Volume 3, Issue 12, December - 2025 **ISSN (E):** 2938-3811

THE INFLUENCE OF GEOLOGICAL CONDITIONS ON THE FORMATION OF THE COLOR OF PRECIOUS STONES

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Abstract

The color of gemstones is formed by a complex interaction of chemical composition, crystal chemistry, and the geological conditions of their formation. Trace elements, lattice defects, and structural features of minerals depend on temperature, pressure, the redox environment, and the composition of the fluids in the rocks where crystal formation occurred. This article examines the main color mechanisms: electron transitions in transition metals, interionic charge transitions, radiation-induced defects, and structural interference effects. Using corundum (ruby and sapphire), beryl (emerald), and topaz as examples, the role of the geochemical environment in the formation of their characteristic colors is demonstrated.

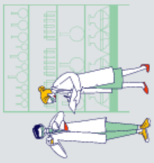
Keywords: Geology of gemstones, color of minerals, impurity elements, crystal lattice defects, genesis of minerals, corundum, emerald, topaz.

Introduction

Scientific novelty. A relationship has been identified between the geological conditions of formation (temperature, pressure, fluid composition, redox environment) and the mechanisms underlying gemstone coloration. It has been shown that the type of geological environment determines the nature of chromophores and color centers in minerals.

Gemology and gem petrology are an interdisciplinary field that combines mineralogy, chemistry, geology, and optics to study the conditions and processes of formation of colored minerals. The formation and vibrant, persistent coloration of gemstones are the result of specific geological circumstances requiring a narrow range of combinations of temperature, pressure, rock composition, and fluids. As noted in a publication by the Gemological Institute of America (GIA), "Beautiful, precious colored stones are exceptionally rare, forming only under precisely defined natural conditions" [1].

The key question is how the geological environment-the parent rock, its composition, and the physicochemical parameters of crystallization-affects the incorporation of trace elements, the formation of defects, and the structural features responsible for color. Mineral color is not simply an aesthetic attribute, but a "mineralogical fingerprint" reflecting the characteristics of its formation (the source of elements, oxidation -reduction potential, pressure/temperature, and subsequent changes) [2].



Color, as an optical property, depends on three main groups of factors:
- chemical composition and impurities (including transition metals and rare earth elements);
- structural defects and color centers;
- macro- and nanostructural features (for example, interference and diffraction in opal).

In all cases, geological conditions determine whether a given impurity will be incorporated, stabilized, and preserved in the crystal structure.

This review aims to systematize modern understanding of how geological conditions influence the formation of gemstone color. This approach will not only help us understand the nature of coloration but also link it to the petrogenesis of gemstone deposits, which is important from both a scientific and applied perspective (evaluation of deposits, authenticity, and origin of stones).

The color of gemstones is the result of several physical and chemical mechanisms, each of which is strictly controlled by the geological environment of the mineral's formation. These mechanisms can be systematized into five main categories, as outlined in fundamental gemological and mineralogical reviews:

1. Dispersed ions (d- and f-transitions). Many rich and stable colors are caused by the presence of trace concentrations of transition metal ions (Cr , V, Mn , Fe , Co , N) or rare earth elements (REE), which substitute for the main ions in the crystal lattice. Electronic transitions within the d- or f-shells create characteristic narrow absorption bands that determine the hue (for example, Cr3+ gives the red color to ruby).

Original chemical composition: the presence of chromophores in the parent rocks or fluids is required.

Temperature and growth rate: these parameters influence the degree of impurity capture by the growing crystal.

Crystal field: Local lattice symmetry influences the splitting of the d-shell energy levels, fine-tuning the hue [3].

2. Interionic charge transitions. This mechanism often results in intense, deep, or dark colors due to broad light absorption caused by the transfer of an electron between adjacent ions in different valence states. A charge transition between ions with different valence states, for example, Fe 2+ \ leftrightarrow and Ti 4+ in blue sapphire. This transition absorbs strongly in the yellow-orange region of the spectrum, producing the blue color [4].

Co-availability of elements: the need for both interacting elements to be present (Fe and Ti in the case of sapphire).

Redox conditions: specific redox conditions must exist to ensure the coexistence of ions in the required valence states. These conditions depend on the petrogenesis (magmatic, metasomatic, or hydrothermal source).

3. Color centers and radiation-induced defects. In this case, color is not associated with a chromophore element, but is the result of crystal lattice defects, often caused by radiation. These defects (vacancies, trapped electrons (F-centers), and impurity-vacancy complexes) absorb light. For example, yellow /blue hues in topaz and green hues in diamonds are often associated with radiation-induced centers.

Radioactive sources: proximity to uranium- or thorium -containing minerals in the vein walls, providing natural ionizing radiation.

Subsequent temperature changes (metamorphism or annealing) can stabilize or annihilate these centers [3].

4. Structural and physical effects (interference, diffraction, scattering). These mechanisms cause color "play" (opalescence, iridescence, mother-of-pearl) due to the interaction of light with ordered nano- or macrostructures. Diffraction and interference of light on regular nanostructures (for example, ordered silica spheres in opal or the layered structure of ammolite) create a spectrally dependent optical effect.

Precipitation mechanisms: specific conditions of colloidal precipitation or biogenic processes are required for the formation and ordering of nanoparticles.

Post-depositional consolidation: the regularity and size of these nanostructures must be preserved or not destroyed during the process of consolidation and subsequent changes [5].

Band structure effects and semiconductor properties. In rare cases (e.g., natural blue diamond), the color is determined by the specific electronic structure of the material. Narrow band gaps or semiconductor absorption require a specific crystal and electronic structure [6].

The implementation of any of the listed mechanisms requires strictly defined geological conditions:

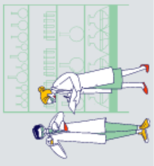
Table 1 - Influence of the geological environment on the implementation of coloring mechanisms

Geological parameter	Influence on coloration mechanisms
Chemical reserve of chromophores	Source Cr , Fe , Ti , etc.; determines whether the chromophore ions will be available for inclusion.
Redox conditions fO2	They control valence states (Fe2+/Fe3+, Ti3+/Ti4+), which is critical for IVCT and for most chromophores.
Temperature and pressure	They affect the solubility of ions , the likelihood of defect formation and the diffusion of impurities.
Crystal growth rate	Fast growth promotes the capture of non-stoichiometric impurities and the formation of color centers; slow growth produces purer crystals.
Post-educational processes	Radiation (creation of color centers), hydrothermal alteration , or metamorphism can alter or destroy the original coloration.

We analyzed three specific cases (for the minerals ruby/sapphire (corundum), emerald (beryl and topaz), demonstrating how geological conditions control color formation. A summary table is provided at the end of each case.

1. Mineral: corundum (α- Al_2O_3) - gem varieties ruby (red) and sapphire (other colors).

Coloration. Ruby's deep red color is due to the presence of Cr^{3+} in the corundum lattice. Sapphire (blue) is often caused by IVCT transitions between Fe and Ti (or other impurities) in corundum. In the scientific review "Ruby deposits: a review and geological classification" indicates that ruby is formed in two main geological environments: (1) amphibolite- granulite



metamorphic belts and (2) alkaline basaltic outflows of the continental rift. For example, this review indicates that corundum-ruby is associated with rocks enriched in Al and poor in Si , as well as with such minerals as pyrope-garnet, Cr -bearing spinel, etc. [7].

In addition, the study “Geology of Corundum and Emerald Deposits” states that chromophores (Cr^{3+}) and the Fe / Ti combination control the coloration of corundum, and geology (deposit type: marble-metamorphic or magmatic -hydrothermal) is important [8].

Conclusion: the color of corundum is directly related to impurities (Cr, Fe, Ti) and formation conditions: the type of metamorphism or magmatic body, the degree of Al enrichment and the t- / redox conditions.

Table 2 – Geological and chemical features of the formation of corundum color (ruby, sapphire)

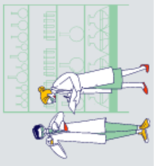
Parameter	**Data**
Mineral	Corundum (α- Al_2O_3)
Main chromophores	Cr^{3+} (in ruby), Fe^{2+}/Fe^{3+} + Ti^{4+} (in blue sapphires)
Geological type of deposit	Metamorphic belt a (amphibolite- granulite) and alkaline basalts/ rift environments
Key geological conditions	High pressure/temperature (8-10 kbar , ≈800 °C) in a single deposit example; silica poor, aluminum rich
Applied commentary	Trace impurities and geochemical isotopes are used to determine the origin of a gem.

2. Mineral: Emerald is a green variety of beryl ($Be_3Al_2Si_6O_{18}$). Color: the green color is due to impurities of Cr^{3+} and/or V^{3+}, which replace Al^{3+} in the beryl structure. On the website " Institute of Agriculture and Natural Resources " states: "emerald is formed in contact metamorphic rock conditions - a hot igneous intrusion contacts sedimentary rocks (e.g., schists) and forms beryl with a green tint" [9]. A study of emeralds from the Delbegetey deposit (Kazakhstan) describes the conditions: fluid homogenization temperature of ≈395-420 °C, liquid-vapor saturation, solution salinity, and the presence of Cr and V [10].

Conclusion: the color of emerald depends on the availability of Cr /V chromophores and on the specific geology of the deposit (often metasomatic skarns or hydrothermal veins at the boundary of granite and schist).

Table 3 - Geological and geochemical features of emerald color formation

Parameter	**Data**
Mineral	Emerald (green beryl)
Main chromophores	Cr^{3+}, V^{3+}
Geological type of deposit	Contact metamorphic zones (black shale + granite/pegmatite)
Key parameters	Fluid temperature ≈395-420 °C, low fluid density (0.40-0.55 g/cm³)
Applied commentary	Isotopic and fluid inclusion data allow determination of the type of mineralization and origin of colored beryl



3. Mineral: Topaz is an aluminosilicate with the formula Al_2SiO_4 (F,OH_2). Color: a comprehensive scientific study study on the gemological and mineralogical characteristics and coloration mechanisms of four color varieties of natural topaz » showed that the colors of topaz (colorless, yellow, blue, brown) are related to impurities (Fe^{3+}) and O^- centers, as well as to the geological type of sediment/fluid [11]. Some sources indicate that topaz is an allochromatic variety: its color is caused by impurities and defects, and not by the basic composition of the mineral [12]. Topaz forms in fluoride -rich granitic pegmatites and/or in hydrothermal veins associated with granites or ultramafic rocks.

Conclusion: topaz demonstrates how not only the chemistry of impurities but also the geological mechanism of formation (e.g. fluid regime, F/OH content, charge defects) influence color.

Table 4 – Geological and mineralogical features of topaz color formation

Parameter	**Data**
Mineral	Topaz (Al_2SiO_4 $(F, OH)_2$)
Chromophores/defects	Fe^{3+} (d–d transitions), O^- centers, charge transitions $O^{2-} \rightarrow Fe^{3+}$
Geological type of deposit	Fluor -rich granites/pegmatites, hydrothermal veins
Key parameters	vs F content, fluid nature, defect structure, concentration «color centers»
Applied commentary	The color of topaz can serve as an indicator of genesis (for example, yellow topaz is hydrothermal /metamorphic)

The study of the colour of gemstones and their origin requires a combination of physical and geochemical methods:

Table 5 - Key methods of color and origin analysis of gemstones

Group of methods	**Method**	**Purpose**
Optical-chemical	Optical spectroscopy (UV- Vis - NIR)	Identification of color mechanisms (dd, IVCT, defects) by absorption bands.
	ESR	Nature and localization of color radiation centers.
	XANES/EXAFS	Valence state and local environment of impurity ions (Cr3+, Fe2+).
Geochemical	LA-ICP-MS / SIMS	Quantitative analysis of trace elements and isotopes - geochemical fingerprint for determining origin.
Geological	Petrography/Geochemistry of the deposit	Reconstruction of the formation conditions (T, P, fO2, fluids) that influenced the introduction of chromophores.

Consequently, gemstone color is the result of multiple intersecting factors: the chemical availability of chromophores, thermobaric and redox conditions, growth rate, and post-formation effects. Interpreting color in a geological context requires a comprehensive approach: spectroscopy, microchemical analysis, and study of the petrological environment make it possible to reconstruct the formation conditions and distinguish natural mechanisms from anthropogenic ones.

References

1. Gemological Institute of America. GIA Colored Stone Research [Electronic resource]. - Access mode: https :// www . gia . edu / colored - stone - research (date of access: 10/17/2025).
2. Gavrilenko EV, Calvo Pérez B., Castroviejo Bolíbar R., García del Amo D. Emeralds from the Delbegetey deposit (Kazakhstan): mineralogical characteristics and fluid-inclusion study // Mineralogical Magazine. - 2006. - Vol. 70, No. 2. - P. 159-173. DOI :10.1180 /0026461067020321.
3. Fritsch E., Rossman GR An Update on Color in Gems. Part 1: Introduction and Colors Caused by Dispersed Metal Ions [Electronic resource] // Gems & Gemology. - Fall 1987. - Vol. 23, No. 3. - P. 126 . - Mode access : https :// www . gia . edu / doc / An - Update - on - Color - in - Gems - Part -1- Introduction - and - Colors - Caused - by - Dispersed - Metal - Ions . pdf (date accesses: 10/19/2025).
4. What causes color in topaz? [Electronic resource] // GeologyIn . com . - 2019, October. - Access mode: https :// www . geologyin . com /2019/10/ what - causes - color - in - topaz . html (date of access: 10/19/2025).
5. Rossman GR Colored varieties of the silica minerals // Heaney PJ, Gibbs GV (eds .). Reviews in Mineralogy. Vol. 29: Silica - physical behavior , geochemistry and materials applications. - Chantilly (VA): Mineralogical Society of America, 1994. - P. 433-468.
6. Emerald [Electronic resource] // Geological Sciences. University of Nebraska–Lincoln. - Mode access: https://snr.unl.edu/data/geologysoils/birthstones/emerald.aspx (date appeals: 10.20.2025).
7. An article in " Color " (Colour: Design & Creativity) // Color. - Vol. 12, No. 10, 2013. - DOI:10.1002/col.5080120105. - Mode access: https://onlinelibrary.wiley.com/doi/abs/10.1002/col.5080120105 (date accesses: 10/20/2025).
8. An article in «Chemical Communications» // Chem. Commun . - 2013. - DOI :10.1039 / c 3 cc 41506 f . - Access mode: https :// pubs . rsc . org / en / content / articlehtml / 2013/ cc / c 3 cc 41506 f (date of access: 21.10.2025)
9. An article in " RSC Advances " // RSC Advances. - 2025. - DOI: 10.1039 /d5ra02029h. - Mode access: https://pubs.rsc.org/en/content/articlehtml/2025/ra/d5ra02029h (date accesses: 10.22.2025).
10. An article in " Minerals " // Minerals. - 2020. - Vol. 10, No. 7. - Art. 597. - Mode access : https://www.mdpi.com/2075-163X/10/7/597 (date accesses: 10.22.2025).
11. Gemological Institute of America. Winter 2019 Gems & Gemology [Electronic resource]. - Access mode: https :// www . gia . edu / doc / Winter -2019- Gems - Gemology . pdf (accessed: 10.22.2025).
12. Geologica Balcanica. Emeralds from the Delbegetey deposit (Kazakhstan) - mineralogical characteristics and fluid-inclusion study // Geologica Balcanica . - Vol. 39, No. 1-2, 2010. - P. 114-115. - Mode access: https://www.geologica-balcanica.eu/journal/39/1-2/pp-114-115 (date accesses: 10.22.2025).