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Palaeogene Sandstones of the Manika Plateau in Kolwezi (DR Congo): Sedimentological and Geochemical Characterization, Provenance, Palaeoalteration and Tectonic Context

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Abstract

This work presents a study of the Paleogene sandstones of the Manika plateau in Kolwezi, DR Congo. These sandstones belong to the "Grès polymorphes" group, which together with the overlying "Sables ocre" makes up the Kalahari Supergroup. Sedimentological and geochemical analyses have enabled us to characterize these sandstones and determine their origin, the conditions of their formation and the tectonic context in which they were developed. The results show that the sandstones are quartz arenites with a high level of mineralogical, textural and chemical maturity. They are recycled sandstones, formed in an intracratonic sedimentary basin, in the context of a passive continental margin, after a long fluvial transport of sediments. These sandstones initially come from intense alteration of magmatic rocks with felsic composition, mainly tonalite-trondhjemite-granodiorite (TTG) complexes, in hot, humid palaeoclimatic conditions and oxidizing environments.

Keywords

Sandstone, Sedimentology, Geochemistry, Palaeoalteration, Tectonic Context, Manika Plateau, DR Congo

1. Introduction

The "Grès polymorphes" group can be found over vast areas of land, from the Batéké Plateau in Congo Brazzaville in the west to the northern extension of the Kalahari Basin in Angola, Zambia, Zimbabwe and Namibia. These sandstones outcrop in particular on the Katanga high plateaux, where, in association with the sands of "Sables ocre" group, they form the Kalahari Supergroup [1]-[3] and [4]. However, this Supergroup and more particularly the sandstones of the "Grès polymorphes" group remain relatively less well documented in the Katanga region. Lithostratigraphic studies of these formations are rare and imprecise, probably due to the poor condition of outcrops. The base of the "Grès polymorphes" group corresponds to the upper Cretaceous levelling surface defined by [5]. The fact that this contact was not observed in the Katanga region suggests, according to [6], the existence of a period of alteration in hot, humid conditions prior to the deposition of these sandstones.

These sandstones have been dated from the Palaeogene [1] to the Eocene [7] in the Kasai and Katanga regions on the basis of fossils (Ostracods, Gastropods and Characeae) observed in silicified lacustrine carbonates, and it was on the basis of gastropod types that the lacustrine origin of the limestones was demonstrated [7].

The geochemical approach discussed in this text is necessary to shed light on the nature of the source rocks of these sandstones, as well as the palaeoenvironmental parameters that governed their alteration. This approach provides a better understanding of the tectonic context in which the materials were developed and deposited [8]. The geochemical and mineralogical study of terrigenous detrital sediments is essential to determine their origin, the tectonic conditions of their deposition and the palaeoalteration of the source rocks [9]-[11].

The aim of this study is therefore to provide the information needed to understand the origin of "Grès polymorphes" group, the palaeoenvironmental processes that influenced their formation, and the tectonic context in which they were produced. This approach is in line with the work recommended by [12]-[17], which stress the importance of geochemical and mineralogical studies of terrigenous detrital sediments for a better understanding of their geological history.

2. Study Area

The study area is located on the Manika plateau to the east of the mining town of Kolwezi in the Congolese province of Lualaba, between latitudes 10°40' and 10˚45' S and longitudes 25˚20' and 26˚00' E (**Figure 1**).

The "Grès polymorphes" are found below a sandy cover known as the "Sables ocre" group, with which they form the Kalahari Supergroup [18]. They outcrop in the form of lenticular banks up to several metres thick, but also in the form of isolated blocks common at the base of the "Sable ocre" [2] [19].

In the Kolwezi region, the "Grès polymorphes" are locally unconformably underlain either by Neoproterozoic shales of the Kundelunguian or by formations of the Mines Group via an erosional surface of late Cretaceous age [5] that cuts all the bedrock. The sands and sandstones are thought to have been deposited in a relatively arid environment following the wet and warm period at the end of the Cretaceous, as indicated by the presence in some places of abundant round-matt grains and faceted eolian pebbles at the base of the "Grès polymorphes" group [20].

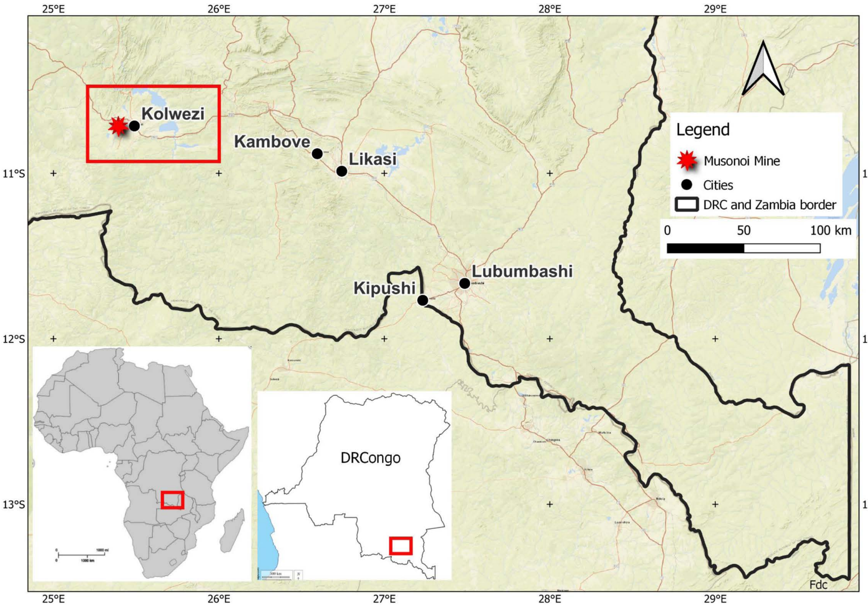

Figure 1. Location map of the Kolwezi region.

3. Materials and Methods

Ten "Grès polymorphes" samples were taken from various outcrops along the small streams that cut into the sandy cover of the Manika plateau in Kolwezi. These samples were subjected to a petrographic, granulometric and geochemical study. The petrographic and granulometric studies were carried out on thin sections using a polarising microscope after macroscopic observation.

The virtual granulometric analysis of these sandstones, despite the imprecision of the results it provides due in particular to the random cross-sections of the grains and their significant diagenetic feeding, is carried out firstly for comparison with the sands whose common origin with the underlying sandstones has been suggested by numerous researchers [2] [3] [19] [21], and secondly to identify the dynamics and palaeoenvironmental context of deposition.

Chemical analyses of these samples covered both major and trace elements, including rare earth elements. The major elements were analysed using an ICP-OES optical emission spectrometer (model: Thermo Fisher Scientific Icap-6500 (Axial Radial) ICP - OES) after alkaline fusion at the Earth and Life Institute-Environmental Sciences laboratory at the Université Catholique de Louvain (UCL) in Belgium, while the trace elements were analysed at the same laboratory using ICP-MS mass spectrometry after triacid digestion of the samples. In both cases, the accuracy of the analyses was below 2%, with detection limits of 0.001 to 0.1 ppm for major elements and 0.0001 to 0.1 ppb for trace elements.

The tectonic context in which these sediments were produced was interpreted on the basis of the tectonic discrimination diagrams in [22] and [23].

4. Results and Interpretation

4.1. Petrography and Granulometric Analysis

The “Grès polymorphes” group of the Manika plateau are outcrops of relatively fine-grained, more or less hard, massive rock, varying in colour from light grey to pink and brownish yellow, depending on the degree of surface weathering.

Transmitted-light petrographic analysis showed an equant facies, composed solely of quartz grains of fairly similar size, relatively fine to medium, with generally subangular to subrounded contours and uniform extinction.

These monocrystalline grains show discontinuous diagenetic feeding as an intergranular siliceous cement; however, they do not show a ferruginous border around them. It is therefore a purely quartz rock, with no carbonate or feldspars, which fits into the petrographic classification of quartz arenites (**Figure 2**).

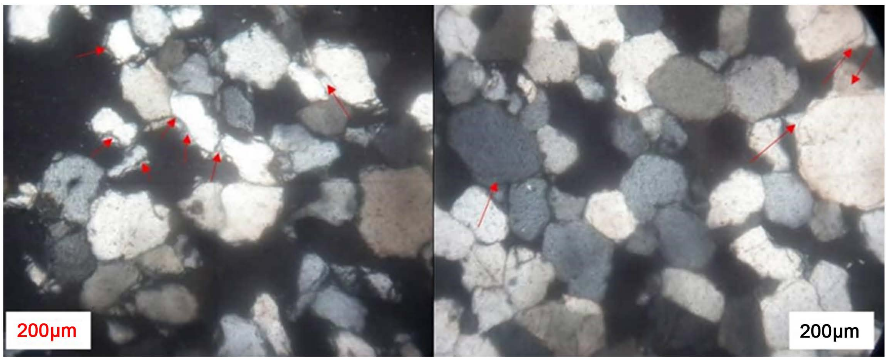

Figure 2. Microscopic view of Manika “Grès polymorphes”: Note the halo of diagenetic grain growth in the photo on the left.

The virtual granulometric study by linear counting of grains under the microscope not only made it possible to specify the average grain size of this sediment (Mz ranging from 120 to 300 µm), which is more or less identical to that of the grains of the so-called “pseudoquartzite” facies defined by [19] and the “Sables ocre” (**Figure 3**); it also made it possible to calculate the granulometric parameters listed in **Table 1**.

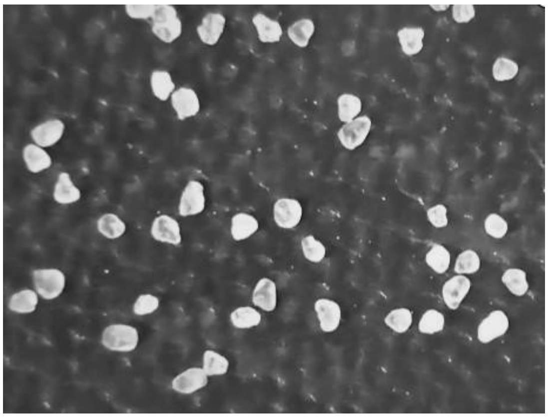

Figure 3. “Sables Ocre” from the Manika Plateau (315 µm grain size fraction): note the abundance of sub-rounded grains.

Table 1. Main particle size indices (expressed in phi units) of Manika sandstones.

Samples	S_0	Mz	K_G	Sk
MSL001	0.66	2.03	0.758	0.074
MSL002	0.75	2.00	0.913	−0.016
MSL003	0.69	2.10	0.892	0.082
MSL004	0.81	1.92	0.784	0.044
MSL005	0.71	2.09	0.766	−0.017
MSL006	0.49	3.10	0.804	0.076
MSL007	0.70	2.41	0.952	−0.019
MSL008	0.76	2.36	0.867	0.079
MSL009	0.68	2.05	0.923	0.059
MSL0010	0.51	1.75	0.811	−0.013

These sediments are composed exclusively of quartz clasts, with a sandy grain size, making up 94.7% to 99.0%, compared with only 1 to 5.3% of silt-clay particles. The sandy grains are predominantly sub-rounded, as in the overlying Sables ocres, despite their contours being marked by diagenetic growth halos.

The average grain size (Mz) of these sediments places them in the category of medium-to fine-grained sandstones. The sorting index (S_0) from [24] shows that these are medium to moderately well sorted sediments (S_0: 0.51 to 0.81) characterised by a platycurtic grading curve (K_G = 0.758 to 0.952), which probably indicates that the sediments were supplied by successively varied stocks. The skewness index (Sk) of the granulometric curve reveals values varying between −0.019 and 0.082, suggesting an almost symmetrical curve (**Figure 4**).

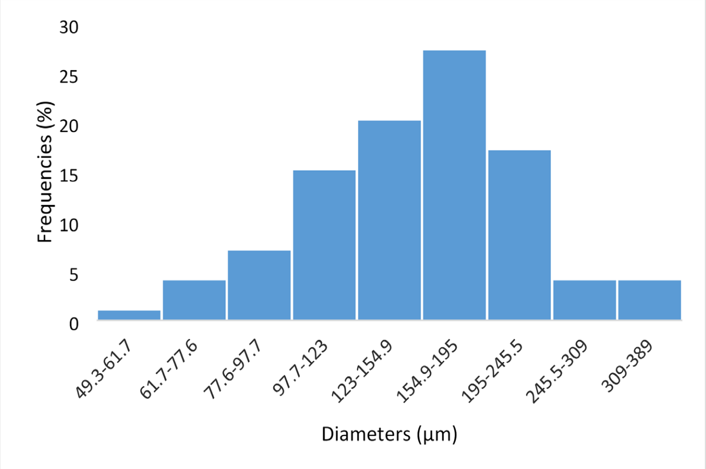

Figure 4. Frequency histogram of Manika "Grès polymorphes" (Echant.MSL003).

The semi-logarithmic cumulative curve (**Figure 5**) is similar to those of the overlying Sables ocres [2] [19]; it has a quasi-sigmoidal appearance tending towards a more or less regular parabolic shape.

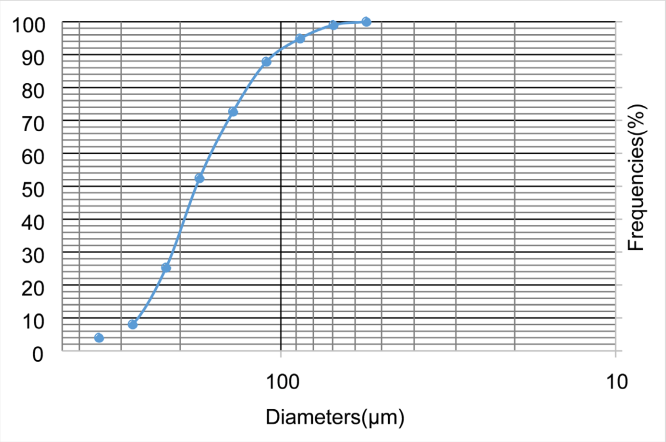

Figure 5. Cumulative particle size distribution of Manika "Grès polymorphes" (Echant.MSL003).

The shape of this curve, and in particular its relatively steep slope, would be characteristic of a stock of more or less homogeneous sands, moderately well sorted and transported in a fluvial environment [25], [26] less agitated [27]. **Figure 6** also suggests, according to [28], that the sediments were transported in a fluvial continental environment.

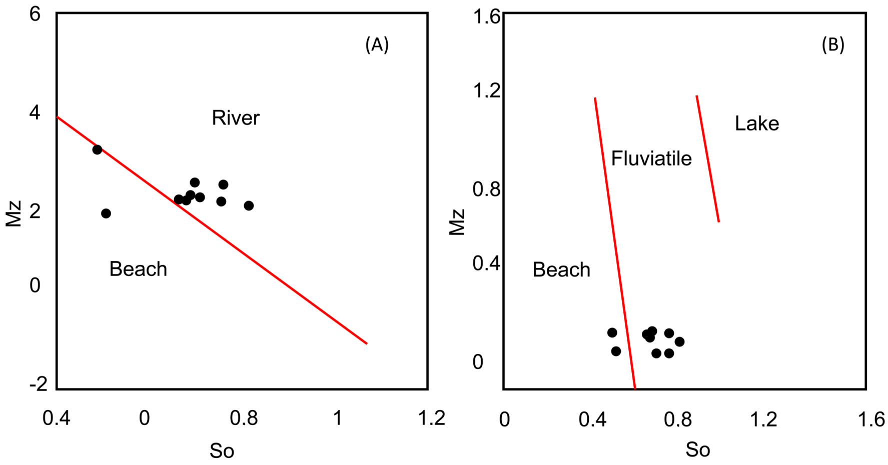

Figure 6. Manika "Grès polymorphes" depositional environment (based on diagrams in A: [25] and B: [28]).

The "Grès polymorphes" were certainly deposited in a warm environment, with deposition interrupted by recurrent wetter periods attested by the interstratification of alluvial and lacustrine sediments, particularly towards the north of the Congo Basin [21].

While [4] considers that the "Grès polymorphes" are derived globally from the silicification of lacustrine limestones, [19] believes that these sandstones were formed simply by the silicification of the overlying sands. This silicification is part of an early and complex diagenetic process that is thought to be common at the base of "Sables ocre" where water circulation was once very intense [2]. According to [29], this process affects the initially carbonated cements of these sandstones and is what sometimes gives them the appearance of millstone.

We observed the concretion of the "Sables ocre", especially in their superficial part (**Figure 7**).

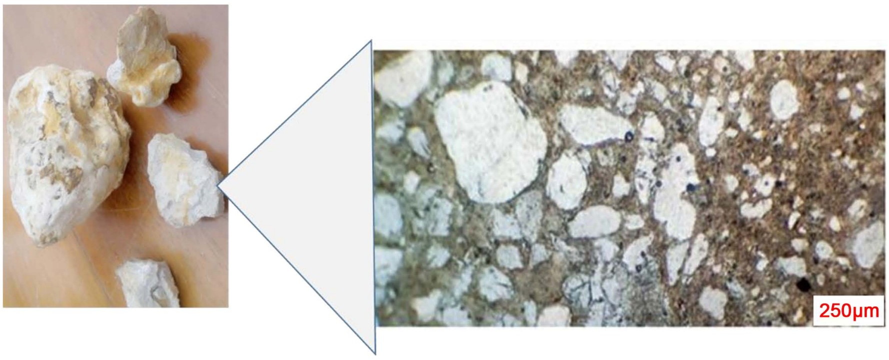

Figure 7. Silicification of the Sables ocres of the Manika Plateau (macroscopic observation, left and microscopic observation of the siliceous concretions, right).

However, this local phenomenon seems to take place under specific conditions due to the infiltration of humic acid solutions from the surface horizons of soils forming on these sands.

4.2. Geochemical Composition and Classification

4.2.1. Major elements

The chemical composition of the major elements in the "Grès polymorphes" of Manika is given in **Table 2**. Examination of this table shows extremely homogeneous contents for the different samples.

The relatively high SiO_2, content varies from 94.98 to 97.20%, with a mean value of 96.11%; the Al_2O_3 content varies from 1.33 to 1.77%, with a mean value of 1.63%. The mean SiO_2/Al_2O_3 ratio, which is an index of chemical maturity, is high at around 59. The Fe_2O_3 varies between 0.25 and 0.87%, with a mean of 0.46%, which is relatively high enough to occasionally rubylize these sediments. K_2O and Na_2O show fairly low levels, varying respectively between 0.04 and 0.10% for K_2O and 0.03 and 0.06% for Na_2O; their mean content being respectively 0.07 and 0.04%.

However, there is no linear correlation between K_2O and Na_2O, nor between each of these elements and Al_2O_3, which seems to be due to the absence of feldspars in these sandstones and also shows that the concentration of Al_2O_3 is controlled by a tiny proportion of neoformed clays, probably kaolinite.

The mean Na_2O/K_2O ratio of 0.65 indicates significant leaching of Na in comparison to K, and therefore fairly high chemical maturity of these sediments according to [30]. Similarly, the average Fe_2O_3/K_2O ratio of 6.72 indicates an almost total absence of feldspars and micas in these sediments. The $SiO_2/(Al_2O_3$ +

$K_2O + Na_2O$) ratio, which also constitutes an index of chemical maturity according to [31], varies from 47.25 to 66.85 with a mean value of 55.20, again suggesting a high level of chemical maturity in these sediments. The high chemical maturity of these sandstones can be explained by their recycled nature and by the fact that they were produced in a highly altering paleoenvironmental context, which was probably humid and warm, under the control of a less pronounced relief that favoured strong weathering of the source rocks and over a fairly long transport period.

The geochemical classification diagrams of [32] (**Figure 8(A)**) and [33] (**Figure 8(B)**) classify these sediments as quartz arenites, certainly because of their low concentrations of Al_2O_3.

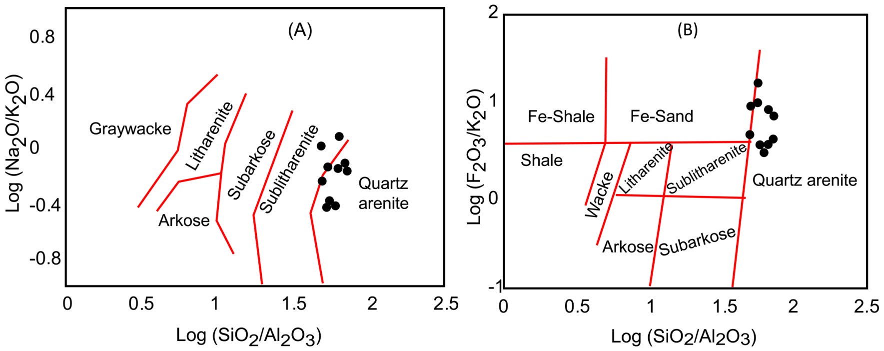

Figure 8. Classification of Manika "Grès polymorphes" ((A): [32], (B): [33]).

4.2.2. Trace elements

The chemical composition of trace elements in Manika "Grès polymorphes" is provided in **Table 2**. The elements are categorized respectively into the large ion lithophile elements (LILE), high field strength elements (HFSE), rare earth elements (REE) and transition elements groups. For all these groups of elements concentrations are low and strongly clustered around the mean values.

It is difficult to speculate on the mineralogical significance of the elements present in such low concentrations. The least we can say is that the main mineralogical support mechanism for elements in the LILE and REE groups would be adsorption onto kaolinite, the only phyllite mineral presumed to be present in this leached context.

On the other hand, the relatively consistent Zr values (13.36 - 22.13 ppm) compared with all the other elements in the HFSE group could be explained by the occurrence of zircon granules as the mineralogical support phase for this element.

As far as transition trace elements are concerned, Cr appears to be the only element whose average content (122.73 ppm), higher than that of Archean cratonic sandstones [13], seems to reflect, in addition to its adsorption on clays (kaolinite), a probable occurrence in the state of fine chromiferous spinel granules; this element with mafic affinity is naturally accompanied by Cu, Ni, Sc and V which share the same affinity with it.

Table 2. Chemical composition of Manika "Grès polymorphes" samples.

	MSL001	**MSL002**	**MSL003**	**MSL004**	**MSL005**	**MSL006**	**MSL007**	**MSL008**	**MSL009**	**MSL010**
Major elements in % of oxides										
SiO_2	95.6	95.28	95.48	97.2	96.25	96.89	96.12	97.01	96.32	94.98
TiO_2	0.06	0.08	0.06	0.09	0.09	0.09	0;07	0.04	0.03	0.05
Al_2O_3	1.38	1.7	1.44	1.76	1.6	1.91	1.77	1.5	1.33	1.9
Fe_2O_3	0.3	0.25	0.53	0.87	0.25	0.49	0.87	0.37	0.39	0.32
MnO	0.004	0.004	0.004	0.005	0.005	0.005	0.05	0.041	0.005	0.001
MgO	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.05	0.03	0.06
CaO	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.1	<0.05	0.11
K_2O	0.04	0.07	0.06	0.05	0.08	0.05	0.08	0.1	0.09	0.07
Na_2O	0.03	0.05	0.07	0.02	0.03	0.05	0.03	0.07	0.06	0.04
P_2O_5	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.04	0.03
PF	0.89	1.05	1.11	1.05	0.99	1.02	1.14	0.81	0.9	0.97
TOT	98.29	98.51	98.79	101.07	99.33	100.55	100.17	100.09	99.2	98.53
LIL elements in ppm										
Rb	1.623	1.802	1.784	1.703	1.713	1.758	1.872	1.099	1.654	1.779
Sr	4.51	4.33	5.264	3.86	5.027	4.027	4.953	4.592	3.998	4.214
Ba	23.986	20.598	26.615	18.622	21.037	23.21	20.37	20.222	17.958	18.695
Pb	5.551	4.991	7.909	6.383	5.703	6.029	7.004	4.298	6.124	4.952
Cs	0.108	0.124	0.117	0.111	0.113	0.099	0.11	0.089	0.098	0.11
HFS elements in ppm										
Th	1.025	1.164	1.063	1.184	1.06	1.025	1.113	1.125	0.893	1.003
Y	2.869	3.848	3.309	4.054	4.036	3.002	2.987	3.524	2.849	4.165
Zr	13.366	22.129	18.176	19.686	20.692	14.982	20.212	14.262	16.324	20.169
Hf	0.383	0.59	0.507	0.543	0.413	0.492	0.398	0.512	0.398	0.492
Nb	0.949	1.211	1.155	0.938	1.098	1.023	0.987	0.945	1.103	1.029
Your	0.097	0.126	0.124	0.091	0.103	0.119	0.116	0.124	0.098	0.103
W	0.228	0.242	0.232	0.18	0.21	0.198	0.24	0.203	0.226	0.213
U	0.565	1.413	0.611	0.663	0.502	0.992	1.105	0.989	0.872	1.049

Continued

Transition elements in ppm										
Sc	1.18	1.367	1.352	1.764	1.569	1.622	1.246	1.295	1.2	1.313
V	20.479	17.046	33.9	30.645	29.982	31.205	19.987	20.198	21.363	19.255
Cr	154.532	167.879	122.026	97.302	100.263	124.683	149.326	112.326	98.655	100.299
Co	2.241	2.055	4.079	3.499	3.287	2.384	3.925	2.269	3.21	2.659
Ni	8.794	9.414	7.623	5.887	8.982	7.983	9.032	8.952	6.259	5.688
Cu	34.09	33.603	56.711	35.872	40.293	42.037	34.293	51.27	45.27	39.254
Zn	8.378	6.326	25.3	5.589	20.215	22.274	8.653	8.653	7.365	13.215

Rare earth elements in ppm														
	La	This	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
MSL001	13.158	27.04	4.69	16.638	1.867	0.278	1.06	0.106	0.589	0.111	0.314	0.046	0.298	0.045
MSL002	13.659	27.821	4.829	17.64	2.119	0.336	1.239	0.136	1.059	0.149	0.424	0.063	0.414	0.064
MSL003	14.957	31.075	5.353	19.222	2.251	0.346	1.257	0.131	0.726	0.133	0.378	0.0571	0.384	0.058
MSL004	12.331	26.645	4.247	15.742	1.993	0.322	1.215	0.137	0.807	0.153	0.435	0.066	0.415	0.063

4.3. Source

The identification of the source material of the sandstones studied was approached using the geochemical discrimination diagram recommended by [23]. This diagram uses the major elements, Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, Na_2O and K_2O, most of which are relatively mobile to help discriminate effectively between the various origins. On the other hand, incompatible trace elements, which are generally not very mobile, appear to be particularly good indicators not only of the nature of the source rocks, but also of the possible sorting action of the carrier minerals during their transport, and also of the tectonic setting and the evolution of the environment [14] [34] [35].

During the sedimentary process, the original composition of immobile elements is preserved and is therefore the signature of source materials and of all sedimentary processes, provided that these elements are not carried by heavy minerals whose distribution is generally affected by sorting and recycling over long distances.

It should be noted that the different origins seem to be implicitly associated with specific geotectonic contexts [36]. Thus mafic rocks are often associated with oceanic island arc contexts, intermediate rocks with mature island arcs, felsic rocks with the active continental margin; recycled continental sources are associated either with intracratonic sedimentary basins, or with the passive continental margin, or with recycled orogenic provinces. The diagram in [23] shows that the 'Grès polymorphes' of Manika are recycled sandstones (**Figure 9**) in the context of an intracratonic sedimentary basin, the interior Congo Basin.

It is clear that in the absence of a consistent fine silt-clay fraction likely to act as a mineralogical support for trace elements in these sediments, the identification of source materials is tricky. It should be noted, however, that rare earths elements, Th, Sc and Th/Sc ratios appear to be particularly good indicators of source control in detrital sediments, as their distribution, unlike that of other elements, is not affected by the fractionation of heavy minerals during sediment transport [14] [23].

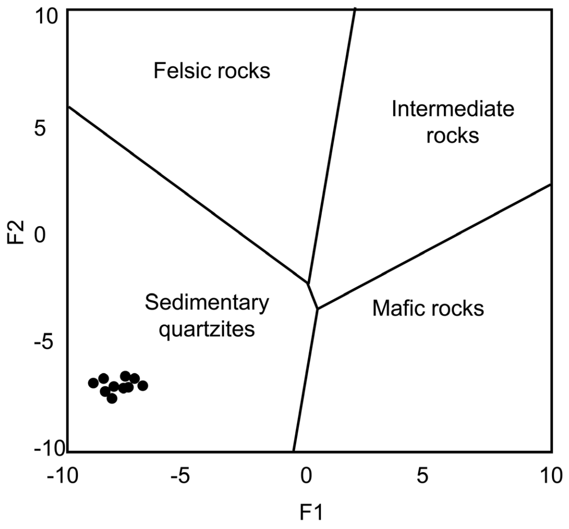

Figure 9. Provenance discrimination diagram [23]. F1= $(-1.773TiO_2) + (0.607Al_2O_3) + (0.76Fe_2O_3) + (1.5MgO) + (0.616CaO) + (0.509Na_2O) + (-1.224K_2O) + (-9.09)$. F2= $(0.445TiO_2) + (0.07Al_2O_3) + (-0.250Fe_2O_3) + (-1.142MgO) + (0.438CaO) + (1.475Na_2O) + (1.426K_2O) + (-6.861)$.

The Th/Sc - Zr/Sc diagram in [12] for the composition of these sediments indicates a primary source close to the more characteristic "tonalite-trondhjemite-granodiorite complex" (TTG) rocks (**Figure 10**) of Proterozoic to Archean age.

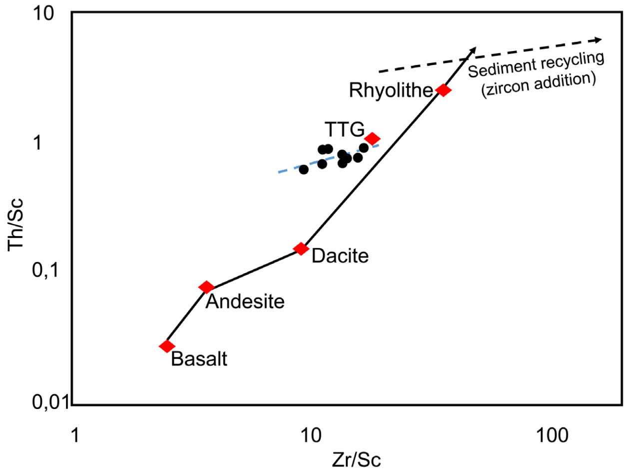

Figure 10. Th/Sc - Zr/Sc diagram [12].

Of particular note in this diagram is the alignment of the points along a trend of increasing Zr/Sc ratio, indicating relative fractionation of zircon during sediment transport, confirming the recycled nature of these sandstones.

These are therefore sandstones developed in the context of the interior intracratonic Congo Basin, whose complex structural evolution and sediment succession have been discussed elsewhere by [3], [4] and especially [37].

Rare earth element spectra normalized to PAAS (**Figure 11**) not only show low rare-earth elements abundances in these sandstones compared with the shales (PAAS), which does not allow their potential source materials to be identified, but they also show a slight fractionation of light rare earths elements and weak negative anomalies in Ce (Ce*/Ce: 0.79 to 0.85) and especially in Eu (Eu*/Eu: 0.93 to 0.98), relatively close to those calculated by [13] for Archean cratonic sandstones; this seems to confirm the Archean source of these sediments.

Manika's "Grès polymorphes" are recycled sandstones resulting from the dismantling of primary sandstones, which were themselves formed by the weathering and erosion of Precambrian craton rocks during various tectonic phases.

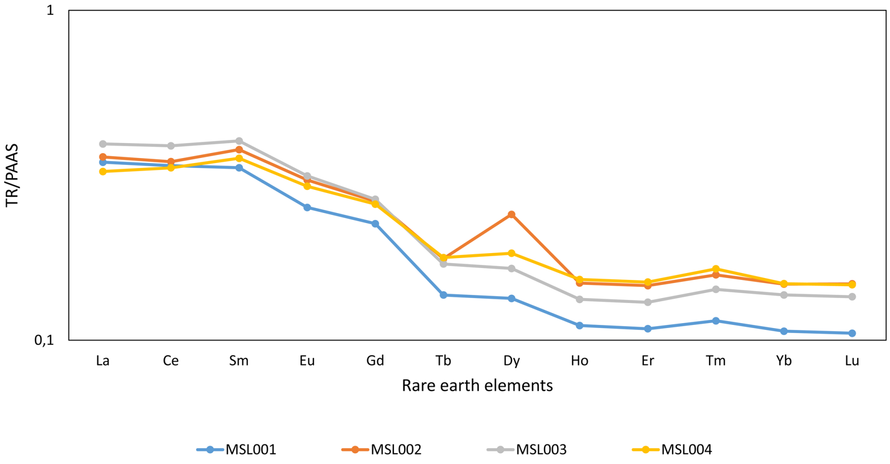

Figure 11. Diagrams of rare earths standardised to PAAS.

The weak negative anomalies in Ce and Eu as well as the average V/Cr ratios of 0.2 well below 2, and Ni/Co of 2.66 below 5 suggest, according to [38], that these sediments were produced under relatively oxidising conditions.

Normalised to the average content of Proterozoic and Phanerozoic cratonic sandstones [13], the polymorphic Manika sandstones appear to be severely depleted in incompatible trace elements (LILE, HFSE) more characteristic of felsic than mafic rocks. On the other hand, they show concentrations of transition elements that are fairly close to those of the reference sandstones, and even higher in some cases, particularly for elements with a mafic tendency such as chromium, vanadium and cobalt (**Figure 12**), suggesting a significant contribution from a mafic or intermediate magmatic source to the original sediments. The same is true of the mean values of the La/Sc (9.85) and La/Co (4.63) ratios, which seem to suggest a felsic origin for these sediments; however, the low Th/Sc (0.77) and Th/Co (0.36) ratios clearly indicate a mafic nature for the primary source of these recycled sandstones.

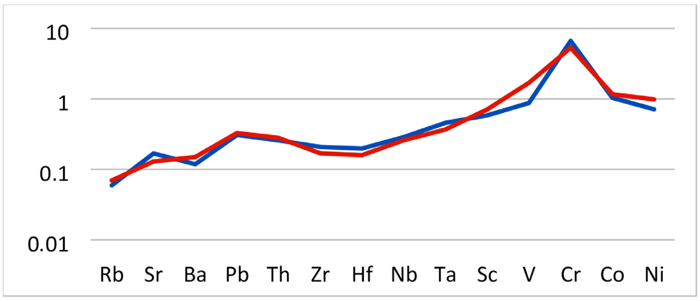

Figure 12. Normalization of the composition of the Manika sandstones to the average of the Proterozoic (blue) and Phanerozoic (brown) cratonic sandstones.

4.4. Palaeoalteration of Source Rocks

The chemical alteration conditions of source rocks have a definite impact on the composition of the resulting sediments. In order to estimate the alteration of source rocks into clay products, [39] have defined the alteration index with the following molar formula: CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$. [39]-[41] interpret this index as a measure of the extent of the conversion of feldspars (the dominant minerals in the upper crust) into clays. For these researchers, AIC values close to 100% correspond to the alteration of source rocks into clay minerals such as chlorite, kaolinite or gibbsite.

Alteration of the source rocks of the Manika plateau sandstones is characterized by very high CIA alteration indices (84% to 91%), suggesting intense aluminosilicate alteration conditions, probably induced by a hot, humid climate and a relatively flat topography, as we have already pointed out.

The A-CN-K diagram (**Figure 13**) from [39] also allowed us to get close to the approximate nature of the source rock, which for these sediments would be a magmatic source of felsic composition.

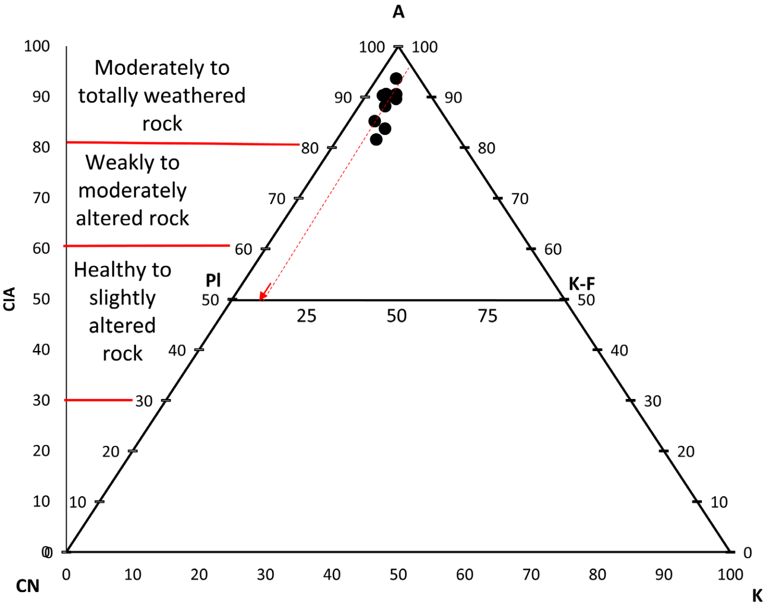

Figure 13. Paleoalteration index (PAI) of source rocks [39].

4.5. Tectonic Context

The chemical composition of terrigenous detrital rocks is tightly controlled by the tectonic setting of their source, so that detrital sediments from different tectonic settings show geochemical signatures specific to the context of their source rock [22] [23].

The tectonic discrimination diagram of [22] identifies four main environments, namely the passive tectonic margin (PM), the active continental margin (ACM), the oceanic island arc context (ARC) and the continental island arc context. In the case of the Manika's "Grès polymorphes", this diagram (**Figure 14**) and that of [23] (**Figure 15**) showed that these sediments were developed in a passive continental margin tectonic context, corresponding here to the Congo interior intracratonic sedimentary basin.

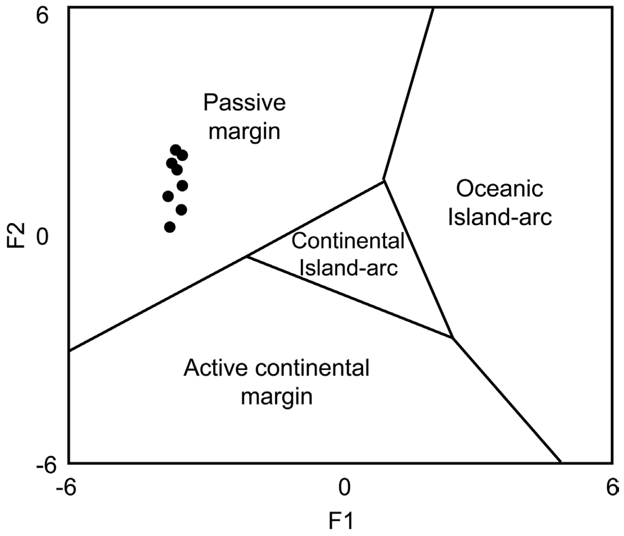

Figure 14. Tectonic discrimination diagram from [22].

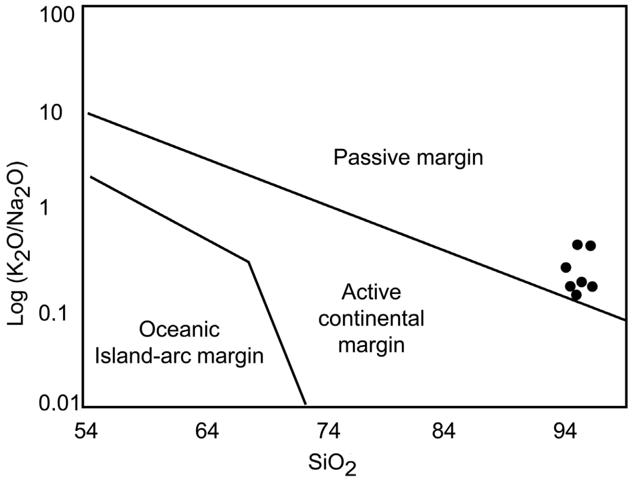

Figure 15. Tectonic discrimination diagram from [23].

The compositional variability ICV = [(Fe_2O_3 + K_2O + Na_2O + *CaO + MgO +

$TiO_2)/Al_2O_3]$ from [42] shows low values, varying between 0.28 and 0.62 with an mean value of 0.42 which is well below 1. These low ICV values indicate that these sandstones are very mature and were developed in a stable intracratonic tectonic environment [43].

5. Conclusions

Petrographic observations of the Manika's "Grès polymorphes" have revealed massive terrigenous sediments composed entirely of quartz, with variability in grain shape and size. These rocks, classified as quartz arenites, show a high degree of textural and mineralogical maturity.

Sedimentological analysis revealed a medium- to fine-grained sandstone sediment, indicating probable deposition by multiple contributions of sediment. The similarity of grain size and morphology with the overlying Sables ocres suggests a common origin for these two types of sediment.

Geochemically, the Manika's "Grès polymorphes" are highly siliceous, depleted in alumina, iron and especially alkaline elements. These characteristics indicate warm and humid palaeoclimatic conditions, as well as ancient environments with a relatively flat relief, favourable to intense meteoric alteration of the source rocks in a relatively oxidizing context.

Discrimination diagrams suggest that the primary sources of these sandstones were magmatic rocks of the tonalite-trondhjemite-granodiorite (TTG) complex type, and that they were deposited in the context of an intracratonic sedimentary basin or a passive continental margin basin, such as the interior Congo Basin. Weathering of these source rocks led to the formation of sandstone sediments that underwent a second sedimentary cycle, involving relatively long transport and resedimentation in a fluvial environment.

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Conflicts of Interest

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

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