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Synthetic (Goldstone) and Natural Aventurine - A Review

Laurent Cormier*

Sorbonne Université, Muséum National d'Histoire Naturelle, UMR CNRS 7590, IRD, Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, IMPMC, 75005 Paris, France

*Correspondence: Laurent Cormier, laurent.cormier@sorbonne-universite.fr

Abstract. Aventurine glass, known for its glittering optical effect due to embedded microscopic metallic or oxide crystals, was developed in Murano, Venice, at the end of the 16th or early 17th century. The historical recipes reveal the complex requirements, including copper reduction, heat treatments and controlled atmospheres, necessary to produce its unique sparkle. Later innovations introduced variants based on chromium and iron, each with distinct crystallization mechanisms and applications. The present study synthesizes the history, production techniques and crystallization processes of aventurine glass, focusing on its relations with nucleation and controlled growth of crystals to obtain desirable optical properties. In addition, comparisons are made with natural aventurine quartzite, where the aventurescence results from mineral inclusions. By exploring both artificial and natural aventurines, this article highlights the links between material composition, manufacturing techniques and aesthetic outcomes.

Keywords: Aventurine, Copper, Goldstone, Color, Crystallization

1. Introduction

Aventurine glass and glazes represent a remarkable blend of art and chemistry and are characterized by a distinctive sparkling effect, also named aventurescence or chatoyancy in mineralogy [1],[2]. This unique glass is a Venetian invention that emerged from the glassmaking tradition of Murano island, where master craftsmen have perfected their art for centuries [3],[4],[5]. The scintillation phenomenon arises from the interaction of light with microscopic metallic or oxide crystals embedded within the glass matrix or glaze. The effect is most striking when light directly hits the surface (Figure 1), causing the crystals to sparkle and creating a dynamic glitter that changes with the angle of the incident light [6].

Aventurine glass is made by melting a silicate-based composition containing metal oxides (like copper, chromium or iron), followed by slow cooling under carefully controlled conditions to induce the crystallization of lamellar microcrystals within the glass matrix. When metallic microcrystals are desired, the redox conditions must be precisely managed, either by using a reducing atmosphere in the furnace and/or by incorporating reducing agents into the batch composition.

Early aventurine glasses contain metallic copper in the form of thin, plate-like crystals or spangles. Today, macroscopic crystals can also be formed using copper, iron, chromium, each with unique characteristics. Depending on the chemistry and firing conditions, the metallic elements crystallize either as pure metals (e.g., metallic copper, Cu^0) or oxides (e.g., Fe_2O_3, Cr_2O_3)

The golden, scintillating effect, known as the aventurine effect, is the result of controlled crystallization during the cooling phase. This effect occurs when light interacts with laminar crystals, which possess a high refractive index, dispersed within a transparent glass matrix. These crystals appear as isolated, shiny, plate-like scales that reflect light distinctly from the surrounding glass medium.

The quality of the aventurine effect depends on several factors: size, shape, quantity, and distribution of crystals [7]. For optimal decorative properties, crystalline formations should cover 6 to 15% of the glaze surface [8]. Insufficient crystal formation fails to produce the desired effect, while excessive growth leads to overcrowding, diminishing the sparkle [9]. The lamellar shape of these crystals occurs under specific conditions, such as low viscosity in the crystallization field and significant oversaturation of metal oxides during cooling [8].

Figure 1. *Example of copper, copper-cobalt and chromium aventurine glasses (from left to right).*

Achieving the aventurine effect requires precise control of composition, firing conditions, and metal oxide concentrations. If the metal oxide content is too low, the crystals dissolve in the glass, preventing the sparkling effect. Conversely, excessive oxide content can result in large surface crystals, resulting in an undesired metallic appearance. Fine-tuning the metal oxide content is essential to balance these outcomes and achieve the desired aesthetic properties [10],[11],[12].

The production process involves two key steps: first, the metallic oxide must dissolve in the glass during firing. Then, controlled crystallization must occur during cooling to produce the desired laminar crystals. Recent advances in understanding these mechanisms have improved process control, but obtaining reproducible results still demands considerable expertise.

Historically, the complexity of the process limited aventurine effects to artistic products, where long firing cycles could be accommodated. Aventurine glass was often worked more like a precious stone, being cut rather than blown, which earned it names such as *pasta venturina*. However, modern developments have enabled the integration of aventurine effects into industrial ceramic production, using shorter firing schedules that are compatible with large-scale manufacturing. This progress marks a significant evolution, extending the applications of aventurine materials beyond traditional artistic fields.

Aventurine glass was not created in imitation of any existing gemstone but an entirely novel material [13]. In this review, we describe the origin of this material, the different variants developed over the centuries and the importance of the crystallization process to achieve the expected optical effect. Nowadays, some natural stones are also called aventurine. As with the glass, natural aventurine includes mineral inclusions giving it a more or less pronounced flicker effect. Although the process is similar, we will show in this paper that the nature of crystals is different between synthetic and natural aventurines.

2. The discovery and early history

Aventurine glass is historically known by various names: *pasta stellaria* (meaning "starry paste"), due to the sparkling effect caused by the inclusions of metallic copper crystals, and *venturina*, derived from the Italian *a ventura* (meaning "by chance"), which reflects its haphazard origin and the challenges of its production, which was a kind of adventure [3],[4],[14],[15].

The exact date of the invention of aventurine remains debated, but documentary evidence helps to establish a chronology. Aventurine is not mentioned in Antonio Neri's treatise *L'Arte Vetraria*, published in 1612 [16], suggesting that its production was not widely known at the time. However, a letter from Philipp Hainhofer to Duke Augustus of Brunswick-Lüneburg in 1614 contains the first documented reference, describing "*a sort of stones with golden stars inside*" sold by Luca Trono, a former goldsmith who likely worked in Venice and is considered the first known seller of aventurine glass [13],[17]. This indicates that aventurine glass was already known and traded across Europe in the early 17th century. We should also mention a goblet from the second half of the 16th century, decorated with ribs and striations in various colors, including aventurine [14]. Although this object suggests that the origin of aventurine dates back to before 1600, the precise dating of this goblet has been called into question [13].

It is therefore reasonable to assume that aventurine was developed in Italy, likely in Murano, Venice, during the late 16th century or very early 17th century. The term *pasta venturina* first appears in a 1626 inventory of the Venetian shop of the jeweler Rimondo Rimondi, listing items such as earrings and buttons made from this material [13],[15]. In 1634, the German term *Goldstein* (also known as *Goldfluss* in Germany), from which the English term *Goldstone* is derived, appears in an inventory describing "*two goldstone necklaces made by Luca Trono*" [13].

The production of aventurine was notoriously challenging and unpredictable. The first known recipe for "*pasta stellaria overo venturina*" was recorded by Giovanni Darduin [15], who began to transcribe his father's recipes Nicolo (d. 1599) in 1644 [14]. As Darduin noted, the composition was "*unpredictable and deceptive*", sometimes resulting in excellent outcomes and other times failing completely. This inherent uncertainty contributed to its high price.

Figure 2. *Blown chalcedony cup with aventurine inclusions – Museum of Murano (Venice, Italy).*

The history of aventurine glass is closely tied to the Miotti family [17],[18], which became its primary producer in Murano. The connection began when Daniele Miotti married Anzola Rigo, daughter of Giovanni Darduin, in 1638. After the deaths of Darduin (1654) and his immediate heirs (1655), the precious recipe book likely passed to Daniele Miotti, who copied it with his son Vincenzo in 1669. The Miotti family carefully guarded and passed on the secrets of aventurine production for several generations until the beginning of the 19th century. The last Miotti glassmaker, Stefano, successfully applied in 1793 for the privilege of continuing the "*fabrica de Smalti, Venturina e Mosaici*" using his inherited recipes [17]. His furnace operated from 1797 to 1805.

The production of aventurine appears to have declined or ceased in the early 19th century, possibly due to its high cost and production difficulties [4],[17]. However, a significant revival occurred around 1825 thanks to Pietro Bigaglia, who presented aventurine glass at the 1826 industrial exhibition in Milan [4],[17].

Aventurine glass was created by melting ordinary glass cullets, to which copper, tin, lead, and iron were added. The process required precise control of conditions and extremely slow cooling in a reducing atmosphere to allow the formation of metallic copper crystals. According to early recipes preserved in the Darduin manuscript, the process involved several steps [14]: melting 100 pounds of opaque red cullet for about 18 hours; adding one pound of lead and tin calx, one and a half pounds of red copper, and eight ounces of iron oxide; after eight hours, adding two pounds of "calcined steel"; allowing the mixture to cool very slowly in a reducing atmosphere.

Aventurine glass is particularly challenging to work with in blown glass applications for which shaping occurs in an oxidizing atmosphere. Prolonged annealing under these conditions can cause the copper crystals to dissolve, causing the glass to lose its characteristic sparkle [14]. Despite these difficulties, it has been used in various decorative applications, including jewelry, buttons, and inlay work (Figure 2). The glass was particularly popular in the 17th and 18th centuries, when it was used in *screziato* (speckled) decoration on *lattimo* (opaque, white glass), with aventurine spots.

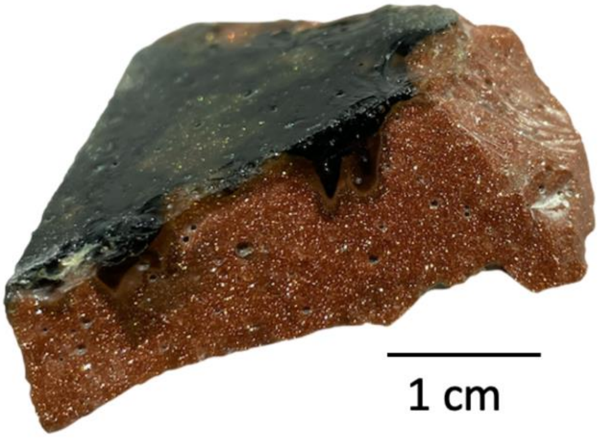

Figure 3. *Copper aventurine glass showing the surface of the melt bath that exhibit a green coloration in contrast to the interior showing the sparkling effect (probably from Choisy-le-Roi glass manufacture. Courtesy of Allain Guillot).*

The second half of the 19th century witnessed important technical innovations. The high cost of aventurine glass and its unique physical characteristics have inspired numerous scientists to master its fabrication and discover the science behind its optical effect. Among them were Friedrich Wöhler (1800-1882) in Germany [19], followed by Edmond Frémy (1814-1894) and Louis Clémandot (1815-?) in France [20],[21], who likely began their research at the Clichy glass factory. Their efforts met with limited success due to difficulties in controlling crystal size and distribution [4]. Paul-Gabriel Hautefeuille (1836-1902) successfully replicated aventurine by adding iron or fine brass turnings into molten glass [22]. Around the same time, in 1865, Théophile-Jules Pelouze (1807-1867) developed a method using sand, carbonates, and potassium dichromate to produce green chromium aventurine in fairly large quantities [23]. Another significant innovation came from Vincenzo Moretti, considered "the foremost technician in Murano", who in 1885 created a new type of aventurine glass [15]. While the traditional aventurine has a cinnamon-colored base that appeared green on the surface (Figure 3), Moretti developed a dark blue variety with stars that appeared gold (Figure 1, middle), silver, or light blue depending on the light. This was achieved by adding cobalt to the mixture, and subsequently a black aventurine was created by increasing the iron and manganese content.

3. Different types of synthetic aventurine

3.1 Cinnamon (copper) aventurine

Copper aventurine glass, historically the first aventurine glass ever produced, has remained relatively understudied due to its complex production [3],[4],[9],[24],[25]. The scintillation effect arises from microscopic metallic Cu (Cu^0) crystals dispersed giving a yellow-cinnamon-colored glass (Figure 4). Copper reduction is achieved using a reduced furnace atmosphere or reducing agents, mainly iron or tin, acting following the reactions:

$$Cu^{2+} + 2Fe^{2+} \rightarrow Cu^0 + 2Fe^{3+} \tag{1}$$

$$Cu^{2+} + Sn^{2+} \rightarrow Cu^0 + Sn^{4+} \tag{2}$$

The manufacturing process is notably complex and was often unpredictable, with recipes being closely guarded secrets in Murano. Numerous historical recipes from the 17th to the 19th centuries have been reviewed in recent literature and will not be given here [3],[4]. The production begins with a base glass, typically recycled cullet, combined with approximately 4-6 wt% Cu_2O as the main ingredient [3],[4],[25]. Additional components include lead oxide to facilitate the copper dissolution, iron or tin oxides that are used as reducing agents [3]. The process takes about a week and includes several stages: initial melting, precise addition of colorants and reducing agents to the molten glass, added gradually in multiple steps, and a crucial cooling period.

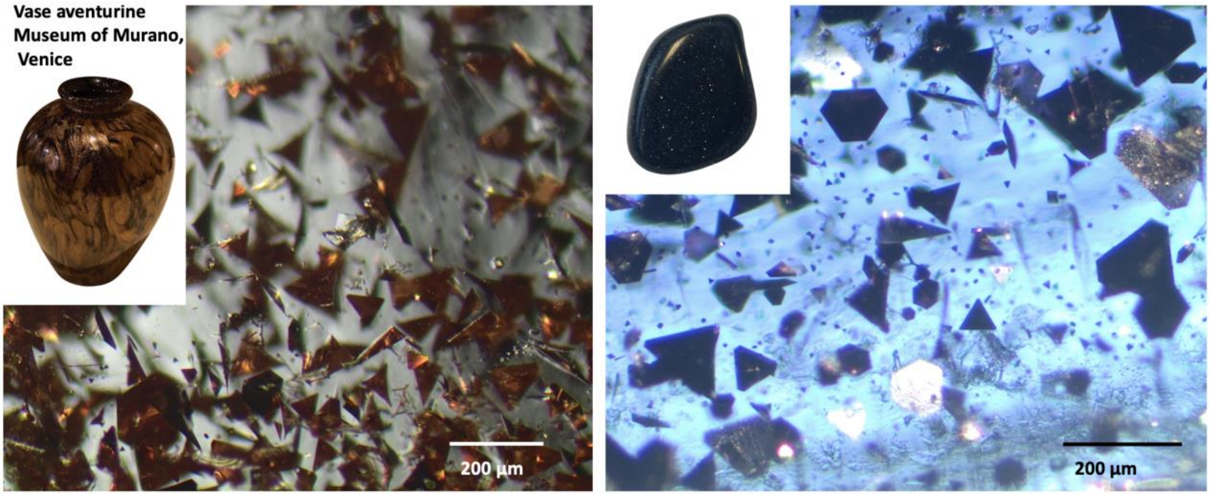

Figure 4. *Optical microscopy images showing copper (left) and copper-cobalt (right) aventurine glass with respective applications.*

The first step is to obtain a red color when the glass is taken from the glass melt [3],[4],[22]. This certainly indicates the formation of nanosized Cu^0 crystals. The reduction is facilitated by reducing agents or reduced furnace atmosphere [26],[27],[28]. After reaching the desired copper reduction state, indicated by the red color, the heating is stopped and the glass melt is cooled down over several days under reducing conditions, obtained by limiting air intake or through the combustion of organic substances. This step is critical as it will allow the Cu^0 crystals to grow into microcrystals, almost visible to the naked eye, producing the characteristic glittering effect. Excessive crystal growth, however, impairs the desired optical properties. Historically, this stage was difficult to control due to the lack of temperature monitoring instruments. No significant differences in compositions are revealed by chemical analysis between aventurine and copper-red glasses [3],[4]; it appears that the main factor that distinguishes aventurine from standard copper-red glasses is thus the size of the Cu^0 crystals and therefore the heat treatment during cooling is the key factor to obtain aventurine.

During melting, the glass develops a layered structure [24], as seen in Figure 3. The extreme surface appears black due to the presence of CuO crystals, followed by a green layer containing dissolved Cu^{2+} ions [3],[4],[9]. The central layer, which produces the finest aventurine effect, contains the highest concentration of dissolved iron [24].

A major limitation of aventurine glass is its incompatibility to be worked directly in the hot state, as reheating and exposure to an oxidizing atmosphere can dissolve the carefully formed Cu^0 crystals. Traditionally, objects were produced by breaking the cooled crucible and processing the glass blocks by cutting or grinding [3]. Hot use was latter obtained by Pietro Bigaglia (1786-1876) in Murano, who developed a technique to protect aventurine with a crystal glass coating, allowing for hot working and the production of blown objects and drawn rods [3],[4]. Later developments included a blue version using cobalt as a coloring agent in the late 19th century (Figure 4, right), and black-based versions using manganese combined with iron oxide [4],[15].

The successful production of copper aventurine demands precise control over multiple parameters, including copper redox balance, reducing agent concentrations, furnace atmosphere and temperature profile during cooling. These technical complexities explain why aventurine glass production remained as much a matter of chance as of skill, making it one of the most challenging and closely guarded secrets in glassmaking history.

3.2 Chromium aventurine

Chromium aventurine (Figure 5), first developed by Theophile-Jules Pelouze [23], is a distinctive aventurine glass characterized by green sparkling Cr_2O_3 crystals precipitated within a silicate glass. The green color is due to the presence of eskolaite (Cr_2O_3) crystals, as well as Cr^{3+} ions dissolved in the glass that also contribute to the color, as seen in Figure 5 [29]. Unlike copper aventurine, which requires slow cooling, chromium aventurine is formed by oversaturation while the glass is still molten, provided that the chromium concentration exceeds a critical threshold [4],[30]. The aventurine effect originates from hexagonal lamellar Cr_2O_3 microcrystals, ranging from 4 to 300 µm in size, with up to 45 crystals per mm^3 [12],[31]. These crystals are sometimes misidentified as fuchsite, likely due to a confusion with natural aventurine quartz (see section 4), which contains inclusions of the chromium mica mineral fuchsite ($K(Al,Cr)_2(AlSi_3O_{10})(OH)_2$) [32].

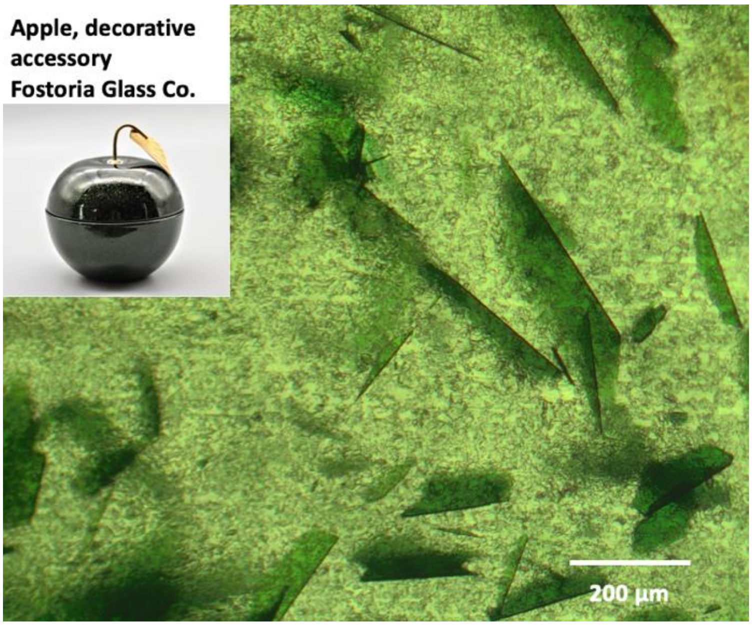

Figure 5. *Optical microscopy images of a chromium green aventurine with an object from the Fostoria Glass Co. (USA) dating from 1956-57 [33].*

Optimal compositions include 1.96-3.81 wt% Cr_2O_3 in a soda-lime silicate glass. Higher concentrations lead to opacity, crystallization issues, and surface defects. Adding blast-furnace slag to the composition improves the solubility of Cr_2O_3, allowing for less alkaline formulations [34]. High-temperature melting under oxidizing conditions is essential to improve the chromium solubility and ensure proper crystal development [12],[31],[34]. The glass can be taken directly from the melt and hot-worked in oxidizing environment like conventional glass, making its production and processing easier than copper aventurine. However, its shimmering effect is less pronounced. Despite its simpler manufacturing process and reduced dependence on heat treatment, maintaining a balanced composition is essential to avoid defects such as bubble formation [30]. While the production of chromium aventurine is relatively straightforward, the mechanisms underlying microcrystal precipitation remain incompletely understood.

3.3 Iron aventurine

Iron aventurine is the most extensively studied type of aventurine, largely due to its relatively ease of formation and striking visual properties, particularly in glaze applications [7],[8],[9],[10],[11],[35],[36],[37],[38],[39],[40],[41]. Due to their high crystallization potential, it is more efficient to achieve aventurine effects in glaze coatings using glass-iron oxide mixtures rather than iron-bearing glasses [8]. The characteristic reddish-brown coloration comes from iron dissolved in the glass, while the sparkling reflections arise from crystallized hematite (α-Fe_2O_3), sometimes accompanied by fayalite (Fe_2SiO_4). These hematite crystals typically exhibit rhombohedral symmetry and have size of 10 to 120 μm [8],[37]. The mechanism of formation consists in dissolving iron oxide in the glass melt, and then crystallizing hematite during cooling as the glass melt becomes oversaturated with Fe^{3+} ions [8],[11],[39].

Optimal compositions generally contain 10-30 wt% Fe_2O_3. Lower concentrations may result in incomplete crystallization or alternative phases like franklinite ($ZnFe_2O_4$) [42], while higher concentrations promote the development of large, well-defined hematite crystals [7]. To facilitate the growth of laminar crystals, the crystallization process requires achieving low viscosity at the temperature range of crystallization, which is usually obtained by means of lead or boric frits while maintaining low alumina content [7],[9]. Controlled cooling, usually in the 950-990°C temperature range for 7 to 24 hours under oxidizing conditions, is necessary for proper crystallization [8],[11]. The decorative effect can be enhanced using nucleation agents such as LiF and CaF_2 [37], while excessive alkaline components (> 12.5 wt% Na_2O) [8],[38] or iron oxide (> 38 wt% Fe_2O_3) can diminish or eliminate the desired scintillation effect.

3.4 Crystallization mechanisms

The aventurine effect in glass relies on the development of coarse laminar crystals that are larger than, typically, 40 μm and with a low crystal number density to create intense light reflections [9]. Additionally, crystallization must primarily occur within the glass, with minimal surface crystal formation to preserve the clarity of the material. The crystallization process takes place in two stages: nucleation followed by crystal growth. The final morphology of the crystals is strongly influenced by the degree of undercooling (ΔT, which is the difference between the temperature of the liquidus and that of the supercooled liquid) and the cooling rate. The influence of these parameters is observed in various materials like rocks, glasses, and slags, following an established pattern [43],[44],[45],[46],[47],[48]: at low undercooling ($\Delta T < 20°C$) and slow cooling rates, crystals develop polyhedral or euhedral shapes; moderate undercooling ($\Delta T = 20\text{-}60°C$) and fast cooling rates lead to skeletal or hopper crystal morphologies; at higher undercooling ($\Delta T > 100$ °C) and cooling rate, crystals develop dendritic shapes.

To produce aventurine glass, it is essential to minimize the formation of dendritic crystals, as these degrade the desired optical properties. Instead, the crystallization process must be optimized to promote the growth of large, flake-like crystals. For copper-based aventurine, historical texts emphasize the importance to achieve the reddish color during the melting stage [3],[4],[22], indicating that initial Cu^0 crystals must formed in the liquid state, resulting from the reduction of copper. The further growth of these crystals must be carefully controlled to avoid dendritic morphologies.

A similar mechanism applies to chromium- and iron-based aventurines. Iron or chromium oxide crystals can form in the liquid state or during cooling, driven by the oversaturation of these elements. Their growth must also be regulated to favor crystal growth while avoiding dendritic morphologies or the formation of new nucleation sites. This requires relatively low degrees of undercooling and extended cooling times (slow cooling rates) to allow crystals to reach micrometric sizes. The prolonged cooling process, which is recommended in historical recipes, aligns with these requirements. This raises the question of whether significant undercooling is necessary. If avoided, the cooling phase can be considerably shortened, enabling faster synthesis while still achieving the desired crystal properties. The replication of glazes containing hematite confirms that hexagonal micrometric hematite crystals can form at temperatures between 925-1020 °C [49]. To refine these processes, a deeper understanding of the relationship between crystal morphologies and degrees of undercooling is necessary. Experiments conducted under varying undercooling conditions will provide valuable insights on how to optimize the balance between cooling rates, crystal growth, and the aesthetic qualities of aventurine glass.

4. Natural aventurine

4.1 Different varieties of natural aventurine

Uniquely, the natural mineral was named after this artificial glass rather than the reverse. The term aventurine to designate specific stones emerged only in the late 18th or early 19th century, following the advent of systematic mineral classification [50]. Aventurine is a gemstone variety of quartz or quartzite, celebrated for its translucency and the unique sparkling effect known as aventurescence [1,2]. Similarly to aventurine glass, this optical phenomenon occurs when light reflects off minute, plate-like mineral inclusions within the quartz matrix [1],[41]. These inclusions not only produce the glittering effect but also determine the color of the stone, which can range from green to orange, brown, yellow, blue, or gray. Among the various species, green aventurine is the most common and prized variety (Figure 6), distinguished by its silvery green or blue sheen caused by fuchsite, a chromium-rich variety of muscovite mica [32],[51]. Other colors emerge from different inclusions (Figure 6): hematite, Fe_2O_3, or goethite, $FeO(OH)$, for orange and red-brown tones [32],[52], dumortierite, $Al_7BO_3(SiO_4)_3(O,OH)_3$, or lazulite, $(Mg,Fe)Al_2(PO_4)_2(OH)_2$, for pink-blue shades [53],[54],[55], mica (lepidolite, $K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$, muscovite, $KAl_2(AlSi_3O_{10})(F,OH)_2$) or covellite (CuS) for pink red or purple shades [2],[32],[56],[57] and muscovite or ilmenite, $FeTiO_3$, for gray or silvery hues [58]. When fuchsite is excessively abundant, the stone can become opaque, leading to confusion with malachite or jade.

Figure 6. *Examples of natural aventurine (quartzite with mineral inclusions). From left to right: raw green aventurine from Brazil (GAB), polished green aventurine from India (GAI), polished red aventurine form South Africa (RAS), polished blue aventurine from Brazil (BAB).*

Aventurine quartzite is typically forms in metamorphic environments, where mineral inclusions are trapped during the growth of quartz crystals [58],[59]. These geological processes produce the distinctive structure and inclusions responsible for the aventurescence of stone. The most notable sources of aventurine are in India, particularly around Mysore and Chennai, which supply much of the world's green aventurine, often mistakenly referred to as "Indian Jade". Brazil is another major producer, with additional deposits found in Chile, Spain, Russia, Oregon (USA).

The aventurescent effect is not exclusive to quartz; it also appears in feldspar minerals, notably found in some lava flows in Oregon (USA) and Afar region (Ethiopia), and known as "sunstone", where inclusions of metallic copper or hematite create a similar glittering quality [1],[60],[61],[62],[63],[64]. The higher transparency and color range of feldspar, ranging from pale yellow to orange and red, differentiate it from aventurine quartz. Other stones of metamorphic origins such as cordierite can also exhibit aventurescence, with blue cordierite containing hematite or biotite, known from locations in India and Tanzania [65],[66],[67].

The exact mechanisms governing the formation of natural aventurine under specific temperature-pressure-time conditions remain poorly understood [1]. In quartzite-hosted inclusions, three formation mechanisms have been proposed each corresponding to a different inclusion size [59]. Nanoscale inclusions, typically rutile TiO_2, are believed to form through exsolution during cooling of the parent melt. Submicron inclusions, such as mica or ilmenite, are thought to form syngenetically, crystallizing simultaneously with the host quartz, often exhibiting oriented intergrowths with the quartz lattice. In contrast, micron-sized and larger inclusions likely result from entrapment of pre-existing minerals during quartz growth.

Sunstone, by comparison, is more directly linked to crystallization processes associated with aventurine glass. In this magmatic context, copper is initially dissolved in the silicate melt. The presence of volatiles (H_2O, F, Cl) enhances the mobility of Cu by forming stable complexes thereby facilitating its transport [68]. Upon cooling and crystallization of feldspar, copper becomes insoluble in the host structure and exsolves as metallic Cu^0. This reduction is likely favored by low oxygen fugacity conditions typical of magmatic environments [64]. Furthermore, the formation of copper platelets with a preferred orientation may result from epitaxial relationships between the exsolved copper and the feldspar crystal lattice [61].

The combination of beauty and versatility in coloring makes aventurine highly sought after for decorative applications. Its shimmering properties and its relative hardness distinguish it from similar-looking stones, such as malachite or jade. Most aventurines are carved into beads and figurines due to their abundance, while higher-quality specimens are crafted into cabochons or faceted gemstones for jewelry. The intensity of the aventurescence varies with the size, density, and orientation of the inclusions, making each piece unique.

4.2 Nature of the inclusions in green, red and blue aventurines

We have examined four natural aventurine samples presented in Figure 6: two green aventurines, one from Brazil (GAB) and the other one from India (GAI), a red aventurine from South Africa (RAS) and a blue aventurine from Brazil (BAB) (exact mining locations are unknown). The samples were analyzed using a combination of optical microscopy, X-ray diffraction (XRD) and Raman and diffuse reflectance spectroscopy to determine their crystalline structure and identify the inclusions responsible for their distinctive color. Diffuse reflectance spectra were recorded using a PerkinElmer Lambda 1050 spectrometer equipped with an integrating sphere covering the ultraviolet (UV) to the near-infrared (NIR) regions. Raman spectra were acquired using a Horiba Jobin Yvon HR460 spectrometer (focal length: 460 mm, Longjumeau, France) coupled with a water-cooled CCD detector (Andor Technology Ltd., Belfast, U.K.) and excited by the 514.5 nm line of an argon laser. The laser beam was focused onto the sample with a 20× Mitutoyo objective producing a spot size of approximately 2 µm. A 1200 lines/mm grating was used to disperse the scattered signal. XRD was performed using a PANalytical X'Pert PRO diffractometer (Malvern PANalytical, Almelo, The Netherlands) equipped with a Co Kα radiation source (λ = 1.789 Å) operated at 45 kV and 40 mA. Diffraction patterns were collected over a 2θ range of 10° to 90° with a step size of 0.0167° and a counting time of 3 s per step.

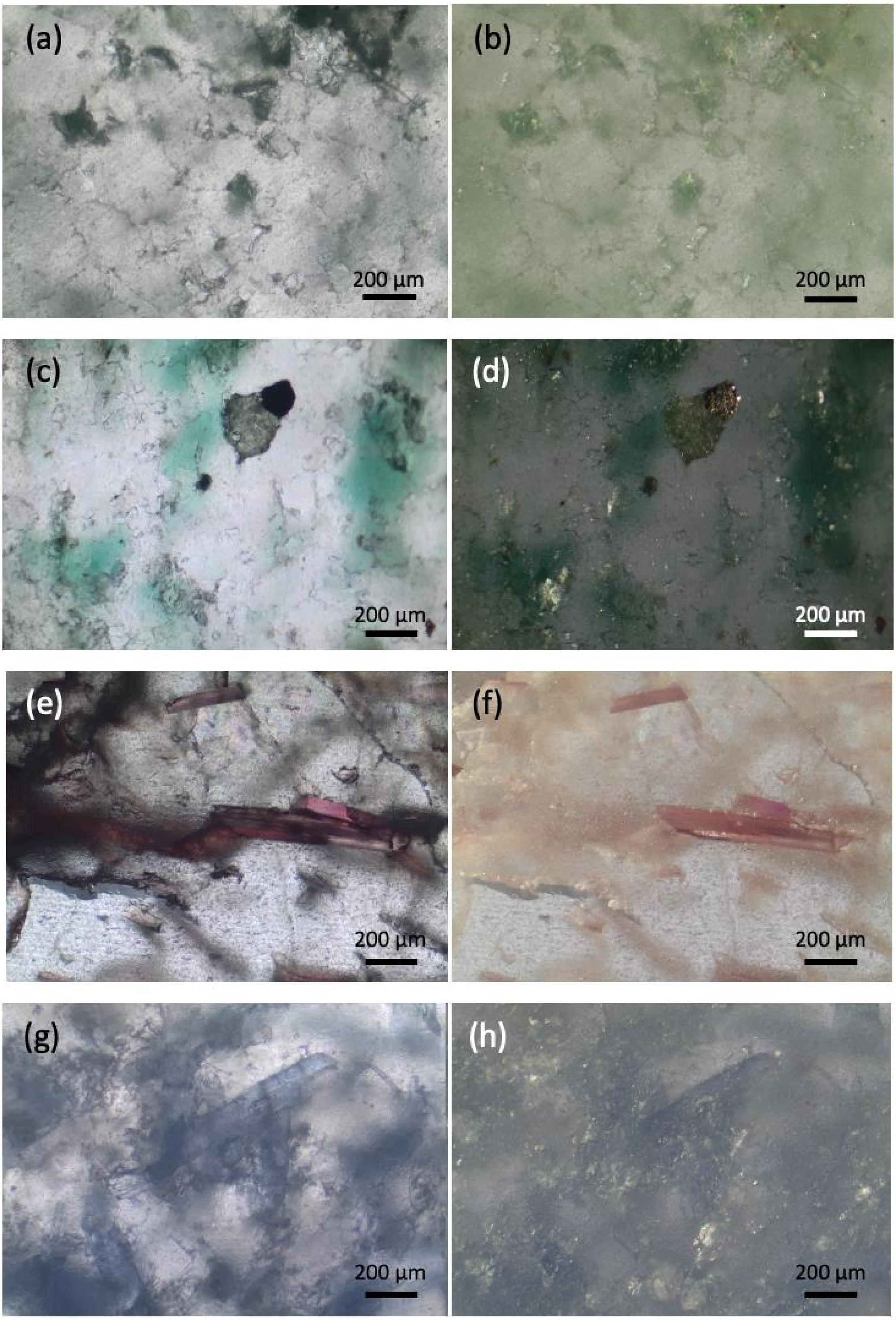

Figure 7. *Optical microscopy images: GAB, green aventurine from Brazil in transmitted light (a) and reflected light (b); GAI, green aventurine from India in transmitted light (c) and reflected light (d); RAS, red aventurine in transmitted light (e) and reflected light (f); BAB, blue aventurine in transmitted light (g) and reflected light (h).*

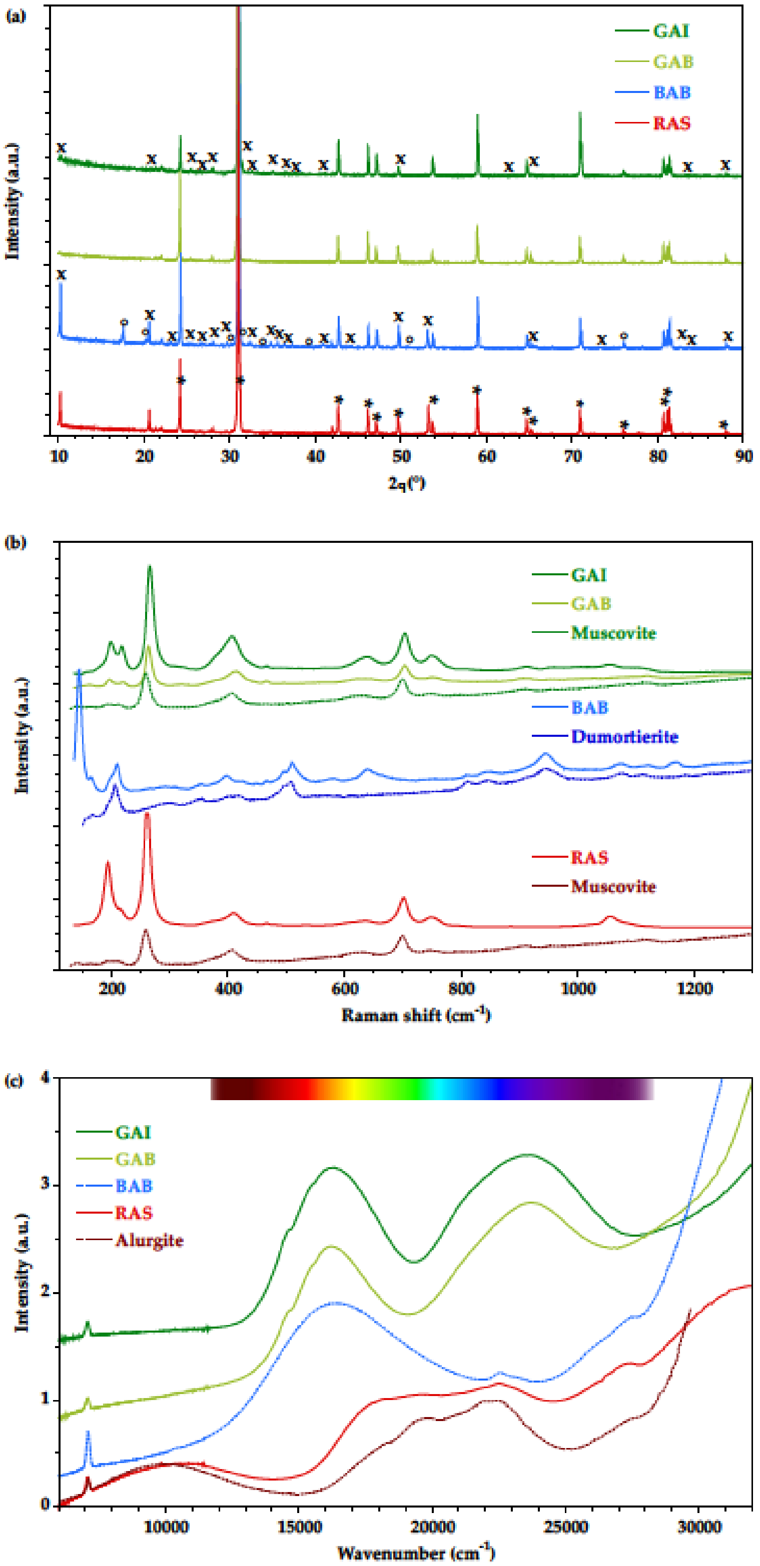

Figure 8. *Analysis of the for natural aventurine samples by (a) X-ray powder diffraction, (b) Raman spectroscopy obtained directly from the colored crystals visible in Figure 7 and (c) diffuse reflectance spectroscopy. In the XRD patterns, the crystalline phases are distinguished by various symbols: * = quartz; x = muscovite; ° = dumortierite. The Raman spectra for muscovite (R04124) and dumortierite (R050628) are obtained from the RRUFF data base. The reference spectrum of alurgite is obtained from the Mineral Spectroscopy Server of Caltech.*

Optical microscopy reveals an uncolored polycrystalline quartz matrix (appearing white in the images in Figure 7) in all samples. This quartzite microstructure is confirmed by Raman spectroscopy measurements in these regions (not shown). XRD analysis further corroborates this finding, with the main Bragg diffraction peaks in all samples corresponding to quartz (Figure 8a).

In both green aventurines (GAB and GAI), XRD and Raman spectroscopy indicate the presence of muscovite (Figures 8a and b). Contrary to glasses, only the crystals appear green due to the presence of a chromium-rich variety of muscovite known as fuchsite, which is identified as responsible for the greenish color. These fuchsite crystals measure less than 200 µm and show different distribution patterns: abundant in the GAI sample (Figure 7c and d) and more dispersed in the GAB specimen (Figure 7a and b). The presence of chromium is clearly identified in reflectance spectra (Figure 8c) with the characteristic bands due to Cr^{3+} at about 16,000 and 23,500 cm^{-1} [69].

In the red aventurine (RAS), large elongated crystals (~200-800 µm) are observed (Figure 7e and f). Raman spectroscopy confirms that these crystals have a muscovite-type structure. However, the RAS sample shows an intense band at 194 cm^{-1} with a shoulder at 215 cm^{-1}, which differs from the green aventurines that exhibit a doublet at 199 and 218 cm^{-1}. This spectral region relates to internal vibrations of the MO_6 octahedron [70], and can be influence by minor elements contributing to the mineral's color. The pink-red color has been attributed either to a Fe^{2+}-Ti^{4+} intervalence charge transfer (IVCT) or to the presence of manganese [71],[72]. The diffuse reflectance spectrum of the stone closely matches that of a Mn-rich variety of muscovite, alurgite (Figure 8c), a mineral previously reported to impart striking violet to reddish-purple colors [56].

The blue aventurine (BAB) contains dumortierite crystals, $(Al,Fe)_7BSi_3O_{18}$, as identified by XRD and Raman spectroscopy. These crystals exhibit needle-like shapes (~200-800 µm) and appear either dispersed throughout the sample or interlocked along visible bands (Figure 6). Muscovite, a major mineral commonly associate with dumortierite [73], is clearly visible in the XRD pattern (Figure 8a). The blue coloration is attributed to traces of iron and titanium, with a Fe:Ti ratio exceeding 1:4 [72]. These impurities give a significant contribution from Fe^{2+}-Fe^{3+} IVCT near 16,400 cm^{-1} and a smaller contribution from Fe^{2+}-Ti^{4+} IVCT near 20,000 cm^{-1} in the diffuse reflectance spectrum in Figure 8c [72],[74].

5. Conclusion

The development of aventurine glass represents a remarkable achievement in glassmaking history, combining artistic creativity and technical innovation. Since its fortuitous discovery in Venice, aventurine glass has evolved through its various modern forms: copper-based (the original form), chromium-based, and iron-based. While the artificial aventurine glass preceded the discovery and naming of natural aventurine minerals, both materials achieve their characteristic glitter through lamellar crystals. The aventurine effect results in the controlled growth of specific crystals within the glass, requiring precise management of the degree of undercooling, the cooling rate, and the composition to achieve the optimal crystal size and morphology. The production process, which is particularly complex for copper aventurine, requires careful control of several parameters including temperature profiles, redox conditions, and cooling rates. These parameters guide crystal morphology toward plate-like shapes that maximize light reflection. Research at different degrees of undercooling is necessary to reveal the relationships between kinetic and thermodynamic factors in the crystallization of aventurine glass. In natural aventurine, XRD patterns consistently show the presence of muscovite in all samples, with notably higher concentrations in the red and blue aventurines. Dumortierite was clearly identified in the blue aventurine through XRD analysis. Raman spectra confirmed that the red and green inclusions are muscovite-type minerals, alurgite and fuchsite respectively, while the blue inclusions are dumortierite. These findings provide a comprehensive understanding of the mineralogical composition and coloration mechanisms in natural aventurines. This knowledge could guide the development of new aventurine glasses incorporating different crystalline phases to achieve a broader range of optical effects and colors.

Data availability statement

Data of presented results can be provided upon request.

Author contributions

Laurent Cormier: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – Original Draft.

Competing interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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