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On the Origin of the Cavities Present in the Sandstone Formations of the Hydroelectric Development Site of Kakobola and Its Surroundings (Kwilu Province/DRC)

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Abstract

Problems due to underground cavities at the level of soft and polymorphic sandstones, collapses and infiltration of acid waters through the fracture networks have been observed around the Kakobola hydroelectric development, constituting potential risks for the stability of the dam. The objective of this article aims to highlight the major cause that can explain the generating processes of these cavities. Indeed, to do this, the exploration of the subsoil was made possible thanks to the eleven (11) boreholes drilled on the site, the determination of cavities by the method of colored tracers and the petrographic characterization using a microscope. The latter, by means of thin sections, reveals the presence of quartz arenites. The mineralogical characterization of rock materials was carried out using X-ray fluorescence and X-ray diffraction methods. X-ray fluorescence revealed the presence of nickel, zinc and iron. Diffraction shows us an abundance of silica, mainly quartz and its metastable phases, in particular tridymite and cristobalite. It also made it possible to question the presence of carbonated minerals. The drillings enabled us to elaborate the logs and to bring out a geological model of the sector of study. These models were produced on the basis of drilling and observations on excavation. These data also reveal the presence of underground cavities which were also confirmed by the colored tracer method. These cavities would be of natural origin due to the presence of carbonate minerals observed in the rocks and which are attacked by acidic waters attested by the pH < 5 measurements of the waters of the Lufuku River. The infiltration of water in rocky materials of low density and through the various networks of fractures and cavities leads to instability of the rock and could damage the hydroelectric development.

Keywords

Development, Cavity, Drilling, Sandstone, Hydroelectric, Kakobola

1. Introduction

The construction of Civil Engineering dams is part of a risk prevention and management policy to better protect human lives and limit the negative impact on the environment (LCPC, 2004; Ndala et al., 2022). Underground cavities are a threat to constructions when their presence is not detected (INCRIS, 2014; Lambert, 2012).

Indeed, if one builds above an underground cavity without knowing it, one does not size the structure correctly and it may prove to be fragile (Fauchard & Potherat, 2004). The weight of the structure causes the roof of the cavity to give way and sudden ruin ensues, all the more serious as there may be bodily injuries (BRGM, https://www.cavites.fr/).

Knowing the risks is the first step towards comprehensive risk prevention. Indeed, it is essential to know which areas are affected by a dangerous phenomenon (Collet et al., 2002; 2004). Undesirable events can be in particular subsidence and collapse related to the presence of underground cavities such as those having disrupted the smooth running of works with a diameter of at least 20 meters (Angelique International Limited, 2011) threatening the stability and the integrity of the structures of the Kakobola hydroelectric site of the Kwilu province in the SW of the Democratic Republic of Congo (DRC) in the central Congo basin. The latter is a vast depression (Kadima, 2011) whose deep structure is very little known because the geological and geophysical study is made difficult by the equatorial forest and recent sedimentary deposits (Kadima, 2007). Some authors consider this basin as representing a major handicap in the knowledge of the tectonic and structural evolution of Africa and more generally in the process of its formation. Geological studies are essential before, during and after the construction of a hydroelectric development. The knowledge of petrography as well as the study of underground cavities proves to be very essential both in civil engineering and in mining research. Some authors consider this basin as representing a major handicap in the knowledge of the tectonic and structural evolution of Africa and more generally in the process of its formation.

Contrary to what is known by earlier authors in particular on the rarity of the outcrops in the study region, recently works by Lusilu and Mbangilwa (2015); Katuku and Mboyo (2017); Ndala (2017); Kapita and Mbongo (2019); Ndala et al., (2022) highlight an unstable zone with a diversity of underground cavities within the sandstones. Eleven 11 boreholes were drilled on the Kakobola site by two companies (Angelique International Limited, 2011; the National Laboratory of Public Works, 2007). The resulting drilling data also revealed the presence of underground cavities. As recognized, the existence of cavities in the subsoil is indeed a potential source of dangerous phenomena from an environmental point of view, as well as industrial and urban constructions. These studies have cast doubt on the decisions made for the choice of the site for this hydroelectric development. This instability could lead to increased rehabilitation and regular maintenance costs.

Therefore, this work aims to highlight the major cause that can explain the generating processes of the cavities observed at the subsurface. It is in this perspective that we designed this work to better understand the geological formations using several investigation methods at different scales.

2. Study Area

The Kakobola hydroelectric development is located in the Central basin, precisely in the province of Kwilu in SW DR Congo (**Figure 1**). It is located 70 km south-southeast of the city of Kikwit and 790 km east-southeast of the city of Kinshasa (Coyne & Bellier, 2008a, 2008b). The Kakobola project is 10.5 MW with 3 units of 3.5 MW each. This dam is the first and only one to be built in this province since colonization (Coyne & Bellier, 2008c). It will be able to supply electricity to three towns: Kikwit, Gungu and Idiofa (Lusilu & Mbangilwa, 2015; Katuku & Mboyo, 2017; Ndala, 2017; Kapita & Mbongo, 2019; Ndala et al., 2022).

3. Methodology

Apart from the documentation stage, this work goes through the different research stages below:

1) Ground stage:

To get a general idea of the geology, topography and morphology of the study area, we carried out a general exploration of the entire area concerned, over a radius of 42 km centered by the dam, while making observations and descriptions of the outcrops and geological processes, the sampling, as well as the macroscopic description of the samples. Our fieldwork was obviously oriented in the perspective of the geology of the dam to have additional elements and more details for the development of the conceptual model of the site.

The samples were cold attacked with hydrochloric acid diluted to 10% to

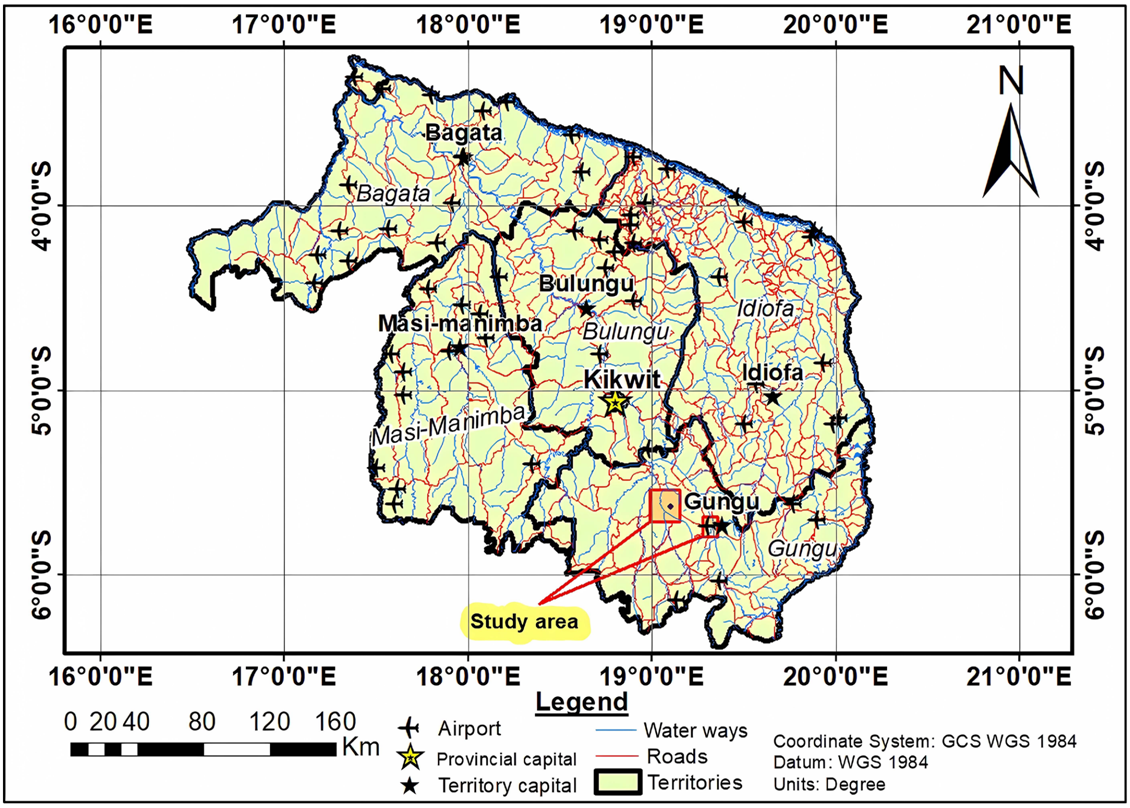


Figure 1. Administrative map of the study area.

detect the presence of carbonate minerals (calcite). It should be noted from the outset that the detection of carbonated phases with the cold effervescence test with 10% dilute hydrochloric acid was not conclusive for some samples. Thus, recourse was made to spectroscopic diffraction and X-ray fluorescence methods in particular to detect carbonated phases of the dolomite type which in fact only effervescence when hot.

In short, this step consisted first of all in the use of the following equipment for the geological survey:

❖ **Equipment used for the geological survey include:**

Geologist's compass with clinometer, geologist's hammer, sledgehammer and chisels, Garmin GPS, monocular magnifier, markers, field notebook, digital camera, pens and pencils, and several other accessories.

The information and/or data subject to the production of the geological logs came from 11 boreholes. Those drillings were carried out by two companies, distributed as follows:

➢ Four (4) boreholes by the National Laboratory of Public Works (2007), including:

✓ 3 boreholes on the route of the water intake and conveyance between the Lufuku River and the head of the penstock: SK1 (13 m); SK2 (25 m) and SK3 (20.1 m) deep;

✓ 1 borehole on the factory site: SK4 (12.65 m) deep.

➢ Seven (7) boreholes by Angelique International Limited (2011), including:

✓ BH-1 and BH-2, respectively 20.50 m and 15.50 m deep, drilled along the axis of the spillway;

✓ BH-3, 25.50 m deep, was drilled at the entrance to the supply channel;

✓ BH-4 and BH-7, 25 m and 38 m deep respectively, drilled in the for ebay and instead of the penstock trench;

✓ BH-5 and BH-6, respectively 25 m and 30 m deep, drilled in the location of the hydroelectric plant.

❖ **Uncovering underground cavities by the colored tracer method**

To ensure and definitively confirm the presence of these underground cavities, we also used the colored tracer method. It consisted in the preparation of the blue and pink tracers in the laboratory (**Figure 2(a)**, **Figure 2(b)**), their injection into the boreholes located at the level of the dam (highest altitude) (**Figure 2(c)**) and at the observation, after a few minutes of waiting, of their manifestation, that is to say of the appearance of colored water coming from the tracer at the level of the site of the hydroelectricity production plant (lowest altitude) through two water inflow points (**Figure 2(d)**).

Figure 2. (a, b) Preparation of stained tracers in the Lab in blue-violet and pink in the field; (c, d) Injection of tracers into boreholes at the dam, Impact of injected tracers and appearances of tracers at the plant site through two points.

2) Laboratory step

This step consisted of:

- ✓ The preparation and microscopic description of thin sections. A total of fifteen rock samples were selected and analyzed at the Center for Geological and Mining Research (CRGM) in Kinshasa, at the Department of Geology at the University of Lubumbashi (UNILU) and at the Department of Geosciences at the University of Kinshasa (UNIKIN). These samples were cold attacked with hydrochloric acid diluted to 10% to detect the presence of carbonated minerals;
- ✓ The analysis and processing of data collected in the field using software, such as Arcgis and Map info (for the development of maps, logs, etc.) and measure by PHYWE for the processing of data from diffraction and X-ray fluorescence. In addition to this software, we used the "PanalyticalXpertPanalytical plus High score plus 2008" for the interpretation of the different spectra by means of the maximum values of each peak of the spectrum. The latter software includes an International Center of Diffraction Data (ICDD) database in its PDF-2 database which deals only with minerals. This processing software allows us to carry out a semi-quantitative study of the results;
- ✓ The X-ray diffraction spectra of our samples were obtained using the XR 4.0 EXPERT UNI brand X-ray diffractometer from the Physics Department of the University of Kinshasa. The analysis of the spectra allowed the identification of the constituent minerals of the rock very precisely in addition to the determination of their respective percentages. This analysis complements the microscopic observations obtained with the preparation of thin sections. We used the PHYWE diffractometer using Cu anode or anticathode. The materials used are as follows: plastic bottles, a beaker, spatulas, a porcelain mortar and pestle, a scale, distilled water (H20), a basin (container), gloves, acetone, a Vaseline ointment, a graduated foot, a pair of scissors and glue;
- ✓ As for X-ray fluorescence: the chemical elements ranging from Na to U are systematically determined by energy dispersive X-ray fluorescence spectrometry (Sharma, 2011). It allows qualitative as well as quantitative determination of major and trace elements in an infinite number of sample types. To carry out this analysis, we used a hammer, a marker, gloves, a vernier caliper, packaging for large samples and a camera. We used small fragments of the rocks. The various stages of sample preparation include the crushing and measurement of rock samples.

3) Interpretation and discussion stage

Our results are not only discussed but also confronted with those of other researchers in order to take a position in relation to pre-existing theories by affirming or invalidating them according to recent published research carried out in the matter.

4. Results

1) Field investigations: production of logs, sections and mapping

The studied land located along the very incised "Lufuku" river, is of Cenozoic age and belongs to the so-called "series of polymorphic sandstone" stage. At the "Kakobola falls", the series of polymorphic sandstone is made up, in the superficial fringe, of blocks of eluvial polymorphic sandstone which surmount the generally calcareous soft sandstone with fine and/or coarse grains. These sandstones are massive, fairly diaclased but becoming friable and more calcareous with depth.

In general, the lithology of the Kakobola hydroelectric development site comprises horizontally the sub-sequence of thick soft sandstone beds overlain by polymorphic sandstones 4 m thick (**Figure 3**). The bedrock is under regolith (soil) cover which is about 20 m thick on the left bank and is only found in patches about 2 m thick on the right bank.

Figure 4 shows the macroscopic view of the geological section at the projected location of the hydroelectric power plant. This section highlights through the formation of loose rocks (sands) in the soft sandstones as the depth of investigation increases.

2) Analysis of boreholes and general geological model of the Kakobola hydroelectric development

All this information from various drillings carried out on the site coupled with our own observations on the ground, enabled us to carry out the logs and the general geological model.

As an illustration, we present two boreholes:

- ✓ BH-2 which is located on the axis of the dam towards the left bank (RG) of the river. It was drilled to a depth of 15.50 m and intersected polymorphic sandstone bedrock at 0.50 m and continues to a depth of 3.00 m. The rock is slightly altered (**Figure 5**);
- ✓ BH-3 which is located on the headrace intake (**Figure 6**). It was drilled to a depth of 25.50 m and intersected polymorphic sandstone bedrock at 0.30 m. Polymorphic sandstone continues up to 4.50 m, from the soft sandstone is encountered up to 25.50 m. The rock is slightly weathered.

Figure 3. The lithology of the project area (Kakobola Falls).

Figure 4. Macroscopic view of the lithostratigraphy section at the projected location of the Kakobola hydroelectric power plant.

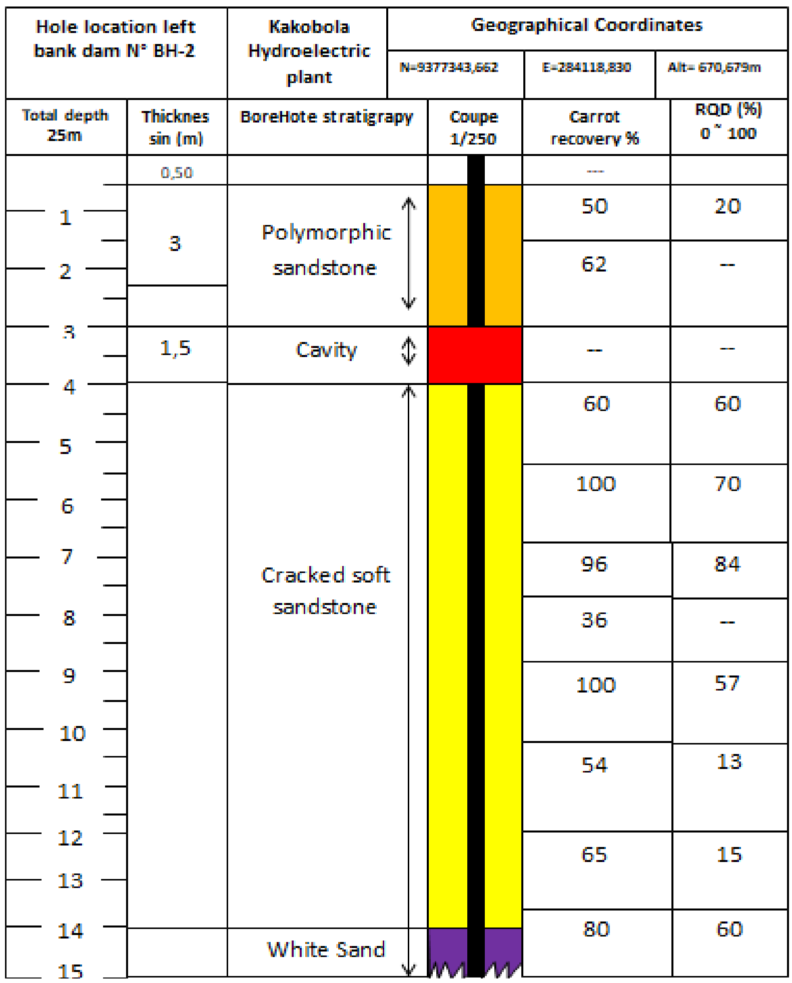


Figure 5. Stratigraphic log of borehole BH-2 (axis of the dam towards the RG of the river).

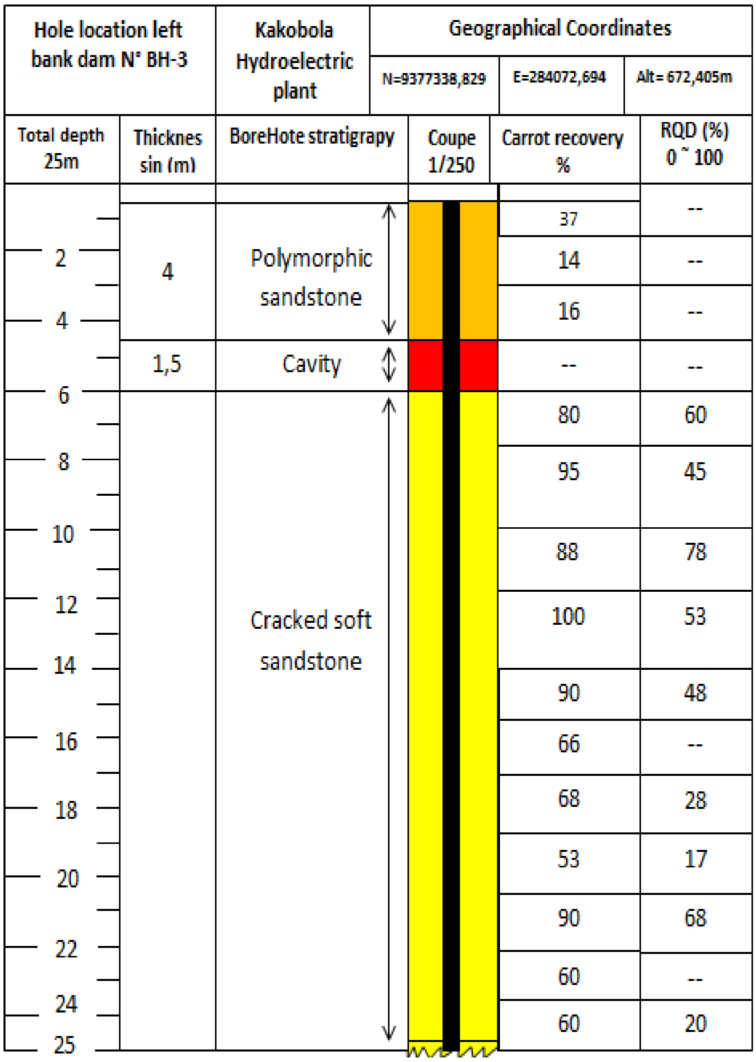


Figure 6. Stratigraphic log of borehole BH-3 (Water intake from the intake canal).

The synthesis of all the geological logs made on the Kakobola hydroelectric development site is represented in a general geological model (Figure 7). This model was produced on the basis of drillings and observations on excavations.

3) Petrography of sampled rocks: macroscopy and microscopy

A visual observation allowed us to describe the different rocks encountered in the study area at the outcrop scale and its samples. This description is usually based on rock color, grain size, etc. As an illustration, we present four (4) samples and thin sections.

a) Sample KM05

Macroscopic descriptions

This outcrop is located at the fall, which is approximately 55 m from the dam site. It is a polymorphic sandstone. This is flush in places as in a buttonhole. This sandstone is massive with a pinkish color (Figure 8).

Microscopic Descriptions

We observed several varieties of minerals (Figure 9):

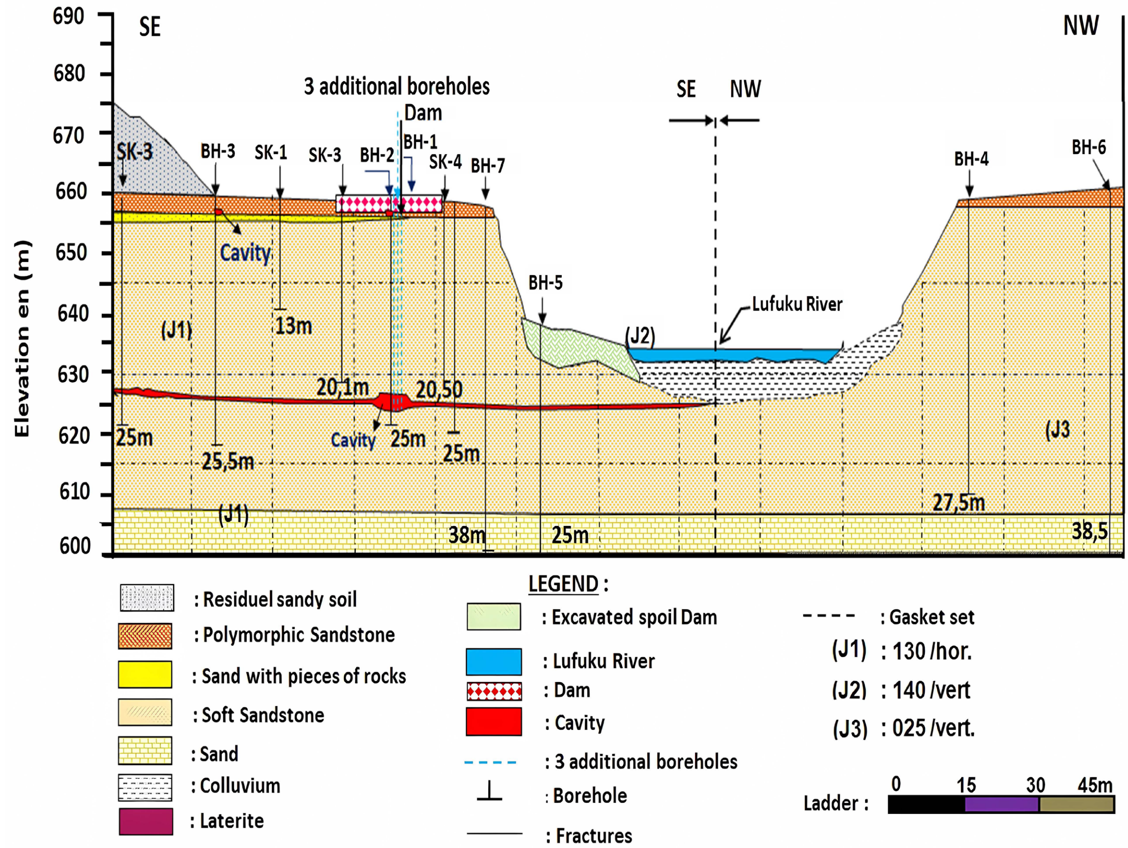


Figure 7. General geological model of the Kakobola hydroelectric site.

Figure 8. Macroscopic view of the outcrop and sample IV 03.

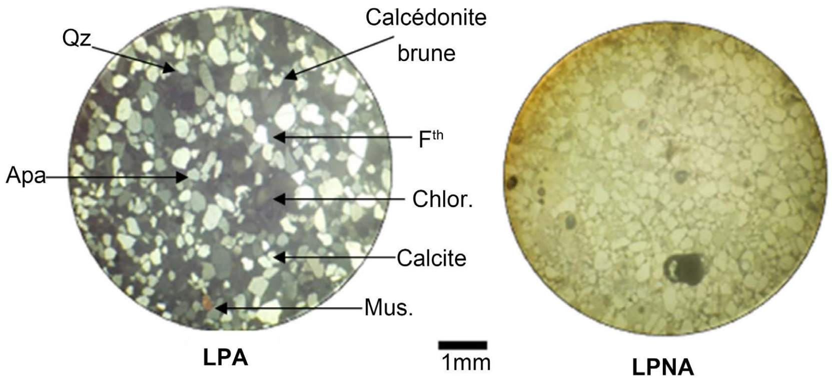


Figure 9. View under the LPA and LPNA microscope of the IV 05 slide (20× magnification).

Equi-dimensional mega quartz: these are grains whose diameter varies between 20 and 300 µm. This quartz is characterized by a wavy extinction and by its arrangement in mosaic of joined grains. In rock, this type of silica constitutes the latest event in matrix silicification. Indeed, the mega quartz is found either on the walls of voids, or in the center of these when the filling of these voids has been significant. In both cases, between the wall rocks and the deposits of this form of silica, there very frequently appear formed intermediate zones.

Microcrystalline quartz: their diameter varies between 3 and 25 µm. This silica constitutes clusters whose general morphology and diameter recall those of certain grains of detrital quartz included in the rock. It should be noted here that most of the corroded detrital quartz grains are often associated with microcrystalline quartz. Furthermore, microscopic grains of residual calcite are often associated with this silica. The size of these grains is similar to that of microcrystalline quartz, that is to say from 3 to 25 µm; and this calcite is recognizable thanks to its fine cleavages giving a lozenge grid;

As for fibrous silica, it is generally expressed in the form of chalcedonite;

The accessory minerals are apatite, chlorite and fine flakes of white mica which polarize in bright second order hues. The rock would be a quartzite.

b) Sample LM 06

Macroscopic descriptions

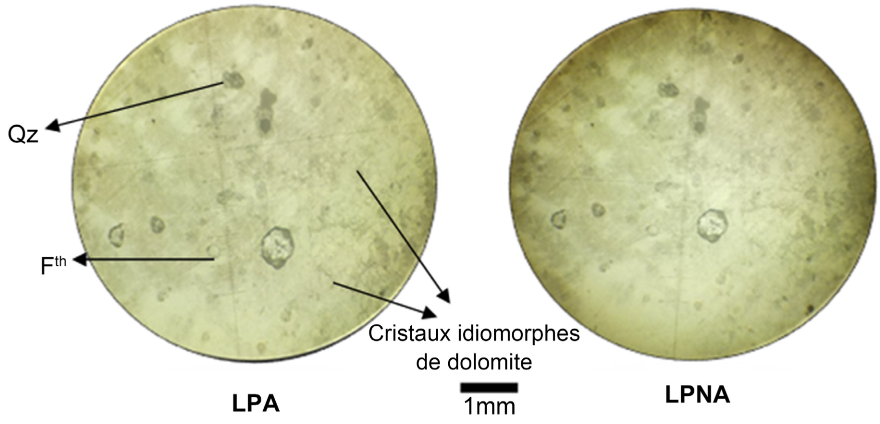
Here, reddish to whitish rock outcrops (**Figure 10**); the grain size is fine and massive in appearance, probably soft arenitic sandstone. The rock presents two families of fractures, some parallel and the others perpendicular to the first. There is no apparent setback between the two families of fractures. Erosion has acted along these planes of weakness within the rock.

Figure 10: Macroscopic view of outcrop and sample IV 06.

Microscopic Descriptions

The texture of the rock (**Figure 11**) is granular showing: the mixture between small and medium quartz grains of sub-angular shape; intercalated with grains of carbonates recognizable by their cleavage; carbonate (dolomite); silica cement. The rock would be a quartzite.

Figure 10. Macroscopic view of outcrop and sample IV 06.



(a) (b)

Figure 11. View under the LPA (a) and LPNA (b) microscope of the IV 06 slide (20× magnification).

c) Sample KM12

Macroscopic description

This sample was taken from the Kakobola site not far from the fall of the dam; it is dominated by two colors: gray and white. The white part breaks easily with a hammer blow unlike the gray part which requires several hammer blows given its hardness, it is also massive (**Figure 12**).

Microscopic Description

The microscope shows that the rock contains a clayey matrix impregnated with dark-colored iron oxides and encompassing the grains of white or gray (LPA) and colorless (LPNA) quartz (**Figure 13**). These grains, fine and medium, have subrounded, subangular, angular and elongated shapes are fine and medium. Rarely are the coarse grains isolated among the fine grains. Grain grading is poor. The rock has a contiguous structure, it is a quartz arenite.

d) Sample KM05

Macroscopic description

This sample was taken upstream from the Kakobola gravity dam. The dense and massive rock presents several colors in itself: brown, pinkish color, etc. Its grains are fine with a barely grainy surface to the touch (**Figure 14**).

Microscopic Description

Under the microscope, the rock shows a contiguous structure underlined by grains of white or gray (LPA) and colorless (LPNA) quartz (**Figure 15**). These grains are slightly cracked, medium and slightly subrounded. The classification is good, that is to say the grains are almost all of the same size and the same shape. It is a quartzite arenite.

4) Mineralogical analysis by diffraction and X-ray fluorescence

a) X-ray diffraction

The analysis results of our samples KM05, KM08, KM12, KM70 and KM246 are represented in detail in the article "Characterization of Ceno-Mesozoic sandstones from the hydroelectric development site of Kakobola and its surroundings

Figure 12. Macroscopic view of outcrop and KM12 sample.

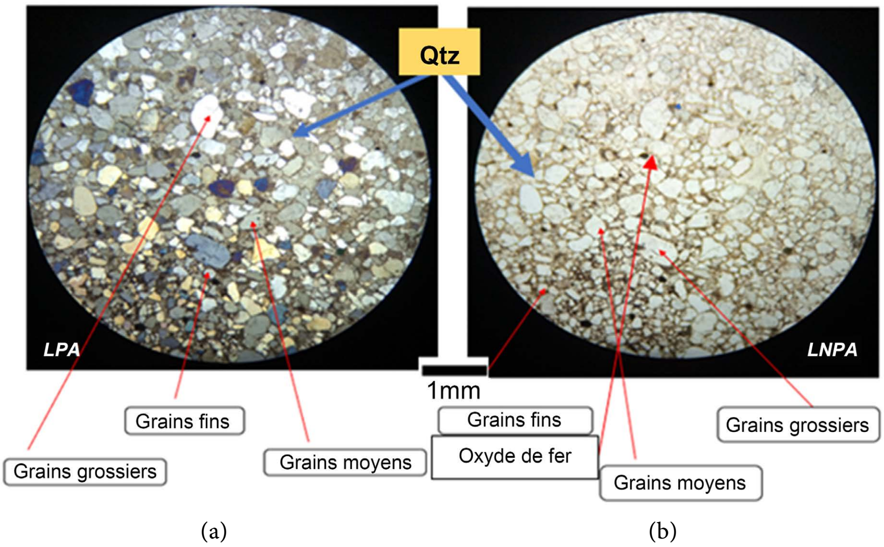


Figure 13. LPA (a) and LPNA (b) microscope view of the KM12 slide.

Figure 14. Macroscopic view of sample KM05.

by diffraction and X-ray fluorescence (Province du Kwilu/RD Congo)" published in the Journal Géo-Eco-Trop (2022): 46.2: 329-342 (Ndala et al., 2022).

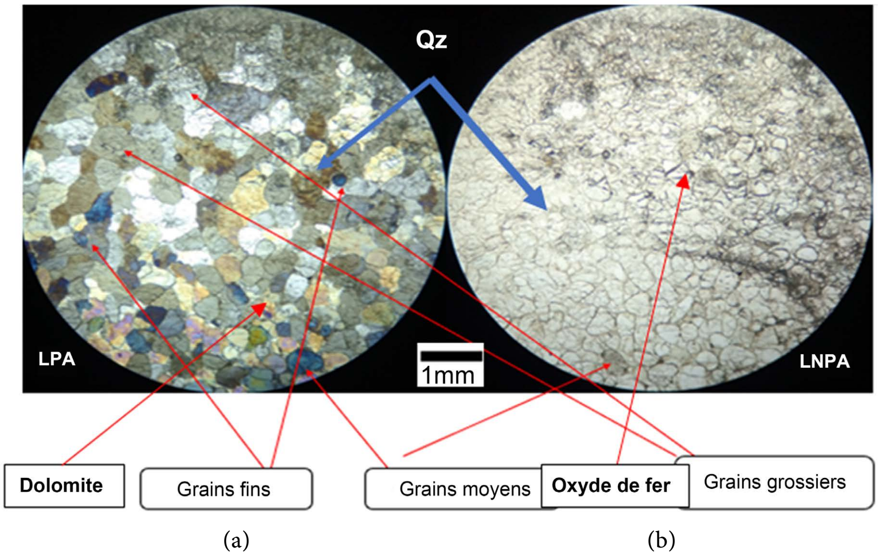


Figure 15. Thin section of the sample with LPA in (a) and LNPA in (b).

The results of this method present the composition of the samples analyzed, in particular:

- The KM05 sample which shows an abundance of quartz of 55% followed by aluminum hydroxide (25%) forming together 80% of the composition of the rock. Dolomite (5%) and cristobalite (2%) are in traces, but they can generate reactions and contribute to the embrittlement of the rock. They can thus be responsible for certain damages. Cristobalite is a metastable mineral and can therefore seek to regain its balance at any time by reacting with other compounds. Dolomite is a mineral easily altered in water, and therefore its alteration also contributes to the embrittlement of the rock;
- The KM08 sample is mainly composed of aluminum hydroxide silicates with a weight proportion of 60% followed by metastable silica, tridymite at 28% as well as cristobalite with 13%;
- This KM12 rock sample is composed of 65% calcium and aluminum double silicates, hydrated carbonates of iron and aluminum hydroxide at 24% and quartz at 11%. The silicate phases represent on the whole 76% against the carbonate phases;
- As for the KM70 sample, it has an abundance of 61% quartz and 23% tridymite. It also highlights the presence of mineral phases rich in some metals such as Zinc, manganese and Nickel;
- The latest sample KM246 is also rich in 44% quartz, 35% pentlandite and 21% magnetite.

The rocks in the area under study are rich in quartz. We also note the presence of some carbonated minerals in reduced proportion such as dolomite and also of a clay mineral that is kaolinite in the analyzed rocks.

However, these easily altered minerals can be the basis of the weakening of these sandstones by the genesis of certain cavities within the rock. The siliceous parts will tend to resist. Once the clay matrix has been destroyed, we can clearly see the isolated sand grains resulting from this alteration following a purely chemical attack from the water at an average pH around 4.5 of the Lufuku River. This new information therefore constitutes a rich database for better understanding the geological processes responsible for the cavities observed on the foundation rocks of the Kakobola site and surroundings (Ndala et al., 2022).

b) X-ray fluorescence

The results from X-ray fluorescence are characterized by a diversity of metals. They show an abundance of nickel (Ni), Zinc (Zn) and (Ge) which are present in almost all the rocks analyzed, followed by manganese (Mn) (Ndala et al., 2022). These rock samples show metal enrichment.

Data from the earlier works of Lusilu and Mbangilwa (2015); Katuku and Mboyo (2017); Ndala (2017); Kapita and Mbongo (2019) and our newly collected data allow us to produce the geological map of the study area (**Figure 16**).

5. Discussions

The cavities highlighted in the area under study are located in non-carbonate rocks (Ndala et al., 2022). Similar cavities are reported in the carbonate sandstones of Luxembourg (Botzem, 1987). Cavities and sinkholes of various sizes have been discovered in South America and even on the African continent (Truluck, 1992). The genesis of different cavities and other forms listed in sandstones and quartzites, would be found in chemical alteration phenomena (Willems et al., 1993); (Sponholz, 1994) including hydrothermal alterations (Urbani, 1981); (Galan & Lagarde, 1988), the dissolution of silica in grains or in the form of cement (Galan & Lagarde, 1988) and processes of alkaline hydrolysis (Marker, 1976) are advanced.

According to some researchers, the appearance of cavities in sandstone is due to stratification joints, fractures, faults and joints, decompression joints (Chabert & Bigot, 1993). The presence of a more resistant layer (of quartzite for example) (Vitek, 1987); (Bigot, 1990) or more impermeable (schist) (Callot, 1981); (Craft, 1987) can cause differential erosion which would be the origin of underground forms (cavities, caves, conduits, etc.).

Such is the case of the study area in which we have a layer of resistant polymorphic sandstones requiring a lot of energy to be broken because of their silicification (Keenen, 1983) unlike soft sandstones.

Erosion by underground streams or surface water, solifluction and exfoliation (Galan & Lagarde, 1988), deflation or eolization (Vitek, 1987), suffosion (piping) (Willems et al., 1996), granular weathering (Joyce, 1974), etc. can also be processes at the origin of underground forms. Studies carried out on the nature of surface water and percolation has shown the influence of the acid nature of water on karstification (Zawidzki et al., 1976); (Gori et al., 1993).

To explain the genesis of underground cavities in which underground rivers flow and those observed on the surface, we propose the following diagram for the conceptual model of the study area (**Figure 17**):

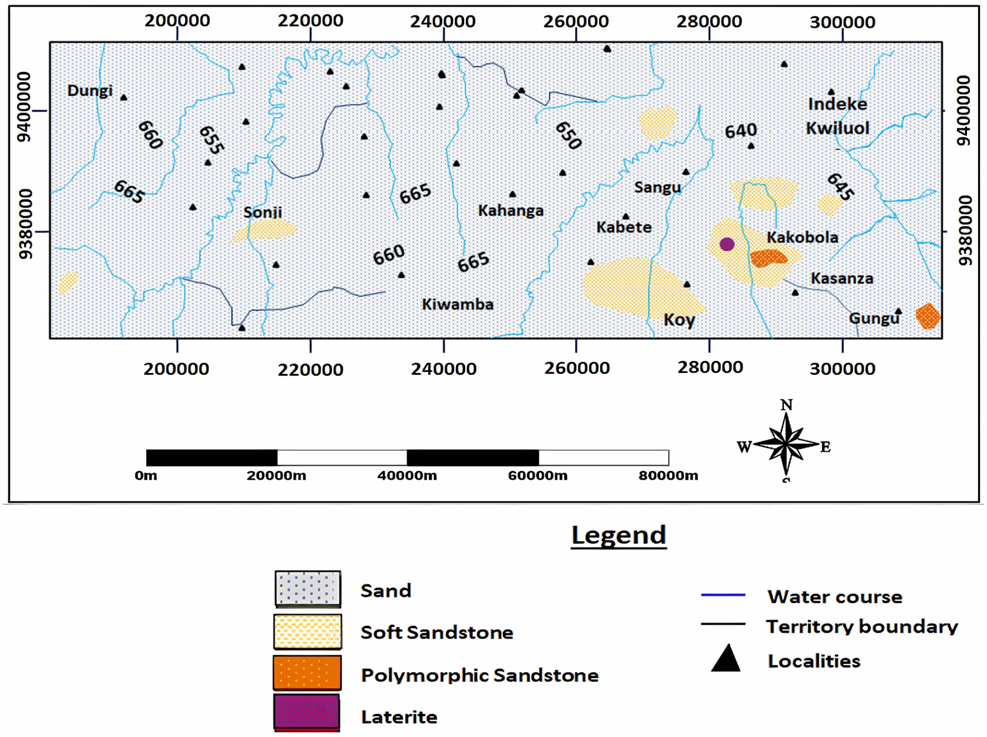


Figure 16. Geological map of the study area.

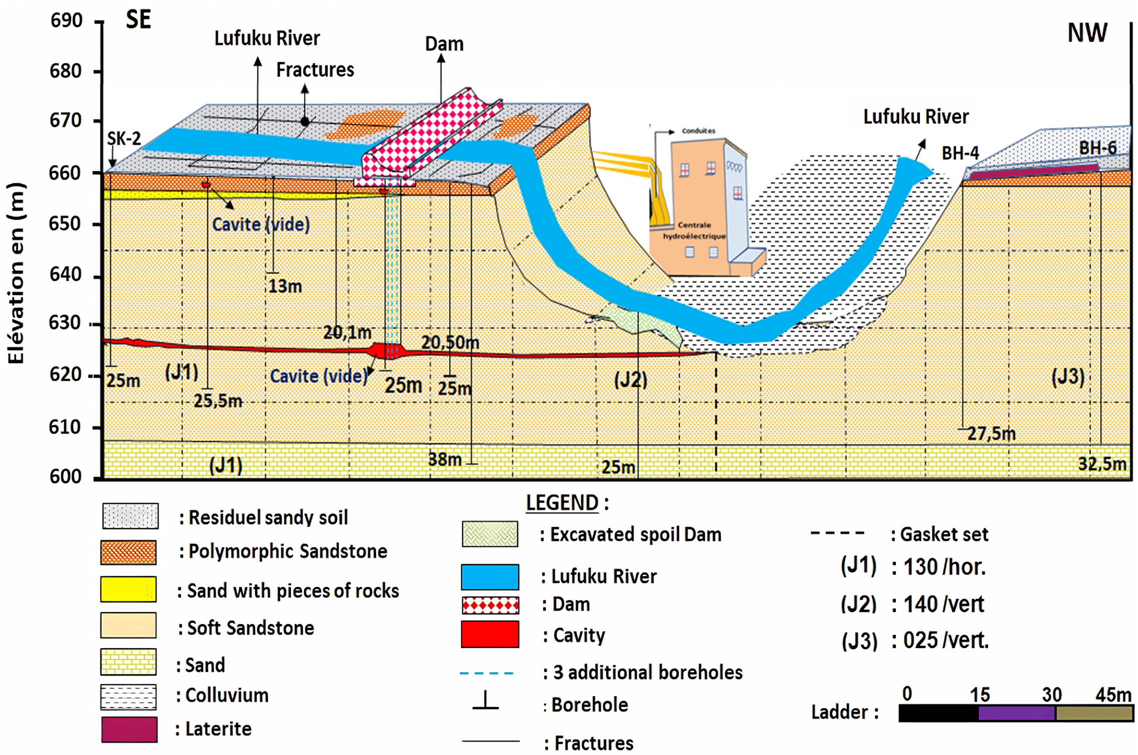


Figure 17. Conceptual geo-hydro-mechanical model of the Kakobola hydroelectric development.

The ground under study being sandstone, with indeed a double porosity, the water of the Lufuku River makes its way through fractures. The porosity being high, the infiltration is too. This results on the one hand in the inception of underground rivers (Kapita & Mbongo, 2019) and on the other hand in the drying up of the river by infiltration over time;

The fractures observed upstream and downstream of the Kakobola dam, the presence of the fall of the Lufuku River at the site of erection of the dam as well as other falls observed in the region and the results from the gravimetry and remote sensing shows significant brittle tectonic activity in the region;

- ✓ The water of the Lufuku River having a pH lower than 5 on average has an acid character (Katuku & Mboyo, 2017). Indeed, during its flow through the cracks and the grains of the rocks, the water causes the phenomenon of chemical dissolution of the minerals that make up the rock. Minerals dissolve in water according to their solubility. The degree of dissolution of rock minerals depends on the duration of water-rock contact and the chemical composition of each. This could explain the fact that polymorphic sandstones are less affected by the inception of cavities within them because they are observed on the surface above the soft sandstones. The infiltration of water through the fractures will be much faster without causing great damage to the polymorphic sandstones. This is in agreement with the hydrothermal alteration due to the acid character of the waters (Zawidzki et al., 1976; Martini, 1987; Galan & Lagarde, 1988; Gori et al., 1993).
- ✓ On the other hand, favored by the porosity of the fractures and the intergranular porosity, the soft sandstones are impregnated in acidic water. The intergranular infiltration of acidic waters takes a very long time and as a result, the acidic water strongly damages the rock, thus generating underground cavities.
- ✓ The occurrence of sand underlying the soft sandstones could also be explained by the suffusion process (Willems et al., 1996). The suffusion process can also take place in very friable rocks such as soft sandstones following the flow of groundwater, which during its flow first tears off the very fine grains. This is referred to as the "Piping" phenomenon. Later, following the rarefaction of fine particles, the process can bring about the conditions of suffusion. As a form of internal erosion characterized by the uprooting, transport and deposition, under the effect of flow, of fine grains of the solid skeleton of the soil concerned (Bonelli et al., 2012), suffusion can generate cavities and gaping chasms.

The study area is therefore a fairly complex area which is the terrain of a diversity of processes responsible for the genesis of both superficial and underground cavities observed in the area which led to forms similar to karstic terrains.

Petrographic descriptions show that chalcedony silica and especially microcrystalline quartz grains must have replaced a carbonate matrix that we had identified. It is mainly composed of calcite. Indeed, brown chalcedonite is considered by several authors as a mineral resulting from the epigeny of calcite by siliceous solutions (Scholle, 1979). The identification in polymorphic sandstone samples of this carbonate in association with microcrystalline quartz confirms the hypothesis of such a substitution (Tshidibi, 1986).

The presence of the idiomorphic crystals of silicified dolomite shows that a second type of carbonate matrix was also in place when the silicifications occurred. Such epigenesis appears to result from diagenetic growth in at least two phases. One could postulate calcification (perhaps preceded by dolomitization) which may have contributed to the formation of a carbonate matrix of the polymorphic sandstones (Tshidibi, 1986).

This calcification could have been followed by silicification processes proceeding by more or less partial substitution of this carbonate. It should be noted that analogous events have been reported elsewhere in numerous works, including for example that of Toulemont (1982) which underlines the siliceous and calciticepigenies of the Upper Lutetian gypsum of the Paris basin.

The silicifications of the polymorphic sandstones took place in at least three episodes:

- ✓ the substitution stage of the carbonate matrix (notably calcite and dolomite). This stage is characterized by the presence of silicification in microcrystalline quartz. The size, shape and arrangement of the grains are comparable to those of the calcite grains encountered in certain thin sections. Brown chalcedonite transformed into megaquartz with idiomorphic zonary crystals are also part of the silicifications by siliceous epigeny of carbonated substances. Indeed, the presence of these two varieties of silica constitutes proof of such a substitution (Scholle, 1979; Toulemont, 1982);
- ✓ the megaquartz characterizes, for its part, late precipitation as suggested by the central position occupied by its grains during the filling of the voids. Its establishment would have occurred from meteoric solutions with temperatures hardly exceeding 40˚C (Miliken, 1979).

As for the corrosion of the detrital quartz grains present in the thin sections, it seems that the presence of the carbonated matrix, in particular calcite, is the main cause. Such dissolution of the quartz must have taken place before the processes of silicification responsible for the current siliceous cement. Indeed, siliceous precipitation seems incompatible with the corrosion of detrital quartz grains.

Furthermore, the formation of the carbonate matrix (calcite) takes place under more or less basic conditions. The latter are favorable to the corrosion of quartz when the role of temperature on this corrosion is negligible (Fritz, 1981).

6. Conclusion

The field investigations in the Kakobola region were carried out under a triple approach based on the geological survey of the region, the petrographic and mineralogical study (X diffraction and X fluorescence) of the various samples brought back from the field as well as the contribution of the study of underground cavities.

Geologically: The exploration of the subsurface was made possible thanks to the eleven (11) boreholes drilled in the study area. All of the geological investigations enabled us to bring out logs, maps and general geological models (2D and 3D) of the area under study. The drilling data reveals the presence of underground cavities which were also confirmed by the colored tracer method. These cavities are of natural origin due to the presence of carbonate minerals observed in the rocks and which are attacked by acidic waters attested by the pH < 5 measurements of the waters of the Lufuku River.

Petrographically: The petrographic analysis of the sandstones made it possible to postulate the presence of an original carbonate matrix composed of calcite and sometimes dolomite. This matrix is in residual form in very small grains (<20 μm). The formation of the carbonate matrix has also been implicated to explain the corrosion of the detrital quartz grains constituting the polymorphic sandstones.

From the mineralogical point of view: The mineral phases detected by x-ray diffraction in the studied sandstone formations are globally consistent with the macroscopic and microscopic observations on thin sections carried out by Ndala et al. (2022). The region under study is a sandstone terrain rich in quartz but polymorphs of silica such as tridymite and cristobalite, and clay and carbonate minerals such as dolomite and sjoegrenite which are not present throughout the site. These sandstone rocks are also rich in iron, nickel and zinc. X-ray diffraction also shows an abundance of silica where quartz is predominant. Metastable phases of silica, including tridymite and cristobalite, and carbonate mineral phases were observed. X-ray fluorescence reveals the presence of the most abundant metals.

The area is strewn with cavities and fractures, thus weakening the sector. Streams run along these fractures. It is made up of low-density rocky materials in which water infiltrates easily, thus weakening the site on which the dam and other hyraulic structures of the Kakobola hydroelectric development are erected.

Conflicts of Interest

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

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