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Article

Mineralogical characteristics and causes of jadeite "structural cotton" in an ecological context: Insights from biomechanical analogies

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Abstract: The causes of jadeite "structural cotton" are complex and varied, and are the result of a combination of factors in an ecological context. Jadeite "structural cotton" not only has a unique appearance, but also its formation mechanism with the conventional emerald there are obvious differences. In view of the exquisite adaptation of organisms to the environment during the long process of evolution, we can analyze "structural cotton" by analogy with the principles of biomechanics. Starting from the adaptability of biological structure and function, we can think about whether the internal mineral crystals of jadeite during its formation process may undergo special arrangement and deformation under the action of geological stress, just like the structure of biological bones adjusted by force, thus forming the unique structure of "structural cotton". For example, when biological bones are subjected to stress in different directions, cells will sense and feedback, prompting the trabeculae to optimize their distribution and achieve the best mechanical support. Similarly, in the underground high temperature, high pressure and complex geological environment, the mineral particles of jadeite may also respond to changes in stress, temperature, and chemical concentrations with a similar "sensing feedback" mechanism, and eventually form the appearance of "structural cotton". In this paper, the definition of jadeite "structural cotton" and its typical features are firstly elaborated, and then the collection and analysis methods of the samples are introduced in detail. Then, the mineralogical characteristics of jadeite "structural cotton" are systematically summarized, including its crystal structure, chemical composition, optical properties, etc. From a biomechanical perspective, we can consider the elastic and plastic properties of the jadeite matrix and how the inclusions of "structural cotton" might affect the overall mechanical behavior. The way in which cracks or voids within the jadeite might propagate or interact with the surrounding material can be related to fracture mechanics principles seen in biological materials such as bones or shells. On this basis, the formation mechanism of jadeite "structural cotton" is discussed and analyzed with the regional geological background. Through the systematic analysis of the characteristics of jadeite cotton, we explore the causes of cotton and its interrelationship with the body of jadeite, which provides a new perspective for further understanding of the process of jadeite jadeite genesis.

Keywords: jadeite; structural cotton; mineralogical features; genesis; biomechanical analogies; mechanical behavior of minerals

1. Introduction

Jadeite is a treasure of nature, and its unique charm attracts many jewelry lovers and researchers. Under the influence of the ecological environment, the formation process of jadeite becomes more complicated. From the viewpoint of the causes, it mainly includes the influence of external forces during the formation of jadeite, the role of impurities and geological effects. The external force makes the internal wafer of jadeite twisted or misaligned, the transparency changes, and the formation of "structural cotton" [1]. The size and distribution of impurities and colored impurities will affect the shape of the cotton and the role of the jadeite color and transparency. Geological effects lead to the size of mineral crystallization particles affecting the obvious degree of cotton, and at the same time make the jadeite internal residual gas or liquid, when the temperature is lowered to form “structural cotton” [2]. As a common phenomenon within Jadeite, the mineralogical characteristics and causes of “structural cotton” have become the focus of our exploration. Through the study of jadeite “structural cotton”, we can better understand the formation mechanism of jadeite, and provide a scientific basis for the evaluation of the quality of jadeite.

The “structural cotton” in jadeite refers to the fissures, healed fissures, and contact surfaces or voids between minerals and minerals, minerals and fissures, and minerals and their internal inclusions in the formation of jadeite due to the arrangement of the jadeite minerals and their different interrelationships [3]. When there is light irradiation, these parts will produce reflection and refraction, thus showing white flocculation on the macro scale. Due to the different ecological environments, the density and distribution characteristics of “structural cotton” are different for jadeite from different origins [4]. For example, Myanmar as one of the main origins of jadeite, the “structural cotton” in its jadeite jadeite is mostly presented as filamentous strips, clumps, fog, dots, etc., and the boundaries with the surrounding matrix are not clear, in a transitional state. Cotton also exists in Guatemala’s jadeite, but its shape is different from Myanmar’s. In addition, climate change is very hot and environmental factors will also affect the formation and change of jadeite “structural cotton”. Abundant precipitation accelerates rock weathering, and active water circulation makes ore bearing solution migrate better, providing material conditions for the formation of the deposit. Temperature changes affect mineral solubility and crystallization, and appropriate temperature drop is helpful for jadeite crystallization to form deposits. For “structural cotton”, precipitation changes may make foreign minerals enter to form inclusion cotton, and temperature fluctuations make cotton distribution disorderly [5]. The plate movement produces high pressure and high temperature environment, which promotes the formation of jadeite ore. the channel formed by rock fracture is conducive to the migration of ore bearing solution. The high temperature, high pressure and rich minerals brought about by volcanic activity help the formation of jadeite through metasomatism. In terms of “tectonic cotton”, the stress generated by plate movement causes cracks in the jadeite crystal, which is filled to form cotton. Its strength and direction also determine the shape and distribution of cotton, and volcanic activity will also make the distribution of cotton more complex [6].

Although the cotton wadding will affect the value of jadeite in the market, if the cotton wadding of jadeite is cleverly distributed, it can also provide inspiration for designers. For example, snowflake cotton can be designed as winter themed ornaments. Through ingenious carving or inlay, the “structural cotton” can be transformed into unique decorative elements to add artistic beauty. As a scarce natural resource, the rational exploitation and efficient utilization of jadeite is the focus of the industry and academia. During jadeite mining, open-pit mining destroys a large number of vegetation, destroys biological habitats, and causes soil erosion; Waste residue and wastewater contain heavy metals and chemicals, pollute soil and water sources, and seriously damage the surrounding ecological environment. In addition, the labor rights and interests are worrying, the working conditions are poor, the safety protection is lack, and the salary is low. All kinds of problems need to be standardized and solved. Based on the above background, this paper will focus on the mineralogical characteristics and formation mechanism of the "structural cotton" in jadeite, aiming to carry out a detailed study of the "cotton" of jadeite, improve the relevant gemological mineralogical characteristics, mineral composition and mutual genetic relationship, in order to provide valuable reference and basis for further understanding and using this valuable resource.

2. Materials and methods

2.1. Experimental samples

In this study, jadeite samples from the main jadeite production area of Myanmar were selected as the research object, and the samples needed for the research were mainly collected for the jadeite with the characteristics of "structural cotton" commonly found in the market. The so-called "structural cotton" refers to the existence of fibrous or cotton like structure inside the jadeite. Through preliminary observation, three Jadeites with the characteristics of "structural cotton" were selected and numbered s-1, S-2 and S-3 respectively (**Figure 1**). Among them, S-1 is a waxy land, with a white cotton strip in the middle, showing a white cotton wadding interwoven structure, surrounded by green and fine texture; S-2 is waxy, light green, uneven background color, filiform cotton balls can be seen, slightly transparent, and the mark is essentially coarse, with a sense of particles visible to the naked eye; S-3 is a waxy, round cotton block with relatively poor texture, surrounded by green and fine texture. The samples were ground into thin slices for subsequent testing and analysis.

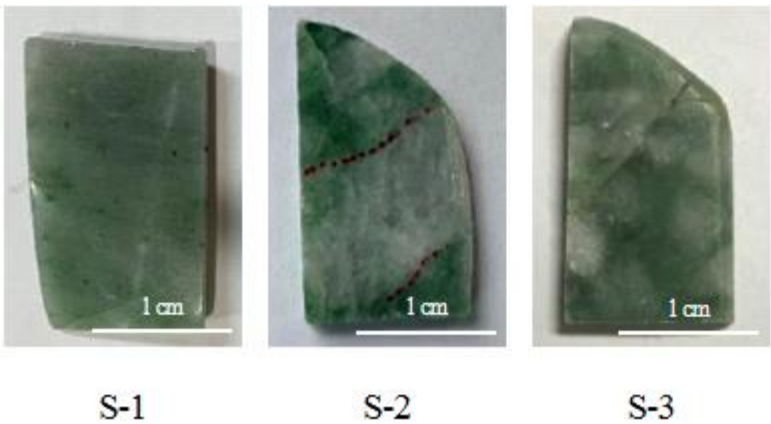

Figure 1. Jadeite sample.

2.2. Relative density and refractive index test

Relative density and refractive index are important parameters when identifying precious stones. These parameters are important for mineral designation and assessment of the purity of precious stones. In this experiment, the density of jadeite samples was tested by hydrostatic weighing method. First prepare the electronic balance, beaker, jadeite sample and thin wire. Use electronic balance to measure the net weight M1 of jadeite sample; Inject an appropriate amount of mineral water into the beaker to completely submerge the jadeite sample; Tie the jadeite sample with thin wire and put it into the beaker. Record the weight m2 of the beaker at this time; Then lift the jadeite sample tied with thin lines and suspend it in the air. Record the weight of the beaker m3 at this time, and then the density of jadeite = [m1/(M2−M3)]. In order to minimize the error, each sample was measured three times to take the average value.

The refractive index of the jadeite samples was tested by a gemstone refractometer (C98, Shenzhen Septo Technology Co., Ltd.), using a combination of faceted and curved telephoto methods to measure. Each sample was measured three times to take the average value.

2.3. Infrared spectral testing

In this study, Fourier transform infrared spectrometer (FT-IR 6600, Shijiazhuang Chopper Technology Co., Ltd.) was used to conduct infrared spectral tests on samples in the lint area and non-lint area. Transmitted light tests were performed on the lint area and the main part, respectively. The test parameters were as follows: scanning range 400 cm^{-1}–4000 cm^{-1}, number of scans 32, resolution 8 cm^{-1}. The experiments were carried out at room temperature 20 °C–22 °C, voltage 220 V–240 V, frequency 50 Hz–60 Hz, and power 250 W. The results are summarized below.

2.4. Laser Raman spectroscopy test

In this study, a laser confocal micro-Raman spectrometer (DXR2xi, Thermo Fisher Scientific (Beijing) Co., Ltd.) was used to perform qualitative micro-area testing of the physical phase composition, mainly to analyze the physical phase composition of the lint part and the jadeite body part more accurately. The test parameters were as follows: Ar^+ excitation line at 532 nm, output power of 10 mW, spectral scanning range of 500 cm^{-1}–4000 cm^{-1}, and analysis area diameter of 0.7 µm.

2.5. Electron probe test

In this study, an electron microprobe analyzer (EMPA-1600, Tsushima, Japan) was used to conduct microprobe analysis on the mineral flakes, and the main chemical composition of the jadeite flakes and the jadeite body were quantitatively tested, and the tested elements included Mg, Ca, Cr, V, Ti, K, Fe, Mn, Ni, etc. During the analysis, random spot tests were conducted and the average values were calculated. During the analysis process, random spot tests were carried out in the cotton wool part and the jadeite body part, and their average values were calculated. The test parameters are as follows: accelerating voltage 15 Kv, current 20 nA, beam spot diameter 5 µm, analyzing accuracy <0.10%.

2.6. Trace element testing

In this study, laser stripping-plasma mass spectrometer (La-ICP-MS, Beijing Guanyuan Technology Co., Ltd.) was used for trace element analysis. Spot testing was performed on the jadeite cotton wool part and the jadeite body part. For the test, the samples were required to be taken in advance under a polarized microscope to take reflection images from low magnification to high magnification, with high magnification up to 200 times, and the sample surface was polished. The test parameters were as follows: laser melting system GeoLasPro, operating wavelength 193 nm, spot size 100 mm, inhomogeneity < ± 3.5% (2 sigma), energy density range 1 J/cm^2–45 J/cm^2, laser safety class IIIb.

3. Experimental results

3.1. Relative density and refractive index analysis

"Structural cotton" is caused by factors such as uneven mineral growth environment, impurity elements or lattice defects during the formation of jadeite, and the filling of cracks caused by late geological stress. The relative density of jadeite, the main component of jadeite, is generally between 3.30 and 3.36. The change of relative density will affect the weight of jadeite. Jadeite with more "structural cotton" and low relative density feels slightly lighter in the same volume. The refractive index of inclusions is different from that of jadeite, which will change the path of light propagation and cause refractive index fluctuations. The change of refractive index will affect the luster and transparency of jadeite. The refractive index of jadeite is about 1.66. It is a jadeite with "structural cotton". The refractive index of cotton is different from that of jadeite. When light propagates, it will scatter and diffuse, reducing the transparency.

Test results show that the jadeite samples in **Table 1**, relative density of 3.32 or so, refractive index of 1.66 or so. Relative density and refractive index values are in the jadeite theoretical values within the normal range, indicating that the jadeite containing "structural cotton" cotton wool parts and jadeite body parts of the physical composition should be consistent.

Table 1. Analysis of relative density and refractive index of jadeite samples.

Number	Shape	Colour	Density (g/cm^3)	Refractive index (RI)
S-1	schistose	green background, white cotton balls	3.295	1.661
S-2	schistose	green background, white cotton balls	3.332	1.660
S-3	schistose	green background, white cotton balls	3.303	1.660

3.2. Infrared spectral analysis

In recent years, infrared spectroscopy has become popular in the field of mineral analysis. This advanced test has become a routine method for gemstone identification, which can accurately identify the molecular structure and functional groups. This study focuses on the cotton wool and main body parts in jadeite, and aims to gain insight into its mineral composition through infrared spectroscopic testing. The infrared spectroscopic analysis technique allows access to the vibrational characteristics of each bonding group within the sample molecule. Resolving the infrared absorption peak data of a sample can reveal its internal chemical bonding and the presence of functional groups. The IR absorption peaks of standard jadeite are known to be located at 1090 cm^{-1}, 1045 cm^{-1}, 990 cm^{-1}, 910 cm^{-1}, 850 cm^{-1}, 740 cm^{-1}, 658 cm^{-1}, 585 cm^{-1}, 520 cm^{-1} and 460 cm^{-1} [7]. As shown in **Figure 2A**, the white cotton wool parts of jadeite, with absorption peaks mainly at 1085 cm^{-1}, 940 cm^{-1}, 528 cm^{-1}, and 585 cm^{-1}, showed sharp absorption peaks typical of hard jadeite, while other weak peaks were also observed. As shown in **Figure 2B**, there are absorption peaks at 1083 cm^{-1}, 940 cm^{-1}, 528 cm^{-1}, and 587 cm^{-1} in the body part of jadeite, and the body of jadeite also exhibits similar spectral peak characteristics. When there is cotton wadding in the jadeite, the position and intensity of the characteristic peak representing the vibration of Si-O bond in the infrared spectrum may change, resulting in the different absorption and scattering of infrared light from that of the non-cotton jadeite, which is reflected in the spectrum. However, the spectrum of "structural cotton" measured in this study is not different from that of jadeite. It can be seen that both the cotton wadding and the main part of jadeite belong to jadeite.

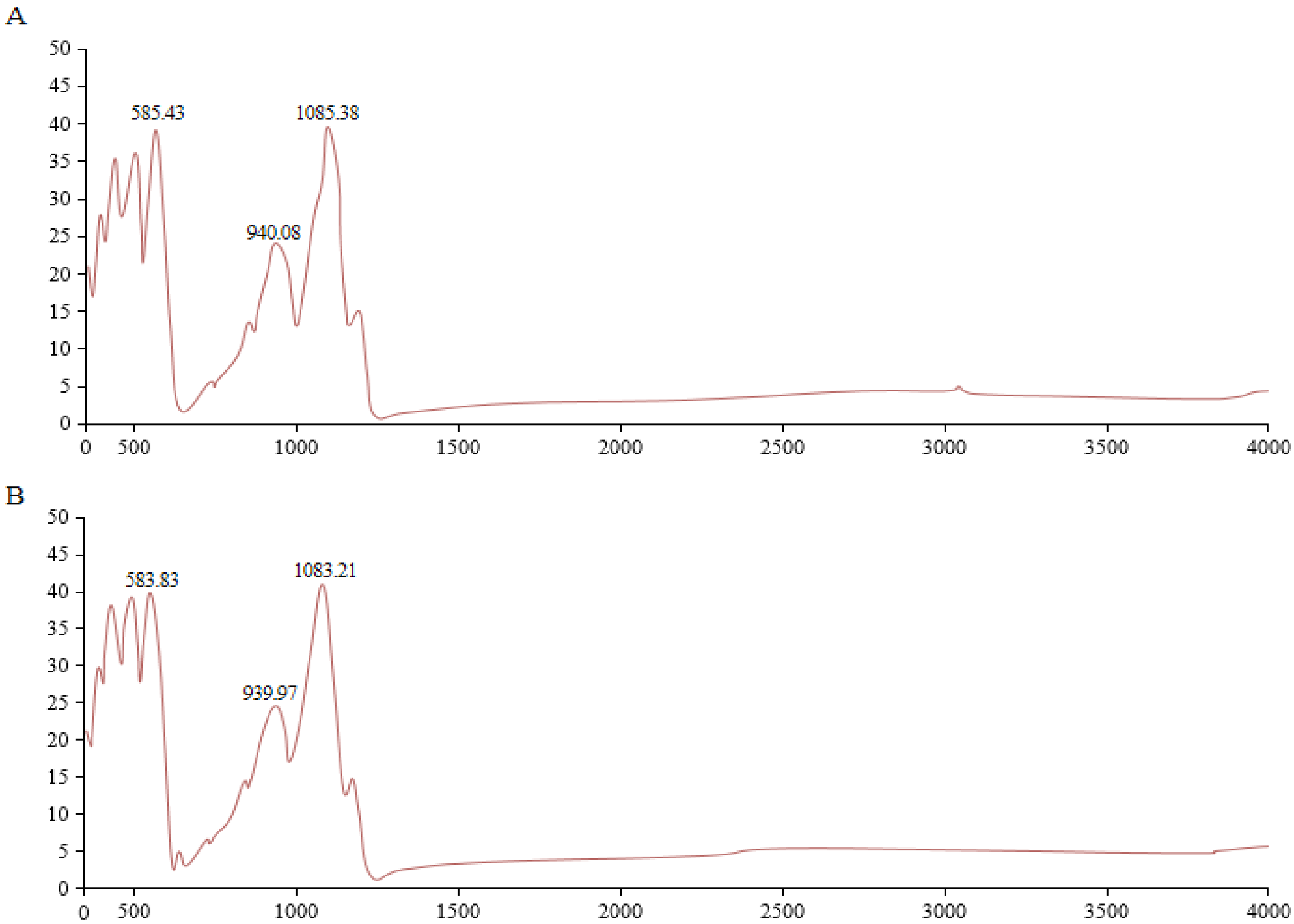

Figure 2. Infrared spectral analysis of jade sample **(A)** cotton fleece parts of jade; **(B)** main body parts of jade.

3.3. Laser Raman spectroscopy

Laser Raman spectroscopy is a spectroscopic technique in which laser photons scatter inelastically with molecular matter [8]. This method can be used for the qualitative analysis of mineral composition. In order to further determine the specific composition of the lint in jadeite, laser Raman was used in this study to test the composition of the lint area and the main part of the jadeite. The characteristic Raman displacement peaks of jadeite are known to be 375 cm^{-1} and 700 cm^{-1}, corresponding to the bending vibration peak of Si-O-Si, and 1039 cm^{-1} for the stretching vibration peak of Si-O [9]. By comparing the spectra, it was found that the major Raman displacement peaks of the jadeite lint part appeared at 204 cm^{-1}, 376 cm^{-1}, 700 cm^{-1}, 992 cm^{-1}, and 1040 cm^{-1}, which were consistent with the characteristic peaks of the steatite. The main Raman shift peaks in the main part of jadeite occur at 206 cm^{-1}, 377 cm^{-1}, 700 cm^{-1}, 992 cm^{-1}, and 1042 cm^{-1}, which are also the characteristic peaks of jadeite (in **Figure 3**).

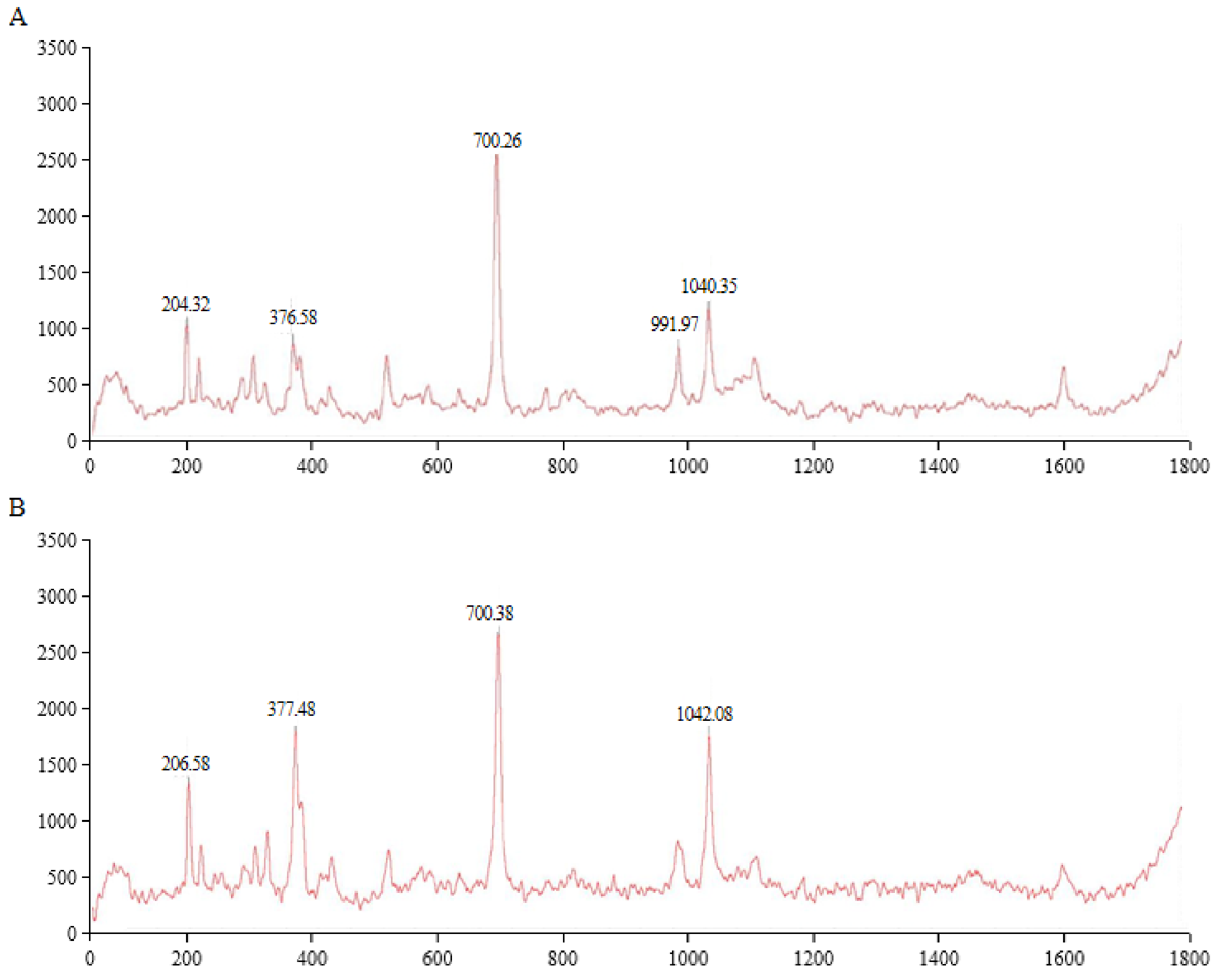

Figure 3. Infrared spectral analysis of jade sample **(A)** cotton fleece parts of jade; **(B)** main body parts of jade.

3.4. Electron probe analysis

Electron probe analyzer can accurately determine the chemical composition of the sample. By bombarding the sample surface with a focused electron beam, the sample can be excited to emit characteristic X-rays, and the chemical composition of the sample can be analyzed qualitatively and quantitatively according to the wavelength and intensity of the X-rays [10]. In order to further verify the mineral compositions of the cotton wool parts containing different kinds of cotton wool and the main part of jadeite, the electron microprobe technique was used to quantitatively analyze the samples. According to **Figure 4**, the mineral compositions of both the cotton wool part and the main part are steatite, while the contents of Mg, Ca, Cr, and Fe in the main part of jadeite are higher than those in the cotton wool part, and it is presumed that the participation of fluid in the main part in the process of metamorphic recrystallization and fine crystallization makes the trace components Mg, Ca, Cr, and Fe increase.

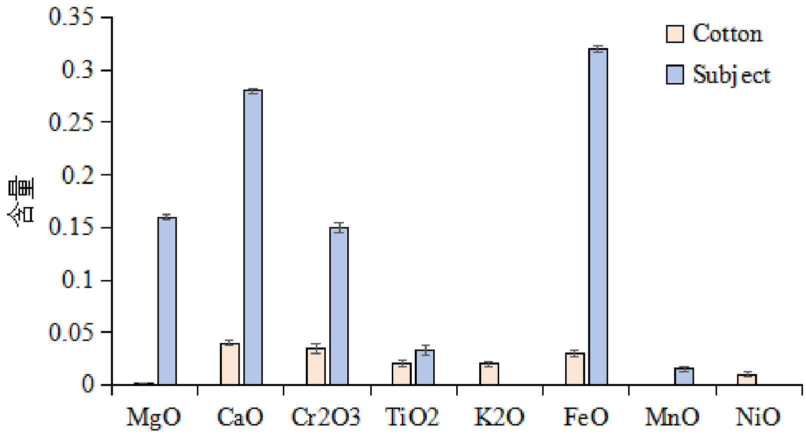

Figure 4. Comparison of secondary components in different parts of jade samples.

3.5. Trace element analysis

To investigate the formation mechanism of cotton wool in depth, the trace element composition of jadeite samples was analyzed, and the La ICP-MS analyzer was used to test the cotton wool area and main body parts of jadeite. According to the analysis in **Figure 5**, it can be seen that the content of Mg, Cr, Fe, Sr and other elements in the white cotton wool part of jadeite containing "structural cotton" is lower than that of the corresponding elements in the main part of jadeite, especially Cr and Fe elements. Only during the jade formation stage will there be migration and enrichment of trace elements such as Mg, Ca, Cr, Fe with larger ionic radii. It can be inferred that "structural cotton" is a residual material preserved during the sedimentary stage of jadeite formation.

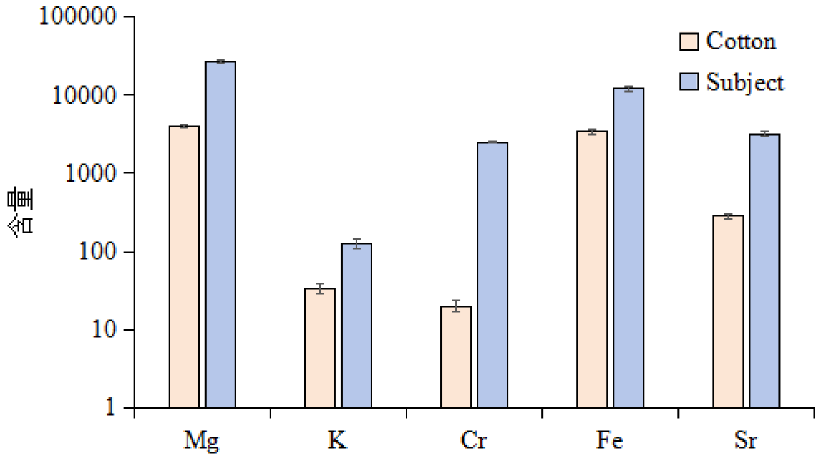

Figure 5. Comparison of trace element composition in different parts of jade samples.

4. Conclusion

Jade culture has been an indispensable part of the culture of the Chinese nation since ancient times. Some folklore, cultural practices, religious beliefs and life beliefs are often reflected in jade, endowed with special cultural connotations. The cultural nature of jade makes jade not only exist in isolation in material form, but also become a form of expression of people's thoughts and emotions and a spiritual support [11]. Therefore, jadeite, as the king of jade, has its unique cultural significance.

For the jadeite containing "structural cotton", the increase of cotton may be a defect, but if such cotton can be reasonably utilized for clever creation, then it will have a different cultural significance, and at the same time increase the value of this piece of jadeite. Jadeite "structural cotton" mineralogical characteristics and causes is a complex issue, by geological action, mineral composition, growth environment and ecological background and other factors [12]. Through the in-depth study of jadeite "structural cotton", we can better understand the formation process and quality evaluation of jadeite. Through the analysis of the "structural cotton", we found that it is actually not very different from the jadeite jadeite mineral composition of the main components. The difference lies in the size of the grains and the degree of bonding of the nephrite minerals in "structural cotton", which shows poorer transparency and rougher texture. The formation of "structural cotton" originates from the metamorphic crystallization of jadeite at different stages of diagenesis [13]. In the early stage of diagenesis, mainly sclerite is formed, with coarse mineral crystallization and relatively loose structure, which results in white, rough-textured jadeite [14]. In the subsequent stages of jadeite formation, however, changes in temperature and pressure conditions prompted fine crystallization and recrystallization of the early-crystallized sclerite minerals, which resulted in jadeite's fine structure and improved transparency [15]. However, this transformation process is not complete, and there may still be residual aggregates of diagenetic stage jadeite minerals, forming the so-called "structural cotton". Further analysis of electron microprobe and trace element data shows that the content of elements such as Mg, Ca, Cr, Fe, etc. in the flotsam part of jadeite containing "structural cotton" is lower than that in the main part. This indicates that these trace elements with large ionic radius are migrated and enriched in the jadeite stage. The formation of "structural cotton" originates from the transformation of jadeite jadeite minerals in the rock-forming stage during the jadeite jade-forming stage, and the degree of transformation determines the amount of cotton flakes. This residual feature confirms the evolutionary process of jadeite from rock-forming to jade-forming.

The existence of "structural cotton" in Jadeite will generally reduce its market value. It is generally believed that the more cotton wadding, the worse the quality of jadeite; On the contrary, the cleaner the interior, the less cotton wool, and the better the quality [16]. From the perspective of consumer preferences, most traditional consumers tend to have pure and flawless jade, "structural cotton" is often regarded as a defect, which will affect the price of jadeite; And some young consumers who pursue individuality may be favored by the uniqueness of the special shape "structural cotton" after being designed and carved. After all, the value of jadeite lies not only in its purity, but also in its artistic expression. Therefore, when judging the quality of jadeite, it is necessary to comprehensively consider its unique structural characteristics. Only by deeply understanding these characteristics can we grasp the intrinsic value of jadeite more accurately. In this study, the origin and texture of jadeite are relatively single, only the waxy jadeite of Myanmar. In the future, we can continue to detect jadeite from different origins such as Guatemala and Russia, as well as ice and egg white.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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