

Sources of Data Used in Text

FORMULA

The chemical composition of a mineral is a primary aspect of its definition as a species. The reader is referred to a periodic table of the chemical elements (page 243) for standard abbreviations of the names of elements.

Many formulas contain parentheses within which are listed several elements, for example (Fe,Mg). This indicates that there is a specific position in the crystal structure that may be occupied by either iron, or magnesium, or both. The element listed first within the parentheses is the one present in greater amount on the structural site. In some cases this determines the species! For example, amblygonite is (Li,Na)Al(PO₄)(F,OH). However, if the formula reads (Li,Na)Al(PO₄)(OH,F), we have a new species in which hydroxyl exceeds fluorine, and the species is now called montebbrasite. Furthermore, if the formula is (Na,Li)Al(PO₄)(OH,F), sodium exceeds lithium and the mineral is classed as yet another species, natromontebbrasite. Obviously, the degree of complexity associated with solid solution can be very great. Any substitution of elements on a crystallographic structural site may (or may not) have an effect on physical properties.

Impurities also affect properties. A good example is beryl, Be₃Al₂Si₆O₁₈, but often containing such elements as Fe, Mn, Cr, V, and Cs. These elements are usually present in such small quantities that they are not written into the formula. However, the mineralogist understands that Cr, for example, which makes beryl the rich green color we know as emerald, substitutes for Al in the structure. A detailed knowledge of chemical substitutions and color changes in crystals requires a much greater sophistication in crystal chemical principles than can be expounded here.

Formulas given in this book are based on the most recent mineralogical studies. Chemical elements listed

after a plus (+) sign following the formula are those most often noted as substituting for elements in the formula.

CRYSTALLOGRAPHY

The reader is referred to standard books on mineralogy or crystallography for detailed background and terminology. It will suffice here to say that crystals grow in such a way that their component atoms and molecules are locked together in periodic arrays, much like three-dimensional wallpaper patterns. These arrays have symmetry of various types that can be described and categorized. When this is done, it is discovered that all known crystals can be organized according to six major crystal systems: *isometric*, *tetragonal*, *hexagonal*, *orthorhombic*, *monoclinic*, and *triclinic*. A subclass of the hexagonal system that is sometimes (though erroneously) regarded as a seventh crystal system is known as *trigonal*. Each crystal system is defined in terms of crystal axes, which are imaginary lines in space that intersect at a common point and whose lengths may be described as equal or unequal to each other. The systems are further described in terms of the angles that these axes make with each other.

Various descriptive terms may be used in describing the crystals exhibited by various mineral species. These terms include prismatic (elongated), bladed, acicular (needlelike), filiform (hairlike), equant (roughly equal-length sides), pyramidal (looking like single or double pyramids), and tabular. Sometimes terms are used that refer to specific forms characteristic of specific crystal systems (octahedron, pyritohedron, and so forth). Other terms used to describe a mineral's appearance refer to state of aggregation: massive (solid and chunky), compact (solid and dense), cleavable (crystalline masses that

can be cleaved), granular (masses of compact grains), stalactitic (resembling the form of stalactites), oolitic (masses of spherical grains), earthy (masses of densely packed powder).

The appearance of a mineral is largely a function of the growth process and the environment of formation. Minerals deposited in sedimentary environments tend to be earthy, stalactitic, oolitic, and sometimes massive. Igneous minerals tend to be crystalline or massive, sometimes cleavable. All these terms are somewhat subjective but are useful in getting a mental image of the appearance of a mineral as it occurs in the Earth.

COLOR

The color of a mineral or gemstone is one of the primary attributes used for identification, but it is, unfortunately, one of the least diagnostic and useful (except in a handful of cases). The colors reported include all those mentioned in the mineralogical or gemological literature. These are useful to gemologists primarily as a guide as to what could be expected in the future, that is, the *potential* color of a gemstone. A mineral may, at any time, be found in gem quality in a new or unfamiliar color. A good example is zoisite, found in Africa in a striking blue variety in the 1960s and given the trade name *tanzanite*.

The streak (color of a mineral powder) is listed where it is useful for identification. This characteristic applies almost exclusively to opaque, metallic minerals, because the powder of most transparent minerals is colorless (white).

The color names applied to gems and minerals have become familiar through long usage. Some gem color names, such as “pigeon’s-blood” (ruby) or “padparadschah” (sapphire), are vague, but have remained in the marketplace because no useful alternatives existed. However, accurate color measurement instrumentation is now available and is about to revolutionize the gemstone industry. Color specification systems for most colored materials (paints, dyes, etc.) have long been employed, and standards and procedures for measurement have been established by international professional societies in the color field. A gemstone colorimeter was used to measure a large array of gemstone color varieties and species for this book. The chapter on color measurement represents the first appearance in the gemological literature of objective gemstone color data, reported in terms considered standard by the color measurement and standardization field.

The future of gemology clearly lies in the direction of greater objectivity and standardization in measurement and terminology. Reference books on color technology should rapidly start to appear on the shelves of any

competent gemologist’s working library. It is vital that the field of gemology start moving toward color designations (CIE, CIELAB, Munsell, OSA-UCS, etc.) that are in daily use in all other color measurement fields.

LUSTER

Luster is considered a basic descriptive parameter for minerals but varies somewhat even within a single crystal, and its usefulness is therefore limited. Lusters include: vitreous (the luster of glass—characteristic of most gem minerals); pearly (iridescent, pearl-like); resinous (luster of resin); greasy (appears covered by oil layer); adamantine (hard, steely brilliance like the reflection from a diamond); silky (fibrous reflection of silk); dull.

Luster is a phenomenon of reflected light and is mostly due to the state of aggregation of the mineral. For example, gypsum may have a vitreous luster on some crystal faces; the luster is pearly on surfaces parallel to the excellent cleavage of this mineral; and if the mineral occurs in aggregates of long fibers (satin spar), it has a silky luster. Luster can hardly be a useful diagnostic property in identifying gypsum under these circumstances!

Luster is primarily divided into two types: *metallic* and *nonmetallic*. There are also intermediate types, called *submetallic*. Any mineral that does not have a metallic appearance is described as nonmetallic, and the above descriptive terms are applied.

HARDNESS

Hardness is the resistance to scratching of a smooth surface. Hardness has little use to the gemologist, since gems are not normally scratched as a part of gem testing. A hardness is sometimes taken on the back of a statue, as for example to differentiate between jade and serpentine. But even using the girdle of a gem to perform a hardness test results in chipping on occasion.

Hardness depends on the bonding that holds the atoms together within a crystal structure. This bonding is reflected in the ease with which the layers of atoms at a surface can be separated, by applying pressure with a sample of another material. If the second material is harder than the first, it will leave a furrow, or scratch, which represents the breaking of millions of atomic bonds on a microscopic scale. The hardness of a mineral is, specifically, its “scratchability,” and all minerals can be ranked in order of which one will scratch which other ones.

Mineralogist Friedrich Mohs established a reference scale of ten common minerals, ranked in order of increasing hardness, as follows:

- | | | |
|-------------|-------------|-------------|
| 1. Talc | 5. Apatite | 8. Topaz |
| 2. Gypsum | 6. Feldspar | 9. Corundum |
| 3. Calcite | 7. Quartz | 10. Diamond |
| 4. Fluorite | | |

In reality, diamond is very much harder than corundum, even though the scale says they are only one division apart. The Mohs scale is approximately linear from 1 through 9; the curve climbs sharply upward at corundum, however.

A mineral may be both hard and brittle, as in the case of diamond. Diamond will scratch any other known material, but a strong hammer blow can shatter a diamond into thousands of pieces. The perfect cleavage of diamond, in fact, allows it to be more expeditiously cut. Cleavage may be an initial diamond cutting operation, as opposed to the long and tedious process of sawing.

Hardness in a gemstone will determine the degree to which it will show wear. An opal, for example, which is quite soft for a ringstone, rapidly becomes covered with fine scratches in daily use, and the polish is quickly lost. A ruby, on the other hand, will remain bright and lustrous for years, because the material is harder than most of the abrasive particles in the atmosphere that contribute to gem wear.

The hardness of a material may vary slightly with composition and also with state of aggregation. The measurement of hardness is very tricky and often a mark that looks like a scratch is actually a trail of powder left by the supposedly harder material! It is really not critical whether the hardness of a mineral is 5 or 5 1/2. Fractional hardnesses are reported where the literature has indicated an intermediate value. A range in hardness is much more meaningful, and the values reported in this book represent all values encountered in the literature. In only one case (kyanite) does the hardness of a mineral vary very widely even within a single crystal. In most cases the hardness range reported is very small (one unit).

DENSITY

Density, or specific gravity, is a bulk property of a material that is independent of direction and is uniform within a mass of material under ideal circumstances.

In actuality, the density of a mineral varies widely, even within a single crystal, due to the presence of impurities, cracks, and bubbles. Density is a useful parameter in gem identification, so the problems in its determination should be well understood.

Specific gravity is the ratio expressing the weight of a given material compared to that of an equal volume of water at 4°C. Thus, a specific gravity of 3 means that, at

4°C, one cubic centimeter of the material in question weighs 3 times as much as one cubic centimeter of water.

The density of a compound is a function of several factors, including chemical composition and crystal structure. For example, consider diamond and graphite, both of which are crystalline forms of the element carbon. Diamond has a density of 3.5 because the carbon atoms are tightly packed together in the structure; graphite, with a much more loose, open structure, has a density of only 2.2.

The density of minerals within a solid solution series may vary linearly with change in composition. The effect of chemical substitution is seen dramatically in the case of the orthorhombic carbonate minerals aragonite and cerussite. Aragonite is CaCO_3 and has a specific gravity of 2.95; cerussite, with the same structure, is composed of PbCO_3 and has a specific gravity of 6.55! This clearly shows the role of lead versus calcium in the structure.

Specific gravities are usually measured with heavy liquids. A liquid is prepared, such as a mixture of bromoform and toluene, to have a specific density value. An unknown material dropped into the liquid may sink, float, or remain suspended in one place within the liquid. If the material sinks, it is denser than the liquid, and if it floats it is less dense. If it remains at one level it has the same density as the liquid. Very accurate measurements of specific gravity can be made by changing the density of a column of liquid through temperature variations and suspending density standards in the column.

An alternative method of measurement is the use of so-called torsion balances, such as the Hanneman balance and the Berman balance used by mineralogists. These devices are designed to weigh a sample first in air and then suspended in a liquid, such as water or toluene. The weights in both media can be measured quite accurately and specific gravities can sometimes be reported to two decimal places.

A major problem in all density measurements is the presence of impurities within the crystal being studied. These impurities hardly ever have the same specific gravity as the host material, and their presence results in measurements that are of limited use for identification purposes. Surface tension may also "float" a mineral grain in both heavy liquids and a torsion balance, resulting in an erroneously low specific gravity measurement. Accurate density measurement involves absolute cleanliness, great care in specimen preparation, accurate temperature control, and replicate measurements.

The specific gravity measurements reported in this book represent values taken from both the mineralogical and gemological literature. In most cases a range is reported, as well as a typical value or (where reported) the value of the pure material.

CLEAVAGE

Hardness, as discussed earlier, is the scratchability of a material. Cleavage and the related property, *fracture*, are both manifestations of the tendency of certain crystals to break along definite plane surfaces. As in the case of hardness, the underlying principle is that of relative bond strengths. If there are planes in a crystal structure along which the atomic bonds are relatively weak, the crystal may tend to break along such planes. Under ideal circumstances, a cleavage plane might be smooth and flat, virtually on an atomic scale.

The atomic arrangement within a crystal is symmetrical; consequently, the planes of specific bonds are symmetrically disposed within the crystal. Cleavage planes are therefore as symmetrical as crystal faces. By the same reasoning, glass can have no cleavage whatever. Glass is not crystalline but is rather a supercooled liquid, in which the atoms are not arranged in a long-range periodic array. There can therefore be no uniform bond layers and hence no cleavage.

Cleavage is usually described with reference to crystallographic axes and directions. However, this nomenclature is beyond the scope of this book, so in all cases only the number of cleavage directions in a gem species has been indicated and whether the cleavage is perfect (eminent), good, fair, or poor. Sometimes there are different degrees of cleavage perfection in different directions within the same crystal, and these have been so indicated in the text.

The term *parting* refers to breakage of minerals along directions of structural weakness. Unlike the situation in cleavage, parting is not present in all specimens of a given species.

Fracture is the way a mineral breaks other than along cleavage directions. The descriptive terms for this property are: conchoidal (shell-like, distinguished by concentric curved lines; this is the way glass breaks); fibrous; splintery; hackly (consisting of sharp-edged and jagged fracture surfaces); uneven.

Gems with perfect cleavage must be set carefully and worn carefully, as a sharp blow to the stone along a cleavage direction may easily split the gem. Spodumene is well known for its difficulty in cutting. Even topaz offers occasional problems to the cutter who is not aware of the cleavage direction, because it is virtually impossible to polish a gemstone surface that is parallel to a cleavage plane.

OPTICS

Accurate measurements of the optical properties of gems are very useful because optical properties are extremely

sensitive to minute changes in composition and strain in the crystal structure.

The basis of crystal optics is the premise that light travels in the form of waves, like ripples on a pond. The distance between successive crests or troughs of such a wave is known as the *wavelength*, and the *amplitude* of the wave is the height of the wave above the median (middle position between crest and trough). In familiar terms, different colors are different wavelengths, and the amplitude is the intensity of the light. Light vibrates at right angles to its direction of motion, and the vibration takes place in all directions perpendicular to the light path.

When light passes from one medium (such as air) into another (such as water) the light is actually slowed down. In addition, the light path is bent. The deviation is always referred to a line perpendicular to the interface between the two media, which is known as the *normal* to the interface. The light is always bent toward the normal in the medium in which the light travels slower.

The ratio between the velocity of light in the two media is called the index of refraction or *refractive index*; the first medium is usually taken to be air, in which the light velocity is considered unity (1). The refractive index then becomes $1/v$, where v is the velocity of light in the denser medium. Refractive index (usually abbreviated n) is also frequently described in terms of the angle to the normal made by the incoming light beam (incident ray) and that made by the refracted beam (traveling within the denser medium). Index of refraction in these terms equals the sine of the angle of incidence divided by the sine of the angle of refraction.

It is possible for light traveling from a given medium into a less dense medium, as, for example from a crystal into air, to strike the interface at such an angle that the light is totally reflected at the interface, back into the denser medium. The incidence angle at which this takes place is known as the *critical angle*. This angle has great significance in terms of gem cutting. If the angles at which the gemstone are cut are incorrectly matched to the refractive index of the material, light entering the stone may "leak out" the bottom, causing a loss of brilliance. If the angles are correct at the bottom of the stone, light is totally reflected internally and returns to the eye of the viewer, creating brilliance that is most pleasing and is, in fact, the whole reason for cutting facets on gemstones.

The optical properties of gemstones and minerals are determined by the crystallographic symmetry of these materials. For example, isometric crystals have crystal structures that are highly symmetrical in all directions; the result is that light traveling in an isometric crystal, or a glass (which is amorphous and has no crystal structure) travels at the same speed in any direction and is not slowed down measurably in any one direction within the

material. Such a material is termed *isotropic* and is characterized by a single refractive index, abbreviated in this book as N .

However, in all other crystals light is separated into two components. These two rays are *polarized*, that is, they each vibrate in a single plane rather than in all directions perpendicular to the direction of travel of the light. The two rays arising in such crystals are known as the *ordinary ray* and the *extraordinary ray*. All crystals other than isometric ones cause this splitting of incident light and are termed *anisotropic*.

The existence of polarized light can be demonstrated by means of a special prism known after its inventor as the *Nicol prism*. This contains specially cut pieces of the mineral calcite that are oriented in such a way as to allow only light polarized in a single plane to pass through. If two Nicol prisms are lined up and turned with their polarization directions at right angles to each other, no light may pass at all. Similarly, a Nicol prism (or similar device) can be used to test for the polarization directions of light that has traveled through a crystal specimen or gemstone. This is the basic function of such devices as the *polariscope* and *polarizing microscope*. The polarizing microscope is not generally used with gemstones, but instead with tiny mineral grains. Gemologists prefer to work with larger polarizing devices, usually 1-3 inch diameter discs of polaroid plastic, mounted in a device called a *polariscope*.

In tetragonal and hexagonal crystals there is a unique crystal axis, which is either longer or shorter than the other two axes in the crystal. Light traveling in a direction parallel to this axis vibrates in the plane of the other two axes. Since the other two axes are equivalent, this vibration is uniform and resembles the light vibration in an isotropic crystal. If a pair of Nicol prisms is placed in line with light traveling in this direction in such a crystal, and the prisms are rotated so that the polarization directions are crossed (perpendicular), no light will be seen emerging from the crystal. As a result of the presence of this unique optical direction in tetragonal and hexagonal crystals, substances crystallizing in these crystal systems are termed *uniaxial*.

All other crystals contain *two* directions in which light vibrates uniformly perpendicular to the direction of travel. Consequently, crystals in the orthorhombic, monoclinic, and triclinic systems are termed *biaxial*. The complete description of the behavior of light in such crystals is very complex and beyond the scope of this book. The interested reader is referred to standard works on optical crystallography indicated in the Bibliography on page 237.

The ray in uniaxial crystals that travels along the optic axis, and which vibrates equally in a plane at right angles to this direction, is the ordinary ray. The other ray, which vibrates in a plane that includes the unique crystal axis

direction, is the extraordinary ray. The refractive indices for these rays (directions) are the basic optical parameters for a uniaxial mineral, and are listed in this book as o and e . If the o ray has a velocity in the crystal greater than the e ray, such a crystal is termed *positive* (+); the crystal is considered *negative* (-) if the e ray has a greater velocity. The *birefringence* in a uniaxial crystal is the difference between the refractive indices for o and e .

In biaxial crystals there are three different crystallographic axes, and in addition there are two unique directions within the crystal that resemble the unique optic axis in a uniaxial crystal. The refractive indices of a biaxial crystal are designated by the Greek letters α (alpha), β (beta), and γ (gamma). Alpha is the lowest index, is referred to a direction in the crystal known as X , and is associated with the fastest light speed within the crystal. Beta is an intermediate index, corresponds to the Y crystallographic direction, and represents an intermediate ray velocity. Gamma is the highest refractive index, corresponds to the Z crystallographic direction, and is associated with the lowest ray velocity.

The birefringence in a biaxial crystal is the difference between the alpha and gamma index. The acute angle between the two optic axes within the crystal is designated $2V$ and is a useful parameter to the mineralogist. It turns out that if the beta index is exactly halfway between alpha and gamma, the $2V$ angle is exactly 90° . Finally, if beta is closer in value to gamma than to alpha, the crystal is considered optically *negative*. If the value of beta is closer to that of alpha, the crystal is termed optically *positive*.

Both refractive indices and birefringence are useful parameters in characterizing and identifying crystals, and both change with composition, the presence of impurities, and may vary even within a single crystal.

It should always be remembered that the refractive index is basically a measure of relative light velocity. Every wavelength of light travels through a given medium (other than air) at a *different* velocity, and consequently every wavelength has its own refractive index. The difference in refractive index with variation in wavelength is known as *dispersion*.

Dispersion is what makes a diamond sparkle with colors. The difference in refractive index for red vs. blue light in a diamond is quite large. As light travels through a cut gemstone, the various wavelengths (colors) therefore diverge, and when the light finally emerges from the stone the various color portions of the spectrum have been completely separated.

Dispersion is reported as a dimensionless number (that is, no units), but there is some degree of choice in selecting the wavelengths to use as reference points. By convention, the dispersion of a gemstone is taken as the difference in refractive index as measured using the Fraunhofer B and G lines. These are spectral lines ob-

served in the spectrum of the sun, respectively at 6870 and 4308 Å (Ångstrom units: one Ångstrom is equal to one ten-billionth of a meter. This unit of length is used to describe light wavelengths).

In some cases, no dispersion information exists for a mineral or gemstone in the gemological literature; however, the mineralogical literature may have data for the refractive index measured at certain different wavelengths (not including the *B* and *G* wavelengths). In such cases it is possible to calculate the dispersion, by means of a special type of graph paper known as a *Hartman Dispersion Net*. This is a logarithmic-type paper on which one can plot refractive indices at specific wavelengths covering the entire useful range. Such plots are linear and can be extrapolated to the positions of the *B* and *G* lines. The *B-G* dispersion is then simply picked off the graph. Approximately 20 gemstone dispersions never before reported and based on calculations such as are included in this book.

In some cases, as with opaque or translucent materials, the gemologist using only a refractometer cannot measure accurate refractive indices; rather the instrument gives only a vague line representing a mean index for the material. Since this number is useful, in that it indicates what can be expected in routine work, it has sometimes been included in the text of this book. Also, the refractometer effectively measures *all* indices of refraction (that is, for all light wavelengths) simultaneously; more accurate measurements can be made if only a single wavelength is selected. This is universally taken to be the spectral (yellow) line known as *D*, which is characteristic of the emission spectrum of sodium.

Light may be absorbed differently as it passes through a crystal in different directions. Sometimes the differences are only in degree of absorption or intensity. In other cases, however, different wavelength portions of the transmitted light are absorbed in different directions, resulting in colors. This phenomenon is termed *pleochroism*. In the case of uniaxial materials, there are only two distinct optical directions and the phenomenon is termed *dichroism*. Other materials may be *trichroic*, and the pleochroic colors are sometimes very distinct and strong and are useful in identification. The pleochroic colors reported for various gems are presented in this book in the order *X/Y/Z*, separated by slashes.

Since isotropic materials (including glasses) do not affect the velocity or properties of light passing through them in different directions, isotropic materials never display pleochroism. Occasionally, however, an isotropic material may display anomalous colors in polarized light. These effects are generally attributed to strain. However, there is abundant evidence that a more likely cause is the ordered arrangement of atoms on specific crystallographic sites.

SPECTRAL

The optical spectrum of a gemstone may be extremely useful in identification or in rapidly distinguishing between two similar gemstones with similar optical properties.

The principle of the spectroscope is fairly straightforward. Light we call white actually consists of a mixture of all the wavelengths in the visible range combined in specific proportions. When such light passes through a colorless material, none of the light is absorbed, and the white light emerges unchanged. However, some materials absorb various portions of the white light, allowing other portions to emerge and reach our eyes. The remaining portions consist of white light from which certain wavelengths have been subtracted. Consequently, if a material absorbs red, orange, and most of the yellow from the original white light, all that remains is blue and green and the material appears to us as a blue-green color. A ruby appears red to us because it absorbs nearly all the violet and green light passing through it.

The optical spectroscope is a device that separates white light into a spectrum of component colors, using either a prism or a diffraction grating. The spectrum consists of either an infinite (in the case of a prism) or finite (diffraction-grating type) assemblage of images of a very narrow slit, each representing a different wavelength. A gemstone placed between the light source and the slit will absorb certain wavelengths. The slit images of these wavelengths are consequently missing from the observed spectrum, and therefore show up as dark lines. The width of the lines depends on the diameter of the slit (which is usually adjustable). Often entire segments of the spectrum are absorbed, and the result is a dark band rather than a line. The light source itself may not produce all visible wavelengths. If a spectroscope is aimed at the sun, for example, the observed spectrum contains dark lines even though there is no absorbing material in front of the slit. These are known as Fraunhofer lines, named after Joseph von Fraunhofer (1787-1826) who showed them to represent absorptions by elements within the gaseous outer layers of the sun's atmosphere.

Certain gemstones have very distinctive spectra. In general, an optical spectrum is created through the agency of certain atoms in the crystal structure, which are, in the final analysis, responsible for the light absorption. Emerald, for example, contains chromium; the spectrum of emerald contains very distinctive absorption lines representing chromium, located in the far red portion of the spectrum. Such minerals as apatite, zircon, olivine, sinhalite, and idocrase have characteristic lines that are frequently used in identification. A glance through a spectroscope, for example, is instantly sufficient to distinguish between a garnet and a ruby.

The absorption spectra of many gemstones have not yet been reported in the gem literature. In other instances the spectrum has no distinctive or useful features. In both cases the abbreviation N.D. (No Data) has been used. It is hoped that the next edition of this book will contain complete spectral information on all the rare gems for which data are currently not available.

INCLUSIONS

Inclusions are crystals of minerals, cracks, healing fissures, bubbles, hoses, and other internal features of minerals that are useful in identification. Inclusions represent minerals that were floating in solutions from which other minerals formed; they are bits of liquid and gas bubbles trapped in a mineral as it grew; they are fractures surrounding radioactive minerals contained within a host mineral. The world of gemstone inclusions is beautiful, vast, and exciting, and one to which data are continually being added.

The instrument for study of inclusions in gems is the microscope, preferably one with darkfield illumination. Sometimes inclusions are too small to be resolved with the 30-60X usually reached by stereoscopic microscopes, and magnifications of 200X or more are required.

An expert in the field of mineral and gemstone inclusions may be able not only to identify a gemstone and pronounce unambiguously whether it is natural or synthetic but also to indicate the very mine from which it came! Inclusions are the most powerful means of distinguishing the bewildering variety of manufactured stones from the much more valuable natural gems they attempt to imitate. Inclusion information in this book represents a summary of what is in the available literature; information is lacking for many of the rarer gemstones, which will, it is hoped, be provided for future editions of this book.

LUMINESCENCE

Certain electrons in atoms within the crystal structure of a mineral may be able to absorb energy and release the energy at a later time. This creates a phenomenon known as *luminescence*. If the absorbed energy is released almost immediately, the effect is called *fluorescence*; if there is a delay (ranging from seconds to hours) in the release of the energy the effect is called *phosphorescence*. The excitation energy may be X-rays, visible light, or even heat, but the most widely used energy source is ultraviolet light. Ultraviolet (UV) light is generated by several different kinds of lamps, basically of two types: longwave

(LW) UV at 3660 Å, which is generated by fluorescent-type lamps, and shortwave (SW) UV, at 2587 Å, generated by special quartz tubes.

Some minerals react in LW, some in SW, some in both, and some in neither. In many cases a mineral is not excited by UV light unless it contains an impurity element that acts as an activator. The element manganese plays such a role in many minerals. Conversely, the element iron quenches fluorescence in most minerals. The detailed reasons for this behavior are beyond the scope of this book.

Luminescence effects are useful in gemstone identification, especially in certain cases in distinguishing synthetics. However, luminescence is best used in conjunction with other gemological tests.

OCCURRENCE

The occurrences reported in this book are condensed from both the mineralogical and gemological literature. Where possible an attempt has been made to indicate the general rock types and geological environments in which a mineral occurs. Following this is a listing of specific localities that have been reported, noting, where possible, whether the material found is of major gemological significance.

It should be remembered that a mineral may be reported from a locality, and none of it is of gem quality (that is, attractive in color, transparent, and so forth). However, an occasional piece may be encountered that is suitable for cutting, and this is sufficient to establish the material in the literature as occurring in gem quality in that locality. Such possibilities are always open. The main emphasis of this section in the book is to indicate how widespread the material is and from what parts of the world it is best known.

STONE SIZES

This section of the book will, perhaps, never actually be completed but rather will continually focus on adding information as obtained.

The objective is to indicate what constitutes a "large one" for a given species in question, with respect to cut gems. In some cases catalog information for major museums exists. Much information has been compiled from verbal sources, information in the minds of expert cutters, museum curators, and collectors. In some cases I have seen no cut examples of a gem in question but have seen references to such gems in the literature or in private communications. Here only an indication can be

provided of expectable gem sizes. I freely acknowledge major omissions in the information presented in this portion of the text and hope that interested readers will make the next edition more useful by providing corrections and additions.

Gemstones of major importance exist in museum collections throughout the world. Some museums have especially complete collections of rare gems, and these institutions have been mentioned frequently in the text. Abbreviations used for some of these museums are as follows:

- BM: British Museum (Natural History) (London, England)
- SI: Smithsonian Institution (Washington, D.C.)
- DG: Devonian Group (Calgary, Alberta, Canada)
- AMNH: American Museum of Natural History (New York)
- ROM: Royal Ontario Museum (Toronto, Ontario, Canada)

- PC: Private Collection
- LA: Los Angeles County Museum (Los Angeles)
- CA: California Academy of Sciences (San Francisco)
- NMC: National Museums of Canada (Ottawa, Ontario)
- HU: Harvard University
- GIA: Gemological Institute of America

The metric carat is a unit of weight equal to one-fifth of a gram. It is the standard measure of gemstones. Where sizes are given in this book without a unit of measurement, the weight in carats is intended. Lower-cost cabochons are measured in millimeter size.

COMMENTS

This section contains general comments on wearing characteristics of gemstones, miscellaneous notes on occurrence, what constitutes high or low quality in the stone, general availability, and scarcity.

Thermal Properties

Gemologists are severely handicapped in analyzing and identifying gemstones because of necessity (and rather obviously) their testing methods must be nondestructive. This limits the measuring process to the areas of optics, including spectroscopy, luminescence, and so forth, density, and microscopic inclusions. Hardness is not routinely measured on cut gems. Moreover, the instrumentation used in this field must be simple enough to be learned by people with no real scientific training (which is the case with the vast majority of gemologists) and must be affordable. Much of the literature of gemology these days reports measurements on gems made with various kinds of advanced instrumentation, including ultraviolet absorption spectroscopy, X-ray fluorescence analysis, and even electron paramagnetic resonance. This is well and good for the literature but is of little practical value for the working gemologist and/or appraiser.

Therefore, it is important to explore the potential of any possibly diagnostic, inexpensive, simple, and non-technical method of gemstone analysis. One such method is the measurement of thermal properties.

Heat energy may be transferred by radiation (for example, sunlight), convection (the creation of currents in a pot of boiling water), and conduction. The latter method of heat transfer is the most relevant to solid materials at room temperature, that is, gemstones. There are four thermal properties of potential interest, three of which are mathematically interrelated. However, the best one for gem testing is the one that can most easily be measured with simple instrumentation; this turns out to be thermal inertia. The others are not as useful, as outlined below:

Specific heat is the amount of heat required to raise one gram of a substance one degree Celsius. This is a constant for a given substance but one that varies little in

different gem materials and therefore is not especially useful for identification purposes.

Thermal diffusivity is a measure of the velocity of heat flow in a material. If heat is applied to a substance, some of the heat energy (to a degree that depends on the specific heat of the material) goes into raising the temperature of the substance. The rest of the heat energy diffuses away from the point where the heat is being applied. The higher the thermal diffusivity of a material, the faster it will pass heat energy from one point to another.

Thermal conductivity on the other hand, is a ratio and relates the flow of heat through a given thickness of material to the temperature difference across this thickness. It turns out that thermal conductivity is directional, just like refractive index, in all but isotropic (isometric or amorphous) materials. The symmetry of optical and thermal properties is usually the same, but very few measurements on the variation of conductivity with direction have been made on gem materials.

Thermal inertia is a measure of how quickly the surface temperature of a material can be changed by a flow of heat into the material. The higher the thermal inertia, the slower the surface temperature will rise when heat is applied. This is why materials, such as plastics, that have a low thermal inertia feel warm to the touch—body heat rapidly raises the surface temperature of such materials—while stone objects feel cold.

Thermal inertia is a directional property but lends itself to simple instrumentation for measuring a mean value. The various *diamond probes* (such as those made by the GIA, Rayner, Kashan and Ceres Corp.) on the market take advantage of this fact. Such probes consist of a temperature-difference sensor (a thermocouple) and an adjacent thermal source (resistance heater) surrounded

by an insulated probe housing. Care must be taken in using such instruments to prevent drafts from affecting the readings. The probe tip is placed against the material being measured (that is, a gemstone facet) and a meter reading is obtained in about one second. This reading can be related to thermal inertia. The commer-

cial probes were developed specifically to distinguish diamond (with a very high thermal inertia) from its imitations, such as cubic zirconia (with much lower thermal inertia). Difficulties may be encountered with very small stones, but the instrument can be calibrated against small gems to avoid this problem.

TABLE 1. Thermal Properties of Gem Materials, Synthetics, and Simulants as well as Some Metals at Room Temperature

<i>Material</i>	<i>Thermal Conductivity (cal/cm °C sec)</i>	<i>Specific Heat (cal/gm °C)</i>	<i>Density (gm/cm³)</i>	<i>Thermal Diffusivity (cm²/sec)</i>	<i>Thermal Inertia (cal/cm² °C sec^½)</i>
Gem Materials, Synthetics, and Simulants					
Diamond	1.6-4.8	0.12	3.52 ^a	3.79-11.4	0.822-1.42
Silicon carbide (synthetic)	0.215 ^b	0.2*	3.17 ^a	0.339	0.369
Periclase (synthetic)	0.110 ^b	0.2*	3.575 ^a	0.154	0.281
Corundum: c axis	0.0834 ^b	0.206	4.0 ^a	0.101	0.262
a axis	0.0772	0.206	4.0 ^a	0.0937	0.252
c axis	0.060 ^c	0.206	4.0 ^a	0.0728	0.222
Topaz: a axis	0.0446	0.2*	3.53 ^a	0.0632	0.177
mean, Gunnison, Colorado	0.0269	0.2*	3.531	0.0381	0.138
Pyrite: Colorado	0.0459	0.136	4.915	0.0684	0.176
Kyanite: c axis	0.0413 ^b	0.201	3.66 ^a	0.0562	0.174
b axis	0.0396 ^b	0.201	3.66 ^a	0.0539	0.171
mean, Minas Gerais, Brazil	0.0338	0.201	3.102	0.0461	0.158
Hematite: Itabira, Brazil	0.0270	0.169	5.143	0.0310	0.153
Spinel: locality unknown	0.0281	0.216	3.63 ^a	0.0358	0.148
Madagascar	0.0227	0.216	3.633	0.0288	0.133
Fluorite: locality unknown	0.0219	0.220	3.18 ^a	0.0313	0.124
Rosiclare, Illinois	0.0227	0.220	3.186	0.0324	0.126
Sphalerite: Chihuahua, Mexico	0.0304	0.115	4.103	0.0646	0.120
Sillimanite: Williamstown, Australia	0.0217	0.203	3.162	0.0339	0.118
Andalusite: Minas Gerais, Brazil	0.0181	0.202	3.102	0.0289	0.107
Pyrophyllite: North Carolina	0.0194	0.2*	2.829	0.0343	0.105
Jadeite: Japan	0.0159	0.206	3.196	0.0242	0.102
San Benito County, California	0.0110	0.206	3.350	0.0160	0.0873
Gahnite: Colorado	0.0103	0.2*	4.163	0.0100	0.102
Magnesite: Transvaal	0.0139	0.236	2.993	0.0198	0.0992
Rutile: c axis	0.0231 ^b	0.189	4.2 ^a	0.0291	0.135
a axis	0.0132 ^b	0.189	4.2 ^a	0.0166	0.102
mean, Virginia	0.0122	0.189	4.244	0.0153	0.0990
Grossular: Connecticut	0.0135	0.196	3.617	0.0188	0.0979
Chihuahua, Mexico	0.0134	0.196	3.548	0.0193	0.0967
Crestmore, California	0.0124	0.196	3.318	0.0190	0.0898
Quartz: c axis	0.0264 ^b	0.196	2.65 ^a	0.0578	0.125
c axis	0.0264 ^c	0.196	2.65 ^a	0.0509	0.117
a axis	0.0140 ^b	0.196	2.65 ^a	0.0270	0.0854
a axis	0.0160 ^c	0.196	2.65 ^a	0.0308	0.0912
mean, Jessieville, Arkansas	0.0184	0.196	2.647	0.0354	0.0978
Spodumene: Maine	0.0135	0.2*	3.155	0.0214	0.0923
Diopside: New York	0.0133	0.196	3.270	0.0208	0.0923
Madagascar	0.00969	0.196	3.394	0.0146	0.0802
Dolomite	0.0132	0.221	2.857	0.0209	0.0911
Olivine (peridot, Fo ₈₆ Fa ₁₄)	0.0115	0.2*	3.469	0.0166	0.0893
Elbaite: Keystone, South Dakota	0.0126	0.2*	3.134	0.0202	0.0889
Talc, Quebec	0.0124	0.221	2.804	0.0200	0.0878
Tremolite: Balmat, New York	0.0117	0.210	2.981	0.0186	0.0854
Ontario, Canada	0.0112	0.210	3.008	0.0177	0.0839
Amblygonite: South Dakota	0.0119	0.2*	3.025	0.0197	0.0850
Zircon: Australia	0.0109	0.140	4.633	0.0167	0.0839
Enstatite (En ₉₈ Fs ₂): California	0.0105	0.2*	3.209	0.0334	0.0821
Bronzite (En ₇₈ Fs ₂₂): Quebec	0.00994	0.2*	3.365	0.0148	0.0818

Material	Thermal Conductivity (cal/cm °C sec)	Specific Heat (cal/gm °C)	Density (gm/cm ³)	Thermal Diffusivity (cm ² /sec)	Thermal Inertia (cal/cm ² °C sec ^½)
Spessartine: Haddam, Connecticut	0.00811	0.2*	3.987	0.0102	0.0804
Datolite: Paterson, New Jersey	0.0106	0.2*	2.996	0.0177	0.0798
Anhydrite: Ontario, Canada	0.0114	0.187	2.978	0.0204	0.0796
Almandine: Gore Mountain, New York	0.00791	0.2*	3.932	0.0101	0.0789
Staurolite: Georgia	0.00828	0.2*	3.689	0.0112	0.0782
Augite: Ontario	0.00913	0.2*	3.275	0.0140	0.0773
Pyrope: Navajo Reservation, Arizona	0.00759	0.2*	3.746	0.0101	0.0754
Andradite: Ontario, Canada	0.00738	0.2*	3.746	0.00984	0.0744
Smithsonite: Kelly, New Mexico	0.00612	0.2*	4.362	0.00701	0.0731
Beryl: c axis	0.0131 ^b	0.2*	2.70 ^a	0.0243	0.0842
a axis	0.0104 ^b	0.2*	2.70 ^a	0.0193	0.0750
mean, Minas Gerais, Brazil	0.00953	0.2*	2.701	0.0176	0.0718
Calcite: Chihuahua, Mexico	0.00858	0.218	2.721	0.0145	0.0713
Axinite: Baja California	0.00767	0.2*	3.306	0.0116	0.0712
Prehnite: Paterson, New Jersey	0.00854	0.2*	2.953	0.0145	0.0710
Rhodochrosite: Argentina	0.00731	0.184	3.584	0.0111	0.0695
Flint: Brownsville, Ohio	0.00886	0.2*	2.618	0.0169	0.0681
Epidote: Calumet, Colorado	0.00627	0.2*	3.413	0.00919	0.0654
Petalite: Rhodesia	0.00856	0.2*	2.391	0.0179	0.0640
Clinozoisite: Baja California	0.00574	0.2*	3.360	0.00854	0.0621
Idocrase: Chihuahua, Mexico	0.00576	0.2*	3.342	0.00863	0.0620
Sphene: Ontario, Canada	0.00558	0.188	3.525	0.00845	0.0607
Iolite: Madagascar	0.00650	0.2*	2.592	0.0126	0.0580
Zoisite: Liksviken, Norway	0.00513	0.2*	3.267	0.00785	0.0579
Aragonite: Somerset, England	0.00535	0.209	2.827	0.00906	0.0562
Microcline: Amelia, Virginia	0.00621	0.194	2.556	0.0126	0.0554
Ontario, Canada	0.00590	0.194	2.558	0.0119	0.0541
Albite (Ab ₉₉ An ₁): Amelia, Virginia	0.00553	0.202	2.606	0.0105	0.0540
Serpentine (lizardite): Cornwall, England	0.00558	0.2*	2.601	0.0107	0.0539
Orthoclase: Goodspring, Nevada	0.00553	0.2*	2.583	0.0107	0.0534
Sodalite: Ontario, Canada	0.00600	0.2*	2.326	0.0129	0.0528
Lepidolite: Dixon, New Mexico	0.00460	0.2*	2.844	0.00807	0.0512
Anorthite (Ab ₄ An ₉₆): Japan	0.00401	0.196	2.769	0.00737	0.0467
Fluor-apatite: Ontario, Canada	0.00328	0.195	3.215	0.00522	0.0454
Chlor-apatite: Snarum, Norway	0.00331	0.195	3.152	0.00539	0.0451
Labradorite (Ab ₄₆ An ₅₄): Nain, Labrador	0.00365	0.2*	2.701	0.00676	0.0444
Barite: Georgia	0.00319	0.113	4.411	0.00639	0.0399
Apophyllite: Poona, India	0.00331	0.2*	2.364	0.00699	0.0396
Leucite: Rome, Italy	0.00274	0.2*	2.483	0.00551	0.0369
Vitreous silica (General Electric)	0.00325	0.201	2.205	0.0074	0.0379
Hyalite: Spruce Pine, North Carolina	0.00290	0.2*	2.080	0.0070	0.0347
Glass: obsidian	0.00330 ^b	0.2*	2.4 ^a	0.00688	0.0398
ordinary flint (lead)	0.0018 ^b	0.117 ^a	3.5 ^c	0.00440	0.0272
very heavy flint (lead)	0.0012 ^b	0.117	4.5 ^a	0.00228	0.0251
Metals					
Copper	0.927	0.092	8.89	1.13	0.871
Silver 100%	1.00	0.056	10.5	1.70	0.767
Silver 69%, gold 31% (weight)	0.237	0.048*	12.3	0.401	0.374
Silver 34%, gold 66% (weight)	0.152	0.040*	15.5	0.245	0.307
Gold 100%	0.707	0.031	19.3	1.18	0.650
Aluminum	0.485	0.214	2.7	0.839	0.529
Platinum	0.166	0.032	21.4	0.242	0.337
Platinum, 10% iridium	0.074	0.032*	21.6	0.107	0.226

Source: From D. B. Hoover, The gem diamondmaster and the thermal properties of gems, *Gems & Gemology*, Summer 1983: 77-86.
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Note: Unless another reference is indicated by a superscript letter, the values for conductivity and density were taken from K. Horai, 1971, Thermal conductivity of rock forming minerals, *Journal of Geophysical Research* 76(5); for specific heat from R. A. Robie and D. R. Waldbaum, 1968, Thermodynamic properties of minerals and related substances at 298.15 degrees K and one atmosphere pressure and at higher temperatures, *U.S. Geological Survey Bulletin* 1259. * = assumed value; not found in the literature.

^a R. Webster, 1982, *Gems*, 3rd ed. Hamden, Conn.: Butterworth & Archon.

^b Chemical Rubber Company, 1966, *Handbook of Chemistry and Physics*, 47th ed. Boca Raton, Fla.: Chemical Rubber Company.

^c S. P. Clark, 1966, *Handbook of Physical Constants*, Memoir 97. Boulder, Colo.: Geological Society of America.

Table 1 was compiled by Dr. Donald Hoover of the U.S. Geological Survey and is generally arranged in order of decreasing thermal inertia. If accurate, quantitative probes become widely used, thermal inertia could become a very useful, easily measured parameter for gemstone analysis.

Note: Quantitative measurement of thermal inertia may be difficult using instruments that were designed specifi-

cally to separate diamond from other stones. New devices specifically designed for such measurements will represent the next generation of thermal meters. Surface quality (degree of flatness and polish) affects readings, as well as degree of crystallinity and chemical composition (especially in solid solution series).

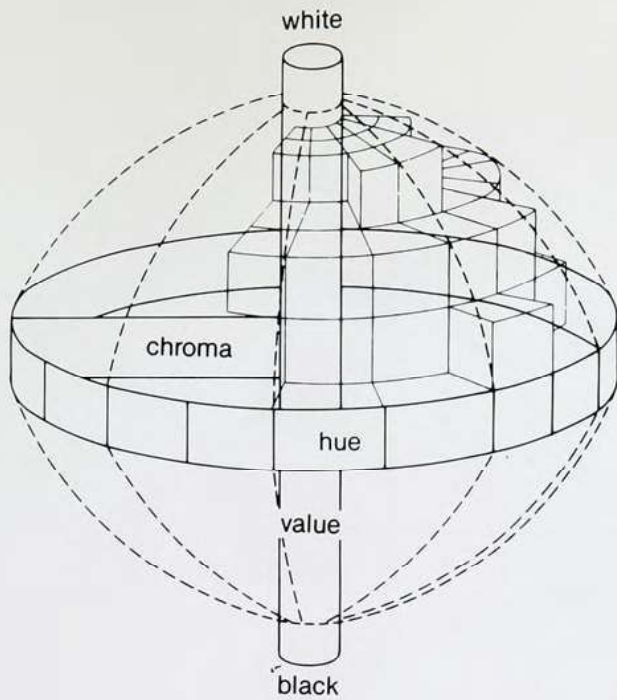


Figure 1. Three-dimensional color system. (From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 8; courtesy of Minolta Camera Company, Ltd., Japan.)

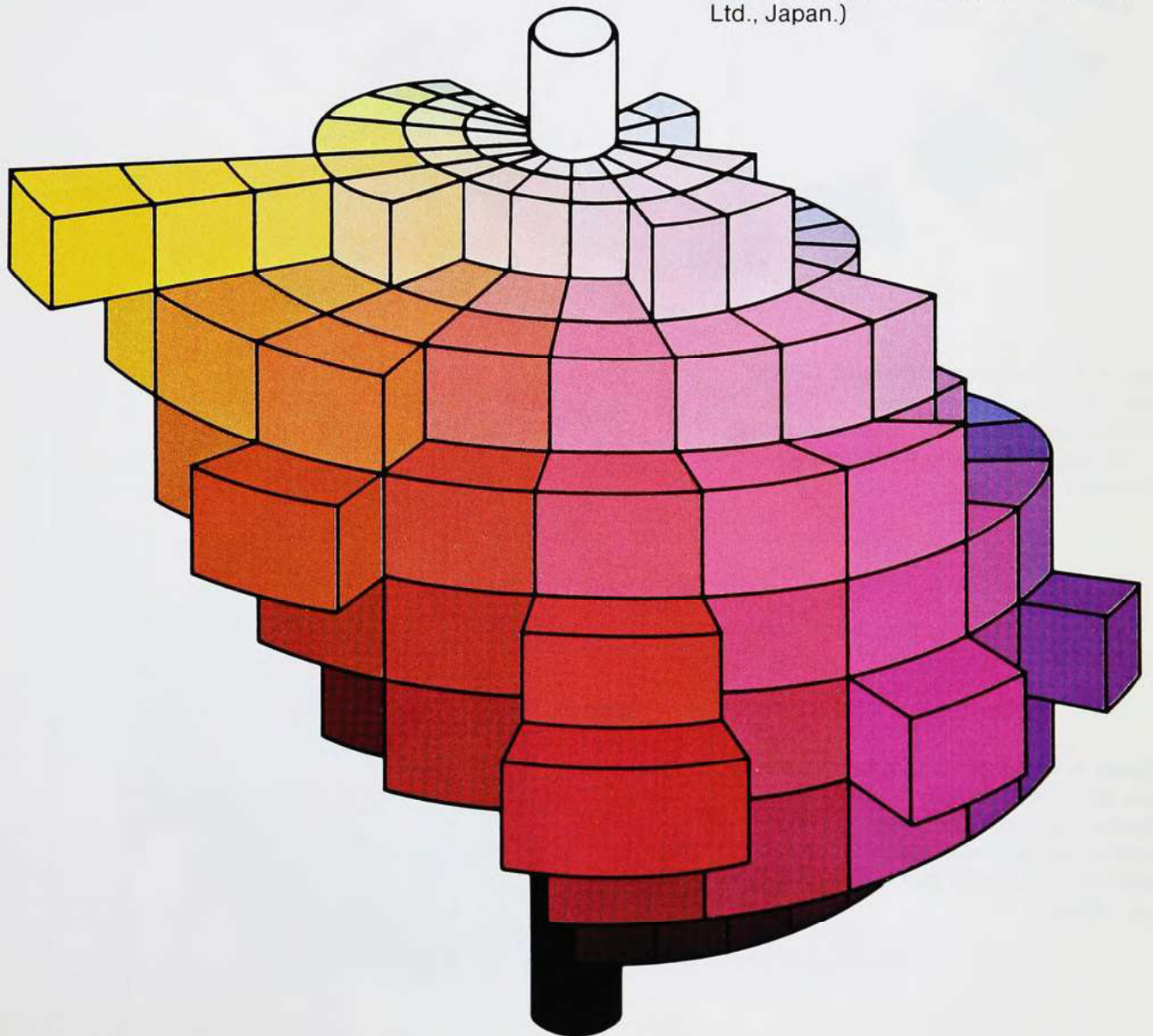


Figure 2. Color solid. (From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 9; courtesy of Minolta Camera Company, Ltd., Japan.)

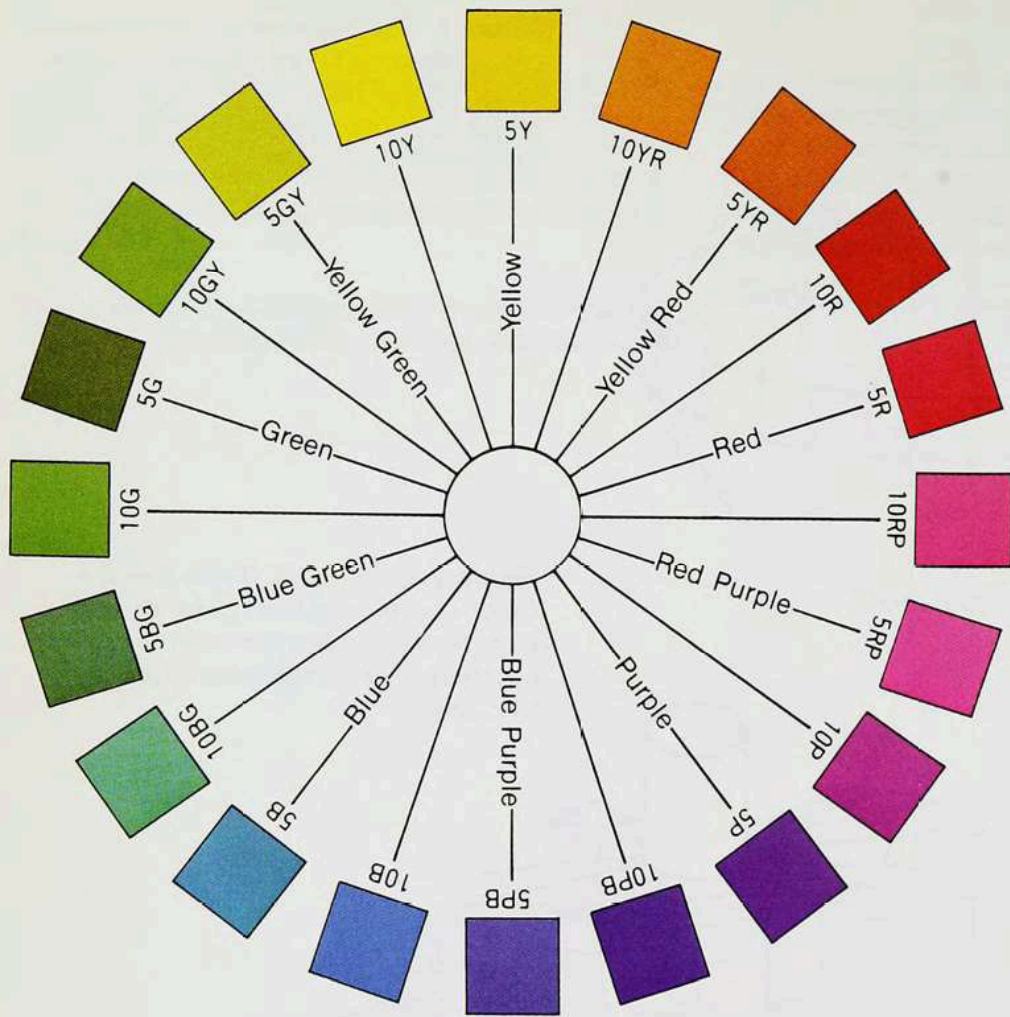


Figure 3. Munsell color wheel. (From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 19; courtesy of Minolta Camera Company, Ltd., Japan.)

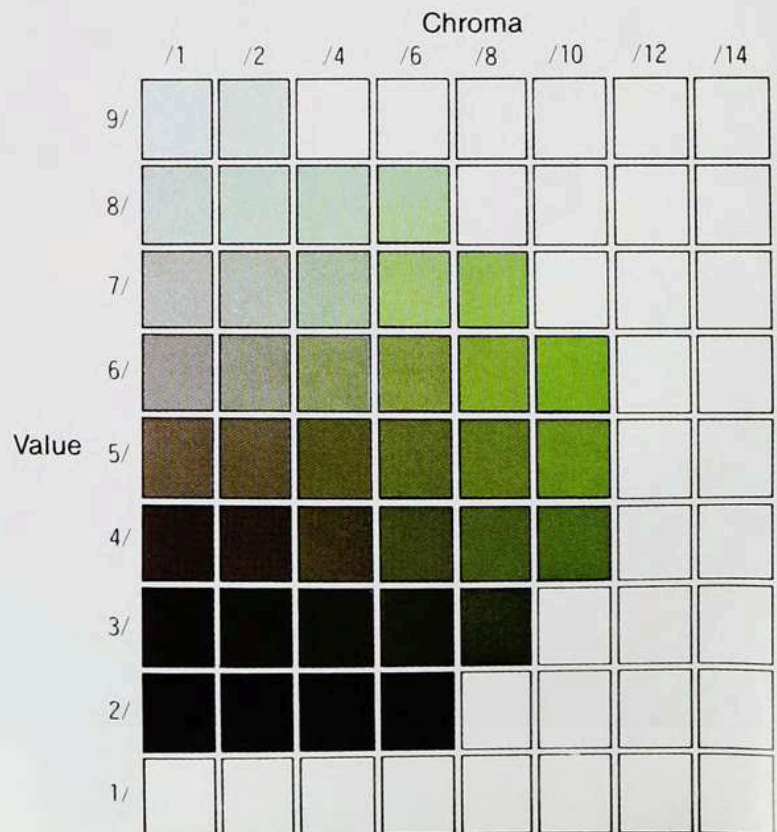


Figure 4. Munsell value and chroma for hue 5G. (From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 17; courtesy of Minolta Camera Company, Ltd., Japan.)

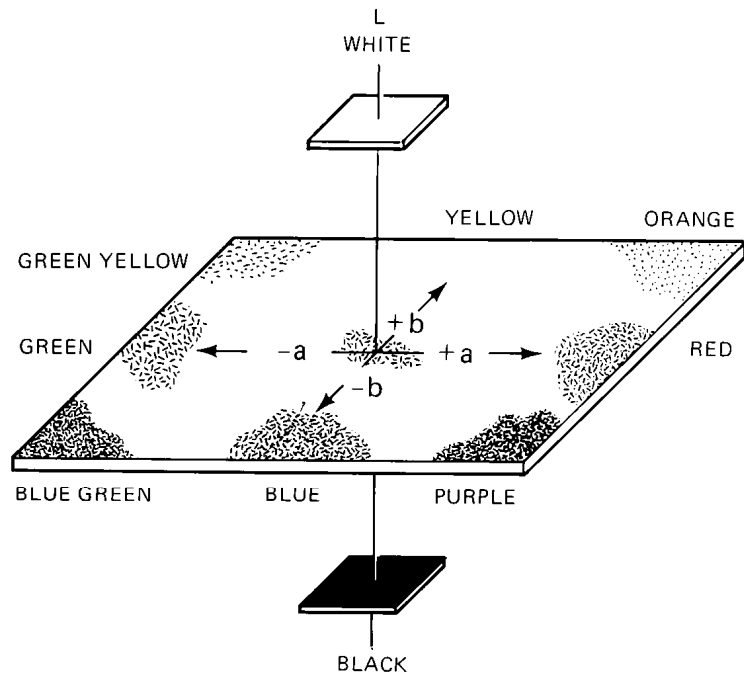


Figure 5A. Lab color space as conceived by Richard S. Hunter.

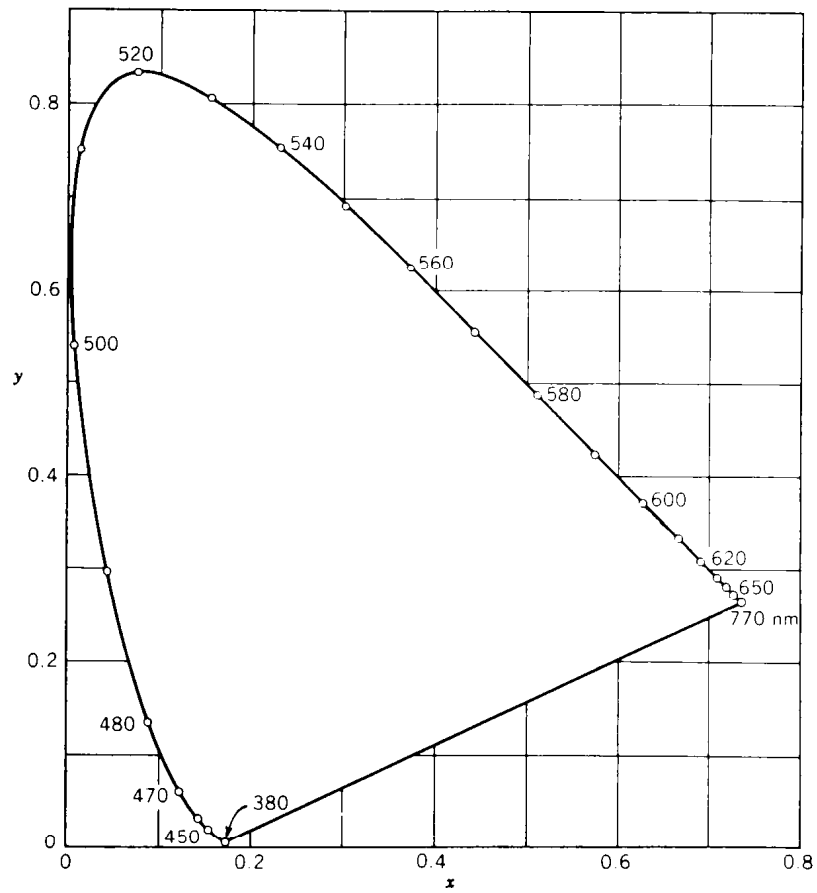


Figure 5B. The CIE chromaticity diagram (1931). All the spectral colors fall on a horseshoe-shaped line called the *spectrum locus*. These colors are indicated by their wavelengths (in nm). (After F. W. Billmeyer, Jr., and M. Saltzman, *Principles of Color Technology*, Wiley, New York, 1981, p. 125.)

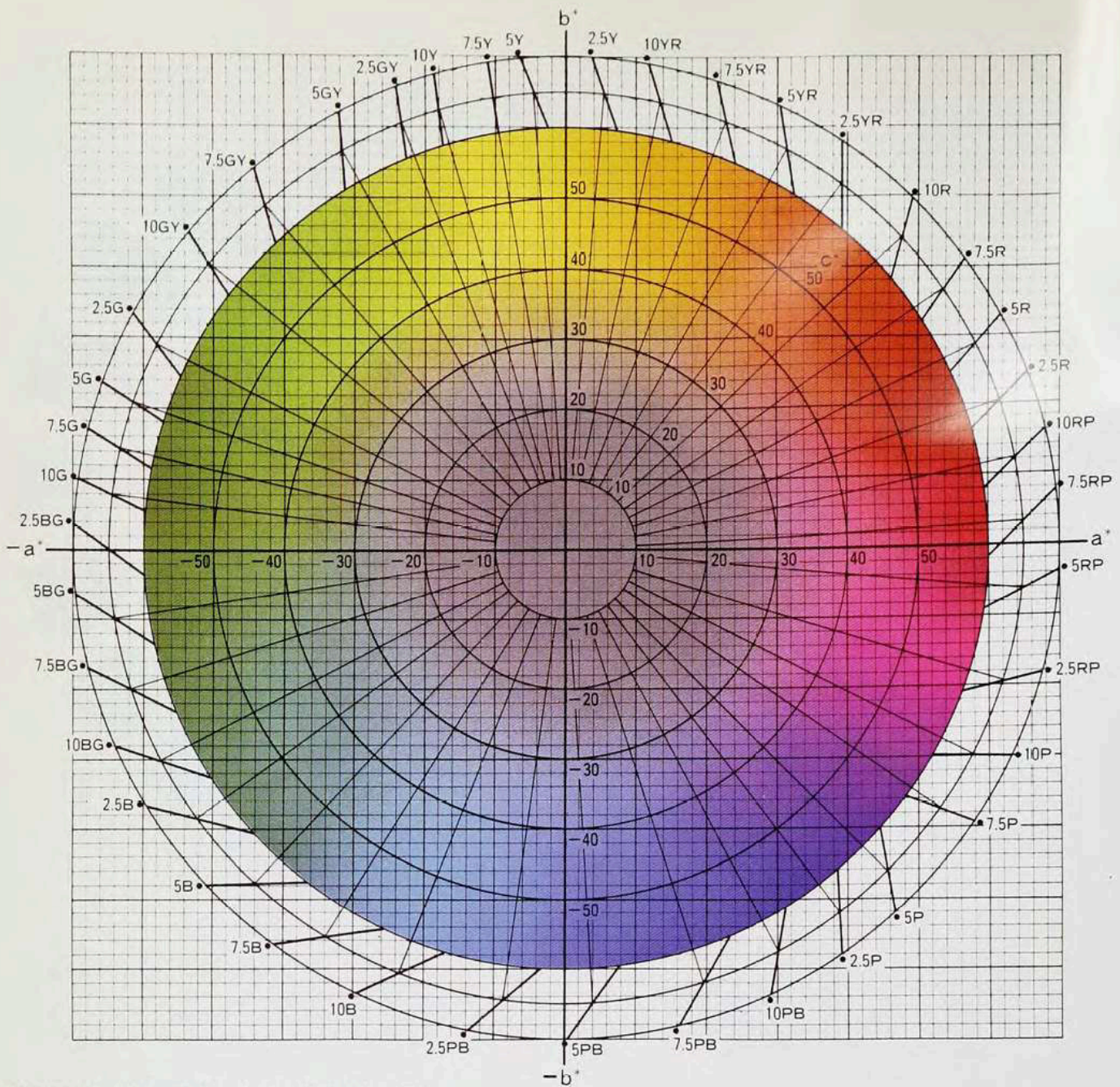


TABLE 3. Munsell (chroma C) and L*a*b* (chroma c*) notations

Munsell hue notation L*a*b* chroma Munsell chroma	R	YR	Y	GY	G	BG	B	PB	P	RP
1	5	7	8	7	6	5	4	4	4	4
2	9	12	15	13	11	10	9	9	9	9
3	15	17	22	22	19	16	15	13	13	13
4	19	22	25	29	29	25	22	20	17	17
6	27	30	34	38	42	45	43	39	34	31
8	37	41	46	50	56	59	58	51	45	42
10	46	51	57	63	70	74	73	65	56	53
12	55	62	68	76	84	88	87	77		
14	64	73	79	90	98				48	55
16	84	94	101	109					66	62
									75	60

Figure 6. L*a*b* and Munsell notations (hue, value). For extremely small or large a*b* values, multiply or divide them by an appropriate amount before plotting and reading the hue values. (From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 19; courtesy of Minolta Camera Company, Ltd., Japan.)

Source: From *Precise Color Communication: Color Control from Feeling to Instrumentation*, p. 19, courtesy of Minolta Camera Company, Ltd. Japan
 Note: In columns with two digits, left figures are for hues 1-5 and right for hues 6-10.

Color Measurement and Specification

One of the great challenges of gemology is the development of an accurate, simple, consistent, and reproducible technique for measuring and specifying gemstone colors. Until the mid-1980s little progress in this direction was made, despite the appearance and widespread promotion of various color-chart systems. None of these systems work, chiefly because they do not adequately cover the total range of gem colors, do not have enough detail in the areas they do cover, and the color-chart materials (whether printed colors or transparencies) are not of sufficiently high quality to prevent variations in production runs. The ideal solution is a gemstone colorimeter; however, such an instrument must deal with the unique optical properties of gems, including such factors as brilliancy and pleochroism, which make gemstones extremely difficult specimens for instrumental measurement.

The science of colorimetry is well established in almost all areas of endeavor where color is important, such as paint, plastics, textiles, and other industrial and consumer materials. Objective instrumentation is now routinely used in these fields, but before such instruments were available people had to rely on visual systems for specifying color, namely, color charts. These charts are sections of what we may refer to as three-dimensional color space. These three color dimensions are termed hue, lightness, and saturation.

Hue is the attribute we are describing when we speak of red, yellow, green, blue, purple, and other hues intermediate to adjacent pairs in this series. These hues can be readily visualized in terms of a color wheel (see Figure 3).*

Substantial portions of this text were provided by W. N. Hale, Jr.,¹ private color consultant and 22-year veteran of Munsell Color Co., Inc. (as both president and technical director), to whom the writer is deeply indebted.

*Figures 1-6 and Table 3 will be found in the preceding insert.

Lightness (also called **value**) is a scale with white and black as endpoints and shades of gray in between. Note, however, that *all* chromatic colors can also be scaled as to lightness as a function of their total reflectance. Lightness can be visualized in terms of a vertical axis with white at the top and black at the bottom (see Figure. 1).

Saturation (or **chroma**) is a measure of the amount of hue in a color, that is, its vividness, or how much it differs from a gray of the same lightness. Chroma can be seen in vertical sections of three-dimensional color space (Figure 2). A section along a specific radial direction of the color circle is designated as a specific hue. Lighter shades of this hue are near the top of the section, darker shades at the bottom. The chroma (vividness) of the hue increases moving outward from the central axis. Figure 2 shows that the range of chroma varies with both hue and lightness; this makes the color solid an irregular shape, rather than a simple ovoid or sphere.

Color specification can be achieved by subdividing the color solid into smaller units and giving each a name or set of numerical coordinates. This results in a classification known as a *color-order system*. There are many ways to subdivide the color solid, and, not surprisingly, there are also many color-order systems.

Some of the color-order systems created during the early decades of this century (including those of Munsell, Ostwald, Ridgway, and others) were represented by charts made of paint colors coated on paper. These were used by architects and designers for selecting and specifying colors, by industry for color selection and quality control, and by biological scientists for color classification of thousands of specimens of flora and fauna. Thus the need for accurate color measurement and specification was firmly established before instruments and related color-order systems were available. Some of these older systems (Ridgway in biology, Ostwald in architecture) are still in use today.

Perhaps the most popular and widespread of the chart-type color-order systems is the one devised by A. H. Munsell and extensively revised by the Optical Society of America (OSA) in 1943. The Munsell hue scale is based on five hues equally spaced around the hue circle (red, yellow, green, blue, purple) and intermediate hues (yellow-red, green-yellow, blue-green, purple-blue, red-purple). The major hues are abbreviated R, Y, G, B, P and the intermediate hues YR, GY, BG, PB, RP (Figure 3). Further subdivision results in forty hue charts in the *Munsell Book of Color*. Colors appear on these charts at value (lightness) intervals of one unit from 2 to 9. Chroma is represented in whole units ranging from 2 (near-gray) in two-step intervals up to as high as 14 and 16 for the most vivid colors (Figure 4). The notation system is decimal, allowing colors to be specified as accurately as required. Munsell color books are available in both matte and high gloss finish, with the latter having about fifteen hundred colors.

All these color-order systems (including the more recent German standard DIN 6164 and the Swedish Standard Natural Colour System) have certain similarities. Color sampling is along lines of constant hue (or a similar metric). Thus corresponding colors on adjacent hue charts become visually farther apart as they become progressively more saturated (that is, move further away, radially, from the center of the color circle). This means that the most vivid colors are more distant from each other than less vivid ones, often by a factor of five or more. The color charts for use with gemstones are inadequate because they do not have sufficient colors in the vivid color regions to which they extend, and they do not extend far enough. Opaque colors on paper simply cannot be produced to the color ranges of vivid, transparent gemstones. In addition, opaque paint colors do not look like transparent gemstones, even when they are, in fact, the same colors.

A major step forward came in 1931 with the international adoption of the Commission International d'Eclairage (CIE) system, resulting in greater interest in color measurement and specification, especially by colorimetry. The CIE system included standard illuminants (incandescent, sunlight, north daylight) a standard observer, and standard response functions of the human visual system. The CIE continues as the principal international organization in the field of color research and standardization and since 1931 has made important improvements and additions to the original concept.

The color industry was built around research and development of spectrophotometers and colorimeters capable of making measurements and reporting data in CIE terms. However, this created a problem with existing color-order systems. Such systems are necessarily spaced visually for their appearance under a specific light source; visual spacings and overall appearance will be accordingly altered if other sources are used. If CIE data are

published for such colors, the numbers are valid only for the light source for which the measurement data were computed.

CIE color space is visually nonuniform. A more uniform color space makes specification of tolerances and small color differences more meaningful and is therefore more useful to science and industry. Extensive research has been done to produce mathematical transformations of CIE data into a more visually uniform color space.

In 1942 Richard S. Hunter designed a filter colorimeter for the measurement of opaque surface colors and with it the Hunter color-order system. This is a transformation of CIE data using simple equations that were incorporated into the computational elements of the instrument. Hunter space was of the "opposite-hue" or "opponent-hue" type as shown in Figure 5. When Hunter a attribute is positive, the color has redness; when negative, greenness. Similarly when b is positive the color has yellowness, when negative, blueness. The third Hunter attribute was L for lightness. Equal steps along the three scales (L, a, b) were intended to represent equal visual steps in the several color directions, permitting color differences to be simply computed by the formula:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2},$$

Where the Greek letter delta (Δ) + E denotes color difference.

It is common practice today for color-measuring instruments to include Hunter color notations as a readout option for expression of measurement results. Although material color samples were never produced to illustrate Hunter color space, the nearly uniform visual spacing became very useful for describing color specifications and tolerances in industry and contributed importantly to the sale and use of these instruments.

Work continued in the CIE and elsewhere to provide a color space with even better visual color spacing, resulting in the 1976 recommendation for the use of CIELAB space. This is similar to Hunter space, is a mathematical transform of CIE data, and is plotted on rectangular coordinates (see Figure 6). CIELAB color attributes are designated L^* (L -star), a^* (a -star) and b^* (b -star) to distinguish them from Hunter and have the same nominal meanings. As with Hunter, CIELAB is a standard readout on current instruments.²

An even newer opponent-hue system, developed by the Optical Society of America and called Optical Society of America-Uniform Color Spacing (OSA-UCS), is not only an improvement over Munsell spacing but is also a direct CIE transform. The OSA-UCS colors (at this writing 558 colors, available as 2×2 inch samples) are in scales with intervals of two units in chromaticity and one in lightness; a prototype OSA color collection produced in Denmark shows chromaticity scale intervals of only one unit, with lightness increments of 0.5

and over two thousand colors. The OSA-UCS colors are the best example of uniform color spacing produced to date and will probably appear soon as a readout option on instruments.

Some gemologists have tried, without success, to use existing color instrumentation to characterize gemstones. Instrument makers have not perceived the gem field to warrant the costly research and development necessary to devise specifically applicable instruments. The existing color charts and simplistic optical devices currently in use by gemologists are severely limited in accuracy and usefulness.

The recent marketing by Minolta Camera Co. of a lower-cost portable colorimeter motivated several researchers to modify this instrument for gemstone colorimetry. A first attempt by Dr. Richard Pettijohn adapted the Minolta sensor unit for specific use with gemstones by reducing the beam size and adding a glass plate to hold the sensor and a small mirror to reflect light passing through the stone to the sensor. However, this arrangement has proven insufficiently accurate and repeatable to be a viable solution. Moreover, the mirror arrangement dictates the "standard" illuminant for measurement to be the xenon flashlamp built into the unit rather than an independently measured white standard.

An improved version of this instrument, also using the Minolta colorimeter, was devised by W. N. Hale and J. J. Rennilson. This replaces the glass and mirror with a small white-lined integrating sphere. A gemstone mounted on a clear plate centered within the sphere is irradiated by a 2-mm light beam from below. Light reflected from the gem is mixed with that transmitted through it and picked up by a detector outlet in the sphere wall. This colorimeter, with patented illuminating and collection geometry is sufficiently accurate and repeatable for gemstone work. The data readout is in CIE data (Y, x, y) and CIELAB (L^*, a^*, b^*), for CIE standard illuminant D65 or C (both representative of standard daylight in slightly different form). It is likely that this kind of instrumentation will totally revolutionize the gemstone field, bringing order and objective reality to a chaotic system of vague and often obsolete terminology.

The Rennilson-Hale instrument was not yet available when the table of gemstone measurements (Table 2) was prepared for this book; the Pettijohn instrument was therefore used. The illuminating and viewing geometry produces results that are neither as accurate nor consis-

tent as the integrating sphere/fiber optic system of Rennilson and Hale. Also, the conversion of CIELAB data to Munsell notation (see Figure 6 and Table 3) was done by the Minolta DP-100 microcomputer;³ errors in conversion may arise due to the limited data storage capacity of this device.⁴ Further errors are inevitable when trying to illustrate gemstones by photography and printed reproduction on paper.⁵ The tabulated numerical color data must therefore not be considered accurate enough to establish benchmark points for specific gemstone species, but this degree of error is small compared to the actual variation in color exhibited by most species. The real purpose of this chapter and these measurements is to establish, for the first time in the gemological literature, the nomenclature, direction and methodology for scientific, accurate, reproducible, and objective color characterization of gemstones. The numbers themselves are considered less important in this context than an understanding of how they were obtained and the implications of this new technology for gemology and the gemstone marketplace.

NOTES

1. Hale Color Consultants, Inc., 1505 Phoenix Road, Phoenix, MD. 21131.
2. In CIELAB terminology, chroma is calculated from a^* and b^* as follows:

$$\text{Chroma} = C^* = \sqrt{a^{*2} + b^{*2}}$$

3. Invaluable assistance in converting measured $L^*a^*b^*$ values to Munsell numbers, along with many valuable suggestions, was provided by Richard E. McCarty of Silver Spring, Maryland.
4. Color data on gemstones reported herein are in the form of CIELAB readout and corresponding Munsell notation. The conversion to Munsell numbers are direct CIELAB conversions. No attempt has been made to simplify the resulting Munsell values in accordance with the limited range of actual Munsell color samples. This approximation is left to the reader.
5. As many as possible of the gemstones photographed in this book were measured with the Pettijohn-Minolta colorimeter; these gems are cross-referenced by notation in the section of color plates at the back of the book, and the tabulated color information herein refers to specific gemstone colors, shapes, and weights, facilitating easy correlation with the photographs.

TABLE 2. Color Measurements

Gemstone	Color	Weight	Shape	Location	L*a*b*		Munsell
Actinolite	dark green	0.63	—	Tanzania	56	-7.7 9.1	7.6GY 5.5/1.7
Adamite	light green	0.86	—	Mapimi, Mexico	82	-0.6 26.0	3.2Y 8.2/3.8
Andalusite	brown-green	9.55	emerald cut	Brazil	58	-3.5 49.0	5.7Y 5.7/6.9
	light brown-green	4.72	antique	Brazil	60	1.0 14.1	1.9Y 5.9/2.1
	medium brown-green	2.92	round	Brazil	38	1.6 20.0	2.8Y 3.7/2.9
Anglesite	yellow	6.99	fancy	Morocco	75	2.7 50.0	2.1Y 7.4/7.4
Amblygonite	light yellow	10.10	round	Brazil	80	5.3 11.4	5.3YR 7.9/2.1
	light yellow	24.6	antique	Brazil	95	-3.5 20.0	6.0Y 9.4/2.8
Apatite	violet	0.59	emerald cut	Maine	71	10.3 -15.0	3.1P 7.0/4.0
	violet	1.02	hexagon	Maine	75	6.0 -7.2	4.9P 7.5/2.0
	yellow-green	8.05	rhomboid	Canada	68	-11.3 32.1	1.9GY 6.7/4.5
	yellow	8.70	antique	Mexico	83	-6.2 36.0	6.7Y 8.2/5.0
	dark blue	0.55	round	Brazil	34	-10.2 -40.6	9.7B 3.3/10.4
	medium blue	0.86	oval	Brazil	52	-22.8 -25.9	4.6B 5.1/7.8
	gray-blue	0.77	round	Burma	50	-7.5 -1.0	4.6BG 4.9/1.5
	light green	12.40	round	?	42	-6.2 9.8	5.3GY 4.1/1.6
	dark green	2.87	round	Brazil	31	-16.4 12.3	0.1G 3.0/3.2
	medium green	1.09	round	Brazil	61	-11.2 11.9	8.5GY 6.0/2.4
	light blue	1.07	emerald cut	Madagascar	76	-20.2 -4.1	7.0BG 7.5/4.2
Axinite	medium brown	1.45	round	Baja, Mexico	42	10.7 9.3	10.0R 4.1/2.6
	dark brown	8.0	pear	Baja, Mexico	21	14.2 20.6	4.8YR 2.0/4.2
Benitoite	pale blue	0.66	round	California	85	5.6 -7.6	4.4P 8.4/2.0
	medium blue	1.07	round	California	68	4.5 -27.0	6.6PB 6.7/6.3
	dark blue	1.19	round	California	46	8.4 -29.1	7.1PB 4.5/7.0
Beryl							
Aquamarine	dark blue	2.40	oval	Coronel Murta Mine, Brazil	61	-2.7 -17.5	2.8PB 6.0/4.3
	dark blue	66.53	antique	Brazil	38	-6.0 -8.0	5.8B 3.7/2.3
	dark blue	45.40	emerald cut	Brazil	54	-4.0 -11.0	0.5PB 5.3/2.8
	medium light blue	18.08	emerald cut	Brazil	80	-6.9 -9.0	8.2B 7.9/2.7
	medium blue	21.80	pear	Africa	65	-3.5 -18.0	2.6PB 6.4/4.4
Emerald	pale green	0.32	round	Colombia	85	-12.0 2.6	8.9G 8.4/2.2
	light yellow-green	—	emerald cut	Colombia	55	-55.0 15.0	6.0G 5.4/10.1
	medium green	0.88	emerald cut	Chivor Mine, Colombia	70	-41.7 2.5	2.0BG 6.9/8.0
	dark blue-green	1.35	emerald cut	Muzo Mine, Colombia	46	-73.2 9.1	8.3G 4.5/13.6
Green beryl	dark green	—	emerald cut	Zambia	40	-60.0 15.0	6.0G 3.9/11.0
	light blue-green	1.96	emerald cut	Nigeria	68	-23.5 0.5	2.7BG 6.7/4.6
	light green	11.25	round	Brazil	65	-3.5 6.5	4.3GY 6.4/1.0
	light yellow-green	18.42	triangle	Brazil	75	-5.1 13.2	2.0GY 7.4/1.9
	greenish-yellow	19.09	antique	Brazil	70	-9.3 21.1	3.2GY 6.9/3.2
	blue-green	4.54	emerald cut	Brazil	68	-5.2 3.1	2.0G 6.7/1.0
Golden beryl	dark yellow	20.00	emerald cut	Brazil	63	-8.2 39.0	8.3Y 6.2/5.4
	medium yellow	32.79	antique	Brazil	74	-6.0 34.2	7.0Y 7.3/4.8
	dark orange	18.60	antique	Brazil	45	17.4 71.7	9.9YR 4.4/11.5
	golden orange	18.98	pear	Brazil	61	-1.0 42.0	4.3Y 6.0/6.0
	golden orange	40.98	oval	Brazil	50	-0.5 41.0	4.5Y 4.9/5.9
	medium dark golden orange	3.90	emerald cut	Africa	70	10.2 70.0	0.2Y 6.9/10.7
Morganite	pink	17.33	square	Brazil	81	4.6 -0.9	2.8RP 8.0/1.1
	peach	6.92	square	Brazil	80	10.4 10.0	9.7R 7.9/2.7
	peach	9.06	oval	Brazil	90	8.9 11.8	1.3YR 8.9/2.6
Brazilianite	yellow-green	2.00	oval	Brazil	74	-1.9 17.0	5.2Y 7.3/2.4
Cassiterite	light brown	14.25	round	Bolivia	47	7.5 26.6	9.3YR 4.6/4.3
	yellow	2.88	round	Bolivia	82	1.3 33.0	1.8Y 8.1/4.9
Calcite	dark brown-orange	12.55	round	Baja, Mexico	41	23.2 58.4	7.3YR 4.0/10.1

Gemstone	Color	Weight	Shape	Location	L*a*b*			Munsell
Calcite-Co	dark rose pink	3.40	cushion	Spain	20	47.4	-16.4	3.1RP 1.9/11.9
Childrenite	peach	1.37	round	Brazil	74	19.0	9.3	3.8R 7.3/4.5
Chrysoberyl	brownish-green	7.80	oval	Sri Lanka	47	-3.6	28.8	6.7Y 4.6/4.0
	medium brown	6.19	oval	Sri Lanka	38	5.8	36.3	1.3Y 3.7/5.4
	brownish-yellow	7.51	round	Sri Lanka	54	2.6	27.7	1.9Y 5.3/4.1
	green-yellow	7.04	round	Sri Lanka	54	-0.4	40.4	4.2Y 5.3/5.8
	yellow-brown	11.84	oval	Brazil	67	2.8	48.1	2.3Y 6.6/7.1
	dark greenish-yellow	13.25	antique	Brazil	49	-6.0	36.3	7.7Y 4.8/5.1
	brown	9.30	emerald cut	Sri Lanka	43	6.7	42.5	1.2Y 4.2/6.5
	dark greenish-yellow	21.30	oval	Sri Lanka	59	-4.9	31.3	7.0Y 5.8/4.4
	lemon yellow	11.49	oval	Brazil	72	-9.4	30.8	0.9GY 7.1/4.2
	greenish-yellow	12.02	round	Sri Lanka	50	-7.1	41.3	8.0Y 4.9/5.7
Chrysocholla	medium blue	13.59	free form	Arizona	39	-36.0	-9.5	5.9BG 3.8/7.4
Cinnabar	red	1.37	fancy	Charcas, Mexico	11	37.4	36.5	1.1YR 1.0/9.4
Clinohumite	orange	1.52	emerald cut	USSR	36	24.8	59.0	7.3YR 3.5/10.3
Corundum								
Ruby	pink-violetish red	3.66	antique	Thailand	23	40.9	-0.8	7.5RP 2.2/9.5
	dark pinkish-red	3.56	oval	Burma	24	48.0	-19.3	2.2RP 2.3/12.3
	dark red	2.23	oval	Thailand	19	44.0	-1.3	7.6RP 1.8/10.2
	medium pinkish-red	2.30	oval	Burma	49	45.8	-21.9	0.6RP 4.8/12.0
	pink-orangy red	2.11	antique	Thailand	26	46.2	2.4	8.5RP 2.5/10.7
	medium red	2.07	antique	Thailand	24	45.9	0.2	7.9RP 2.3/10.6
	violetish-red	3.56	antique	Thailand	18	42.5	-7.2	5.4RP 1.7/10.2
	violet	1.02	pear	Thailand	38	38.8	-19.3	0.6RP 3.7/10.3
	pinkish-red	0.98	oval	Thailand	37	50.5	-19.1	2.2RP 3.6/12.8
Sapphire	light pink	2.12	oval	Sri Lanka	23	19.6	-12.1	9.1P 2.2/5.1
	medium purple-blue	3.76	antique	Sri Lanka	38	21.7	-40.7	8.9PB 3.7/10.2
	dark green	4.25	oval	Sri Lanka	20	-11.6	11.5	8.2GY 1.9/2.4
	fine medium dark blue	5.21	oval	Sri Lanka	21	23.0	-48.2	7.6PB 2.0/12.1
	medium blue	6.05	oval	Sri Lanka	47	9.7	-30.9	7.4PB 4.6/7.3
	dark blue	2.60	oval	Sri Lanka	17	15.5	-39.0	7.0PB 1.6/9.7
	violetish-pink	4.02	oval	Sri Lanka	37	33.7	-21.8	8.5P 3.6/8.9
	dark lemon yellow	16.12	oval	Sri Lanka	70	-0.3	56.8	3.8Y 6.9/8.2
	medium green	1.98	antique	Umba Valley, Tanzania	52	-5.4	19.8	9.3Y 5.1/2.7
	very pale yellow	1.40	antique	Umba Valley, Tanzania	79	4.7	5.4	1.0YR 7.8/1.3
	red-violet	1.86	emerald cut	Umba Valley, Tanzania	34	7.2	-8.9	3.1P 3.3/2.5
	orangy-yellow	3.41	antique	Umba Valley, Tanzania	55	8.3	38.2	0.1Y 5.4/6.0
	brown-pink	3.28	emerald cut	Umba Valley, Tanzania	36	15.4	12.3	9.5R 3.5/3.7
	orangy-red	0.96	antique	Umba Valley, Tanzania	40	44.7	15.6	2.8R 3.9/10.5
	blue-violet	3.77	antique	Umba Valley, Tanzania	42	8.4	-19.3	8.7PB 4.1/4.6
	green	1.46	round	Umba Valley, Tanzania	55	-9.1	19.2	3.5GY 5.4/2.9
	powder-blue	2.56	round	Umba Valley, Tanzania	54	5.4	-23.3	6.9PB 5.3/5.5
	brownish-orange	4.64	antique	Umba Valley, Tanzania	30	33.7	35.6	1.1YR 2.9/8.9

(continued)

TABLE 2. (Continued)

Gemstone	Color	Weight	Shape	Location		L*a*b*		Munsell
Heated Geuda	dark golden yellow	6.13	oval	Sri Lanka	81	11.6	78.3	0.1Y 8.0/12.1
	medium orange	3.89	oval	Sri Lanka	42	11.2	54.6	0.4Y 4.1/8.4
	dark orange	4.00	oval	Sri Lanka	53	31.5	92.3	7.3YR 5.2/15.7
	yellow	2.21	oval	Sri Lanka	80	8.0	78.3	1.0Y 7.9/11.9
	orangy-yellow	3.60	oval	Sri Lanka	58	11.4	70.0	0.7Y 5.7/10.7
Miscellaneous	dark blue	3.87	emerald cut	Australia	15	8.7	-32.0	5.7PB 1.4/7.8
	dark blue-green	5.75	emerald cut	Australia	18	-7.1	-7.3	2.5B 1.7/2.2
	dark pink	6.20	oval	Sri Lanka	52	25.8	-18.1	7.7P 5.1/7.0
	dark blue	—	—	Kashmir	25	5.0	-25.0	5.4PB 2.4/6.0
	beige-yellow	5.55	oval	Sri Lanka	60	13.7	29.9	6.0YR 5.9/5.4
	dark blue	2.30	pear	Montana	28	-7.3	-8.4	4.0B 2.7/2.5
	medium blue	1.35	octagon	Montana	40	-6.0	-13.5	8.8B 3.9/3.6
	medium light blue	1.19	pear	Montana	52	0.9	-17.0	4.8PB 5.1/4.1
	light blue	1.40	shield	Montana	77	2.0	-13.5	7.0PB 5.7/3.1
	blue-green	1.47	pear	Montana	48	-8.2	0.7	1.1BG 4.7/1.5
	light yellow-green	1.77	pear	Montana	75	-8.6	13.3	6.1GY 7.4/2.2
	light greenish-yellow	1.66	shield	Montana	70	-11.9	25.3	4.0GY 6.9/3.8
	light green	1.10	octagon	Montana	64	-4.0	13.3	0.1GY 6.3/1.8
	yellow	0.95	shield	Montana	70	-2.0	26.7	4.8Y 6.9/3.8
	orange-mauve	0.96	shield	Montana	58	5.8	5.8	0.6YR 5.7/1.5
beige	1.03	pear	Montana	60	8.1	9.5	1.7YR 5.9/2.2	
Creedite	violet	0.96	emerald cut	Mexico	60	15.7	-12.6	6.6P 5.9/4.4
Crocoite	orangy-red	1.87	emerald cut	Tasmania	33	50.0	75.0	3.0YR 3.2/15.8
Cuprite	dark red	11.62	round	South Africa	6	48.5	27.7	6.9R 0.9/11.1
Diaspore	pale gray-yellow	2.10	emerald cut	Turkey	69	-0.8	13.8	4.2Y 6.8/2.0
Diopside	medium green	2.23	round	New York	72	-3.5	15.6	7.6Y 7.1/2.2
chrome	dark green	0.75	round	Kenya	36	-26.2	51.0	4.7GY 3.5/8.0
chrome	dark green	4.95	antique	USSR	10	-18.0	35.7	3.5GY 0.9/5.5
Diopside	green	0.41	emerald cut	Tsumeb, Namibia	28	-62.6	-1.2	1.5BG 2.7/12.0
Enstatite	brown	0.52	round	Burma	52	3.3	32.5	1.9Y 5.1/4.8
	green	2.43	pear	Africa	32	-20.2	54.0	2.4GY 3.1/7.8
	light brown	4.38	emerald cut	Africa	50	14.8	40.0	7.7YR 4.9/6.8
Epidote	dark brown	3.43	cushion	Africa	2	7.3	21.7	0.1Y 0.9/3.5
Euclase	light blue-green	1.33	emerald cut	Brazil	77	-4.6	0.0	3.6BG 7.6/0.9
	dark blue	0.24	emerald cut	Zimbabwe	35	-4.5	-20.4	0.8PB 3.4/5.0
Fluorite	emerald-green	3.05	pear	Colombia	59	-27.0	19.1	0.9G 5.8/5.3
	pink	0.92	round	Switzerland	70	18.4	6.8	2.0R 6.9/4.4
	violet	5.75	round	Illinois	17	20.3	-25.1	1.8P 1.6/7.1
	blue-green	6.05	oval	England	44	-19.8	7.6	4.5G 4.3/3.6
	yellow	8.80	round	Illinois	62	0.1	49.8	3.8Y 6.1/7.2
	blue	75.77	marquise	Illinois	36	-2.8	31.3	2.2PB 3.5/7.6
Garnets								
Andradite	medium green	0.47	round	Korea	50	-13.2	33.2	2.5GY 4.9/4.8
	olive green	0.51	round	Korea	47	0.3	40.3	4.2Y 4.6/5.8
	brown	0.33	round	East Siberia, USSR	29	15.6	44.3	8.9YR 2.8/7.4
Demantoid Grossular	medium green	0.68	emerald cut	USSR	51	-38.8	54.6	7.2GY 5.0/9.8
	medium orange	9.81	round	Asbestos, Quebec	44	14.4	28.0	5.9YR 4.3/5.2
	light mint green	4.15	antique	Tanzania	70	-11.9	19.6	5.8GY 6.9/3.2
	light brownish-yellow	5.01	triangle	Tanzania	55	6.3	32.9	0.1Y 5.4/5.1
	light brownish-yellow	2.59	emerald cut	Tanzania	84	9.4	38.9	8.2YR 8.3/6.3
	cinnamon brown	4.48	antique	Tanzania	51	19.6	17.9	10.0R 5.0/5.0

Gemstone	Color	Weight	Shape	Location	L*a*b*		Munsell	
Malaya	near colorless	2.18	round	Tanzania	92	0.9	8.4	0.1Y 9.1/1.3
	medium mint green	3.88	antique	Tanzania	58	-16.8	23.0	6.9GY 5.7/4.1
	dark green	2.47	emerald cut	Tanzania	50	-46.6	34.6	0.5G 4.9/9.2
				(tsavorite)				
	dark orange	4.82	antique	Tanzania	88	44.4	66.0	0.3YR 8.7/14.7
	very pale green	4.14	antique	Tanzania	77	2.9	4.6	3.5YR 7.6/0.9
	medium brownish-orange	12.80	triangle	Tanzania	30	25.6	24.6	0.6YR 2.9/6.5
	brownish-pink	11.39	antique	Tanzania	44	17.3	5.6	9.1R 4.3/1.7
	orange	6.38	triangle	Tanzania	45	16.9	30.7	5.3YR 4.4/5.9
	gray-brown	8.23	antique	Tanzania	39	8.0	20.6	8.0YR 3.8/3.5
Pyrope-Almandine	pinkish-orange	8.56	antique	Tanzania	48	19.1	21.3	1.3YR 4.7/5.2
	dark orange	14.46	antique	Tanzania	25	35.9	48.9	3.3YR 2.4/10.6
Rhodolite	medium rose-pink	3.09	round	Sri Lanka	28	36.7	1.8	8.3RP 2.7/8.5
	light rose-pink	0.74	round	North Carolina	54	-24.8	-5.7	3.4RP 5.3/6.0
	dark red	0.58	round	Arizona	23	33.5	38.4	2.1YR 2.2/9.0
	brown-orange	1.27	round	Mozambique	30	38.1	22.0	6.5R 2.9/8.9
Spessartine	brownish	6.48	emerald cut	?	26	38.6	28.4	8.5R 2.5/9.3
	red-violet	10.88	oval	Tanzania	12	22.5	-9.1	2.3RP 1.1/5.7
	brownish-violet	13.10	round	Tanzania	10	31.7	7.3	2.0R 0.9/7.3
Spessartine	fine dark violet	24.46	antique	Tanzania	16	37.6	-4.8	6.0RP 1.5/9.0
	light orange	3.61	round	Orissa, India	55	18.1	38.3	5.9YR 5.4/7.0
Spessartine	medium orange	3.81	round	Orissa, India	45	29.1	55.8	5.2YR 4.4/10.6
	dark orange	5.65	oval	Orissa, India	22	34.2	54.2	4.7YR 2.1/10.8
	dark brownish-orange	4.05	pear	Brazil	25	31.1	31.8	1.2YR 2.4/8.0
Tsavorite	dark brownish-orange	15.40	emerald cut	Madagascar	14	30.3	41.4	4.1YR 1.3/8.8
	light orange	4.65	oval	Amelia, Virginia	40	28.3	37.9	2.8YR 3.9/8.2
	medium brownish-orange	6.41	antique	?	31	37.2	58.6	4.1YR 3.0/11.9
	dark orange	1.27	round	Africa	38	27.5	29.6	1.2YR 3.7/7.3
	very dark brownish-orange	16.80	antique	Brazil	4	26.5	26.7	2.0YR 0.9/6.7
	light orange	1.75	round	Ramona, California	74	34.5	62.4	3.1YR 7.3/12.5
	medium dark green	4.11	oval	Tanzania	40	-49.0	32.4	1.0G 3.9/9.4
Häüyne Hypersthene Idocrase	fine medium green	2.47	emerald cut	Tanzania	50	-46.6	34.6	0.5G 4.9/9.2
	medium green	1.25	emerald cut	Tanzania	44	-47.2	27.8	1.6G 4.3/8.9
	dark green	4.01	oval	Tanzania	32	-51.8	32.6	1.1G 3.1/9.8
	blue	0.04	fancy	Germany	52	1.0	-40.0	4.1PB 5.1/9.7
	dark bottle green	2.52	pear	Arizona	25	-6.0	41.7	8.1Y 2.4/5.7
	brown	2.30	round	Africa	46	14.9	52.6	9.2YR 4.5/8.5
	green	1.05	round	Africa	52	-14.4	51.5	1.0GY 5.1/7.1
	brown	3.82	emerald cut	Switzerland	35	15.9	42.6	8.3YR 3.4/7.2
	brown	1.40	cushion	Italy	51	6.6	67.0	2.4Y 5.0/9.9
	Iolite	blue	1.56	round	India	28	10.7	-24.0
blue		3.00	emerald cut	India	26	10.1	-25.3	7.6PB 2.5/6.1
Kornerupine (chrome)	light green	0.40	round	Africa	65	-32.1	28.6	0.1G 6.4/6.7
	light brown	12.07	round	Sri Lanka	50	5.4	30.5	0.3Y 4.9/4.6
	olivy-brown	2.62	oval	Sri Lanka	34	-1.0	19.7	5.5Y 3.3/2.8
Kyanite	medium blue	8.30	cushion	Brazil	48	-11.6	-21.7	7.9B 4.7/5.8
	dark blue	4.01	cushion	Brazil	40	1.0	-33.0	3.8PB 3.9/8.0
Lazulite	blue	0.70	round	Brazil	47	-6.1	-31.5	1.5PB 4.6/7.8
Microlite	green	0.14	oval	Brazil	59	-24.0	23.3	9.4GY 5.8/5.1
Manganotantalite	red	4.85	cushion	Mozambique	11	37.2	36.5	1.2YR 10.7/9.4
Opal	yellow	11.74	emerald cut	Idaho	49	5.5	59.3	2.5Y 4.8/8.7
	brown-gray	5.15	round	Mexico	35	0.7	12.7	3.2Y 3.4/1.8

(continued)

TABLE 2. (Continued)

Gemstone	Color	Weight	Shape	Location		$L^*a^*b^*$		Munsell
Peridot	orangy-red	0.76	round	Mexico	46	50.9	95.4	4.0YR 4.5/18.6
	light orange	8.04	oval	Mexico	46	19.3	55.7	8.1YR 4.5/9.5
	medium green	8.25	antique	Arizona	47	-20.9	52.3	3.2GY 4.6/7.7
	medium green	9.20	triangle	Arizona	34	-11.9	48.5	0.1GY 3.3/6.6
	light green	4.51	pear	Norway	66	-19.0	31.7	5.9GY 6.5/5.2
Phosphophyllite	light green	8.22	oval	Egypt	58	-13.3	31.9	3.0GY 5.7/4.7
	light blue-green	0.81	emerald cut	Bolivia	85	-4.2	-1.4	9.8BG 8.4/0.9
Proustite	dark red	2.58	round	Germany	18	51.6	50.0	10.0R 1.7/13.5
Quartz								
Amethyst	lilac	6.22	emerald cut	Brazil	57	19.4	-12.0	8.6P 5.6/5.0
	light violet	9.18	oval	Brazil	37	18.5	-14.5	7.1P 3.6/5.2
	dark violet	8.52	fancy oval	Zambia	6	25.5	-26.0	3.0P 0.9/8.0
	medium dark violet	4.40	oval	Brazil	6	22.8	-21.1	3.9P 0.9/6.9
	medium dark violet	3.61	round	Brazil	12	29.8	-29.0	3.3P 1.1/9.2
	medium dark purple	6.41	round	Brazil	14	20.1	-23.2	2.3P 1.3/6.8
	dark purple	6.38	fancy emerald cut	Brazil	12	25.9	-25.3	3.5P 1.1/8.0
Citrine	"Siberian"	14.91	oval	Para, Brazil	8	30.8	-23.4	7.8P 0.9/8.5
	medium yellow-orange	7.55	round	Brazil	52	13.5	43.1	8.4YR 5.1/7.1
	brownish-orange	4.20	round	Brazil	38	7.9	34.8	0.1Y 3.7/5.4
	dark straw-yellow	8.81	oval	Brazil	55	5.4	23.9	9.8YR 5.4/3.8
	pale straw-yellow	12.64	oval	Brazil	61	0.7	19.3	2.7Y 6.0/2.8
	light orange	16.90	antique	Brazil	56	12.1	61.0	0.1Y 5.5/9.5
	medium orange	19.72	oval	Brazil	53	19.2	66.5	8.7YR 5.2/10.9
	dark orange	15.76	oval	Brazil	33	21.7	51.1	7.4YR 3.2/8.9
	dark orange ("Madeira")	15.33	oval	Brazil	29	30.5	61.1	6.3YR 2.7/11.3
	Green quartz	apple green	4.48	oval	Brazil	52	-9.5	13.0
Rose quartz	medium pink	14.20	emerald cut	Brazil	51	13.1	4.2	2.0R 5.0/3.1
	pale pink	18.79	antique	Brazil	71	6.0	6.1	0.2YR 7.0/1.5
Smoky quartz	medium brown	23.78	round	Brazil	26	7.6	12.3	5.6YR 2.5/2.4
	light brown	15.61	emerald cut	Brazil	63	4.5	23.7	0.1Y 6.2/3.7
	medium yellow-brown	9.37	emerald cut	Brazil	43	5.6	22.5	0.1Y 4.2/3.5
Rhodochrosite	dark brown	13.57	emerald cut	Brazil	20	8.6	15.1	6.5YR 1.9/2.8
	very dark brown	7.49	emerald cut	Brazil	1	6.8	11.6	6.6YR 0.9/2.2
	pink	11.88	antique	Colorado	39	40.2	11.4	1.8R 3.8/9.4
	pink	7.15	rhomboid	Peru	51	42.1	11.9	1.3R 5.0/9.9
	orangy-red	9.42	round	South Africa	30	52.7	52.3	10.0R 2.9/14.0
	pink	3.95	round	Argentina	49	37.6	15.6	3.5R 4.8/8.8
	red	24.60	antique	South Africa	16	43.6	44.9	1.2YR 1.5/11.4
Scapolite	gold-yellow	32.44	oval	Tanzania	67	3.0	55.4	2.5Y 6.6/8.1
	gold-yellow	32.00	antique	Tanzania	53	3.2	53.7	3.0Y 5.2/7.9
	very pale yellow	5.77	antique	Brazil	76	-1.8	11.8	5.9Y 7.5/1.6
	lemon yellow	9.03	antique	Burma	61	1.0	37.0	3.1Y 6.0/5.4
	violet	4.36	oval	Tanzania	30	16.1	-16.2	4.2P 2.9/5.0
Scheelite	straw yellow	2.85	pear	Korea	84	0.0	30.3	2.5Y 8.3/4.4
Scorodite	violet-blue	1.15	fancy	Namibia	23	5.7	-13.4	8.0PB 2.2/3.3
	violet-blue	1.50	pear	Namibia	15	5.3	-26.8	4.9PB 1.4/6.6
Sinhalite	dark straw-yellow	4.58	antique	Sri Lanka	50	6.6	32.5	0.1Y 4.9/5.1
	brown	7.07	oval	Sri Lanka	16	16.7	37.6	8.1YR 1.5/6.5
	green	4.18	oval	Sri Lanka	47	1.0	25.6	3.2Y 4.6/3.7
	yellow	9.18	oval	Sri Lanka	65	8.9	37.0	9.1YR 6.4/5.9
Smithsonite	pale yellow	8.00	round	Namibia	75	4.2	9.0	5.6YR 7.4/1.6
	beige	10.40	oval	Namibia	73	1.3	6.0	9.3YR 7.2/0.9

Gemstone	Color	Weight	Shape	Location		L*a*b*		Munsell
Sodalite	intense dark blue	0.85	emerald cut	Namibia	23	20.0	-43.2	7.7PB 2.2/10.8
Sphalerite	light green	1.93	round	Colorado	68	-2.8	73.4	5.1Y 6.7/10.4
	yellow-orange	3.30	round	Spain	72	6.9	100	2.7Y 7.1/14.7
	dark green	4.65	round	Mexico	43	0.6	55.0	4.6Y 4.2/7.9
	dark orange	14.48	round	Spain	39	38.1	86.6	6.3YR 3.8/15.5
	light orange	5.57	round	Spain	55	26.6	10.3	2.9R 5.4/6.3
Sphene	brownish yellow-green	6.22	emerald cut	Madagascar	49	2.3	66.9	4.0Y 4.8/9.7
	light yellow-green	1.55	round	Baja, Mexico	73	-10.8	56.2	8.1Y 7.2/7.8
	light brown	1.76	round	Baja, Mexico	28	21.2	51.0	7.9YR 2.7/8.9
	medium green	7.01	emerald cut	India	34	-17.5	47.5	2.3GY 3.3/6.9
	emerald green	1.01	round	Baja, Mexico	24	-33.3	34.2	8.5GY 2.3/7.2
	brown	1.44	round	Baja, Mexico	60	11.9	80.4	1.0Y 5.9/12.3
	yellow-green	4.22	round	India	51	-1.3	67.8	5.2Y 5.0/9.6
	yellow	2.65	antique	India	79	-5.8	74.9	5.7Y 7.8/10.5
	Spinel							
Blues	dark blue	8.35	oval	Sri Lanka	12	-0.6	-12.7	2.1PB 1.1/3.1
	medium dark blue	9.20	oval	Sri Lanka	15	-6.9	-12.7	6.2B 1.4/3.3
	light blue	9.30	oval	Sri Lanka	31	-6.6	-11.9	7.2B 3.0/3.2
	lavender-blue	15.22	oval	Sri Lanka	50	4.8	-16.8	7.5PB 4.9/3.9
	greenish-blue	4.78	round	Sri Lanka	21	-13.6	-11.1	0.7B 2.0/3.8
	cobalt-blue	11.23	emerald cut	Sri Lanka	6	-2.3	-19.7	0.8PB 0.9/4.8
	slightly violetish-blue	7.27	round	Sri Lanka	29	2.8	-20.8	4.8PB 2.8/5.1
	dark violet	5.46	antique	Sri Lanka	13	5.2	-13.7	7.2PB 1.2/3.4
	magenta	3.96	oval	Sri Lanka	19	44.4	-4.5	6.3RP 1.8/10.6
	medium purple	11.98	antique	Sri Lanka	14	7.2	-9.2	2.0P 1.3/2.5
	blue-violet	8.53	oval	Sri Lanka	25	6.0	-12.6	8.6PB 2.4/3.1
	light purple	7.98	oval	Sri Lanka	27	14.4	-9.0	9.0P 2.6/3.7
	gray-blue	14.96	antique	Sri Lanka	30	-5.1	-8.5	6.9B 2.9/2.3
	Pinks	dark rose-red	8.21	round	Sri Lanka	14	27.0	2.4
light rose-red		7.65	oval	Sri Lanka	30	25.3	-0.7	7.1RP 2.9/5.8
dark pink		5.23	oval	Burma	24	-24.8	-4.8	4.7RP 2.3/6.0
dark violetish-red		9.02	oval	Sri Lanka	21	19.3	-2.2	5.9RP 2.0/4.6
medium reddish-purple		7.07	oval	Sri Lanka	26	27.1	-6.8	3.9RP 2.5/6.6
grayish-pink		5.89	oval	Sri Lanka	47	21.4	2.0	8.1RP 4.6/4.9
medium pink		6.56	oval	USSR	68	41.6	3.8	7.4RP 6.7/9.7
slightly bluish-pink		8.87	oval	Sri Lanka	42	15.4	-2.5	4.5RP 4.1/3.7
light dusty-pink		11.40	antique	Burma	54	16.2	-2.8	4.1RP 5.3/3.9
Reds		dark orangy-red	5.30	round	Burma	27	24.7	20.7
	medium pinkish-orange	2.98	oval	Burma	41	43.5	10.4	0.9R 4.0/10.3
	medium brownish-pink	3.07	round	Burma	42	34.5	7.8	0.7R 4.1/8.2
	medium brown	2.34	round	Burma	45	26.4	14.4	5.7R 4.4/6.2
	light brownish-pink	10.98	oval	Burma	48	23.6	8.1	2.4R 4.7/5.5
	dark grayish-pink	3.95	round	Burma	31	14.7	4.1	2.0R 3.0/3.4
	dark red	8.89	oval	Burma	8	36.8	31.8	0.2YR 0.9/9.1
	medium red	2.68	oval	Burma	30	41.5	25.1	6.8R 2.9/9.7
	medium pinkish-red	3.21	round	Burma	27	47.5	7.4	0.1R 2.5/11.1
	Spodumene	blue	29.85	oval	Brazil	53	-2.7	-3.4
medium pink		16.06	emerald cut	Afghanistan	59	-17.7	-12.9	2.3B 5.8/4.8
medium pink		17.76	oval	California	58	19.1	-10.9	9.1P 5.7/4.8
yellow-green		17.01	emerald cut	Afghanistan	63	-5.3	28.0	7.5Y 6.2/3.9
dark pink		47.33	oval	Brazil	65	32.2	-19.0	8.7P 6.4/8.3

(continued)

TABLE 2. (Continued)

Gemstone	Color	Weight	Shape	Location	L*a*b*			Munsell
Taaffeite	gray-mauve	1.60	rhomboid	Sri Lanka	50	4.5	0.8	9.0RP 4.9/1.0
Topaz	yellow-brown	6.72	round	USSR	38	13.0	37.2	8.6YR 3.7/6.2
	red-orange	12.59	emerald cut	Brazil	49	38.6	37.5	9.9R 4.8/10.1
	dark beige	5.29	round	Mexico	56	12.0	26.3	6.2YR 5.5/4.8
	yellow	4.65	oval	Brazil	59	8.6	27.7	8.3YR 5.8/4.6
	dark orange	25.25	oval	Brazil	61	23.9	61.5	6.6YR 6.0/10.8
	brownish-pink	8.76	antique	Brazil	63	35.0	5.7	8.6RP 6.2/8.2
	medium blue	7.20	oval	Brazil	60	-14.3	-17.6	6.1B 5.9/5.2
	red-orange	8.45	antique	Brazil	65	34.4	26.8	7.6R 6.4/8.7
	medium pink	17.84	oval	USSR	73	25.2	-16.9	7.7P 7.2/6.7
	Tourmaline							
Rubellite	pinkish-orange	36.85	emerald cut	Madagascar	25	38.3	21.2	6.4R 2.4/8.9
	dark red-violet	13.16	oval	Brazil	24	47.8	-0.9	7.6RP 2.3/11.1
	very dark violet-red	17.13	emerald cut	Brazil	5	28.0	2.8	9.6RP 0.9/6.5
	medium violet	16.73	antique	Brazil	20	38.1	-5.0	5.8RP 1.9/9.1
Blues and Greens	dark red	10.26	antique	Ouro Fino, Brazil	12	39.5	7.4	0.1R 1.1/9.1
	dark pinkish-red	36.56	emerald cut	Brazil	19	41.8	10.4	2.0R 1.8/9.7
	intense smalt blue	9.84	emerald cut	Brazil	41	-21.0	18.8	9.6GY 4.0/4.3
	blue-green	15.96	emerald cut	Brazil	50	-40.1	-0.1	2.3BG 4.9/7.7
	fine green (chrome)	10.05	triangle	Africa	30	-30.7	23.9	0.1G 2.9/6.0
Orangy Colors	slightly yellowish-green	9.68	emerald cut	Brazil	52	-39.7	15.9	3.9G 5.1/7.3
	dark green	14.75	emerald cut	Brazil	32	-38.8	31.1	0.1G 3.1/7.7
	peachy-orange	10.90	round	Mozambique	42	31.1	20.5	7.2R 4.1/7.4
	medium brownish-orange	5.74	antique	Tanzania	43	18.6	56.6	8.5YR 4.2/9.4
	dark brownish-orange	4.84	round	Tanzania	48	20.9	70.4	8.7YR 4.7/11.6
	medium orangy-brown	10.39	oval	Tanzania	28	10.7	46.0	0.4Y 2.7/7.1
	medium pinkish-brown	46.84	oval	Tanzania	31	24.0	26.4	1.8YR 3.0/6.4
Pinks	medium pink	32.32	oval	Afghanistan	57	34.7	0.0	6.5RP 5.6/8.2
	medium dark rose-pink	10.95	round	Brazil	28	34.0	-4.2	5.6RP 2.7/8.1
	slightly brownish-pink	11.13	antique	Mozambique	44	28.7	12.5	4.1R 4.3/6.6
	brown-pink	21.22	emerald cut	Stewart Mine, Pala, California	38	18.7	20.6	1.7YR 3.7/5.0
Mozambique Color Suite	medium pinkish-beige	2.51	round	Mozambique	66	23.7	7.7	1.4R 6.5/5.6
	light pinkish-beige	2.37	round	Mozambique	78	19.1	5.5	0.4R 7.7/5.6
	near colorless	2.59	round	Mozambique	85	7.9	3.9	3.5R 8.4/1.9
	light pink	2.19	round	Mozambique	56	33.2	-5.7	4.1RP 5.5/8.0
	dark rose-pink	2.15	round	Mozambique	35	47.0	-11.6	3.9RP 3.4/11.5
	dark green	2.16	round	Mozambique	24	-12.8	22.0	4.6GY 2.3/3/5
	dark brownish-green	2.34	round	Mozambique	34	-14.7	37.0	2.4GY 3.3/5.4
	medium green	2.68	round	Mozambique	52	-8.3	41.4	8.5Y 5.1/5.7
	lime green	2.10	round	Mozambique	64	-8.6	26.0	1.2GY 6.3/3.7
	very pale green	3.08	round	Mozambique	69	0.1	12.8	2.9Y 6.8/1.8
	colorless	2.22	round	Mozambique	84	1.5	2.1	2.3YR 8.3/0.4
	beige-yellow	2.04	round	Mozambique	87	3.8	21.6	9.3YR 8.6/3.4
	light brown	2.33	round	Mozambique	37	9.0	51.1	1.2Y 3.6/7.8
	dark brown	1.81	round	Mozambique	36	18.9	33.8	5.6YR 3.5/6.4
	blue	2.30	round	Mozambique	45	-8.4	-2.1	6.2BG 4.4/1.7

<i>Gemstone</i>	<i>Color</i>	<i>Weight</i>	<i>Shape</i>	<i>Location</i>		<i>L*a*b*</i>		<i>Munsell</i>
Willemite	golden yellow	2.35	pear	Franklin, New Jersey	85	-7.4	63.0	6.2Y 8.4/8.9
Wulfenite	yellow	6.11	oval	Namibia	63	1.0	29.0	2.8Y 6.2/4.2
	orangy-red	2.54	emerald cut	Red Cloud Mine, Arizona	45	43.8	96.1	5.4YR 4.4/17.6
Zircon	reddish-brown	19.03	oval	Sri Lanka	17	16.2	16.7	2.2YR 1.6/4.1
	brownish-yellow	17.43	oval	Sri Lanka	37	12.2	49.6	0.1Y 3.6/7.8
	violet-rose	14.20	round	Sri Lanka	20	30.9	3.4	9.4RP 1.9/7.2
	dark orange	9.26	oval	Sri Lanka	33	25.5	66.0	7.9YR 3.2/11.4
	green	4.36	oval	Sri Lanka	48	-15.4	25.8	5.4GY 4.7/4.2
	rose-red	11.26	emerald cut	Sri Lanka	19	26.2	8.3	3.1R 1.8/5.9
	lemon yellow	15.70	oval	Sri Lanka	50	-0.3	31.6	4.2Y 4.9/4.5
	medium blue	5.56	oval	Cambodia	46	-12.3	-14.1	4.9B 4.5/4.2
	yellow	8.92	oval	Sri Lanka	65	10.8	58.1	0.1Y 6.4/9.0
	pale gray-green	16.63	antique	Sri Lanka	55	7.8	14.6	5.4YR 5.4/2.7
	reddish-brown	7.77	oval	Sri Lanka	26	23.0	29.1	3.2YR 2.5/6.5
	light olive green	5.34	round	Sri Lanka	47	-0.3	19.2	4.3Y 4.6/2.7
	dark blue	2.87	round	Cambodia	56	-8.4	-11.1	6.8B 5.5/3.3
	light pink	1.36	round	Sri Lanka	71	-11.9	-5.8	0.7B 7.0/2.8
	light orange	1.44	round	Sri Lanka	59	26.2	58.1	5.7YR 5.8/10.6
	medium orange	2.59	round	Sri Lanka	52	39.4	70.9	4.0YR 5.1/13.9
	pale blue-green	2.67	round	Cambodia	77	-6.9	-1.4	7.2BG 7.6/1.4
	Zoisite	violet-blue	26.54	pear	Tanzania	20	55.0	-76.3
light blue-gray		1.06	round	Tanzania	75	0.7	0.6	9.5R 7.4/0.1
medium blue		2.30	round	Tanzania	60	3.5	-20.7	6.4PB 5.9/4.8
violet-blue		0.96	emerald cut	Tanzania	47	16.8	-35.7	8.8PB 4.6/8.7
brown-blue		0.92	emerald cut	Tanzania	61	7.1	-11.7	2.0P 6.0/3.0