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Kaélé quartzites: Physicochemical and mineralogical characterization of exceptionally pure natural materials for high-tech applications

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Abstract

The aim of this work is to identify the chemical, mineralogical and physical properties of quartzites from the Kaélé deposit, in order to identify their potential applications. To achieve this, characterization methods such as X-ray fluorescence spectrometry and X-ray diffraction, Fourier transform infrared spectroscopy (FTIR) and a furnace for melting temperature determination were deployed. The chemical composition of the quartzites determined by X-ray fluorescence spectrometry revealed that silicon oxide (SiO_2) is the majority constituent, with a mass percentage of 99.02%. The X-ray diffraction spectrum shows only quartz as the mineralogical phase present in quartzites. Quartzites have an average melting point of 1725°C, which is close to the theoretical value and makes the materials studied pure bodies. The various results obtained highlight the high purity of the quartzites from Kaélé. High-purity quartz has numerous applications in high-tech industries. The main ones are semiconductors, high-temperature lamp tubes, telecommunications and optics, microelectronics and photovoltaic cells. Kaélé quartzites can therefore be considered as highly valuable local mineral materials in the above-mentioned fields.

Keywords: Quartzite; Kaélé; Physicochemical and Mineralogical Characterization; Purity; High Technology

1. Introduction

Quartzites are compact siliceous rocks composed of tightly-welded quartz crystals. They are one of the most abundant mineral resources in the earth's crust and are renowned for their beauty and hardness. Their mechanical properties are quite similar to those of quartz, but with more conchoidal fractures and better overall cohesion, limiting spontaneous breakage [1]. Quartzites are highly prized in the manufacture of glass, ceramics and refractory materials [2]. They are also used in high-tech industries when their purity is proven [3].

In Kaélé, more precisely from Manoré to Gohing, there is an open-cast white quartzite deposit. Little known to the general public, this deposit has never been the subject of any scientific work, let alone any application.

Given the quantity and attractive whiteness of these quartzites, this work aims to characterize them with a view to identifying them and finding applications for them. The methods and means used for these characterizations are:

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elemental chemical analysis by X-ray fluorescence (XRF), mineralogical analysis by powder X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR) and determination of melting temperature in an electric furnace.

2. Materials and methods

2.1. Materials

The quartzites used in this study come from a chain extending from the Manoré locality to the Gohing locality. The two localities are approximately 7 km apart and are located respectively 11 and 18 km from Kaélé, a department in the Far North region of Cameroon. The dome-shaped deposit is outcropping, and the material is scattered along the Manoré - Gohing axis, in blocks of varying shapes and sizes. The materials are white in color according to Munshell Code N 8/ (figure 1) and can be located at geographic coordinates X = 10.115211666666665 and Y = 14.509426666666664. Figure 2 shows the location of the deposit.

Figure 1 Quartzite views from the Kaélé deposit

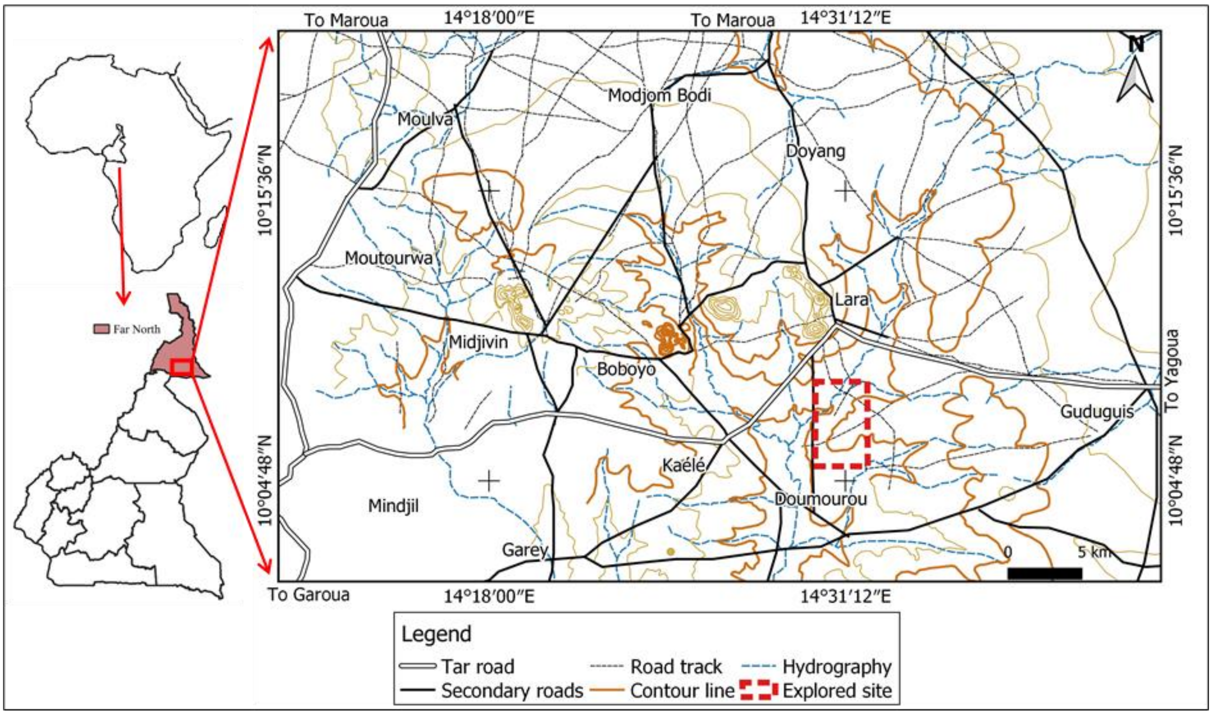

Figure 2 Study area location map

2.2. Methods

2.2.1. X-ray fluorescence spectrometry

The chemical composition of the materials was determined by X-ray fluorescence spectrometry using the XRFSPW1404K spectrometer in the Quality Control laboratory of a nearby industrial facility. The molten bead method was used. The beads were obtained by dissolving the materials in lithium tetraborate ($Li_2B_4O_7$) and homogenizing at 1150°C.

2.2.2. X-ray diffraction

X-ray diffraction is obtained using a diffractometer adapted to the characterization of polycrystalline mineral materials, the Bruker D8 Advance diffractometer. The angular range scanned is between 2 and 70° in 2θ (angle of incidence). The copper Kα1 radiation (wavelength = 1.540598 Å) used was produced at a voltage of 40 kV and an intensity of 40 mA.

Diffractograms were plotted using Panalytical X'Pert Highscore Plus 3.0 software. They were processed using the Powder Diffraction File (P.D.F.) of Materials Data Inc.'s MDI JADE 6.5 software, which matches the inter-lattice distances d to the 2θ angles recorded and the mineralogical phases contained in the material samples.

2.2.3. Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy provides a potentially rapid method of relatively non-destructive analysis that can be used to establish a database on the crystallinity and mineral constituents of rocks [4]. It was carried out on quartzite powders using a Bruker Vertex 80 V instrument operating in absorbance mode (4000 - 400 cm^{-1}).

2.2.4. Quartzite melting temperature

Heat treatment was carried out in a fast-heating furnace, a Nabertherm LHT04, with a heating chamber 20 cm high, 20 cm wide and 20 cm deep. The maximum operating temperature is 3000°C. The heating elements are positioned on the left and right walls. The furnace atmosphere is natural air, and temperature programs can be selected manually. Samples deposited on refractory substrates are placed on the furnace floor.

3. Results and discussion

3.1. X-ray fluorescence spectrometry: chemical composition

The results of the chemical analyses, expressed as mass percentages of the oxides contained in the quartzites, are shown in Table 1.

Silica is the predominant oxide, accounting for over 99% by mass. This percentage testifies to the high purity of the quartzites studied. The presence of other oxides in a minor state, in this case iron, explains the absence of their impact on the color of the materials [5]. The absence of titanium in these quartzites is an industrial advantage, as its elimination goes beyond a simple purification process and increases production costs.

Table 1 Chemical composition of natural quartzites (Mass percentage relative to air-dried material, LOI = Loss on Ignition).

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Mn_2O_3	P_2O_5	LOI	Total
Quartzite	99.02	0.209	0.111	0.172	0.1	0.107	0.101	0.024	0.005	0.005	0.13	99.984

3.2. X-ray diffraction: mineralogical composition

Figure 3 shows the X-ray diffraction spectrum of natural quartzites. The well-resolved peaks in the spectrum testify to the presence of crystallized mineralogical phases in the materials studied [6]. The main mineral identified on the spectrum is quartz (SiO_2: PDF # 461045). This result shows that the quartzites of the Kaélé Formation are mineralogically mature and completely devoid of aluminosilicates such as feldspars and clay materials [7].

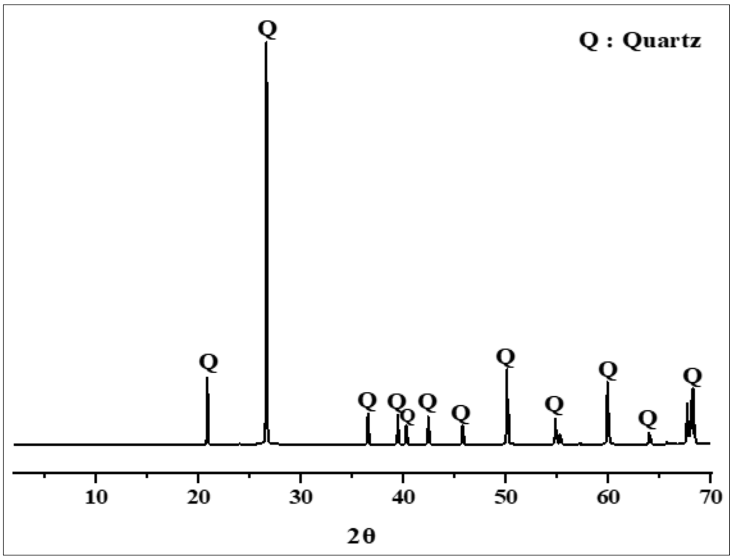

Figure 3 XRD spectrum of natural quartzites

3.3. Fourier transform infrared spectroscopy (FTIR)

Figure 4 shows the Fourier Transform Infrared (FTIR) spectra of natural quartzites in the frequency range 4000 - 400 cm^{-1}. The spectra obtained can be classified into four bands distributed around 1059, 780, 694 and 454 cm^{-1}. Analysis of the four spectral regions attributed the peak at 694 cm^{-1} to crystallized silica [8], in agreement with the results obtained from the X-ray diffractogram. The bands around 1059 cm^{-1} are due to Si-O elongation vibrations. Absorption bands at 780 cm^{-1} and 454 cm^{-1} involve Si-O symmetrical bending vibrations [9].

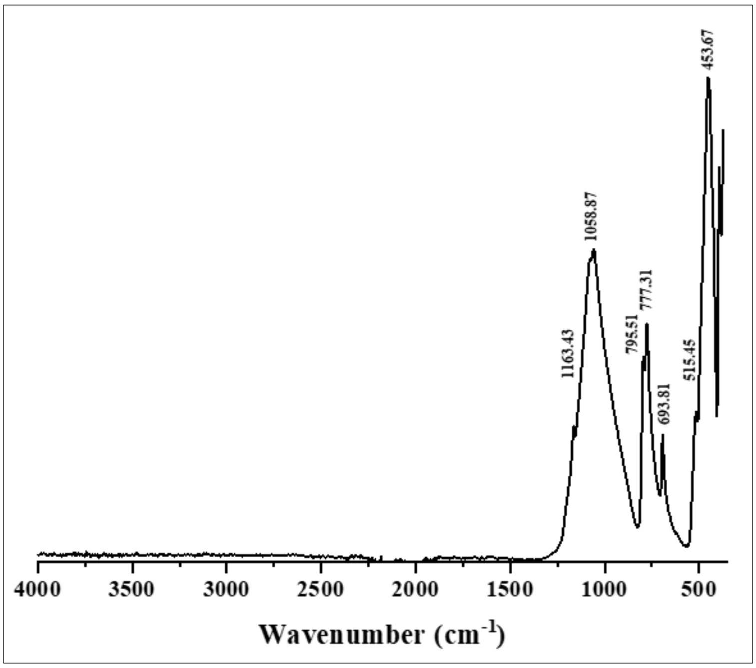

Figure 4 Infrared spectrum of natural quartzites.

3.4. Melting temperature of quartzites

The melting temperature test was carried out four times. These tests revealed an average softening temperature of 1696.5°C and an average complete melting temperature of 1725°C. These values are close to those obtained by Fenner, Rockett, Foster and Comstock on the three polymorphic varieties of silica (quartz, tridymite and cristobalite) and their thermodynamic stability domains at normal pressure [10] [11] [12]. The time elapsed between the start of the experiment and complete melting was 114 minutes.

3.5. Potential applications

The purification process for high-purity quartz first crushes the quartzite to the required particle size and removes certain impurities, then separates or dissolves the impurities by physical and chemical means. The entire purification process can be simply summarized as pre-treatment, physical treatment and chemical treatment, and specifically adopts various beneficiation methods such as crushing, grinding, screening, magnetic separation, pickling and chlorine roasting. The resulting quartz has a number of applications in high-tech industries, including:

Semiconductor production: semiconductors are obtained by adding (doping) a very small quantity of phosphorus or aluminium atoms to silicon single crystals, giving them the necessary electrical conductivity. This strict control of electrical conductivity can only be achieved using ultrapure silicon (purity 99.99999%) [13], which in turn can only be sourced from pure silicon raw materials;

high-temperature lamp tubes: quartz tubes for high-temperature lamps are made from high-quality quartz glass of extremely high purity and excellent heat resistance [14]. The purity of quartz glass reaches 99.95%, which can withstand high temperatures of up to 1100 °C, to ensure that lamps in high-temperature environments operate stably over the long term. In addition, quartz glass has excellent light transmission properties, can greatly improve the luminous efficiency of lamps, so that the light is brighter and more uniform;

In polycrystalline, monocrystalline or amorphous silicon photovoltaic cells, the semiconducting properties of silicon enable the photoelectric effect required for electricity generation. In the case of crystalline Si cells, the silicon metal is refined to a purity of 99.999 9% (6N) to 99.999 999 9 (9N) [15], corresponding to solar grade (SoG). After refining, silicon metal is in a high-purity polycrystalline state. It is then called "polysilicon". It undergoes a number of further processes, including ingot recrystallization, wafer cutting and doping, before it can be used in the manufacture of photovoltaic cells. In the case of amorphous silicon cells, silicon in the form of silane gas is deposited directly in the vapor phase by plasma;

In microelectronics, silicon's semiconducting properties also enable the operation of integrated circuits [16], as well as the storage and transmission of information. Polysilicon is refined to an extreme purity level of 10N to 13N, corresponding to EG quality for "electronic grade", before being recrystallized into a high-precision cylindrical single crystal. The ingot is then cut into wafers before undergoing the many additional physico-chemical treatments required to obtain the final components;

In telecommunications, quartz glass is the most important component in the optical fiber manufacturing process, and its importance is growing all the time. The material requirements for optical fiber production are: high purity, ability to withstand very high temperatures and strict compliance with dimensional specifications [17]. Manufacturing is divided into two main processes: optical fiber preform production and fiber drawing. The production of optical fiber preforms mainly involves the MCVD (Modified Checmical Vapor Deposition), OVD (Outer Vapor Phase Deposition) and VAD (Vapor Phase Axial Deposition) processes. MCVD is the most commonly used manufacturing technique, resulting in a low-loss fiber well suited to long-distance fiber optic communication cables [18]. The optical fiber preform is placed in a fiber-drawing tower. A fiber-drawing tower can be more than 10 meters high. The optical fiber preform is drawn into a 125µm-thick optical fiber and coated with resin layers for protection.

4. Conclusion

The present work has enabled us to characterize quartzites from Kaélé, a department in the Far North region of Cameroon. Examination of the chemical composition shows that the materials studied contain over 99.02% silica (SiO_2). The X-ray diffraction used for mineralogical analysis shows only peaks characteristic of quartz in its spectrum. In addition to the attractive white color of the quartzites studied, their melting point, whose average value of 1725°C is close to the melting temperature of pure silica, reflects the behavior of pure materials. All these considerations prove that the quartzites studied are mature and of high purity. High-purity quartz has many applications in high-tech industries. The main ones concern semiconductors, high-temperature lamp tubes, telecommunications and optics, microelectronics and photovoltaic cells.

Ultimately, the quartzites studied cover all their applications, from the most traditional to the most high-tech. They can now be considered as high-value local resources in the above-mentioned sectors.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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