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Gemology and Chemical Aspects of Aquamarines from Quixeramobim, Brazil

Gemologia e Aspectos Químicos das Aquamarinhas de Quixeramobim, Brasil

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Abstract

Since the end of the 20th century, it has become extremely common for countries with a significant exploration of gemstones to catalog and disclose the properties of their gems for various purposes. This paper aimed to analyze the gemological characterization and geochemical aspects of aquamarines from the County region of the city of Quixeramobim (State of Ceara). Usual gemology equipment was used; in addition, we used a scanning electron microscope with energy dispersive system (SEM-EDS). The studied minerals have the standard characteristics of aquamarines from different parts of the world, except for above-average birefringence and the presence of fluorescence. In the case of Quixeramobim aquamarine studied, a linear correlation was noted involving the geochemistry and some gemological aspects. However, the studied gems diverge in four characteristics and chemical elements, if compared to the aquamarines of a nearby region, named Berilândia (CE). This demonstrates the importance of gemological characterization, not only at a state/regional level. The Quixeramobim aquamarines are unique within the Brazilian scenario.

Keywords: Gemological beryl; Gemological characteristics; Ceará gems

Resumo

Desde o final do século 20, tornou-se extremamente comum que países com uma exploração significativa de gemas cataloguem e divulguem as propriedades de suas gemas para diversos fins. Este trabalho teve como objetivo analisar a caracterização gemológica e aspectos geoquímicos de águas-marinhas da região do município de Quixeramobim (Estado do Ceará). Foram utilizados equipamentos usuais de gemologia, além disso, também foi utilizado um microscópio eletrônico de varredura com sistema de energia dispersiva (MEV-EDS). As amostras estudadas possuem as características padrão das águas-marinhas de diferentes partes do mundo, exceto pela birrefringência acima da média e pela presença de fluorescência. Entretanto, as gemas estudadas divergem em quatro características e elementos químicos, se comparadas às águas-marinhas de uma região próxima, denominada Berilândia (CE). Isso demonstra a importância da caracterização gemológica, não apenas em nível estadual/regional. As águas-marinhas de Quixeramobim são únicas no cenário brasileiro.

Palavras-chave: Berilo gemológico; Características gemológicas; Gemas cearenses

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1 Introduction

Globally, gemological studies have not stopped, and gemological mineral data is frequently updated. Furthermore, properties of minerals used as gemstones can help or even reveal new aspects about the geological evolution of the region where it was found. In Brazil, there is a gap in this aspect; many mineral occurrences do not have their gemological properties tabulated nor disclosed, even in regions that already had relevant mineral productions. Even though the country is one of the main suppliers of gemstones, paradoxically Brazilian scientific gemology is still underdeveloped (Terra 2020).

Aquamarine, part of the beryl group, is a blue-colored mineral that can be used as a gem, and it is the third most valued in the beryl group, behind only emerald and bixbite. Its blue tint is due to traces of ferrous iron (Arem & Clark 2022). Beryl is an aluminum and beryllium silicate that crystallizes in a hexagonal system, considering the general formula $Be_3Al_2Si_6O_{18}Fe$. Beryl, although normally considered to be $Be_3Al_{12}Si_6O_{18}$, contains some alkalis and, in certain varieties, the total alkali content can reach around 5-7%. In addition to Na and Li, there are also alkaline ions with higher ionic radius, K and Cs, but Rb is less common (Deer, Howie and Zussman 2010). This gem occurs characteristically in drusen, granites, and in granitic pegmatites (Deer, Howie and Zussman 2010). There are aquamarine deposits on every continent, the most important are those from Brazil (in the States of Minas Gerais, Bahia, Espírito Santo) (Schumann 2020). Brazil is the world's main source of gems of excellent aquamarine quality. The mineral can be found in locations in the states of Minas Gerais, Rio Grande do Norte, Ceará, and others (Schumann 2020) (Arem & Clark 2022).

In Brazil, due to the abundance of aquamarines, studies were carried out by Ferreira, Fonseca and Pires (2005); Proctor (1984); Viana, Jordt-Evangelista and Costa (2001) and Viana et al. (2002), and regarding different properties and host rocks of aquamarines. In Ceará, Marques Jr., Nogueira Neto and Neri (1988) carried out a research on pegmatites bearing buds, including the aquamarine ones. Studies regarding crystallo chemical properties were carried out by Cavalcanti (2017). More comprehensive studies focusing in different aquamarine properties were carried out by authors such as Adamo et al. (2008); Bello et al. (1997 and 1996); Beurlen, Silva and Castro (2001); Beurlen et al. (2008); César-Mendes, Jordt-Evangelista and Wegner (2001); César-Mendes et al. (1992); Graziani & Di Giulio (1979); Keller (1990); Schmetzer, Kiefert and Hänni (2004).

This paper deals with the gemological and geochemistry characteristics of six aquamarine crystals from the city of Quixeramobim (County region), in the state of Ceará, geologically inserted in the Pegmatitic District Solonópole-Banabuiú. The properties of these aquamarines were compared with general world data as part of the gemological identification, an usual procedure when a gemological occurrence of a location is studied for the first time. It is noteworthy that the gemological characterization is also useful in cases of expertise and criminal investigation against fraud and imitations (IBGM 2009), and to identify possible mineral sources for commercial valorization (directly interfering in the economic value). In Brazil, in addition to the reasons cited above, this study has great importance because, Art. 655 of the Brazilian Civil Code establish that banks and government agencies accept gems in pledge if a debt is collected in court (Brasil 2002).

2 Regional Geological Context

The gemological aquamarine studied are from the city of Quixeramobim (Figure 1) (located in the Ceará Central Domain) comprises approximately 3275 km^2, representing 2.44% of the area of the state of Ceará. It is inserted in the central portion of Ceará, which is located in the northeast region of Brazil. Quixeramobim is the second largest city in the central hinterland, with a population of 75,565 inhabitants according to IBGE (Brazilian Institute of Geography and Statistics in the Portuguese acronym), and it is 203 km away from the capital, Fortaleza.

The Ceará Central Domain (DCC) (Figure 2) is located in the province of Borborema, more precisely in the sub-province Borborema Septentrional. The DCC is limited on the north by the Coastal Province and by the Sobral–Pedro II shear zone, on the west by the Sedimentary Province of Parnaíba, and by the Orós and Aiuaba Shear Zones on the east and south, respectively. The area can be subdivided into five sets: polycyclic basement, monocyclic metasedimentary coverings, monocyclic anatetic-igneous complex, brasiliano granites s.l., and late-Brazilian molasses.

The studied aquamarines come from the County district, in the city of Quixeramobim, part of the Acopiara Complex. This complex is predominantly composed of metasedimentary rocks, mainly metatexists, pegmatites, leucogranites, biotite schists, diatexists, and aluminous gneisses (Pinéo et al. 2020). In general, these metasedimentary rocks were affected by a high amphibolite facies metamorphism, often accompanied by migmatization.

The Acoipara Complex corresponds to a Neoproterozoic basin with deposition initiated in the

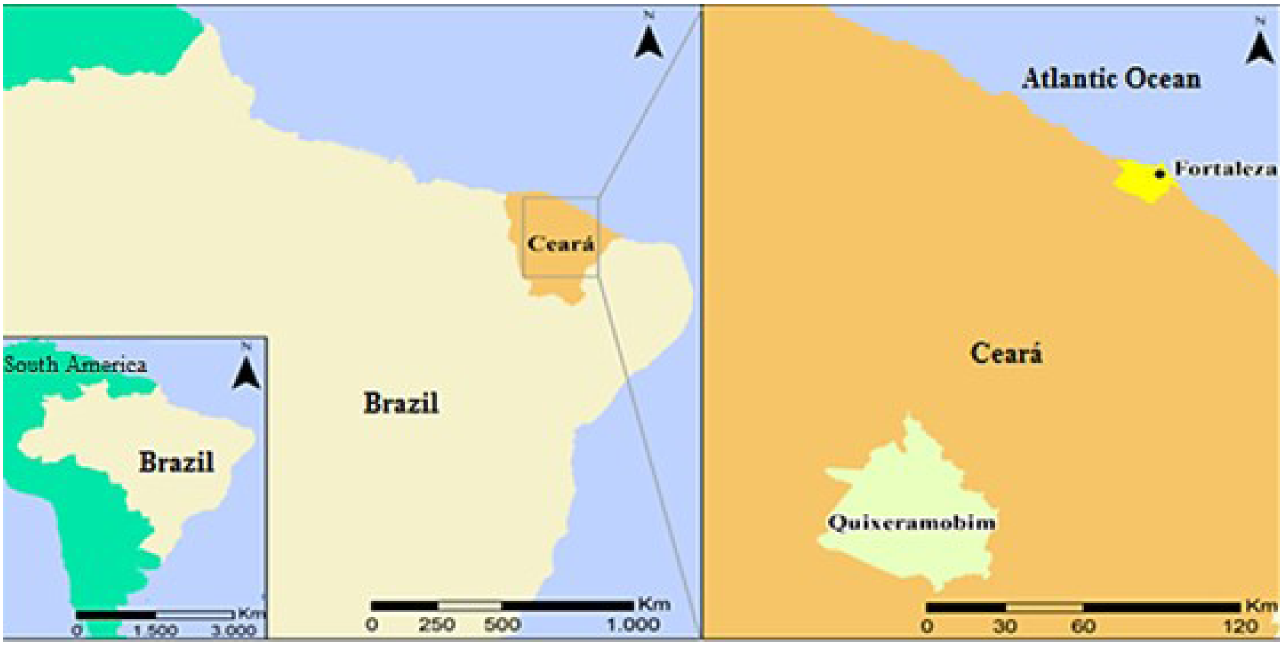

Figure 1 Research Area, placed in the interior of Ceará, located in the northeast region of Brazil. Source: Authors.

Tonian (929 Ma) and Brazilian tectonic inversion (620 Ma), concomitant to syncolisional plutonism materialized in the type S leucogranites of the Banabuiú suite. According to Palheta (2017), the transcurrence process started 585 Ma ago and it is associated with the placement of the bodies of the Quixeramobim river suite and the mineralized pegmatites.

These pegmatites are intrusive bodies, predominantly formed by schists, gneisses and migmatites, and minority by granites. These bodies have tabular geometry, sometimes lenticular, which may vary from centimeter to decimeter and fill discontinuities, such as faults and fractures (Parente, Almeida and Arthaud 2008). This results in a structural control for mineralizations that are obliquely oriented to regional foliation, with subvertical dip. According to Almeida et al. (1968), these dwellings of the pegmatites of the DCC are between 470 and 530 Ma in age.

2.1 Pegmatites of the Quixeramobim Region

The pegmatites with the six gemological aquamarine studied of the region (Figure 3) are located in the Solonópole-Quixeramobim Pegmatitic District (SQPD). It has the highest concentration of economically mineralized pegmatites and is in the Midwest region of Ceará.

According to Marques Jr., Nogueira Neto and Neri (1988) and Almeida & Ulbrich (2001), the pegmatites in Northeastern Brazil can be divided into 3 large groups according to mineralogical and textural criteria: (a) homogeneous pegmatites have an uniform texture and simple mineralogy; (b) heterogeneous pegmatites have a high degree of textural differentiation, with well-marked zoning and metallogenetic specialization; and (c) mixed pegmatites that have intermediate characteristics between the other two.

Homogeneous pegmatites show abrupt and intrusive relationships with basement gneisses and migmatites, as well as with brazilian granites and supracrustals. These rarely present mineralization, and their essential constituents are quartz, feldspar, and micas, with granulation ranging from centimeter to decimeter (Vidal & Nogueira Neto 2005).

Zone I (marginal or edge) – composed of quartz + potassium feldspar (microcline + graphic intergrowth) + plagioclase (albite) + muscovite as main phases, and cassiterite, garnet, and aphrysite as common accessories. The texture is predominantly aplitic, and the thickness is thin;

Zone II (wall) – it has a texture and composition similar to that of homogeneous pegmatites. It occupies, in general, a significant volume of the pegmatitic bodies;

Zone III (intermediate) – defined by the presence of large feldspar crystals and by a varied procession of accessory phases (apatite, amblygonite, beryl, columbite-tantalite, cassiterite, tourmaline, spodumene, petalite, and lepidolite);

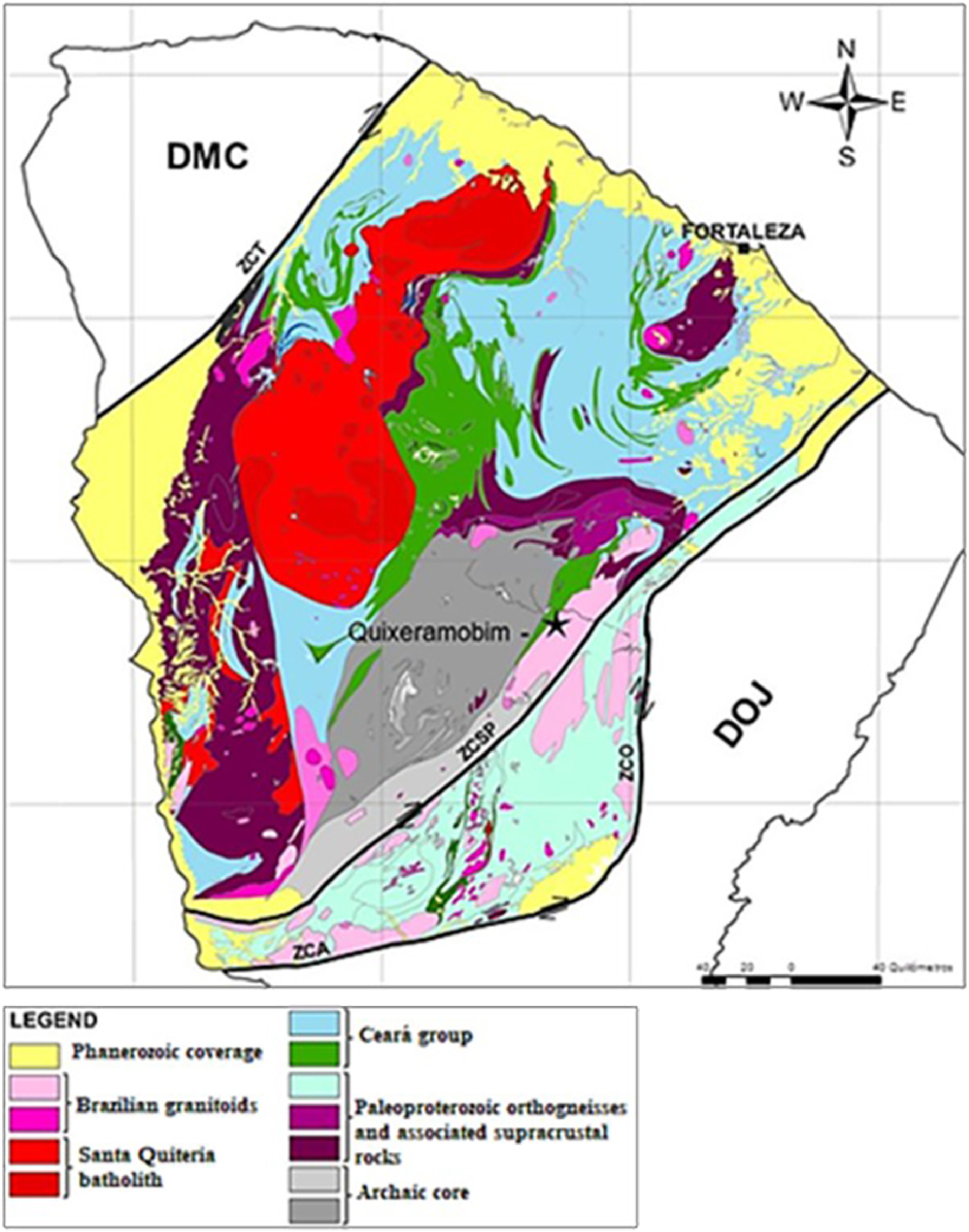

Figure 2 Central Ceará Domain (DCC) limited to the northwest by the Transbrasiliano Lineament and to the southeast by the Orós Shear Zone (Marques, 2014).

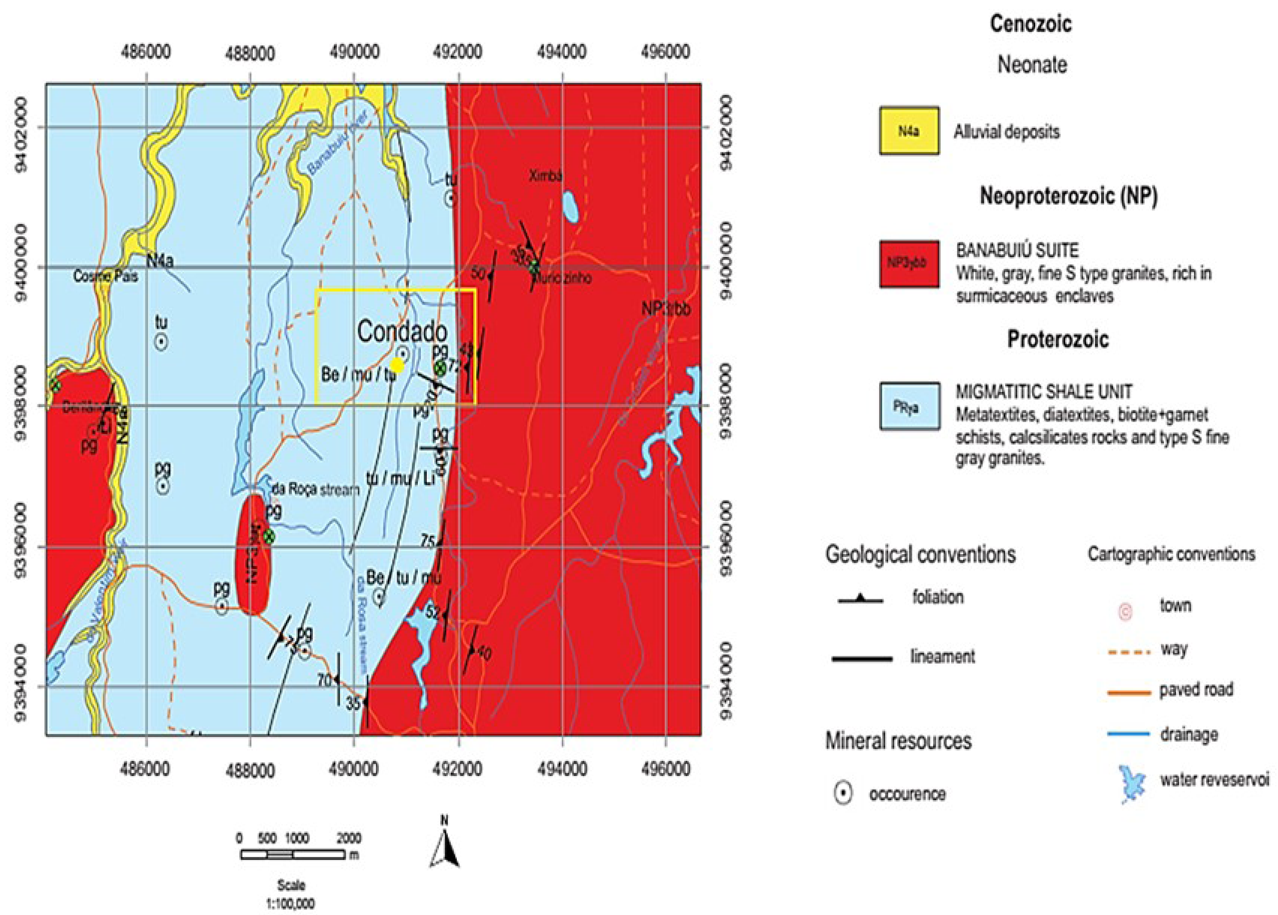

Figure 3 Geological map of the Quixeramobim region from which the studied samples are derived. Region of origin of aquamarines (County) in yellow. Source: Modified from Parente, Almeida and Arthaud (2008).

Zone IV (axial) – formed by a solid quartz core of varied colors, to which different accessory minerals can be associated.

In many cases, a "metasomatic substitution zone" (ZS) is developed at the contact between zone III and the quartz core. These zones are constituted by saccharoidal albite, greenish muscovite, lepidolite, and quartz. ZS occurs in lenticular bodies or miarolitic cavities, with dimensions that may vary from metric to decimeter, often called "pockets" (Leal Neto 2005).

3 Material and Methods

In this paper, six aquamarine crystals (Figure 4) from the city of Quixeramobim (Ceará) were randomly selected from several commercial specimens, thus representing a sample. The samples were obtained in a raw state, and were cut into different formats later. Additionally, a color table used by trade that has 384 colors (Color Code: Infographic of color codes in Devmedia, 2013) was used to classify the gemstones' colors.

The research method applied for the gemological characterization performed in the gems of the Solonópole-Quixeramobim Pegmatitic District (Ceará) included the use of classical instruments of optical analysis, such as refractometer, polariscope, hydrostatic balance, spectroscope, dichroscope, fluorescent lamp, and microscope gemological.

To identify the composition and chemical contents of the samples, we employed a Scanning Electron Microscope (SEM), Quanta 450 FEG – FEI is coupled with an energy dispersive spectrometer (EDS) and has a nominal resolution of 1 nm was used. As preparation the gems were placed in a stub and fixed with a carbon tape, a beam intensity

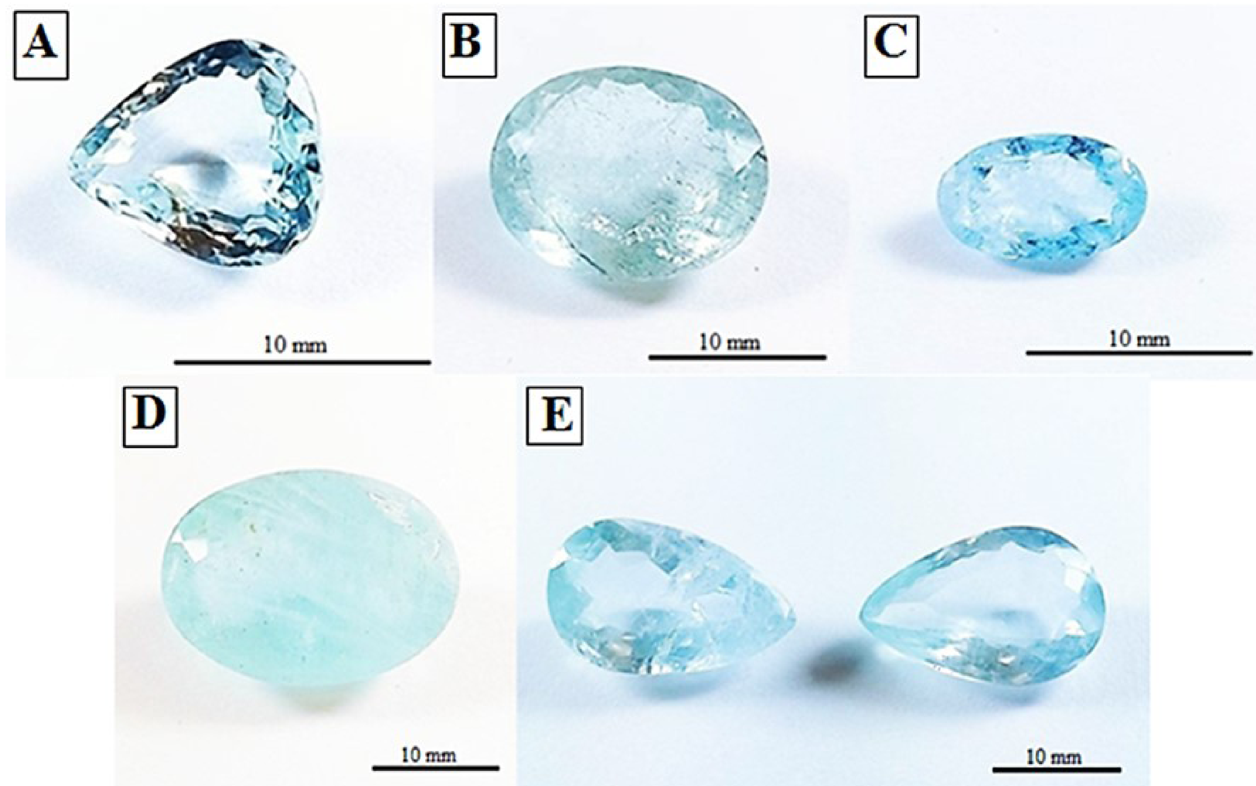

Figure 4 Studied aquamarines from the Solonópole-Quixeramobim Pegmatitic District, Brazil: A. Gemstone (Cyan 2) with dimensions: 10.00 x 8.99 x 5.04 mm; B. Gemstone (Cyan 1) with dimensions: 14.48 x 11.58 x 5.61 mm; C. Gemstone (Dodger Blue 1) with dimensions: 10.35 x 6.80 x 3.96 mm; D. Gemstone (Cadet Blue 1) with dimensions: 23.15 x 14.70 x 9.69 mm; E. Sample from left to right: Gemstone (Steel Blue 1) with dimensions: 20.42 x 12.10 x 7.67 mm and gem (Steel Blue 2) with dimensions: 20.05 x 12.89 x 6.80 mm. Source: Authors.

of 10000 electron volt (KeV) was used in which the high vacuum was used for the analyses, the beam is applied to the entire aquamarines.

4 Results and Discussions

Through comparison with the commercial color table, it was determined that the aquamarine samples from the County region of the city of Quixeramobim (Ceará) have a blue color. Half (3) have a color (result of the combination of the hue, saturation and shade) considered good; and the other half (Cyan 2, Dodger Blue 1, Steel Blue 2) have a color judged excellent by the trade, which corresponds to an intense and light blue (Arem & Clark 2022), unlike the aquamarine gems in the region of Berilândia (Cavalcanti 2017), also in the State of Ceará, which do not have an attractive color and do not have gemological quality, since their hue have a tendency towards green and low saturation. Gemologically the data acquired was compared with the base of worldwide data from the International Gem Society (IGS) (Arem & Clark 2022) and in several works of great recognition and worldwide credibility, works from 1971 to 2020 (Anderson 1984; Bonewitz 2013; Franco & Campos 1971; IBGM 2009; Hurlbut & Switzer 1979; Nassau 1980; Schumann 2006; Schumann 2020; Webster 1981).

For the optical characterization of these minerals, the refractometer was essential, proving that the studied minerals are uniaxial negative. The values of no (ordinary radius) in the analyzed aquamarines are always greater than the values of ne (extraordinary radius), which is why their optical signal is negative: the value of no is greater than that of ne. The refractive indices of the analyzed gemstones varied subtly between 1.566 (Dodger Blue 1 sample) and 1.571 (Cyan 2 sample) for ne, and between 1.580 (Dodger Blue 1) and 1.585 (Cyan 2) for no (Table 1). These values are relatively close to the indices of aquamarines in the region

Table 1 Gemological characteristics of aquamarines from Quixeramobim, Brazil.

Gemological characteristics							
Sample/ Properties	**Diaphaneity**	**Refractive index; Character and Optical Signal; birefringence**	**Pleochroism**	**Absorption Spectrum**	**Fluorescence**	**Relative Density**	**Inclusions and internal aspects**
Cyan 2	Transparent	1.585 – 1.575; Uni (-) 0.010	Present: Weak	460 and 420 nm	Absent	2.67 g/cm3	Solid and fluid inclusions without orientation.
Cyan 1	Transparent	1.580 – 1.570; Uni (-) 0.010	Present: Moderate	460 and 420 nm	Absent	2.71 g/cm^3	Solid and fluid inclusions, rarely oriented; fluid inclusions sometimes put together; inclusions of other minerals (possibly apatite and/or quartz); growth lines; skeletal rutile crystals.
Dodger Blue 1	Semi-transparent	1.580 – 1.567; Uni (-) 0.013	Present: Moderate	480 and 420 nm	Absent	2.83 g/cm^3	Fluid inclusions and rarely with remarkable orientation, with syngeneic configuration; solid inclusions; oriented hollow tubes containing fluids; solid inclusions (possibly garnets) amid fluid inclusions.
Cadet Blue 1	Semi-transparent	1,582 – 1,570; Uni (-) 0.012	Present: Weak	520 and 420 nm	Present: Weak	2.67 g/cm^3	Fluid and rarely oriented inclusions, with syngeneic configuration; hollow and elongated tubes occasionally filled with fluids; solid inclusions; other mineral crystals like garnet; tubes perpendicular to the oriented liquids; biphasic inclusions (liquids and gas).
Steel Blue 1	Transparent	1,582 – 1,570; Uni (-) 0.012	Present: Weak	460 and 420 nm	Absent	2.70 g/cm^3	Fractures; Fluid inclusions rarely oriented; hollow and elongated tubes occasionally filled with liquids; solid inclusions; other mineral crystals such as garnet; tubes oriented perpendicular to liquids with orientation
Steel Blue 2	Transparent	1,582 – 1,570; Uni (-) 0.012	Present: Weak	460 and 420 nm	Absent	2.70 g/cm^3	Fractures; Fluid inclusions rarely oriented; hollow and elongated tubes occasionally filled; solid inclusions; tubes oriented perpendicular to liquids with orientation.

of Berilândia according to Cavalcanti (2017). The author did not inform the character and optical signal of the samples, but based on the available values, the minerals in this region are uniaxial positive, unlike the gems analyzed in the County region (Quixeramobim), which are uniaxial negative. The refractive index of this blue beryl is 1.567-1.590, and the character and optical sign is uniaxial negative (Arem & Clark 2022; Bonewitz 2013; IBGM 2009; Schumann 2006; Schumann 2020).

A peculiarity of these blue gems from the Quixeramobim region is that they have a high birefringence for the mineral species. The values of the analyzed specimens of the County are always superior to 0.009, with values ranging from 0.010 to 0.013 (Table 1). Amethysts from the municipality of Santa Quitéria (Ceará) also have above-average birefringence (Oliveira et al. 2020b). Anomalous birefringence in gems may occur due to a possible deformation in the crystalline lattice of crystals, which can interfere with the speed of ray routing of crystals, ordinary and extraordinary ray, thereby modifying and increasing the double refraction (birefringence) without necessarily compromising the gemological quality. While gems from Quixeramobim have an above average double refraction, the aquamarines of Berilândia (also from the State of Ceará) have a birefringence within the average of 0.005 to 0.007 (Cavalcanti 2017). Aquamarines have a double refraction between 0.005 and 0.007 (Arem & Clark 2022; Anderson 1984; Franco & Campos 1971, Nassau 1980, Schumann 2020),

Gems dichroism, or pleochroism, which is analyzed with the dichroscope, showed the presence of dichroism with low intensity in four samples and moderate in two (Dodger Blue 1 and Cyan 1). This is a common feature in aquamarine, since the buds with moderate pleochroism also have a pattern behavior. In this case, it is only rarer a medium dichroism in aquamarine. In general terms, the pleochroism classified as weak is the result of a low absorption, in which one of the rays has a higher reflection due to the structural and compositional aspects of the gems, decreasing the compensation of the ordinary (no) and extraordinary (ne) rays. The smaller this compensation (difference), the smaller is the observed absorption (pleochroism). There are no data available for this characteristic by Cavalcanti (2017). Aquamarine pleochroism is commonly weak (Arem & Clark 2022; Hurlbut & Switzer 1979; IBGM 2009; Schumann 2020).

The absorption spectrum captured by the spectroscope is very close to the standard characteristic of aquamarines. The values commonly acquired for the samples were of the order of 520, visualized only in the Cadet Blue 1 gem, as well as 480, 460, and 420 nm visualized in the other gems. It is known that the 370 and 427 nm intervals are indicative of the presence of Fe^{3+} ion (Bunnag et al. 2020), in addition to the intervals at 475, 540, and 568 nm, which are related to $Mn^{3+,}$ according to Adamo et al. (2008). There are no data available for this characteristic by Cavalcanti (2017). The values obtained in common for this mineral species are 537, 456, and 427 nm (Arem & Clark 2022; IBGM 2009; Schumann 2020).

Using a polariscope, it was also possible to infer that aquamarines are anisotropic, which was expected, since they are birefringent and crystallize in a hexagonal system (Schumann 2020).

Five of the six gems analyzed using the incidence of ultraviolet light did not show fluorescence (Table 1). This data shows that the specimens do not have fluorescence or phosphorescence activating elements, such as Cr and REE. One specimen, Cadet Blue 1, has fluorescence when exposed to ultraviolet light, since it has only 0.46 % (Wt) of the FeO in its structure. Even though FeO inhibits fluorescence, in such a small amount it does not fully inhibit the reaction caused by REE. REE were not detected in the Cadet Blue 1 sample, as they occur in low amounts (< 1 %) in beryl. These elements (REE), when in the presence of a UV lamp, are energized, jumping to the next layer of its valence and returning after a period of time, repeating this cycle as long as the exposure to ultraviolet light lasts. Furthermore, on being energized and returning to its normal and stable valence layer, the element releases the accumulated energy in the form of light. There are no data available for this characteristic by Cavalcanti (2017). Nevertheless, aquamarine generally does not fluoresce (Anderson 1984; Arem & Clark 2022; Hurlbut & Switzer 1979, IBGM 2009; Nassau 1980, Schumann 2020).

Quixeramobim gems have a large variability in density and not a single value for all samples, with the lowest values ranging from 2.67 g/cm^3 (Cyan 2 and Cadet Blue 1) to 2.83 g/cm^3 (Dodger Blue 1). With the use of the hydrostatic balance, results were obtained as expected, except for the Dodger Blue 1 sample, which has a relative density of 2.83 g/cm$^{3.}$ This can be explained by the composition of these gems: there are quantities of denser elements in its chemical composition. Aquamarines from the region of Berilândia (State of Ceará) have a relative density between 2.71 and 2.72 g/cm^3 (Cavalcanti 2017). By presenting a constancy in this characteristic, it differs from the gems of the County (Table 1) region that have an oscillation in this aspect. Aquamarines' density ranges between 2.66 to 2.80 g/cm^3 (Arem & Clark 2022; IBGM 2009; Schumann 2020; Webster 1981)

The analysis of gems' diaphaneity was done through the visualization of a pen tip through the aquamarine. While in transparent samples the image has a well-defined outline and sharpness, in semi-transparent samples the sharpness is not so noticeable (Table 1).

In the gemological microscope, the studied aquamarine crystals are characterized by fractures, elongated, and fluid solid inclusions. These features may help when necessary in cases of mineral origin. Solid and fluid inclusion without guidance were seen, but they are rarely oriented in growth lines and fractures. There are also inclusions of other minerals in some gems, such as in Cyan 1, in which the included minerals are apatite or quartz (Figure 5A – Cyan 1). Solid skeletal rutile inclusions were identified (Figure 5B – Cyan 1). A common feature in beryls (Arem & Clark 2022; IBGM 2009), oriented and perpendicular to oriented fluids, and often filled with them, hollow tubes were also found (Figure 5C – Cadet Blue 1). Hollow or liquid-filled tubes were also found in samples from Berilândia (Cavalcanti 2017). These liquids and solid inclusions have variable composition and are formed before, at the same time, or after the host minerals. In addition, aphasic inclusions (liquid and gas) without orientation were observed (Figure 5D – Cadet Blue 1).

These fluid inclusions indicate that, during geological events with decreased intensity activity (cooling and crystallization), some fluids that remained containing volatiles were retained in the structure of aquamarines, which is a common phenomenon in beryls. Depending on their concentration, organization, and distribution along the crystal, it allows them to be classified into syngenetic (during the mineral's growth) and epigenetic (after the specimen's formation) (Hughes 2017). Most of the aforementioned inclusions have a shape more similar to syngenetic inclusions, formed at the same time as the host crystal. Solid inclusions are generally reduced-size particles, minerals, or the same mineral, which could have been formed before, at the same time, or after the host minerals. Growth lines are a "mark" of mineral growth. Internal fractures, on the other hand, are a consequence of some compressive regime, stretching, or shear forces to which the crystals were subjected after crystallization (Anderson 1984).

Chemical composition (Table 2) directly influences several characteristics of aquamarines, such as color, inclusions, optical properties, and relative density. A similar situation occurs in the aquamarines of Yukon (Canada) (Groat et al. 2010), where samples have a clear correlation involving their crystallochemistry properties. Six samples were used, but a greater number of chemical analyses made the correlation more evident.

In addition to more samples of Quixeramobim aquamarines and covering more crystallochemistry characteristics, it will be possible to note correlations as visible as in Yukon minerals (Groat et al. 2010). In the case of Quixeramobim gems, some linear correlations are expected due to the data already acquired and observed.

Similar to the tourmalines from the Quixeramobim region, the analyzed aquamarines have amounts of CaO and Na_2O (Oliveira et al. 2020a). As expected, the Cadet Blue 1 gem has a low amount of FeO (< 1%) when compared to other samples, which allows low fluorescence. This is possible because rare earth elements (REE) (which cause fluorescence) were not detected in the Cadet Blue 1 sample by the EDS equipment, since they occur in low amounts (< 0.1%) in beryl. An average was made for 4 aquamarines (Cyan 2, Cyan 1, Steel Blue 1, Steel Blue 2), as they both have a similar color, relative density, and chemical contents. The amount of FeO and NiO in these specimens is higher than that of Cadet Blue 1 and lower than that of the gem Dodger Blue 1 with the most intense blue color (Table 2). Furthermore, the Figure 6 will be showcasing the correlation between said indicators. To improve the visualization of Figure 6, the relative density and wt% value were multiplied by 100. Then, there seems to be a correlation between color, relative density, and the amounts of FeO and NiO, in which, the greater the amount of these two elements, the greater the relative density and intensity of color in aquamarines. So there seems to be a correlation between color, relative density and the amounts of FeO and NiO. In which, the greater the amount of these two elements, the greater the relative density and intensity of color in aquamarines. The reason for this is the fact that Fe and Ni are high-density elements, and Fe influences the color of aquamarines (Dana & Hurlbut Jr. 1976).

The mineral chemistry of Berilândia's aquamarines diverges from the County's gems in FeO amount. Besides, the samples from Berilândia do not have amounts of CaO, MnO, MgO and NiO (Cavalcanti 2017).

The chemical contents of the 3 main elements present in the studied aquamarines are consistent with the world standard, with the amounts of 10% of BeO, 22% of Al_2O_3 and 60% of SiO_2, presenting values very close to the world literature, in which normality is 13% for BeO, 18% for Al_2O_3, 65% for SiO_2 (Černý & Hawthorne 1976; Deer, Howie and Zussman 2010; Franco 1967; Hawthorne & Černý 1977; Marfunin 1994; Roberts, Campbell and Rapp 1990; Sherriff et al. 1991).

However, the amounts and correlations involving FeO (0.90 – 4.15), MgO (0.57), Na_2O (1.22 – 2.46) e NiO (0.78 – 3.52) are peculiar characteristics of the samples from the region. Correlations involving Fe and Ni are associated with their geochemical compatibility, which are: atomic weight, melting point, density, thermal capacity,

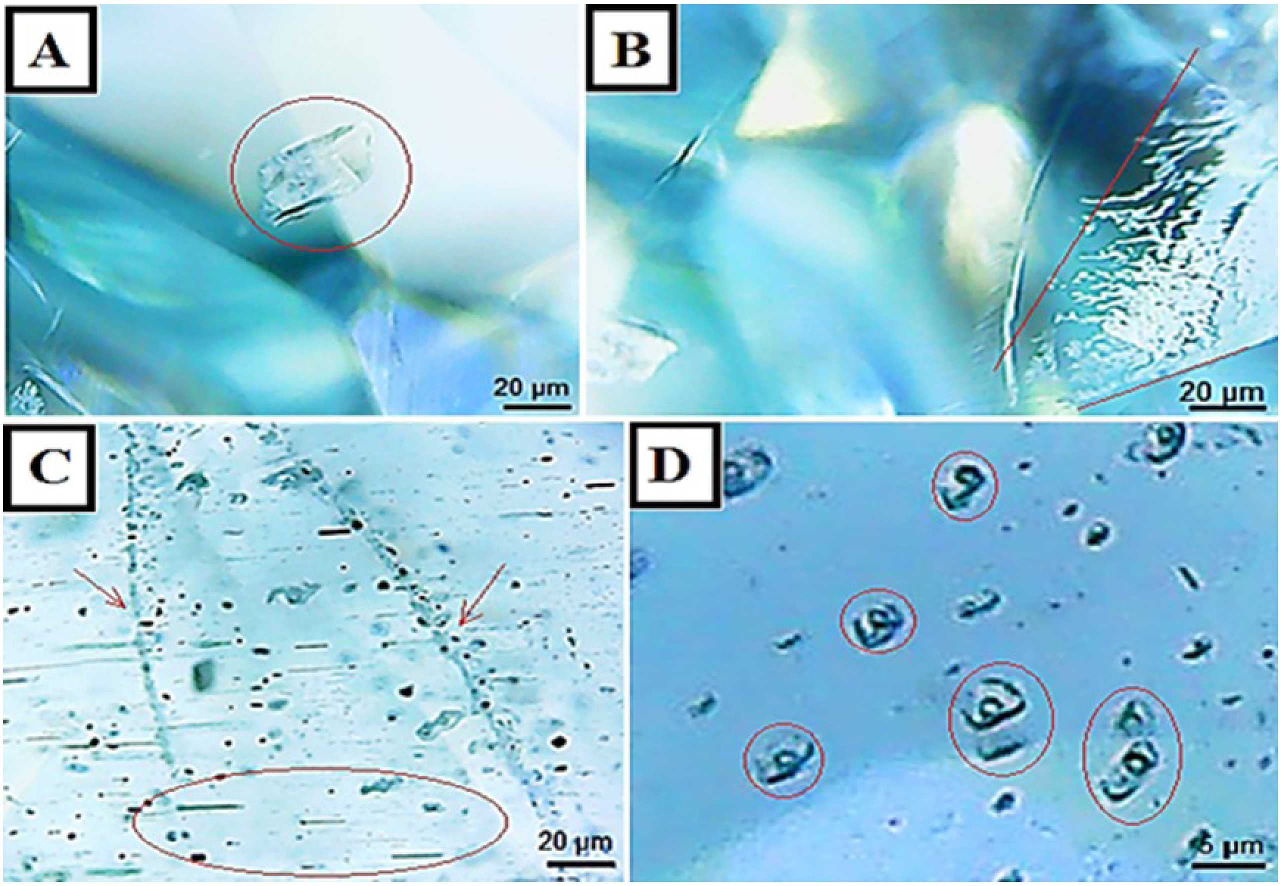

Figure 5 Transmitted light photomicrograph of inclusions in aquamarines from the County region of Quixeramobim-CE, Brazil. Aspects indicated in red: A. Inclusion of a mineral (transparent) and with moderate relief; B. Skeletal rutile crystals, whiter; C. Solid inclusions with a well-defined orientation (darker coloration) and perpendicular to the fluid inclusions in the background; D. Biphasic inclusions (gas and liquid) without orientation.

Source: Authors.

Table 2 Chemical components of aquamarine samples from Quixeramobim - CE.

Samples	Cadet Blue 1 (With fluorescence)	Average light color aquamarines (Cyan 2, Cyan 1, Steel Blue 1 and Steel Blue 2)	Dodger Blue 1 (Most intense color of the samples)
Chem. Formula	$Be_3Al_2Si_6O_{18}$	$Be_3Al_2Si_6O_{18}$	$Be_3Al_2Si_6O_{18}$
OXIDES	Wt%	Wt%	Wt%
BeO	9.84	10.01	10.22
SiO_2	65.64	60.86	55.16
Al_2O_3	20.00	20.53	24.15
FeO	0.90	2.43	4.15
Na_2O	1.22	1.70	2.46
MgO	0.57	0.57	0.00
MnO	0.00	0.00	0.17
NiO	0.78	0.65	3.52
CaO	0.00	3.12	0.00
Density (g/cm^3)	2.67	2.70	2.83

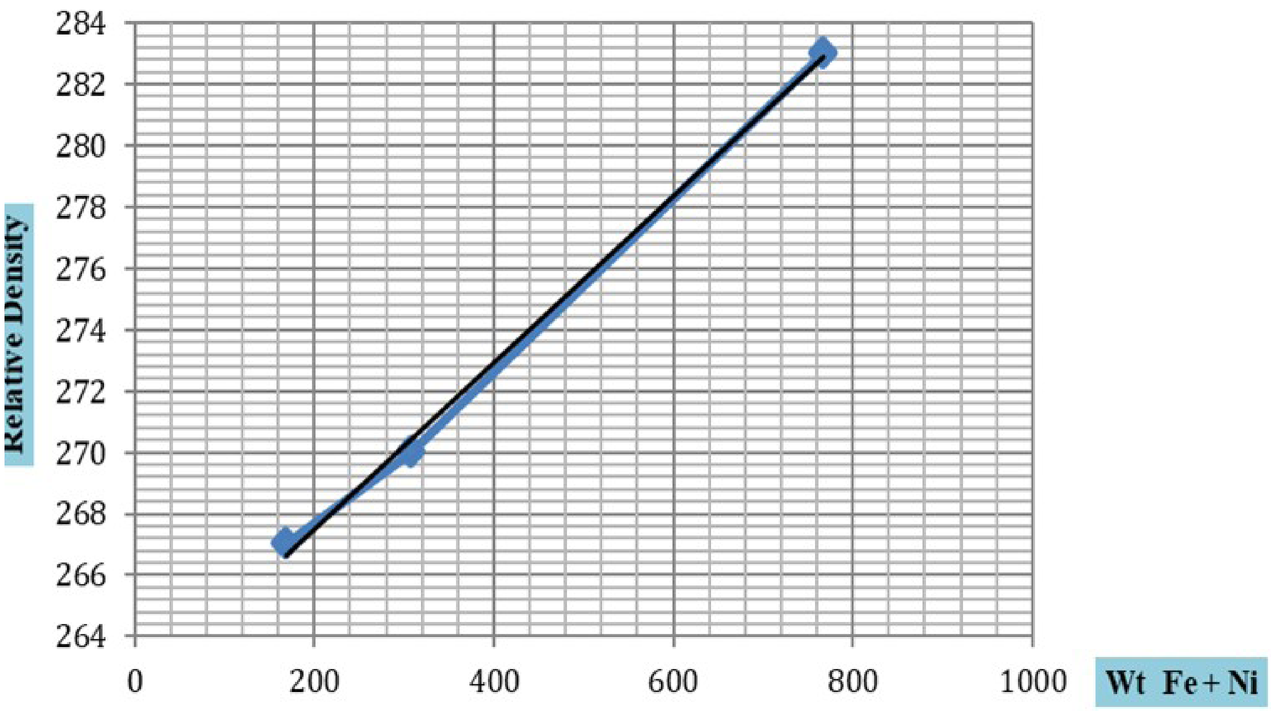

Figure 6 Correlation between relative density and weight of iron + nickel in Quixeramobim aquamarines. Relative Density and Wt (Weight total) multiplied by 100. The black straight line is an automatically generated regression.
Source: Authors.

electronegativity, and atomic radius. All these characteristics mentioned are very similar in the two elements. The Mg does not have the same compatibility of Fe and Ni, even though the atomic radius of Mg has some proximity to the two elements mentioned, thus there is an inversely proportional relationship: the greater the amount of these two ferromagnetic elements, the smaller the amount of MgO. In this way, because of this similar atomic radius, Mg enters the crystalline system of aquamarine replacing the elements mentioned. This situation occurred because the magmatic liquid that generated the lighter-colored aquamarine was not as rich in these two elements which allowed Mg to enter the structure (Klein & Dutrow 2012). It is notable and peculiar that Na is proportional to the elements Fe and Ni, as these two are incompatible elements with it.

This set of gemological and geochemical aspects allows the identification of the aquamarines as coming from the region of the County of Quixeramobim (Ceará).

5 Conclusions

Aquamarines of the County region of the city of Quixeramobim (Ceará) have the gemological quality to be used as gems, for they have a color range from good to excellent, in addition to an aquamarine (Dodger Blue 1) presenting an intense and saturated blue color. The six gems studied are uniaxial negative and they have oscillating refractive indices ranging from 1.567 to 1.585. The birefringence of all samples is above 0.009, with values reaching 0.013. Pleochroism is present and classified as weak in most samples. The captured absorption spectra are in the order of 520, 480, 460, and 420 nm. Five of the six gems analyzed using the incidence of ultraviolet light did not show fluorescence. One specimen, Cadet Blue 1, fluoresces when exposed to ultraviolet light. County´s aquamarines have an oscillating relative density, ranging from 2.67 to 2.83 g/cm^3. Completing the gemological characterization of the six gems, solid and fluid inclusions were visualized, along with growth lines, hollow tubes, skeletal inclusions, and fractures. All these characteristics mentioned are standard for species of aquamarine in different parts of the world, with the exception of two characteristics: the birefringence well above the average of 0.005-0.007 and the presence of luminescence (fluorescence) in a sample. In the case of Quixeramobim gems, some linear correlations were noted involving Fe plus Ni, color, and relative density. The presence of NiO in amounts ranging from 0.65-3.52% in the samples is another unusual factor. These mentioned characteristics can allow the identification of the aquamarines as coming from the County region in Quixeramobim (State of Ceará). Furthermore, the aquamarines of the County diverge from the minerals of Berilândia (State of Ceará) in color, optical signal, birefringence, and relative density, and also in the chemical contents of FeO, CaO, MnO, MgO and NiO.

This demonstrates the importance of gemological characterization not only at a State/Regional level, but also at a specific scale, as in the same State there may be some occurrences of the same mineral, but with divergent properties and characteristics. Therefore, it is important to characterize the occurrences in different geological contexts, as the formation environment directly interferes with the characteristics of the minerals. The gemological and geochemical data of aquamarines studied are unique within the Brazilian scenario.

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Conflict of interest
The authors declare no conflict of interest.

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