained on the major elements could be interpreted as those of an enrichment of the sedimentary material in Si and Al (**Figure 10**) coupled with a double migration (ascending and descending) of iron oxy-hydroxides [36]. The intermediate level is seen, at the same time, enriched in silicates (Al, Si, Zr), oxides or hydroxides (V, Cr) by leaching, impoverished by the ascent towards the roof and the descent towards the iron wall in the sequence. Associated with iron and uranium ore [37], vanadium determines levels in which it associates with Zr in the intermediate zone and, in the upper horizons, more with ilmenite ($FeTiO_3$) than with titanomagnetite.

In other words, vanadium derives from the weathering of ilmenite and/or magnetite grains in the host sediment. These formations are therefore relatively enriched in iron-titanium vanadium-bearing oxides [38]. Zr is a very resistant natural body with often traces of radioactive Th and U, which confirms the clayey-sandy detrital character of the intermediate level. The association of Zn with As, Co, Ni indicates that many minerals which are sulphides such as FeS_2 are [secondary] formed in the upper and lower zones. It seems that there are great equivalences between the maximum Zn contents of the ferruginous oolitic facies (519 ppm; **Table 1**) and those of the Liptako clay shales which provided up to 510 ppm of zinc [1]. In these clay shales, Franconi *et al.* [1] specify that the zinc mineralization corresponds to ferruginous sandstone lenses which are hosted there. Thus, the mimicry between the Fe_2O_3 and Zn content peaks makes Fe-S-Zn paragenesis a real possibility in the Niamey region. The U contents in the base horizons and at the top, three times higher than the average of the granitic rocks of the Liptako. But the equivalence to those of their alterites [36] could be the result of a secondary fixation due to the precipitations of the oxy-hydroxides of iron (gœthite: FeO-OH). The absence of U in the intermediate horizons and the enrichment in Th (19 ppm) indicates the reinforcement of a groundwater drainage of the aquifer. The highest values of arsenic content (74 ppm) are located in the upper zone of Ct^3 (**Figure 11**). Fed by rainwater percolation [20], the increased use of the groundwater table of the Continental terminal could constitute a significant health risk for a majority of the inhabitants of Niamey. Compared to other groundwater reserves of African cities, the geochemical characters (major and traces) of the Ct^3 in the Niamey region indicate that the potential contamination of these aquifers could be related to the land use land cover (LULC) change over time [21], in addition to the context of the formation of current aquifers and processes that can cause its natural composition to vary [22].

6. Conclusion

The iron mineralization of the Continental Terminal 3 (Ct^3) formation in the Niamey region is essentially located in three (3) stratigraphic levels, two of which are relatively important at the top and the bottom and in the intermediate level of the Ct^3 formation. The ferruginous horizons have two aspects, namely: a friable aspect at the base with coarse to medium-sized oolites indicating a submerged medium with variable energy (high to medium energy) and a hardened aspect showing a relatively emerged medium (with very fine) and totally emerged (with hardened surfaces) indicating the sedimentation stopping. Niamey's Ct^3 iron ore is in the form of oolites, the majority of which are ante-diagenetic. This feature is attributable to their buoyant appearance and the small amount of coalescent oolites that can be considered syn-diagenetic. Associated with certain elements by ionic substitution, the iron mineralization of the Niamey region remains essentially gœthitic. Thus, these factors are those on which it is necessary to investigate to improve the punctual prospecting of sulphide deposits for zinc and lead or even gold in western Niger. Studies should continue to monitor the evolution high levels of arsenic (As) in surface waters and particularly in the deep aquifer. The induration of the cuirasses results from an impregnation of the clays by silica, which evokes climates with alternating wet and dry seasons. The ferruginous hardpans mark the arid-wet transition, while the siliceous indurations (silcretes) form at the humid-arid transition, the dating of hematites could be a tool for setting the induration age. Thus, if a diversification of geochemical analyses could show a variability of the source rocks of the Ct^3 sedimentary material, a paleogeographic and geodynamic evolution model of the Niamey region can serve as a basic tool to better understand the depositional process of the Continental terminal formation on a regional scale.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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