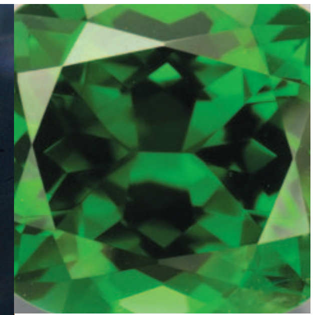

Gemology: The Developing Science of Gems

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Prompted by the increasing number of laboratory-grown gems and the growing sophistication of treatments of natural stones, gemology has evolved into a science of its own. The discipline is rapidly incorporating relevant aspects of materials science and chemistry, and it is consolidating its activities and its terminology. Gemology is becoming an important area of specialization for mineralogists. If the study of beautiful, fashioned materials seems frivolous to some, it is worth noting that 20 to 25 billion dollars per year are at stake, and the study of natural gem materials and their treated and manufactured counterparts is essential in order to avoid frauds and protect the consumer.

Keywords: gemology, gems, history of gemology, gem treatment, gem terminology, synthetic gems

INTRODUCTION

Diamonds, rubies, emeralds, jade, pearls—these are the seeds of many dreams (Fig. 1). Gems are associated with love and romance, but also with power, money, and the plundering of riches. Gems have always played an integral role in cultures worldwide. One can be dazzled one minute by splendid jewelry glistening on stars at the Academy Awards, and the next minute hear about the embargo on Burmese gems. Let us not forget that, for a gem to be a true treasure, it must be authentic. This is where gemologists play an important role. At first, it was just a matter of recognizing an imitation, and a good knowledge of minerals, combined with a keen sense of observation, was all that was needed. But soon, people tried to modify and improve gems. Even the ancient Egyptians heated agate to give it a more attractive color. The production of "Egyptian blue" (cuprorivaite), a turquoise look-alike, can be considered a starting point of crystal growth technology. This "new technology" eventually led in the 19th century to the first gem rubies and emeralds grown by man (Nassau 1980). For centuries, gemology was exclusively a branch of mineralogy, as most gems were natural minerals. The expansion in production of man-made gems in the 1970s and 1980s and the explosion in the number and sophistication of gem treatment processes since the 1990s have spurred a more multidisciplinary approach. Gemology now incorporates elements of spectroscopy, materials physics, chemistry, and even some biology (e.g. in work on pearls). Today, gemology has evolved from a trade practice to a recognized science. Its economic field of application is the gems and jewelry trade. About 150 billion dollars' worth of gems and jewelry are sold annually. Gems by themselves are worth 20 to 25 billion dollars, with the lion's share (about 85%) accounted for by diamond.

Gems are mined worldwide, but some countries, such as Brazil, Sri Lanka, Myanmar, Australia, and Madagascar, have acquired over the years a reputation for producing many or particularly beautiful gems. Shigley et al. (2000) provide a detailed list of gem-producing localities, and a world map of these was edited by Gübelin (1994).

In this issue, we address key aspects of gemology. Groat and Laurs (2009) explain how gems grow in nature and how they are extracted. Rossman (2009) details the role of geochemistry in characterizing gemstones, while Devouard and Notari (2009) address the problem of identifying the exact nature of faceted gems. Shigley and McClure (2009) provide an overview of important gem treatment processes and their detection, while Kane (2009) introduces synthetic gems. Gauthier and Karampelas (2009) also present a brief account of pearls and corals as biomineral gems.

GEMS ARE NOT SO EASY TO DEFINE

Gems are materials used for adornment or decoration that must satisfy several criteria: they must be relatively rare, hard, and tough enough (shock resistant) to resist "normal" wear and withstand corrosion by skin contact (sweat) and cosmetics.

This very general definition calls for several comments. The notion of rarity is relative. If a gem is too rare, it tends to be less well known and is less expensive, as there is not enough of it to build a market. A number of gems fit into the category of "rare stones"—they belong to the domain of specialized collectors; examples include jeremejevite, taaffeite, and preobrazhenskite. In fact, less than 200 materials are considered relatively common gems; the rest are "rare" (see Fritsch 1992). Nevertheless the price of a rare stone can be increased by a strong marketing campaign, as has been the case for benitoite and red beryl. Also, although most common gems are relatively hard and tough, a number of gems are interesting precisely because they are difficult to facet (brucite and halite are excellent examples) and so cannot be mounted in jewelry. These are for "collectors on paper," as such fragile pieces are usually kept in a "fold," a piece of paper folded several times over to safely hold the specimen.

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The vast majority of gems are natural minerals. This led to the expression "precious stones." According to culture and country, this term typically encompasses (at least) diamond, ruby, sapphire, and emerald. For a given gem, only a few varieties are highly priced, and the rest do not truly deserve the term *precious* [for example, a 50 carat (ct) D-flawless diamond versus a 3 mm diameter brown or black faceted diamond, or a 15 ct bright blue faceted Paraíba tourmaline versus a 1 ct dark green tourmaline cabochon (cab); Fig. 2]. Not all gems are precious, as a number of gemstones are moderately priced (Fig. 3). This is why we prefer the expression "gem materials" or simply "gems." These terms better cover the large variety of products found in the jewelry market today. Needless to say, we recommend not using the term "semiprecious stones," which, in our view, is meaningless. In addition, not all "stones" or minerals are of interest to gemologists, who work only on those that can be fashioned into gems or are known as inclusions in gems, and these represent a limited subset of the existing mineral species. Finally, not all gems are "stones"—pearls are a notable example (Fig. 1).

Figure 1 The term *gem* covers a large range of products: single crystals, amorphous minerals, organics, rocks, imitations, synthetics, treated stones, faceted or rough objects, and even assemblages of various materials. This composite picture shows (from top to bottom): a natural jadeite-jade carving; lapis lazuli with matrix, accompanied by a high-quality lapis cabochon; a precious boulder opal-A from Queensland, Australia; a pear-shaped, briolette-cut near-colorless glass; a slightly dissolved octahedral diamond crystal; a gem intarsia by N. Medvedev (containing malachite, opal, lapis, turquoise, and purple sugilite); a red andesine feldspar; a beryllium-diffused, orangey-red sapphire (right); a dyed, green jadeite cabochon; and five white to golden, South Seas, beaded, cultured pearls. Photo by R. Weldon, courtesy GIA

A natural gem is one that has been fashioned (or faceted) after having been found in nature, even if it later undergoes treatment processes. Among natural gems, most are single crystals. However, others are amorphous (opal, natural glass), some are not pure species but solid solutions (garnets, peridot), others are rocks (jade, lapis), and some are composed partly or wholly of organic materials (amber, pearl, coral, etc.) (Fig. 1).

"Fakes"

Among gem materials, there are several types of "fakes." The oldest historically are imitation gems—fashioned stones that look like more valuable materials but have a different structure and composition. Only imitations would be considered fakes by gemologists. Imitations have been produced since antiquity because beautiful natural gems are so rare. Some experts distinguish imitations (still natural gems) from simulants, which are man-made products (Fritsch 1992). Until the early twentieth century, heat-treated colorless zircon was the most common diamond imitation.

Synthetics are laboratory-grown materials with the same crystal structure and chemical composition (apart for impurities) as their natural counterparts (Kane 2009 this

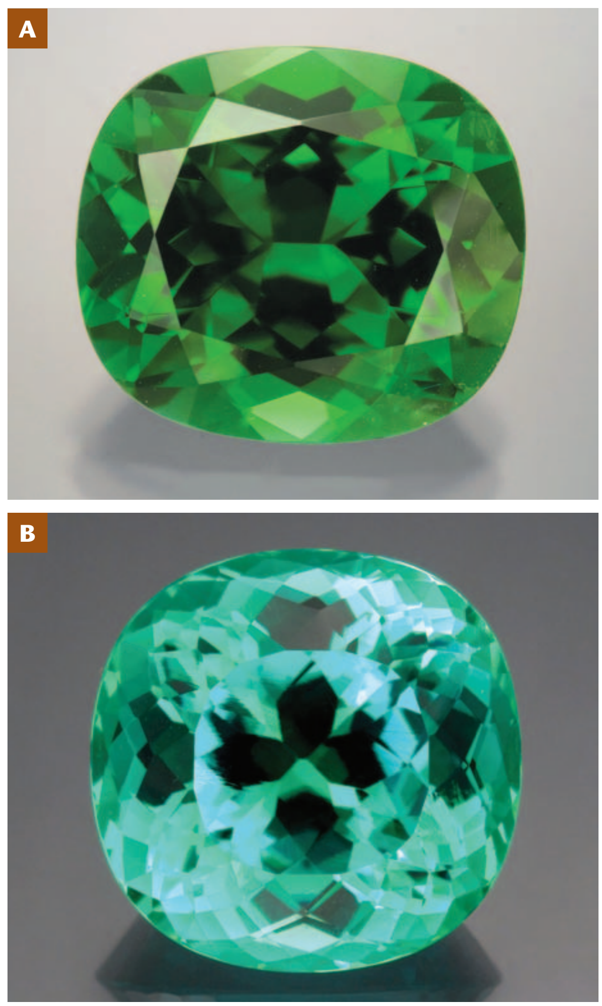

Figure 2 Not all tourmalines are of equal value. This fairly common green tourmaline (**A**) is relatively inexpensive, whereas the blue Cu-colored "Paraíba" tourmaline (**B**) may sell for thousands of dollars per carat. The mineralogical nature of a gem species does not directly command its value. The precise variety and its locality of origin are also determining factors. Incidentally, a "Paraíba" tourmaline can be more precious than some emeralds or sapphires. The stones weigh 13.12 and 70.74 ct, respectively. Photographs by Wimon Manorotkul/www.palagems.com

issue). Synthetic gems have been around for well over a century (Fig. 4), as melted and recrystallized natural ruby was sold as "Geneva ruby" starting in 1885.

Treated gems are objects (either natural or synthetic) that have undergone a treatment process to modify their appearance, usually their color or purity (Shigley and McClure 2009 this issue), for example, worthless light-colored sapphire made orange by beryllium diffusion at high temperature.

Some names are much more appealing than others. To make the material commercially more attractive, a look-alike stone of lesser value borrows the name of a glamorous cousin, with the addition of a local or locality name, to avoid flat-out identity theft. For example, "Herkimer diamond" is certainly not diamond, but a bright, colorless, bipyramidal quartz found near Herkimer in New York State; similarly, grossularite garnet from South Africa glorifies itself as "Transvaal jade." Any scientifically inadequate or deliberately ambiguous name is termed a misnomer. This category does not include confusing names of specific gems such as the "Black Prince Ruby," which has been known to be a spinel for quite some time (ruby and spinel were confused in the past, spinel then being referred to as "balas ruby").

Composite gems are made of several materials assembled together. A very common example is the opal doublet or triplet. Nice play-of-color opal is rare and is often found as a fragile filling in very thin seams. To circumvent these frustrations, thin opal slices are glued, as in a sandwich, between a black base highlighting color and a mechanically resistant, rounded, colorless top (often quartz or glass). These opal "triplets" look like regular opal cabochons, and they help put on the market beautiful pieces that otherwise would be hard to sell. At the other end of the spectrum, stone mosaics called "intarsia", made with no intent to deceive, play on the boldness of color and a sharp geometrical pattern to create one true gem out of many fragments (Fig. 1).

Engineered gems are man-made but have no natural equivalents. The raw material is often natural, but is modified to give an aspect (color, most often) never encountered in nature. The road to engineered gems was opened by Aqua Aura quartz, colorless quartz made aquamarine blue by a thin film of gold. The material was hugely successful. Today, topaz is also coated with a thin metallic film, providing different colors and optical effects–an example is "mystic topaz". All in all, as many as 500 different materials can probably be considered as gems, and the list continues to grow.

Diamonds and Colored Stones

There has been a historical divide between diamonds and "colored stones," an expression meaning in essence "everything but diamond." The distinction is sometimes inadequate, as colorless varieties of other species then become "colorless colored stones," whereas colored diamonds remain in the "diamonds" category and not in the "colored stones" one! These two broad categories are often considered as belonging to different fields, with their own specialists and practices, and even different, often unrelated, training courses. This is nonsensical from a scientific standpoint, but no better system has been proposed so far.

Figure 3 This string of beads (courtesy John Saul) from Ethiopia is made of various fragments: glass, pottery, agate beads, chalcedony, and metal chips. All of these materials have very little commercial value, if any. However, as they are considered worth being worn as jewels by the owner, they are gem materials. For more details on the nature of these gems, see http://gemnantes.fr/research/others/ethiopia.php.

Figure 4 Contrary to popular belief, synthetic gems have been available for over a century. The first commercial "synthetic" was the Geneva ruby, circa 1885. This ring (top right) contains nine such synthetic rubies, easily recognized by their strong, internal, curved striae (bottom right), which are derived directly from a rather brutal melting and mixing process. The text of this postcard (printed in 1904; left) advertising Geneva rubies reads "Oriental ruby is the most sought-after gem and, as a consequence, the most expensive, its price being far greater than that of the brilliant. We have discovered the means to agglomerate small parcels of natural oriental rubies by melting them at 2000°C. Therefore, we offer to the public the reconstituted oriental ruby. It has all the qualities of natural oriental ruby since the material is the same, as well as the density, hardness, and refringence. Our production and cutting workshops are equipped with all the improvements of modern mechanics, which make it possible for us to solve this problem: make available to all budgets a precious stone that, until now, was accessible only to millionaires."

FIGURE 5 These five stones (ranging in weight from 2.38 to 4.18 ct) look like natural emeralds, and it takes a gemologist to tell them apart, using simple tools available in a jewelry store. From left to right, natural emerald, synthetic YAG (yttrium aluminum garnet), glass, fluorite, synthetic emerald. PHOTOGRAPH BY R. WELDON, COURTESY GIA

A MULTIDISCIPLINARY SCIENCE

Gemology is the science of gems. Its core business is the identification of gem materials, first by establishing their identity and then by determining whether they are natural or synthetic and if they have been treated (Webster 1975; Liddicoat 1987; Hurlbut and Kammerling 1991; Devouard and Notari 2009 this issue) (FIGS. 5 and 6). Also, quality grading of diamonds (the famous "4Cs": carat, color, clarity, cut) is an important part of gemology. Quality grading of pearls has recently been introduced, and various systems for colored stones (particularly with respect to their color) have been proposed, even if none is universally accepted.

The geographical origin of gems is also an important specialty, as some colored stones have significantly higher value if they can be recognized as coming from certain preferred deposits: blue sapphires from Kashmir have always commanded higher prices than those from Burma or Sri Lanka, for example. It is interesting to note that over a century ago, the same was true of diamond: Indian diamonds were worth more than those from Brazil, themselves more valuable than South African newcomers (Jannettaz et al. 1881). This distinction disappeared with the introduction of a detailed quality-grading system. Hence, the locality-of-origin issue is today akin to branding, a marketing procedure.

Related Fields

In an effort to understand—or even better, predict—criteria for identification or determination of geographical origin, gemology often involves related fields of expertise. For example, crystal growth studies help the gemologist understand growth structures often visible inside faceted gems and the formation of inclusions as a function of the growth environment. These optical features can be especially useful in establishing the locality of origin for a gem, and whether it is natural or synthetic. The geology of gem deposits is fundamental to understanding the nature of inclusions and trace elements (FIG. 7). Of course, such knowledge eventually leads to the development of prospecting guidelines, and hence helps ensure future production of gems and, ultimately, market stability (Groat and Laurs 2009 this issue). More recently, geochemistry has become an important part of gemology. The development of trace element analysis and isotope gemology has contributed criteria that can also help distinguish between natural and synthetic gems or identify geographical origin (Rossman 2009 this issue). An understanding of the origin of color is fundamental, as the value of a gem is often related to its color, especially the stability of that color and whether it is natural or treatment-induced. The related property of luminescence is an integral part of gem identification, but is not always well understood.

New Techniques and Instrumentation

The foundation of gemology is observation, because it is extremely useful, yet quick and nondestructive. As observation does not require complex, expensive instrumentation, there was a perception that gemology was not very scientific. However, simple solutions are the most elegant, and one should not use complex machines if the correct scientific answer can be gained by adequate use of one's sight. This negative perception is fading away, as, since the 1960s, gemologists have become major users of optical spectroscopic techniques, starting with ultraviolet–visible–near infrared absorption spectroscopy, then mid-infrared, and more recently Raman scattering and a variety of luminescence techniques. Many of the fields of investigation mentioned above can benefit from such techniques: UV–visible absorption spectroscopy is fundamental for color-related problems, and infrared spectroscopy helps in the detection of minor constituents such as water, CO_2, and organic impregnation materials, some of which are relevant to the geology of gem deposits and to the identification of treated or synthetic gems (FIG. 6). Gemologists are also frequent users of various microscopic techniques, such as optical and electron microscopy. The development of spectroscopic methods at the microscopic scale for specific gemological use is continuing.

Terminology Issues

One of the first steps for a science is establishing a correct classification of relevant objects or concepts. Gemological nomenclature still requires some clarification as it develops from a trade practice into a science. A key issue currently is the conflict between a scientific terminology and one that is more acceptable commercially but occasionally incorrect or ambiguous. For example, *synthetic opal*, a commercial term accepted for decades, covers materials that contain silica but no water (such as Gilson synthetic opal), although a true synthetic should contain all components of natural opal ($SiO_2 \cdot nH_2O$), including water (e.g. Schmetzer 1983). There is considerable debate today on how far merchants can go in the language they use to advertise synthetic diamonds: "man-made" and "laboratory-grown" are accepted, but "cultured" is not approved by many international organizations.

The term *graining* is a good example of a poorly defined concept: it is used for many different phenomena, virtually all concerning diamond, including variation of indices of refraction in colorless diamonds (simply “graining”); pink or brown lamellae alternating with colorless ones (“colored graining”)(Fig. 8); green luminescence zoning in brown diamonds (“fluorescent graining”); minute inclusions in white diamonds (“whitish graining”); and difference in hardness, for example, at growth sector limits (“hardness graining”. There is even reflective graining (seen in purple diamonds) and iridescent graining. In most cases, some local variation of index of refraction is associated with another physical phenomenon, so “graining” might be narrowed to just that first characteristic in the list. Unfortunately, in materials science and even mineral physics, *graining* has a different meaning and refers to the fact that a crystal is constituted of different grains.

THE GEMOLOGICAL CROWD

A gemologist is a practitioner of gemology and is, therefore, able to correctly and efficiently identify and grade gem materials (Fig. 5). Very few gemologists practice “full time.” These would include laboratory gemologists, working in the main gem labs around the world, mostly grading diamonds. There are probably a few dozen “research gemologists,” people dedicating their time to gemological research. Among them, only some are scientists by training.

Most gemologists practice gemology in addition to a range of related activities. Jewelers create jewels and art objects using gem materials. They must know the physical and optical properties of gemstones in order to mount them safely (some can break easily) and aesthetically (some change color with direction, for example). The same is true for cutters, who transform rough gem materials into faceted gemstones. Retailers need gemological knowledge to buy and sell gems and gem-set jewelry and adequately evaluate repairs (for example, to make sure a diamond brought in for retipping of prongs has not been fracture-filled). Wholesalers and rough dealers sell faceted and rough gems, respectively. They obviously have a strong financial interest in distinguishing “true” from “fake” gems. This is also the case for experts (judicial, insurance, customs), who are legally responsible for providing information regarding gems (either mounted or not), and appraisers, who assign the commercial value of a gem at a given time. Archeogemologists study gems from past civilizations. They first have to identify them correctly. A growing part of archeogemology is the reconstruction of trade routes, hence the strong interest in the determination of geographical origin. Last but not least, gemology attracts a number of enthusiastic amateurs, who are often the driving force in associations and local gem clubs.

That few scientists and many trade people are involved has contributed to the perception that gemology is not a science, a view not uncommon among geologists and physicists. This is accentuated by the rarity of academic gemology

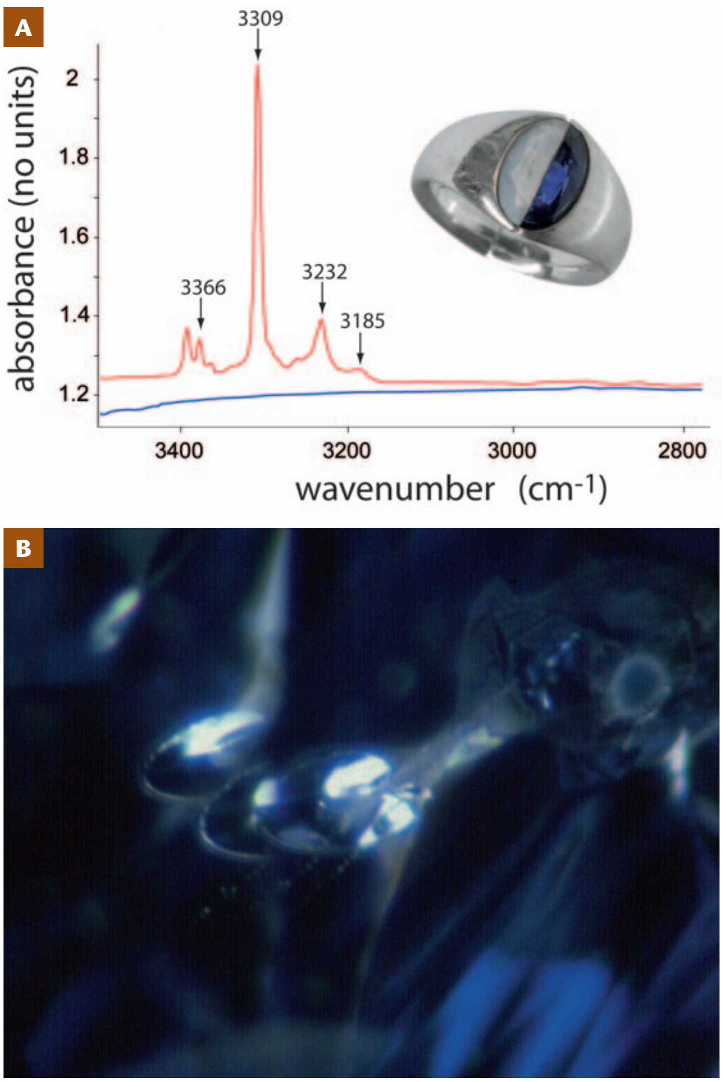

Figure 6 Gemologists often need to use several classical gemology and laboratory methods to resolve an issue. One half of the sapphire in the ring (**A**, inset) has been heat treated to a desirable transparent blue from an initial valueless milky appearance. High-temperature treatment is revealed by optical microscopy (**B**); the zircon inclusion in the top-right corner has melted and now looks like a whitish sphere (“golf ball” inclusion), and needle-like TiO_2 (silk) inclusions in the center have been partially dissolved and now appear as dotted lines. 40x magnification. Transmission infrared spectroscopy (**A**) provides further information: the peak at 3309 cm^{-1} and its companions indicate heat treatment under reducing conditions, with capture of an H atom by an Fe–Ti pair (red spectrum), absent in the untreated part (blue spectrum). Ring photo courtesy Pascal Entremont

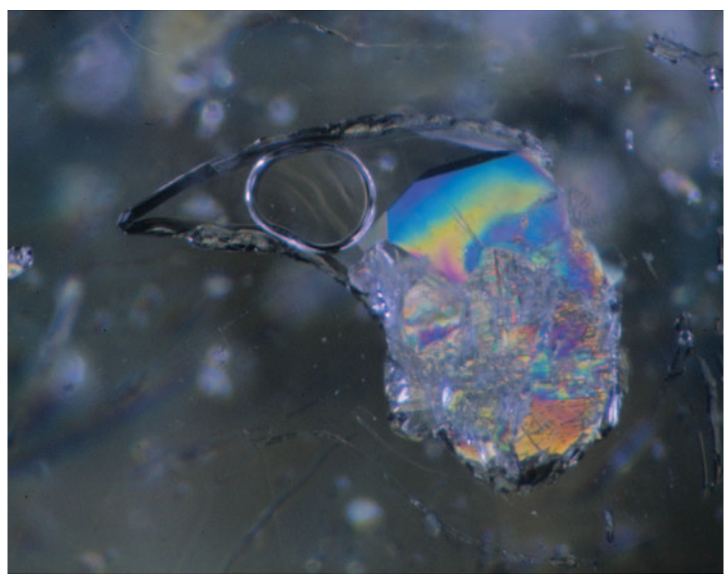

Figure 7 Inclusions in gems often give a strong indication of the geological environment of formation of the host gem. In this spectacular eagle-head-shaped fluid inclusion in colorless beryl, three daughter crystals have been identified (15x magnification). The sharp-faced, partially terminated crystal nearest to the bubble is quartz, and the more granular or fragmented portion in the ruff of feathers on the eagle’s neck is albite. There are some tiny needles as well, too small to identify, but which are suspected to be tantalite by analogy with other, larger, needle-shaped inclusions commonly found in beryl. This indicates that all three minerals are present in the pegmatite in which this gem was discovered. Photo by J. Koivula

FIGURE 8 For any science, precise terminology is essential. However, in gemology, some terms are still poorly defined and therefore confusing. As an example, the term *graining* refers to many phenomena occurring in parallel planes, including color lamellae in pink and brown diamonds (left, field of view ~4 mm), green fluorescence (middle, field of view ~6.5 mm), and high-optical-relief planes running across colorless diamond (right, here seen between crossed polarizers, field of view ~14 mm). However, most of these phenomena are accompanied by slight variations in index of refraction, which might be used as a more precise definition of *graining*.
PHOTOGRAPHS BY T. HAINSCHWANG

programs in universities worldwide and by the lack of visibility of high-quality gemological research. However, gemology actually has a long history as a discipline, and some excellent research is being conducted by gemologists.

A NEW SCIENCE, FOR THE FUTURE OF MINERALOGY

Gemology has its roots in work by the Greek and Roman naturalists and philosophers. In 315 AD, Theophrastus described how stones (including gemstones) form. Pliny (circa 79 AD) had already mentioned identification issues, particularly regarding green gem materials (smaragdus) and treated materials (such as treated agates). Centuries later, around Renaissance times, Pliny was still a reference in the field. The development of gemology as a modern science started with Haüy (1817) and his contemporaries. During the 19th century, many gemological tools were invented, such as the refractometer and polarizing filters (at the time, made of gem tourmaline). These two examples of equipment are still fundamental to gemological identification.

Gemology has benefited from input from scientific methods over many years, even if this was very gradual (see the "state of the art" by Gramaccioli 1991). However, it is only in the last ten years that special sessions have been dedicated to gem materials in international conferences, mostly in the fields of geology and mineralogy (for example, at the International Mineralogical Association meetings and the International Geological Congress). Only recently has gemology become a truly independent branch of science, with its first ISI journal (*Gems & Gemology,* accepted in May 2004) and the first scientific conference based on accepting abstracts after a full peer-review process (Gemological Research Conference, August 2006, San Diego, California, USA). A growing number of scientists focus their work on gemological materials and topics, in laboratories devoted to well-established disciplines such as mineralogy, geology, physics, and mathematics. Hence gemology is becoming a more widely recognized science. It represents one of the future areas of specialization for students in mineralogy, geochemistry, and petrology. We would like to believe that the excitement of working with gems is one of the driving forces behind the development of gemology—gems are beautiful, have a rich history, and offer complex challenges and rewarding research opportunities.

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