TYPES OF COLORING IN MINERALS*

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ABSTRACT

Data relative to the various types of coloring which can occur in minerals have been collected and correlated. These types are classified and subdivided according to the means or mechanism of the color production, their characteristic features are described, and illustrative examples are cited. A fundamental distinction is made between coloring due to characteristic absorption or reflection which is determined by the chemical composition of the substance, and coloring caused by structural characteristics. Both body color and surface color are significant in the former type of coloring, while the more important types of structural coloring are those produced by interference and scattering. Other minor types are briefly described. Practical criteria are suggested for the recognition and identification of the type or types of coloring displayed in any particular specimen. An extensive bibliography is given.

* A more extensive paper on this same general subject, containing supplementary and explanatory data, is available through *Auxiliary Publication* as *Document* No.1515, microfilm or photoprint copies of which may be obtained for 76 cents or $5.80, respectively, from the AMERICAN DOCUMENTATION INSTITUTE, 2101 Constitution Ave., Washington, D. C.

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Introduction

In the rather voluminous literature pertaining to the color of minerals there is a large amount of data and discussion regarding the presence of various chemical elements and compounds, or less commonly, physical structures, which are considered to be responsible for the particular color in question. Relatively little attention has been paid, however, to a consideration of the manner in which these elements, compounds or structures have caused the material to be colored. The purpose of this paper is to classify and describe the various types of coloring which can occur, and to propose criteria for their recognition and identification. A definite need for such classification and criteria was felt as a result of several spectrographic examinations of smoky quartz (16), blue halite (18), Siamese zircons (17), kunzite, and benitoite, which were made in an attempt to correlate color with chemical composition.

Extensive discussions of color production in nature as well as the related subjects of lustre and visibility of objects are to be found in the series of articles by Bancroft (3, 4, 5, 6, 7) and Mason (21), and in Wood (39). Many of the data presented below are derived from these sources, to which due acknowledgment must be made.

Fundamental Types of Coloring

If a mineral or other substance which does not emit any light itself is illuminated by white light, any color displayed, other than white, must obviously be a subtractive color resulting from the removal or weakening of certain components of the original white light. The mechanism or means whereby such selective weakening or removal is accomplished may be used as a primary basis for classifying the various types of coloring which can occur. There are two fundamentally different cases: (1) in consequence of the *chemical composition* of the material, part of the light is either absorbed or else suffers selective reflection which is intimately connected with intense absorption at other wave lengths; or, (2) due to the *physical structure* of the material the direction of propagation of some of the components which make up the white light is characteristically altered. In the first case we obtain *chemico-compositional coloring;* in the second case we have what is generally termed *structural coloring*. These two fundamental types may be divided further into sub-types, based on the details of the mechanism responsible.

It is to be emphasized that the color displayed by a particular specimen may be due to only one of the various causes which are to be described, or may be attributable to several of them acting at the same time. Thus the observed color might be partly chemico-compositional

and partly structural, while the structural color itself might be produced in several ways simultaneously. The method of illumination and observation, the size, and the optical properties of the surrounding or contacting medium (e.g., air, water, or another mineral) may each have an effect in determining what type of coloring predominates in cases in which the observed color is due to several causes.

In the case of fluorescent or phosphorescent minerals the color observed may be modified greatly if any fluorescent or phosphorescent light is emitted. Fluorite is an example of a mineral which often fluoresces in the light commonly used for examination. Color which is due to fluorescence or phosphorescence will not be considered further in this paper, but care must be taken, in examining such minerals, to avoid confusion.

CHEMICO-COMPOSITIONAL COLORING[1]

When light falls upon a substance which exhibits coloring due to its chemical composition rather than its physical structure, part of the light is usually reflected from the surface while the rest penetrates the material. A portion of the light which actually enters may be transmitted through the substance, if the latter is sufficiently transparent or translucent; the remainder is absorbed.

The mechanism of such absorption of light energy, and hence the production of chemico-compositional coloring, may be explained on the basis of electron displacement or excitation in the absorbing material. Thus part of the energy in the incident radiation is utilized in producing excitation, from which state the energy usually degenerates into simple heat energy, or, in some cases, may be reradiated as fluorescence, or may initiate chemical reaction.

If light of only certain wave lengths is selectively absorbed, the material will display some particular hue,[2] such as red, yellow or blue; if there is strong absorption throughout all the visible portion of the spectrum, the material is said to be black.

All substances which show chemico-compositional coloring are characterized to a varying degree by both *body color* and *surface color*.

Body Color

Body color, or, as it is sometimes called, *transmission color*, is due to

[1] The terms *pigment* and *pigmental* are often used to designate this type of coloring. However, these terms are frequently used in other or restricted senses. Their use may therefore lead to considerable ambiguity and confusion, and hence has been avoided in this discussion.

[2] Definitions and discussion of the terms used in color nomenclature and color specification may be found in the reports of the committees of the *Optical Society of America* (14, 15, 27, 35).

this selective absorption, within the colored substance, of part of the light which enters. This is a very important type of coloring in minerals, and is displayed, for example, by hematite, malachite and azurite. The amount of absorption and consequently the saturation of the observed body color may be increased by internal and other reflections which serve to lengthen the path of transmission.

The color is independent of the direction of propagation of the light in isotropic material, while in anisotropic substances it may vary with the crystallographic orientation. In the latter case the color, for any given direction of propagation, depends upon the plane or planes of vibration of the polarized light. This color change which results from change in the plane of vibration of the light is called *pleochroism*, and is to be distinguished from color changes due to polychromatism. The latter are due to the fact that the hue and saturation of the color, in isotropic as well as anisotropic materials, are dependent on both the concentration of the absorbing substance and the depth or thickness of the medium traversed. These color changes have been designated sometimes by the word *dichromatism*, but the general term, *polychromatism*, which is not limited to a two-color change, is preferred by the authors. Ferric oxide is strongly polychromatic, displaying hues ranging from yellow through red to nearly black.

Surface Color

In the case of materials which absorb very strongly, light of certain wave lengths which falls upon the surface tends to be reflected selectively, thus producing *surface color*, or, as it is sometimes called, *reflection color*. The light which passes on into the material is absorbed rapidly, due to the relatively high degree of opacity. It is to be emphasized that this selective reflection of part of the light is dependent upon the chemical composition of the material rather than upon its physical structure, and is closely related to the intense absorption of the light actually entering the material. In general, there is also some non-selective reflection of part of the incident whit elight, thus causing a decrease in saturation of the surface color.

Selective reflection of this type can occur only when the material has a nearby absorption band, or bands. The intense absorption and the selective reflection are caused by the same mechanism, and are thus inter-related.

Typical minerals exhibiting prominent surface color are the native metals, such as copper and gold, and various oxides and sulfides which display marked metallic lustre, such as pyrite, chalcopyrite, galena and

stibnite. Substances showing metallic lustre ordinarily exhibit either surface or interference color (5a).

The surface color of a given substance is dependent on both the angle of observation and the relative optical indices of the substance and the contacting or embedding medium (which is usually the air, but may be another mineral). Increasing the angle of incidence (i.e., moving away from normal or perpendicular incidence) tends to displace the hue toward the blue end of the spectrum. Usually this color change is not large, and, according to Mason (21a), is observed only at nearly grazing incidence.

Michelson (23) and Mason (21a) emphasize that the orientation of the plane of polarization of the reflected light is significant in determining the amount of the color change. If the reflected light is examined through a nicol prism, that light which vibrates perpendicular to the plane of incidence and reflection shows little or no appreciable change in color with increasing angle of incidence, while the light vibrating parallel to this plane shows a relatively marked color change.

The light selectively reflected at all angles other than zero is elliptically polarized to a greater or less degree; the amount depends on the angle of reflection. This property may be used as a means of distinguishing surface color from thin-film reflections, since in the latter case, according to Mason (21b), elliptical polarization occurs at angles greater than the polarizing angle, but is not produced at angles less than this.

The change in color produced by varying the index of the surrounding or contacting medium is described by Wood (39a) and Mason (21a) for certain synthetic dyes. Color changes of this type are probably not prominent in the case of minerals, although the observed color of a metal could easily be affected in this manner as a result of the formation of a transparent film of oxide, or other alteration product.

The selectively reflected light is often roughly complementary in color to that which is transmitted. This, however, is not necessarily the case, since the transmitted light is composed of white light minus the selectively reflected components, and also minus those removed by absorption. If the body absorption is nearly non-selective, the surface and transmitted colors are nearly complementary in hue (as in some metals), and Haidinger's law is therefore approximately obeyed; if the absorption is large and selective, the two colors may be far from complementary.

The cause of surface color has been ascribed to optical resonance (4a). This phenomenon also probably explains the transmission colors of thin films of metals. Thin films of gold are green, or, if thin enough, even blue (4b); the surface color of gold, as intensified by repeated reflection, is a red-orange (4b, 4c). Thin films of silver are blue, while the surface color,

as observed after repeated reflection, is orange (4b, 4c). This change in apparent surface color on repeated reflection is simply another case of polychromatism.[3]

Effect of Size on Chemico-Compositional Coloring

The state of subdivision or absolute size of a substance possessing body color has an important effect upon the saturation of the observed color, and may affect the hue. Since colorless, transparent substances, if finely divided or powdered, appear white (e.g., snow, foam or fog, sand, chalk and powdered glass are white, while pure ice, water, rock crystal, Iceland spar and sheet glass, which, respectively, have corresponding chemical compositions, are highly transparent), due to the large amount of light diffusely reflected by their tremendously large number of surfaces, colored substances which display body color will show a progressive lightening on continued grinding or subdivision. This is attributable, of course, to the fact that the light which enters the particles is reflected out again before it can traverse more than a relatively thin layer of the absorbing material. Consequently relatively little absorption takes place, and the color due to this absorption is diluted by a large amount of white, diffusely reflected light.

The amount of diffuse reflection is increased both by increasing the fineness of subdivision (provided that the particles are not made so fine that diffraction, scattering, interference or other structural coloring becomes prominent), and by increasing the difference in index of refraction between the particles and the surrounding medium.

Conversely, the white light which is diffusely reflected can be eliminated by immersing the powder in an oil or other transparent medium which has the same index of refraction as the particles. Light which falls upon the material will then pass through greater thicknesses, and will show the original body absorption color.

Chalcanthite or common copper sulfate, for example, is deep blue in color if large crystals are examined, but, on continued grinding, the powder becomes pale blue and finally nearly white. Immersing the white powder in an oil of the same, or nearly the same, index of refraction restores the original blue color. An oil or other medium of index intermediate between the indices for air and the particles will, of course, merely reduce the diffuse reflection, and so decrease the whiteness of the reflected light. A piece of white paper or cloth, for instance, looks less

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[3] The orange hue produced by repeated reflections from a silver surface may be observed very readily by folding a piece of polished silver foil into a deep, narrow V. If the open part of the V is then pointed toward the light, the orange hue may be seen on the interior surface (20).

white and more nearly transparent when wetted, because the air spaces between the fibers have been replaced by water which has an index closer to that of the fibers. Wet mud is likewise more deeply colored than dry mud.

Inclusions of a transparent, colored mineral would therefore show varying saturation, and often change in hue, depending on both the particle size and the relative indices of the inclusions and the embedding mineral.

It is well known that metals such as platinum (4e), silver (4e), gold (4f), copper and iron appear black when very finely divided. As the particle size increases, the characteristic surface color may also begin to appear, and will ultimately predominate. Finely divided gold, for instance, may appear black, dark brown, or yellow-brown, according to the particle size (4b, 4f). Wood (39b) accounts for the black color by considering that the particles form a light trap, so that the light falling upon them is absorbed by the resulting multiple reflections from particle to particle. However, this explanation does not seem entirely satisfactory.

It is interesting to note that with increasing subdivision the color of one class of substances, such as the metals mentioned above, tends to become *black*, while in another type of materials, such as glass or blue copper sulfate, the color approaches *white*.[4] In the first case, the substances cited are relatively highly opaque, and may display prominent *surface color;* in the second case, the materials are relatively transparent, and any color shown is due primarily to *body absorption*.

Since the color of the streak of a mineral is that of its fine powder, it may be readily seen why the color of the streak may vary considerably from the color observed in a large crystal or massive specimen. Likewise, if the mineral is composed of aggregates of minute crystals, or a compacted powder, or other fine particles, the color may vary from that shown by a single large crystal. For example, with decreasing particle size hematite may change in color from nearly black to red (which is the color of the streak), and finally to yellow (which is also the color of solutions of ferric iron) (6a). These color changes are prominent because ferric oxide is markedly polychromatic.

Correlation with Composition

Chemico-compositional coloring is always to be correlated with chemical composition, as shown by analysis or synthesis. The state of oxidation, combination, coordination, or hydration of the various components is highly significant. Ferrous iron, for example, is sometimes considered to cause a greenish color in minerals, although many ferrous compounds

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[4] This white may, under certain conditions, appear somewhat bluish (22).

tend to be colorless. According to Bancroft (6a), ferrous iron alone causes little or no color; ferric oxide, however, may cause a yellow or red color, while the simultaneous presence of both ferric and ferrous iron may produce a blue. Greens are considered to result from mixtures of the blue and yellow, while red and blue together cause the appearance of purple. The ratio of ferrous to ferric iron consequently has an important bearing on the color exhibited.

Likewise, dilute solutions of manganous manganese are nearly colorless, while the same concentration of trivalent manganese shows an intense purple color. Hexavalent manganese (as in manganates) is green; heptavalent manganese (as in permanganates) is again purple. Although the two purple forms of manganese (trivalent and heptavalent) may usually appear to the eye to have the same, or a very similar hue, the absorption spectra of the two forms are very different in character (19).

If the coloring is due to absorption, chemical analysis or synthesis must consequently show the presence of a chemical substance which can act in this manner. However, the mere presence of a substance which, under the proper conditions, can cause selective absorption does not necessarily mean that the color observed must be chemico-compositional in character and due to that substance. The state of oxidation or mode of combination or coordination may be such that the resulting color is not the same as that usually associated with the simple ion or molecule indicated by the analysis.

STRUCTURAL COLORING

Structural colors are those produced when certain components in the original incident white light are selectively changed in direction of propagation as a result of the physical structure or composition of the material. The coloring therefore is not a function of the chemical composition, as such, but is dependent on physical or structural characteristics such as laminae, thin films, and minute particles, which are often of colloidal dimensions. Certain types of structures, such as those which produce prismatic or refraction colors, may be much larger. All of these structures are relatively large, however, in comparison with the molecules, ions or other units which compose them.[5]

This selective redirection of certain components means that the composition of the light which is diffracted, scattered, refracted, or other-

[5] It is true, of course, that selective absorption or reflection of light is dependent upon the electronic structure of the molecules, ions, or complexes themselves, and hence chemico-compositional coloring is, in this sense, a structural phenomenon. However, the term *structural coloring,* as used in this article, has been generally adopted to designate only the colors produced by relatively large-scale structural arrangements, in which there is no conversion of energy into other forms, but only a selective change in direction of propagation.

wise selectively affected by the physical structure of the material, varies according to the direction of observation, the direction of illumination being kept constant. Consequently, for any given direction of observation, only certain components of the original white light may be seen. Another direction of observation may cause an entirely different set of components to be visible, and so cause an entirely different distribution of energy to appear. It is to be emphasized that there is no conversion of energy into another form, such as heat.

The various types of structural coloring may be sub-classified according to the types of physical structure which produce them. Structural colors may be displayed by either transparent or opaque materials, which, in turn, may or may not show chemico-compositional coloring in addition.

1. *Interference Colors*

These are produced by the phenomenon of interference, which occurs when light impinges upon laminae, or thin films, which are usually roughly comparable in thickness with the wave length of the incident white light.

The mechanism of production consists of partial reflection of light from both upper and lower surfaces of the film, with consequent reinforcing interference for those components of the white light which have the proper wave length in relation to the effective thickness and relative index of refraction of the film. The other components of the light suffer destructive interference in reflection and are completely transmitted. Multiple reflections serve to intensify and purify the color. The colors are subtractive, since one or more of the components forming the original white light are selectively weakened or removed. The hue changes greatly and sharply, according to Newton's series, on varying the angle of incidence or observation, since the path differences in the film are changed. Increasing the angle of incidence shifts the color toward the low-order side of the series, which is equivalent to thinning the film (8). This iridescence, or change of color with angle, is a very striking characteristic of interference colors.

There are quite definite limits to the thickness of film which is effective in producing these interference colors. If the film is too thick, the colors will be greatly diluted and very weak; if the film is too thin, interference colors can no longer be obtained. Instead, selective laminary diffraction and reflection may result.

The saturation of the observed color may be affected by the geometrical character of the illuminating light. A narrow beam in which the light rays are all parallel produces greater saturation in the interference colors than does diffuse illumination.

The colors observed in precious opal are generally attributed to interference produced in thin, curved lamellae which vary somewhat in index of refraction (9). Due to multiple reflection the colors may be very pure and intense (39c).

In mother-of-pearl, or nacre, the more brilliant of the colors exhibited are likewise due to interference in the thin laminae which compose the inner portion of the shell. Diffraction colors also are to be observed here, but they are usually much fainter (25, 4g).

Parsons (24) apparently attributes the color observed in peristerite to interference due to reflection from twinning planes. He also presents and discusses extracts from the literature, many of which agree with more recent statements (10, 30, 32, 38) ascribing the iridescent coloring of labradorite to interference. Andersen (2) considers that hematite lamellae cause interference colors in aventurine feldspar.

Other examples are the brilliant interference colors displayed by oil films, as on a wet street, and by soap bubbles, and the temper or tarnish colors on metals, such as copper and steel, which are caused by the presence of thin films of oxide (21c). Corresponding thin films of oxides or other alteration products may account for the iridescence of minerals such as covellite and bornite.

Gaudin (12) has described a method of identifying minerals by means of the interference films which they form in a selective manner when etched or stained by suitable chemical reagents. The optical properties of such films are discussed in detail.

Interference colors are more brilliant if they are observed against a dark background, since then there is less admixed reflected white light to dilute the color. The laminae themselves need not be highly transparent in order to produce vivid coloring (although they must of course be at least partially transparent); a moderate amount of cloudiness or turbidity may enhance the vividness of the coloring by reducing the amount of admixed white light (21c).

The reflection spectra of substances exhibiting interference coloring show bands which may be extremely narrow and well-defined. This is particularly noticeable in cases in which the color is intensified by repeated reflections from regularly spaced laminae. The unusual sharpness and narrowness of the absorption bands in some opals (39c) is attributed to this cause. In general, the spectra which result from interference resemble that of the incident white light (i.e., continuous) except that one or more regions are rather sharply weakened in intensity. These regions of increased absorption may be very narrow (corresponding to the removal of only a few adjacent wave lengths), or they may be fairly broad,

depending on the index, effective thickness, number and regularity of the laminae.

Interference colors can be distinguished from surface color by observing the effect of changing the polarization of the incident light; details are given by Mason (21e).

Interference colors may be distinguished from diffraction colors by means of a reflection test described by Stokes (33, 4h). This is based upon the fact that in the former the reflection is specular, although it may be from a many-planed surface; in diffraction colors there is no specular reflection.

The retardation or polarization colors which are observed when minerals are examined through a microscope with crossed nicol prisms are not to be confused with the interference colors described above. The latter are produced by the effect of the mineral on non-polarized incident light.

2. *Diffraction Colors*

These are caused by regularly repeated and properly oriented structural forms, or optical non-homogeneities, which are larger than the wave length of the light, and consequently act as a diffraction grating. The incident white light is thereby spread out into a spectrum, so that the color observed is dependent on the angles of incidence and observation, as well as on the fineness of the structure.

The sequence of colors observable with changing angle of incidence or observation follows the spectrum order. This, of course, is entirely different from the Newton sequence observed with interference or retardation colors. Also, the colors themselves are those found in the normal spectrum. Purple, for instance, is not produced by a simple diffraction grating. However, it is conceivable that there might be two sets of structures which would diffract red and blue, respectively, at a given angle. The observed color would then be purple.

Ordinary diffraction colors do not appear to be common in nature. According to Pfund (25, 4g), some of the fainter coloring seen in mother-of-pearl is due to diffraction arising from the regularly repeated laminae. The thin films in agate are reported to act like a diffraction grating, if the agate is properly cut (3a). Certain finely-striated beetle wings are said to exhibit iridescence due to diffraction (21f).

3. *Selective Scattering*

A. Tyndall Scattering

The term *Tyndall scattering* may be applied to the selective scattering of light by particles or structures the size of which, compared with the

wave length, is small. Such scattering could be caused by colloidal particles, free electrons, meta-stable electrons, or, in general, any small-scale, optical non-homogeneity. The significant factor in all these cases is the repeated, abrupt change in refractive index between particle or structure and the contacting or embedding medium.

These particles or structures must have a relatively random orientation or positional arrangement; otherwise with a regular and suitable orientation, diffraction gratings might be formed.

In the production of this type of coloring, light is scattered in all directions by the particles or structures. The amount of the scattering, for any given direction, is inversely proportional to the fourth power of the wave length. Hence, for a certain particle size, blue may be scattered strongly and red very little. A transparent substance containing such particles would look red by transmitted light, since the red light would come through relatively unchanged in intensity. The blue light would be greatly scattered in all directions, and so the appearance of the material, when viewed in any direction except that of the transmitted beam, would be blue.

The transmitted and scattered light show hues which lie toward the opposite ends of the visible spectrum. This can usually be seen best by illuminating the material with a concentrated or narrow, intense beam of light; with diffuse illumination, the color of the scattered light usually predominates. The scattered blue is ordinarily much purer and more intense than the transmitted brown or red. This is easily explained by the fact that since the scattering is inversely proportional to the fourth power of the wave length, with particles of the proper size the scattered light is nearly all blue, while the transmitted beam is white minus blue, and blue-green, which would be brownish or reddish in color.

The intensity is dependent on the number of scattering particles, the difference in refractive index, and the angle of observation. A more intense blue can be obtained, for example, from media containing large numbers of such particles than from material containing fewer particles.

Tyndall scattering may be easily observed in the familiar Tyndall beam or cone, which appears when a pencil or cone of light is passed through a medium containing small, suspended particles. A searchlight or automobile light beam at night shows this type of scattering in the air, due largely to the dust and moisture particles contained in it. The blue of the sky is attributed to scattering by the air molecules (28, 29, 39e). The coloring in smoky quartz is considered to be due to scattering (13, 34, 36).

This scattered light is strongly polarized, the vibrations being in the plane normal to the direction of propagation of the incident beam. Almost no scattered light is observed through a nicol set to transmit vibrations in the plane parallel to the beam.

B. Large-Particle Scattering

The blue color weakens with increasing particle size and gradually disappears, so that the scattered light finally becomes white. Under these conditions, however, if a nicol prism is held in such a position as would ordinarily extinguish the scattered light, a blue color is again seen. This was named the *residual blue* by Tyndall, and may be much purer and more intense than the Tyndall blue produced by smaller particles. Rayleigh attributed this residual blue to a type of scattering which varied inversely as the 8th power of the wave length (29, 4*j*).

With still greater particle size, colors appear which are visible without the use of a nicol prism. In this case, on increasing the particle size, the colors change through a regular sequence which, according to Bancroft, shows an astonishing parallelism with interference colors. No adequate physical explanation seems to be available. The subject has been discussed by Bancroft and Gurchot (7).

Thus, with sulphur particles of the proper size, the scattered light is blue, and the transmitted light deep orange; with larger particles, the reverse is true, the scattered light being orange-red, and the transmitted light a deep blue (7*a*). This type of scattering is probably exhibited by blue halite, which is blue by transmitted light, and red-orange by scattered light.

In some cases the chemico-compositional color of the particles themselves adds appreciably to the observed color. This is particularly true for relatively coarse colloidal dispersions of highly-absorbing materials. Colloidal ferric oxide, for example, would be expected to show an appreciable chemico-compositional coloring in addition to the color due to scattering, provided that some of the particles were sufficiently coarse. For finer dispersions, the color observed would be essentially a function of the size and index of the particles themselves, regardless of their inherent selective absorption. For still finer particles which are colored, the phenomenon of mass resonance may appear (39*f*).

4. *Refraction Colors*

Structural colors may be caused by refraction from prismatic or globular structures which are, in general, very large in comparison with the wave length of the incident light so that diffraction and interference effects are small. The rainbow is an example of globular refractions; the Christiansen effect is due to selective non-refraction; the colored borders sometimes seen in mineral grains under the microscope when determining the index of refraction by the Becke line method are due to selective refraction. This latter color production has been described by Ambronn (1) and Schroeder van der Kolk (31).

5. *Miscellaneous Other Causes*

Possible, but probably minor causes, which are listed here primarily for the sake of completeness, are electromagnetic mass resonance (39*f*) (which is really due to a combination of structural and chemico-compositional coloring), transmitted structural blue (21*i*), mixed plates (4*i*, 39*d*), mosaic powder films (26), and various types of differential reflection from powders (22), thin films, or surfaces which may be optically smooth for long waves, such as the red, while rough for shorter ones, such as the blue.

IDENTIFICATION OF TYPE OF COLORING

The following criteria are suggested as guides for recognizing and identifying the type or types of coloring displayed. It is to be borne in mind that the observed color may be due to two or more causes, all of which can be effective at the same time. One might have scattering, for example, due to colorless particles suspended in a transparent solid, which, in itself, showed chemico-compositional coloring.

These proposed tests are therefore intended to indicate the most probable type or types of coloring observed in a particular specimen, but are not considered to result in positive proof by themselves. Other confirmatory evidence, as already detailed under the descriptions of the various types of coloring, should be sought.

1. Change in hue as a result of varying the angle of observation, or angle of incident light.

(a) *No color change is observed.* The color is therefore chemico-compositional, with body coloring predominating. (The incident light should be unpolarized if the specimen is anisotropic, in order to avoid possible effects due to pleochroism.)

(b) *A color change is observed.* If the changes in hue are prominent, and follow the sequence of colors which is to be observed in Newton's series, or in the normal spectrum, the color is structural, and is due, in the first case, to interference, or, in the second case, to either diffraction or a prismatic effect.

A very slight change in hue (especially if seen only at nearly grazing incidence), observed in minerals which have a metallic lustre, may indicate prominent surface color.

If no color change is noticed on varying the angle moderately, but if hues corresponding to nearly opposite ends of the spectrum are observed in the linearly transmitted beam and at right angles to this direction, scattering is indicated.

2. Lustre. Metallic lustre indicates either surface or interference color (5*a*).

3. Presence of certain indicative colors. Purple, for instance, is a non-spectrum color, and so is not seen in a normal spectrum, which might be formed by diffraction or a prismatic structure. It is readily caused by interference, or by chemico-compositional absorption.

White is always structural (21g, 21h), and is due to repeated, diffuse reflection. Black is always ultimately chemico-compositional. If the material absorbs strongly, very few reflections may suffice in order to produce nearly complete absorption; if the material reflects strongly, but absorbs only weakly, repeated reflections may be necessary.

4. Effects of wetting, or changing the index of refraction of the contacting medium.

Wetting or oiling often serves merely to intensify the effect of the inherent color by reducing the scattering or diffusing effect of surface irregularities. Under other conditions the color may be weakened, or even changed in hue, particularly if examined with light polarized so that it vibrates parallel to the plane of incidence and observation (37). Interference colors produced by a surface film may be weakened, or even destroyed (21d).

5. Polarization of the non-incident light.

Plane polarization, in cases in which it is not attributable to anisotropic properties in the material, or to favorable reflections, such as those occurring at or near the polarizing angle, usually indicates scattering. The plane of polarization should be checked for orientation.

Although this test is much more difficult to apply in anisotropic material than in isotropic substances, it is often possible to examine for polarization in the former by observing in a direction parallel to an optic axis.

6. Absorption spectra.

Due to the complexity of absorption spectra, and the relatively great difficulty in making significant measurements of the absorption curves, this criterion is perhaps of more value in confirming the deductions drawn from the other proposed tests than in making the original deduction as to the type of coloring displayed.

If several prominent absorption bands are observed, the color may often be due either to chemico-compositional absorption, or to interference. In the first case the shape of the curve is usually quite irregular; in the second case, the shape more nearly resembles that of the incident light, but with one or more prominent absorption regions.

If a band of the original light is apparently transmitted nearly unchanged, while the rest of the spectrum on either or both sides is nearly or completely removed, a diffraction or scattering effect is usually indicated. An absorbing substance could be responsible, however, as well as the Christiansen phenomenon.

7. Temperature effect.

According to Dewar (11, 3b), colors due to chemico-compositional absorption may undergo marked changes in both hue and saturation on cooling to low temperatures, such as that of liquid air. Bancroft (3b) states that structural colors show little or no change under such conditions. However, coloring caused by the Christiansen effect may be very sensitive even to slight temperature changes.

REFERENCES

1. AMBRONN, H., Ber. Gesell. Wiss. Leipzig, Math.-phys. Kl., 48, 134–140 (1896).
2. ANDERSEN, O., Am. Jour. Sci., [4] 40, 351–398 (1915).
3. BANCROFT, W. D., Applied Colloid Chemistry, 3rd Ed., (1932)
3a. ibid., p. 254
3b. ibid., p. 244.
4. BANCROFT, W. D., Jour. Phys. Chem., 22, 309–336, 385–429, 601–630 (1918); 23, 1–35, 154-185, 253–282, 289–347, 356–361, 365–414, 445–468, 554–571, 603–633, 640–644 (1919); 28, 12–25 (1924).
4a. ibid., 23, p. 559.
4b. ibid., pp. 561, 566, 567, 571.
4c. ibid., p. 168.
4d. ibid., p. 20.
4e. ibid., p. 169.
4f. ibid., p. 561.
4g. ibid., p. 295.
4h. ibid., p. 304
4i. ibid., p. 265.
4j. ibid., p. 278.
5. BANCROFT, W. D., AND ALLEN, R. P., Jour. Phys. Chem., 28, 588–610 (1924); 29, 564–586 (1925).
5a. ibid., 29, pp. 568, 585.
6. BANCROFT, W. D., AND CUNNINGHAM, G. E., Jour. Phys. Chem., 34, 1–40 (1930).
6a. ibid., pp. 29, 35.
7. BANCROFT, W. D., AND GURCHOT, C., Jour. Phys. Chem., 36, 2575–2587 (1932).
7a. ibid., p. 2583.
8. BOYS, C. V., Soap-Bubbles, 1924. Esp. pp. 151–154.
9. CROOKES, W., Proc. Roy. Soc., 17, 448 (1869). Vide BANCROFT, W. D., Jour. Phys. Chem., 23, 298 (1919).
10. DALE, A. B., The Form and Properties of Crystals, Cambridge (1932), p. 91.
11. DEWAR, J., Proc. Roy. Inst., 19, 921–928 (1910).
12. GAUDIN, A. M., Jour. Phys. Chem., 41, 811–859 (1937); Am. Inst. Mining, Met. Engrs., Tech. Publ. #912 (1938); GAUDIN, A. M., AND McGLASHAN, D. W., Econ. Geol., 33, 143–193 (1938).

13. HOLDEN, E. F., *Am. Mineral.*, **10**, 203–252, esp. p. 224 (1925).

14. JONES, L. A., *Jour. Optical Soc. Am.* **27**, 207–213 (1937).

15. JUDD, D. B., *Jour. Optical Soc. Am.*, **23**, 359–374 (1933).

16. KENNARD, T. G., *Am. Mineral.*, **20**, 392–399 (1935).

17. KENNARD, T. G., AND HOWELL, D. H., *Am. Mineral.*, **21**, 721–726 (1936).

18. KENNARD, T. G., HOWELL, D. H., AND YAECKEL, M. P., *Am. Mineral.*, **22**, 65–67 (1937).

19. KOLBE, E., *Neues Jahrb. f. Mineral.*, Beilage-Bd. **69**, Abt. A, pp. 183–254, esp. pp. 193, 195 (1935).

20. Private Communication, J. D. Laudermilk, Claremont, Calif.

21. MASON, C. W., *Jour. Phys. Chem.*, **27**, 201–251, 401–447 (1923); **28**, 498–501, 1233–1244 (1924); **30**, 383–395 (1926); **31**, 321–354, 1856–1872 (1927); **35**, 73–81 (1931).

21a. *ibid.*, **27**, p. 413.

21b. *ibid.*, p. 415.

21c. *ibid.*, **28**, pp. 1243–1244.

21d. *ibid.*, p. 1237.

21e. *ibid.*, **27**, p. 408.

21f. *ibid.*, **31**, pp. 1871–1872.

21g. *ibid.*, **30**, p. 386.

21h. *ibid.*, **27**, p. 209.

21i. *ibid.*, **35** pp. 73–81.

22. MERWIN, H. E., *Proc. Am. Soc. Testing Materials*, **17**, Pt. II, 496–530, esp. pp. 503–504 (1917).

23. MICHELSON, A. A., *Phil. Mag.*, [6] **21**, 554–567, esp. p. 556 (1911).

24. PARSONS, A. L., *Am. Mineral.*, **15**, 85–97 (1930).

25. PFUND, A. H., *Jour. Franklin Inst.*, **183**, 453–464 (1917).

26. ———, *Jour. Optical Soc. Am.*, **29**, 10–15 (1939).

27. Progress Committee on Spectrophotometry, *Jour. Optical Soc. Am.*, **10**, 169–241 (1925).

28. RAYLEIGH, *Phil. Mag.*, [4] **41**, 107–120, 274–279 (1871).

29. ———, [5] **12**, 81–101 (1881).

30. ———, *Proc. Roy. Soc.*, **103A**, 34–45 (1923).

31. SCHROEDER VAN DER KOLK, J. L. C., *Kurze Anleitung zur mikroskopischen Krystallbestimmung.* Wiesbaden, **(1898)**. Esp. p. 45.

32. SMITH, G. F. H., *Gem-Stones*, Methuen & Co., London, **(1935)**. Esp. p. 255.

33. STOKES, G. G., *Nature*, **32**, 224 (1885).

34. STRUTT, R. J., *Proc. Roy. Soc.*, **95**, 476–479 (1918–1919).

35. TROLAND, L. T., *Jour. Optical Soc. Am.*, **6**, 527–596 (1922).

36. VANZETTI, B. L., *Atti congresso Naz. chim. pura applicata*, **(1923)**, p. 419.

37. WALTER, *Die Oberflächenfarben oder Schillerfarben*, **(1895)**. *Vide* BANCROFT, W. D., *Jour. Phys. Chem.*, **23**, 445 (1919).

38. WILD, G. O., *Praktikum der Edelsteinkunde*, Stuttgart, **(1936)**, pp. 108–109.

39. WOOD, R. W., *Physical Optics*, 3rd Ed., **(1934)**.

39a. *ibid.*, p. 510.

39b. *ibid.*, p. 106.

39c. *ibid.*, p. 198.

39d. *ibid.*, p. 279.

39e. *ibid.*, p. 423.

39f. *ibid.*, pp. 438–439.