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Case Report

Petrographic and Mechanical Study of Aggregates from Central Chad: A Case for Natural Selection of Hard Rocks

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Abstract: This study focus on the geological formations of the Alfallé massif located approximately 75km east of the town of N'Goura, in the Hadjer-Lamis Province of Chad (13°N, 17°E), and their ability to provide good quality aggregates in an area with poor hard rock ressources. We investigated the petrographic and mechanical characteristics of these formations in a resource perspective. The massif is made up of three lithologies: alkali feldspar megacrystalline granite, biotite-rich fine grained quartz monzonite and biotite-rich fine grained gneiss. Alkali feldspar megacrystalline granite is composed of quartz (30%), orthoclase (30%), plagioclase (20%), biotite (15%) and opaque minerals (≈5%). Micro-monzonite is composed of quartz (15-20%), orthoclase (20-25%), plagioclase (18-25%), biotite (20-25%) and opaque minerals (≈4%). The biotite gneiss is composed of quartz (25-30%), alkali feldspars (25-27%), plagioclase (17%), biotite (25-27%) and opaque minerals (≈5%). The mechanical characteristics of the aggregates show that the aggregates studied have specific density values of between 2.58 and 2.75g/cm3 with an average value of 2.66g/cm3, a Los-Angeles coefficient of 11.2% to 28.9% with an average value of 20.1% and a wet Micro-Deval coefficient of 5.2% to 10.8% with an average value of 7.6%. The values obtained indicate that the materials studied have excellent to satisfactory properties, and that Alfallé massif provide the best characteristics among six different quarrying area in Central Chad. We propose that such rare residual reliefs within the mega-Chad paleolake area reach optimal mechanical properties through a natural selection process, specific of the paleolake erosional conditions.

Keywords: Chad; granites; gneiss; petrography; aggregates mechanical properties

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1. Introduction

Natural aggregates are more or less abundant depending on the region, and their systematic use as construction materials is beginning to make them a scarce resource in some parts of Africa [1]. Resistance to degradation is the main quality sought in aggregates for application purposes [2,3]. However, the quantification of this resistance, investigated in the present contribution, may also be relevant in terms of geomorphology to explain residual reliefs in highly eroded area [4]. According to [3] the best resistance is encountered in fine grained silicic rock aggregates without weathering, porosity and fracturation.

Central Chad (Figure 1), is mostly an extremely flat area, characterized by an endorheic basin, once occupied by the mega-Chad lake, of one third million km^2 extension [5]. Therefore, basement very rarely outcrops above the ubiquitous plio-quaternary fine sediments. Central Chad has very scarce resources of hard rock for quarries (Figure 1) so the identification of proper resources for aggregates, in particular used for road construction, is needed to improve the existing un-asphalted network. Indeed, this network is characterized by near total traffic cuts in rainy season and heavy conditions the rest of the year, thus hampering economic development. The present study of

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aggregates in the Alfallé area was initiated with this aim in mind. A few small hard rock quarries pits have been already opened in the area, Alfallé one being nearly the northermost (Figure 1). The nearest opened pits lay in N'Goura and Moyto (60 km to the West), and Birni (130 km to the East) massifs. To the North, no rock outcrops in the next 600 km. To the South, the Massif of Guera outcrops more largely [6] but it lays outside the main road from the capital city to Sudan, via Abéché. To gauge the scarcity of aggregate resource in the area we can mention the fact that N'Goura and Moyto active quarries are becoming significant providers for the capital city N'Djamena, 170 km to the West. Indeed, the only quarries nearer to the capital, Hadjer el Hamis and Dandi, are approaching exhaustion.

All outcropping rocks in the area of Figure 1 belong to the Neoproterozoic orogeny and correspond to granitoids with minor presence of more mafic intrusions as well as metamorphic rocks [7–9]. Intrusions are dated in between 545 and 590 Ma. In particular the N'Goura and Birni massif are made of granites. To the west and North of Lake Fitri (in particular for quarries 1-3) lays the former mega-Chad lake [5]. During the 3-14 ka period in Holocene the above-mentioned outcrops were totally or partly drown into the lake, whose level peaked at 329 m above sea level [10]. One may wonder about the relationship between resistance to digradation and the preservation of Neoproterozoic outcrops in these specific erosional conditions.

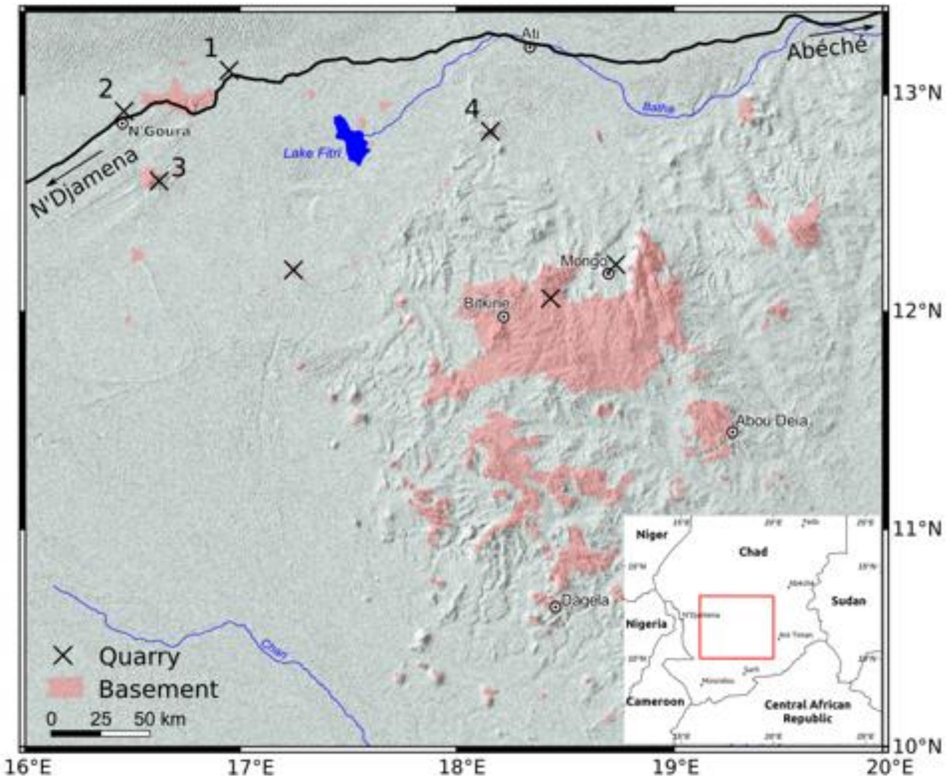

Figure 1. Basement outcrops map of the study area on a shaded relief view. Inset shows position within Chad. Cross indicates existing quarries, in particular 1 Alfallé, 2 N'Goura, 3 Moyto, 4 Birni.

2. Sampling and Methods

The Alfallé Massif appears as an inselberg about 30 meters above a vast sandy plain (Figures 2 and 3a). Its maximum altitude is 324 m, i.e. just below the mega-Chad lake high stand. Visual inspection around the massif identifies three petrographic facies: medium to coarse-grained granite with pink megacrystals, biotite-rich fine grained magmatic rock and biotite-rich fine to medium grained gneiss. The last two facies show variable darkness related to variable amount of biotite. Field relationships show that the granite is intrusive in the gneiss, while the fine grained magmatic rock is intrusive in the other two facies.

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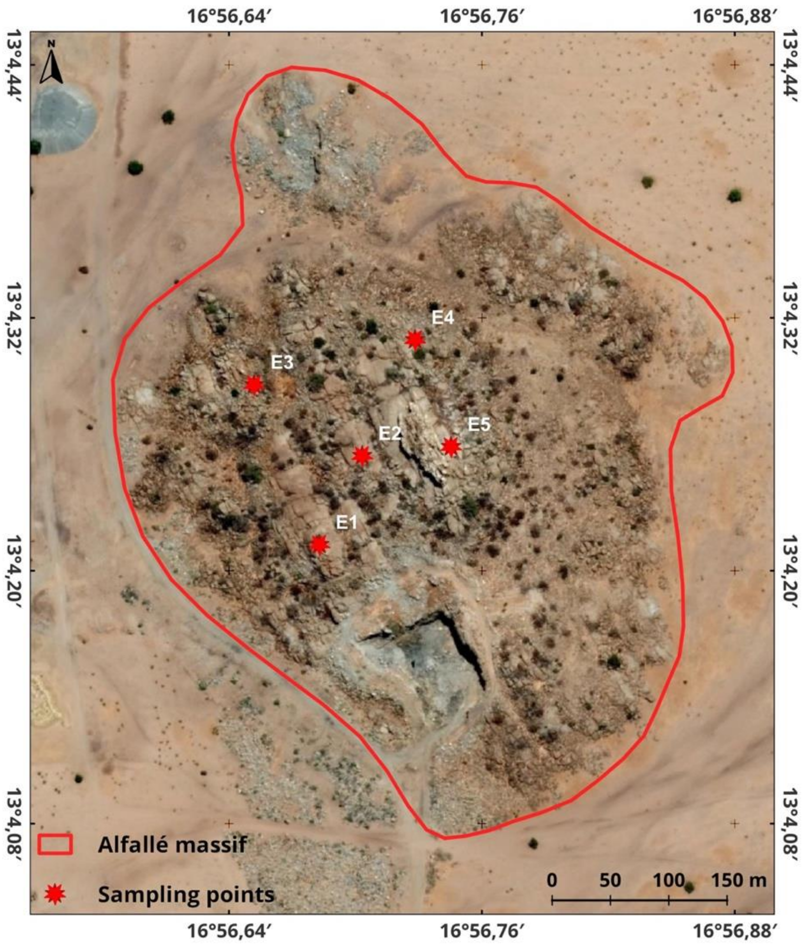

Figure 2. Sampling map of the study zone over satellite image (Google Earth).

A total of five samples were taken outside the pit, corresponding to the three different petrographic types (T1 to T3) identified during visual survey of the study area. Large samples were taken so that they could be used to make thin sections for optical microscopy and prepare aggregates for mechanical testing. The sampling map shows where the samples were taken (Figure 2). Physical and mechanical properties were measured on aggregates obtained by hammering of the material to the granular class 10/14mm. Mechanical tests were carried out in the Civil Engineering Laboratory in N'Djamena. The mechanical parameters Los-Angeles (LA) and micro-Deval coefficients were determined in accordance with European norms EN 1097-1 and EN 1097-2. The LA and micro-Deval coefficients are the percentage of the initial aggregate that passes a 1.6 mm sieve after being tumbled together with steel balls in a normalized test. While the Los Angeles test is designed to produce more shock in between the gravels and steel balls, the micro-Deval test privileges wear by friction, in particular through tumbling with water. The grain density was determined using the weighing method in water. The quality level of mechanical properties is categorized using the thresholds empirically defined in Table 1.

Independently the three petrographic types were sampled in the pit for chemical analysis. Major elements were determined using ICP-AES.

Table 1. Assessment of material quality and durability according to CLA and CMDE values in %, after [11].

Criteria	standards	Excellent	satisfactory	Limited	Poor
C_{LA}	EN 1097-1	< 15	15-25	25-35	> 35

CMDE	EN 1097-2	< 10	10-20	20-30	> 30

3. Results

3.1. Petrography and Geochemistry

3.1.1. Feldspar Megacrystals Granite (T1)

This facies outcrops in grey balls and blocks from the summit to the foot of the hill (Figure 3b). In these balls and blocks, pink and sometimes milky white feldspar crystals up to 3 cm in size are scattered among the medium grains, giving the rock a gritty porphyroid texture (Figure 3c). In thin sections, granite is composed of quartz, orthoclase, plagioclase, biotite and opaque minerals. Quartz (30%) is xenomorphic, no larger than 1.5 mm, with undulating extinction (Figure 3d). Orthoclase (30%) is automorphic to sub-automorphic, sometimes up to 1cm in size, and alters to damourite. Plagioclase (20%) is automorphic to sub-automorphic, sometimes up to 1.5 mm in size, and is often close to quartz and orthoclase crystals. Biotite (15%) is generally in contact with quartz, plagioclase and alkali feldspar but is also sometimes included in plagioclase. Opaque minerals constitute about 5% of the studied section. Major element analysis (Table 1), confirms a typical granite composition, with 72 wt.% SiO_2 and 8.6 wt.% $Na_2O + K_2O$.

3.1.2. Biotite-Rich Fine Grained Granitoid (T2)

Major elements (Table 2) point toward a monzonitic composition: 57.6 wt.% SiO_2 and 6.9 wt.% $Na_2O + K_2O$. However, the color variability observed on the field suggests that the analysis, obtained on a particularly dark independent sample, may not be representative of the E2-E3 samples. Therefore, we will call this facies "fine grained granitoid". It outcrops in balls and blocks mingled with the alkali feldspar megacrystals granite (Figure 3e). It is light to dark grey (Figure 3e-f) and shows a texture with medium to fine grains of quartz, orthoclase, plagioclase and biotite (Figure 3g and i). Quartz (15-20%) is automorphic to sub-automorphic, sometimes up to 1mm in size (Figure 3h). Orthoclase (20-25%) is sub-automorphic, up to 1.2 mm in size, and alters to damourite. Plagioclase (18-25%) is automorphic up to 0.75 mm in size and is often associated with quartz and orthoclase. However, some sections are as large as 1.5mm. Biotite (20-25%) occurs as small flakes in association with quartz, plagioclase and alkali feldspar. The accessory phases consist of opaque minerals and sphene. Opaque minerals (≈4%) are frequently associated with biotite, from which they are derived by alteration, but are also included in plagioclase, alkali feldspar and quartz. Sphene (trace) is diamond-shaped and generally associated with orthoclase and quartz. A significant amount of sulfide (pyrite) indicates absence of weathering.

Table 2. Major element composition of the studied petrological types in wt.%.LOI is loss on ignition.

	SiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	Total
T1	72.00	13.43	2.10	0.029	0.38	1.17	3.39	5.20	0.29	0.17	0.81	98.96
T2	57.45	14.92	7.37	0.094	3.14	5.11	3.56	3.32	1.77	0.81	1.62	99.16
T3	60.84	14.92	7.03	0.097	2.65	4.26	3.32	2.17	1.68	0.76	1.29	99.00

Figure 3. Photographs and microphotographs of the different petrographic types outcropping in the Alfallé massif: (a) general view (b) Outcrop in balls and blocks of alkaline feldspar megacrystalline granite. (c) Sample of alkali feldspar megacrystalline granite. (d) Microphotograph of alkali feldspar megacrystalline granite. (e, f, g, h, i) Boulder outcrop (e), samples (f and h) and microphotographs (g and i) of biotite microgranitoid.

3.1.3. Biotite-Rich Gneiss (T3)

The biotite-rich gneiss outcrops in balls and blocks ranging in size from 120cm to 3.4m in diameter at the foot and on the eastern side of the hill. Composition of the analyzed sample is dioritic: 60.8 wt.% SiO_2 and 5.5 wt.% Na_2O + K_2O. The rock has fine to medium-sized grains and a finely foliated structure, marked by the preferential orientation of minerals organised in alternating fine bands of different colour and composition (Figure 5a-d). The light bands, less than 1 mm thick, are rich in quartz and alkali feldspars). The dark bands, less than 0.5 mm thick, are made up of biotite flakes. Microscopically, the rock has a heterogranular granolepidoblastic microstructure characterized by close-packed phenoblasts (quartz, alkali feldspars and plagioclase) and biotite flakes (Figure 5b and d). Accessory phases are represented by sphene and opaque minerals. Quartz (25-30%) is in the form of xenomorphic crystals with undulating extinction. It is very often associated with alkali feldspars and plagioclase, with which it forms the clear band. Alkali feldspars (25-27%) are represented by orthoclase and microcline. Orthoclase (20-22%) is in the form of sub-automorphic to xenomorphic crystals with blunt contours (Figure 5b), ranging in size from 0.5 to 2mm, and in places shows undulating extinctions. The orthoclase, like the other phenoblasts (quartz, alkali feldspars and plagioclase) is molded by biotite flakes, shows signs of alteration to sericite. Microcline (≈5%) is sub-automorphic to xenomorphic and results from mechanical alteration of orthoclase. Plagioclase (17%) occurs as large sub-automorphic patches of up to 1mm (Figure 5b). It sometimes has the polysynthetic macle of albite. Opaque minerals are sometimes found as inclusions in these plagioclases. Some sections show damourite alteration. Biotite (25-27%) appears as elongated, preferentially oriented flakes (Figure 5b), molding the phenocrysts. Opaque minerals (≈5%) are

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globular in shape as inclusions in the phenoblasts or as streaks along the edges of the biotite (Figure 5d). A significant amount of sulfide (pyrite) indicates absence of weathering.

Figure 4. Photographs (a and c) and microphotographs (b and d) of the two biotite gneiss samples.

3.2. Physical Characteristics of the Aggregates

The results of the mechanical Los-Angeles and Microdeval wet tests, as well as density determinations are presented in Table 3. The studied aggregates have specific density values between 2.58 and 2.75 g/cm^3, with an average value of 2.66 g/cm^3. This is in the high range for granitoids according to average values for three other massifs in central Chad (Table 3), and similar to values observed in eastern Chad Abéché granites around 2.67 g/cm^3 [12]. These high values suggest minor weathering, porosity and fracturing. The highest value, obtained in E3 micro-granitoid, suggests this sample is particularly rich in Fe and Ti bearing minerals. Negligible weathering of our samples is confirmed by the presence of sulfides (in T2 and T3) and the low loss on ignition (see Table 2), from 0.8 to 1.6%, typical for dehydratation of biotite rather than clays and hydroxides.

The Los Angeles coefficient in the study area varies from 11.2% to 28.9%, with an average value of 20.1%. The wet Micro Deval coefficient varies from 5.2% to 10.8%, with an average value of 7.6%. Variability of these parameters by a factor over 2 is in agreement with the variable mineralogy, texture and grain-size observed in the Alfallé massif. This is in line within results obtained on the different facies of heterogeneous migmatites from Brasil by [13], with CLA varying from 20 to 54 % and CMDE varying from 8 to 32 %. The averages from the Brasil study, at 47 and 19%, are higher than the ones obtained in the Alfallé massif.

According to Table 1 categorization, all samples have excellent to satisfactory LA test results apart from sample E1 coarse grained granite, in agreement with observations that CLA increases significantly with increasing grain size [3]. The highest resistance to abrasion in LA test is observed for the E4 gneiss. In terms of Micro-Deval coefficients all samples show excellent resistance to wear, excepted micro-granitoid sample E3 which shows satisfactory resistance. This may be due to a lower quartz content in this sample, as indicated by a higher measured density.

Table 3. Mechanical parameters of the studied aggregates in %, grain density in g/cm3. Excellent and limited to poor quality parameters are highlighted in bold and italics, respectively (based on the thresholds of Table 3). Data from Alfallé are compared with literature data from N'Goura [14], Birni [15] and Mongo [16] coarse granite quarries (see Figure 1).

Sample	E1	E2	E3	E4	E5	Mean	N'Goura	Birni	Mongo
C_{LA}	*28.9*	20.7	16.9	**11.2**	23	20 ±7	*30 ± 5*	*32±1*	*36±10*
C_{MDE}	**8.6**	**5.2**	10.8	**5.4**	**7.9**	**7.6** ±2.3	**7.1** ± 3.4	*28±1*	10.0±3.6
ρ_s	**2.66**	**2.66**	**2.75**	**2.66**	**2.58**	2.66±0.06	2.55±0.08	2.6	2.55±0.02
type	T1	T2	T2	T3	T3		T1	T1	T1

4. Discussion and Conclusion

In terms of resistance to abrasion and shock (LA test) the Alfallé massif, despite its heterogeneity, appears to show the highest resistance measured in Central Chad quarries (see Table 3 and Figure 5) as well as Eastern Chad Abéché quarries with Los Angeles coefficients of 28 to 31%. The second highest average resistance is observed in N'Goura massif. In terms of resistance to wear (MDE coefficient) average values for Alfallé and N'Goura are statistically identical, and significantly more resistant than other granites from central Chad (Table 3), while the Abéché quarries yeld values from 7 to 8%, similar to Alfallé The largest aggregate quarries in Chad, the Hadjer el Hamis and Dandi microgranite to rhyolite massifs, just North of N'Djamena, show average CLA of 25 ±9 % and CMDE of 10 ±6 % [17], again less resistant than the Alfallé massif, despite the small grain size.

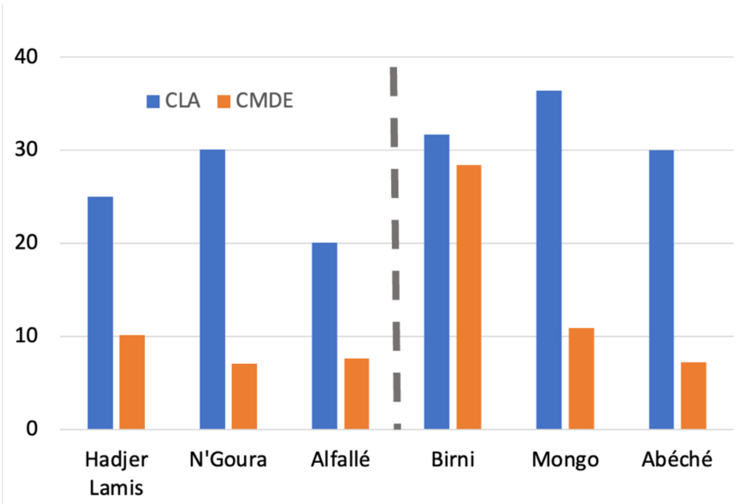

Figure 5. Synthesis of aggregate mechanical data obtained in Chad from W to E in the latitude band 12-14°N. Average per site are shown, pooling the two nearby quarries of Abéché and of Hadjer Lamis-Dandi. Vertical line indicates the eastern limit of mega-Chad paleolake.

In the context of the rare residual reliefs of the overall very flat landscape of Chad, it is understandable that hundreds of million years of erosion has selected naturally the hardest rock to emerge a few tens of meters above the Quaternary deposits [4,18]. Still the limited data available point toward the fact that the reliefs that were flooded by mega-Chad lake (Alfallé, N'Goura, Dandi and Hadjer el Hamis) are more mechanical resistant according to LA and MDE tests, than the other three sites (Birni, Mongo and Abéché) outside the mega-lake (Figure 5). We note that all measurements reported were obtained in the same laboratory and the same procedure, thus they should not be subjected to differential experimental biases. Also, all compared sites are situated around 13°N latitude (minimum and maximum for Mongo and Abéché at 12.1 and 13.8°, respectively) and show similar Sahelian climate, with pluviometry around 400 mm/yr [19]. If we assume that this contrast is not linked with a grain size or lithological contrast, as suggested by considering overall petrographic characteristics, what could be the specificity of mega-Chad lake in terms of natural selection of the hardest rocks? It could be linked to the fact that residual relief are much rarer within the mega-lake than outside, pointing toward a more efficient erosional and peneplanation process. What happens in the mega-lake area, besides the ubiquitous meteoritic weathering, is that when the relief are submerged periodically, a specific erosion process arises through the wave action on the rocky islands that are circled by a boulder beach, still visible today. These boulders are moved on the rocky surface by the waves, thus wearing very efficiently the outcrop. Therefore, only the more wear resistant relief will survive to the process. Alternatively, one could also evoke sand-blasting by strong winds during dry periods. The mega-lake area is indeed characterized by ubiquitous dunes, compared to the surrounding areas. When visiting the various massifs mentioned in this study it is visually obvious that bold flagstone surfaces are more abundant within the mega-lake, pointing toward a process that eliminates materials detached from the outcrop.

In conclusion, the Alfallé rocks are made up of three petrographic types: alkali feldspar megacrystal granite, biotite microgranite and biotite gneiss. The granites have micrograined and grained textures, while the gneisses have a foliated structure with a grano-lepidoblastic texture. These formations are composed of quartz, orthoclase, microcline, plagioclase, biotite and opaque minerals. Five aggregates samples from this massif yield variable resistance to degradation as measured by the Los Angeles and Micro-Deval wet tests, in agreement with heterogeneous petrographic types. On average the mechanical tests place Alfallé material among the most resistant quarries studied in central Chad. This may point toward a natural selection process of the harder rocks linked to the specificity of erosional processes within the Chad mega-lake basin.

Author Contributions: H.Z. Al-hadj, designed the study, performed the sampling and wrote the article.; P. Rochette corrected the article and performed submission and revision; A.B. Allafouza performed some measurements and interpretations.

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Conflicts of Interest: The authors declare no conflict of interest.

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