

Gems & Gemology

VOLUME XX

SUMMER 1984



The quarterly journal of the Gemological Institute of America

Gems & Gemology

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Subscriptions in the U.S.A. are priced as follows: \$24.50 for one year (4 issues), \$65.00 for three years (12 issues). Subscriptions sent elsewhere are \$34.00 for one year, \$95.00 for three years.

Special annual subscription rates are available for all students actively involved in a GIA program: \$19.50 U.S.A., \$29.00 elsewhere. Your student number *must* be listed at the time your subscription is entered.

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Gems & Gemology is published quarterly by the Gemological Institute of America, a nonprofit educational organization for the jewelry industry, 1660 Stewart St., Santa Monica, CA 90404.

Application to mail at second class postage rates is pending in Santa Monica, CA 90404 and at additional mailing offices.

Any opinions expressed in signed articles are understood to be the views of the authors and not of the publishers.

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ABOUT THE COVER: Most of the aquamarine on the world gem market has come from the rich pegmatites found throughout the northeastern section of the state of Minas Gerais, Brazil. The history of gem exploration and mining in this area in general, and the geology and occurrence of the famous aquamarine deposits in particular, are discussed in the article by Keith Proctor in this issue. The 898-gran aquamarine crystal on the cover, which is 13.8 cm high × 7 cm wide (5 $\frac{3}{8}$ " × 2 $\frac{3}{4}$ "), is from the Pioneer mine in the Teófilo Otoni-Marambaia pegmatite district of Minas Gerais. As is common with most aquamarines, the stones cut from this greenish crystal would be heat treated to remove the yellow component and produce the blue color associated with fine aquamarine. Photo © 1984 Harold © Erica Van Pelt—Photographers, Los Angeles, CA. Crystal courtesy of Keith Proctor, Colorado Springs, CO.

Typesetting for Gems & Gemology is by Scientific Composition, Los Angeles, CA. Color separations are by Effective Graphics, Compton, CA. Printing is by Waverly Press, Easton, MD.

THE MAGIC OF PEGMATITES

When one considers that all of the aquamarine and most of the tourmaline, topaz, kunzite, morganite, and many other gem materials are found exclusively in pegmatites, it becomes obvious that the gemologist must be aware of and understand the nature of this unusual rock type.

Although pegmatites are not uncommon and are found virtually worldwide, only a small percentage contain worthwhile gem materials. Yet the often superb quality of the gemstones that are found in pegmatites and the fact that they formed under a unique set of conditions conducive to crystal growth has captured the interest of gemologists and geologists for many decades.

The late Richard H. Jahns, a member of the GIA Board of Governors, was a world-recognized authority on pegmatites. In a real sense, this issue of *Gems & Gemology* is dedicated to his memory. Dr. Jahns gave wise counsel to the Gemological Institute of America over many years—from the time that he was a professor at the California Institute of Technology through his tenure as head of the Earth Sciences group at Pennsylvania State University and, most recently, as dean of Earth Sciences at Stanford University.

The article by James Shigley (who studied under Dr. Jahns) and Anthony Kampf is an excellent compilation of what we currently know about pegmatites. The essentially two-part article by Keith Proctor reviews both the history and exploration of, and actual mining of aquamarine in, one of the most important gem pegmatite regions of the 20th century: Minas Gerais, Brazil.

With these articles, we hope to take you, the reader, from the basics of what a pegmatite is to the fascinating story of what pegmatite gems have meant historically in Brazil and the production of one very important pegmatite gemstone, aquamarine.

Richard T. Liddicoat, Jr.

GEM-BEARING PEGMATITES: A REVIEW

By James E. Shigley and Anthony R. Kampf

Many of the important gem minerals seen on today's market—aquamarine, tourmaline, and topaz, among others—come from an unusual type of rock known as a pegmatite. Gem-bearing pegmatites are crystalline igneous rocks that are distinguished by their large-size crystals, concentrations of certain chemical elements otherwise rare in the earth's crust, and various unusual minerals. Pegmatites are typically rather small bodies of rock that are found in particular geologic environments; the gem minerals occur in open cavities or "pockets" within the pegmatite. This article surveys our current understanding of pegmatites, beginning with a brief description of their characteristics and following with a discussion of the occurrence of gem minerals in them. The article concludes with a summary of the specific conditions necessary during pegmatite formation for the crystallization of abundant gem minerals.

Aquamarine, tourmaline, topaz, kunzite, morganite—these are but a few of the gemstones found in the remarkable mineral deposits that geologists call pegmatites (figure 1). Of the many different kinds of rock exposed at the earth's surface, pegmatites contain the greatest abundance and variety of gem minerals. Pegmatite deposits in various parts of the world have yielded spectacular crystals of gem tourmaline (figure 2), topaz (figure 3), and beryl (figure 4), as well as a host of other minerals occasionally used as gems (see tables 1 and 2). Most of these minerals are only rarely found in other geologic environments in crystals suitable for faceting. In addition, pegmatites are a major source of certain rare elements of great economic importance.

This article briefly summarizes current knowledge concerning the nature and formation of these fascinating rocks and the occurrence of gem minerals within them. Individual pegmatite localities are not discussed in detail here. Rather, a broad overview is presented to demonstrate the remarkable similarities between gem-producing pegmatites in diverse parts of the world. Armed with this perspective, the reader should be able to better appreciate detailed reports of pegmatite occurrences such as those in Brazil that are discussed elsewhere in this issue.

WHAT IS A PEGMATITE?

The famous mineralogist Haüy first used the word *pegmatite* in the early 1800s to refer to a rock with a patterned geometric intergrowth of feldspar and quartz (now commonly termed *graphic granite*). Today it is applied to any crystalline rock that is, at least in part, extremely coarse grained. The term *pegmatite*, then, primarily refers to the texture of a rock, that is, the size, shape, and arrangement of mineral grains. In practice, it can be applied to a wide range of rocks of igneous or metamorphic origin that exhibit large crystals.

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Figure 1. A selection of gemstones of pegmatite origin ranging from 5.87 to 11.25 ct. Minerals shown (from left to right, and from front to back) are as follows: tourmaline (elbaite), garnet (spessartine), chrysoberyl; topaz, feldspar (orthoclase), beryl (morganite); beryl (aquamarine), tourmaline (elbaite), tourmaline (elbaite); beryl (heliodor), spodumene (kunzite). Photo by Tino Hammid.

In reality, the vast majority of pegmatites are found to be chemically and mineralogically similar to ordinary granites and, hence, are called "granitic" pegmatites (as opposed to "gabbroic" pegmatites, "syenitic" pegmatites, etc.). Because gem minerals are, for the most part, found only in granitic pegmatites, these will be the focal point of the ensuing discussion.

Texture. Although pegmatites are commonly thought of as very coarse-grained rocks, they actually vary considerably in grain size. This variability is important in distinguishing pegmatites from most other crystalline rocks. For example,

the mineral grains in a granite are quite uniform in size and only rarely exceed several millimeters in diameter. Those in a pegmatite are usually several centimeters across on average, but they can range from millimeters to meters in diameter (figure 5). Typically there is an increase in crystal size from the outer margins toward the interior of the pegmatite body.

The largest crystals ever found have come from pegmatites (see, for example, Jahns, 1953; Rickwood, 1981; Sinkankas, 1981). Outstanding examples include a 14-m-long spodumene crystal from the Etta mine in the Black Hills of South Dakota and an 18-m-long beryl crystal from a



Figure 2. Multicolored crystal of tourmaline with albite feldspar and quartz from a pegmatite in Afghanistan (14 × 9 cm). Photo © Harold & Erica Van Pelt. Specimen courtesy of David Wilber.

pegmatite at Malakialina, Madagascar. The famous Harding pegmatite in New Mexico contains spodumene crystals that are 5 m long (figure 6). Unfortunately, these and most other giant crystals are not of gem quality. There are, however, exceptions: for instance, a 300-kg transparent gem topaz from a pegmatite in Minas Gerais, Brazil, is now on display in the American Museum of Natural History in New York.

Mineralogy and Chemistry. The minerals that occur in any rock depend on the rock's overall chemistry and the pressure and temperature conditions under which it formed. Most granitic pegmatites are composed of the same minerals found in ordinary granites, that is, feldspars (microcline, plagioclase), quartz, micas (muscovite, biotite), and on occasion some common accessory minerals (table 3; also figure 5). As such

these pegmatites have generally been of limited economic, scientific, or gemologic interest. A small percentage of pegmatites, however, contain additional minerals, such as beryl and tourmaline, which incorporate certain rare elements. This latter group of granitic pegmatites, which are the source of most gem rough, have been the principal objects of pegmatite exploration and mining.

Establishing the chemical composition of a rock provides important clues regarding its origin, geologic history, and relationships to other rock types. Relatively fine-grained rocks, such as granites, are easily sampled and analyzed to determine overall chemical composition; however, this is not generally the case for pegmatites. Their coarse and variable grain size, nonuniform distribution of minerals, and often poor surface exposure pose serious obstacles to accurate chemical analysis. Nevertheless, painstaking work at a number of



Figure 3. Topaz crystals with smoky quartz from a pegmatite in the Ural Mountains of the Soviet Union (9 cm wide). Photo © Harold & Erica Van Pelt. Specimen courtesy of David Wilber.

Figure 4. A superb crystal of morganite beryl with albite feldspar from the White Queen mine, Pala, California (4 × 5 cm). Photo © Harold & Erica Van Pelt.



Table 1. Occurrence of gem minerals in pegmatites.

| Mineral | Relative abundance ^a | Pegmatites the major source? |
|--|---------------------------------|------------------------------|
| Common | | |
| Feldspar (gem varieties orthoclase, amazonite, moonstone) | A | no |
| Quartz (gem varieties rock crystal, amethyst, smoky, rose, citrine) | A | no |
| Unusual (containing rare elements such as Li, Be, B, P, F, Cs, etc.) | | |
| Apatite | R | no |
| Amblygonite | C | yes |
| Beryl (gem varieties aquamarine, morganite, heliodor, goshenite) | C | yes |
| Beryllonite | VR | yes |
| Brazilianite | VR | yes |
| Chrysoberyl | R | no |
| Danburite | R | no |
| Euclase | R | yes |
| Garnet (spessartine) | R | yes |
| Hambergite | VR | yes |
| Herderite | VR | yes |
| Lepidolite | C | yes |
| Petalite | R | yes |
| Phenakite | VR | yes |
| Pollucite | VR | yes |
| Spodumene (gem varieties kunzite, hiddenite) | C | yes |
| Topaz | C | yes |
| Tourmaline (elbaite—gem varieties rubellite, achroite, indicolite; liddicoatite) | C | yes |

^aRelative abundance in granitic pegmatites: A = abundant and widespread; C = common or locally abundant; R = rare or uncommon; VR = very rare.

localities has yielded meaningful estimates of the chemical composition of granitic pegmatites (see table 3).



Figure 5. Small pegmatite body cutting through granite at the Fletcher stone quarry near Westford, Massachusetts. Both the pegmatite and enclosing granite are composed of feldspars, mica, and quartz, but within the pegmatite the crystals are much larger. In addition, the crystals near the center of the pegmatite are larger than those along the outer margins. Photo by Richard H. Jahns.

Common granitic pegmatites show little deviation from typical granite chemistry (compare columns 1 and 2 in table 3). In contrast, those that contain small amounts of unusual minerals exhibit marked enrichments in a variety of rare elements (table 3, column 3). Lithium, beryllium, boron, and fluorine, in particular, are essential constituents in several important gem minerals. Despite their small total amounts (seldom over 2 wt. %, expressed as oxides), the concentrations of these and other rare elements in some granitic

TABLE 2. Some of the more important gem pegmatite regions.

| Region | Tourmaline | Beryl | Spodumene | Topaz | Quartz | Garnet |
|----------------------|------------|-------|-----------|-------|--------|--------|
| Afghanistan/Pakistan | X | X | X | X | X | X |
| Brazil | X | X | X | X | X | X |
| Madagascar | X | X | X | X | X | X |
| Mozambique | X | X | X | X | | X |
| Namibia | X | X | | X | X | |
| Soviet Union | | | | | | |
| Ural Mountains | X | X | | X | X | X |
| Transbaikalia | X | X | | X | | |
| Ukraine | X | X | | X | X | |
| East Africa | X | X | | X | | X |
| United States | | | | | | |
| New England | X | X | | | | |
| Colorado | | X | | X | X | |
| California | X | X | X | X | X | X |



Figure 6. View of the Harding pegmatite in Taos County, New Mexico. Several internal zones are visible as colored bands with differing texture and mineral content. This large, complex pegmatite, approximately 80 m thick, is rich in lithium minerals and rare elements, but apparently crystallized at too great a depth in the crust to allow for the formation of gem-bearing pockets. The elongate, light-colored crystals are common spodumene reaching 5 m in length. Photo by Richard H. Jahns.

TABLE 3. Chemical and mineralogical comparison of granite and granitic pegmatites.

| Component/ phase | Granite ^a | Common pegmatite ^b | Gem-bearing pegmatite ^c |
|---------------------------------------|---|---|---|
| Chemistry | | | |
| SiO ₂ | 72.34 | 74.2 | 70.22 |
| Al ₂ O ₃ | 14.34 | 15.0 | 17.20 |
| FeO + Fe ₂ O ₃ | 1.81 | 0.6 | 1.76 |
| TiO ₂ | 0.26 | — | — |
| MnO | 0.02 | — | 0.28 |
| H ₂ O | 0.36 | 0.6 | 0.39 |
| MgO | 0.37 | — | trace |
| CaO | 1.52 | 0.3 | 1.36 |
| Na ₂ O | 3.37 | 4.6 | 4.45 |
| K ₂ O | 5.47 | 4.2 | 2.85 |
| Li ₂ O | — | — | 1.49 |
| P ₂ O ₅ | — | 0.3 | 0.07 |
| F | — | 0.1 | 0.11 |
| B ₂ O ₃ | — | — | 0.18 |
| BeO | — | trace | trace |
| Rb ₂ O + Cs ₂ O | — | — | trace |
| Total | 99.86 | 99.9 | 100.36 |
| Mineralogy | | | |
| Major phases | Microcline Quartz Plagioclase Muscovite Biotite | Microcline Quartz Albite Muscovite | Microcline Quartz Albite Muscovite |
| Minor phases | | Beryl Tourmaline Apatite Garnet | Beryl Tourmaline Apatite Garnet Spodumene Rhodizite Lepidolite Hambergite Danburite |

^aWesterly granite, Westerly, Rhode Island (Tuttle and Bowen, 1958).
^bDiamond Mica pegmatite, Keystone, South Dakota (Norton, 1970).
^cGem-bearing pegmatite, Manjaka, Madagascar (Schneiderhöhn, 1961).

pegmatites can exceed by several orders of magnitude the amounts found in other rocks. In fact, the mining of pegmatites for rare elements, or even for the common pegmatite minerals, has at times been of far greater economic importance than the mining of pegmatites for gemstones. For instance, the Harding pegmatite (figure 6) was an important wartime source of beryl for beryllium, of lepidolite and spodumene for lithium, and of microlite for tantalum.

DESCRIPTIVE CLASSIFICATION

Efforts over the past century to better understand granitic pegmatites and their distinctive features have led to numerous attempts to classify them according to some logical framework. Most early schemes were descriptive in nature, and were based on various observable features such as shape or key minerals (see Landes, 1933; Jahns, 1955; Vlasov, 1961; Černý, 1982). One of the most widely accepted of these descriptive classifications was summarized by Heinrich (1956). This scheme, which is still useful today, divides granitic pegmatites into three types on the basis of internal structure:

1. Simple (figures 5 and 7a)—lack any segregation of minerals; may or may not display a systematic variation in texture; consist mostly of common silicate minerals with accessory minerals on some occasions.
2. Zoned (figures 7b, 8, and 9)—possess distinct internal zones of contrasting mineral content and texture; often larger than the simple types; consist of common silicate

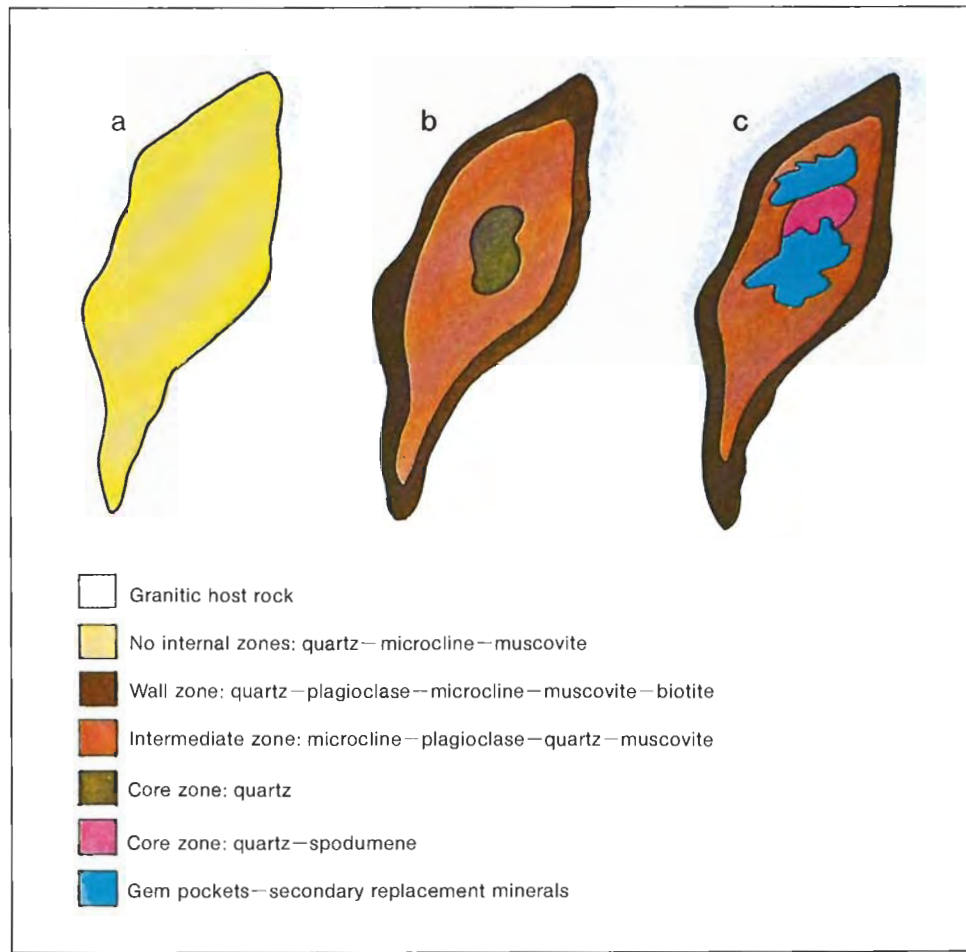


Figure 7. Idealized diagram showing internal structural relationships in simple (a), zoned (b), complex (c), pegmatites. Artwork by Christine Wilson; adapted from Jahns (1953).

minerals and various accessory species; minerals become more coarse grained toward the interior of the pegmatite.

3. Complex (figures 6 and 7c)—similar to the zoned types except also exhibit extensive mineral alteration and replacement; often contain high concentrations of rare elements and unusual minerals.

Simple pegmatites are by far the most numerous, while complex pegmatites are the least common but of greatest interest to the geologist and miner. Giant crystals, rare elements, and gem minerals are generally restricted to zoned and complex pegmatites.

Minerals found in the latter two types of pegmatites are arranged in layers or zones. As illustrated in figures 8 and 9, in an ideal situation these shell-like zones are concentrically disposed around an innermost core and tend to follow the exterior shape of the pegmatite body. Although the internal structure of many zoned pegmatites is rarely so uniform, and may be quite complicated,

fieldwork at numerous localities has documented a basic internal arrangement of minerals in pegmatites that is generalized in table 4. In the field, recognition of this mineral arrangement in a pegmatite is of enormous help both to the student of pegmatites and to the miner (Sinkankas, 1970).

GENETIC CLASSIFICATION

Building on the earlier studies, more recent attempts to classify granitic pegmatites have emphasized the geologic environment of pegmatite formation rather than descriptive details. For example, an alternative scheme proposed by Ginzburg et al. (1979; summarized in Černý, 1982) uses the conditions present at various levels in the earth's crust to help explain observed differences in the nature of pegmatites. They recognized four classes of pegmatites:

1. Those formed at very great depth (more than 11 km), which are generally unzoned and possess little economic mineralization other than occasional concentrations of



Figure 8. View of the Oregon No. 2½ pegmatite in the South Platte pegmatite district, Jefferson County, Colorado. This zoned granitic pegmatite is a vertical, column-shaped body with an exceptionally well-developed internal arrangement of minerals. The feldspar-rich intermediate zones were removed during mining operations, while the central quartz core was left standing. The pegmatite body is approximately 70 m in diameter. Photo by William B. Simmons, Jr.

uranium, thorium, and rare-earth elements.

2. Those formed at great depth (approximately 7–11 km), which may be zoned, are generally rich in mica, but have few rare elements.
3. Those formed at intermediate depth (approximately 3.5–7 km), which are often zoned, may contain small crystal-lined pockets, and possess a number of rare elements.
4. Those formed at shallow depth (less than 3.5 km), which are zoned, and which sometimes contain rare elements and gem pockets.

Ginzburg et al. further contend that at very great depth pegmatites are formed largely through the partial melting or metamorphic recrystallization of existing rocks essentially in place, while at lesser depths pegmatite formation becomes more and more an igneous process involving the injection of a magma (molten rock) and its subsequent crystallization.

OCCURRENCE

Geologic Setting. Compared to most other rock types, pegmatites are relatively rare, yet they are widely scattered in the earth's crust and can be locally abundant. Pegmatites tend to be most common in particular geologic settings, generally where igneous or metamorphic rocks are exposed at the earth's surface (Jahns, 1955; Schneiderhöhn, 1961; Černý, 1982). Those pegmatites formed at very great depths are usually found in metamorphosed rocks that comprise the ancient cores of continents (e.g., the uranium–rare-earth peg-

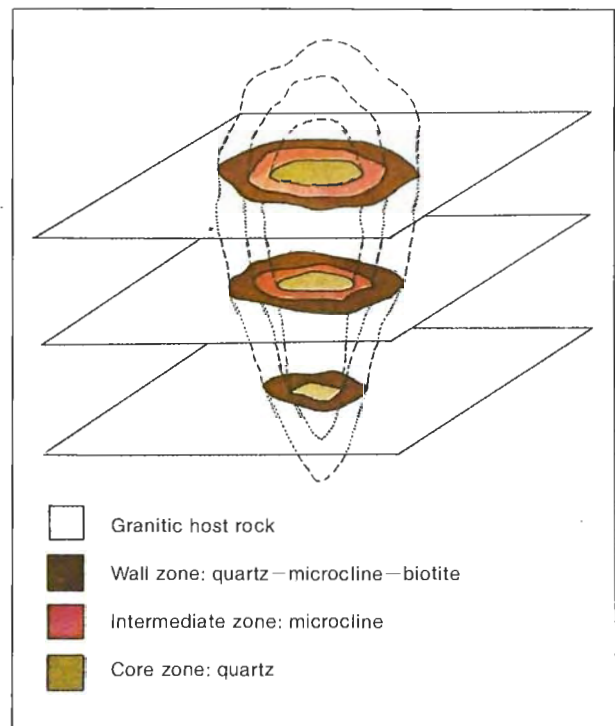


Figure 9. Idealized block diagram of a zoned granitic pegmatite similar to the one shown in figure 8. Note the horizontal and vertical zone structure and the apparent outcrop pattern resulting from the different levels of exposure possible. Artwork by Christine Wilson; adapted from Simmons and Heinrich (1980).

matites near Bancroft, Ontario). Those formed at deep and intermediate depths occur in folded and metamorphosed rocks in mountain belts (e.g., the mica pegmatites in the Soviet Union, and the beryl-spodumene pegmatites of the Black Hills, South Dakota). The shallow-depth pegmatites are

associated with large, buried masses of intrusive igneous rocks, known as plutons or batholiths, that frequently underlie mountainous areas (e.g., the gem-bearing pegmatites of southern California, of the Hindu Kush region of Afghanistan, and of Minas Gerais, Brazil). Pegmatites in each of these depth-of-formation categories gradually become exposed at the surface over geologic time by either erosion or large-scale mountain uplift, and thereby become accessible.

Genetic Relationships. The close petrologic relationship that is sometimes apparent between pegmatites and plutonic igneous rocks has been taken as evidence that most pegmatites themselves result from the crystallization of silicate magmas. However, this connection is most obvious for the shallow pegmatites. As depth increases, metamorphic processes seem to play a greater role in pegmatite formation.

Age. The ages of pegmatites span much of the geologic time scale from 3.9 billion to less than 100

million years ago. As might be expected from their frequent occurrence in mountainous regions, pegmatites can often be correlated in age with the corresponding orogenic (mountain-building) periods.

Size. In general, pegmatites are rather small rock bodies, although quite large ones do occur. Outcrops of pegmatites have been observed to range from centimeters to meters in minimum dimension and up to several kilometers in maximum dimension (e.g., compare figures 5 and 6). Typically, pegmatite bodies are completely enclosed by other kinds of rocks. The actual dimensions of pegmatites are often difficult to estimate, not only because they are frequently irregular in shape, but also because very little of the pegmatite is exposed on the surface.

Shape. Pegmatites are among the least regular and most varied in shape of all rock bodies. This wide diversity can be attributed to a number of factors, including the depth of formation, the mechanical

TABLE 4. Some generalized features of internally zoned granitic pegmatites.^a

| Zone | Thickness | Texture | Mineralogy (accessory phases) | Other comments |
|---------------------------------------|--|---|---|---|
| Border | Usually a few centimeters, but sometimes thicker | Fine-grained | Plagioclase-quartz-muscovite (garnet, tourmaline, other phases) | May or may not have sharp contacts with the surrounding host rocks |
| Wall | Usually on the order of several meters | Generally coarser than border zone | Plagioclase-microcline-quartz (muscovite, beryl, tourmaline, garnet, other phases) | May not be continuous or of uniform thickness around the entire pegmatite |
| Intermediate (possibly several zones) | Each zone may reach several meters in thickness depending on the size and shape of the pegmatite | Progressively coarser grain size proceeding inward; some giant crystals; innermost zones may contain some pocket-rich areas | Microcline-quartz-spodumene-amblygonite-muscovite-plagioclase (tourmaline, phosphate minerals, beryl, other phases) | May consist of a number of distinct zones of differing mineralogy; each may or may not completely enclose the central core; intermediate zones contain the giant crystals and comprise the bulk of the pegmatite; unusual minerals often concentrated toward core |
| Core | Up to several meters in thickness depending on the size and shape of the pegmatite | Variable—may contain both coarse- and fine-grained material; some giant crystals; may include pocket-rich areas | Quartz-spodumene-microcline (tourmaline, lepidolite, beryl, topaz, gem minerals, other phases) | Core zone may be composed of several segments; gem pockets often located on the contact between the core and the enclosing intermediate zones |

^aAdapted from Cameron et al. (1949) and Norton (1983).



Figure 10. Portion of an open gem pocket in the famous Himalaya pegmatite of Mesa Grande, California, with multicolored crystals of gem tourmaline up to several centimeters in length along with pale crystals of feldspar and quartz. Photo by Michael Havstad.

properties of the host rock at that depth, and the tectonic and metamorphic processes that took place at the time of formation. Shallow pegmatites often form sheet-like dikes, veins, or lenses that occur along faults or fractures in pre-existing host rocks. Deeper pegmatites, on the other hand, tend to be elliptical or ovoid as a result of the more plastic character of the enclosing rocks at depth.

OCCURRENCE OF GEMSTONES

Gemstones never constitute more than a small portion of any pegmatite body. Certain of the more common gem minerals, such as tourmaline, beryl, and spodumene, can occur as giant crystals in the intermediate or core zones of pegmatites. However, such large crystals are almost always highly fractured and clouded with inclusions, and consequently are of little or no gem value. The smaller, transparent crystals of these and other gem minerals are generally found only in pegmatite cavities, or "pockets."

Pockets are irregular openings in otherwise solid pegmatite (see figure 10). As found today, these pockets are usually filled partly or completely with clay, but during pegmatite crystallization they provided the necessary open space into which crystals could grow unimpeded, thereby attaining a very high degree of internal and external perfection.

Pockets are most common in the complex,

internally zoned pegmatites, but even here they are infrequent. Although pocket-bearing granitic pegmatites are widespread in such regions as Minas Gerais, Brazil, and southern California, Jahns (1955) suggested that these cavities probably occur in less than one percent of all known pegmatites. Furthermore, few pocket-bearing pegmatites have the rare elements necessary for the formation of gem minerals in high-quality transparent crystals (figure 10). In fact, most contain only crystals of the basic constituents of the pegmatite itself, namely quartz, feldspars, micas, and schorl.

Even within the same pegmatite body, pockets can vary greatly in size and shape. Most are less than several centimeters in diameter, but a few several meters across have been reported. Nevertheless, the total volume of pockets is usually trivial in comparison to that of the enclosing pegmatite. There seems to be no particular relationship between the dimensions of the pegmatite and the number, size, or shape of its pockets. Even within the same pegmatite region, some pegmatites are remarkably rich in pockets (e.g., the Himalaya pegmatite shown in figure 11), while others have few if any.

Pockets are usually found within the central core or along the margins between the core zone and the enclosing intermediate zones. The mineral content from one pocket to another, even in a given pegmatite, is likely to vary considerably.

Figure 12, a diagram of an actual gem pocket found in a granitic pegmatite in southern California, illustrates several important characteristics of gem pockets. Pocket crystals are firmly rooted in the surrounding massive pegmatite, but in the open space of the pocket they are able to grow freely and thereby develop regular crystal faces. Crystals of feldspar and quartz are usually larger and more abundant than those of any gem minerals that may be present. Pocket crystals are often distributed nonuniformly, as is the case with the pocket in figure 12, where tourmaline was only found in place on the roof of the cavity. In some instances these crystals are etched or corroded as a result of chemical attack (see figure 13) and may exhibit replacement by secondary minerals. Broken crystals of feldspar, quartz, tourmaline, and other minerals that once grew from the walls are sometimes found scattered about in the pocket, usually embedded in clays that formed after the crystals had finished growing. Few gem species are



Figure 11. Underground mine view of the Himalaya pegmatite. The pegmatite, only about 1 m thick, is remarkably rich in gem pockets and has been a noted producer of gem tourmaline. The pegmatite consists of tan and grayish feldspars, grayish quartz, pink lepidolite, and black schorl. The light-colored areas along the central portion of the pegmatite are newly exposed but still intact gem pockets. Within the pockets, crystals of gem tourmaline are embedded in clays and other secondary alteration minerals. Photo by Michael Havstad.

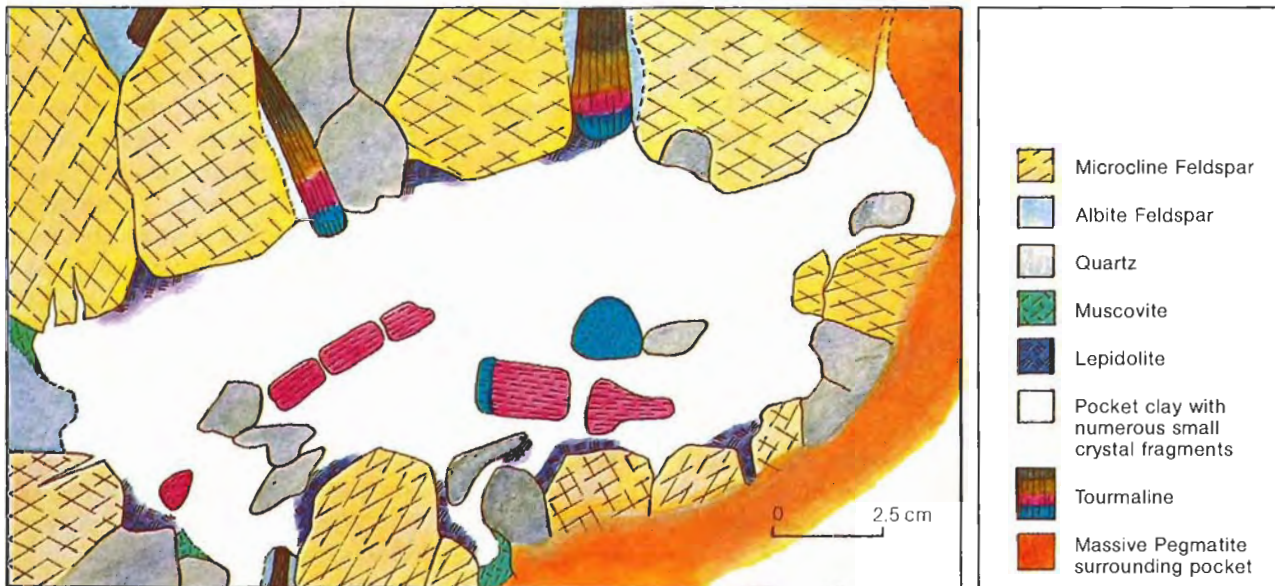
found in any one pocket—in this case tourmaline was the only gem mineral present.

Some gem minerals exhibit compositional zonation to a varying degree within individual crystals. In an extreme example, such as tourmaline, this zonation is reflected in color zoning. That is, tourmaline crystals may have black, opaque (schorl) roots in the solid pegmatite and become pink, green, blue, etc. (elbaite) as they approach

and project into a pocket.

Miners often use the color changes in tourmaline embedded in the massive pegmatite as an indication that a pocket area may be close by. Other indicators are the presence of lepidolite, the increased transparency of quartz, the black staining of the pegmatite by manganese oxides, extensive rock alteration, and the presence of clays. Miners quickly learn, however, that each pegmatite is

Figure 12. Diagram of a mapped, vertical cross section through a small, tourmaline-bearing gem pocket in the Stewart pegmatite, Pala, California. Crystal fragments of quartz and gem tourmaline, broken during the final stages of pocket formation, are embedded in the pocket-filling clay material. Artwork by Christine Wilson; adapted from Jahns (1979).



unique, with its own set of pocket indicators. They also learn that, despite careful attention to these clues, the location of productive gem pockets is still largely a matter of luck and hard work.

THE GENESIS OF GEM PEGMATITES

Although in the past there has been considerable disagreement among geologists regarding the origin of granitic pegmatites, there is a general consensus today that at least the shallower ones formed by crystallization from a magma. Numerous theories have been proposed to explain the formation of pegmatites via magmatic crystallization (see Landes, 1933; Jahns, 1955), but perhaps the most widely accepted general model is that of Jahns and Burnham (1969; also see Jahns, 1953, 1979, 1982). Their model is based on the work of many early investigators, notably Fersman (1931). The key points of this genetic model relevant to internally zoned granitic pegmatites containing gem minerals are described below.

Starting Materials. The starting material for a gem-bearing pegmatite is a volatile- and rare element-rich silicate magma derived from the final stages of crystallization of certain granitic magmas. Water is the most important volatile constituent of this pegmatite magma; however, other volatiles—such as fluorine, boron, lithium, carbon dioxide, and/or phosphorus—may be present. The rare elements include beryllium, cesium, niobium, tantalum, and tin, among others. Both groups of constituents may be present at much higher levels in pegmatite magmas than in the parent granitic magmas.

Emplacement and Initial Crystallization. This pegmatite magma is injected into fractured rock in the upper portion of the crust; as the temperature falls, the magma begins to crystallize. Mineral formation begins at the outer margin of the pegmatite magma chamber at temperatures somewhat below 1000°C. Plagioclase feldspar, quartz, and muscovite mica crystallize first as the fine-grained border zone. Later, these are joined in the coarser-grained intermediate zones by microcline feldspar and additional minerals, such as common spodumene and beryl.

Concentration of Volatiles. The major chemical elements of the pegmatite magma determine the nature of the abundant, first-formed minerals such



Figure 13. This crystal of gem green beryl from the Ukraine region of the Soviet Union (9 × 17.5 cm) displays intriguing surface features caused by chemical etching that took place subsequent to its formation in a pegmatite gem pocket. Photo © Harold & Erica Van Pelt.

as feldspars, quartz, and micas. Because of their chemical and structural makeup, the early-formed minerals cannot, for the most part, incorporate the volatiles or rare elements present in the magma. As a result, these components are preferentially retained in the magma, where they become progressively concentrated. As crystallization continues with further cooling, the water content of the magma eventually reaches a saturation level. At this point, an aqueous fluid, rich in volatiles and certain rare elements, separates from the remaining pegmatite magma at between 750° and 650°C.

Nature of Aqueous Fluid. The physical properties of this aqueous fluid are markedly different from

those of the magma and, therefore, the fluid greatly affects the subsequent crystallization of pegmatite minerals. The much lower viscosity of the aqueous fluid permits the rapid transport of chemical nutrients to the growing crystals, thereby promoting their growth in the innermost zones of the pegmatite. Its greater concentration of volatiles and many of the rare elements contributes to the partitioning of elements between magma and fluid, and thereby to the segregation of minerals in separate zones. In addition, vertical segregation of minerals has been attributed to the rise of the less-dense fluid within the pegmatite magma chamber. The aqueous fluid seems, in general, to be a superior solvent. Minerals crystallize from it at lower temperatures, and can grow to greater size, than from the magma. The fluid also tends to redissolve some earlier-formed minerals with which it comes in contact. This fluid is probably responsible for much of the secondary mineral replacement observed in complex pegmatites.

Intermediate Stages of Crystallization. The volatile-rich, aqueous fluid continues to exsolve from the magma as crystallization proceeds, and minerals in the inner zones of the pegmatite form in the presence of both the fluid and the magma. The last remaining magma eventually disappears at temperatures between 600° and 500°C. The innermost portions of the pegmatite are now occupied by large crystals of feldspar and quartz (and possibly common spodumene or beryl) with a few isolated, intervening "pockets" of trapped fluid.

Formation of Pocket Crystals. The formation of minerals in open pockets is the final stage in the primary crystallization of the pegmatite. With decreasing temperature (600° to 400°C) and rising internal pressure (resulting from the release of volatiles), crystallization continues from the fluid. Euhedral crystals of various minerals are able to form from the fluid within the open space of the pockets. At this stage, the concentrations of certain rare elements may reach sufficiently high levels for the crystallization of corresponding unusual minerals. In some instances, non-gem-quality crystals projecting into the pocket continue to grow and attain a more flawless, gemmy termination. This continued mineral growth is accompanied by changes in the chemical composition of the fluid which, in turn, are reflected in corresponding changes in some minerals (i.e., as exemplified by the color zonation of tourmaline). The

occurrence of abundant liquid inclusions in many pocket crystals (and the gems faceted from them) attests to their growth from an aqueous fluid. The final temperature for mineral crystallization from this fluid may be as low as 250°C.

Evolution of the Pocket. Unfortunately, the changing fluid chemistry, coupled with decreasing temperature and increasing pressure, can eventually lead to the destruction of many pocket crystals. In addition, earlier-formed minerals may become unstable in contact with this highly reactive fluid. As a result, some pockets are found to contain only the remnants of what may have been gem-quality crystals altered to secondary minerals such as lepidolite mica and montmorillonite clay. Most of those pockets that ultimately produce gem minerals are thought by some to have undergone a final, very important step. This step involves the leakage of volatile fluids through breaks in the pocket walls that may have resulted from one or more of a number of possible mechanisms:

1. Increase in fluid pressure within the pockets that eventually exceeds the confining pressure or strength of the surrounding massive pegmatite.
2. Cooling and contraction of the pegmatite body.
3. Earth movements in the vicinity of the pegmatite body.

If the leakage of volatiles is gradual, the pocket crystals will remain intact. Unfortunately, evidence indicates that the pocket fluid often escapes rapidly, resulting in a very sudden drop in pressure and a consequent dramatic decrease in temperature. The resultant "thermal shock" is thought to be responsible for much of the internal fracturing often observed in gem crystals, as well as for the shattered fragments of crystals found on the floors of many gem pockets or embedded in the pocket clay. The fluid lost from the pocket is injected into fractures in the surrounding pegmatite where it results in the replacement of earlier-formed minerals.

Depth of formation is an important factor in determining whether pocket rupture will occur. It also seems to be a factor in determining whether pockets will form at all, because pockets are only found in the shallow and intermediate-depth pegmatites. It has been suggested that the separate, less dense, aqueous fluid phase, thought to be required for pocket formation, is only able to exsolve

from the magma under the lower confining pressures experienced by pegmatites formed at shallower depths. This would explain the apparent lack of pockets in deeper pegmatites and the absence of pockets altogether from pegmatites in many parts of the world.

SUMMARY

Pegmatites are among the most geologically interesting and gemologically important types of rocks exposed at the earth's surface. They are crystalline rocks that are often characterized by highly variable texture, giant-size crystals, unusual minerals, and concentrations of rare elements. Pegmatites originate from residual magmas derived by partial melting of crustal rocks or as products of the final stages of igneous crystallization. Crystallization of these magmas, which are sometimes rich in volatiles and rare elements, gives rise to the distinctive mineral content and textural features of peg-

matites. A small percentage of pegmatites contain well-formed crystals of gem minerals in pockets in their interiors.

With the increased demand for colored gemstones, the mining of pegmatites for gem material will continue to be an activity of small scale but great economic importance. This demand is leading to accelerated exploration of pegmatite regions for new sources not only in long-established areas such as Brazil and southern California, but also in newly discovered or recently accessible areas such as East Africa, Madagascar, and Afghanistan. Gem-bearing pegmatites are most likely to be found in geologic environments where the pegmatite magmas crystallized at shallow crustal depths. Pegmatites that form in other geologic settings hold less promise as sources of gemstones because physical and chemical conditions in these instances seem to preclude the formation of open pockets and, therefore, gem crystals.

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GEM PEGMATITES OF MINAS GERAIS, BRAZIL: EXPLORATION, OCCURRENCE, AND AQUAMARINE DEPOSITS

By Keith Proctor

The northeastern portion of the state of Minas Gerais, Brazil, contains the world's greatest concentration of complex granitic pegmatites, which are especially noted for the production of gem beryl, chrysoberyl, topaz, tourmaline, and kunzite. Pegmatite gemstones were first found in this region over 400 years ago; in the last 100 years, Brazil has supplied most of the world market for these five gemstones. As the first of a series of articles on this region and these gem materials, this article reviews the early exploration for gemstones, their occurrence, and the mining methods and miners responsible for the development of the deposits. Focus is then given to some of the major deposits of aquamarine and other beryls, especially in the Teófilo Otoni–Marambaia and Jequitinhonha River valley districts.

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Acknowledgments: The author thanks the following people, only some of the many who helped with this article: for translating, H. Arosteguy, F. Bastos, R. Downes, R. McClellan, P. Neto, J. Uemura; for artwork and typing, Melita Marie Fife and Lyn Moffett; for reviewing and critiquing the original manuscript, Drs. P. Bariand, R. Gaines, P. Keller, P. Moore, R. Nash, F. Pough, J. Shigley, and J. Sinkankas; and for their invaluable information and assistance, Dr. C. Barbosa, K. Elawar, H. F. Kennedy, A. Lucio, A. Sabbagh, J. Sauer, H. Stern, and A. Tavares. Special appreciation goes to Mauna Proctor for her help in translating, typing, and editing and for her constant support.

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Millions of carats of fine gem aquamarine, tourmaline, topaz, chrysoberyl, and kunzite have come from northeastern Minas Gerais in this century. Their source is the complex series of granitic pegmatites found throughout this 233,000 km² (90,000 sq. mi.) region. Their chief producers were the colorful garimpeiros who extracted them from the thousands of diverse deposits in this region. The result is some of the most beautiful gems ever to appear in fine jewelry (figure 1).

This series of articles reviews the most important pegmatite deposits in this region for the five types of gemstones mentioned above (figure 2). Because of the enormous complexity of the area, the author has attempted to simplify the discussion by grouping the occurrences into districts. Although the districts are seldom as sharp as indicated on the map in figure 2, they do help manage this unwieldy subject.

The story of the gem pegmatite deposits of Minas Gerais begins over 400 years ago with the first expeditions into the interior of Brazil. This article continues with a discussion of early mining in the area, the geochemistry and geologic development of the pegmatite deposits, and the mining methods used in recent times. Following this introduction, the major deposits of aquamarine and other beryls are described, including associated minerals, major specimens produced, geologic occurrence, and production figures where available. Future articles in this series will deal with the major tourmaline, topaz, chrysoberyl, and kunzite deposits in this important region.

HISTORY, OCCURRENCE, AND MINING

EARLY EXPLORATION AND MINING

Brazil was discovered first by the Spaniard Vincente Pinyon in 1500 and then by Portuguese navigator Pedro Cabral that same year. Cabral was looking for spices,



Figure 1. These stones represent the variety of fine aquamarines found throughout the Minas Gerais pegmatite region. The 54-ct stone in the brooch at the top of the photo is from the famous Marta Rocha crystal; the approximately 35-ct stone in the ring is from the Medina mine. Photo © Harold & Erica Van Pelt; courtesy of Jules Sauer (Sauer, 1982).

precious metals, and a route to the Far East for the Portuguese crown. He found none of these, and one of his pilots even reported in a letter, "It can be said, we found nothing profitable" (Lucio, 1980).

For the first 50 years, settlement and development were limited entirely to the coastal areas, where no gold or precious gems were to be found. Within this short time, however, the new colony became a major producer of sugar cane, dyes (from the Brasil tree), and timber. But the Portuguese crown was not satisfied with this wealth; frustrated at not having discovered gold, as the Spaniards had in the regions that are now Mexico and Peru, they pushed incessantly for the exploration of the vast interior territory to the west.

Letters written in 1500 by Pero Vaz de Caminha to King Manoel I made reference to the existence of gold and silver in the colony, but omitted proof of such discoveries (Burns, 1965). Although local Indians wore no ornaments of gold, they told stories of its existence deep within the interior. The Indians did wear "precious stones," and when they described a green gemstone commonly found inland, the Portuguese greedily assumed that it was emerald. They began to plan large expeditions to explore and colonize the interior (Ball, 1930; Bank, 1979; Zeitner, 1979; Lucio, 1980; Moura, 1981).

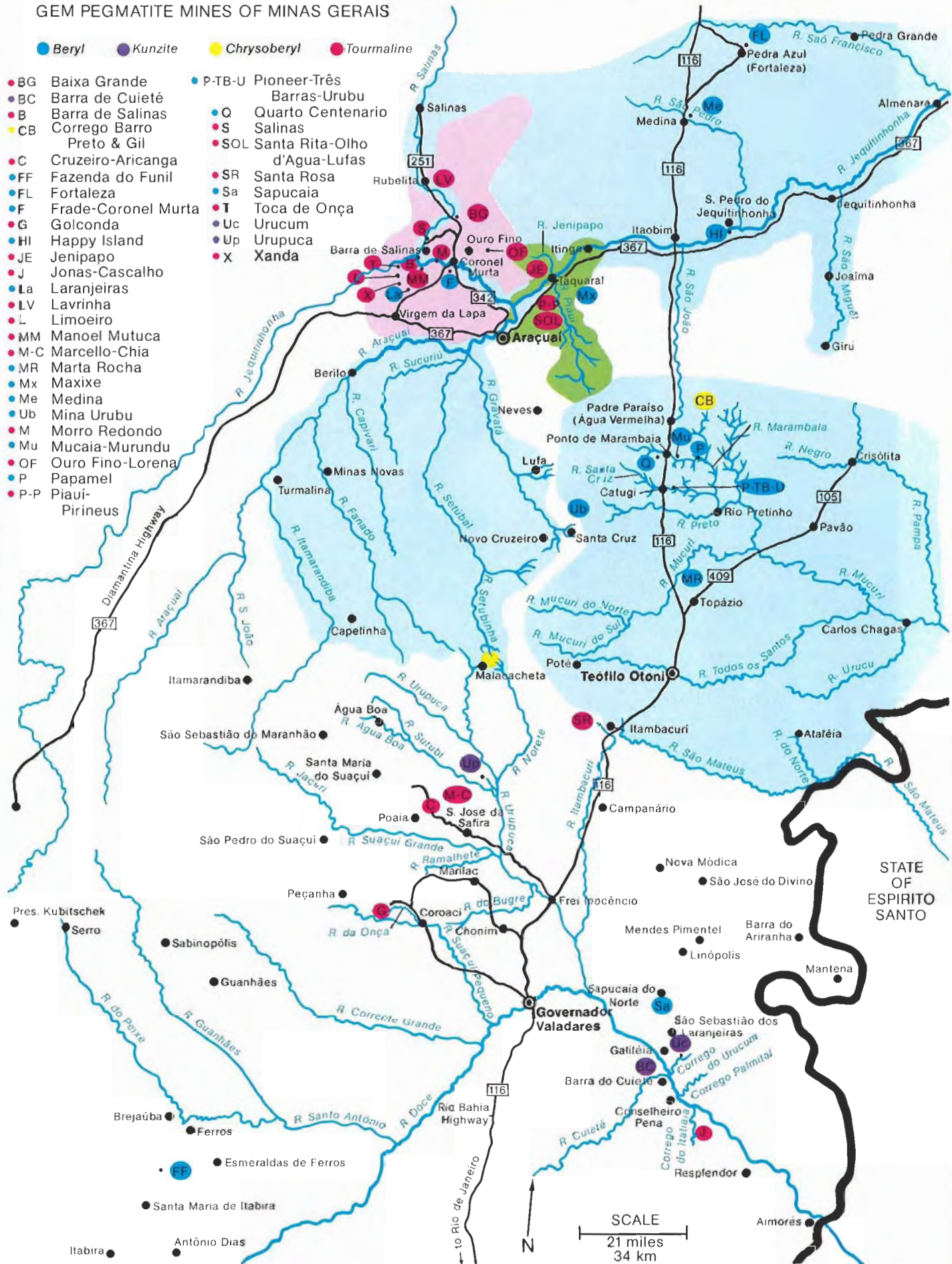
The major barrier to exploration was the range of mountains that borders much of the coast of

GEM PEGMATITE MINES OF MINAS GERAIS

● Beryl
● Kunzite
● Chrysoberyl
● Tourmaline

- BG Baixa Grande
- BC Barra de Cuieté
- B Barra de Salinas
- CB Corrego Barro Preto & Gil
- C Cruzeiro-Aricanga
- FF Fazenda do Funil
- FL Fortaleza
- F Frade-Coronel Murta
- G Golconda
- HI Happy Island
- JE Jenipapo
- J Jonas-Cascalho
- La Laranjeiras
- LV Lavrinha
- L Limoeiro
- MM Manoel Mutuca
- M-C Marcello-Chia
- MR Marta Rocha
- Mx Maxixe
- Me Medina
- Ub Mina Urubu
- M Morro Redondo
- Mu Mucaia-Murundu
- OF Ouro Fino-Lorena
- P Papamel
- P-P Piauí-Pirineus

- P-TB-U Pioneer-Três Barras-Urubu
- Q Quarto Centenario
- S Salinas
- SOL Santa Rita-Olho d'Água-Lufas
- SR Santa Rosa
- Sa Sapucaia
- T Toca de Onça
- Uc Urucum
- Up Uruçuca
- X Xanda



STATE OF ESPIRITO SANTO

SCALE
21 miles
34 km

Figure 2. This map of the northeastern portion of Minas Gerais, Brazil, shows the major gem pegmatite deposits in this region. Three of the four major aquamarine districts discussed are shaded in blue here (for the broad Governador Valadares region, only cities near major deposits are noted). Two of the better-defined tourmaline districts are also shaded: red for the district that has produced many of the most important rubellite deposits; green for the one responsible for much of the finest green and blue tourmaline. Blue topaz, not shown on the map, was found to occur with tourmaline in the Limoeiro and Xanda mines. Colorless topaz, often treated to produce blue, is found over the entire Teófilo Otoni–Marambaia district. (Sources: Ferraz, 1929; Freyberg, 1934; Calmbach, 1938; Sinkankas, 1974, 1981; and field investigations of the author.)

Brazil; it was so heavily forested that passage was almost impossible. The area now called Minas Gerais (General Mines) could only be entered via the valleys of the six major rivers that drained the region. Portuguese pioneers made four large expeditions up these river valleys in the years 1554, 1568, 1571, and 1674 (see figure 3).

The first expedition was led by Francisco Spinoza. His bandeirante group, so-called because of the banners the men carried on their horses, took a torturous route following the Jequitinhonha River to the region where the cities of Serro and Diamantina exist today (Calógeras, 1904; Abreu, 1937, 1965; Sousa, 1943; Paiva, 1946).

No emeralds or gold were found during this grueling three-year, 1,800-km expedition, but it is highly likely that Spinoza's men brought back the world's first recorded gem tourmaline (Ball, 1930). In his book *De Rerum Fossilium*, published in 1565, Conrad Gesner provided a quaint woodcut of an elongated, striated crystal with a pointed termination which he called "Smaragdus Bresilicus cylindri specie" ("A cylindrical species of Brazilian emerald"). The appearance and description of this striated crystal indicate that in fact it was tourmaline (Sinkankas, 1974, 1981).

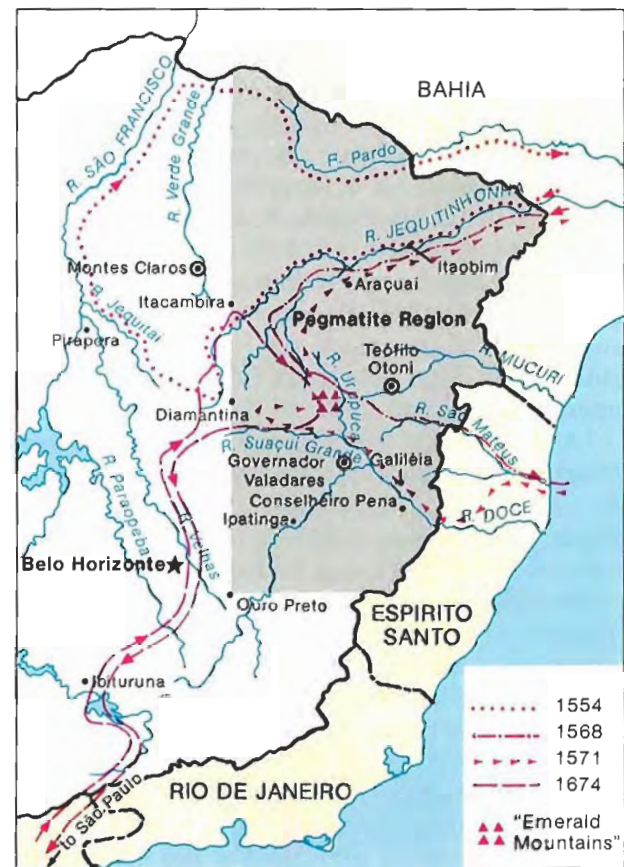
The second expedition (1568) was commanded by the explorer Martim de Carvalho after he was tempted by some "green stones" brought to Pôrto Seguro—the earliest seaport—by the Indians from the interior (Bastos, 1972, 1981; Moura, 1981). These were thought to be emeralds, like those reported from Colombia. Carvalho's bandeirante

group also followed the Jequitinhonha River to the mountains of Itacambira. From there the bandeirantes proceeded southeast to what is now Minas Novas, where they discovered sands bearing gold nuggets (Moura, 1981). Carvalho also brought back "Brazilian emeralds," just like the crystals he had originally seen at Pôrto Seguro.

The green stones were shipped to Portugal, where they were cut and subsequently set in the crown of Nossa Senhora da Penha. Only after many years had passed were the "Brazilian emeralds" identified as green tourmalines (Bastos, 1972). Bank (1979) and Sinkankas (1974) point out that for over 300 years a number of gemological treatises continued to use the term *Brazilian emerald* for green tourmaline.

A third expedition, led by Fernandez Tourinho, departed in 1571 and traveled by way of the Doce River until they passed the site of the

Figure 3. The routes taken by the four major bandeirante groups that entered what is now the state of Minas Gerais in search of gemstones and precious metals between 1554 and 1674.



present-day gem center Governador Valadares. They then proceeded to the headwaters of the Suaçuí Grande River, passing through the region of the future Cruzeiro and Golconda tourmaline mines. Turning north, the bandeirantes traversed three river valleys and entered the richest pegmatite region in Brazil, near the present town of Araçuaí. They returned to the coast via the Jequitinhonha River, but not before discovering green and blue tourmaline and blue beryl crystals, which they incorrectly identified as emerald, sapphire, and turquoise, respectively (Eschwege, 1833; Moura, 1981).

In the early history of Brazilian mining, most gems were discovered during the process of testing alluvial (placer) gravels for gold, and Paiva (1946) gives Tourinho credit for being the first to find precious stones by this method.

A hundred years passed before the fourth and most famous of the bandeirante expeditions was organized and led by Fernão Dias Paes Leme to search for the fabled "land of emeralds." In a journey that began in São Paulo in 1674 and lasted almost seven years, he and his band of adventurers finally stumbled onto the famous "Emerald Mountains" (Bank, 1979; Lucio, 1980).

In the immediate vicinity of today's famous Cruzeiro mine and the village of São José da Safira (misnamed "sapphire" for the blue tourmaline found there), Paes Leme discovered the first recorded pegmatite—a mountain of mica with the green crystals of his dreams. Soon after his discovery, however, he was taken ill with malaria and died. Although he never found true emeralds—again, the green crystals were tourmalines—it is ironic that Itabira, one of the hamlets his roving band settled, later became an important center of emerald production in Brazil (Lucio, 1980).

A total of 128 gems (about 430 g), including "emerald," aquamarine, and topaz, found during the expedition were shipped to Lisbon in 1682 (Paiva, 1946; Moura, 1981). In 1698 another shipment of stones was sent to Portugal; and these stones, when examined by experts familiar with emeralds from India, were pronounced "worthless tourmaline" (Bastos, 1972; Bank, 1979).

These bandeirante expeditions, the longest of which lasted almost seven years and traversed a staggering 10,000 km (6,250 mi.), were responsible for opening Brazil's enormous interior. Innumerable hamlets along the river valleys were settled by expedition members who tired of the march and

decided to take advantage of the free land. It is no accident that many years later, when the first mining would be done in alluvial deposits, these hamlets became the major gemstone mining centers. Two additional events produced waves of immigration that greatly accelerated exploration for gemstone deposits: the discoveries of gold near Ouro Preto in 1669 and of diamonds near Araçuaí in 1721 (Sinkankas, 1974).

Paes Leme's discovery of gem-bearing pegmatites in 1676 was virtually ignored for almost 200 years because there was no significant market for Brazilian pegmatite gemstones. At the beginning of the 19th century, however, aquamarine and topaz were mined from near Ouro Preto; and in 1811, the first large aquamarine on record, a grass-green crystal weighing approximately 7 kg (15 lbs.) was found in the headwaters of the São Mateus River near Teófilo Otoni (Oakenfull, 1913; Calmbach, 1938; Moura, 1981). In Europe, much interest was aroused in Brazilian gems by London jeweler, lapidary, and mineralogist John Mawe, when he described a great variety of gemstones he had encountered during his travels in Brazil and offered to supply them on a regular basis (Mawe, 1812).

MODERN DEVELOPMENTS

The key factor in the modern development of gemstone mining in Brazil, however, was the colonization of large areas of southern Brazil by European immigrants starting around 1850. In particular, many German families settled in the Teófilo Otoni area between 1860 and 1900.

When shiny, transparent, colored crystals began to appear in the burrow excavations of armadillos and as a result of almost any kind of digging activity, the gem-conscious German immigrants immediately recognized the potential and sent some of the stones to the lapidary center of Idar-Oberstein for examination. Thus was forged a close relationship between Brazil and Germany with respect to gemstone mining and marketing that was to last for many decades to come (Rolff, 1968; Lucio, 1980; R. Nash, pers. comm.).

From the early 1900s onwards, Lebanese immigrants also established themselves in Teófilo Otoni, and the natural association of their traditional commercial skills with the industriousness of the Germans led to an enduring relationship. During the formative years of the Minas Gerais

gem trade, the only foreign buyers were the Germans and one of the first local export firms was that of Abel Jacinto Ganem.

As early as 1902, a regular system of trading was established between Teófilo Otoni and Germany, with the rough being shipped via the newly completed railroad to Caravelas on the coast of the state of Bahia. Within a few years, German dealers began to make the arduous trek to the small hamlet of Teófilo Otoni. In 1907, Abel Jacinto Ganem and his partner, Feliciano Bamberg, established an office in Idar-Oberstein.

The first *garimpos* (a series of mining pits, or *catras*; a *garimpeiro* is a miner) were started around 1900, about 83 km north of Teófilo Otoni in the Marambaia valley, which was known to be a plentiful source of aquamarine (Lucio, 1980). In late June 1910, a major gemstone discovery was made that was to have a profound and lasting effect on the development of gem mining in Minas Gerais. The largest and most famous gem aquamarine crystal found in this century, weighing 110.5 kg (244 lbs.) was unearthed at the Papamel mine on the Marambaia River, approximately 20 km east of the village of Ponto de Marambaia. This abraded and waterworn, doubly terminated, hexagonal prism measured 48.5 cm long × 38 cm in diameter (19 × 15 in.). The major portion was a fine blue-green. The crystal was flawless and so transparent that one could read print through it from end to end (Sinkankas, 1974, 1981).

The crystal was discovered by the Syrian Tanuri brothers, less than one meter below the bottom of a colluvial-alluvial pit that had just been abandoned in disgust by another miner (Dreher, 1912; Sinkankas, 1981). They sold it to two German gem dealers, August Klein and Viktor Bohrer-Borges, who happened to be in the area. George Kunz (1911) reported the purchase price as equivalent to US\$25,000 and accurately estimated that the crystal would produce 200,000 ct of finished gems. August Klein then undertook a 20-day struggle to transport the massive crystal to the coast, hauling it first by mule 72 km through the jungle to the village of Araçuaí, and then floating it by canoe down both the Araçuaí and Jequitinhonha rivers to the coast. From there it traveled via coastal steamer to the city of Bahia (now Salvador), at which point a German steamer carried it to Germany (Hahn, 1955; Sinkankas, 1981).

After reaching Hamburg, Klein assumed the

large wooden crate with its treasure would be shipped directly to Idar-Oberstein. Upon reaching Idar a few days later, however, he was shocked to find that the crystal had not yet arrived. He backtracked to Hamburg and found the crate, unidentified, sitting in the corner of a freight warehouse waiting for a claimant. This time he personally escorted the crystal to Idar-Oberstein, where the firm Bohrer-Borges took possession and offered it for sale for the equivalent of US\$139,000. When no museum or other institution stepped forward to buy the crystal in its entirety, it was cut up and the pieces sold individually (Hahn, 1955; Sinkankas, 1981). The American Museum of Natural History in New York City now displays the nearly 6-kg remnant (presumably the only uncut piece of the Papamel aquamarine) in the J. P. Morgan gem collection (Gaines, 1976; Anderson, 1978; photo in Sauer, 1982, p. 30). It is interesting to note that the Papamel aquamarine is the first crystal on record to have been heat treated to obtain its optimum blue color (Bank, 1973). The current wholesale value of this piece has been estimated at close to US\$25 million (J. Sauer, pers. comm.)

News of the selling and asking prices for the Papamel crystal precipitated a sudden flurry of activity by Brazilian miners and German dealers alike. This enthusiasm stimulated the search for aquamarine and eventually contributed to the development of the entire central and northern portions of the Minas Gerais pegmatite region.

Aquamarine was popular in Europe even as early as 1910; the popularization of tourmaline came somewhat later, with the development of gemstone mining around the hamlets of Governador Valadares and Araçuaí. At this time, German dealers could reach Governador Valadares, 145 km south of Teófilo Otoni, only by horseback along a narrow path cut in the jungle (Lucio, 1980; Caplan and Wilson, 1980).

In 1914, the deposit of green and blue tourmaline first discovered by Paes Leme in 1676 at Serra Resplandecente, near the present-day Cruzeiro mine, was rediscovered and mining was begun. Magnificent crystals were produced and used for cutting (Lucio, 1980).

In the early 1930s, a *garimpeiro* named Barbosa discovered spectacular four- and five-color gem tourmalines at the Cascelho mine on the slopes of the Itatiaia mountain range near the town of Conselheiro Pena. These tourmalines, called *papagaios* (parrots) because of their brilliant

colors, contributed greatly to the increased demand for tourmaline in Europe (R. de Vasconcelos and H. Bank, pers. comm.).

World War II provided the greatest stimulus to pegmatite exploration in Brazil. Beryl, mica, feldspar, quartz, and lithium minerals—mostly pegmatitic in origin—were needed in great quantities (O'Leary, 1970; Sinkankas, 1974, 1981; Lucio, 1980). By 1950, the search for these strategic minerals had resulted in the discovery of several hundred gemstone mines (Gonsalves, 1949; Pecora, 1950), and this set the stage for the enormous increase in interest in Brazilian gems that followed the war. The city of Governador Valadares, the commercial hub for strategic minerals in the area, became second only to Teófilo Otoni as a gemstone center.

A major impetus to the development of these gemstone mines was that the sale of strategic minerals provided a basic income for the mine owners while the sale of gemstones provided a margin of profitability. For example, some gemstone mines in the Governador Valadares area pay for their entire operation just with sales of mica and feldspar.

Another vital source of income for gemstone miners developed starting in the late 1950s, when thousands of mineral collectors worldwide began buying rare gem crystals and even competed with museums for the best specimens (Sinkankas, 1974, 1981; Caplan and Wilson, 1980; Lucio, 1980). The sale of natural gem crystals and other rare pegmatite minerals kept many a mine operating during hard times. For example, the Jonas mine recently operated for 18 months on the money generated from the sale of tourmaline specimens.

GEOLOGIC DEVELOPMENT OF THE PEGMATITE DEPOSITS

The pegmatite region of the state of Minas Gerais is undoubtedly the finest laboratory in the world for the study of pegmatite gemology, because it contains the world's largest and richest concentration of gem-bearing pegmatite deposits. Extending approximately 320 km east to west and 720 km north to south, it is limited to the eastern and northeastern parts of the state (again, see figure 2). These deposits were created by a unique combination of geochemical, climatic, and other events that are briefly summarized below.

Formation of the Pegmatites. The reader is referred to the article by Shigley and Kampf in this issue for

a general discussion of the formation of gem pegmatites. It is important to note again that although granitic pegmatites are extremely numerous worldwide, only a small percentage are gem bearing. Yet literally thousands of gem-bearing pegmatites are found in Minas Gerais. The granitic magmas responsible for the formation of these deposits were not only rich in the more common components of silicon, aluminum, iron, magnesium, potassium, sodium, and calcium, but also in the volatiles such as fluorine and chlorine, as well as such rarer elements as boron, lithium, beryllium, manganese, tin, niobium, tantalum, phosphorus, and the radioactive elements uranium and thorium (Cameron et al., 1949; Pough, 1969; Moore, 1973; Jahns, 1982). The availability of this diverse group of chemical elements resulted in the formation of thousands of gem pegmatite deposits in all stages of mineralogical complexity and containing virtually every gem pegmatite mineral species known (Sinkankas, 1974, 1981; Anderson, 1978). In most cases in Minas Gerais, the gem materials originated in pockets within the host pegmatite.

The events that carved the present landscape of Minas Gerais had their beginning so long ago that it is estimated that the surface geology we see today was actually formed at some depth (at least 3 km [2 mi.] beneath the original surface before erosion took its toll). The pegmatites themselves are estimated to be approximately 490 million years old (Dirac and Ebert, 1967; Cassedanne and Lowell, 1982). During this period, the older, or "basement," metamorphic rocks—schists, gneisses, and some quartzites—which covered much of the area, acted as a "roof" capping the upward movement of the molten granitic magmas. However, as the magmas pushed upward, the overlying basement rocks were fractured and the cooling pegmatitic magmas were injected into the systems of cracks, commonly in an approximate north-south direction (Bassett, 1967; Lucio, 1980). This material eventually solidified into the *primary* pegmatite deposit, in which the pegmatite body is still enclosed in the original schistose or gneissic host rocks. Depending on local erosion and weathering, as explained below, such deposits exist today in various stages of decomposition.

During the same geologic time period, large masses of granitic magma also intruded the fractured metamorphic rocks vertically and eventually solidified as rounded or hump-like forms.

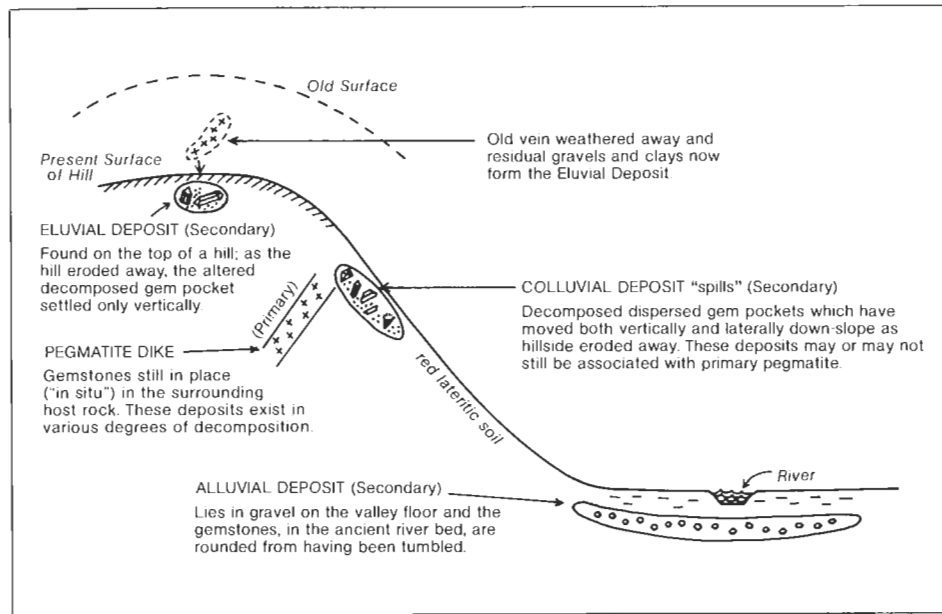


Figure 4. Diagram of primary (pegmatite dike) and secondary (eluvial, colluvial, and alluvial) deposits. All three secondary deposits have traveled some distance from their original primary pegmatite.

They were subsequently exposed by erosion to form the peculiar domed hills and mountains known by the German word *inselbergs* (island mountains) that are common in many parts of Brazil (the mountain known as "Sugar Loaf," in Rio de Janeiro harbor, is a perfect example). Hundreds of these tall, deeply grooved, forest-topped batholiths, commonly found in the immediate vicinity of gem pegmatite deposits, are the most prominent physiographic features of the pegmatite region of Minas Gerais. These domes represent the hardened "backbones" of the granite intrusions, and their presence today is evidence that most of the metamorphic "capping rocks" have long since eroded away (Dana, 1959; Rolff, 1968; Pough, 1969; Jahns, 1982).

Formation of Secondary Deposits. Weathering. As a result of extensive uplift and the erosion typical of a tropical climate and monsoonal conditions, the once-buried schists and gneisses, studded with pegmatite dikes, eventually became exposed on the surface as "hills," hundreds of meters higher than their present level. Subsequently, this "new" surface was again subjected to erosion; the exposed pegmatites weathered away along with the rest of the hill and shed their treasures on its slopes. The sands, clays, gravels, and loose gemstones now found blanketing the valley floors, and the red lateritic (clay-like) soil found on the slopes, are the residues of hillside erosion and contain the decomposed and dispersed contents of pegmatites (Sinkankas, 1964, 1974).

A distinctive feature of this entire region is the deep chemical weathering of the pegmatite bodies brought about by the soil conditions and the monsoon-like rains that make mining all but impossible from October through February. In many hillside deposits, the pegmatites are commonly altered and decomposed to depths of 50 m or more. Since pegmatite bodies are generally not large, frequently the weathered zone extends far beneath the pegmatite itself (Bassett, 1967; Sinkankas, 1974; Lucio, 1980). The contents of gem pockets are also chemically altered, with some of their constituents being broken down into secondary alteration minerals such as clays (Jahns, 1982). Generally, only the gem minerals survive; even the feldspar crystals eventually succumb to the attacks of water, air, carbon dioxide (carbonic acid), and soil (humic) acids, and alter to crumbly white clays principally composed of kaolin. The more resistant minerals, such as quartz, beryl, tourmaline, and topaz, survive and are found intact in the "softened" decomposed pocket.

Miners consider the white kaolin a sign that they may be close to gem-bearing pockets. Another indication is the occurrence of pocket residues such as fine muscovite mica flakes in the soil and, better still, clear or smoky quartz crystals with sharp faces. Once they reach such an altered deposit, they look for scattered and detached gem crystals lying loose in the clay.

Types of Secondary Deposits. In Minas Gerais, then, gemstones are found not just in pockets in

the primary pegmatite deposit but also (and more commonly) in one of three types of secondary deposits—eluvial, colluvial, and alluvial (figure 4). The secondary deposits are those that result from the complete decay of a gem-bearing pegmatite body with consequent release of its resistant minerals into the soil. In these three types of secondary deposits, gemstones have all traveled some distance from their original pegmatite. *Eluvial deposits* commonly occur on hilltops; as the hill is eroded, the decomposed pocket material moved directly downward from the original pegmatite. *Colluvial deposits* are pegmatite materials that moved both downward from and lateral to the pegmatite as the pegmatite and its enclosing rocks eroded; a colluvial deposit may or may not be closely associated with its parent pegmatite. Sometimes the pocket material is found as a "spill" of gem crystals in the red lateritic soil below the pegmatite outcrop. A textbook example of this deposit type is the Frade aquamarine mine near Coronel Murta, discussed later in this article; in this case, the resistant pocket crystals are still closely associated with the parent body. Lastly there are the *alluvial deposits*, which are always found in the valley floors and which contain rounded, waterworn stones and gemstones that represent gravels of a former or still-existing riverbed. The condition of the gem material itself usually reflects the distance it has traveled from the original pegmatite. Those specimens found closer to the primary source have sharper crystal faces and are less damaged than those found farther away (i.e., crystals found in the pocket itself are usually sharper than those found in the eluvial or colluvial deposits, which in turn are less damaged than those found in the alluvium). Interestingly, however, although gemstones found in the alluvium are usually smaller and more rounded, the material itself is much cleaner, since flawed crystals erode more easily (see the discussion of the Três Barras aquamarine deposits later in this article). The exception to this general rule is seen in the Frade aquamarine mine, where even crystals found in the primary pegmatite are highly fractured. This is apparently the result of decompression explosion and consequent thermal shock during late-stage pocket formation (see Shigley and Kampf, 1984).

MINING METHODS

Hard-Rock Mining (Primary Deposits). When a primary deposit is discovered with the pegmatite

and its host rock (schist or gneiss) still unaltered, bulldozers, explosives, drills, and other types of heavy equipment are required to mine the gemstones (figure 5). These deposits are often the richest and most productive (e.g., the Jonas mine) because their contents have not yet been altered or dispersed. The government grants mining concessions (registered claims) for such operations because of the great expense involved; today there are only a few—perhaps 30—of these concessions in Minas Gerais (Lucio, 1980).

For the most part, the hard-rock mining methods used in Minas Gerais are simple. Miners drill, place dynamite charges, blast, and then clear away the rubble by hand or with some type of earth mover. However, even in such mechanized operations, the miners still resort to hand sorting when they reach the gem-bearing pockets.

Soft-Rock Mining (Secondary Deposits). Historically, most of the mining of pegmatite minerals has taken place in the altered and dispersed secondary deposits that occur by the thousands in Minas Gerais. Because of the softness of the earth and the fact that the rock has decomposed, only the most basic tools—pick, shovel, and sorting basket—are needed to free the gemstones (figure 6). Many of the pits were started even before the turn of the century, when the *garimpeiros*, or miners, could not make a living in agriculture or other pursuits. The *garimpeiro*, usually alone and almost always independent, has been a major factor in Brazil's preeminence as a gemstone producer for close to 100 years.

THE GARIMPEIRO: KEY TO THE PAST, QUESTION MARK FOR THE FUTURE

By federal law, the mineral deposits belong to the government, and any licensed *garimpeiro* may work unprohibited on any state-owned lands where gems and minerals have been found (and also on many private lands, with the prior consent of the owner). The only exceptions are the registered claims granted as concessions. However, the *garimpeiro* must pay a 10–50% commission to the landowner on all gemstones found, with the exact amount determined by how much equipment and food, if any, the landowner gives the *garimpeiro* as his "grubstake." Only occasionally is the landowner compensated for the damage done to his property.

The *garimpeiro* labor force is largely landless, rootless, and illiterate, but also free and independ-



Figure 5. Heavy machinery is often required for hard-rock mining in Brazil. At the Golconda tourmaline mine, bulldozers are used to move the overburden and waste from the mine entrance.

ent and ready to move whenever a “bigger” bonanza beckons from over the next hillside. At the earliest word of a new, more promising find, often a veritable army of garimpeiros—many with their entire families—will pick up and leave. At each new area, the garimpeiro stakes out a few square meters of land for his private pit, his rights protected by an unwritten but rarely broken code. Large, sprawling temporary villages of shanties lacking utilities or sanitation have been known to spring up overnight.

Since 1970, however, several events have combined to make the garimpeiro almost an endangered species. During the past 15 years, about 90% of the garimpeiro mining force has left pegmatite mining to obtain steady employment in industry, agriculture, and gold mining.

Because of the lack of coal in Brazil and the high cost of its importation, steel companies around Itabira have been forced to buy land and plant millions of fast-growing eucalyptus trees, eventually to be burned into charcoal for use as a reducing agent for iron ore in the production of steel. Both the reforestation projects and the burning of the wood into charcoal are labor-intensive pursuits and now employ thousands of former or potential garimpeiros (Lucio, 1980).

Figure 6. Pick and shovel are the basic tools of the garimpeiro searching for aquamarine crystals in the “soft rock” of this colluvial pit near the bottom of Frade valley.





Figure 7. This 40-ct faceted aquamarine sitting on the 898-g "Pioneer" aquamarine crystal represents the color that would result if the natural crystal were cut and the stones heat treated, the standard practice with aquamarine worldwide. Photo © Harold & Erica Van Pelt.

In addition, government-financed coffee plantations have sprung up all over the region. By 1980, 28 million coffee trees had been planted in the Teófilo Otoni region alone, providing jobs for six to eight thousand former garimpeiros. Also, land under plantations or in reforestation projects is lost to gem mining. The entire hillside known as the Lavra José de Sousa (lavra means workings), at the famed Três Barras aquamarine deposit, is now covered with coffee trees (Lucio, 1980; Sauer, 1982).

Lastly, gold mining offers a more certain source of income. Thousands of garimpeiros have been lured away to work at just one gold mine, the Serra Pelada, in the northern state of Pará; 45,000 miners work in a single huge pit. This, and other, gold-mining ventures are likely to go on for decades (C. Barbosa and R. Nash, pers. comm.)

All of these events have given the descendants of the gem-mining garimpeiros a whole new set of job options. Many have chosen the security of a steady wage rather than the uncertainty of the garimpos their parents mined.

The labor shortage and the depletion of the

most easily accessible secondary deposits dictates that in the future the great majority of gemstone mining in Minas Gerais will have to be done on primary pegmatites using more expensive mechanized means (Sinkankas, 1974, 1981; Lucio, 1980). To produce any kind of volume, even the mining of "softened" secondary deposits will require mechanization. This situation suggests that fewer gems will be produced—at even greater production costs.

The unique history and geology of the gem pegmatite region of Minas Gerais forms the basis for the discussion of specific beryl, chrysoberyl, topaz, tourmaline, and kunzite deposits that follow. The beryl (primarily aquamarine) deposits of northeast Minas Gerais are the focus of the next section presented here; the other gem materials will be covered in future articles.

AQUAMARINE AND OTHER BERYLS

Virtually all varieties of gem beryl are found in Minas Gerais, and all except emerald are of pegmatitic origin. While heliodor (yellow or golden beryl) and morganite (the pink variety) are found in small quantities in some localities, by far the most important pegmatitic beryl in Minas Gerais is aquamarine. Since the discovery of the Papamel crystal in 1910, several other major crystals and millions of carats of fine aquamarine have been mined from the thousands of deposits that dot the region.

Four districts in Minas Gerais have produced major amounts of aquamarine: (1) Teófilo Otoni–Marambaia, (2) Jequitinhonha River valley, (3) Araçuaí River–Capelinha–Malacacheta, and (4) Governador Valadares (see figure 2).

The following discussion will examine the important aquamarine deposits in the first two areas, many of which the author visited in 1983, in terms of their location and access, history and production, and the important mines and major specimens found there. Please keep in mind while reading the discussion and viewing the accompanying photographs that most aquamarine has a strong yellow component and thus appears green when viewed right out of the mine. It is generally heat treated to remove this yellow component to produce its optimum blue color (figure 7). Virtually all aquamarine is heated in this manner; the process duplicates one that commonly occurs in nature and the resulting color is stable. Depending

on the mine the crystals come from and the clarity of the rough, finished stones are heat treated to between approximately 250°C and 720°C for a varying length of time (e.g., a stone with some inclusions will be heated at a lower temperature for a greater number of hours). Less than 5% of the aquamarines produced in this region yield top-quality, dark blue stones (figure 8).

This section will also review the production of heliodor and morganite in this area. While large amounts of emerald have been mined in Minas Gerais, they will not be discussed here because most deposits are not found in association with pegmatites.

TEÓFILO OTONI-MARAMBAIA PEGMATITE DISTRICT

The Teófilo Otoni–Marambaia pegmatite district is now easily accessible from Teófilo Otoni by

Figure 8. These aquamarines from the Mucuri River region (within the Teófilo Otoni–Marambaia pegmatite district) represent some of the best color produced in Minas Gerais. The stones range in weight from 18 to 35 ct. Photo © Harold & Erica Van Pelt; courtesy of Jules Sauer (Sauer, 1982).



traveling on highway BR-116 north toward Itaobim. Although scattered aquamarine deposits exist farther south near Teófilo Otoni at Ataleia and Itambacuri—and extensively along the Mucuri, Urucu, and Mateus rivers—the great preponderance of pegmatite deposits in this district is concentrated in an oval area encompassing a region roughly 50 km north, south, and west of the village of Catugi and extending east beyond the village of Crisólita to include the Pampã River valley (see figure 2).

This region, dominated by relatively quartz-poor, coarse-grained gneisses, is perhaps geochemically the most distinct pegmatite district in all of Minas Gerais. There are no schists. The pegmatite magmas in this district were rich in silicon, beryllium, aluminum, fluorine, and boron. All varieties of beryl except morganite are found here, as are relatively large deposits of chrysoberyl and alexandrite. Cassiterite and columbite also occur.

Topaz and aquamarine often occur in the same pegmatite deposit, but never in the same pocket. In secondary deposits, of course, beryl and topaz are often found together.

Black tourmaline is common in this region, but there are no lithium minerals, no colored tourmalines, and no known occurrences of morganite. Smoky quartz, citrine, and noncommercial amethyst are also common.

This district is noted particularly for the size of the aquamarines found there and the cut stones produced (probably the largest is the 911-ct stone in the Smithsonian Institution, Washington, D.C., illustrated on p. 90 of Desautels, 1970). The most important aquamarine finds in this district have been principally in secondary (eluvial, colluvial, and alluvial) deposits in three major areas: the Topázio–Pavão–Crisólita valleys, source of the 34.7-kg (76-lb.) Marta Rocha crystal; the Marambaia valley, where the Papamel aquamarine was found early in this century and then the 22-kg (48-lb.) Quarto Centenario in 1964; and the Três Barras valley, origin of the 19.2-kg (42-lb.) Estrela de Alva (Dawn Star) crystal.

Topázio-Pavão-Crisólita Valleys. The valleys and basins surrounding the three villages Topázio, Pavão, and Crisólita are easily accessible via highways BR-116 and MG-409 (see figure 2). These basins are part of the watershed of the Mucuri, Preto, Negro, and Pampã rivers. The abundance of aquamarine in this area led to the sinking of tens of

thousands of pits in secondary deposits and many tunnels in primary pegmatites since prospecting was first begun in 1908 (Sinkankas, 1981). These have consistently produced large quantities of aquamarine. In fact, one of the most important aquamarines ever discovered in Brazil, the Marta Rocha, was found in this region.

After the 1910 discovery of the Papamel aquamarine, it became the dream of every garimpeiro to find a great crystal of his own to ensure lifetime fame and security. In July 1954, this dream came true for the garimpeiro Wilson Martins da Silva and the 12 miners he led and helped finance. Digging in the red soil in the side of a hill only 100 m high, they unearthed the second most valuable aquamarine crystal found in this century. This garimpo, the Lavra de Clemente Francisco, was located 6 km northeast of the village of Topázio, only 200 m west of the Pavão road.

Jules Sauer, the prominent Rio de Janeiro jeweler, was in Teófilo Otoni that morning when he got word of the find. He arrived at the mine barely two hours after the discovery, and quickly negotiated the purchase. This 34.7-kg rounded prism, with superb, uniform color throughout, eventually yielded 57,200 ct of finished gems. A 54-ct stone cut from this crystal appears in the brooch illustrated in figure 1.

Judging by its rounded and battered condition, the aquamarine appeared to be river-rolled, that is, alluvial in origin. But one cannot establish that origin with certainty because a stone can become extremely worn in a colluvial environment when mixed with abundant and large blocks of quartz, as is often the case with aquamarine, which usually occurs in pockets adjacent to or near the quartz core of the pegmatite.

Before it was cut, this stone was appropriately named after a beautiful woman, Marta Rocha, Miss Brazil of 1954. To this day, the subject of superb cut aquamarines doesn't come up in Brazil without mention of Marta Rocha. Some stones from this material can still be found, but they are dearly held and carry a premium (Bastos, 1964; Abreu, 1965).

The discovery of the Marta Rocha aquamarine triggered another "rush," and thousands of garimpeiros overran the hillside and valley below, completely devastating the area. Land damage was so extensive that the farmer who owned the land had to move his cows off the property because there was nothing left for them to graze on—only bare

earth and abandoned pits. Sauer (pers. comm.) estimated that six million man-hours were wasted by the garimpeiros over the next 12 months, and not one additional aquamarine was found.

Marambaia Valley. The Marambaia River valley lies perpendicular to the asphalt road 83 km (52 mi.) north of Teófilo Otoni at the hamlet of Ponto de Marambaia. Traveling 20 km east of the asphalt road on a good dirt road, you reach the Papamel mine, the source in 1910 of the first great aquamarine find.

During the 70 years following the discovery of the Papamel, thousands of kilos of aquamarines were removed from some primary and mostly secondary deposits over the entire length of the valley. In 1958, two major colluvial deposits were discovered on hillsides overlooking the diggings. At Murundu, 22 kg of crystals were removed. Then, at Mucaia (figure 9), Clemente Fell de Sousa, his son Zeca, and fellow garimpeiros found 520 kg of pale blue aquamarine. In a matter of weeks, over 2,000 garimpeiros descended on the hill. Eventually so much fighting erupted over digging sites that the military police had to be called in. In 1968, a few hundred meters from the original find at Mucaia, 165 kg of aquamarine were unearthed, with the largest crystal (medium blue) weighing 36 kg. And in 1978, an 18-year-old garimpeiro found an exceptional 3.9-kg prism in the Filipe valley below the Mucaia hilltop; this aquamarine eventually yielded 10,000 ct of superior stones (A. Tavares, pers. comm.).

Another *bomba* (major find) was unearthed on May 20, 1964. Five km west of the highway and the hamlet of Ponto de Marambaia, a garimpeiro discovered four pieces of a crystal that produced some of the highest quality, darkest blue aquamarine ever recorded. The four pieces that comprised this etched and abraded, doubly terminated crystal were found by Abelo Ferreira in red lateritic soil more than 6 m under the top of a hill at the Pine Tree (Pinheiro) mine (Bastos, 1964; A. Tavares, pers. comm.). Less than 2 kg of additional small stones were found by Ferreira in this classic eluvial deposit.

This material was said to have the color of fine blue tourmaline (Sinkankas, 1974, 1981). When the nearly cylindrical crystal was reconstructed, it measured 68.5 × 10.9 cm (27 × 4.3 in.) and weighed 22 kg; it was almost entirely clean.

Agenor Tavares, a well-known Teófilo Otoni

Figure 9. Alluvial diggings run the full length of the Marambaia valley on the low residual hills overlooking Marambaia Creek. At the height of production, 2,000 miners worked the hillside diggings at Mucaia. This topography is typical of the entire Teófilo Otoni–Marambaia pegmatite district.



gem dealer, was living in nearby Padre Paraíso (formerly *Água Vermelha*) when he heard the exciting news. The first dealer to arrive at the site, he purchased the four pieces of the crystal directly from Ferreira for one hundred million cruzeiros (roughly US\$45,000 at that time). Although the price he received was enormous for the *garimpeiro* (and very small given the thousands of carats of faceted stones it would produce), Ferreira's dream did not end happily. He quickly started on an extended celebration spree—and died two years later, totally destitute.

The three darker pieces of this aquamarine were sold to Abdul Millah and João Pessoa. The fourth piece, weighing over 7 kg, was sold to the firm H. Stern in Rio de Janeiro. This lighter colored piece was the first to receive the name IV (Quarto) Centenario to commemorate Rio de Janeiro's 400th anniversary. This piece was cut into 15,000 ct of medium-quality aquamarine (A. Tavares and H. Stern, pers. comm.). The stones cut from the other three pieces—all of which were much darker than the first—are also referred to as Quarto Centenario and are actually responsible for the reputation of this famous crystal.

Agenor Tavares later obtained the mining rights to the Pine Tree mine; using heavy bulldozers, he spent six full months looking for additional aquamarines. Deep in the red earth he even-

tually hit a pegmatite, but it produced only 5 kg of aquamarine plus colorless topaz and some citrine. As with the Marta Rocha, the location yielded no additional bonanza of aquamarine. These two famous crystals graphically illustrate the frustrations of gemstone mining in Brazil: the only thing consistent about such discoveries is their inconsistency. Although of different hues, these two crystals are both touchstones by which the highest quality aquamarines are measured.

Três Barras Valley. The Três Barras (Santa Cruz River) valley lies south and runs roughly parallel to the Marambaia valley; it crosses highway BR-116 at the village of Catugi (formerly called Três Barras).

The first *garimpos* were started in the 1930s amid great activity at Pont Alete, 6.5 km south of the village of Três Barras. In 1967 and 1968, some of the largest aquamarine deposits ever found anywhere were mined in this valley and the surrounding low-lying residual hills. At the height of production, many aquamarines were found 1 km west of highway BR-116, just west of Catugi, but most of the famous Três Barras production was found east of the highway.

The Pioneer (Pioneira) Mine and the Dawn Star Aquamarine. On October 10, 1967, 5 km south-



Figure 10. One-fourth of the Dawn Star crystal (originally 1 m long \times 18 cm in diameter) and some of the stones cut and heat treated from other sections of the same piece. This photo, by Richard Gaines, was taken in Teófilo Otoni in late 1967.

east of Catugi and highway BR-116, a government bulldozer was carving a road up to the top of a hill where a microwave relay station was being built near a Sugar Loaf-like prominence. Near the top of the hill, the blade of the bulldozer rolled a large aquamarine crystal out from its hiding place onto the side of the road, where it lay unobserved by the bulldozer operator. However, seven men who had unsuccessfully sought employment at the microwave tower passed the bulldozer on their way back to Catugi, and as they stopped to examine the cut in the side of the hill, they found the 19.2-kg aquamarine. Ecstatic over their discovery, they took turns carrying their treasure back to the village of Catugi. One of the first gem dealers contacted was the same Agenor Tavares of Quarto Centenario fame. Tavares rushed northward and again managed to arrive before the multitude of dealers who soon followed. He made his deal with the leader of the group, Zeferino dos Santos, and agreed to buy the stone for the equivalent of US\$30,000. The I.O.U. was scribbled on the paper liner from a pack of cigarettes. Eventually, Tavares decided to share the stone (and his indebtedness) with three other dealers. It was subsequently named the Estrela de Alva, or "Dawn Star." The crystal was almost 100% gem clean (figure 10): Mr. Tavares's 26% portion cut 8,017 ct of fine gems (A. Tavares, pers. comm.; Gaines, 1976).

The source of this stunning crystal became the Pioneer mine, which proved to be what was probably the greatest deposit of fine-quality aquama-

rine crystals in history. This small mine—a series of eluvial pits unrelated to any primary pegmatite body—produced over 1,500 kg of superior aquamarine crystals.

According to extensive research done by the author, all of these aquamarine crystals, with the exception of the 4,500-ct specimen pictured on the cover and in figure 7, were destroyed by cutting—a tremendous aesthetic and scientific loss. This specimen, which was dug by Colatino Ferreira, survived only because it passed through a series of crystal collectors rather than cutters.

Figure 11. This hillside at the José de Sousa workings of the Três Barras deposit has been totally stripped by the hundreds of pits dug during the height of mining in this region (1968). Note the white kaolin dumps on the higher slopes, crescent-shaped series of tunnels into the colluvium, and the inselbergs, and garimpeiro shanties rising from the valley floor. Photo by Frederick H. Pough.





Figure 12. Working on the valley floor at Três Barras, these *garimpeiros* must contend with the constant flooding of their alluvial pits. Staking of the pits to avoid cave-ins is one solution. Note the layers of multicolored sand and clay, typical of alluvial deposits, in the back wall.

Três Barras Deposits. When the Pioneer mine was discovered, thousands of *garimpeiros* descended on the area; as was usually the case, only a few pit diggers were successful. Seven months later, in May 1968, massive deposits were discovered less than a kilometer north over the crest of the microwave hill and down the adjacent Três Barras valley. The partially worked pits below the Pioneer mine were abandoned in great haste, as the *garimpeiros* poured into the adjacent valley. Within a few weeks, they had set up their shanty towns on several sites—mostly on the valley floor.

Living conditions for the *garimpeiros* were appalling. Thousands of miners huddled in shacks with only a few huts set up to provide for their simple needs. Women and children were seldom present at this discovery (Pough, 1968).

Nevertheless, the miners attacked the 200-m-high hill with such ferocity that, according to Pough, in only a few weeks the once tree-clad slopes were totally denuded, transformed into a prairie-dog village of burrows and red soil dumps; the entire steep, raw, red hillside was scarred from top to bottom, as if the excavation had been going

on for years (figure 11). The two major mining areas on this small part of the cirque became known as the Lavra José de Sousa and Lavra Matto Frio.

Within 40 days of its discovery, this new find, called the Três Barras deposits, produced over 1,000 kg (one ton) of gem-quality crystals, albeit paler in hue and rougher in appearance than those from the nearby Pioneer mine (Pough, 1968; Rolff, 1968). These new hillside deposits extended down the valley floor to the Santa Cruz stream, and aquamarine-bearing alluvium was found several kilometers west back to and even crossing highway BR-116. Alluvial (placer) pits—cellar-like excavations that tended to fill with water—were eventually dug over the entire length of the valley. The gem-bearing gravel layer (*cascalho*) was found approximately 3 m under the valley floor, buried in many layers of multicolored clays and sands (figure 12).

A few weeks later, three miners investigating the activities of a group of vultures 3 km southeast of the Pioneer mine found aquamarine exposed on top of the ground where the vultures had landed.

Within a few days, they dug over 600 kg of clean but pale aquamarine. The Serra do Urubu (Vulture Mountain) deposits produced over 2,000 kg of aquamarine in the next few months (Rolff, 1968; R. Nash and H. G. Kennedy, pers. comm.).

Examination of the aquamarine "crystals" found in various parts of the Três Barras deposits, from the top of the hill to the bottom of the valley several kilometers away, clearly illustrates how the physical condition of the gem specimens relates to the distance traveled from the primary pegmatite. The crystals found in the eluvial, colluvial, or (occasionally) primary deposits near the top of the hill, in conjunction with white kaolin, were etched but not worn and had good terminations (similar to the crystals pictured in this article). Crystals found in colluvial pits farther down the hill (where no kaolin showed on the dumps) were badly abraded, with pits and cracks iron stained from the red clay. Two large "crystals" (50 kg and 32 kg, respectively) found on the lower slopes had no terminations and were merely broken cores of what must have been much larger crystals. The aquamarines found in the valley floor (alluvial deposits) were found with ancient river gravel; they were well worn and nearly rounded. Although these aquamarines were much less common and much smaller than those found closer to the primary deposit, the material itself was much cleaner; interestingly, the color was generally better, too (Pough, 1969; Lucio, 1980).

Future Production from the Teófilo Otoni–Marambaia Pegmatite District. It is likely that massive deposits still remain in this region; only a small percentage of the more obvious and more easily accessible deposits have been exploited, and relatively few are being mined today (R. Nash, K. Elawar, pers. comm.). In the 1960s, a gem dealer could purchase 3–6 kg of rough aquamarine per week from miners. At this writing, however, only a few grams are available to each dealer in an average week. In the last two years, the three largest pieces recovered have been only 0.9–2.9 kg.

Unfortunately, accurate production figures, or even close estimates, for the various gemstone deposits in Brazil are impossible to obtain since the system of monetary regulation encourages the quiet movement of gemstones without official records.

The Teófilo Otoni–Marambaia pegmatite belt historically has been Brazil's major supplier of aquamarine.

Large amounts of aquamarine may come from this area in the future, but only with the mechanized (strip) mining of the alluvium (just now beginning), since the garimpeiro population has diminished so drastically. During the author's 1983 visit to the Marambaia and Três Barras valleys, only a handful of *catras* were in operation.

JEQUITINHONHA RIVER PEGMATITE DISTRICT

North of the Teófilo Otoni–Marambaia pegmatite district, at Itaobim, highway BR-116 enters the Jequitinhonha River pegmatite district. The eastern and western limits of this rich aquamarine district can be reached by dirt road MG-367, and the northern limits are easily accessible and well defined by the northern villages of Salinas, Pedra Azul, and Pedra Grande (see figure 2).

Thousands of diverse pegmatites and their associated secondary deposits occur in this region. A tremendous network of creeks, streams, and rivers drains the interlaced system of valleys and basins of the Jequitinhonha River watershed, with aquamarine deposits occurring over the entire 250-km (155 mi.) length of this pegmatite district.

The aquamarine-bearing pegmatites of this region are geochemically very similar to those of the Teófilo Otoni–Marambaia district, except that very little topaz of any type has been found here, indicating the lack of fluorine in the magmas. Also, the region overlaps with the Araçuaí-Itinga green tourmaline district along the Jequitinhonha River; therefore, green and blue-green tourmalines appear in many decomposed pegmatites but always separate from any existing aquamarine deposits. Likewise, in the west near Coronel Murta and Barra de Salinas, there is some overlap with the Araçuaí-Salinas tourmaline district running due north. The Piauí valley running south from Taquaral is the source of the famous Maxixe beryls.

The earliest reported discoveries of aquamarine in this region were made by a farmer in 1903 at Ilha Alegre (Happy Island) on the banks of the Jequitinhonha River near the village of São Pedro do Jequitinhonha. Many secondary deposits have been found on low hills on both sides of the river. According to Fernandes (1905) and Oakenfull (1922), the Happy Island deposits produced many large (up to 9 kg), superb aquamarines and golden beryls. As recently as 1972, this same deposit produced a 65-kg rounded, good-quality blue-green

specimen, which was named Cachacinha (a small shot of rum) and subsequently sold in Idar-Oberstein (A. Tavares and R. Nash, pers. comm.). Three other major aquamarine deposits in this district will be discussed here: Fortaleza, Medina, and Coronel Murta (the Frade mine).

Fortaleza. The city of Pedra Azul (blue stone), located 80 km north of Itaobim, was originally called Fortaleza because of the fortress-like inselbergs that surround it. Exceptionally clean chunks of aquamarine, some up to 12 kg, have been produced from a nearby altered pegmatite at Laranjeiras since about 1910. Etched masses were common from this mine, but sharp crystals were never found. One of the largest, totally clean pieces was mined in 1935 and weighed 8 kg. The lapidary firm of Oscar Machado cut three major stones from this piece: the two "smaller" stones were 293 ct and 910 ct, respectively; the third, which was presented by the Brazilian government to U.S. President Franklin D. Roosevelt in 1937, was an incredible 1,285 ct (Calmbach, 1938). This last stone, possibly the largest cut aquamarine in existence, can be seen at the Roosevelt Museum in Hyde Park, New York. Two-kilo pieces of rough were common from this mine.

The mine itself consisted of a very large opening on a hillside, with the decomposed primary pegmatite at least 15–18 m wide. The mine has been inactive for many years, but attempts are now being made to reopen it. Many exceptionally clean and dark aquamarines from along the entire Jequitinhonha River valley have received the name Fortaleza in honor of their resemblance to the high-quality gems found at this locale (Sinkankas, 1974, 1981).

Medina. The village of Medina is located near a mountain range 45 km north of Itaobim on highway BR-116. Many secondary deposits were found in the valleys and basins of this mountain range, but most of the best aquamarines from this locale were taken from primary deposits still encased in the host gneisses of these mountains. Hundreds of tunnels (adits) have been sunk attempting to reach the primary pegmatites, and dozens of workings were very successful, producing much of the finest quality aquamarine to come from Brazil in recent years (again, see figure 1). Mining conditions and terrain are similar to those of the Frade mine discussed below. Almost no aquamarine is found in



Figure 13. One of the small (approximately 5 ct) but superb Coronel Murta aquamarines. Photo © Harold & Erica Van Pelt; courtesy of Jules Sauer (Sauer, 1982).

Medina now, although 3,000 ct from this deposit were produced in October 1983.

To the author's knowledge, the largest, most intense faceted Medina aquamarine is an octagonal 107-ct stone in the collection of Kalil Elawar in Teófilo Otoni; the 7.9-kg crystal from which this stone was cut in 1978 yielded a total of 8,000 ct of fine gems (K. Elawar, pers. comm.).

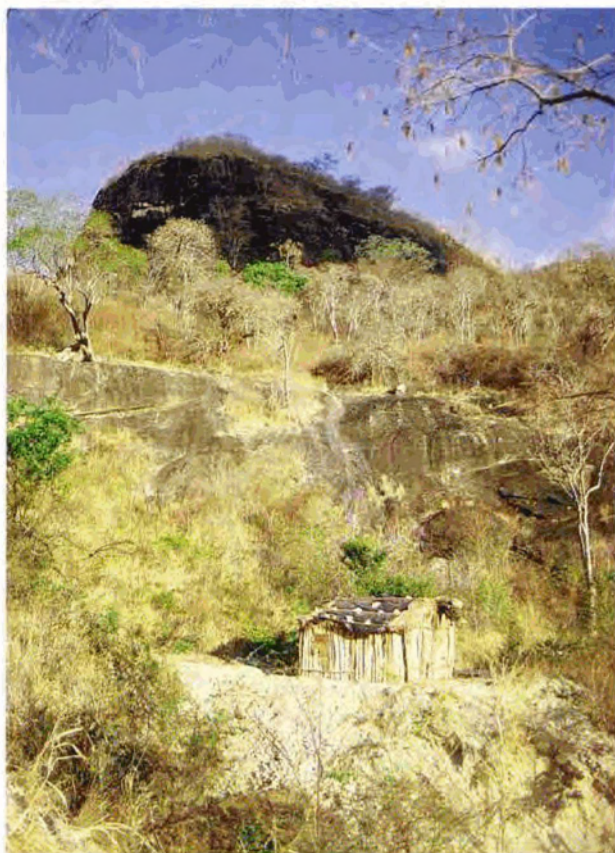
Coronel Murta (Frade mine). The city of Coronel Murta, on the banks of the Jequitinhonha River, was founded around 1830 by a retired colonel of that name. Within 6 km of the city by road is a prominent inselberg that is visible from a great distance. As one approaches Coronel Murta from Araçuaí, the back side of the inselberg looks like a giant reclining friar with a fat belly. When alluvial and primary deposits were discovered at the base of the inselberg early in 1973, the mine was given the name Mina do Frade (Friar mine). Few people in the trade have heard of Frade mine aquamarine, but nearly everyone has marveled at the small but stunning blue stones known simply as Coronel Murta; they are one and the same (figure 13).

In 1973, Inacio Moura Murta, a great-great grandson of the founding colonel, led a group of

five garimpeiros to dig in the red soil on Murta's property where aquamarine had been found. These diggings were begun in a north-south valley 1,200 m long that rises gradually for 750 m and then, abruptly, becomes very steep for the last 450 m, peaking on a hill overlooking the city of Colonel Murta only a hundred meters to the west of the giant Frade inselberg (figure 14).

The first valley-floor diggings, some as deep as 3–4 m, exposed only loose crystals in the red soil of the colluvial deposit (again, see figure 6). But within a few months, an expanded garimpeiro work force of more than a hundred men enthusiastically extended their pits and tunnels over literally half the valley, up the slopes of the hills. In the higher regions, after digging only a meter or so into the colluvial soil, they began to strike the primary pegmatite wall, which had been intruded into the east side of the valley for what appeared to be at least 750 m in a north-south direction (figure 15). This was the pegmatite that had sloughed off

Figure 14. The mine shack and main tunnel at Frade mine are only a short distance from the inselberg after which the area is named.



its crystals as the hill eroded away, forming the lower colluvial deposits.

During 1974, the garimpeiros began attacking large outcrops of this pegmatite even higher on the hill by digging large caves (figure 16). Later that same year, they started a labyrinthine series of tunnels in the primary pegmatite 120 m below the top of the ridge at the far north end of the valley. These tunnels extended deep inside the mountain, entering only 30 m from the main mine shack. In this tunnel system, the pegmatite vein has been cleaned out completely for 60 m inside the mountain, leaving nothing but the schist wall rock and some support pillars.

As the miners tunneled deeper into the hillside, the direction of the veins indicated that the pegmatite might continue straight through the hill with an outcrop on the opposite side. Although exploration in this new area revealed no outcrop where the garimpeiros had hoped to find it, in the course of their preliminary digging they discovered extensive crystal deposits in the eluvium directly on top of the hill. Eventually, colluvial deposits were discovered extending at least 150 m down the hillside facing Coronel Murta village. Again, in some locations, after digging down only a meter or so, they encountered the primary pegmatite. It seems, then, that the pegmatite they had been working on 120 m below had been intruded clear through the top of the hill; and as the hill eroded away, it had shed its crystals down the slope.

A monumental excavation project began, and eventually the entire top of the hill was pitted, dug up, and turned over repeatedly, until the area resembled an artillery range. In the process, though, thousands of crystals were found.

Occurrence. This pegmatite is unusual for its long, narrow shape. Mineralogically, however, it is typical of other deposits in this district. Specifically, black tourmaline is abundant, as are small plates of biotite mica, big smoky quartz crystals, and approximately 25-cm unaltered feldspar crystals (reflecting the unaltered state of the primary pegmatite body). In fact, hundreds of tons of fine feldspar lie on the dumps, unsalable, because of the 450-km distance to the marketplace in Governador Valadares. The Frade mine, like most in the Araçuaí-Salinas-Itinga region, has to meet expenses strictly through the sale of gem rough.

There were two unusual occurrences at this time, however. First is the presence of green mi-



Figure 15. After only a meter of tunneling, this garimpeiro has reached the primary pegmatite (note the white feldspar) at Frade.

crocline (amazonite), which was common and—along with black tourmaline—was the best indicator that gem aquamarine was close by. Second, a few gem crystals of rose tourmaline, some as long as 4 cm, were found in the main tunnel. The lithium and manganese required to produce rose tourmaline are seldom found associated with aquamarine. No topaz or kunzite was found.

Current and Future Production. When the Frade mine reached its peak production in 1981, the 200 kg of aquamarine recovered meant an average of only one kilo per garimpeiro. All of the crystals were highly fractured; 70–80% of the pieces weighed less than 100 g (3 ozs.). The highest quality aquamarine was found in pockets in the pegmatite. The largest piece of rough weighed a little over 260 g; the largest intact (but internally fractured) crystal was only 7.6 × 3.8 cm (3 × 1½ in.). These production figures contrast sharply with those from Três Barras, although the best Coronel Murta color is far better than the best Três Barras color.

In fact, the best aquamarine from this mine is among the finest in Brazil. Yet, because the crystals are so fractured, intense faceted stones are usually less than 1 ct, although totally clean stones as large as 4–5 ct do exist and 3-ct stones are not uncommon. Ten-carat stones have been faceted but they are not completely clean.

Production has dropped off sharply in the last three years, and only 70 garimpeiros work the Frade mine today. The mine owners insist that there will be considerable future production be-



Figure 16. This garimpeiro is indicating the width of the pegmatite body in one of the large caves excavated on the upper slopes of Frade mountain.

cause there are additional “virgin” areas of the pegmatite and colluvial deposits still to be exploited; however, the extent of the reserves is speculative. Because of the expense of hard-rock mining, the shortage of manpower, and the unproved reserves, it is the author’s belief that this unusual occurrence will continue to produce only very small quantities of fine aquamarine in the years to come. Although hundreds of alluvial pits have been dug near Coronel Murta, as might be expected they have produced only a fraction of the material found in the primary deposit.

OTHER AQUAMARINE DEPOSITS

The Araçuaí River–Capelinha–Malacacheta District. Along the Araçuaí River on the north and its tributaries on the south, in the area enclosed by the cities Minas Novas, Turmalina, Capelinha, Malacacheta, Novo Cruzeiro, and Lufa, hundreds of valleys and basins have yielded notable primary and secondary aquamarine-bearing deposits [Calmbach, 1938; Sinkankas, 1974, 1981; Pecora

Figure 17. This 6-cm heliodor (golden beryl) from near Colatina, E.S., accompanied by a 40.4-ct faceted mate, is representative of some of the fine material that has been found in the area around northeastern Minas Gerais. Photo © Harold & Erica Van Pelt.



et al., 1950). Additionally, deposits of both gem beryl and tourmaline have been found in the northernmost portion of the three rivers Gravatá, Setúbal, and Sucuriú and of the larger river Araçuaí (to the city of Araçuaí), as early as the 1890s (Sinkankas, 1974). The countryside surrounding virtually all of the cities in the areas shaded in blue on the map in figure 2 has produced significant quantities of gem-quality aquamarine.

Governador Valadares District. One of the most productive regions of Minas Gerais in both volume of gem beryl and size of crystals is the area within a 150-km (90 mi.) radius of Governador Valadares and embracing the watershed of the Doce and Suaçuí Grande rivers. The countryside surrounding all of the cities in this area on the map in figure 2 has produced major finds in both primary and

secondary deposits (Calmbach, 1938; Sinkankas, 1974, 1981).

Three of the largest single aquamarine crystals ever recovered were found in the Governador Valadares region: a 108-kg piece at Ariranho on the Rio Bugre, in 1942 (Ball, 1943); a 25.4-kg piece near Resplendor, in 1946 (Sinkankas, 1974), and a particularly fine 61-kg specimen (called the Lucia) found in gravels at Garajatú, in 1955 (Abreu, 1965; Sinkankas, 1974).

The quality of the aquamarine varies throughout Minas Gerais, but most of the gem rough found is pale to medium blue-green (heat treated to produce a comparable intensity of purer blue). One advantage of this gem is that large (15+ ct), totally clean stones are readily available.

Currently, this region is producing only small amounts of aquamarine. There continues to be

great potential, however; the strip mining of alluvial deposits in the Teófilo Otoni—Marambaia region, in particular, holds promise for significant future production. Judging from the past, major deposits could be found in the vicinity of any of the cities in figure 2.

HELIODOR (GOLDEN OR YELLOW BERYL)

Top-quality golden or yellow beryl (figure 17) is much rarer than aquamarine, although the best heliodor is not as valuable as the best aquamarine. Some yellow and golden beryls, when heat treated for 1–12 hours to between 280°C and 600°C (depending on the source of the material and the inclusions), will turn a pleasing, more salable aquamarine color (no greater in intensity than the original yellow or gold); others, however, will just become a lighter yellow. Still others may also turn such a pale blue that they are worth much more left as heliodor. One can be sure that the best golden or yellow stones offered for sale have not been heat treated—but that others from the same crystal were undoubtedly tested.

Heliodor usually occurs mixed with bluish and greenish beryls as a small portion of the total deposit. The author knows of only one mine where heliodor constituted a large percentage of total beryls produced: Mina Urubu, near the city of Santa Cruz immediately east of Novo Cruzeiro. Yellow and golden beryls have also been found in significant amounts at the Marambaia, Medina, Ilha Alegre, and Farrancho deposits, with notable production also from Bom Jesus do Lufa, Dois de Abril, Guanhões, Joaíma, Minas Novas, Sabinópolis, Serro, and Sapucaia as well. Quality gems, however, are always in short supply, especially large stones.

The world's largest cut heliodor, at 2,054 ct, is in the Gem Hall at the Smithsonian Institution, Washington, D.C. (illustrated in Sinkankas, 1981).

MORGANITE (PINK BERYL)

Morganite, the popular rose-pink variety of beryl, is also rarer than aquamarine. Morganite occurs commonly in two "less desirable" color phases: peach and salmon. Generally, the rose-pink tints are more fashionable. Cut morganites are commonly heated individually in a test tube over an alcohol flame (200°–400°C) for a few minutes to obtain a delicate pink hue (which is totally stable). As with aquamarine, virtually all morganite is heated by this process, which essentially dupli-

cates the geothermal processes that produce the rose-colored stones occasionally found in nature.

The largest deposit of morganite crystals ever found occurred at the Corrego do Urucum mine in Galiléia in 1973. Approximately 300 crystals, some weighing as much as 10 kg (22 lbs.), were discovered lining the walls of an immense cylindrical pocket. This deposit will be discussed in greater detail in the upcoming article dealing with kunzite, which was also found in great quantity at this locality.

Other significant deposits of morganite in Brazil were all found in Minas Gerais. These include Sapucaia (municipality of Galiléia), Calisto, Minas Novas, and along the Jequitinhonha River valley. No production is currently coming from any of these localities. Occasional kilograms of material, however, have been found recently at the Salinas mine and at an unnamed deposit near Conselheiro Pena, which produced some 5,000 ct in 1982 from a single pocket. This rose-pink gemstone is in chronic short supply; no major deposit has been discovered since 1973.

To the author's knowledge, the two best faceted Brazilian morganites are both at the Smithsonian Institution: 236 ct and 250 ct (Desautels, 1965, photo on p. 38; Desautels, 1979, photo on p. 39).

SUMMARY AND CONCLUSION

Aquamarine is found over most of the northeastern part of Minas Gerais; millions of carats have been mined since the discovery of the Papamel crystal in 1910. Both heliodor and morganite are significantly less common. Aquamarine is usually heat treated to obtain its optimum blue; heliodor may be heat treated to turn from yellow to aquamarine blue; peach- and salmon-colored morganites are often heat treated to obtain the preferred rose-pink color.

Most of the aquamarine is found in secondary deposits, although much of the darkest material has come from the primary pegmatites at Fortaleza, Medina, and Frade (Coronel Murta). Currently, little aquamarine (or heliodor or morganite) is being produced because of the shortage of garimpeiro labor and the expenses involved in mining, although small amounts are coming from other states in Brazil. Nevertheless, there continues to be great potential for the discovery of major deposits anywhere in the Minas Gerais pegmatite area.

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NOTES • AND • NEW TECHNIQUES

THE FIRST-ORDER RED COMPENSATOR: AN EFFECTIVE GEMOLOGICAL TOOL

By John Ilmari Koivula

This note deals with some gemological applications for a tool well known to microscopists: the first-order red compensator. In gemological microscopy, the compensator can be useful in locating interference colors and optic figures in birefringent materials and in delineating strain in gemstones. In polarized-light photomicrography, a properly positioned compensator can reduce the exposure time required and thus the risk of film reciprocity failure and of poor-quality images resulting from random vibrations of the microscope and its accessories.

Mineralogists, petrologists, chemical microscopists, and crystallographers are all familiar with the usefulness of a first-order red compensator in locating fast and slow vibration directions of light in crystals, in helping determine the optic character of unknown crystalline compounds, and in defining areas of strain. Use of this microscopist's tool in gemology, however, is virtually unknown.

While exploring potential gemological applications for the classic uses of the first-order red compensator — specifically, enhancing interference colors and determining areas of strain — this article highlights a new use for the compensator, in the field of polarized-light inclusion photomicrography.

WHAT IS A FIRST-ORDER RED COMPENSATOR?

Traditionally, first-order red plates have been constructed of a small, thin (approximately 0.0625 mm), uniform layer of selenite (gypsum), cut par-

allel to the perfect cleavage; or quartz, cut parallel to the c-axis. The plates produce an optical retardation of 530 to 550 nm.

Because of the brittle nature and small size of the ultra-thin gypsum and quartz plates needed to make a first-order red compensator, these compensators were poorly suited for use with a low-power gemological stereo microscope. It was not until the late 1970s, when the Polaroid Corporation introduced large-format first-order red compensators in plastic sheet form, that the application of such a compensator became practical for use with a polarizing gemological microscope. The compensator manufactured by Polaroid is a proprietary product, a plastic laminate of undisclosed nature, that produces an optical retardation of approximately 530 nm.

HOW THE COMPENSATOR WORKS

Several good texts are available that describe the use of the first-order red compensator in the areas of microscopy, optical mineralogy, and optical

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Acknowledgments: The author would like to thank Dr. John DeHaas, of DeHaas Optical Engineering and the University of Southern California, and Alan DeHaas, of DeHaas Optical Engineering, for the gift of the first-order red compensator sheet and for their review and comments on this article. Kristi Koivula also deserves special thanks for her patience in typing the manuscript.

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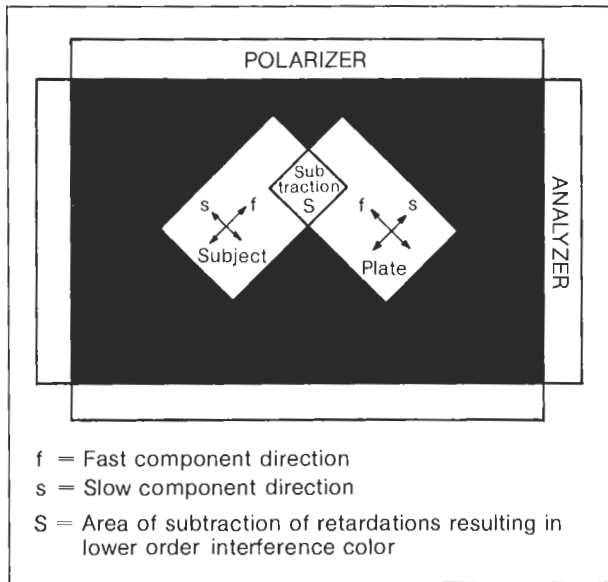


Figure 1. Drawing showing the test subject and compensator plate oriented in subtraction position in a polarized light field when the polarizer and analyzer are in total extinction. Drawing by Christine Wilson, after McCrone et al., 1979.

crystallography (e.g., Phillips, 1971; McCrone et al., 1979). When inserted in a field of polarized light, the compensator basically serves to brighten and enhance an image by the addition or subtraction of optically retarded wavelengths as they pass through the compensator into an optically anisotropic subject. When two anisotropic materials, one being the compensator, are superimposed in a field of polarized light, addition or subtraction of their individual retardations will occur, depending on their orientations to each other and to the polarizer and analyzer. If both the compensator and the subject are oriented in the position of total brightness in the polarized light field (which is 45° away from the vibration directions of the analyzer and polarizer) and their slow vibration directions (corresponding to the higher refractive index) are perpendicular or at right angles to each other (see figure 1), then *subtraction* of retardations occurs, resulting in lower-order interference colors. If, however, the slow vibration directions of the compensator and the test subject are oriented parallel to each other (as in figure 2), then *addition* of retardations occurs, resulting in higher-order interference colors; low-intensity blacks, grays, and whites and very pale yellows, oranges, and reds are enhanced into the more vibrant first- and second-order colors. The Michel Levy chart (McCrone

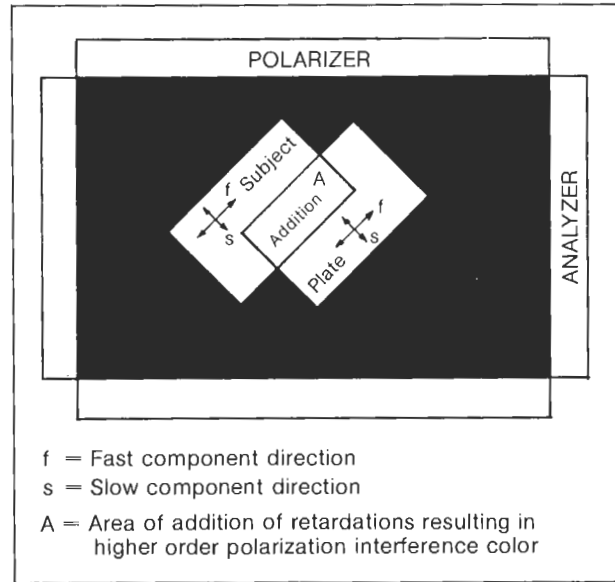


Figure 2. Drawing showing the test subject and compensator plate oriented in addition position in a polarized light field when the polarizer and analyzer are in total extinction. Drawing by Christine Wilson, after McCrone et al., 1979.

et al., 1979) illustrates the "Newton's Series" sequence of interference colors. If we can enhance, or brighten, low-intensity interference colors either by subtraction from the higher orders or by addition of the lower order, then they will be much easier to locate and observe. The first-order red compensator is well suited to this task.

GEMOLOGICAL APPLICATIONS

The first thing the gemologist notices when using a first-order red plate is the vivid magenta color it produces when it is inserted in the light path between the polarizer and the analyzer when they are in a position of total extinction. The view through the GEM polariscope shown in figure 3 illustrates this effect.

It should be noted that the first-order red compensator plate is not a filter that is red in color as the name might imply. Rather, it is a very pale yellowish, almost colorless, material that gives a first-order red or magenta color to a field of polarized light. The first-order red compensator has a number of practical applications in gemology, as described below.

Observing Interference Colors and Locating the Optic Axis. During orientation of a doubly refractive gemstone in the polariscope or microscope,



Figure 3. View through a polariscope with the first-order red compensator inserted halfway through the polarized light field.

as the gemologist searches for an optic axis, the first-order red plate can prove helpful. Here it serves as a means of brightening interference colors that start to appear as the optic axis direction is approached. Brighter colors are much easier to locate. It follows that if the optic axis interference colors are easier to locate, then the optic axis itself can be found more quickly.

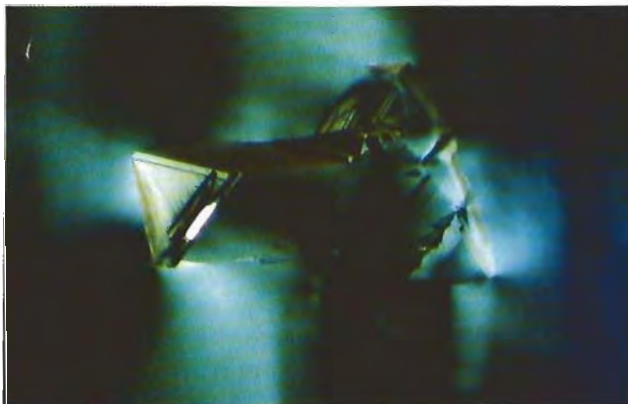
Determining Strain. When present — either as a result of unseen internal disruption, twinning, or

crystalline intergrowth, or as halos surrounding solid included crystals — strain will often reveal itself under polarized light conditions as color anomalies in shades of brown, gray, and black. Because of this lack of color intensity, it is sometimes very difficult to detect. The first-order red compensator can be used to enhance strain colors and patterns (figures 4 and 5), producing more vivid blues and yellows or sometimes reds and greens. Inasmuch as strain is commonly present in diamonds, microscopic examination under polarized light with a first-order red compensator is a helpful method of separating diamonds from substitutes such as cubic zirconia and yttrium aluminum garnet.

Use with Polarized Light Inclusion Photomicrography. When using polarized light to photograph inclusions, the gemological microscopist is commonly confronted with low light intensity and a correspondingly long exposure time that all but makes quality photomicrography impossible. With the first-order red compensator, however, the image is enhanced by a vivid array of bright interference colors and the exposure time required — and, consequently, the effect of vibrations — is greatly reduced.

If we look again at the polariscope image in figure 3, we see how much brighter the magenta side of the polarized light field in this image is. When the compensator is used with a gemological microscope equipped with a light-polarizing system, the difference in brightness is equally obvious and also readily measurable with a light metering system. Light metering showed that the exposure

Figure 4. Left—Included crystal of diamond in diamond, photographed in polarized light without the compensator. Exposure time, 1 minute 25 seconds. Right—the same crystal photographed in polarized light with the first-order red compensator. Exposure time, 22 seconds. Magnified 50×.



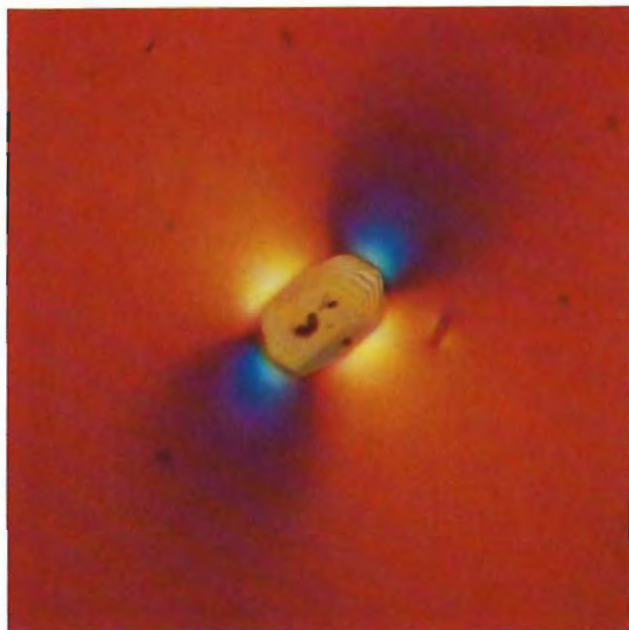
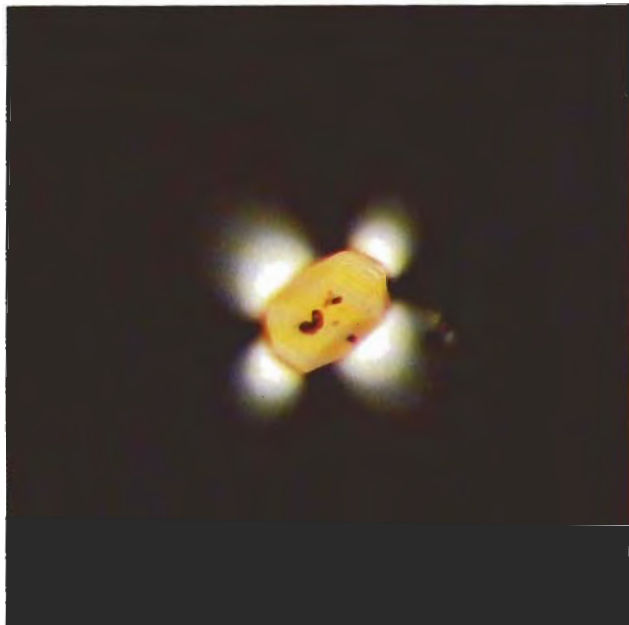


Figure 5. Left—Monazite crystal in an African rhodolite garnet in polarized light without the first-order red compensator. Exposure time, 3 minutes, 13 seconds. Right—Monazite crystal but with the first-order red compensator inserted. Exposure time, 25 seconds. Magnified 50 \times .

time required to properly expose film with an ASA of 160 when the polarizer and analyzer are in 90° extinction is over 10 hours. With insertion and proper orientation of the first-order red compensator in the field between the polarizer and analyzer, the exposure time is cut to less than one minute. The brighter the image is the less the required exposure time will be.

Although the above-mentioned difference in exposure time is dramatic, no inclusion subject was present in the light path to demonstrate the true value of the compensator plate to the gemologist-photomicrographer. To illustrate the point, three test subjects showing a wide range of optical properties — a diamond, a garnet, and a rock crystal quartz, all with inclusions — were selected.

The first subject, the diamond, has an inclusion of another diamond that shows only partial interfacing, making some of the edges virtually invisible as they blend with their host of the same refractive index. The diamond within a diamond was photographed first using only the polarizer and analyzer in extinction. The photograph, shown in figure 4 (left), reveals a great deal of lattice strain in and around the inclusion. The exposure time was one minute and 25 seconds. The strain colors in this photomicrograph are all of low intensity and the image is quite dark. With insertion of the

first-order red compensator into the field, the inclusion picture (figure 4, right) is immediately decorated by an array of vivid strain colors and the exposure time reduced to 22 seconds.

The second subject, a rhodolite garnet, plays host to a euhedral monoclinic crystal of transparent yellow monazite. As shown in figure 5 (left), taken under polarized light without compensator, strain in low-intensity colors is visible around the radioactive monazite. The exposure time was three minutes and 13 seconds. In figure 5 (right), taken with the compensator in place, the image is now alive with bright interference colors; time for the exposure was only 25 seconds.

The last test subject, a colorless quartz, contains a number of small, noninterfaced, unoriented, slightly distorted quartz crystals. Without polarized light (figure 6, top), only a few faint areas of the quartz inclusions are visible because they have virtually no interfacial separation and the same refractive index as their host. This transmitted light image was recorded in one second. In figure 6 (bottom left), under polarized light, all of the quartz crystal inclusions are now visible. However, the exposure time was 18 seconds. With the first-order red compensator (figure 6, bottom right), the included crystals are still vivid but the exposure time was reduced to 8 seconds.

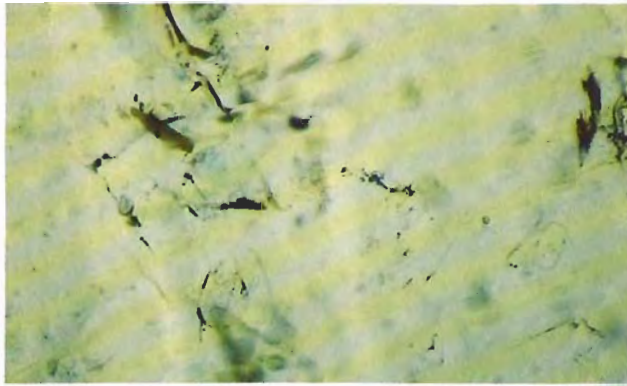
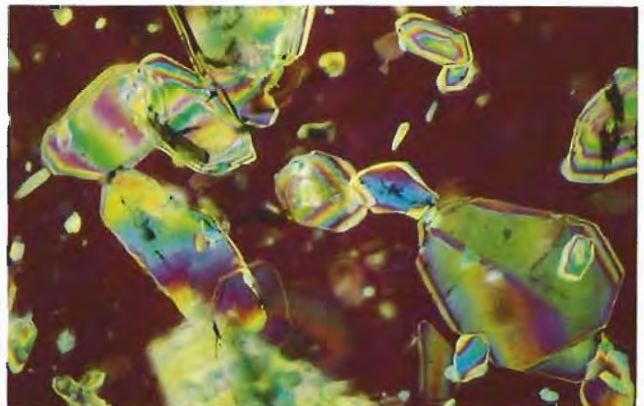
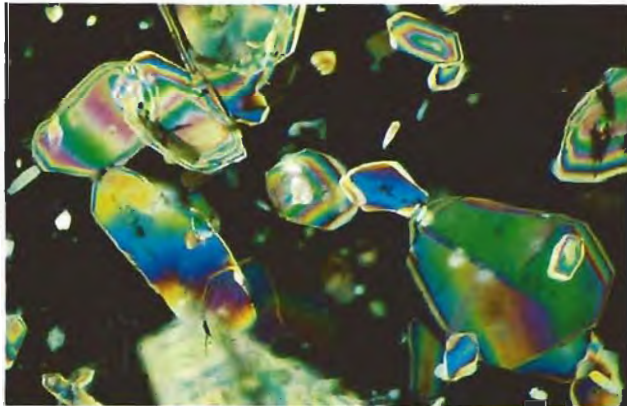


Figure 6. Top—These inclusions of rock crystal quartz in rock crystal quartz are virtually invisible in transmitted light. Exposure time, 1 second. Bottom left—The same inclusions of quartz in quartz shown above become visible under polarized light. Exposure time, 18 seconds. Bottom right—Use of the first-order red compensator reduced the exposure time in polarized light for the image shown at left to 8 seconds. Magnified 20 \times .



CONCLUSION

Comparing the photographic images with their corresponding exposure times shows that the first-order red compensator has something to offer the gemologist who is interested in polarized light photomicrography. The technique is easily adapted to any standard stereo gemological microscope and the results can be worth the effort.

Additionally, the first-order red plate enhances strain colors, making strain areas more easily visible and thereby simplifying the location of strain centers. In many instances, the compensator also

aids efforts to locate an optic axis direction in a doubly refractive gemstone by making the location of interference colors, as an optic axis is approached, much easier.

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Gem Trade LAB NOTES

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AMETHYST, Unusual Natural Inclusion

Before synthetic amethyst was available on the market, we seldom felt it necessary to examine every amethyst under magnification to observe any inclusions that might be present. However, the advent of the synthetic material has made it necessary to study the inclusions in each stone to determine, if possible, natural or synthetic origin. Figure 1 shows an amethyst that came into the New York lab for identification. The inclusions, which resemble a pie-shaped galaxy of red stars, are goethite, an iron-oxide mineral. While the presence of goethite establishes the natural origin of the stone, this is the first time we have observed this unusual zonal distribution in amethyst. *R.C.*

CUMMINGTONITE-GRUNERITE, A Series in the Amphibole Group

Recently submitted to the Los Angeles laboratory for identification

Figure 1. Unusual zonal distribution of goethite inclusions in amethyst. Magnified 30 \times .

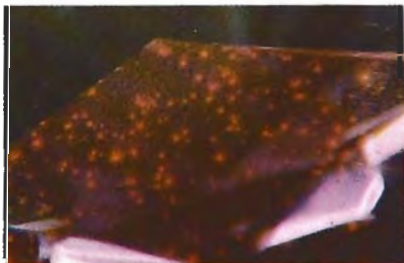


Figure 2. This amphibole rock—measuring 36.3 \times 23.0 \times 21.2 mm—is slated for use as an ornamental stone.

was a piece of rough material with one polished face that consisted of an opaque black center section bordered by two opaque yellowish brown areas (figure 2).

When the specimen was examined with the unaided eye, white inclusions were observed scattered throughout the opaque black material. Testing of the black area with a refractometer revealed vague readings of 1.54 to 1.55 and 1.64 to 1.65, indicating the presence of more than

one mineral within that portion of the rock.

A minute amount of powder was scraped from the black portion for X-ray diffraction analysis. The results of the X-ray powder diffraction showed that the black material is a

Editor's note: The initials at the end of each item identify the contributing editor who provided that item.

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rock consisting of at least three different minerals, one of which is an amphibole, probably in the cummingtonite-grunerite series. There were not enough diffraction lines to identify the other components. Nongemological, probably petrographic, tests would be required to identify the rock type.

This material is reportedly from a deposit in North Carolina. The client who submitted the sample for identification explained that the owner of the specimen had several hundred kilos of this material and planned to market it for use as an ornamental gem, that is, for carvings, cabochons, and inlaid stones in jewelry. The jeweler-gemologist should not be surprised, therefore, if he encounters this material at some future time. *R.K.*

DIAMOND

Coated Diamonds

Longtime readers of *Gems & Gemology* will no doubt recall the important article by Eunice R. Miles on "Diamond Coating Techniques and Methods of Detection," which appeared in the Winter 1962-63 issue. At that time, the practice of coating diamonds had become so insidious and damaging to the trade that in September 1962 the New York state legislature enacted a law prohibiting the use of the technique unless it was fully disclosed to the purchaser.

Since then, the Gem Trade Laboratory has seen only about three or four coated stones a year. In fact, some of the more recent staff members had never even seen or tried to color grade such a stone. Approximately six months ago, however, an unusual number of coated diamonds started to come in to both the Los Angeles and the New York labs.

These stones were not being submitted by appraisers or jewelers who were suspicious of the color, but rather by cutters and brokers. Twenty years ago, graders familiar

with coated stones became cautious when the stones looked "wrong" in the color grader. However, using the same "double lighting" recommended originally by Mrs. Miles, very discrete coatings were detected. For the most part the actual colors of the stones before coating have been found to be H or I. With the coating, some might have been graded as high as G if they hadn't had that suspicious grayish appearance. In at least one recent case, the client submitting an uncoated stone that had been found to grade H asked for a color recheck within a week after the report had been issued. When the stone was reexamined, it was found to have a coating that gave it an F to G appearance, but with a grayish cast. Clearly, the laboratory was being used.

For the most part, the coatings seen recently are beautifully applied and could be easily overlooked. Sometimes only a ghostly band on one side of the girdle can be detected. In other cases, the band lies on both the pavilion and the crown side of the girdle, as in figure 3. The coating is so thin that no effort has been made to analyze it. However, its resistant nature suggests that it may be similar to the blue-to-violet hard enamel (flux) reported by Mrs. Miles in 1962. *R.C.*

Dendrite-like Inclusion

The Gem Trade Lab Notes section of the Spring 1984 issue featured a photo of a stepped laser drill hole connecting several inclusions. Figure 4 shows a rare, step-like natural dendrite-like inclusion that appears to connect several included crystals in a diamond that was submitted to our New York laboratory for grading. *R.C.*

DIOPSIDE

A few months ago, a gemologist from Sri Lanka asked the Santa Monica lab to help in the identification of a 0.72-ct emerald-cut grayish lavender

stone. This stone was highly birefringent, .029, with a refractive index of 1.671-1.700. The optic character was biaxial positive; a biaxial optic figure could even be obtained on the pavilion of the stone near the culet. No absorption lines were visible in the hand spectroscope. The fluorescence was faint chalky greenish white to short-wave ultraviolet radiation, but inert to long-wave ultraviolet radiation. We determined the specific gravity by the hydrostatic method to be 3.31. The properties of this stone indicated diopside, despite its unusual color. X-ray diffraction confirmed our other test results. *K.H.*

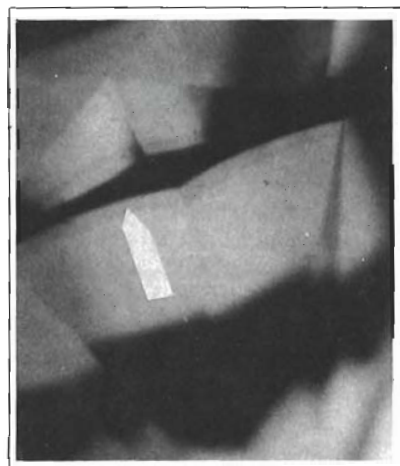


Figure 3. The arrow points to areas of coating that are evident on both sides of the girdle of this coated diamond. Magnified 30x.

Figure 4. This unusual dendritic inclusion in diamond resembles a step-like laser drill hole. Magnified 20x.

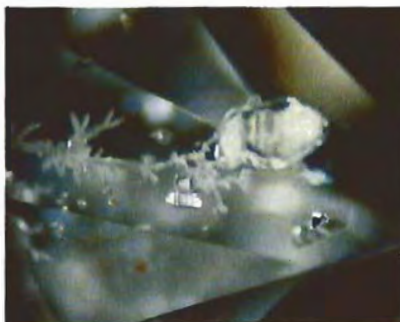




Figure 5. Artistically stained nephrite carving, 23.4 × 7.2 × 9.5 cm.

JADE
Artistically Stained Nephrite

The Los Angeles laboratory received for identification a translucent to opaque variegated pale green and brown carving of two birds which measured approximately 23.4 × 7.2 × 9.5 cm. Subsequent testing of the carving revealed that it was nephrite jade.

During preliminary examination, we observed that the variegated brown coloration was unnatural in

appearance. In addition to somewhat large areas of brown color on the carving, nearly all of the shallow carved depressions (see the wing areas of figure 5) showed brown coloration in contrast to the pale green raised areas directly next to them. This appearance very strongly suggested that the brown color in these areas was probably caused by artificial staining or dyeing in an attempt to highlight the carved details.

The least destructive test for

Figure 6. A strand of dyed green nephrite beads, each approximately 9 mm in diameter.



dyed gem materials was then implemented. When an inconspicuous brown area was rubbed with an acetone-soaked cotton swab, however, absolutely no stain appeared on the swab. Inasmuch as some dyes and stains are not removed from certain gem materials with acetone alone, we decided to try a 10% hydrochloric acid solution next. When the same area of the carving was rubbed vigorously with a cotton swab soaked in the acid solution, a light brown stain was produced on the swab. This evidence, together with the unnatural appearance of the piece, led us to conclude that this carving had been artistically stained in a manner similar to that commonly seen on nephrite jade carvings. Since no attempt had been made to enhance the color of the entire carving, with the dye or stain having been applied only in selected areas to highlight the details of the carving, the following conclusion was stated on our gem report: NEPHRITE JADE, with some areas of artistic staining. R.K.

Dyed Nephrite

Unlike the artistic staining described above, some nephrite is being dyed so that the color is changed throughout the material. The first potentially commercial quantity of green dyed nephrite we have encountered for some time were the cabochons reported in the Spring 1984 issue of *Gems & Gemology*. Figure 6 shows the first strand of beads of this material submitted to our New York laboratory. The absorption spectrum of these 9-mm beads is very similar to that seen in the more familiar dyed jadeite, indicating that the same dye may have been used. If so, the stones would probably be just as susceptible to fading as dyed green jadeite is. R.C.

PEARLS

Imitation Mabe Pearls

The two items shown in figure 7 were brought to our Los Angeles lab-



Figure 7. Imitation Mabe pearls. The finished "pearl" on the right measures 17 × 15 mm.

oratory for identification. They were being offered on the market as "Mabe pearls." Gemologists should remember that a Mabe pearl is an induced blister pearl that has been cut from the shell and the nacreous half-dome then cemented over a mother-of-pearl bead of approximately the same size as the hollow in the dome. The rest of the hollow is then filled with a material that looks like Canada balsam and a base of mother-of-pearl is cemented on.

As figure 7 shows, the "pearl" on the left appears to be a blister pearl still attached to the shell, whereas the one on the right looks like a finished product. Clearly visible in the specimen on the right is a line of demarcation, which suggests a mother-of-pearl base cemented to the blister pearl. Preliminary examination indicated that both items were imitations, since both had a very low specific gravity judging by their heft; both felt very smooth and warm to the touch, and neither had any orient. Under magnification, some small gas bubbles were visible; in addition, both items were easily indented by the pin point of a brush probe, which suggests that these "pearls" were made from some type of plastic.

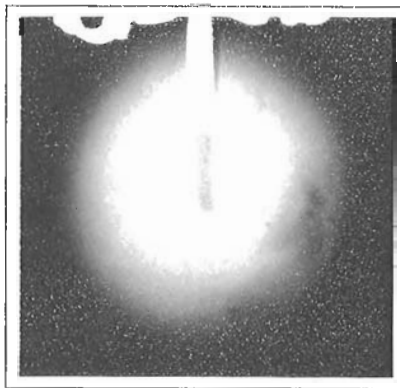
When we viewed the two samples with the microscope, we noticed many small bubbles oriented in very closely spaced parallel layers, thus

producing the appearance of a demarcation line within the otherwise



Figure 8. Flattened freshwater cultured pearl earrings, 18 mm in diameter.

Figure 9. This X-radiograph of one of the pearls pictured in figure 8 was taken in the flat direction and shows no evidence of a nucleus.



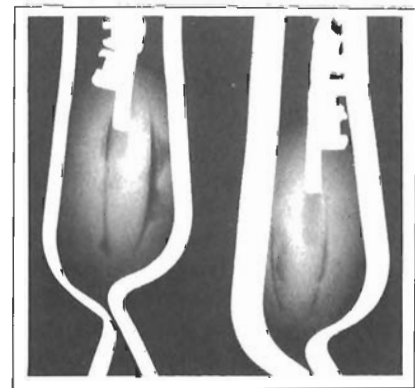
uniform material. These "Mabe pearls" were certainly the most realistic imitations we have encountered. *K.H.*

Unusual Cultured Pearls

An attractive pair of somewhat flattened 18-mm pearls on pendant earrings (figure 8) fluoresced strongly to X-radiation, indicating freshwater origin. Although the X-radiograph taken in the flat direction (figure 9) was inconclusive, that taken with the pearls on edge (figure 10) shows flattened lentil-shaped nuclei. These are the first freshwater cultured pearls of this type we have seen in the New York laboratory.

Coincidentally, the New York laboratory also received a pair of button-shaped pearls set in stud earrings for testing (figure 11). They displayed weak to moderate fluorescence when exposed to X-radiation. The X-radiograph (figure 12) shows that they, too, are cultured pearls with lentil-shaped nuclei. The weak fluorescence indicates saltwater origin. We have only encountered such nuclei a few times in the past 30 years. We have been told that such pearls are rare because off-round nuclei in saltwater mollusks increases the mortality rate to an unacceptable level.

Figure 10. This X-radiograph of the pearls in figure 8 was taken with the pearls on edge; it shows their lentil-shaped nuclei and thus proves their cultured origin.



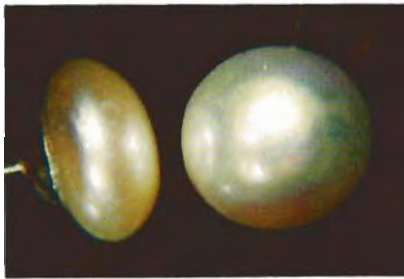


Figure 11. Saltwater cultured pearls set in earrings, 10 mm in diameter.

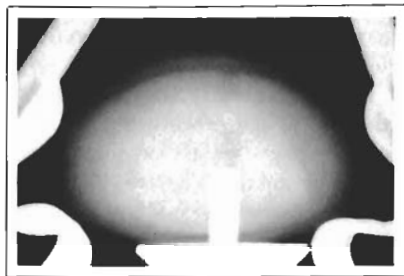


Figure 12. This X-radiograph of one of the pearls in figure 11 also reveals a lentic-shaped nucleus under a thin layer of nacre.

A third pearl received for testing proved to be a half-drilled freshwater cultured pearl. The X-radiograph shown in figure 13 revealed that the nucleus had been drilled prior to insertion in the mollusk. Evidence of the drilled nucleus shows up in the finished pearl as small depressions on the surface (figure 14). In an article on freshwater pearl cultivation (*Gems & Gemology*, Spring 1962), we learned that round nucleated freshwater pearls were still in the experimental stage at Lake Biwa. Nuclei insertion in freshwater clams, unlike insertion in saltwater mollusks, required special tools which in turn required the drill hole in the nucleus. With a diameter of more than 13 mm, the pearl described here is larger and more attractive than any we have seen before. It may be an American nucleated freshwater cultured pearl; however, we do not know whether the same drilled nu-

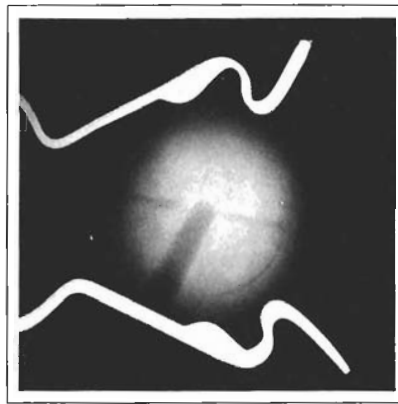


Figure 13. Note the drilled nucleus evident in this X-radiograph of a 13-mm cultured pearl.

cleus technique is used in the Mississippi area. R.C.

**QUARTZ,
Unusually Large Multi-Star**

Contributing Editor Bob Crowningshield reports that he was surprised to see a selection of multi-star

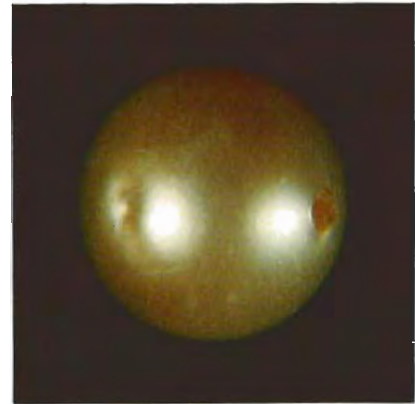
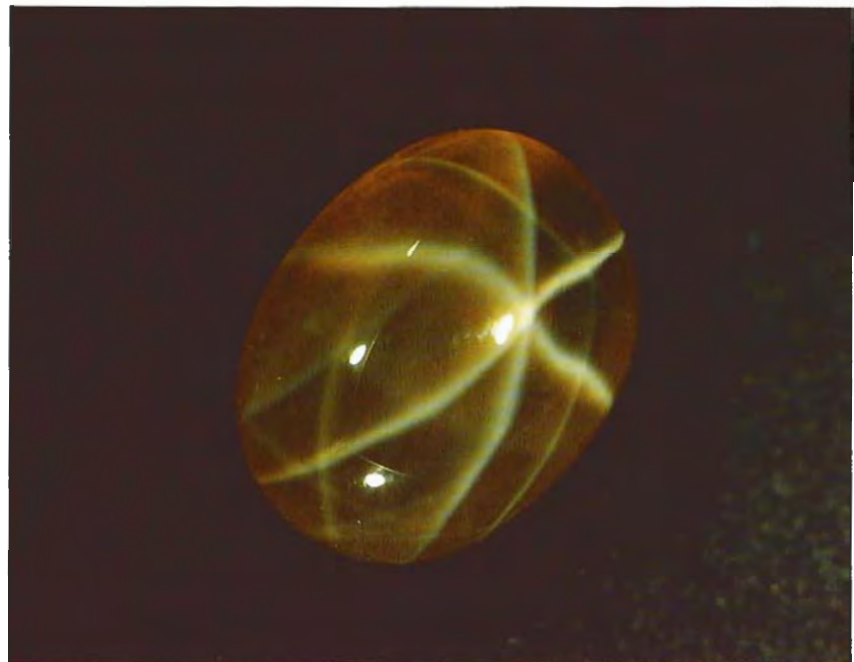


Figure 14. These surface dimples suggest the presence of a drill hole in the nucleus of this 13-mm pearl.

quartz cabochons at the Tucson Gem and Mineral Show held in February of this year. Few of these attractive stones have come to our attention since we first added the beautiful cabochon shown in figure 15 to our New York study collection (*Gems & Gemology*, Summer 1977).

Dr. Edward Gübelin studied

Figure 15. Multi-star quartz cabochon in the collection of the New York Gem Trade Laboratory, 22 ct.



several stones from Sri Lanka to establish that sillimanite inclusions cause the star in that material. However, we had not encountered any significant commercial offering of these stones until Tucson, 1984. Our thanks to the New York gem dealer who allowed us to photograph the 170-ct multi-star quartz shown in figures 16 and 17. We are still hoping to see a sphere made of this phenomenal material. R.C.

RUBY, Heat Treated

Because Burma rubies fluoresce stronger than those from other sources, a gem dealer exposed the 83.01-ct ruby cabochon shown in figure 18 to ultraviolet radiation in

Figure 16. Note the sharp star in this 170-ct quartz cabochon.



Figure 18. An 83.01-ct ruby cabochon.



an effort to determine if the stone was of Burmese origin. When exposed to long-wave ultraviolet radiation, it fluoresced a bright red similar to that of a Burma stone. However, with short-wave ultraviolet radiation, a peculiar bluish patchiness and a number of concentric rings became evident (figures 19 and 20). Because it was suspected that the ruby might have been oiled, the stone was submitted to the New York lab. This theory was rejected when it was determined that the bluish areas did not follow fractures or rhomboidal "bulls-eye" zones. The irregular patch (figure 19) corresponds to a lighter color zone in the stone. It was concluded that the

Figure 17. Viewed from a different angle, the stone pictured in figure 16 shows other stars.



Figure 19. The stone illustrated in figure 18 fluoresced a patchy blue when exposed to short-wave ultraviolet radiation.



stone was probably heat treated, a process known to produce bluish fluorescence in blue sapphire when exposed to short-wave ultraviolet radiation. The heating could also be responsible for the absence of identifying silk in what the dealer assumed to be a Burma stone. R.C.

SAPPHIRE, Verneuil Synthetic

Figure 21 illustrates the curved color banding typical of a Verneuil synthetic blue sapphire. In this instance the approximately 5-ct stone, set in a ring, had been submitted to the New York lab for identification. When the stone was viewed through the table, however, a series of bright parallel reflection planes were seen (figure 22). These planes reached the surface of the table and appeared similar to the surface grain lines in diamond. We could not determine if they were present before the stone was polished and therefore were inherent to the rough material, or if they are the result of some treatment or trauma after cutting. Certainly, they are not typical of synthetic material. Since some heat-treated natural blue sapphires fluoresce a chalky greenish white similar to synthetic stones, a casual examination of this stone after a fluorescence test could mis-

Figure 20. Concentric rings were also evident in the fluorescence of the stone in figure 18 when exposed to short-wave ultraviolet radiation.

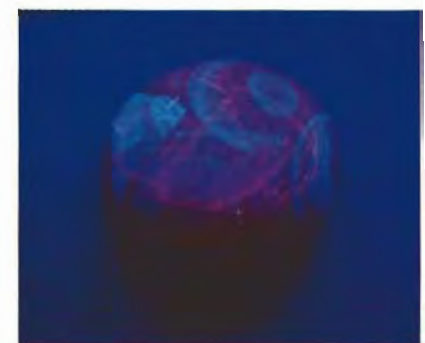




Figure 21. Curved striae in a synthetic blue sapphire. Magnified 15x.



Figure 22. Unusual reflection planes observed in the stone shown in figure 21. Magnified 15x.

lead the gemologist if he noted only the reflection planes and not the curved striae. It is possible that since this type of structure has been seen only recently in both New York and Los Angeles, it may be the result of the continuing experimentation with heat treatment in gem-cutting centers. R.C.

Black SPINEL

In the Gem Trade Lab Notes section of the Fall 1982 issue of *Gems & Gemology*, we mentioned that our New York laboratory had been asked to identify an oval, black, opaque faceted stone that was supposed to have been cut from a portion of a Mexican meteorite named "The Black Ruby." Limited gemological testing indicated that the material was black spinel. However, its iden-



Figure 23. An 8.63-ct. brownish yellow cat's-eye zircon with a fine eye.

tity could not be verified by means of X-ray diffraction since permission for this test could not be obtained.

By chance, we recently received the same material for identification in our Los Angeles lab. The sample consisted of a rough specimen and

two faceted stones that weighed approximately 2 ct each. The client stated that the stones came from a Mexican "andromediorite" (black metallic ruby). Limited testing again indicated that the faceted stones were probably cut from black spinel. With the permission of the owner, we performed an X-ray diffraction analysis that confirmed our tentative identification: the material was indeed a variety of spinel and not meteoritic. K.H.

Cat's-eye ZIRCON

In this section of the Winter 1983 issue of *Gems & Gemology*, we featured a green cat's-eye zircon that had been brought to the Santa Monica laboratory. Recently, another of these rare stones, but in a different color, was submitted to our New York lab. Figure 23 shows this attractive 8.63-ct brownish yellow cat's-eye zircon, with an "eye" equal to that found in fine chrysoberyl. The stone was easily identified by its typical absorption spectrum. Unfortunately, we have no information on its country of origin. R.C.

PHOTO CREDITS

Ricardo Cardenas took the photos used in figures 1, 3, 4, 6, 16, 17, and 21-23. Shane McClure is responsible for figures 2, 5, and 7. Andrew Quinlan provided figures 8-15 and 18-20.

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Editorial Forum

BRIOLETTE OF INDIA

In my article "Harry Winston: A Story Told in Diamonds" (Spring 1983), I described 14 "named" diamonds that Mr. Winston had handled during his career. However, it has recently come to my attention that the known history of the 90.38-ct Briquette of India, which had been reported to be the oldest diamond on record, is not as ancient as many scholars had believed.

Mr. Hans Nadelhoffer, who is compiling a history of the Cartier firm, uncovered some interesting information concerning the true history of this unusual stone. During the course of his research, Mr. Nadelhoffer had the opportunity to interview a 90-year-old Parisian gentleman whose father, Atanik Eknayan, ran a very important diamond faceting shop in Neuilly, France. According to the younger Mr. Eknayan, the Briquette of India was cut in his father's shop in 1908–1909. He remembers that the briquette cut was chosen because of the odd shape of the original rough. Cartier purchased the stone in 1910, marking the beginning of its verifiable history.

Laurence Krashes
Harry Winston, Inc.,
New York

DIASPORE

Following your published data on a rare 1.24-ct faceted diaspore (Gem Trade Lab Notes, Fall 1983), your readers might be interested to learn that a deposit of gemmy material is said to have been discovered in Turkey

within the past few years. In October 1982, I saw several unusually large, transparent, faceted diaspores. One stone weighed 26 ct and showed a slight color change from yellow-green to brownish. The largest stone was yellow-green and weighed 157 ct. In all, there were about 100 pieces available, ranging from 3 to 27 ct, as well as some rough material.

C. A. Schiffmann, G.G., F.G.A.
Gübelin Gemmological Laboratory
Lucerne, Switzerland

ERRATA

In the article "'Cobalt-blue' Gem Spinel," which appeared in the Spring 1984 issue, Mr. Dan Duke was inadvertently omitted from the acknowledgments. Mr. Duke loaned several deep-blue natural gem spinels for the study. Also, the last sentence of the abstract for that article should read, "Flame-fusion synthetics may still be distinguished by their *higher* R.I.'s."

Also in the Spring 1984 issue, in the Gem Trade Lab Notes section, the natural pearl is the *fifth* from the right in the bar pin shown in figure 19 (p.49).

In the article, "The Rubies of Burma: A review of the Mogok Stone Tract" (Winter 1983 issue), the locality photos in figures 2, 4, 5, and 6 were taken by Dr. Edward Gübelin.

We apologize for any confusion that these errors and omissions may have caused our readers.

GEMOLOGICAL ABSTRACTS

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COLORED STONES AND ORGANIC MATERIALS

Crystal chemistry of tsilaisite (manganese tourmaline) from Zambia. K. Schmetzer and H. Bank, *Neues Jahrbuch für Mineralogie Monatshefte*, No. 2, 1984, pp. 61–69.

Gem-quality yellow, yellowish brown, and greenish yellow tourmalines from a new occurrence reportedly near Chipada, Zambia, have manganese contents among the highest ever found in tourmaline group minerals. This material has refractive indices of $\epsilon = 1.622-1.623$, $\omega = 1.645-1.648$, birefringence of 0.023–0.025, density of about 3.13 g/cm³, and MnO content of 6.37–6.80 wt%.

This section is designed to provide as complete a record as possible of the recent literature on gems and gemology. Articles are selected for abstracting solely at the discretion of the section editor and her reviewers, and space limitations may require that we include only those articles that will be of greatest interest to our readership.

Inquiries for reprints of articles abstracted must be addressed to the author or publisher of the original material.

The reviewer of each article is identified by his or her initials at the end of each abstract. Guest reviewers are identified by their full names.

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Unit-cell parameters are $a = 15.915 \text{ \AA}$ and $c = 7.123 \text{ \AA}$. Because of their negligible iron content, these tourmalines have chemical compositions that fall along the solid-solution series between end-member elbaite [ideally $\text{Na}[\text{Al}, \text{Li}]_3\text{Al}_6\text{B}_3\text{Si}_6\text{O}_{27}(\text{O}, \text{OH}, \text{F})_4$] and a hypothetical end-member known as "tsilaisite" [ideally $\text{Na}[\text{Mn}^{2+}]_3\text{Al}_6\text{B}_3\text{Si}_6\text{O}_{27}(\text{O}, \text{OH}, \text{F})_4$]. "Tsilaisite" has not yet been found as a distinct mineral species in nature but has been synthesized in the laboratory.

Citing work on manganese tourmalines of Slivko (*International Geology Review*, Vol. 3, 1961, pp. 195–210), Schmetzer and Bank identify this new natural material as "tsilaisite" and report its ideal chemical formula as $\text{Na}[\text{Mn}_{1.5}^{2+}\text{Al}_{1.5}]\text{Al}_6\text{B}_3\text{Si}_6\text{O}_{27}\text{O}_{1.5}(\text{OH}, \text{F})_{2.5}$. However, they give no indication that this usage has been formally approved by the Commission on New Mineral Names of the International Mineralogical Association, which is the normal procedure for new mineral descriptions. The authors discuss possible isomorphic replacement mechanisms along the elbaite-"tsilaisite" solid-solution series. These mechanisms appear to involve the two reactions $\text{Li}^+ + (\text{OH})^- = \text{Mn}^{2+} + \text{O}^{2-}$ and, to a lesser extent, $\text{Al}^{3+} + \text{O}^{2-} = \text{Mn}^{2+} + (\text{OH})^-$. When combined, these reactions give $\text{Li}^+ + \text{Al}^{3+} = 2\text{Mn}^{2+}$. The extent to which this substitutional mechanism is compatible with the crystal structure of tourmaline is presently unknown but under investigation.

JES

The geochemistry of beryllium and fluorine in the gem fields of Sri Lanka. M. S. Rupasinghe, A. Banerjee, C. Dissanayke, and J. Pense, *Mineralium Deposita*, Vol. 19, No. 1, 1984, pp. 86–93.

Sri Lanka has long been an important source of various gemstones, including corundum, chrysoberyl, beryl, garnet, spinel, tourmaline, and topaz. The island is primarily composed of a series of crystalline metamorphic rocks and pegmatites of Precambrian age. Most gem minerals are not found in situ, but rather occur as part of heavy-mineral placer deposits in sediment gravels derived from the erosion of these underlying crystalline rocks. This particular study focuses on the geochemical behavior of beryllium and fluorine in this sedimentary weathering environment and on their role in the formation of gem deposits. Beryllium is an important constituent of beryl and chrysoberyl, while fluorine occurs in tourmaline and topaz.

Although fluorine and beryllium have a common origin in pegmatites, the results of this study demonstrate that they behave differently during the subsequent erosional cycle and are not concentrated in the same minerals in gem sediments. This study is one of the first detailed investigations of the geochemistry of the gem sediments of Sri Lanka, and points the way to a better understanding of gemstones in such environments in the earth's crust. JES

Identifying turquoise. G. Brown, *Australian Gem-mologist*, Vol. 15, No. 3, 1983, pp. 289–299.

Brown divides "turquoise" into five categories and discusses methods of identifying each. The first is natural turquoise. The second, impregnated turquoise, is subdivided into three types: Paraffin wax and thermosetting resin impregnation are both identified by use of the microscope and hot point; sodium silicate impregnation is indicated when a drop of ammoniacal silver chromate solution produces a reddish brown spot.

Stones in the third category, imitation turquoise, are identified by normal gemological properties with the exception of reconstructed turquoise; a drop of hydrochloric acid on the surface of a reconstructed turquoise leaves a yellow spot. Next, the characteristic surface patterning of synthetic turquoise is magnified to obtain an identification. Stones in the last category, naturally occurring turquoise simulants, can be identified with the usual gemological tests. GSH

New hole centers in natural quartz. D. Maschmeyer and G. Lehmann, *Physics and Chemistry of Minerals*, Vol. 10, No. 2, 1983, pp. 84–88.

Atomic-level structural defects known as color centers are responsible for the coloration of certain gem materials. Such is the case in some varieties of natural quartz. Electron paramagnetic resonance (EPR) measurements of several citrines from Madagascar have led to the

identification of five new color centers not previously recognized. In citrine, the new centers are similar to those long suspected to be the cause of color in smoky quartz. They seem to involve the oxygen atoms that are adjacent to either aluminum or other atoms that are substituting for silicon in the quartz crystal structure. Details of the nature of these individual centers are presented. JES

DIAMONDS

Cathodoluminescence of natural diamond associated with implanted impurities (in Russian). V. S. Vavilov, A. A. Gippius, V. A. Dravin, A. M. Zajcev, and B. S. Zakupbekov, *Soviet Physics of Semiconductors*, Vol. 16, No. 11, 1982, pp. 1288–1290.

This article, by a team of Soviet researchers from the Lebedev Physics Institute of Moscow, provides help in understanding the role of specific impurities in the physical constants displayed by both natural and synthetic diamond. The information provided may further be useful in developing quick techniques for distinguishing the two, should this become necessary on a commercial level.

The authors note that nitrogen in diamond has already been singled out as playing the dominant role in optical properties such as absorption and luminescence. The latter phenomenon has also been associated with traces of silicon. In their experiments the writers "doped," or implanted, relatively pure natural diamonds of the IIa type with ions of some nine metallic elements in order to observe any distinctive effects on the cathodoluminescent spectra of the stones. The depth to which bombardment by the accelerator managed to penetrate the diamonds was also studied, by etching away layers as thin as 200 Å (one fifty-thousandth of a millimeter) and checking for evidence of centers of luminescence.

Typical of the results obtained are some observations on the nature of nickel impurities introduced into the natural stones. Synthetic diamonds often display a triplet of lines in their spectra around 484 nm (at 484, 489, and 491 nm) and a single line at 510 nm; these are caused by nickel contamination from the catalyst used to help manufacture the crystals. According to the authors, these lines have never been observed in natural diamonds—but were successfully induced during the course of the experiment in those natural diamonds implanted with the nickel ion.

Similar results for other elements are discussed, demonstrating the usefulness of luminescent spectra in synthetic detection. We may also speculate that a knowledge of how to induce spectral lines previously restricted to synthetics could lead to methods of obscuring these same lines, giving gemologists yet another challenge in identification. MPR

De Beers returns to Zaire. *Indiaqua*, Vol. 35, No. 2, 1983, pp. 11–14.

This article begins with a quote from a statement issued by the chairman of De Beers on April 27, 1983, to the effect that the "Government of Zaire has recently judged it to be in the best interest to renew its old-established relationship with us." Using excerpts from six news items, this discussion goes on to argue that one factor influencing Zaire was the decision by Australia to market the majority of the diamonds from the Argyle operations through De Beers. Zaire will, undoubtedly, be better off not having to compete with these diamonds as an independent.

Production of alluvial diamonds will continue outside De Beers control. To combat smuggling, the Zaire government now allows independents to set up buying offices near alluvial areas. One such group, Harry Winston, Inc., reportedly paid \$110,000 to the government for the permit. Among the 11 photographs are examples of both the alluvial and hard-rock mining.

DMD

Guinea diamond project on schedule. *Mining Journal*, Vol. 301, No. 7740, 1983, pp. 451–452.

Diamonds—Aredor update. *Mining Journal*, Vol. 302, No. 7744, 1984, p. 36.

Mining Journal reports on the progress of the Aredor alluvial mining project in Guinea, West Africa. The Aredor plant, located at Kerouane, near the Sierra Leone border, contains a recovery facility with heavy media separation, washing, and feed sections, as well as a separator house. With treatment of the first diamond-bearing gravels expected this year, the partners of the project predict an initial output of 250,000 ct/yr. Information gained by prospecting suggests that 90% of the diamonds are gem quality, with an average stone size of 0.53 ct. If production follows the prospecting prediction, there should be sufficient gravel for 16 years of plant operation.

Sierra Leone geologists located the Guinea deposits in 1932. While these were worked by Selection Trust (the company working the alluvial deposits in Sierra Leone) and by the Soviet Union in the late 1960s, this is the first large-scale, fully mechanized mining operation. Included in the update are further details about the corporate holdings of Aredor Holdings Ltd., as well as expansion plans. The rough will be distributed through Jack Lunzer's Industrial Diamond Company. In the long term, there may be potential for hard-rock mining, since 19 kimberlite pipes are known to exist within the Aredor lease area.

DMD

Sea diamond developments. J. J. Gurney, *Indiaqua*, Vol. 36, No. 3, 1983, pp. 13–17.

In an interesting update, Gurney summarizes the developments in the sea mining of diamonds since its spec-

tacular initial success six years ago. He traces the fortunes of two companies, Theron Holdings and Trans-Hex, both active in the Atlantic Ocean off the west coast of southern Africa.

In 1978, Theron Holdings formed a subsidiary company, Dawn Diamonds, which was partly financed by an overseas consortium that included Swiss oceanographer Jacques Piccard. Dawn Diamonds obtained rights to mine diamonds from Terra-Marina, a subsidiary of Trans-Hex.

From 1979 to 1983, Dawn Diamonds produced an average of 22,000 ct annually from gravels recovered by divers using suction hoses. Some of the early profits were reinvested as the company expanded and diversified. Then, in 1981, not only did diamond prices fall, but the concentration of diamonds in gravels also dropped significantly from a high of 18 ct per cubic meter to a low of 3 ct.

Gurney emphasizes the difficulties encountered in mining at sea as he describes the financial upheavals of these two companies. He concludes with a short discussion of recent changes in the leasing program for rights to offshore mining. Since 1970, the Department of Mineral and Energy Affairs of the Republic of South Africa has issued two-year leases to the western coast area. In July of 1983, these leases were further subdivided into near shore, middle, and deep water. Gurney speculates that, with the new leases, opportunities abound, and the prospects for these two companies are promising.

DMD

Zoned garnets in porphyroblast lherzolites from the Mir kimberlite pipe (in Russian). V. P. Serenko, K. N. Nikinov, and E. E. Laz'ko, *Doklady Akademii Nauk SSSR*, Vol. 267, No. 2, 1982, pp. 438–441.

Zoned garnets in a xenolith of cataclastic peridotite from the Udachnaya kimberlite pipe in Yakutia (in Russian). E. E. Laz'ko, V. P. Serenko, and G. N. Muravickaja, *Doklady Akademii Nauk SSSR*, Vol. 268, No. 5, pp. 1204–1208.

Garnets are often found in association with diamonds in kimberlite pipes, a phenomenon exploited to great advantage by those searching for such treasures. The rich Orapa pipe of Botswana, for example, was located by De Beers geologists far below the overlying sands of the Kalahari Desert using indicators such as garnet particles carried to the surface by ants. As reported in this pair of articles, Soviet researchers investigated garnets from two of the major Russian pipes in order to gain clues not only to how diamond appears in the kimberlite, but also to the geologic processes taking place in the upper mantle of the earth itself.

The garnet samples studied were purposely taken from rocks within the kimberlite that are known to form at great depth: from lherzolites found in the Mir pipe of the Malo-Botuobinsky kimberlite field and from a cata-

clastic peridotite derived from the Udachnaya pipe of the Daldynsky field. Pyrope and almandine were the most common species encountered, with grossularite, andradite, and uvarovite also represented.

Variations in both color and chemical content according to the location of the garnets in the rock were analyzed and are compared in detailed tables and graphs. The authors interpret these results to indicate that the garnets formed by diffusion metasomatism (mineral replacement), during a drop in pressure and rise in temperature, below the layers of sedimentary rocks through which the diamond-bearing kimberlites later were injected.

MPR

INSTRUMENTS AND TECHNIQUES

Advances in the study of mineral inclusions. G. Graziani, *Neues Jahrbuch für Mineralogie Monatshefte*, No. 11, 1983, pp. 481–488.

In this article, Professor Graziani describes his ingenious and unique method of extracting the contents of fluid inclusions for analysis by Gandolfi X-ray camera and/or an electron probe microanalyzer. The method utilizes an original microtechnique called "microscopic extracting assemblage" (MEA).

The required apparatus consists of (1) an inverted microscope modified for mineralogical observation and photomicrography; (2) a dental microdrill, with a motor speed ranging from 1,500 to 30,000 r.p.m., that can be used in a vertical or horizontal position and employs a variety of small diamond tools; (3) a simplified, liquid nitrogen-based, gas flow freezing stage system to freeze the inclusions and control heat build-up during drilling (the positioning of the inverted microscope also allows the drilling tool to be cooled down during use); (4) a Leitz-type micromanipulator to control the sample during extraction; and (5) a chromel vs. alumel thermocouple-potentiometer assembly for accurate temperature measurement during the extraction process.

Using Professor Graziani's MEA technique, the microscopist can locate fluid inclusions, define the optical properties of both the inclusions and the host crystal, and extract the contents of the inclusions for analysis without having to move the specimen and while keeping it at a desired constant temperature. The MEA method is quite intriguing and should prove helpful to inclusionologists worldwide.

John I. Koivula

Analysis of gold jewellery artifacts—characterization of ancient gold solders by PIXE. G. Demortier, *Gold Bulletin*, Vol. 17, No. 1, 1984, pp. 27–38.

New, sophisticated, nondestructive analytical techniques are beginning to be used to establish the antiquity of jewelry artifacts. Two such techniques, particle-induced X-ray emission (PIXE) and particle-induced

gamma ray emission (PIGE), are discussed in this article. Both methods involve the exposure of an item to a high-energy beam of protons which gives rise to characteristic X-ray or gamma-ray emission of energy that can be detected with suitable equipment. Analysis of this energy emission can provide an indication of the chemical elements in an item, as well as their abundance. The practical application of these techniques to determine the origin of soldering and brazing compounds used in the manufacture of gold jewelry is described.

The presence of cadmium (Cd) in soldering alloys has often been interpreted as identifying an object as being of modern origin because this element has only been known since the early 1800s. However, recent PIXE analyses of several ancient, soldered gold objects found to contain small amounts of cadmium have cast some doubt on this hypothesis. The cadmium contents of these ancient alloys apparently resulted from the mixing in small quantities of the mineral greenockite, a naturally occurring cadmium sulphide, in the alloy material to lower its melting point. Thus, while the mere presence of cadmium does not establish the age of an artifact, comparison of the proportions of cadmium to other alloy elements, such as copper or silver, does provide a more reliable indicator of origin. For solder alloys in ancient jewelry, there is a mutual increase in both cadmium and copper contents, whereas for modern times an inverse correlation is observed in which the copper/silver content decreases as the cadmium content is increased. These analytical techniques offer a rapid and accurate means of determining the element composition of jewelry. As the methods are further refined with the analyses of additional objects, they will provide an important tool for examining ancient jewelry artifacts.

JES

X-ray unit for gemmological use. S. Folgueras-Dominguez, *Journal of Gemmology*, Vol. 19, No. 1, 1984, pp. 14–23.

Transparency to, and luminescence excitation by, X-rays are two advanced techniques used in gemstone identification. This article describes the operation of a simple, portable X-ray unit for documenting the relative X-ray transparency of gem materials. The degree to which a material will absorb a beam of X-rays depends on the thickness of the material and the nature of its constituent atoms. For a given thickness, there is a marked difference in relative X-ray transparency from one gem material to the next. The author illustrates this difference with a table of diamond and possible diamond simulants in which this transparency is shown to vary by a factor of 10^6 or more. The differentiation of various gem materials by this method becomes even more pronounced as the thickness of the gemstone increases because of the greater degree of X-ray absorption.

The portable unit consists of an X-ray tube mounted

in a shielded box with windows that allow for direct observation of either the X-ray transparency by means of a mirror or the X-ray fluorescence and phosphorescence of a gemstone. The brief exposure time, on the order of one second, appears to be insufficient to produce color changes in the gemstone being examined. The unit can also be used to obtain radiographs of pearls. As with all X-ray equipment, caution must be exercised during its operation. Check that the equipment is properly shielded so that the X-rays are completely contained within the unit. In addition, an approved operator's license from local health authorities would be required.

JES

JEWELRY ARTS

The art of Fabergé. B. Foran, *Robb Report*, Vol. 7, No. 12, 1983, pp. 104–113.

Just when it seems that everything that *can* be written about Fabergé has been written, along comes an article with a new perspective, offering practical information to the Fabergé enthusiast.

Since the *Robb Report* specializes in investment advice, it follows that this aspect of Fabergé collecting is emphasized. Oddly enough, the escalating prices and profit potential of these exquisitely crafted objects are often obscured by the romantic aura surrounding the legendary firm of Russian goldsmiths and its enigmatic founders. While this article does dwell on the history of Fabergé, it also provides useful information on the value of these collectibles.

Writing for a general but presumably informed audience, the author reviews the life and times of Peter Carl Fabergé, detailing the rise of the firm in St. Petersburg and recalling the glittering list of international society, royalty, and just plain rich who patronized his shops in Russia and the branches in London, Paris, and Monte Carlo from the late 19th century to the Bolshevik revolution and the fall of the Romanov dynasty. Interesting anecdotes on prominent Fabergé collectors (notably, publisher Malcolm Forbes), a short list of current and forthcoming publications on the subject, and information on permanent Fabergé exhibitions are illustrated with representative but infrequently published Fabergé objects. The *Robb Report* and author Barbara Foran have presented a fresh, readable article to wind up a year in which Fabergé became a household word and two major exhibitions of his work were held in America.

NL

Crowning glories: sumptuous jewels of dynastic Europe.

Prince Michael of Greece, *Smithsonian*, Vol. 14, No. 7, 1983, pp. 129–141.

Despite the cumbersome title, this is a splendidly illustrated article adapted from Prince Michael's *Crown Jewels of Europe*, published late last year by Harper & Row. The article traces the use and variety of royal and

imperial regalia from the time of Charlemagne to the present day. Readers will be surprised by the number of ancient crowns still surviving and the extraordinary lack of precise information about them. The crowns, orbs, scepters—"indispensable instruments of coronation"—are seldom used in the 20th century, yet they seem to have more prestige now than in former times and continue to serve as emblems of national, if not personal, sovereignty.

Prince Michael provides some surprising and curious anecdotes, but adds little new information to knowledge of the subject. Considering his relationship to two royal houses, more previously unpublished material might have been expected. His research lacks objectivity, and he has allowed some serious errors in fact that appeared in the book to carry over into the article.

The article is aimed at a wide public, and while serious jewelry historians may be disappointed, the photographs serve as some compensation. Hopefully, the book and the present adaptation will encourage more scholarly consideration of a subject which has almost unlimited potential.

NL

Enameling—I: Introduction and cutting cells for Champlevé enamelling. C. Walton, *Aurum*, No. 16, 1983, pp. 33–41.

This is an interesting, though not particularly informative, article. The subtitle, "Introduction and Cutting Cells for Champlevé Enamelling," promises more than the article delivers. The "Introduction" consists of a short professional biography of three members of a London enameling firm along with their accomplishments, a hazy definition of enamel, a brief description of each of the four basic raw enamels, and an esoteric mention of the techniques behind four of the main types of enameling.

The discussion concerning cell preparation for Champlevé enameling is only a bit more informative. Section headings would have the reader believe that there will be insights into the process, but attention is given to the difficulty of execution rather than to the process itself.

The photographic essay accompanying the article is more informative and valuable than the text. The article does, however, serve to whet the appetite, and the promise of a follow-up article leaves hope of real information to come.

Archie V. Curtis

Gold coins as jewellery through the ages. A. Oddy, *Aurum*, No. 15, 1983, pp. 10–16.

The current vogue of incorporating gold coins in jewelry undoubtedly prompted this article on the early use of gold coins for adornment. Concentrating primarily on the Roman and Byzantine periods, the author shows the influence of politics and religion on the fashion of wearing coins. Although coinage was invented in the late

seventh century B.C., it was not until the second century A.D. that the Romans first used coins in jewelry. By this time, the minting of coins had been standardized and all coins were stamped with the head or bust of the emperor. Wearing his image denoted support of the ruler, and some of the earliest examples of brooches and pendants may have been made as gifts for foreign ambassadors or citizens favored by the emperor. "Coin" jewelry also appeared in the form of bracteates, or thin sheets of gold stamped out using coins as dies. These bracteates were often grouped together to form necklaces and wreaths for the hair. In light of their fragility, Oddy suggests that bracteate jewelry may have been made specifically for funereal use.

We see the decline of the Roman Empire and the rise of the Byzantine Empire in the use of coins from various barbarian kingdoms that replaced former Roman provinces, as well as in coins from Byzantium set in garnet and gold mounts. As Christianity spread through Europe, the practice of burying goods with the dead was discontinued, so that fewer pieces of coin jewelry have survived from this period than from earlier ones. One of the survivors is a neck ring made up of coins and medallions that span the fourth to sixth centuries. The author speculates that this may have been a *maniakion*, the badge of office worn by the Byzantine imperial guard during the sixth century.

Although gold coins were minted from the fifth to the 14th centuries by the Byzantine Empire, virtually no gold was minted in the rest of Europe from the seventh until the 13th century. Coins introduced at this time were often inscribed with religious phrases and were worn as amulets to protect travelers.

Oddy then speeds us through the subsequent centuries to the present day in two paragraphs, informing us that coins in jewelry were prevalent, especially in the 19th century, due to a revival of interest in the classical age, and that examples of these can still be found in antique shops. EBM

Precious time. T. N. Murari, *Connoisseur*, Vol. 213, No. 861, 1983, pp. 106–111.

A small group of jeweled watches, "The Ermitage Collection," by Piaget of Geneva, will tour the United States in 1984. The watches resemble in style the Art Deco watches of the early 20th century. T. N. Murari, a novelist, has written more of an advertisement than an essay; nevertheless, the illustrations and some of the verbal descriptions make the article worthwhile. JG/FS

Some ancient Near Eastern seals. W. G. Lambert, *Arts of Asia*, Vol. 18, No. 6, 1983, pp. 84–86.

In part because of its imperialistic past, Great Britain is very rich in Eastern antiquities. Lambert describes an English collection of Eastern seals that is housed in the rather obscure Oriental Museum located at the Durham

University. This issue of *Arts of Asia* focuses on the various collections at this institution.

The first half of the article presents a terse history of stone seals in the Near East up to the introduction of the cylinder seal. The stamp seal, which first appeared in northern Mesopotamia around 5000 B.C., served as both art and a device for sealing. Around 3000 B.C., in the Tigris-Euphrates River plain, there appeared a different, distinct type—the cylinder seal. For the cultures of Sumer, Babylon, and Assyria, the cylinder seal achieved the status of a major art form, although its primary purpose was to serve as a means of applying a signature by rolling the cylinder over clay or some other impressionable substance. The earlier cylinder seals were made of soft stone, such as limestone, but later such materials as hematite and the variously colored quartzes were more commonly used.

The second half of the article describes six examples of individual cylinder seals in the Oriental Museum collection. Six photographs of impressions of the seals accompany an interesting text. The article concludes with a reference to a more complete discussion of the collection. FLG

Southern collections: jeweled bibelots in the Headley-Whitney Museum. N. Letson, *Southern Accents*, Vol. 6, No. 1, 1983, pp. 34–40.

Located in Lexington, Kentucky, the Headley-Whitney Museum was founded in 1968 by George W. Headley and his late wife, Barbara Whitney Headley. The museum offers changing exhibits of art, Oriental porcelains, a large collection of rare shells and fossils, and the largest contemporary collection of jeweled *bibelots* (small household curios or trinkets) in the United States. These bibelots are housed in the Jewel Room, one of the standing exhibits at the museum. Both the Jewel Room and many of the objets d'art it contains were designed by George Headley and represent his taste and discernment in the assemblage of rare and unusual treasures.

Fabricated by leading craftsmen of this century from detailed water-color designs by Headley, these curios incorporate gems and precious metals with natural materials and antiques. Branch coral, volcanic rock, petrified wood, and rhinoceros horn as well as existing sculptures, antique coins, and carved jade and ivory are some of the materials used, all of which were collected by Mr. Headley on his travels around the world.

One of the outstanding pieces described in this article is a miniature classical temple made by Bulgari of Rome. The temple, constructed of 18-karat gold, frosted rock crystal, and diamonds, is seated on a large natural crystal from Brazil.

From the author's descriptions of the Headley-Whitney, one gets the feeling that the entire museum is a jeweled ornament, fascinating and beautiful in its design and execution. EBM

SYNTHETICS AND SIMULANTS

Gilson created fire opal imitation with play of colours.

M. Gunawardene and R. Mertens, *Journal of Gem-mology*, Vol. 19, No. 1, 1984, pp. 43–53.

This article reports on the examination of a Gilson product variously described by the producer as "Mexican fire opal—type synthetic" or "synthetic honey opal." The properties of this material were determined to be as follows: (1) General appearance—distinct yellowish brown body color with a pronounced play-of-color; a predominance of reddish flashes was noted, particularly in one specimen. (2) Refractive index = 1.41 ± 0.001 , and specific gravity = 1.91 ± 0.001 . (3) There is an affinity for water (hydrophilic), but it is much less than previously reported for Gilson black opal and white opal simulants. (4) "Feel" test—feels rough to the moistened thumb (natural honey opal reportedly feels smooth). (5) Ultraviolet fluorescence—inert or distinct bluish white; those specimens that fluoresced also phosphoresced, with reactions stronger to long-wave than to short-wave radiation; further, those specimens that fluoresced also exhibited a strong, chalky bluish white thermoluminescence at 30°C to 40°C.

Microscopic examination using transmitted high-intensity fiber-optic illumination revealed a "chicken-wire" pattern. A number of additional characteristics were noted under lower-intensity lighting conditions, including the characteristic "lizard skin" or "fish-scale" effect previously noted in the Gilson black materials and white materials, as well as dendritic patterns reminiscent of those seen on moss agate. Examination at oblique angles revealed a dangling "stalactitic" color distribution; when the Gilson stone was viewed from the side, substructural boundaries to the color columns were noted.

The article is accompanied by seven photomicrographs and two drawings illustrating these structural features. RCK

An investigation of the synthetic products of Gilson showing a play of colours.

K. Schmetzer, *Journal of Gemmology*, Vol. 19, No. 1, 1984, pp. 27–41.

The recent introduction of a Gilson product resembling fire opal with play-of-color led the investigator to thoroughly examine a number of different Gilson materials marketed as synthetic opal. Five basic sample types were evaluated using X-ray powder diffraction, thermogravimetry, chemical analysis, flame ionization analysis, and mass spectrometry.

Results of these investigations showed significant differences in the chemical composition of these man-made materials as compared to natural gem-quality opal. The five basic sample types and the major differences noted are as follows: sample 1 (white body color with violet to green play-of-color)—no distinct water content, presence of crystalline ZrO_2 (supposedly producing the white body color); sample 2 (gray body color

with violet to red play-of-color)—no distinct water content; sample 3 (black body color with violet to blue play-of-color)—presence of at least one organic compound; sample 4 (black body color with violet to red play-of-color)—presence of at least one organic compound; sample 5 (yellowish brown body color with violet to red play-of-color, resembling fire opal)—no distinct water content, presence of 16% organic compounds.

The investigator concludes that, on the basis of the above examination results, all five products are more properly designated opal imitations than synthetic opal.

RCK

Large crystal sapphire optics.

F. Schmid and C. P. Khat-tak, *Laser Focus/Electro-Optics*, September 1983, pp. 147–152.

This article reports on a new crystal-growing technique known as the Heat Exchanger Method (HEMTM). The HEMTM process is the only melt process that uses a vacuum in which to grow crystals. During crystal growth, a seed is placed at the bottom of the crucible and prevented from melting by starting a flow of gaseous helium through the heat exchanger. This lowers the temperature of both the heat exchanger seat and the seed crystal resting on it. Crystal growth then takes place from the seed *outward*. This method has produced large-diameter (up to eight inches or so) synthetic colorless sapphires that are free of the light-scattering bits that generally occur in the boules grown by the Verneuil or Czochralski processes.

Scatter-free sapphire slices make very effective windows for detectors in satellites. Synthetic ruby and titanium-doped sapphire have also been grown by HEMTM for laser research. The process allows an in-situ annealing of the solidification stresses, and thus can make large-size crystals without stress-related cracking. Efforts are now under way to grow Cc:Mg and Nd:YAG crystals by HEMTM. BFE

MISCELLANEOUS

Mammoth unearthed.

D. Hemenway, *Earth Science*, Vol. 36, No. 3, 1983, pp. 16–17.

To comply with the restrictions on ivory included in the Endangered Species Act, some lapidaries have substituted fossil ivory. One form used is the tusks of woolly mammoths. Hemenway presents insight into the lifestyle of *Mammuthus primigenius*, one of the woolly mammoth species that lived in Siberia.

In terms of size, the mammoth is between the larger African elephant and the smaller Asian elephant. However, mammoth tusks are the largest of all the elephants, weighing up to 120 kg and reaching lengths of 3 to 4 m.

The author concludes this well-written article with accounts of discoveries of mammoth fossils. DMD

GEM NEWS

John I. Koivula, *Editor*

DIAMONDS

Brazil

Large diamond found in Brazil. A 260-ct yellow diamond of stated "good quality" was recently found at Coromandel (about 300 km northwest of Belo Horizonte) in Minas Gerais, Brazil, by a local garimpeiro. This area has produced many fine diamonds over the years. Perhaps this discovery will spawn a more organized and detailed exploration of the area than has been carried out in the past.

India

Diamond exploration. The Mineral Exploration Corporation and the National Mineral Development Corporation, with cooperation from the Geological Survey of India, are implementing the first phase of a nationwide diamond exploration program. The first area targeted is Andhra Pradesh. Diamonds have already been found and pilot processing plants have been constructed.

Philippines

First diamond-cutting factory in Philippines. A diamond-cutting factory has now been set up in the Philippines near Manila. The company, called Manila Gem Polishers, is jointly owned by an Israeli, Mr. Y. Goldenberg, and a Philippine, Mr. Antonio Marco. The factory is presently cutting only small (1-50 points), lower-quality goods.

Singapore

Diamond exchange. The Singapore Diamond Importers Association recently announced that its new diamond exchange will be operational by the middle of 1984. The exchange, which is already affiliated with the world federation, will have approximately 200 members and will be the first such exchange in Southeast Asia.

COLORED STONES

Activity in Pakistan. The Gemstone Corporation of Pakistan reports that three new emerald deposits have been found in Charbagh, Gujar Killi, and Makad. As a by-product of initial exploration, 11,728 ct of rough emeralds have been recovered. Opened in 1981, the aquamarine and beryl deposits in Dassu (Skardu) and the topaz deposits in Katlang (Mardan) continue to produce consistently.

Amethyst from Rhode Island. Mr. Clifford H. Stevens, a gemologist from Gansevoort, New York, reports that he has rediscovered a deposit of gem-quality amethyst

from a locality in Rhode Island that was previously thought to be exhausted. The deposit is situated along the shores of Narragansett Bay near the Bristol-Mount Hope Bridge area. Mr. Stevens has found gem crystals as large as 100 ct.

Exploration in Zambia. The International Development and Construction Company of Saudi Arabia and the Reserved Minerals Corporation have reportedly joined forces to recruit qualified mining personnel to prospect for and mine emeralds and other precious minerals in Zambia.

New mining policy in Tanzania. The Tanzanian government is preparing a new mining policy that will affect small mining operations. The new policy will allow individuals, groups or even entire villages to prospect for and mine diamonds, colored stones, gold, and other minerals on a small scale with minimal government interference.

New source for beryllium. Highwood Resources Ltd. has encountered significant concentrations of beryllium during drilling operations at their Thor Lake property, North West Territories, Canada. Values as high as 2.38% beryllium oxide have been reported, and plans now exist to perform a feasibility study on the prospect. Although the beryllium found at this locality has not been in association with gem materials, whenever beryllium is found in a mining area the potential for beryllium-containing gem crystals exists. Such localities are always exciting sites for gemological prospecting.

New York chrysoberyl. Mr. Clifford Stevens also reports of reworking an old Dana locality for chrysoberyl in his home state of New York near Greenfield. In *Gemstones of North America* (Sinkankas, 1976), this locality is listed as being located "immediately west of a small pond just north of the township road which crosses Highway 9 leading north from Saratoga. The pond is about one-half mile west of the intersection of the township road with Highway 9."

Many small crystals (up to 1.5 cm) displaying the typical wedge-shaped twin habit have been found. They are greenish yellow and mostly translucent.

Recent finds in Yugoslavia. Gemologically interesting deposits of the silica gems opal, chalcedony, and jasper have been discovered in Serbia, Yugoslavia, on the

slopes of Mount Rudnik. Whether or not mining of these deposits will be economically feasible remains to be seen.

PRECIOUS METALS

Canadian gold. The Canadian gold producer, Lac Minerals, has reported that recent drilling activity on its Williams gold property at Hemlo, in Ontario, has upgraded the previous estimate of reserves for the property from 10.0 million tons at 5.8 g (0.18 oz.) of gold per ton of ore to 13.9 million tons at 5.9 g of gold per ton. This is in addition to 3.5 million tons of near-surface ore with gold values grading at 6.2 g (0.19 oz.) per ton. The Hemlo area promises to be one of the most important sources of gold in the world. Production at Hemlo could begin in 1984.

Gold in Quebec. A strata-bound gold-bearing zone has been found by Camflo Mines about 65 km north of Kirkland Lake, Quebec, Canada, on its property in the

Holloway and Harker townships. Initial drilling has begun on the property to determine the extent of the mineralized structure and to test any extensions of the main zone. Preliminary testing of the area is scheduled to be completed in 1984.

OK gold. Production at the giant OK gold mine located in Papua, New Guinea, may begin sometime this year. However, some serious problems with mud slides will increase the recovery costs for the gold.

Reid mine. Exploratory drilling at Terramar Resource Corporation's Reid mine in northern California has revealed gold values as high as 46.9 g (1.50 oz.) per ton. A section extending vertically from 7 m to 43 m showed a weighted average of 21.6 g (0.69 oz.) per ton of ore and 50.4 g (1.62 oz.) per ton of silver. Another section, extending from 57 m to 59 m, showed 12.3 g of gold and silver values of 19.9 g per ton.

ANNOUNCEMENTS

Winner of the 1984 George A. Schuetz Memorial Fund Design Contest is Mr. Sekikazu G. Nakakura, of Okayama-City, Japan, for his original design of a 14K white-gold and yellow-gold man's bracelet (figure 1). Other winners in the design competition were Mrs. Shizuyo Hara, of Tokyo, Japan, in second place, and Ms. Catherine D. Villeneuve, of Montreal, Quebec, Canada, in third place.

The Schuetz contest, held annually, awards scholarships in the amounts of \$500 for first place, \$300 for second place, and \$200 for third place for training in a jewelry-related subject at any institution of the winner's choice. Only original designs of men's jewelry are eligible for entry in the competition. The 1985 Schuetz contest will be open in October of this year. Contest rules and applica-

tions will be available at that time from the Scholarship Office, Gemological Institute of America, 1660 Stewart St., Santa Monica, CA 90404.

The Geo-Literary Society was formed at Tucson in February of this year. Mrs. Alexandra Filer, of Filer's Minerals, has been elected the first president. The Geo-Literary Society has an initial goal of bringing together those who are interested in the literary arts related to minerals, gems, and fossils. The sharing of sources and the exchange of information about books, maps, drawings, and related printed matter on the subject of the natural substances of the earth is of prime concern to the group. For further information, contact: Filer's Minerals, Box 487, Yucaipa, CA 92399; or Herb Obodda,

P.O. Box 51, Short Hills, NJ 07078; or Elna Hauck, 8 Rowe Pl., Bloomfield, NJ 07003.

The International Exhibition of Jewelry, Gold, Silverware, Clocks, and Gifts ("BIJORHCA") will be held September 7-12, at Parc des Expositions, Porte de Versailles, Paris. Further information and entrance cards are available from: Pierre Wagner and Caline Thomas, International Trade Exhibitions in France, Inc., 8 West 40th St., New York, NY 10018; (212) 869-1720.

You are cordially invited to attend GIA GemFest '84, a program of seminars specifically designed to increase your jewelry sales ability and gem knowledge, to be held August 21 and 22 at GIA Santa Monica. Please call GemFest at (213) 829-2991 for further information.

Figure 1. Schuetz award-winning bracelet design by Sekikazu G. Nakakura.



THE PHYSICS AND CHEMISTRY OF COLOR

By Kurt Nassau, 454 pp., illus., publ. by John Wiley & Sons, New York, 1983. US\$43.95*

As the title suggests, this book delves into the fundamental processes that produce or alter the patterns of visible radiation that are perceived as color. The author, a research scientist at Bell Laboratories, has added *The Fifteen Causes of Color* as a subtitle to his book. When he lists these 15 causes in the first chapter, he mentions that this number is somewhat arbitrary and that fewer, more general, groupings would probably be sufficient to cover the physical origins of color. No matter how the topics are divided, however, this reviewer has seen no other book with as comprehensive a survey of the basic processes behind color as this one. It fills a long-standing gap in the scientific literature. Dr. Nassau has effectively collected in one volume a mass of information that was previously scattered in a broad assortment of books and journal articles, some of which he had authored.

Following the introduction (which provides definitions of color, the spectrum, chromaticity, color-mixing schemes, color perception, models of light behavior, and energy considerations), the next five sections examine the 15 causes of color. Each section deals with a broad group of color origins and relates them to a particular model or physical theory. Almost all involve, in one way or another, the interaction of light and electrons.

Various gemstones are cited as examples in all but one of these five sections. Although most of these examples have appeared in articles published previously by Dr. Nassau, he does include an interesting interpretation of the padparadscha color in the section involving ligand field effects. Ruby, emerald, and alexandrite form a significant part of the

*This book is available for purchase at the GIA Bookstore, 1660 Stewart Street, Santa Monica, CA 90404.

BOOK REVIEWS

Michael Ross, Editor

discussion in that same section. (It is interesting to note, however, that when Nassau explains charge-transfer colors in part 4, he attributes the color of tanzanite to an iron-titanium combination like the one in blue sapphire. Other researchers have identified vanadium as the coloring agent of tanzanite.) In the section on band theory and color collectors, Nassau discusses color in diamonds and metals, and devotes some attention to the influence of radiation and heat on certain gem colors. Part 6 deals with the scattering phenomena seen in asteriated and cat's-eye stones, as well as with the interference and diffraction effects seen in feldspars and opal.

The last section of the main text, titled "Color-Related Topics," covers such fascinating subjects as vision, paint deterioration, color changes in food, lasers, and holography. It also provides a summary of gemstone coloration. These discussions help tie together the ideas presented in the preceding sections and also flesh out the general concepts with additional examples. However, in the summary on gem colors, Nassau neglects to specify whether or not the yellow and green sapphires colored by nickel are synthetics; the colors of the natural varieties are attributed to iron. At the end of each chapter there are problems and questions for the reader who enjoys a challenge. With this feature, the book could readily be used as the text for a college-level course.

Although the author has placed some of the difficult and more technical details in the appendices, the main body of the text remains a fairly advanced treatment. One of the appendices is an extensive reading list

that accommodates many different interests.

Numerous line drawings, diagrams, graphs, and assorted tables appear throughout the book. Eight pages with 31 color photos are sandwiched in the middle of the text and provide some beautiful illustrations. There are also 11 black-and-white photos scattered throughout. The greatest value of the book, however, is the amount of information presented and the skill with which it has been organized. It is a worthwhile investment for the serious student of this complex but fascinating subject.

BOB EFFLER
Course Development, GIA

CASTELLANI AND GIULIANO: REVIVALIST JEWELLERS OF THE 19TH CENTURY

By Geoffrey C. Munn, foreword by A. K. Snowman, 208 pp., illus., publ. by Rizzoli International Publications, New York, 1984 (French language edition publ. by Office du Livre, Fribourg, Switzerland, 1983). US\$60.00*

Rarely has so authoritative and well written a monograph been published in the field of jewelry arts, or has so handsome a tribute been paid to its subjects. This is the first definitive study of the two Italian artist-jewelers whose work represents the essence of 19th-century eclecticism and who founded the movement called "Archaeological Jewelry," inspired by discoveries in Greece, Italy, Russia, and Egypt.

Fortunato Pio Castellani (1793-1865) opened a shop in Rome in 1814, and began making reproductions of Greek and Etruscan jewelry with a quality of granular and filigree work unknown since antiquity. The accuracy of these reproductions, achieved by craftsmen Castellani discovered who were still using ancient techniques, gained him an international reputation. After his death, the work was carried on by a son, Augusto (1829-1914), whose style and technique were so similar to his father's that, with few

exceptions, his pieces are difficult to date. Augusto Castellani later became director of the Capitoline Museum in Rome, and much of his collection remains there today. An elder brother, Alessandro (1824-1883), was also a collector and dealer in antique jewelry, and did much to promote the firm at the major exhibitions of art and industry held in Europe and America after 1851. Much of the antique jewelry in the British Museum was acquired through Alessandro, and many of the pieces served as models for the firm's production.

The London and Paris branches, opened in the 1860s, gained an independent reputation under manager Carlo Giuliano (c. 1831-1895) and his son, Arthur (c. 1864-1914). Carlo Giuliano's work differs from other jewelry in its refinement and superior execution. Although Giuliano also worked in the Greek and Etruscan styles, he developed a manner distinct from Castellani, and created jewelry unlike any other made before. His knowledge of antique and Renaissance jewels is obvious, but his own pieces are not simply essays in archaeological reconstruction. While the Castellanis applied their superb craftsmanship and unerring taste to reproductions expressing the style of their time and the values of archaeological scholarship, Giuliano's pieces are more imaginative and no less finely made. His attitude toward the past was that of an artist rather than a scholar. His later works, made in the light, elegant forms of the turn of the century, are distinctive and express understanding and sympathy with the jewelry of Egypt, of the 16th century, the Orient, and Art Nouveau, but do not reflect transiently fashionable tastes; it is the stature of his own personality as an artist-jeweler that is most apparent.

Geoffrey Munn (himself a jeweler and a director of the London firm of Wartski, Ltd.) has skillfully drawn a vivid and fascinating portrait of the personalities and firms of Castellani and Giuliano, placing each in its correct historical setting, tracing the

sources of design inspiration and the development of technical virtuosity. He has so successfully presented their full characters as goldsmiths, antiquarians, art dealers, and liberal political thinkers that we have not only the men and their manners—their art expressed in the 200 sumptuous, and for the most part previously unpublished, photographs—but also their private thoughts, their attitudes toward patrons and clients, and their methods of salesmanship.

The technical chapters of the book are as compelling as the art-historical ones, with classical metallurgy, enamel, mosaics, and electrotypes receiving literate and perceptive consideration. The important matter of marks (genuine and spurious) is given attention, and the author has been meticulous in his presentation of extensive notes, a glossary, and a comprehensive bibliography listing both exhibitions and sales where Castellani and Giuliano pieces figured prominently.

This book has clearly been a labor of love on Mr. Munn's part, and his publishers have supported him wholeheartedly by turning out what must be regarded as the major contribution to jewelry history to appear so far in this decade.

NEIL LETSON
Anniston, Alabama

THE EMERALD

By I. A. Mumme, 135 pp., illus., publ. by Mumme Publishing, Australia, 1982. US\$21.00*

The title page of this book reads, "*The Emerald: Its Occurrence, Discrimination, and Valuation*, by I. A. Mumme B.Sc. Hons. (Mineralogy and Petrology), M.Eng.Sc., A.M. Aust. Imm., etc. Formerly Chairman of the Federal Board of Studies in Education of the Gemmological Association of Australia and Convener for Education of the Geological Society of Australia (New South Wales Branch). Member of the Scientific Education Panel of the Lapidary Club of New South Wales." At the bottom of the page, it reads: "Mumme Publications." The book is evidently pub-

lished by Mr. Mumme himself, and it obviously involves his own lengthy studies of the various emerald-producing areas of the world. Unfortunately, while the book contains much interesting and valuable information, the facts are uneven and the absolutely unbelievable proof-reading leaves one aghast. The book begins with, "Emerald is a gem-quality member of the Beryl family. It is one of the gem Kingdom's truly precious stones, the others being diamond and ruby." In these fascinating sentences, *beryl* and *kingdom* are capitalized, but no other words. One also does not expect to see words such as "distained," "stupidly," or "posponed" throughout a professional publication. Every editor (or author) misses a couple in the course of a book or article, but not in virtually every chapter and on almost every page.

One can get carried away with what are really rather minor criticisms, in a sense, but errors such as those cited above are annoying and distracting. The many good summaries in this book, and its usefulness as a compilation of information from all over the world are weakened by sentences like the one that appears on page 62: "According to Julius Petch, Jr., the Ida Oberstein expert, the source could be nearly as important a supply as Brazil." The name is Petsch, the city is Idar-Oberstein, and the result is irritating.

At the end of the book, Mumme discusses the separation of natural from synthetic emerald, and presents some material which suggests that he has never done it himself and that he does not really understand gem identification. For example, his reference to a test for opacity, using a photographic method, is backwards. One wonders, when much of this material is available elsewhere, just what the purpose of this book is, and whether it should not have been submitted to a number of outsiders for comment, criticism, and proof-reading before it was put into such flawed print.

RICHARD T. LIDDICOAT, JR.