AN UPDATE ON COLOR IN GEMS. PART 3: COLORS CAUSED BY BAND GAPS AND PHYSICAL PHENOMENA

By Emmanuel Fritsch and George R. Rossman

The previous two articles in this series described the origins of color in gems that derive from isolated structures of atomic dimensions—an atom (chromium in emerald), a small molecule (the carbonate group in Maxixe beryl), or particular groupings of atoms (Fe^{2+}–O–Fe^{3+} units in cordierite). The final part of this series is concerned with colors explained by band theory, such as canary yellow diamonds, or by physical optics, such as play-of-color in opal. In the case of band theory, the color-causing entity is the very structure of the entire crystal; in the case of physical phenomena, it is of microscopic dimension, but considerably larger than the clusters of a few atoms previously discussed.

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All of the colors discussed in parts 1 and 2 of this series (Fritsch and Rossman, 1987 and 1988) arise from processes in which electrons are localized on a single atom or are delocalized over no more than a few atoms. The colors that arise from these processes depend on the presence of specific minor components or defects in the host crystal. However, colors can arise, though less commonly, from processes that involve the entire crystal, through either its electronic structure (band theory) or its internal texture (physical phenomena such as interference effects, diffraction effects, scattering, and inclusions; see figure 1). These, the most unusual causes of color in gems, are covered in this last article of our series.

BAND THEORY

In contrast to the processes described in the first two parts of this series, the electrons in some gem minerals can be delocalized over the entire crystal, and produce color through their interaction with visible light. Such delocalization is a characteristic property of most metals and semiconductors. The physical theory that describes the cause of color in such materials is called *band theory.* Examples of the various gem colors explained by this theory are presented in table 1.

In numerous solid materials, billions of atoms contribute to the possible energy levels, which are so numerous and so close together that they are considered collectively as an energy *band.* This is of particular interest in the case of some semiconducting and metallic minerals (Marfunin, 1979a). There are two bands in these solids: a low-energy valence band that is fully populated with electrons, and a high-energy conduction band that is generally empty (figure 2). The energy that separates these bands is well defined and is called a "band gap." This energy separation is of dramatic importance to the optical properties of certain types of gemstones.

Figure 1. Colors in gem materials can be caused by a wide variety of processes. This article explains color-producing mechanisms related to band theory and physical phenomena. Examples of the latter include diffraction in opal (in the center top and bottom right), scattering of light in "moonstone" feldspar (the necklace), and coloration by inclusions in fire opal (center bottom) and "sunstone" feldspar (bottom left). The necklace is courtesy of Elise Misiorowski; photo by Robert Weldon.

For these gemstones, transitions between bands rather than between energy levels of single atoms are responsible for the color. These "interband transitions" occur when electrons from the valence band receive sufficient energy by absorbing light to "jump" over the band gap and reach the conduction band. As illustrated in figure 2, three different scenarios are possible for interband transitions.

When the energy of the band gap is greater than the maximum energy of the visible range (i.e., the violet light), visible light does not supply enough energy to cause an electron to jump from the lower band to the upper one (figure 2A). Consequently, all of the visible spectrum is transmitted (none is absorbed) and, in the absence of impurities or defects, the mineral is colorless. Such materials—e.g., corundum, beryl, quartz, diamond, and topaz,

TABLE 1. Types of gem materials for which color can be explained by the band theory and examples of the colors produced.

Origin of color	Type of material	Color	Examples
Band gap less than the energy of visible light	Conductors and some semiconductors = colored opaque materials with metallic luster	**Violet to blue**	Covellite (Berry and Vaughan, 1985)
		Yellow	Gold, pyrite (Nassau, 1975; Fritsch, 1985)
		Red	Copper (Nassau, 1975)
		White	Silver, platinum (Nassau, 1975)
Band gap in the visible range	Some semiconductors	**Red**	Cuprite, cinnabar (Fritsch, 1985)
Band gap greater than the energy of visible light	Some semiconductors and all insulators	**Intrinsically colorless**	Diamond, corundum, beryl, quartz, topaz, fluorite (Fritsch, 1985)
Color modified by minor components	Some semiconductors	**Blue**	Type IIb diamond, containing dispersed boron atoms (Collins, 1982)
		Yellow	Type Ib diamond, containing dispersed nitrogen atoms (Collins, 1982)

as well as many other oxides and silicates—are inherently electrical insulators.

When the energy of the gap is less than the energy of violet light (i.e., is *in* the visible range), the most energetic radiations in the visible range (violet to blue to green) are absorbed, leaving the low-energy range unaffected, that is, transmitted (figure 2B). The exact energy of the band gap varies among different materials, so the transmitted color will also vary. Usually band-gap colors range from deep yellow to deep red. Cuprite and cinnabar (figure 3) are colored red by such a process.

The energy in the band gap may be even less than the lowest energy of the visible spectrum (red). In such a situation, all wavelengths of visible light will cause a transition from the valence band to the conduction band, so the whole visible spectrum is absorbed (figure 2C). As a consequence, the mineral usually appears black and opaque. All metals have just such a small band gap or no band gap at all. They appear, however, to be shiny (metallic luster) because their electrons quickly return to their original energy level, emitting the exact same energy (light) that they formerly absorbed (Nassau, 1975b). In some metals, the number of available excited states may vary throughout the conduction band, so that some wavelengths are absorbed and re-emitted more efficiently than others, thus producing color. Although silver and platinum absorb and emit all wavelengths with about the same efficiency and appear white, gold (or pyrite) absorbs and emits more yellow than the other wavelengths and so gets its distinct golden coloration (again, see figure 3).

The band gaps discussed thus far are an intrin-

Figure 2. The three possible types of intrinsic coloration of gem materials are explained by examining the width of the band gap in relation to the visible range. (A) Band gap greater than the energy of the visible range: All visible radiation is transmitted and the gem is intrinsically colorless. (B) Band gap in the visible range: Only the high-energy part of the spectrum (violet to blue to green) is absorbed, and the gem is yellow to red. (C) Band gap less than the energy of visible light: All visible radiation is absorbed and the material is black, or displays metallic colors due to re-emission. Artwork by Jan Newell.

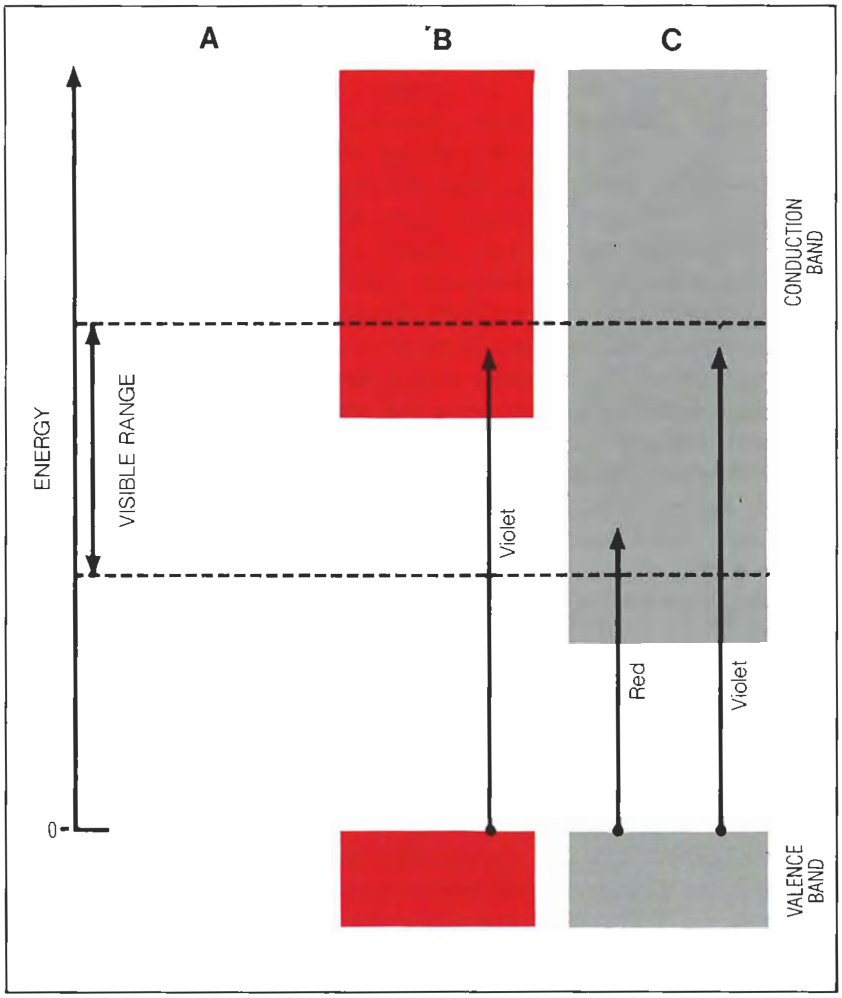


Figure 3. The red color of cuprite (the cushion cut) and cinnabar (the pentagon cut) has little to do with the fact that these gems contain copper and mercury, respectively. The color occurs because the band gap of these minerals is within the visible range: All wavelengths from violet to orange are absorbed, so that only red light is transmitted. The band gap in gold is much smaller than the energy of the visible range: All visible light is absorbed but some wavelengths are re-emitted preferentially, giving gold its yellow color and metallic luster. (Remember that the energy scale is inverse to the wavelength scale.) Photo by Robert Weldon.

sic property of the material; they are ultimately directly related to its chemical composition and atomic structure. In some semiconductors, however, color is caused by small amounts of impurity atoms that normally do not produce color in intrinsically colorless minerals. Specifically, these atoms can introduce electronic energy levels at an energy between the valence band and the conduction band of the host mineral (see figure 4). Some of the most striking examples are canary yellow and fancy blue diamonds, which contain isolated nitrogen and boron atoms, respectively. Although pure (colorless) diamonds are insulators, they may also be considered semiconductors with a band gap so large that they have neither color nor appreciable electrical conductivity (figure 4A). Nitrogen can easily substitute for carbon, which it follows in the periodic table of elements. Because nitrogen possesses one more electron than carbon, however, it becomes an electron "donor" when it substitutes for carbon in diamond. This additional electron contributes an additional energy level situated above the diamond valence band, but below the diamond conduction band (figure 4B). However, because this donor level has a finite width, light of a variety of wavelengths extending from the ultraviolet into the visible range up to 560 nm (green) will be absorbed, creating a strong yellow color. This type of coloration occurs only in type Ib diamonds, in which isolated nitrogen atoms substitute for carbon atoms in the proportion of about 1 to 100,000 (Collins, 1982). This color is distinct from the yellow color commonly caused by the nitrogen-related N3 color center, which produces the familiar Cape series of absorption lines.

Boron has one less electron than carbon, which follows it in the periodic table of elements. Therefore, boron is an electron "acceptor" when substituting for carbon in diamond. It contributes its own electron energy band, which is situated within the diamond band gap (figure 4C). The excitation of an electron from the diamond valence band to the acceptor level requires only a very low energy, in the infrared range (Collins, 1982). Because the boron energy band is broad, it can cause absorption extending from the infrared up to 500

Figure 4. The band gap in pure diamond is much greater than the visible range (A), so this gem is intrinsically colorless. However, a substitutional nitrogen atom introduces a level that donates electrons to the diamond conduction band (B), creating an absorption in the ultraviolet that extends into the blue end of the visible range (see spectrum); such stones are of an intense yellow color, and are therefore called "canary" (type Ib) diamonds. By contrast, a boron atom substituting for carbon can introduce a broad energy level available for electrons from the diamond valence band (C), which will induce an absorption of the near-infrared and the red end of the visible range (see spectrum), giving a blue hue to such a stone (type IIb diamond). These three mechanisms are illustrated by the colorless, De Beers synthetic type Ib yellow (photo © Tino Hammid), and natural dark blue diamonds shown here. Artwork by Jan Newell.

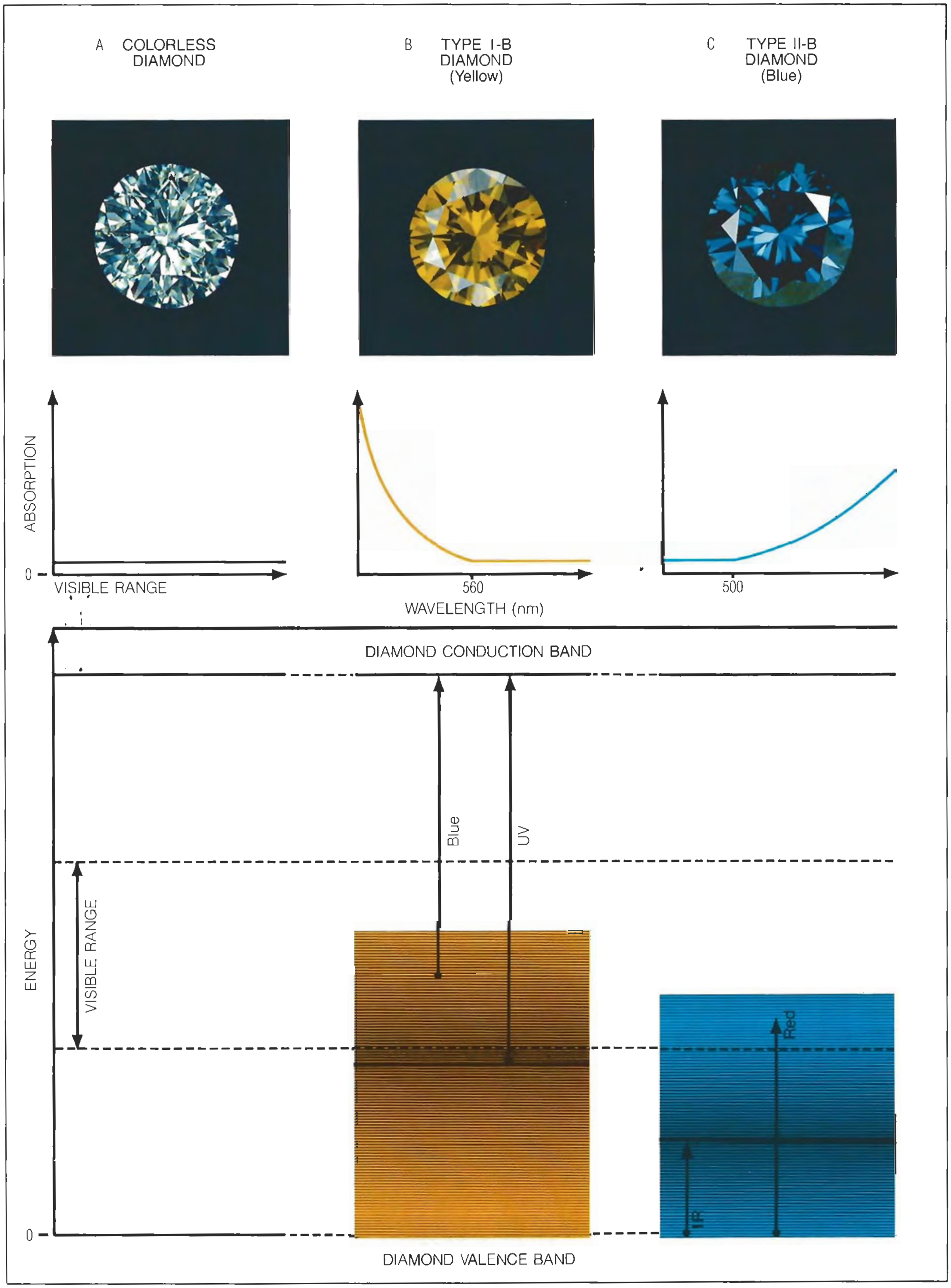

A COLORLESS DIAMOND
B TYPE I-B DIAMOND (Yellow)
C TYPE II-B DIAMOND (Blue)
ABSORPTION
0
VISIBLE RANGE
560
WAVELENGTH (nm)
500
DIAMOND CONDUCTION BAND
Blue
UV
ENERGY
VISIBLE RANGE
Red
IR
0
DIAMOND VALENCE BAND

Figure 5. Minute amounts of boron contribute the intense blue color to blue diamonds. Yellow in diamonds can arise from a variety of processes, all of which are related to the presence of nitrogen impurities. The possible origins of color for orange, brown, and pink diamonds are listed in table 4. The blue marquise shown here is 3.88 ct; the intense yellow oval weighs 29.16 cts; the two intense yellow diamonds mounted in earrings weigh a total of 12.26 ct. Jewelry courtesy of Harry Winston, Inc.; photo © Harold & Erica Van Pelt.

nm (the edge of the green). The resulting blue color, which can be produced with boron concentrations as low as one part per million (Nassau, 1975b), may be quite intense (figure 5). The Hope diamond is the most famous example of a blue diamond. There is no known commercial treatment that would affect band-gap coloration.

COLORS THAT ARISE FROM PHYSICAL PHENOMENA

All of the colors discussed thus far in this series have been due to the absorption of light. But as the introduction to part 1 pointed out, other causes of color are possible. In some gem materials, physical properties such as inclusions or lamellar texture can influence the hue. In this next section, we will explore how light interference, diffraction, and scattering can interact with these physical features to create colors in gem materials. These processes are rarely related directly to the chemistry of the stone, but rather are connected to the texture or internal arrangement of the mineral. The various colors obtained in gems as a consequence of physical phenomena are summarized in table 2.

Interference Effects from Thin Films. Interference phenomena occur when two rays of light travel along the same path or in closely spaced parallel paths. If these rays, or light waves, vibrate in phase, the wave crests reinforce each other to produce bright light (constructive interference). If the light waves vibrate exactly out of phase, they cancel each other to produce darkness (destructive interference).

Iridescence, the most common interference phenomenon, occurs when light passes through a thin transparent film that has a different index of refraction from the surrounding medium (e.g., a thin film of air in "iris quartz"). Rays reflected from the bottom of the film will travel beside waves reflected from the top of the film. At certain wavelengths, dictated by the thickness and the index of refraction of the film, the rays vibrate out of phase and the corresponding colors are removed from the reflected light through destructive interference. The remaining wavelengths produce the familiar colored effects that appear when a drop of oil expands as a thin film on water. The possible colors in iridescence are illustrated in figure 6. None of these colors is a pure spectral color.

In gemology, examples can be found as interference color in cracks (again, "iris quartz"), or in tarnish films on oxidized cut stones and sulfide crystals, such as pyrite and bornite (Nassau, 1975b). Iridescent cracks are sometimes created by heating and rapidly cooling a stone ("quench crackling"), especially quartz. The color observed in many pearls is also due in part to interference effects (again, see figure 6). Pearls are constructed from concentric alternating layers of aragonite and conchiolin, two substances of different refractive indices. Incoming overhead light is reflected from the surfaces between those successive layers. The reflected light interferes with the incoming light to create delicate iridescent colors, called orient. Mother-of-pearl and some abalone pearls exhibit similar interference effects, but the colors generally are stronger and less subtle (figure 7). In addition to "quench crackling," interference effects can also be generated by coating thin films of various substances on the surface of a gem.

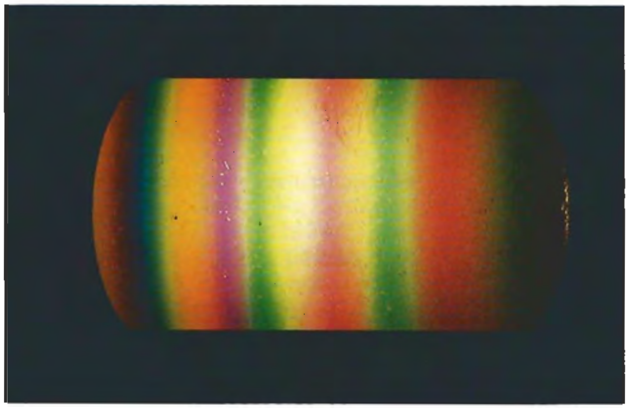
Diffraction Effects. Diffraction effects are special types of interference phenomena. The most important of these for gem materials is that caused by a regular stacking of alternating layers that have different indices of refraction. This diffraction effect produces pure spectral colors, in contrast to iridescence, which gives rise to colors that are a combination of several spectral colors (again, see figure 6).

Opal is one of the very few gems that can exhibit all colors of the spectrum in a single stone. It is interesting to note in play-of-color opal that although the pattern may be quite irregular, within each color region the color is homogeneous (see, for example, figure 1 of this article and the cover of this issue). The color of any one patch depends on the orientation of the overhead light source; when the stone moves, the color changes, giving "life" to the opal. If the light emerging from one of the color patches is analyzed, it appears to be a pure spectral color, that is, essentially of only one wavelength. These properties are characteristic of the diffraction effect created by the interaction of white light with a regularly layered structure (figure 8).

TABLE 2. Physical phenomena and examples of the colors they cause in various gem materials.

Process	Color and gem material
Interference on a thin film	**Various (nonspectral) colors:** iris quartz, iridescent coatings and tarnish, "orient" in pearls, mother-of-pearl (Nassau, 1975)
Diffraction	**All (spectral) colors:** play-of-color opal (Darragh and Sanders, 1965), labradorite/spectrolite (Ribbe, 1972), some rare andradites (Hirai and Nakazawa, 1982)
Scattering	
Rayleigh scattering	**Blue:** feldspar/moonstone (Lehmann, 1978), some blue quartz (Zolensky et al., 1988), some opal (Lehmann, 1978)
Mie scattering	**Violet:** fluorite, scattering by calcium microcrystals (Braithwaite et al., 1973) **Red:** ruby glass, scattering by copper or gold microcrystals (Nassau, 1983)
Scattering from structures larger than visible wavelengths	**White:** milky quartz (Fritsch, 1985)
Presence of colored inclusions	**Blue:** dumortierite inclusions in quartz (J. Koivula, pers. comm., 1988) **Green:** nickel-bearing clays in chrysoprase and prase opal (A. Manceau, pers. comm., 1987; Koivula and Fryer, 1984), chromian mica (fuchsite) in aventurine quartz (Lehmann, 1978) **Orange:** hydrous iron oxides in carnelian agate and fire opal (J. Koivula, pers. comm., 1988) **Red:** hematite platelets in orthoclase (Andersen, 1915), hematite or copper platelets in sunstone feldspar (Lehmann, 1978), cordierite/"bloodshot iolite" (Gübelin and Koivula, 1987)

The structure of opal was first revealed with scanning electron microscopy more than 20 years ago (Darragh and Sanders, 1965). It is an extraordinarily regular stacking of parallel layers of small spheres composed of hydrous silica. Color phenomena occur when the diameter of these spheres is less than the wavelengths of visible light. The conditions for diffraction of a given color are met when the distance between two successive layers is approximately equal to the wavelength of that color divided by the index of refraction of the spheres. The exact conditions are described in Nassau (1983). Consequently, the diffracted wavelength is proportional to the size of the particle. For example, the intense red is selected by spheres of about 250 nm in diameter (Darragh and Sanders,



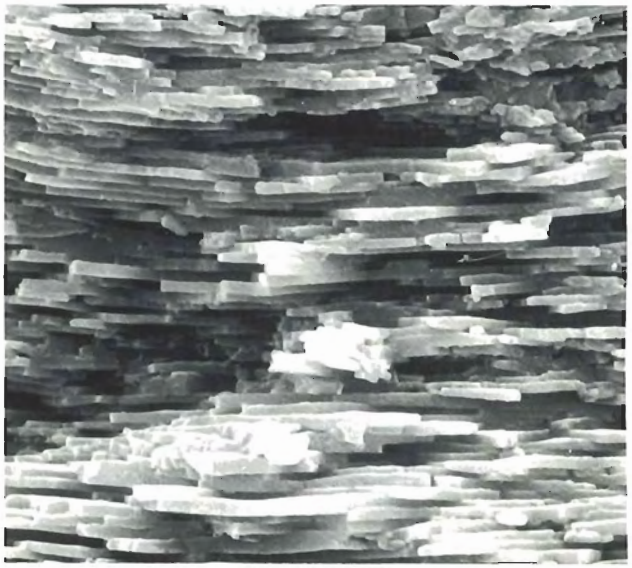


Figure 6. The colors produced by interference on a thin film are the same as those observed on this quartz wedge (top left) in polarized light. None of them is a pure spectral color. Notice that the "higher orders" on the right produce mostly pink and green. Interference colors are caused in pearls by light passing through and reflected back by alternating concentric layers of aragonite and conchiolin, which are readily visible on the electron photomicrograph of a pearl section (left). The resulting "high order" interference colors (mostly green and pink) are called orient and overtone (the latter, when they are stronger and homogeneous all over the pearl). They are readily apparent in these black pearl cufflinks (top right). Photomicrograph courtesy of B. Lasnier, Gemology Laboratory, Nantes University, France. Jewelry courtesy of Harry Winston, Inc. Color photos by Robert Weldon.

1965). The other colors are diffracted by smaller spheres, down to 140 nm in diameter.

As stated earlier, the color of the diffracted light varies with the angle between the direction of illumination and the direction of observation. The observed wavelength is at a maximum (e.g., red) when those two directions are perpendicular. When the stone is rocked away from this position, the observed wavelength decreases (e.g., goes to orange; Lehmann, 1978).

For the more commonplace play-of-color opals, those with mostly blue and green patches, the remainder of the incoming light (i.e., yellow to red) is transmitted so that an orange coloration is seen in transmitted light. Fire opal, however, probably owes its yellow-to-red body color (figure 9) to both diffraction and body absorption by Fe^{3+}-rich submicroscopic to microscopic inclusions between the silica spheres (J. Koivula, pers. comm., 1988).

Similar effects are encountered in some feldspars belonging to the plagioclase series. These feldspars display regions of color, often violet to green, against a generally black background. Finnish "Spectrolite," a variety of labradorite, appears to show every color of the spectrum. This phenomenon is called "labradorescence," after the classic occurrence of these stones on the Isle of Paul, Labrador, although varieties of plagioclase feldspars other than labradorite may display this effect. The diffracting objects in labradorescence are alternating layers, known as exsolution lamellae, of two feldspars with different chemical compositions. One layer is calcium rich and the other is calcium poor. The color created by the lamellar structures depends on their respective thicknesses and indices of refraction (figure 10). Another gemstone that occasionally shows diffraction colors is andradite from Hermosillo, Mexico

Figure 7. Pink and green interference colors make a spectacular display in this abalone pearl. Courtesy of Lowell Jones, St. Louis, MO; photo © Tino Hammid.

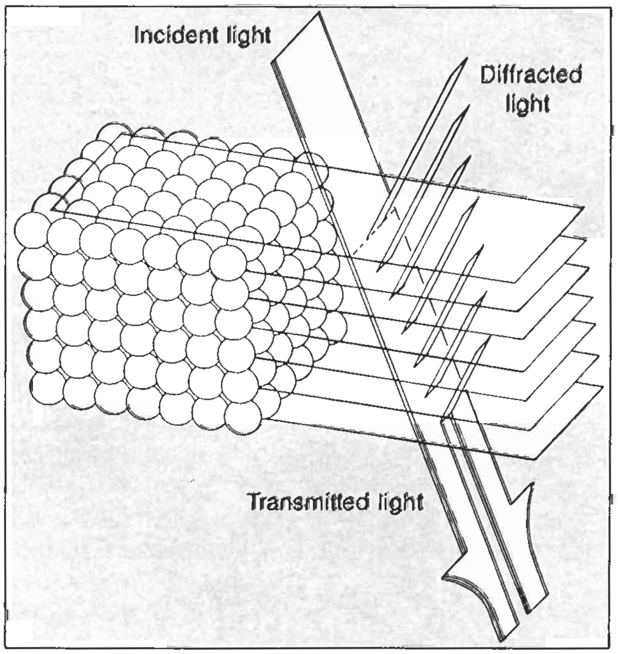
(Koivula, 1987). Similar material from Japan has lamellar structures about 100 nm thick (Hirai and Nakazawa, 1982), which give rise to some very rare crystals with patches of color. Diffraction effects probably account for the color phenomena observed in some varieties of agate (e.g., iris agate, fire agate).

Diffraction cannot be induced by any known commercial treatment. However, an already existing diffraction color can be enhanced by inducing a dark background (sugar and smoke treatment of opals, for example, as well as doublets), or by reducing the scattering of light in the matrix through impregnation with various kinds of polymers.

Scattering. When the internal structure of the stone is irregular and/or the size of the components is outside the very narrow range needed for diffraction (approximately 100–400 nm), visible light cannot be diffracted. It can, however, still be scattered, the process by which light entering a stone in a given direction is deflected in different directions through interaction with the scattering centers. This creates both striking color effects and optical phenomena. The exact phenomenon depends on the size and shape of the scattering centers. When the scattering centers are smaller than the wavelength of visible light (including down to molecular dimensions) and not regularly distributed, the process is called *Rayleigh scattering;* when the scattering centers are comparable in size to visible wavelengths, the process is called *Mie scattering.* (The names are derived from the mathematical theories used to describe scattering.) A third type of scattering occurs when the centers are larger than visible wavelengths.

Rayleigh Scattering. When the incoming light ray encounters randomly distributed objects smaller

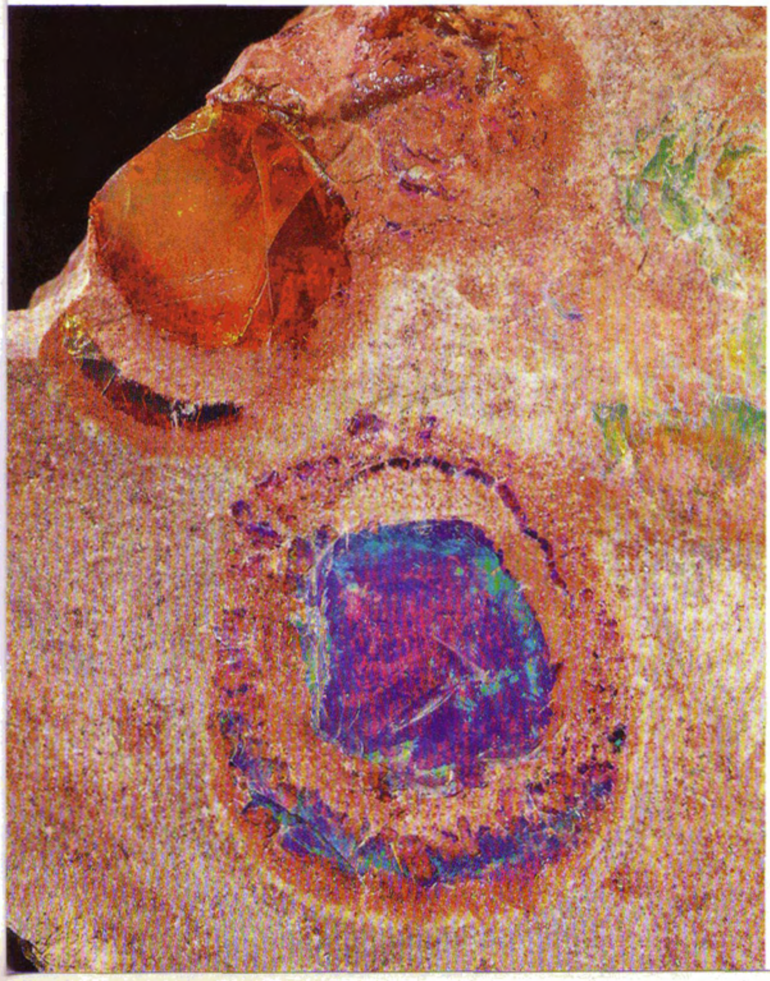
Figure 8. The homogeneous color in a patch of opal arises because light rays entering the stone are diffracted by an orderly array of silica spheres and the holes in between them. The diffracted color depends on the size of the spheres (after Lehmann, 1978).



than the wavelengths of visible light, the most energetic radiations—violet and blue—are scattered much more strongly than the others. In fact, violet light is scattered 16 times more efficiently than red. As a result, the majority of the orange-red light passes through the stone and appears as transmitted light, whereas violet and blue light is scattered and can be observed at right angles to the incident beam.

This phenomenon is familiar to all of us as the scattering of sunlight by molecules and molecular aggregates in the upper atmosphere, which causes the sky to appear blue in the daytime (scattered light) and orange-red at dawn and twilight (transmitted light). Examples in gemology are few but well known. Common opal (potch) contains spheres that are too small and too irregularly stacked to diffract. Instead, it has a bluish white appearance called "opalescence," which is due to scattering by the silica spheres. Such an opal indeed also transmits orange light. "Moonstone" is so called because light scattered from exsolution lamellae creates a bluish white "moon-like" hue (in the best specimens; see figure 1). Moonstone is actually an alkali feldspar, with alternating parallel planes of potassium- and sodium-rich feldspars forming an assemblage called a microperthite. These component layers in moonstone range from 50 to 1000 nm (1 μm) thick (Lehmann, 1978). The thinner layers produce the Rayleigh scattering. The same colors from scattering can also occur in plagioclase, and are sometimes called "adularescence." Some blue quartz receives its color from the scattering effect created by dispersed ilmenite inclusions that are approximately 60 nm in diameter (Zolensky et al., 1988).

Figure 9. This extraordinary opal specimen from Mexico shows a diffraction-caused play-of-color zone close to a region of fire opal, which is colored by a combination of diffraction and body absorption by Fe^{3+}-containing inclusions. Specimen courtesy of the Paris School of Mines; photo © Nelly Bariand.



Mie Scattering. When the scattering elements are roughly the size of the visible wavelengths, the scattering is best described by the "Mie theory." This theory has applications in gem materials only in those very special cases in which the color is created by metallic inclusions.

A common example is provided by some varieties of violet fluorite. This color is generated by irradiation, which expels a fluorine atom from the crystal, leaving partially bonded calcium atoms behind. Over time, the calcium atoms coagulate and form small hexagonal platelets about the size of visible wavelengths (Lehmann, 1978). Part of the light is absorbed by the calcium crystals and part is reflected. The combined effect of this absorption and reflection is a strong absorption from the green to the red, which leaves a violet transmission window. The position of the bands, and therefore the hue, varies slightly with the size of the metallic particles. Such an effect has been known for a long time in man-made glasses (which are often used as gemstone simulants). "Ruby" glasses are colored by microscopic particles of copper (or gold), and the brown glass used for beer bottles (and to imitate topaz) is usually tinted by metallic oxysulphide precipitates (J. F. Cottrant, pers. comm., 1987).

Scattering from Structural Components Larger than Visible Wavelengths. When the inclusions are larger than the wavelengths of visible light, they scatter light in all directions, including toward the observer's eye. Unlike the case of Rayleigh scattering, all wavelengths are scattered equally and recombine to produce a white light with a translucent milky appearance. This is typical of crystals

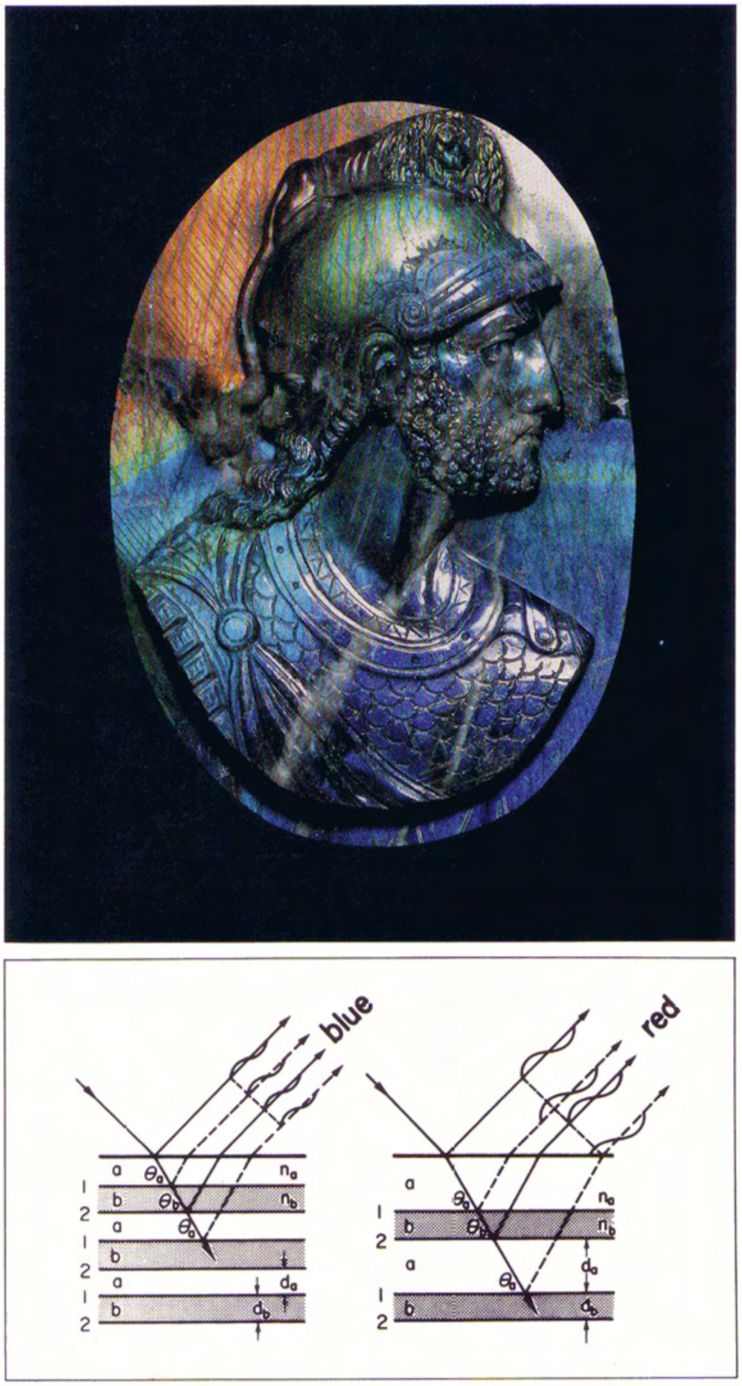


Figure 10. The schematic drawings illustrate why various diffraction colors occur in plagioclase feldspars. The two sets of lamellar feldspars have different thicknesses (d_a and d_b) and indices of refraction (n_a and n_b); therefore, the light beam will go through interfaces 1 and 2 at different angles (θ_a and θ_b). As a consequence, the beam at interface 2 is retarded relative to the one at interface 1, although the wavelengths are the same, and generally attenuate each other. For one given combination of thicknesses, refractive index, and incident wavelength, the beam from interface 2 is exactly one wavelength behind the beam of interface 1, so they combine in a coherent monochromatic beam. The color of this beam of light is blue for relatively thin lamellae, red for larger ones. The cameo (by Tiffany & Co.) is a rare example of carved red and blue labradorite. The line drawing is courtesy of the Mineralogical Record; *the photo is by Chip Clark, reprinted by permission of Harry N. Abrams, Inc., courtesy of the Smithsonian Institution.*

containing pervasive fluid inclusions (such as milky quartz), colorless microcrystals, microfractures, bubbles, and the like.

In some cases, a particular orientation of the scattering elements may produce special optical effects. If they are fibrous, the result is a "white adularescence" or silky sheen, as in gypsum ("satin spar" variety), some malachite, or pectolite. Chatoyancy or asterism arises when the scattering elements are sets of parallel fibers, tubes, or platelets. These effects, beyond the scope of this article, do not affect color. However, for the sake of clarity and completeness, the various kinds of phenomena (in the gemological sense) have been grouped in table 3. With the exception of the alexandrite effect, which was discussed in part 1 of this series (Fritsch and Rossman, 1987), all gemstone phenomena can be understood as the interaction of visible light with particles in a particular size range. The size of the particle can be used as a basis

TABLE 3. Descriptions, causes, and examples of phenomena in gem materials and considerations they require in fashioning.[a]

Phenomenon	Description	Cause	Examples	Considerations in fashioning
Iridescence **Orient**	Interference colors on, or in, a stone, like those produced by a drop of oil on water	Interference of visible light rays, due to the presence of a thin film or thin structure in, or on, a material of different refractive index	Iris quartz, "ammolite," pearls	Thin film or structure oriented to the girdle plane
Play-of-color **Labradorescence**	On a given spot, for a given illumination angle, only one pure spectral color is seen; rotating the stone changes the color	Diffraction of visible light by regularly layered structures *smaller* than the visible wavelengths	Opal, feldspar ("spectrolite")	Diffraction layers oriented parallel to the girdle plane
Adularescence	Floating bluish sheen in a stone	Scattering of visible light by randomly distributed structures *smaller* than visible wavelengths	Feldspar (moonstone)	No relation
Chatoyancy ("cat's-eye") **Asterism**	One or more lines of white light appearing on a curved surface (chatoyancy = one ray, like a cat's eye; asterism = several rays—up to 6—building a star)	Scattering of light by oriented parallel needle-like or plate-like inclusions or structures *larger* than visible wavelengths (chatoyancy = one set of inclusions or structures; asterism = multiple sets)	Chrysoberyl, corundum, quartz, diopside	Curved surface (not well focused on flat surface)
Aventurescence	Colored metallic-like spangles in the stone, especially obvious when the stone is rotated in reflected light	Reflection of light by *large* eye-visible plate-like inclusions	Aventurine quartz, feldspar (sunstone), goldstone glass	No relation
Change-of-color ("Alexandrite effect")	The stone changes color when the illumination is switched from sunlight or fluorescent light to incandescent light	A major absorption band around 550–600 nm cuts the visible range in two transmission windows: one at the blue end (dominating in daylight), the other at the red end (dominating in incandescent light)	Chrysoberyl (alexandrite), corundum, garnet, spinel, fluorite	Observed in all directions, better colors in some

[a] *This table includes all terms used for phenomena in gem materials. It describes each of the phenomena and shows how similar some of them are and how others relate to one another almost in a continuum.*

for classification. There is a continuum in the size of the particles between color-creating phenomena (such as adularescence) and phenomena that do not affect color (such as chatoyancy). This continuum is emphasized in table 3.

Some of these phenomena can be induced or enhanced by treatment—especially heat treatment. Basically, the heat precipitates a second phase in the matrix, which creates oriented inclusions, which in turn induce chatoyancy or asterism (Nassau, 1984).

Presence of Colored Inclusions. The last type of coloration encountered in gemstones is coloration caused by the body color of inclusions in a near-colorless host crystal. These inclusions can be extremely small, like the nickeliferous clays that color chrysoprase or the small hydrous iron oxide crystals that make carnelian orange (figure 11). Somewhat larger but still microscopic inclusions of hematite cause the color of red orthoclase from Madagascar (Malagasy Republic) and some cordierites ("bloodshot iolite"). Fire opal is colored by submicroscopic inclusions of iron hydrous oxides (J. Koivula, pers. comm., 1988).

When the platelets are large enough to be distinguished with the naked eye (say, when they reach 1 mm), they can produce "aventurescence." This term is used to describe the reflective powder-like appearance of crystalline flakes disposed *a l'aventurra* (the term refers to a Murano glass—first made in Venice, Italy—in which copper platelets have been dispersed at random). In aventurine quartz, mica crystals colored green by chromium sparkle when the stone is tilted back and forth. "Sunstone" can be either native-copper-included labradorite (most commonly), or oligoclase containing red hematite spangles (again, see figure 1).

SUMMARY AND CONCLUSION

In most gem materials, color is caused by selective absorption of light by different processes. In a few instances, phenomenal colors are caused by the interaction of light with certain physical characteristics, such as inclusions, texture, or the structure of component materials.

Absorption processes in gemstones can be divided into four broad categories. First, absorption caused by dispersed metal ions explains how an isolated Fe^{2+} metal ion makes peridot green. Second, when certain ions come close enough together, oxygen-to-metal or metal-to-metal charge-transfer transitions are possible, like the $O^{2-} \rightarrow Fe^{3+}$ charge transfer that causes the yellow of citrine, or the Fe^{2+}–O–Fe^{3+} intervalence charge transfer responsible for the blue in cordierite. Third, color centers represent an extremely varied class of often complex structures or defects that absorb light; for example, carbon vacancies associated with nitrogen aggregates cause an orangy yellow color in diamond. These first three categories give colors that are sometimes easily modified, removed, or enhanced by treatment, usually heat and/or irradiation. In our fourth category, band gaps provide colors that cannot be induced or modified by commercial treatment because they are directly related to the crystal structure of the gem and not to minor amounts of defects or small concentrations of impurities. They could, however, be modified by overriding color-generating processes, but there are no known examples of such a treatment used for gem materials.

It is important to keep in mind, however, that a single color in a given gem can have more than one cause. In emerald, for example, color can be due to Cr^{3+}, V^{3+}, or both. Table 4 lists the origins of color in most currently available gem materials and illustrates the variety of potential origins for each. This listing refers only to known studies. Consequently, a common color for a given gem might be absent, because no one has yet investigated its cause, whereas the cause of a very unusual color might be known because it attracted the curiosity of researchers.

Ongoing research in a number of laboratories may lead to results that contradict former origin-of-color assignments. Usually this is because many of our earlier ideas were "educated guesses" that were never proven, but nevertheless were often repeated. This probably is also a consequence of the fact that the exploration of the origin of color in a gem material can be a long, difficult, and expensive process, especially when a color center is involved.

Figure 11. This magnificent Turkoman bracelet was made in Central Asia in the 18th century. The carnelian is colored by inclusions of hydrous iron oxides. The precious metals owe their white or yellow coloration to preferential re-emission of some visible wavelengths. Photo © Nelly Bariand.

The origin of color in gem materials is an increasingly important topic as more color-altering treatments are used. A detailed understanding of the origin of color in natural-color gems and the color-inducing processes involved in the various enhancement techniques is necessary to provide a better means of separating natural- from treated-color gem materials. Likewise, the origin of color in some synthetic materials may differ significantly from that in their natural counterparts, and therefore can also be used as a way of distinguishing these two groups.

As can be seen from our final table, conflicting hypotheses on some color varieties and the absence of documentation on others attest to the continued existence of substantial gaps in our understanding of color. In-depth research is still needed on some of the most critical gemological issues, such as treated colored diamonds and color stability. As new treatments are developed and new color varieties are discovered, the need for ongoing research in this area will continue for many years to come.

TABLE 4. Causes of color in most gem materials.[a]

Gem material	Color (variety or trade name, if any)	Cause	Reference
Actinolite	Yellowish green to green (nephrite)	Fe^{2+} in octahedral coordination	Burns, 1970
	Green	Traces of Cr^{3+}	Anderson, 1954–55
Almandine	Red	Fe^{2+} in distorted cubic coordination	Manning, 1967a
Amber	Blue to green	Fluorescence under visible light in Dominican amber; blue is due to light (Rayleigh) scattering in Baltic amber	Schlee, 1984
	Yellow to orange to red to brown	Charge-transfer processes in large organic molecules	Nassau, 1975a
Amphibole group (see actinolite, anthophyllite and gedrite, glaucophane, hornblende and pargasite, or tremolite)			
Andalusite	Green and brown, pleochroism	$Fe^{2+}-O-Ti^{4+}$ charge transfer	Smith, 1977
	Dark green (viridine)	Mn^{3+} in octahedral coordination	Smith et al., 1982
Andradite	Multicolors	Diffraction	Hirai and Nakazawa, 1982; Koivula, 1987
	Yellow-green	Fe^{3+} in octahedral coordination	Manning, 1967b, 1972
	Green (demantoid)	Cr^{3+} in octahedral coordination	Anderson, 1954–55; Stockton and Manson, 1983, 1984
	Yellow (topazolite) to black (melanite)	Various charge-transfer processes and dispersed ion absorption involving Fe and Ti	Dowty, 1971; Moore and White, 1971
Anthophyllite and gedrite (ortho-amphiboles)	Multicolor ("nuummite")	"Iridescence," likely diffraction	Appel and Jensen, 1987
Apatite series	Pink	F vacancy with a trapped electron	Marfunin, 1979b
	Dark blue	$O^{2-}\rightarrow Mn^{5+}$ charge transfer	Marfunin, 1979b
Apophyllite	Green	V^{4+} in distorted octahedral coordination	Rossman, 1974a
Axinite group	Blue	V^{3+} in octahedral coordination	Schmetzer, 1982
	Brown	Fe^{2+}	Faye, 1972
Azurite	Blue	Cu^{2+} in elongated octahedral coordination	Marfunin, 1979a
Benitoite	Blue	$Fe^{2+}-O-Ti^{4+}$ charge transfer	Not fully proven: Burns, 1970
Beryl	Dark blue (Maxixe and Maxixe-type)	CO_3^- (Maxixe-type) and NO_3 (Maxixe) color centers due to irradiation	Andersson, 1979
	Light blue (aquamarine)	Fe^{2+} in the channels of the structure	Goldman et al., 1978
	Darker blue (aquamarine)	$Fe^{2+}-O-Fe^{3+}$ intervalence charge transfer	Goldman et al., 1978
	Green: yellow + blue	$O^{2-}\rightarrow Fe^{3+}$ charge transfer and Fe^{2+} in the channels	G. Rossman, unpub. data
	Green (emerald) and light green ("mint beryl")	Cr^{3+} and/or V^{3+} in octahedral coordination	Wood and Nassau, 1968
	Yellow to orange (heliodor)	$O^{2-}\rightarrow Fe^{3+}$ charge transfer	Loeffler and Burns, 1976; Goldman et al., 1978
	Red	Mn^{3+} in octahedral coordination	Shigley and Foord, 1984
	Pink (morganite)	Mn^{2+} in octahedral coordination	Wood and Nassau, 1968
Calcite	Pink	Co^{2+}	Webster, 1983; Rossman, 1988
Chalcedony	Purple	Microscopic sugilite inclusions	Shigley et al., 1987
	Purple ("damsonite")	Color center similar to that found in amethyst	Shigley and Koivula, 1985
	Blue to greenish blue (chrysocolla quartz)	Microscopic to submicroscopic inclusions of chrysocolla	J. Koivula, pers. comm., 1988
	Green (chrysoprase)	Microscopic inclusions of nickeliferous clay-like material	A. Manceau, pers. comm., 1985

This 1759-ct emerald from the collection of the Banco de la República in Bogotá, Colombia, owes its magnificent color to a small amount of Cr^{3+} in octahedral coordination. Photo © Harold & Erica Van Pelt.

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[a] *This list of the origin of color in gem materials is based on spectra or explicit discussions as they appear in the literature or have been communicated to the authors. One color can be due to a combination of processes, while visually similar colors can have a variety of different causes. Within each gem group or subgroup, colors are listed in the order of the spectrum, from violet through purple, blue, green, yellow, and orange to red, and then pink, brown, black, and white when relevant. Dyes and colored coatings can be used on many of these materials, but they are mentioned here only if they are the most common cause of color in a particular material.*

Gem material	Color (variety or trade name, if any)	Cause	Reference
	Orange to red (carnelian, jasper)	Submicroscopic to microscopic inclusions of hydrous Fe oxides	J. Koivula, pers. comm., 1988
Chrysoberyl	Yellow	Fe^{3+} in octahedral coordination	Loeffler and Burns, 1976
	Color-change (alexandrite)	Cr^{3+} in octahedral coordination	Farrell and Newnham, 1965
Chrysocolla	Blue	Cu^{2+} in octahedral coordination	Lehmann, 1978
Clinozoisite	Green (tawmawite)	Cr^{3+} in octahedral coordination	Schmetzer, 1982
Conch "pearl" and shell	Pink	Organic pigment from the carotenoïd family	Délé-Dubois and Merlin, 1981
Copal (same as amber)			
Coral	Blue (*Heliopora caerulea)*	An organic pigment of the bilins family, helioporobilin	Fox et al., 1983
	Red to pink	Organic pigments from the carotenoïd family, at least for *Corallum rubrum*	Délé-Dubois and Merlin, 1981
	Black	Various organic materials of unknown nature	Rolandi, 1981
Cordierite	Violet to blue (iolite)	Fe^{2+}–O–Fe^{3+} charge transfer	Faye et al., 1968; Smith, 1977; Goldman et al., 1977
	Red ("bloodshot iolite")	Hematite and/or lepidocrocite inclusions	Gübelin and Koivula, 1987
Corundum	Purple	Fe^{2+}–O–Ti^{4+} charge transfer coexisting with Cr^{3+} in octahedral coordination	Schmetzer and Bank, 1981
	Blue	Fe^{2+}–O–Ti^{4+} charge transfer with influence of $Fe^{2+} \rightarrow Fe^{3+}$ charge transfer	Smith and Strens, 1976; Schmetzer, 1987
	Green	Fe^{3+} in octahedral coordination coexisting with $Fe^{2+} \rightarrow Ti^{4+}$ charge transfer, Ti^{3+} and Cr^{3+} in octahedral coordination	Schmetzer and Bank, 1981
	Yellow	$O^{2-} \rightarrow Fe^{3+}$ charge transfer	Schmetzer et al., 1982; Nassau and Valente, 1987
		Fe^{3+} and Ti^{3+}	Schmetzer and Bank, 1981
		A variety of unstable color centers of unknown structure	Schiffmann, 1981; Schmetzer et al., 1982, 1983; Nassau and Valente, 1987
		Fe^{3+} pairs	Ferguson and Fielding, 1971
	Orange to orange-brown	Cr^{3+} in octahedral coordination and color centers; with a contribution of Fe^{3+}	Schmetzer and Bank, 1981 Schmetzer et al., 1982, 1983
	Orangy pink ("padparadscha")	Cr^{3+} in octahedral coordination and color centers	Schmetzer and Bank, 1981
		Cr^{4+} in octahedral coordination due to Cr^{4+} and Mg^{2+} substituting for two Al^{3+} in the crystal structure	Nassau, 1983
	Red (ruby)	Cr^{3+} in octahedral coordination, with minor contributions of V^{3+} and Fe^{3+} in octahedral coordination	Harder, 1969; Gübelin, 1975
	Pink	Cr^{3+} in octahedral coordination	G. Rossman, unpub. data
	Color-change	Cr^{3+} and/or V^{3+} in octahedral coordination in a particular range of concentration	Schmetzer et al., 1980
Covellite	Blue and orange, pleochroism	Band theory	Berry and Vaughan, 1985
Crocoite	Yellow to red	$O^{2-} \rightarrow Cr^{6+}$ charge transfer	Loeffler and Burns, 1976; Abou-Eid, 1976
Cuprite	Red	Band theory	G. Calas, pers. comm., 1984
Diamond	Purple, pink to red	In natural-color diamonds, attributed to a structural defect of unknown nature	Collins, 1982
		In treated pink diamonds, attributed to the N-V defect (a carbon vacancy trapped at an isolated nitrogen impurity)	Collins, 1982
	Blue	Band transitions caused by the presence of dispersed boron atoms	Collins, 1982
		GR1 center (neutral carbon vacancy) in a colorless diamond irradiated in nature or in the laboratory	Collins, 1982
	Green	Generally GR1 center (neutral carbon vacancy), plus defects that absorb in the blue (e.g., N3)	Collins, 1982

This 32.50-ct "padparadscha" sapphire owes its beautiful color to a combination of Fe^{3+}- and Cr^{3+}-related absorptions. Jewelry courtesy of Harry Winston, Inc.; photo © Harold & Erica Van Pelt.

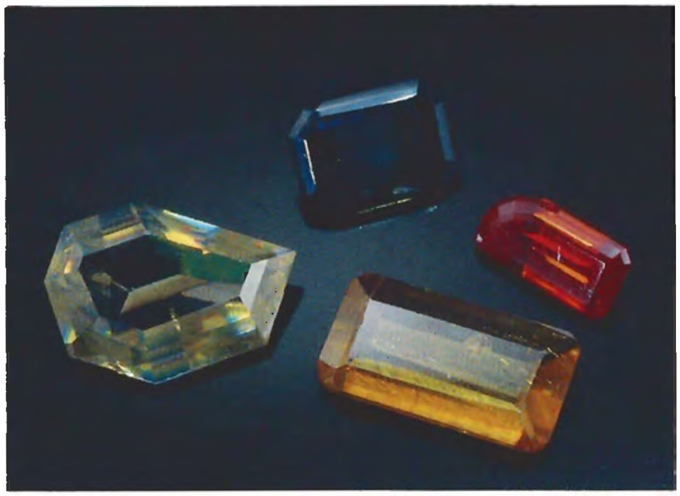
Gem material	Color (variety or trade name, if any)	Cause	Reference
		More rarely, due to very strong green fluorescence under visible light ("green transmitter" effect) of the H3 and/or H4 defect (a carbon vacancy trapped at an aggregate of two or four nitrogen atoms)	Collins, 1982
	Yellow	Most commonly due to the N3 defect, an aggregate of three nitrogen atoms (color center) at a carbon vacancy	Collins, 1982; Lowther, 1984
		More rarely, due to band transitions caused by the presence of isolated nitrogen atoms	Collins, 1982
	Orange	Most commonly H3 center (a carbon vacancy trapped at an aggregate of two nitrogen atoms), in natural and treated orange diamonds	Cottrant and Calas, 1981
		More rarely, originating from a color center of unknown nature	Collins, 1982
	Brown	Color center of unknown nature, with various other color centers adding orange, yellow, pink, or green	Collins, 1982
Diopside	Green (chrome diopside)	Cr^{3+} in octahedral coordination;	Rossman, 1980
		V^{3+} in octahedral coordination	Schmetzer, 1982
	Yellowish green	Fe^{2+} in octahedral coordination	Burns, 1970
Dioptase	Green	Cu^{2+} in octahedral coordination	Lehmann, 1978
Dravite	Green ("chrome tourmaline")	V^{3+} generally with minor amounts of Cr^{3+}, both in octahedral coordination	Schmetzer and Bank, 1979
	Yellow to brown	Related to titanium; due to Fe^{2+}–O–Ti^{4+} charge transfer, with those low in iron yellow and those rich in iron brown	Smith, 1977; Rossman, as cited in Dietrich, 1985
	Red	Fe^{3+} pairs	Mattson and Rossman, 1984
Elbaite and liddicoatite	Blue (indicolite)	Fe^{2+} in octahedral coordination with possible influence of some iron-related charge-transfer processes	See Dietrich, 1985
	Green	Fe^{2+} and Ti^{4+} in octahedral coordination. The influence of various charge transfer processes involving iron is a distinct possibility	Mattson, as cited in Dietrich, 1985
	Yellow-green	Mn^{2+}–O–Ti^{4+} charge transfer	Rossman and Mattson, 1986
	Greenish yellow	Mn^{2+} in octahedral coordination (rare)	Rossman and Mattson, 1986
	Orange	Yellow + pink	See Dietrich, 1985
	Pink to red (rubellite)	Related to manganese, generally believed to be due to Mn^{3+} in octahedral coordination, sometimes created by irradiation	Manning, 1973; De Camargo and Isotani, 1988
	Brown	$Fe^{2+} \rightarrow Ti^{4+}$ charge transfer	Rossman and Mattson, 1986
Enstatite	Greenish brown	Fe^{2+}	Rossman, 1980
	Green	Fe^{2+} with minor Cr^{3+}	Anderson, 1954–55
Epidote group (see clinozoisite, epidote, piemontite, or zoisite)			
Epidote	Green and brown, pleochroism	Fe^{3+} in distorted octahedral coordination	Burns, 1970
Euclase	Blue	Fe^{2+}–O–Fe^{3+} charge transfer	Mattson and Rossman, 1987
	Green	Cr^{3+} in octahedral coordination	Anderson, 1954–55
Feldspar group (see labradorite, microcline, oligoclase, orthoclase, or plagioclase series)			
Fluorite	Violet	Mie scattering on calcium microcrystallites	Braithwaite et al., 1973; Lehmann, 1978
	Blue	Y^{3+} + F vacancy + 2 electrons	Bill and Calas, 1978
	"Emerald" green ("chrome fluorite")	Sm^{2+}	Bill and Calas, 1978; Rossman, 1981
	Yellowish green	Color center containing Y and Ce associated with an F vacancy	Bill and Calas, 1978
	Yellow	O_3^- color center = O_2 substituting for fluorite	Bill and Calas, 1978
	Pink	YO_2 color center (Y^{3+} + O_2^{3-})	Bill and Calas, 1978
	Color change	Y^{3+}-associated color center and Sm^{2+}, with minor influence of a Ce^{3+}-associated color center	Bill and Calas, 1978; Schmetzer et al., 1980
Gahnite and "gahnospinel"	Blue	Fe^{2+} in tetrahedral coordination	Dickson and Smith, 1976
Garnet group (see almandine, andradite, grossular, hydrogrossular group, pyrope, spessartine, or uvarovite; also rhodolite)			
Glass (natural)	Yellowish green (moldavite, tektite)	Fe^{2+} in octahedral coordination	Pye et al., 1984
	Brown	Fe^{3+} in octahedral coordination	Pye et al., 1984
Glaucophane	Blue	Fe^{2+}–O–Fe^{3+} charge transfer	Smith and Strens, 1976
Grossular	Green (tsavorite)	V^{3+} in octahedral coordination	Gübelin and Weibel, 1975
	Orange (hessonite)	Mn^{2+} in distorted cubic coordination;	Manning, 1970
		Fe^{3+}	Manson and Stockton, 1986
Gypsum	All (alabaster)	Color usually due to dyes exclusively, except for some brown staining due to hydrous iron oxides	J. Koivula, pers. comm., 1988
Hematite	Gray in reflection, red in transmission	Fe^{3+}	Bell et al., 1975
Hornblende and pargasite	Green to brown	Fe^{2+} in various sites	Rossman, 1988
Howlite	Blue	Dyes exclusively	

Gem material	Color (variety or trade name, if any)	Cause	Reference
Hydrogrossular group	Green ("Transvaal jade")	Cr^{3+} in octahedral coordination	Manning and Owens, 1977
	Pink	Mn^{3+} in octahedral coordination	Manning and Owens, 1977
Jadeite	"Emerald" green (chrome jadeite)	Cr^{3+} in octahedral coordination	Rossman, 1981
	Yellowish green	Fe^{3+} in octahedral coordination	Rossman, 1981
	Violet ("lavender jadeite")	Fe^{2+}–O–Fe^{3+} charge transfer;	Rossman, 1974b
		synthetic is colored by Mn^{3+}	Nassau and Shigley, 1987
Kornerupine	Blue	Cr^{3+} in octahedral coordination	Schmetzer, 1982
	Green	V^{3+} in octahedral coordination	Schmetzer, 1982
Kyanite	Blue	Fe^{2+}–O–Ti^{4+} charge transfer, Fe^{2+}–O–Fe^{3+} charge transfer, Fe^{2+} and Fe^{3+} in octahedral coordination can all be involved;	Parkin et al., 1977
		with contribution from Cr^{3+} in octahedral coordination	Bosshart et al., 1982
	Green	V^{3+} in octahedral coordination;	Schmetzer, 1982
		Fe^{3+} in octahedral coordination	G. Rossman, unpub. data
	Color change	Cr^{3+} in octahedral coordination	Bosshart et al., 1982
Labradorite	Multicolors	Diffraction of light by the internal lamellar structure	Ribbe, 1972; Lehmann, 1978
	Red (in the material from Oregon)	Submicroscopic metallic copper particles	Hofmeister and Rossman, 1985b
	Green and orange-pink, pleochroism	Could be Cu^{+} IVCT or Cu^{0} pairs	Hofmeister and Rossman, 1985b
Lazulite	Blue	Fe^{2+}–O–Fe^{3+} charge transfer	Amthauer and Rossman, 1984
Lazurite	Blue (lapis lazuli)	S_3^- (charge transfer)	Loeffler and Burns, 1978
Lepidolite	Pink	Mn^{2+} in octahedral coordination;	Faye, 1968
		Mn^{3+} in octahedral coordination	Marfunin, 1979a
Liddicoatite (see elbaite)			
Malachite	Green	Cu^{2+} in octahedral coordination	Marfunin, 1979a
Maw-sit-sit (rock)	Green	Cr^{3+} in octahedral coordination in the kosmochlor	Khomenko and Platonov, 1985
Microcline	Blue (amazonite)	Color center involving Pb^{3+} and structural water	Hofmeister and Rossman, 1985a
Nephrite (see actinolite)			
Oligoclase	Blue (moonstone)	Rayleigh scattering of light by lamellar structure	Lehmann, 1978
	Red (sunstone)	Red lepidocrocite or hematite platelets give the aventurescence	J. Koivula, pers. comm., 1988; Lehmann, 1978
Olivine group:			
Forsterite-fayalite series	Yellowish green (peridot)	Fe^{2+} in octahedral coordination	Loeffler and Burns, 1976
	Green (peridot, the material from Hawaii)	Fe^{2+} with minor amounts of Cr^{3+} in octahedral coordination	Anderson, 1954–55
Opal	Multicolors (play-of-color opal)	Diffraction by the regular stacking of silica spheres	Darragh and Sanders, 1965
	Orange to red (fire opal)	Microscopic to submicroscopic inclusions of iron hydrous oxides	J. Koivula, pers. comm., 1988
	Green (prase opal)	Microscopic to submicroscopic nickeliferous clay-like inclusions	Koivula and Fryer, 1984
Orthoclase	Yellow	Fe^{3+} in tetrahedral coordination	Hofmeister and Rossman, 1983
	Pink to red	Microscopic hematite and/or lepidocrocite inclusions	Andersen, 1915; J. Koivula, pers. comm., 1988
Pearls (oyster)			
Body color	All colors	Charge-transfer processes in traces of porphyrins and metalloporphyrins	Fox et al., 1983
	Green	High proportions of metalloporphyrins, apparently involving lead and zinc	Fox et al., 1983
	Pink	Less total porphyrin than green	Fox et al., 1983
Orient and overtone	Pink and green usually	Interference colors	E. Fritsch, unpub. data
Pectolite	Blue	Cu^{2+} in octahedral coordination	Koivula, 1986a
Phosphophyllite	Bluish green	Fe^{2+}	G. Rossman, unpub. data
Piemontite	Purplish red	Mn^{3+} in octahedral coordination	Burns, 1970

These freshwater baroque and round saltwater cultured pearls exhibit the delicate iridescent color (here mostly pink) that gemologists call orient. Photo © Harold & Erica Van Pelt.

Gem material	Color (variety or trade name, if any)	Cause	Reference
Plagioclase series	Blue	Color center involving Pb and water	Hofmeister and Rossman, 1986
	Yellow	Fe^{3+} in tetrahedral coordination and Fe^{2+} in octahedral coordination	Hofmeister and Rossman, 1983
Pumpellyite	Green (chlorastrolite)	Fe^{2+}–O–Fe^{3+} charge transfer plus Fe^{2+}	G. Rossman, unpub. data
Pyrope	Brownish red	Fe^{2+} in distorted cubic coordination	Manning, 1967a
	Red	Fe^{2+} in distorted cubic site plus Cr^{3+} in octahedral coordination	Anderson, 1954–55; Manning, 1967a
	Color change (in pyrope and pyrope-spessartine)	V^{3+} and/or Cr^{3+} in octahedral coordination	Schmetzer et al., 1980
Pyrope-Almandine	Reddish purple (rhodolite)	Fe^{2+} in distorted cubic coordination	Manning, 1967a
Pyroxene group (see enstatite, diopside, jadeite, kosmochlor in maw-sit-sit, or spodumene)			
Quartz	Violet to purple (amethyst)	$O^{2-}\rightarrow Fe^{4+}$ charge transfer, due to irradiation	Cox, 1977
	Blue	Inclusions of blue dumortierite	C. Fryer, pers. comm., 1988
		Inclusions of tourmaline	Gübelin and Koivula, 1987
		Inclusions of ilmenite of a diameter smaller than visible wavelengths	Zolensky et al., 1988
	Green ("greened amethyst" or prasiolite)	Fe^{2+}	Nassau, 1980
	Green (aventurine quartz)	Chromian mica (fuchsite) inclusions	Lehmann, 1978
	Greenish yellow	Color center	Nassau and Prescott, 1977
	Yellow to orange (citrine)	$O^{2-}\rightarrow Fe^{3+}$ charge transfer	Balitsky and Balitskaya, 1986
		Various Al^{3+}-related color centers	Samoilovich et al., 1969
	Smoky (smoky quartz)	Color center related to the Al^{3+} impurity	Partlow and Cohen, 1986
	Pink (rose quartz)	Charge transfer between a substitutional Ti^{4+} and an interstitial Ti^{3+};	Cohen and Makar, 1985
		unstable color center O^{-} ion bridging between substitutional aluminum and substitutional phosphorus atom;	Maschmeyer and Lehmann, 1983
		dumortierite inclusions	Applin and Hicks, 1987
	White (milky quartz)	Scattering of light by inclusions larger than the visible wavelengths	Fritsch, 1985
Rhodochrosite	Pink to red	Mn^{2+} in octahedral coordination	Rossman, 1988
Rhodolite (see pyrope-almandine)			
Rhodonite	Pink	Mn^{2+} in octahedral coordination, with minor Fe^{2+};	Marshall and Runcinam, 1975
		Mn^{3+} in octahedral coordination	Gibbons et al., 1974
Rutile	Blue (synthetic rutile)	Band transition due to the presence of Ti^{3+}	G. Rossman, unpub. data
Scapolite series	Various colors	Due to color centers related to irradiation of Cl, CO_3^{2-} or SO_4^{2-} groups present in the large voids of the crystal structure	Marfunin, 1979b
Scheelite	Yellow	Fe	Not proven: Gunawardene, 1986
Serpentine	Green (williamsite)	Cr^{3+} around chromite inclusions	J. Koivula, pers. comm., 1988
Shattuckite	Blue	Cu^{2+}	Fleischer, 1987
Shell	Pink (see conch shell)		
	Black	A violet organic pigment, haliotiviolin, has been recovered from the shell of the black abalone, *Haliotis cracherodii*	Fox et al., 1983
Sillimanite	Blue	Fe^{2+}–O–Ti^{4+} charge transfer, probably similar to blue kyanite	Rossman et al., 1982
	Yellow	Fe^{3+} or Cr^{3+} in tetrahedral coordination	Rossman et al., 1982
	Brown	Fe features of yellow sillimanite plus inclusions of iron-rich phase	Rossman et al., 1982
Sinhalite	Brown	$O^{2-}\rightarrow Fe^{3+}$ charge transfer and Fe^{2+} in octahedral coordination	Farrell and Newnham, 1965
Smithsonite	Blue-green	Cu^{2+}	G. Rossman, unpub. data
	Pink	Co^{2+}	G. Rossman, unpub. data
Sodalite	Blue	Interstitial oxygen ion O^{-} near Al or Si	Pizani et al., 1985
	Pink (hackmanite)	Unstable electron substituting for Cl^{-} in a tetrahedron of Na^{+} ions	Pizani et al., 1985

Pink rhodochrosite and yellow willemite contrast in hue, although they are both colored by Mn^{2+}. Different coordination of the Mn^{2+} ion is the clue here: octahedral in rhodocrosite, tetrahedral in willemite. Photo by Robert Weldon.



Wulfenite is an intrinsically colorless mineral (left), but it commonly acquires an orange coloration when impurity chromium atoms produce $O^{2-}\rightarrow Cr^{6+}$ charge transfer (center bottom), which is the intrinsic cause of color in crocoite (right). In contrast, blue wulfenite (top) is said to get its color from Mo^{4+}. Photo by Robert Weldon.

Gem material	Color (variety or trade name, if any)	Cause	Reference
Spessartine	Orange	Mn^{2+} in distorted cubic coordination	Manning, 1967a
Sphalerite	Yellow to black	Iron → sulfur charge transfer	Marfunin, 1979a
	Green	Co^{2+} in tetrahedral coordination	Marfunin, 1979a
Spinel group (see gahnite and gahnospinel, or spinel)			
Spinel	Violet to purple	Cr^{3+} in octahedral coordination and Fe^{2+} in tetrahedral coordination	G. Rossman, unpub. data
	Cobalt blue	Co^{2+} and Fe^{2+} in tetrahedral coordination	Shigley and Stockton, 1984
	Bluish green	Fe^{3+} and Fe^{2+} in tetrahedral coordination	G. Rossman, unpub. data
	Green (synthetic spinel)	Cr^{3+} in octahedral coordination	Vogel, 1934
	Pink to red	Cr^{3+} in octahedral coordination	Vogel, 1934; Anderson, 1954–55; Sumin, 1950
Spodumene	Purple to pink (kunzite)	Mn^{3+} in tetrahedral coordination; Mn^{3+} in octahedral coordination	Hassan and Labib, 1978; Cohen and Janezic, 1983
	Emerald green (hiddenite)	Cr^{3+} in octahedral coordination with also unstable Mn^{4+} color center; V^{3+} in octahedral coordination	Cohen and Janezic, 1983 Schmetzer, 1982
	Paler green	Unstable Mn^{4+} in octahedral coordination plus $Fe^{2+}\rightarrow Fe^{3+}$ charge transfer; Fe^{3+} in octahedral coordination	Cohen and Janezic, 1983 E. Fritsch, unpub. data
	Greenish yellow to brownish orange	Color center of unknown structure	Rossman and Qiu, 1982
Staurolite	Brown	Fe^{2+} in tetrahedral coordination	Burns, 1970
	Blue	Co^{2+} in tetrahedral coordination	Cech et al., 1981
Sugilite	Purple	Mn^{3+} and Fe^{3+}, presumably in octahedral coordination	Shigley et al., 1987
Taaffeite	Red to violet	Cr^{3+} in octahedral coordination	Schmetzer, 1983
Titanite (sphene)	Green	High Fe content	Mottana and Griffin, 1979
	Green (chrome sphene)	Cr^{3+} in octahedral coordination	Schmetzer, 1982
	Pink	Mn^{2+} in octahedral coordination, for certain Mn/Fe ratios, as well as pink carbonate inclusions	Mottana and Griffin, 1979
Topaz	Blue	Color centers of unknown structure	Schmetzer, 1986
	Green	Yellow and blue color centers	Petrov, 1977
	Yellow	Color center of unknown nature	Petrov, 1977
	Orange ("imperial topaz")	Yellow color center and Cr^{3+} in octahedral coordination	Petrov, 1977
	Pink	Cr^{3+} in octahedral coordination	Petrov, 1977
	Reddish brown ("sherry topaz")	Yellow and red color centers	Petrov, 1977
Tortoise shell	Yellow to brown	Charge transfer in organic products	Nassau, 1975a
Tourmaline group (see dravite, elbaite and liddicoatite, or uvite)			
Tremolite	Pink (hexagonite)	Mn^{3+}	Hawthorne, 1981
Tugtupite	Pink	Color center(s) involving sulphur	Povarennykh et al., 1971
Turquoise	Blue	Cu^{2+} in octahedral coordination	Diaz et al., 1971
Uvarovite	Green	Cr^{3+} in octahedral coordination	Manning, 1969; Calas, 1978
Uvite	Green ("chrome tourmaline")	V^{3+} generally with minor amounts of Cr^{3+}, both in octahedral coordination	Schmetzer and Bank, 1979; Schmetzer, 1982
Variscite (and Metavariscite)	Green	Cr^{3+} presumably in octahedral coordination	Anderson, 1954–55; Koivula, 1986b
Vesuvianite (idocrase)	Green	Fe^{3+} in octahedral coordination; with possible influence of $Fe^{2+}\rightarrow Fe^{3+}$ charge transfer	Manning, 1976, 1977
	Yellow	$O^{2-}\rightarrow Fe^{2+}$ charge transfer	Manning, 1977
	Brown	$Fe^{2+}\rightarrow Ti^{4+}$ charge transfer	Manning, 1977
Willemite	Yellow	Mn^{2+} in tetrahedral coordination	G. Rossman, unpub. data
Wulfenite	Blue	Mo^{4+}	Embrey et al., 1977
	Yellow to red	$O^{2-}\rightarrow Cr^{6+}$ charge transfer	Edson, 1980
Zircon	Blue	U^{4+}	Mackey et al., 1975
	Red	Nb^{4+} color centers	Fielding, 1970
Zoisite	Blue (tanzanite—heat treated)	V^{4+} in octahedral coordination; with V^{3+} in octahedral coordination	Hurlbut, 1969 G. Rossman, unpub. data
	Brown-violet	V^{3+} in octahedral coordination (treatment turns blue, tanzanite)	Hurlbut, 1965
	Green	Cr^{3+} in octahedral coordination	Schmetzer, 1982
	Pink (thulite)	Mn^{3+} in presumably octahedral coordination	Marfunin, 1979a

REFERENCES

Abou-Eid R.M. (1976) Absorption spectra of transition metal bearing minerals at high pressure. In R. J. G. Strens, Ed., *The Physics and Chemistry of Minerals and Rocks*, John Wiley & Sons, New York, pp. 641–675.

Amthauer G., Rossman G.R. (1984) Mixed valence of iron in minerals with cation clusters. *Physics and Chemistry of Minerals*, Vol. 11, pp. 37–51.

Andersen O. (1915) On adventurine feldspar. *American Journal of Science*, Vol. 40, pp. 351–399.

Anderson B.W. (1954–55) The spectroscope and its applications to gemmology, parts 10 to 17. *The Gemmologist*, Vol. 23, Nos. 275–282.

Andersson L.O. (1979) The difference between Maxixe beryl and Maxixe-type beryl: An electron paramagnetic resonance investigation. *Journal of Gemmology*, Vol. 16, No. 5, pp. 313–317.

Appel P.W., Jensen A. (1987) A new gem material from Greenland: Iridescent orthoamphibole. *Gems & Gemology*, Vol. 23, No. 1, pp. 36–42.

Applin K.R., Hicks B.D. (1987) Fibers of dumortierite in quartz. *American Mineralogist*, Vol. 72, pp. 170–172.

Balitsky V.S., Balitskaya O.V. (1986) The amethyst-citrine dichromatism in quartz and its origin. *Physics and Chemistry of Minerals*, Vol. 13, pp. 415–421.

Bell P.M., Mao H.K., Rossman G.R. (1975) Absorption spectroscopy of ionic and molecular units in crystals and glasses. In C. Karr, Jr., Ed., *Infrared and Raman Spectroscopy of Lunar and Terrestrial Minerals*, Academic Press, New York, pp. 1–38.

Berry F.J., Vaughan D.J. (1985) *Chemical Bonding and Spectroscopy in Mineral Chemistry.* Chapman and Hall, New York.

Bill H., Calas G. (1978) Color centers, associated rare-earth ions and the origin of coloration in natural fluorites. *Physics and Chemistry of Minerals*, Vol. 3, pp. 117–131.

Bosshart G., Frank E., Hänni H.A., Barot N. (1982) Blue color-changing kyanite from East Africa. *Journal of Gemmology*, Vol. 18, No. 3, pp. 205–212.

Braithwaite R.S.W., Flowers W.T., Hazeldine R.N., Russel M. (1973) The cause of the colour of Blue John and other purple fluorites. *Mineralogical Magazine*, Vol. 39, pp. 401–411.

Burns R.G. (1970) *Mineralogical Applications of Crystal Field Theory.* Cambridge Earth Science Series, Cambridge University Press.

Calas G. (1978) Le chrome et la couleur des minèraux: Un example "pédagogique." *Revue de Gemmologie a.f.g.*, Vol. 54, pp. 6–8.

Cech F., Povondra P., Vrana S. (1981) Cobaltoan staurolite from Zambia. *Bulletin de Minéralogie*, Vol. 104, pp. 526–529.

Cohen A.J., Janezic G.G. (1983) The crystal-field spectra of the $3d^3$, Cr^{3+} and Mn^{4+} in green spodumenes. In *The Significance of Trace Elements in Solving Petrogenetic Problems and Controversies*, Theophrastus Publications, Athens, Greece.

Cohen A.J., Makar L.N. (1985) Dynamic biaxial absorption spectra of Ti^{3+} and Fe^{2+} in a natural rose quartz crystal. *Mineralogical Magazine*, Vol. 49, pp. 709–715.

Collins A.T. (1982) Colour centres in diamond. *Journal of Gemmology*, Vol. 18, No. 1, pp. 37–75.

Cottrant J.-F., Calas G. (1981) Etude de la coloration de quelques diamants du Museum d'Histoire Naturelle. *Revue de Gemmologie a.f.g.*, No. 67, pp. 2–5.

Cox R.T. (1977) Optical absorption of the d^4 ion Fe^{4+} in pleochroic amethyst quartz. *Journal of Physics*, Vol. C10, pp. 4631–4643.

Darragh P.J., Sanders J.V. (1965) The origin of colour in opal. *Australian Gemmologist*, No. 46, pp. 9–12.

De Camargo M.B., Isotani S. (1988) Optical absorption of natural and irradiated pink tourmaline. *American Mineralogist*, Vol. 73, pp. 172–180.

Délé-Dubois M.-L., Merlin J.-C. (1981) Etude par spectroscopie Raman de la pigmentation du squelette calcaire du corail. *Revue de Gemmologie a.f.g.*, No. 68, pp. 10–13.

Diaz J., Farach H.A., Poole C.P. Jr. (1971) An electron spin resonance and optical study of turquoise. *American Mineralogist*, Vol. 56, pp. 773–781.

Dickson B.L., Smith G. (1976) Low temperature optical absorption and Mossbauer spectra of staurolite and spinel. *Canadian Mineralogist*, Vol. 14, pp. 206–215.

Dietrich R.V. (1985) *The Tourmaline Group.* Von Nostrand Reinhold Co., New York.

Dowty E. (1971) Crystal chemistry of titanian and zirconian garnet: I. Review and spectral studies. *American Mineralogist*, Vol. 56, pp. 1983–2009.

Edson G.M. (1980) The Red Cloud mine, Yuma County, Arizona. *Mineralogical Record*, Vol. 11, No. 3, pp. 141–152.

Embrey P.G., Dunn P.J., Clark A.M. (1977) Blue wulfenite from Tsumeb. *Mineralogical Record*, Vol. 8, No. 3, pp. 86–87.

Farrell E.F., Newnham R.E. (1965) Crystal field spectra of chrysoberyl, alexandrite, peridot and sinhalite. *American Mineralogist*, Vol. 50, pp. 1972–1981.

Faye G.H. (1968) The optical absorption spectra of certain transition metal ions in muscovite, lepidolite and fuchsite. *Canadian Journal of Earth Sciences*, Vol. 5, pp. 31–38.

Faye G.H. (1972) Relationship between crystal field splitting parameter "Δ_{VI}" and M_{host}-O bond distance as an aid in the interpretation of absorption spectra of Fe^{2+}-bearing materials. *Canadian Mineralogist*, Vol. 11, pp. 473–487.

Faye G.H., Manning P.G., Nickel E.H. (1968) The polarized optical absorption spectra of tourmaline, cordierite, chloritoid and vivianite: ferrous-ferric electronic interaction as a source of pleochroism. *American Mineralogist*, Vol. 53, pp. 1174–1201.

Ferguson J., Fielding P.E. (1971) The origins of the colours of yellow, green and blue sapphires. *Chemical Physics Letters*, Vol. 10, No. 3, pp. 262–265.

Fielding P.E. (1970) The distribution of uranium, rare earths, and color centers in a crystal of natural zircon. *American Mineralogist*, Vol. 55, pp. 428–440.

Fleischer M. (1987) *Glossary of Mineral Species*, 5th ed. Mineralogical Record, Inc., Tucson, AZ.

Fox D.L., Brown F.A., Losey G.S. (1983) Coloration, biological. *New Encyclopedia Brittanica*, Encyclopedia Brittanica, Chicago, IL, pp. 911–929.

Fritsch E. (1985) La couleur des minéraux et des gemmes: Des couleurs du diamant aux étoiles du saphir. *Monde & Minéraux*, No. 70, pp. 12–22.

Fritsch E., Rossman G.R. (1987) An update on color in gems. Part 1: Introduction and colors caused by dispersed metal ions. *Gems & Gemology*, Vol. 23, No. 3, pp. 126–139.

Fritsch E., Rossman G.R. (1988) An update on color in gems. Part 2: Colors involving multiple atoms and color centers. *Gems & Gemology*, Vol. 24, No. 1, pp. 3–15.

Gibbons R.V., Ahrens T.J., Rossman G.R. (1974) A spectrographic interpretation of shock-produced color change in rhodonite ($MnSiO_3$): The shock-induced reduction of Mn(III) to Mn(II). *American Mineralogist*, Vol. 59, pp. 177–182.

Goldman D.S., Rossman G.R., Dollase W.A. (1977) Channel constituents in cordierite. *American Mineralogist*, Vol. 62, pp. 1144–1157.

Goldman D.S., Rossman G.R., Parkin K.M. (1978) Channel constituents in beryl. *Physics and Chemistry of Minerals*, Vol. 3, pp. 225–235.

Gübelin E.J. (1975) *The Color Treasury of Gemstones.* Elsevier

Phaidon, London.

Gübelin E.J., Koivula J.I. (1987) *Photoatlas of Inclusions in Gemstones*, ABC Edition, Zurich.

Gübelin E.J., Weibel M. (1975) Green vanadium grossular garnet from Lualenyi, near Voi, Kenya. *Lapidary Journal*, Vol. 29, pp. 402–426.

Gunawardene M. (1986) Colombage-Ara scheelite. *Gems & Gemology*, Vol. 22, No. 3, pp. 166–169.

Hassan F., Labib M. (1978) Induced color centers in α-spodumene called kunzite. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 134, No. 1, pp. 104–115.

Harder H. (1969) Farbgebende Spurenelemente in den natürlichen Korunden. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 110, pp. 128–141.

Hawthorne F. (1981) Amphibole spectroscopy. In D. R. Veblen, Ed., *Reviews in Mineralogy*, Vol. 9A: *Amphiboles and Other Hydrous Pyriboles—Mineralogy*, Mineralogical Society of America, Washington, DC, pp. 103–137.

Hirai H., Nakazawa H. (1982) Origin of iridescence in garnet: An optical interference study. *Physics and Chemistry of Minerals*, Vol. 8, pp. 25–28.

Hofmeister A.M., Rossman G.R. (1983) Colors in feldspars. In P. H. Ribbe, Ed., *Reviews in Mineralogy*, Vol. 2, 2nd ed.: *Feldspar Minerals*, Mineralogical Society of America, Washington, DC, pp. 271–280.

Hofmeister A.M., Rossman G.R. (1985a) A spectroscopic study of irradiation coloring of amazonite: Structurally hydrous, Pb-bearing feldspar. *American Mineralogist*, Vol. 70, pp. 794–804.

Hofmeister A.M., Rossman G.R. (1985b) Exsolution of metallic copper from Lake County labradorite. *Geology*, Vol. 13, pp. 644–647.

Hofmeister A.F., Rossman G.R. (1986) A spectroscopic study of blue radiation coloring plagioclase. *American Mineralogist*, Vol. 71, pp. 95–98.

Hurlbut C.S. (1969) Gem zoisite from Tanzania. *American Mineralogist*, Vol. 54, pp. 702–709.

Khomenko V.M., Platonov A.N. (1985) Electronic absorption spectra of Cr^{3+} ions in natural clinopyroxenes. *Physics and Chemistry of Minerals*, Vol. 11, pp. 261–265.

Koivula J.I. (1986a) Gem news: Pectolite. *Gems & Gemology*, Vol. 22, No. 3, pp. 187–188.

Koivula J.I. (1986b) Gem news: Metavariscite. *Gems & Gemology*, Vol. 22, No. 4, pp. 247–248.

Koivula J.I. (1987) Gem news: Iridescent andradite garnets. *Gems & Gemology*, Vol. 23, No. 3, pp. 173–175.

Koivula J.I., Fryer C.W. (1984) Green opal from East Africa. *Gems & Gemology*, Vol. 20, No. 4, pp. 226–227.

Lehmann G. (1978) Farben von Mineralen [sic] und ihre Ursachen. *Fortschritte der Mineralogie*, Vol. 56, No. 2, pp. 172–252.

Loeffler B.M., Burns R.G. (1976) Shedding light on the color of gems and minerals. *American Scientist*, Vol. 64, pp. 636–647.

Lowther J.E. (1984) The form of different charge states of the vacancy in diamond. *Journal of Physics and Chemistry of Solids*, Vol. 45, pp. 127–131.

Mackey D.J., Runcinam W.A., Vance E.R. (1975) Crystal-field calculations for energy levels of U^{4+} in ZrSiO$_4$. *Physical Review B*, Vol. 11, pp. 211–218.

Manning P.G. (1967a) The optical absorption spectra of the garnets almandine-pyrope, pyrope and spessartine and some structural interpretations of mineralogical significance. *Canadian Mineralogist*, Vol. 9, pp. 237–251.

Manning P.G. (1967b) The optical absorption spectra of some andradite and the identification of the $^6A_1 \rightarrow {}^4A_1\ {}^4E(G)$ transition in octahedrally bonded Fe^{3+}. *Canadian Journal of Earth Sciences*, Vol. 4, pp. 1039–1047.

Manning P.G. (1969) Optical absorption studies of grossular, andradite (var. colophonite) and uvarovite. *Canadian Mineralogist*, Vol. 9, pp. 723–729.

Manning P.G. (1970) Racah parameters and the relationship to lengths and covalence of Mn^{2+}- and Fe^{3+}-oxygen bonds in silicates. *Canadian Mineralogist*, Vol. 10, pp. 677–688.

Manning P.G. (1972) Optical absorption spectra of Fe^{3+} in octahedral and tetrahedral sites in natural garnets. *Canadian Mineralogist*, Vol. 11, pp. 826–839.

Manning P.G. (1973) Effect of second nearest-neighbour interaction on Mn^{3+} absorption in pink and black tourmaline. *Canadian Mineralogist*, Vol. 11, pp. 971–977.

Manning P.G. (1976) Ferrous-ferric interaction on adjacent face-sharing antiprismatic sites in vesuvianite: Evidence for ferric iron in eight coordination. *Canadian Mineralogist*, Vol. 14, pp. 216–220.

Manning P.G. (1977) Charge transfer interaction and the origin of color in brown vesuvianite. *Canadian Mineralogist*, Vol. 15, pp. 508–511.

Manning P.G., Owens D.R. (1977) Electron microprobe, X-ray diffraction, and spectral studies of South African and British Columbian "jades." *Canadian Mineralogist*, Vol. 15, pp. 512–517.

Manson D.V., Stockton C.M. (1982) Gem-quality grossular garnets. *Gems & Gemology*, Vol. 18, No. 4, pp. 204–213.

Marfunin A.S. (1979a) *Physics of Minerals and Inorganic Materials, An Introduction.* Trans. by N. G. Egorova and A. G. Mishchenko, Springer Verlag, Berlin.

Marfunin A.S. (1979b) *Spectroscopy, Luminescence and Radiation Centers in Minerals.* Trans. by V. V. Schiffer, Springer Verlag, Berlin.

Marshall M., Runcinam W.A. (1975) The absorption spectrum of rhodonite. *American Mineralogist*, Vol. 60, pp. 88–97.

Maschmeyer D., Lehmann G. (1983) A trapped-hole center causing rose coloration of natural quartz. *Zeitschrift für Kristallographie*, Vol. 163, pp. 181–196.

Mattson S.M., Rossman G.R. (1984) Ferric iron in tourmaline. *Physics and Chemistry of Minerals*, Vol. 11, pp. 225–234.

Mattson S.M., Rossman G.R. (1987) Identifying characteristics of charge transfer transitions in minerals. *Physics and Chemistry of Minerals*, Vol. 14, pp. 94–99.

Moore R.K., White W.B. (1971) Intervalence electron transfer effects in the spectra of the melanite garnets. *American Mineralogist*, Vol. 56, pp. 826–840.

Mottana A., Griffin W.L. (1979) Pink titanite (greenovite) from St. Marcel, Valle D'Aosta, Italy. *Rendiconti Societa Italiana di Mineralogia e Petrologia*, Vol. 35, pp. 135–143.

Nassau K. (1975a) The origin of color in gems and minerals. Part 2. *Gems & Gemology*, Vol. 15, No. 1, pp. 2–11.

Nassau K. (1975b) The origin of color in gems and minerals. Part 3. *Gems & Gemology*, Vol. 15, No. 2, pp. 34–43.

Nassau K. (1980) *Gems Made by Man.* Chilton Book Co., Radnor, PA.

Nassau K. (1983) *The Physics and Chemistry of Color: The Fifteen Causes of Color.* John Wiley & Sons, New York.

Nassau K. (1984) *Gemstone Enhancement.* Butterworths, Stoneham, MA.

Nassau K., Prescott E. (1977) Smoky, blue, greenish yellow and other irradiation-related colors in quartz. *Mineralogical Magazine*, Vol. 41, pp. 301–312.

Nassau K., Shigley J.E. (1987) A study of the General Electric synthetic jadeite. *Gems & Gemology*, Vol. 23, No. 1, pp. 27–35.

Nassau K., Valente G.K. (1987) The seven types of yellow sapphire and their stability to light. *Gems & Gemology*, Vol. 23, No. 4, pp. 222–231.

Parkin K.M., Loeffler B.M., Burns R.G. (1977) Mossbauer spectra of kyanite, aquamarine, and cordierite showing intervalence charge transfer. *Physics and Chemistry of Minerals*, Vol. 1, pp. 301–311.

Partlow D.P., Cohen A.J. (1986) Optical studies of biaxial Al-related color centers in smoky quartz. *American Mineralogist*, Vol. 71, pp. 589–598.

Petrov I. (1977) Farbuntersuchungen an Topas. *Neues Jahrbuch für Mineralogie Abhandlungen*, Vol. 130, No. 3, pp. 288–302.

Pizani P.S., Terrile M.C., Farach H.A., Poole C.P. Jr. (1985) Color centers in sodalite. *American Mineralogist*, Vol. 70, pp. 1186–1192.

Povarennykh A.S., Platonov A.N., Tarashchan A.N., Belichenko V. P. (1971) The colour and luminescence of tugtupite (beryllosodalite) from Ilimaussaq, South Greenland. *Meddelelser om Grønland*, Vol. 181, pp. 1–12.

Pye L.D., O'Keefe J.A., Freéchette V.D., Eds. (1984) *Natural Glasses*. North Holland Publishing, Amsterdam.

Ribbe P.H. (1972) Interference colors in oil slicks and feldspars. *Mineralogical Record*, Vol. 3, pp. 18–22.

Rolandi V. (1981) Les gemmes du regne animal: Etude gemmologique des sécrétions des Cnidaires. *Revue de Gemmologie a.f.g.*, Vol. 66, pp. 3–9.

Rossman G.R. (1974a) Optical spectroscopy of green vanadium apophyllite from Poona, India. *American Mineralogist*, Vol. 59, pp. 621–622.

Rossman G.R. (1974b) Lavender jade. The optical spectrum of Fe^{3+} and Fe^{2+}–Fe^{3+} intervalence charge transfer in jadeite from Burma. *American Mineralogist*, Vol. 59, pp. 868–870.

Rossman G.R. (1980) Pyroxene spectroscopy. In C. T. Prewitt, Ed., *Reviews in Mineralogy*, Vol. 7: *Pyroxenes*, Mineralogical Society of America, Washington, DC, pp. 93–113.

Rossman G.R. (1981) Color in gems: The new technologies. *Gems & Gemology*, Vol. 17, No. 2, pp. 60–71.

Rossman G.R. (1988) Optical spectroscopy. In F. C. Hawthorne, Ed., *Reviews in Mineralogy*, Vol. 18: *Spectroscopic Methods in Mineralogy and Geology*, Mineralogical Society of America, Washington, DC, pp. 207–254.

Rossman G.R., Mattson S.M. (1986) Yellow, manganese-rich elbaite with manganese-titanium intervalence charge transfer. *American Mineralogist*, Vol. 71, pp. 599–602.

Rossman G.R., Qiu Y. (1982) Radioactive irradiated spodumene. *Gems & Gemology*, Vol. 18, No. 2, pp. 87–90.

Rossman G.R., Grew E.S., Dollase W.A. (1982) The colors of sillimanite. *American Mineralogist*, Vol. 67, pp. 749–761.

Samoilovich M.I., Tsinober L.I., Kreishop V.N. (1969) The nature of radiation-produced citrine coloration in quartz. *Soviet Physics – Crystallography*, Vol. 13, pp. 626–628.

Schiffmann C.A. (1981) Unstable colour in a yellow sapphire from Sri Lanka. *Journal of Gemmology*, Vol. 17, No. 8, pp. 615–618.

Schlee D. (1984) Ungewöhnliche Farbvarianten des Baltischen Bernsteins: Blau, grau, orange und "gold" als Folge von Rissesystemen. *Bernstein-Neuigkeiten, Stuttgarter Beiträge zur Naturkunde, Series C*, No. 18, pp. 2–8.

Schmetzer K. (1982) Absorptionsspektroskopie und Farbe von V^{3+}-haltigen natürlichen Oxiden und Silikaten – ein Beitrag zur Kristallchemie des Vanadiums. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 144, pp. 73–106.

Schmetzer K. (1983) Crystal chemistry of natural Be-Mg-Al-oxides: Taaffeite, taprobanite, musgravite. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 146, pp. 15–28.

Schmetzer K. (1986) Färbung und Bestrahlungschaden in elektronenbestrahlten blauen Topasen. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 35, No. 1/2, pp. 27–38.

Schmetzer K. (1987) Zur Deutung der Farbursache blauer Saphire – eine Diskussion. *Neues Jahrbuch für Mineralogie, Monatshefte*, No. 8, pp. 337–343.

Schmetzer K., Bank H. (1979) East African tourmalines and their nomenclature. *Journal of Gemmology*, Vol. 16, pp. 310–311.

Schmetzer K., Bank H. (1981) The colour of natural corundum. *Neues Jahrbuch für Mineralogie, Monatshefte*, Vol. 11, No. 2, pp. 59–68.

Schmetzer K., Bank H., Gübelin E. (1980) The alexandrite effect in minerals: Chrysoberyl, garnet, corundum, fluorite. *Neues Jahrbuch für Mineralogie, Abhandlungen*, Vol. 138, pp. 147–164.

Schmetzer K., Bosshart G., Hänni H.A. (1982) Naturfarbene und behandelte gelbe und orange braune Sapphire. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 31, No. 4, pp. 265–279.

Schmetzer K., Bosshart G., Hänni H.A. (1983) Naturally-coloured and treated yellow and orange brown sapphires. *Journal of Gemmology*, Vol. 18, No. 7, pp. 607–621.

Shigley J.E., Foord E.E. (1984) Gem-quality red beryl from the Wah-Wah Mountains, Utah. *Gems & Gemology*, Vol. 20, No. 4, pp. 208–221.

Shigley J.E., Koivula J.I. (1985) Amethystine chalcedony. *Gems & Gemology*, Vol. 21, No. 4, pp. 219–223.

Shigley J.E., Koivula J.I., Fryer C.W. (1987) The occurrence and gemological properties of Wessels Mine sugilite. *Gems & Gemology*, Vol. 23, No. 2, pp 78–90.

Shigley J.E., Stockton C.M. (1984) "Cobalt-blue" gem spinels. *Gems & Gemology*, Vol. 20, No. 1, pp. 34–41.

Smith G. (1977) Low temperature optical studies of metal–metal charge transfer transitions in various minerals. *Canadian Mineralogist*, Vol. 10, pp. 500–507.

Smith G., Strens R.G.J. (1976) Intervalence transfer absorption in some silicate, oxide and phosphate minerals. In R. G. J. Strens, Ed., *The Physics and Chemistry of Minerals and Rocks*, John Wiley & Sons, New York, pp. 583–612.

Smith G., Hålenius U., Langer K. (1982) Low temperature spectral studies of Mn^{3+}–bearing andalusite and epidote type minerals in the range 30000–5000 cm^{-1}. *Physics and Chemistry of Minerals*, Vol. 8, pp. 136–142.

Stockton C.M., Manson D.V. (1983) Gem andradite garnets. *Gems & Gemology*, Vol. 19, No. 4, pp. 202–208.

Stockton C.M., Manson D.V. (1984) Editorial forum: "Fine green" demantoids. *Gems & Gemology*, Vol. 20, No. 3, p. 179.

Sumin N.G. (1950) Accessory elements in spinels. *Trudy Mineralog. Museya, Akad. Nauk S.S.S.R.*, No. 2, pp. 113–123.

Vogel P. (1934) Optische Untersuchungen am Smaragd und einigen anderen durch Chrom gefärbten Mineralien. *Neues Jahrbuch für Mineralogie, Geologie und Paleontologie*, Vol. A68, pp. 401–438.

Webster R., rev. by B. W. Anderson (1983) *Gems, Their Sources, Descriptions and Identification*, 4th ed. Butterworths, London.

Wood D.L., Nassau K. (1968) The characterization of beryl and emerald by visible and infrared absorption spectroscopy. *American Mineralogist*, Vol. 53, pp. 777–800.

Zolensky M.E., Sylvester P.J., Paces J.B. (1988) Origin and significance of blue coloration in quartz from Llano rhyolite (llanite), north-central Llano County, Texas. *American Mineralogist*, Vol. 73, pp. 313–323.