Effects of chemical composition and temperature on the formation of beryl varieties

Arūnas Kleišmantas

Kleišmantas A. Effects of chemical composition and temperature on the formation of beryl varieties. *Geologija*. Vilnius. 2003. No. 41. P. 3-13. ISSN 1392–110X. Chemical and physical properties of 116 beryl minerals from different localities over the world have been investigated in order to determine the major factors influencing the formation of beryl varieties, *i.e*. changes in colour. Vanadium, along with chromium, was found to influence the green emerald colour in Colombian emeralds. Colourless beryl is characterised by a low content of impure ions. The light blue colour of some beryls appeared because of ferrous iron occurring in the void within the channel site. The ferrous iron caused some high-chromium beryls to acquire slightly blue colour and to look like aquamarines. The author suggests them to call *chromium aquamarines*. The ratio of ferric and ferrous iron is responsible for slight yellow, yellowish brown and slight green colour of some beryl varieties. Golden beryls and heliodors were found to have "colour memory". The following range in colour was established after heating of golden beryls and heliodors: yellowish brown → yellow (golden beryl) → slight yellow (heliodor) → slight green (green beryl) → colourless (goshenite) → slight blue (aquamarine). The Beryl Colour Cycle was compiled on the basis of Goethe's colour cycle.

Keywords: beryl varieties, chemical composition, temperature, beryl colour cycle

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INTRODUCTION

Beryl is allochromatic because of some chromophoric impure elements occurring along with essential constituents such as berylium. Their valency and place in the crystal cell control the colour. Temperature is another important factor influencing the colour. Many beryl varieties appeared because of impure ions, changes of their valency and place in the crystal cell.

Beryl ($Be_3Al_2[Si_6O_{18}]$) is a cyclosilicate with six-membered rings. Six-membered rings are connected by Al^{3+} and Be^{2+} ions (Figs. 1 and 2; Karanth, 2000). Within the large hexagonal rings there is an empty place (Fig. 1). The structure itself is placed between six-membered radicals, and is normal to the axis ***c***. Beryl contains a considerable amount of impurities. Al^{3+} is usually replaced with Fe^{3+}, Fe^{2+}, Cr, V, Sc as well as small amounts of Mn, Se, Mg and Li.

To a certain extent, Be may be replaced by Li and Si by Al with a compensation of electronegative residual charge by alkaline and alkaline earth elements (Na, K, Rb, Cs, Ca), entering the void within the channel site in the crystalline structure.

Beryl colour depends on the presence and quantity of impure ions, *i.e*. Cr, V, Fe^{3+}, Fe^{2+}, Mn, on the position of Fe^{3+} and Fe^{2+} ions in the crystal cell (*cf*. Fig. 1 and Table 1), and on NO_3^-, CO_3^- radicals.

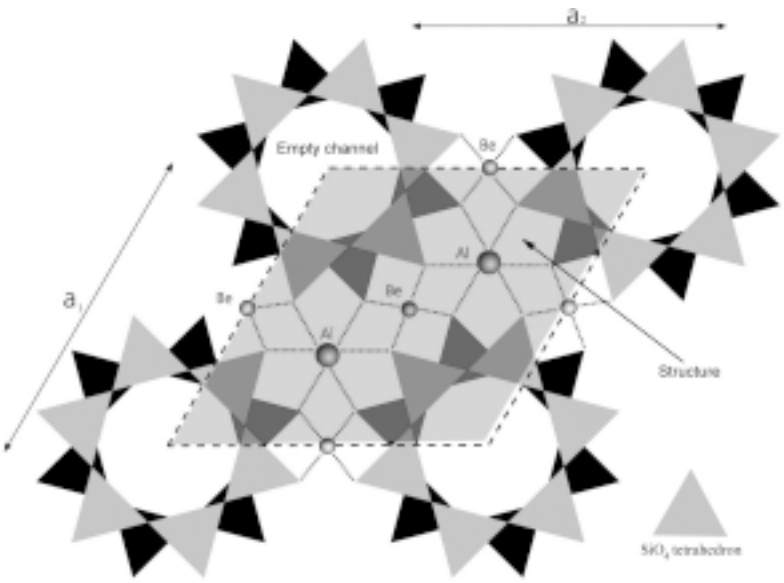

Fig. 1. Structure of beryl crystal cell. Section perpendicular to long (*c*) axis
1 pav. Berilo kristalo gardelės struktūra. Pjūvis statmenai ilgajai *c* ašiai

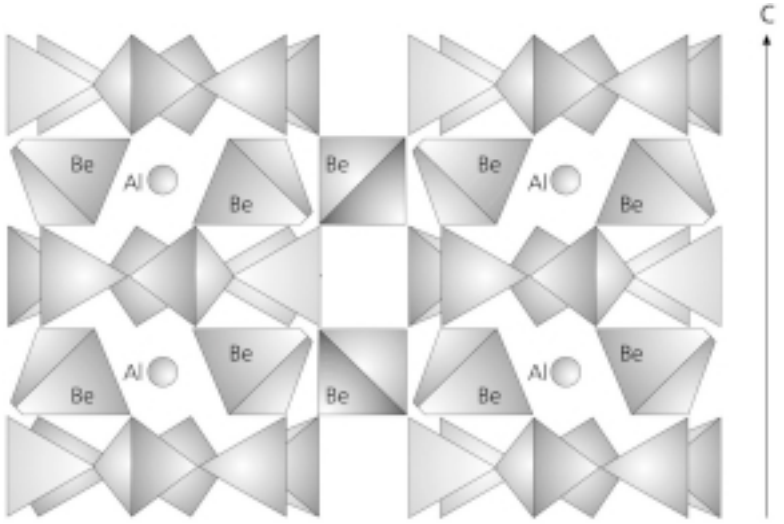

Fig. 2. Structure of beryl crystal cell. Section perpendicular to long (*c*) axis
2 pav. Berilo kristalo gardelės struktūra. Pjūvis lygiagrečiai ilgajai *c* ašiai

METHODS

For this study, chemical composition and physical parameters were estimated for 116 beryl minerals from Brazil, Columbia, Zambia, Zimbabwe, Nigeria, Russia, India, Australia and unknown localities.

The content of chemical elements was analysed by with a JXA-50A X-ray raster microscope, using 25kV voltage and 5–10 × 10^{-7} current. The analysis was performed by V. Matulionis at the Institute of Chemistry (Vilnius). The contents of Cr, V, Mn and Fe in beryl minerals are given per cent. The composition of essential constituents (Si, Al, Be and O) was excluded because of a large analytical error. Minerals were heated with incremental steps of 5 °C. Beryl spectra were defined by means of a two-ray Pye Unicam 8800 spectrophotometer at the Institute of Geological Exploration in Moscow. The obtained spectra were plotted in CIE (Commission International de l'Eclaire (International Commission on Illumination)) colour graphs (1931) (Judd and Wyszecki, 1978).

INFLUENCE OF CHEMICAL ELEMENTS ON BERYL COLOUR

The content of Cr^{3+} and V^{3+}, mostly "greening" emeralds, ranges from 0.019 to 0.709 and from 0.002 to 0.279%, respectively (Fig. 3). Iron (0.037–1.184%) has no influence on colour if its content is low or it occurs in the lattice structure. The greater amount of ferrous iron (Fe^{2+}) occurring in the void within the chan-

Table 1. **Location of impure ions in a beryl crystal cell and their influence on beryl colour (according to Karanth, 1997, personal communication)**
1 lentelė. **Priemaišinių cheminių elementų, nuo kurių priklauso spalva, vieta berilo kristalo gardelėje (pagal Karanth žodinį pranešimą, 1997)**

No.	Location of accessory chemical element		Colour	Varietes
	in structure	in channel		
1	*2*	*3*	*4*	*5*
1	–	–	Colourless	Goshenite
2	Fe^{2+}	–	Colourless	Goshenite
3	–	Fe^{3+}	Colourless	Goshenite
4*	Fe^{3+}	$\pm Fe^{2+}$	Slight yellow, greenish yellow	Heliodor

Table 1 (continued)
1 lentelės tęsinys

1	*2*	*3*	*4*	*5*
5	Fe^{3+}	–	Yellow, yellowish brown	Golden beryl
6	–	Fe^{2+}	Blue, slight blue	Aquamarine
7	Fe^{3+}	Fe^{2+}	Slight green, green	Green beryl
8	Cr^{3+}	–	Green, strong green	Emerald
9	Cr^{3+}, (V^{3+}), ($\pm Fe^{2+}$)	Fe^{2+}	Green, strong green	Emerald
10	Mn	–	Pink	Morganite
11	Mn	–	Red	Biksbite
12	Mn, Fe^{3+}	–	Orange	Morganite
13	Mn, ($\pm Fe^{3+}$)	Fe^{2+}	Purple	Morganite
14**	V^{3+}, ($\pm Fe^{2+}$)	($\pm Fe^{2+}$)	Green, strong green	Vanadium beryl
15*	Cr^{3+}	Fe^{2+}	Slight blue, greenish blue	Chromiun aquamarine

*Added by the author.
** Some gemologists consider beryls containing only V^{3+}, without Cr^{3+}, to be vanadium beryls.

nel site of the crystal cell changes the green emerald colour to bluish green.

Among the emeralds from Colombia, Brazil, Zambia, Zimbabwe and Australia, the Zimbabwe emeralds had the highest (up to 0.225–0.709%) and the Colombian ones the lowest (0.019–0.053%) content of Cr.

The most valuable emeralds come from Colombia. Even though the Cr content in them is low, they display a typical green emerald colour. A high level of V^{3+} (0.089–0.279%) considerably influences the green colour of the Colombian emeralds. The amount of Fe^{2+} is relatively low (0.037–0.188%), therefore does not affect the colour at all.

Colourless beryls (goshenites) are poor in all impure ions, with Cr ranging only from 0.001 to 0.006, V from 0 to 0.001 and Mn from 0 to 0.002% (Fig. 3). The iron content in goshenites varies from

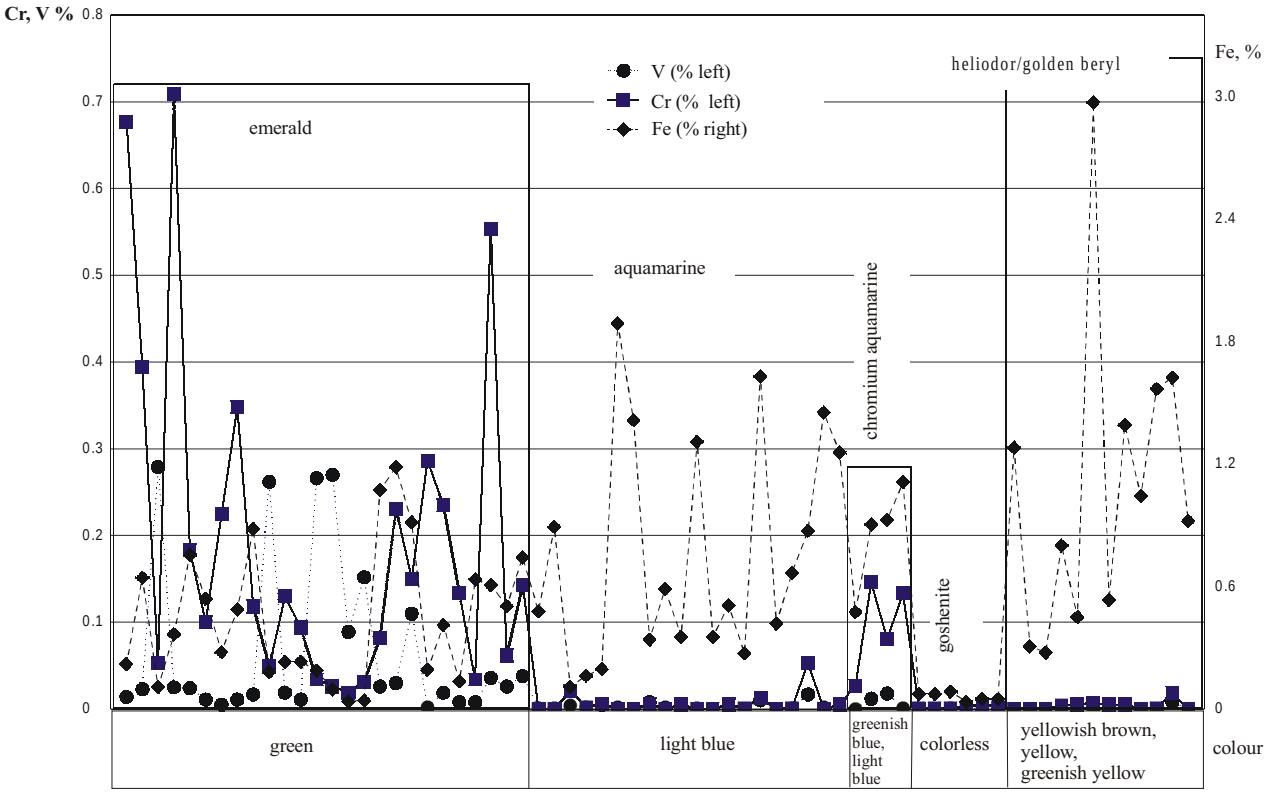

Fig. 3. Effects of vanadium, chromium and iron contents on the colour of known beryl varieties
3 pav. Vanadžio, chromo ir geležies kiekio įtaka berilo atmainų spalvai

0.035 to 0.084%, however, it has no influence on the colour (Table 1).

In one aquamarine sample, the blue colour depended on ferrous iron (Fe^{2+}) in the void within the channel site. The yellowish brown, yellow and greenish yellow colour of the other beryl varieties, *i.e*. golden beryl and heliodor, depends on the content of ferric and ferrous iron (Table 1, Fig. 1).

In several light blue samples the content of Cr, unusually high for aquamarines, was detected. The latter were from the Zambian emerald deposit. The results of investigations revealed the chromium content to be much lower (0.027–0.146%) than iron (0.475–1.11%). As a matter of fact, this relatively high content of iron caused the blue colour (Fig. 3).

The mixing of green and blue colours results in greenish blue colour. Which colour will dominate, depends on the intensity of this colour. However, in order to get a blue beryl, the iron content has to exceed the chromium content.

Beryls containing chromium are called emeralds and belong to precious stones. However, the samples studied resemble aquamarine because of their light blue colour. The gemstones of such kind are more precious than aquamarines, nevertheless, they do not belong to emeralds because of this light blue colour. We suggest to call them *chromium aquamarines*.

INFLUENCE OF TEMPERATURE ON BERYL COLOUR

Heliodor and golden beryl samples were heated in an electrical stove. The temperature was incremented by 5 °C. The colour was defined after each step (Table. 2).

The yellowish brown and yellow (golden) beryl started to change its colour at a temperature of 350–365 °C. The light yellow beryl (heliodor) started to change at 380 °C and transferred into light blue beryl, *i.e*. aquamarine, at 430–475 °C.

Table 2. **Heliodor, golden beryl and heliodor/golden beryl color changes due to heating**
2 lentelė. **Heloidorų, auksinių berilų ir dvispalvio heliodoro/auksinio berilo spalvų pokyčiai kaitinant**

No.	Mineral and natural colour	Temperature °C	Colour of heated mineral
1	*2*	*3*	*4*
1	Heliodor	380	Light yellow- green
	greenish yellow	415	Light green
		430	Light green- blue
		475	Light blue
2	Heliodor	380	Light yellow-green
	greenish yellow	385	Light green
		405	Light blue-green
		420	Colourless, slightly blue-green
		430	Light blue
3	Heliodor	380	Light yellow-green
	greenish yellow	385	Light green
		405	Light blue- green
		420	Colourless, slightly blue- green
		430	Light blue
4	Heliodor	380	Light yellow- green
	greenish yellow	415	Light green
		430	Light green- blue
		475	Light blue
5	Heliodor	380	Light yellow-green
	greenish yellow	400	Light green
		405	Light green- blue
		420	Colourless, slightly green- blue
		430	Light blue
6	Heliodoras	380	Light yellow- green
	greenish yellow	385	Light green
		405	Light blue- green
		420	Colourless, slightly green-blue
		450	Colourless, slight blue
7	Golden beryl	365	Light green-yellow
	yellowish	380	Light yellow-green
		385	Light green

Table 2 (continued)
2 lentelės tęsinys

1	*2*	*3*	*4*
		405	Light blue- green
		420	Colourless, slightly blue- green
		430	Light blue
8	Golden beryl	350	Light yellow brown-patched
	yellowish brown	360	Greenish yellow, brown-patched
		375	Greenish yellow
		380	Light yellow- green
		385	Light green
		395	Green
		405	Light green-blue
		420	Blue with greenish tone
		475	Blue
9	Golden beryl	350	Light yellow
	yellowish brown	360	Light green -yellow
		380	Light yellow- green
		385	Light green
		395	Green
		405	Light green-blue
		420	Blue with greenish tone
		450	Blue
10	Heliodor/golden beryl	350	Light yellow, greenish yellow
	two-coloured:	365	Greenish yellow
	greenish yellow and yellowish brown	380	Light yellow-green
		385	Light green
		395	Green
		405	Light green-blue
		420	Blue with greenish tone
		450	Blue
11	Golden beryl, two-coloured:	350	Light yellow
	Yellowish brown and brownish yellow	360	Light green-yellow
		380	Light yellow-green
		385	Light green
		395	Green
		405	Light green-blue
		420	Blue with greenish tone
		450	Blue

At the beginning, the golden beryl becomes yellowish brown and yellow. With increasing the temperature, golden beryl loses its colour at 350 °C, acquires a greenish yellow tone and transfers into heliodor at 360–365 °C, finally becoming light green beryl at 380–415 °C. An important conclusion can be drawn that golden beryl crystallizes at the lowest temperature among beryls. The iron valency is responsible for the colour, because part of Fe^{3+} turns into Fe^{2+} due to heating. As this iron occurs in the void within the channel site, the mineral will acquire a light blue colour. Furthermore, the mixing of blue and yellow colours will result in green colour (Fig. 1, Table 1).

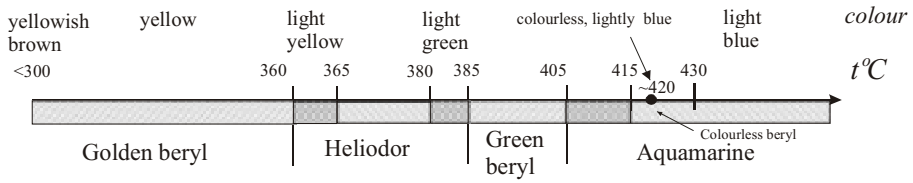

Fig. 4. Changes in colour of golden beryls, heliodors, and bicolour heliodor/golden beryl and variety sequence for beryls under heating
4 pav. Auksinių berilų, heliodorų bei dvispalvio heliodoro/auksinio berilo spalvos pasikeitimas ir berilo atmainų kitimo seka keliant temperatūrą

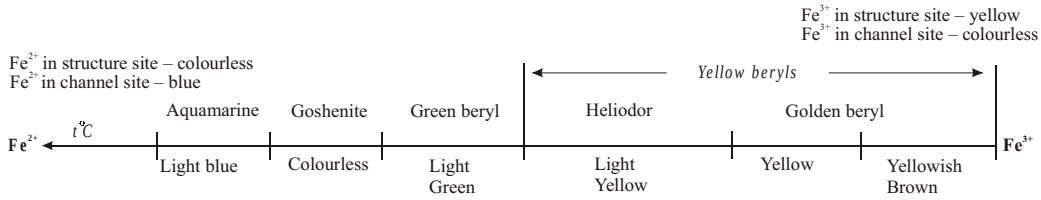

Fig. 5. Distribution of beryl varieties by colour. Their dependence on iron valency and position in a crystal cell under heating.
5 pav. Berilo atmainų kitimo seka pagal spalvas. Jų priklausomybė nuo geležies valentingumo ir užimamos vietos kristalo gardelėje keliant temperatūrą

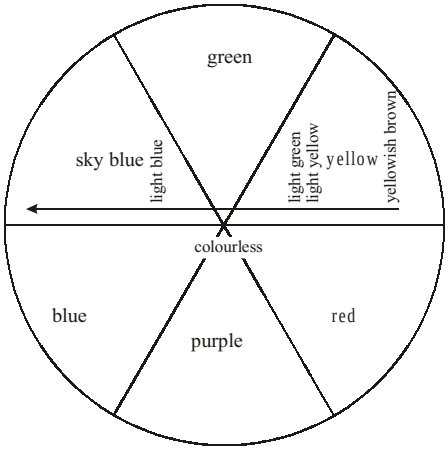

Fig. 6. Distribution of beryl colours in Goethe's colour cycle (Judd and Wyszecki, 1978) according to the author
6 pav. Berilo spalvų išsidėstymo seka Getės spalvų rate (Judd and Wyszecki, 1978) pagal autorių

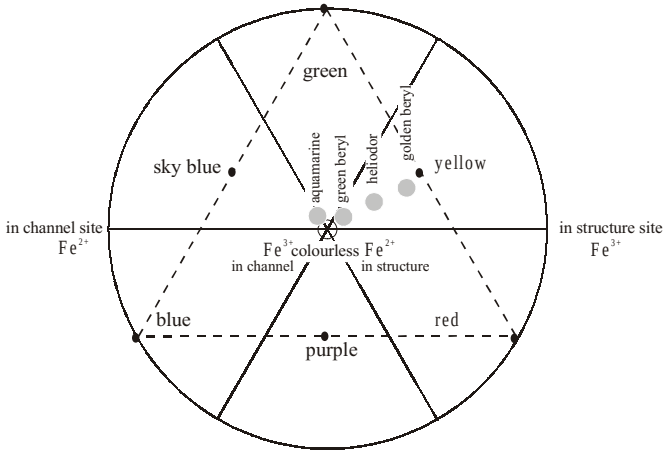

Fig. 7. Distribution of beryl varieties in Maxwell's triangle and Goethe's colour cycle (Judd and Wyszecki, 1978) according to the author
7 pav. Berilo atmainų išsidėstymo seka Maksvelo trikampyje ir Getės spalvų rate (Judd and Wyszecki, 1978) pagal autorių

While the temperature increases, more ferric iron (Fe^{3+}) becomes ferrous (Fe^{2+}). As a result, a light blue colour appears along with a light green at a temperature of 405–430 °C, and the green beryl transfers into aquamarine. The light blue colour finally takes over the light green at 430–475 °C. This means that at this temperature all ferric iron was replaced by ferrous one. Furthermore, the results show that aquamarines form at the highest temperature among crystallizing beryls, where iron dominates the colour. Heliodor and green beryl are intermediate varieties between the end-members, golden beryl and aquamarine. With increasing the temperature, the colour of beryl, in which iron is a chromophoric element, ranges as follows: yellowish brown → yellow → slight yellow → slight green → colourless with green-blue tone → slight blue.

It was defined that the heliodors and green beryls lost their colour at 420 °C. The colourless minerals are placed in the above-mentioned colour range between slight green and slight blue beryls (Figs. 4 and 5).

To sum it up, the temperature that defines the ratio between ferric and ferrous iron is one of the major colour-defining factors during beryl crystallization.

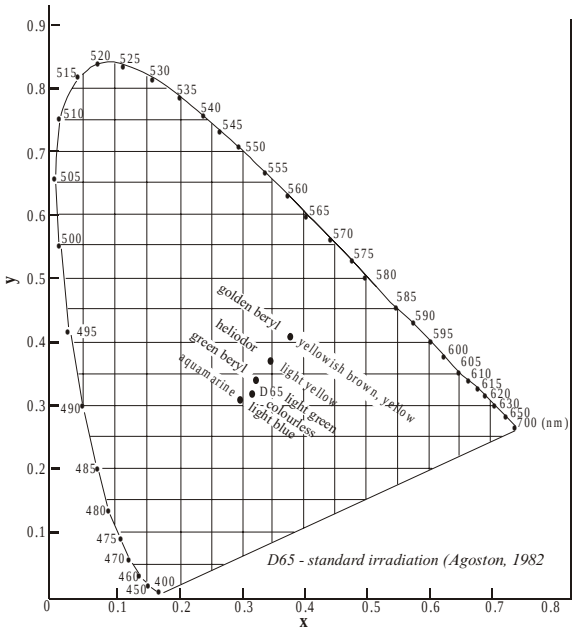

Fig. 8. Distribution of beryl colours and varieties in the CIE colour (1931) graph (Agoston, 1982) according to the iron valency and its position in the crystal cell. The distribution as in Fig. 9
8 pav. Berilo spalvų ir atmainų, lemiančių geležies valetingumą ir užimamą vietą kristalo gardelėje, išsidėstymo seka CIE (1931) spalvų grafike (Agoston, 1931) pagal 9 pav.

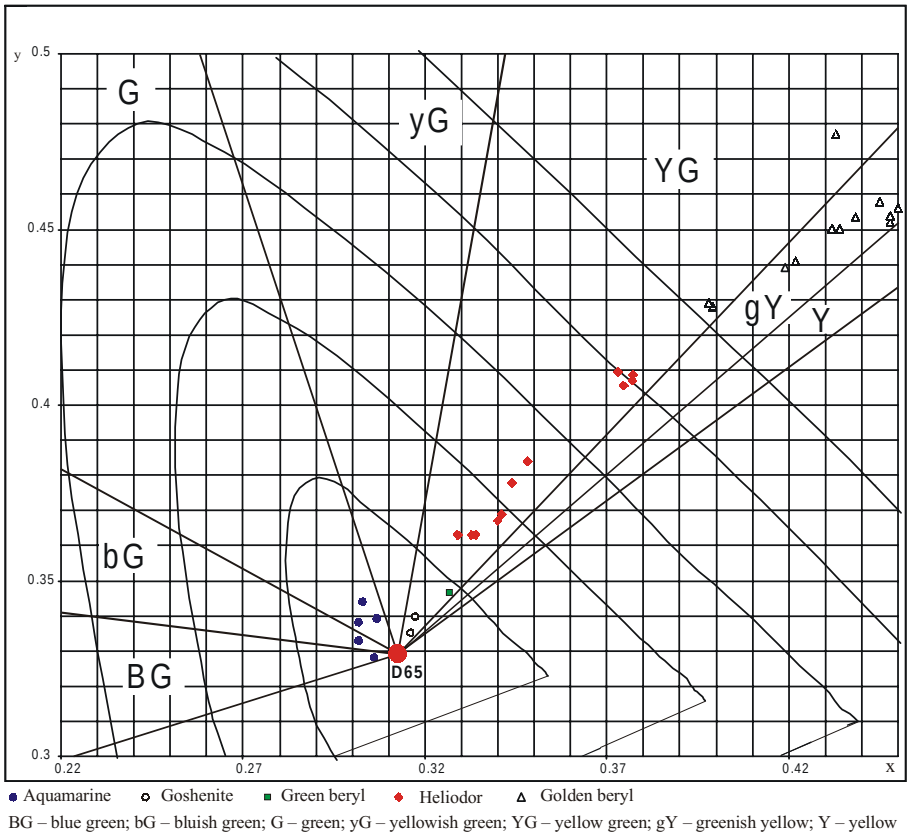

Fig. 9. Distribution of beryl varieties in the CIE (1931) colour graph according to iron valency and its position in the crystal cell
9 pav. Berilo atmainų, kurias lemia geležies valentingumas ir užimama vieta kristalo gardelėje, išsidėstymas CIE (1931) spalvų grafike

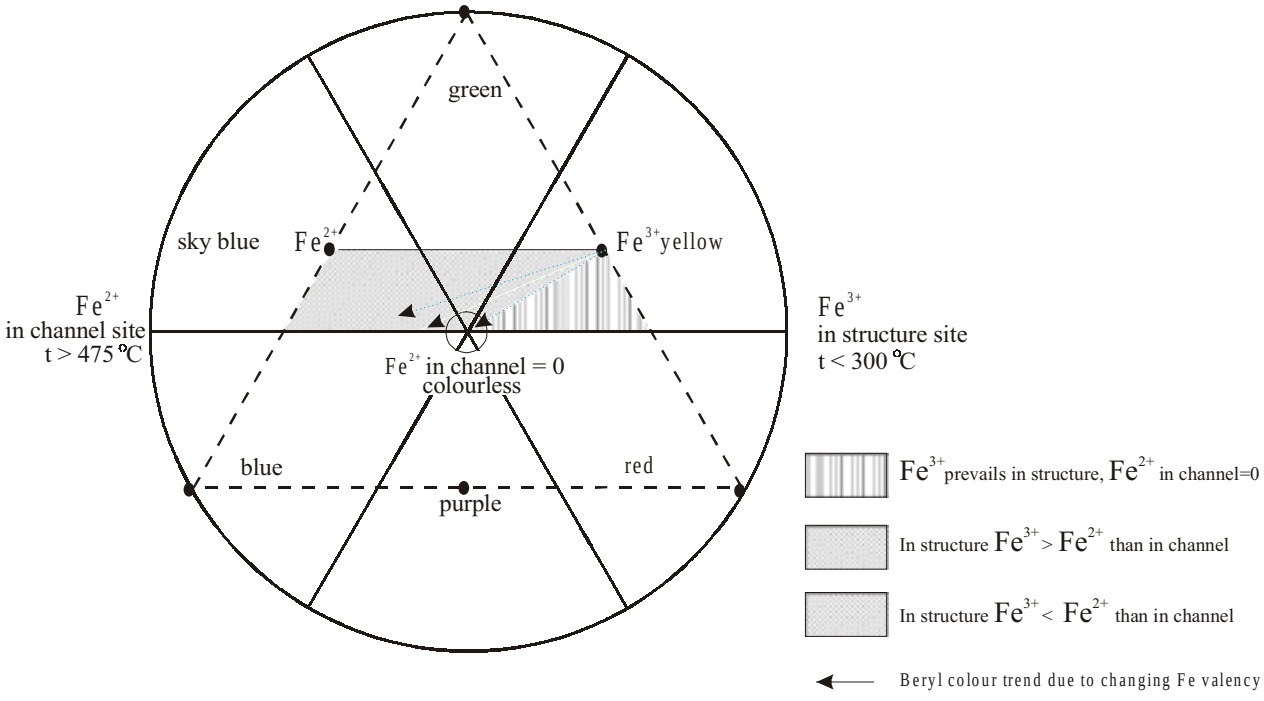

Fig. 10. Beryl colour trends according to iron valency and its position in the crystal cell in response to heating. Plotted by the author in Maxwell's triangle and Goethe's colour cycle (Judd and Wyszecki, 1931)
10 pav. Berilo spalvų linijų išsidėstymas pagal geležies valentingumą ir jos vietą kristalo gardelėje. Autoriaus duomenys Maksvelo trikampyje ir Getės spalvų rate (Judd and Wyszecki, 1978) veikiant temperatūrai

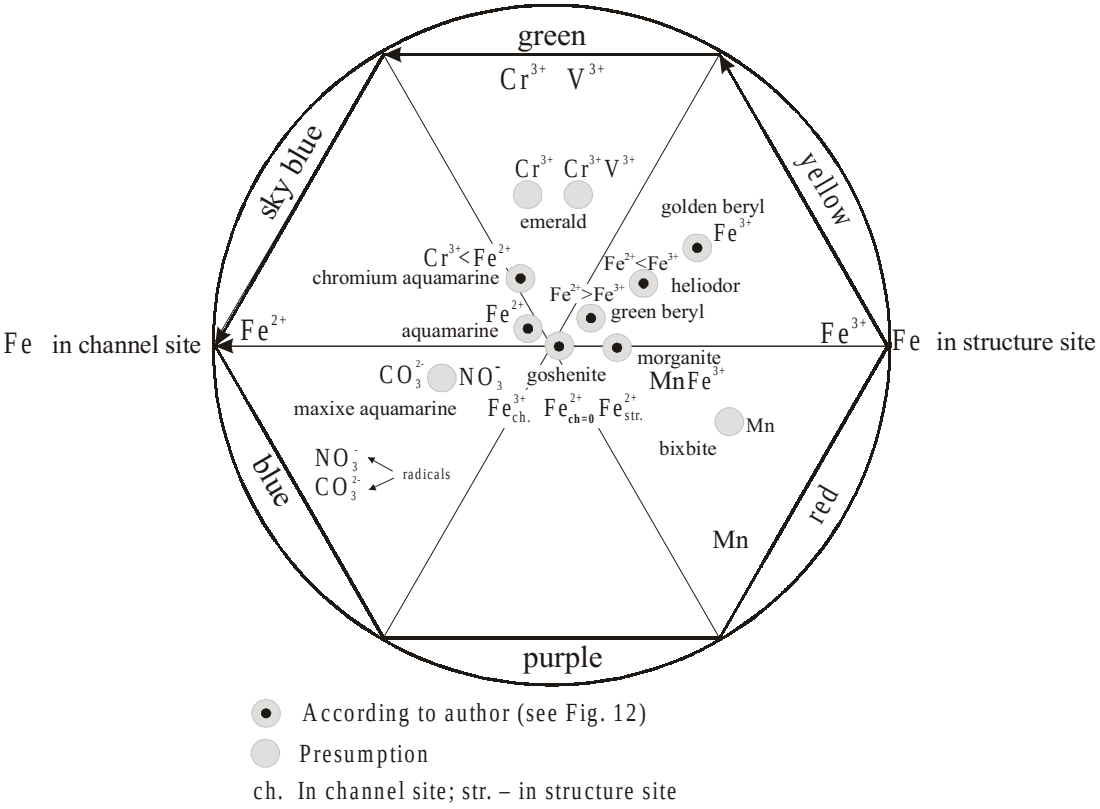

Fig. 11. The Beryl Colour Cycle chemical elements
11 pav. Berilo spalvų ratas pagal cheminius elementus

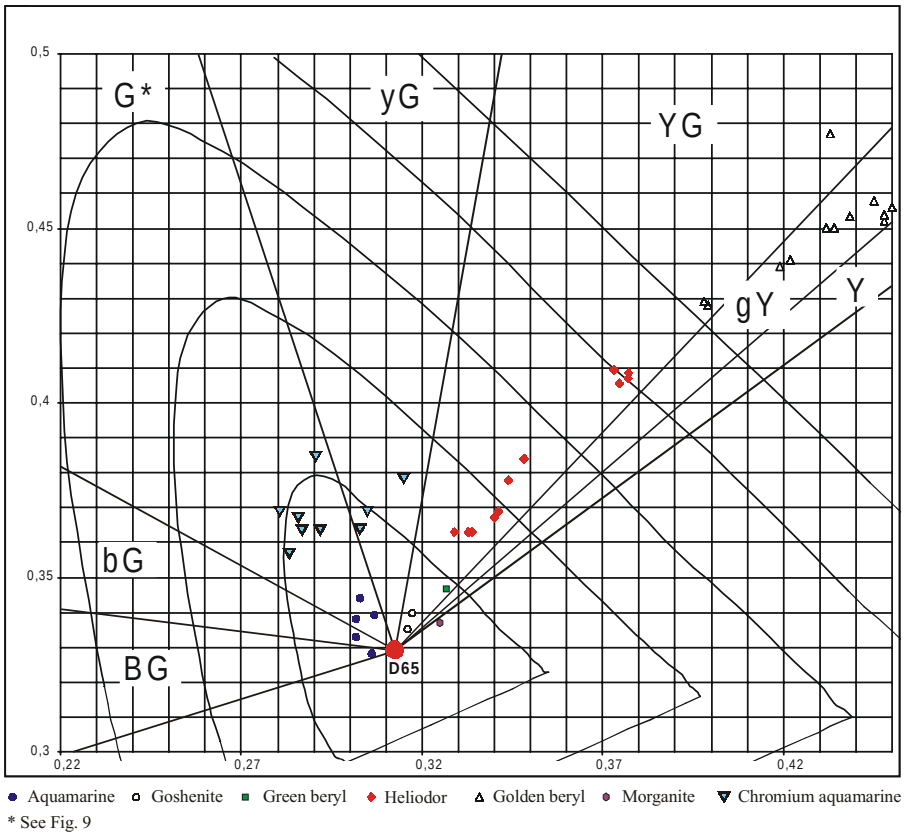

Fig. 12. Beryl varieties in the CIE (1931) colour graph
12 pav. Berilo atmainų išsidėstymas CIE (1931) spalvų grafike

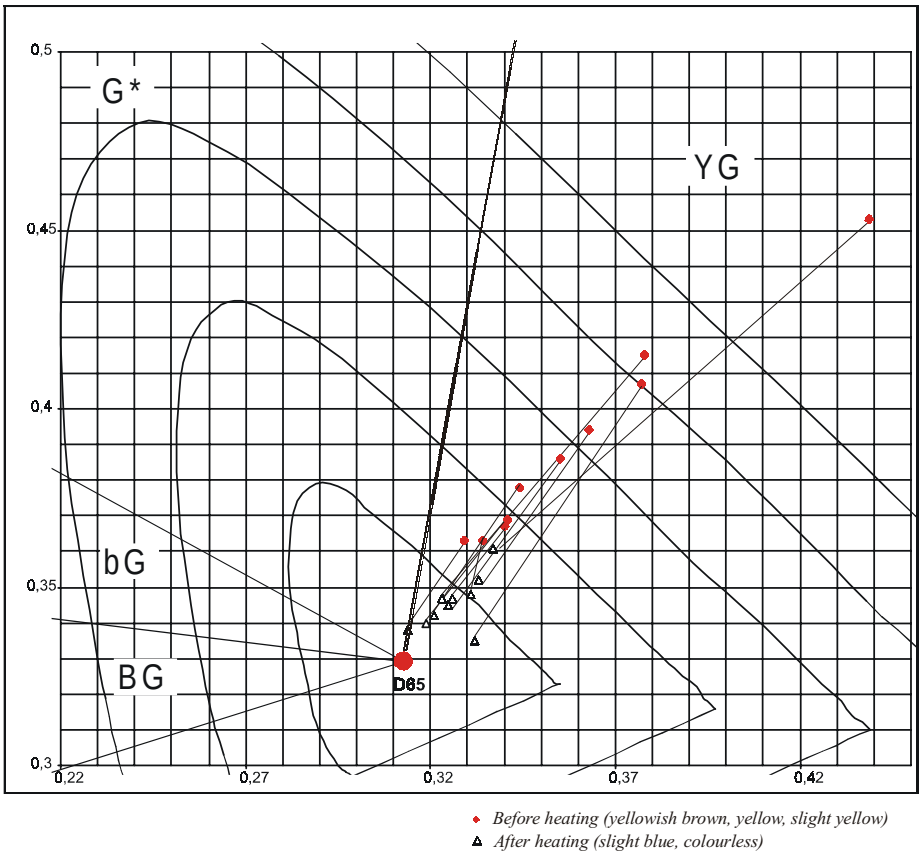

Fig. 13. Colour memory of the golden beryl and heliodors in the CIE (1931) colour graph
13 pav. Auksinio berilo ir heliodoro spalvos atmintis CIE (1931) spalvų grafike

THE BERYL COLOUR CYCLE

The obtained colour range (Fig. 5) is an important issue. The light green colour cannot be transferred into light blue without passing the colourless zone. This can be proved with the help of the Goethe's colour cycle (Fig. 6), Maxwell's triangle (Fig. 7; Judd and Wyszecki, 1978) and CIE (1931) colour graph (Agoston, 1982; Judd and Wyszecki, 1978; Fig. 8). We took photos of beryl spectras from the different varieties with a spectrophotometer and plotted them in the CIE (1931) colour graph. The following colour range was obtained, coinciding with the known varieties of beryl minerals: golden beryl → heliodor → green beryl → goshenite → aquamarine (Fig. 9).

The trend from golden beryl, heliodor and green beryl passes the colourless zone before entering the aquamarine zone. This means that the minerals lose their colour before becaming aquamarines. No uncoloured mineral appears if there is an excess of Fe^{3+} in the channels of golden beryl, heliodor and green beryl. The uncoloured mineral appears when the level of Fe^{3+} in the channel is low. Golden beryl, heliodor and green beryl usually lose their colour when heated if iron is lacking in the channel (Fig. 10).

A "Beryl Colour Cycle" was compiled on the basis of Goethe's colour cycle (Judd and Wyszecki, 1978), where the beryl varieties studied were plotted (Fig. 11). Each variety was plotted according to its element composition, their valency and place in the crystal cell. It was also confirmed by the results obtained by means of colorimetry (Fig. 12). Chromium aquamarine (Cr^{3+}, Fe^{2+}) appears to be a new isomorphic beryl variety, which differs from green beryl and aquamarine by its chemical composition and place in the Beryl Colour Cycle.

COLOUR MEMORY

After spectral photos of golden beryl and heliodor had been taken, the minerals were heated again. Photos of the newly formed aquamarine absorption spectra were taken repeatedly. When we plotted these spectra in the CIE (1931) graph, the light blue colour plotted on the yellow colour side. The latter fact can be explained by the so-called 'colour memory', or 'optical memory' according to V. Chukova (1988).

Under heating, the yellowish brown colour of golden beryl and heliodor changes subsequently into yellow, light yellow, light green, colourless and light blue (Figs. 4 and 5). However, the spectra after heating remain in the field of yellow colour in the CIE (1931) graph as if they had never crossed the colourless zone (Fig. 13). Actually we observed the colour to change gradually from light green through colourless to light blue (Figs. 6, 7 and 10). In order to explain the latter fact, psychophysics and human physiology should be employed. As is known, human eye cannot distinguish the spectra of former yellowish brown and yellow colours.

CONCLUSIONS

The highest chromium (Cr^{3+}) levels among emeralds from the five emerald deposits studied is characteristic of the Zimbabwe emeralds, while the lowest of the Colombian ones. Colombian emeralds are famous for their special intense colour caused by the highest content of vanadium (V^{3+}).

Green colour of the light blue Zambian beryls is controlled by chromium (up to 0.146%). The mineral turns light blue because of a high level of iron (from 0.475 to 1.1%). That is why the author suggests to call this variety chromium aquamarine. The following range in colour was established during the incremental heating: yellowish brown → yellow → slight yellow → slight green → colourless → slight blue. The range is well established, what was confirmed also by the results of colorimetry plotted in the CIE (1931) colour graph. In case the trend passed above the colourless zone, the colour might not fade at all.

The Beryl Colour Cycle for all beryl varieties was compiled on the basis of Goethe's colour cycle and Maxwell's triangle. The colorimetry results plotted in the CIE (1931) colour graphs have been also used.

The colorimetrical results for yellow beryls have shown the actual colour to remain the same after heating, even though our eye fixes a change in the colour. The latter phenomenon is called 'colour memory' or 'optical memory'.

ACKNOWLEDGMENTS

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Arūnas Kleišmantas

BERILO ATMAINŲ PRIKLAUSOMYBĖ NUO CHEMINIŲ ELEMENTŲ PASISKIRSTYMO BEI TEMPERATŪROS POVEIKIO

S a n t r a u k a

Rengiant šį straipsnį, buvo tirta 116 berilo mineralų iš įvairių radimviečių, atlikti jų kristalų cheminiai tyrimai, nustatyti fiziniai parametrai, turintys įtakos berilo spalvai.

Mineralai buvo kaitinami krosnelėje. Cheminiai elementai nustatyti rentgeno rastriniu mikroskopu JXA–50A, berilo praleidimo spektrai – su dvispinduliniu spektrofotometru Pye Unicam 8800. Gautų spektrų duomenys perkelti į CIE (1931) spalvų grafikus (Judd and Wyszecki, 1978).

Iš tirtų penkių smaragdų radimviečių daugiausiai chromo yra Zimbabvės, o mažiausiai – Kolumbijos smaragduose. Vertingiausi yra pastarieji. Nors chromo (Cr^{3+}) nėra daug, tačiau smaragdai yra tipiškos žalios spalvos, kurią nulemia didelis vanadžio (V^{3+}) kiekis.

Bespalviuose beriluose (gošenituose) cheminių elementų priemaiša nėra didelė.

Vieno iš akvamarino atmainų mėlyna spalva priklauso nuo dvivalentės geležies (Fe^{2+}), esančios kristalo tuščiame kanale. Kitų berilo atmainų gelsvai rudą, gelsvą ir žalsvą spalvą lemia dvivalentė ir trivalentė geležis.

Keliuose melsvuose bandiniuose nustatytas palyginti didelis chromo kiekis, nebūdingas akvamarinams. Pastarieji yra iš Zambijos smaragdų telkinio. Tyrimais nustatyta, kad juose chromo yra gerokai mažiau (0,027–0,146%) nei geležies (0,475–1,11%) – santykinai didelis kiekis geležies ir lėmė melsvą jų spalvą.

Berilai, kurių sudėtyje yra chromo, yra vertingi ir vadinami smaragdais. Tačiau tirti bandiniai, melsva spalva panašūs į akvamarinus. Tokio tipo mineralai vertingesni už akvamarinus, tačiau dėl melsvos spalvos smaragdams nepriskiriami, todėl juos siūlome vadinti **chromo akvamarinais**.

Pakaitinus gelsvai rudus ir gelsvus berilus – auksinius berilus ir heliodorus, jie tampa melsvais – akvamarinais. Kaitinami auksiniai berilai spalvą pradeda keisti esant 350–365°C temperatūrai, heliodorai – 380°C ir visai ją pakeičia esant 430–475°C temperatūrai, virsdami akvamarinais. Kaitinami heliodorai ir auksiniai berilai gelsvą spalvą pakeičia žalsva ir virsta žaliais berilais. Keliant temperatūrą iki 420°C, spalva gali išblykšti, o mineralai tapti bespalviais berilais. Kaitinimo metu nustatyta tokia dėsninga auksinių berilų ir heliodorų spalvos kitimo seka: gelsvai ruda → geltona (auksinis berilas) → gelsva (heliodoras) → → žalsva (žalias berilas) → bespalvė (gošenitas) → melsva (akvamarinas). Tai patvirtina kolorimetriniai tyrimai ir gautų duomenų CIE (1931) spalvų grafikas. Kylant tempera-

tūrai vis daugiau Fe^{3+}, lemiančios geltoną spalvą struktūroje, virsta Fe^{2+}, kuri kanale suteikia mėlyną spalvą.

Pasinaudoję Getės spalvų ratu, Maksvelo trikampiu (Judd and Wyszecki, 1978), galime sudaryti Berilo spalvų ratą, kuriame dėsningai išsidėsto berilo atmainos. Užimama mineralo atmainos vieta priklauso nuo cheminių elementų, jų valentingumo, užimamos vietos kristalo gardelėje. Tai patvirtina kolorimetrijos metodu atlikti tyrimai. Chromo akvamarinas (Cr^{3+}; Fe^{2+}) yra nauja berilo izomorfinė atmaina, kuri tiek chemine sudėtimi, tiek berilo spalvų rate užimama vieta neatitinka žalio berilo ar akvamarino atmainos.

Kolorimetriniais tyrimais nustatyta, kad po kaitinimo geltoni berilai spalvos nepakeitė, nors akis fiksuoja kitą spalvą. Manoma, kad tai spalvos atmintis arba optinė atmintis.

Арунас Клейшмантас

ЗАВИСИМОСТЬ РАЗНОВИДНОСТЕЙ БЕРИЛЛА ОТ РАСПРЕДЕЛЕНИЯ ХИМИЧЕСКИХ ЭЛЕМЕНТОВ И ВЛИЯНИЯ ТЕМПЕРАТУРЫ

Р е з ю м е

Было исследовано 116 минералов берилла из разных месторождений, проведены кристаллохимические исследования, определены физические параметры, влияющие на цвет берилла.

Химические элементы определялись растровым микроскопом „JMA-50A“. Минералы разогревались в специальном разогревателе. Двухлучевым спектрофотометром „Pye unicam 8800“ определены пропускаемые спектры берилла. Данные полученных спектров представлены в цветовых графиках CIE(1931) (Judd and Wyszecki, 1978).

В результате исследований образцов из пяти месторождений наибольшее количество хрома (Cr) обнаружено в изумрудах Зимбабве, наименьшее – Колумбии. Изумруды из Колумбии ценятся больше, поскольку они имеют типичный зеленый изумрудный цвет, определяемый высокой концентрацией ванадия (V).

В бесцветных бериллах (гошенитах) определены малые количества примесей химических элементов.

Голубой цвет одной из разновидностей аквамарина зависит от двухвалентного железа (Fe), находящегося в пустом канале кристалла. Оттенки желто-коричневого, желтого и зеленого цветов других разновидностей берилла определяет двух- и трехвалентное железо.

В нескольких голубоватых образцах установлено относительно большое количество хрома, что не свойственно аквамарину. Они происходят из месторождений изумрудов в Замбии. Исследовав их состав, установлено, что голубоватый цвет обусловлен большим соотношением железа (0,475–1,11%) и хрома (0,027–0,14%).

Бериллы, в состав которых входит хром, ценятся и называются изумрудами. Однако исследованные образцы из-за голубоватого цвета похожи на аквамарин. Минералы этого типа ценятся больше, чем аквамарины. Однако на практике из-за голубоватого цвета они к изумрудам не причисляются, поэтому предлагаем их именовать **хромаквамаринами**.

Подогретые желто-коричневые и желтоватые бериллы – золотистые бериллы и гелиодоры – становятся голубоватыми аквамаринами.

Окрас золотистых бериллов изменяется при температуре 350–360°C, гелиодоров – при 380°C и становятся аквамаринами – при 430–475°C. При повышении температуры гелиодоры и золотистые бериллы становятся зелеными бериллами. Повышая температуру до 420°C, окрас может исчезнуть и кристаллы могут стать бесцветными бериллами. Установлена следующая очередность изменения окраски золотистых бериллов и гелиодоров: желто-коричневый – желтый (золотистый берилл) – желтоватый (гелиодор) – зеленоватый (зеленый берилл) – бесцветный (гошенит) – голубоватый (аквамарин). Данная очередность носит закономерный характер. Это доказано проведенными колориметрическими исследованиями, результаты которых были введены в цветовой график CIE (1931). При повышении температуры все большее количество трехвалентного железа, определяющего желтый цвет структуры, становится двухвалентным, которое, находясь в канале кристалла, определяет его синий цвет.

Используя цветовой круг Gette, треугольник Максвела (Judd and Wyszecki, 1978), можно составить цветовой круг берилла, в котором закономерно распределяются разновидности минерала. Место, занимаемое минералом, зависит от наличия в нем химических элементов, их валентности и места в кристаллической решетке. Это подтверждено колориметрическими исследованиями. Хромаквамарин (Cr + Fe) – новая изоморфическая разновидность берилла, которая как химическим составом, так и местом в цветовом круге берилла неидентична разновидностям зеленого берилла и аквамарина.

Колориметрические исследования желтого берилла показали, что после нагревания прежний окрас сохраняется, хотя глаз фиксирует другой цвет. Возможно, это „память цвета“ (оптическая память).