

EIGHTEENTH ANNUAL SINKANKAS SYMPOSIUM

Alexandrite and Other Color-Change Gemstones





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EIGHTEENTH ANNUAL SINKANKAS SYMPOSIUM

Alexandrite and Other Color-Change Gemstones

April 25 through June 6, 2022

Dedication

This symposium and proceedings are dedicated to John Sinkankas for his lifetime of contributions to the lapidary arts, gemology, mineralogy, and crystallography. His numerous articles and books are still used as sources of information on the earth sciences. The Sinkankas Collection, housed at GIA's Richard T. Liddicoat Library and Information Center in Carlsbad, contains 49,000 volumes.

Roger L. Merk (1948–2015) was the original organizer of the Sinkankas Symposium. We are grateful for his leadership, generosity, and passion over the years.

Acknowledgments

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Very special thanks to all speakers and authors for sharing their knowledge of alexandrite and other color-change gemstones.



Front cover



Back cover

Above: The alexandrite crystal measures 32.35 mm. It is from the Malysheva mine, Russia. The oval cabochon-cut cat's-eye alexandrite weighs 6.74 ct and is from the Hematita mine, Minas Gerais, Brazil. The front cover shows the gems in daylight-equivalent (blue green) and the back cover in incandescent light (magenta to red). Courtesy of William Larson. Photo by Robert Weldon.

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Evan Caplan began his journey with gems in the 1980s when a friend who was in the business of colored stones needed help for a few days. This was Evan's introduction to the unique and beautiful world of rare stones, and he soon developed a serious interest in them. He later studied at GIA, earning a Graduate Gemologist diploma.

A noted jazz musician by profession, Evan originally studied at Berklee College of Music in Boston. He discovered that the sensitivity and artistry needed for appreciating contemporary jazz allowed him to easily adapt into his new world of rare and exotic stones.

Evan travels the world, and over the years has developed business relationships in Myanmar, Thailand, Brazil, Kenya, Tanzania, Sri Lanka, India, and many other sources of stones. He was among the first to bring the unique Paraíba tourmaline to the United States, for example. He later was involved in the cutting and sale of the world's largest *padparadscha* sapphire. In tandem with the growth of his reputation, collectors and major museum curators have come to eagerly visit his small office in Los Angeles. Collectors trust his instinct and his appreciation for beauty, nicknaming him "The Eye." They often visit him first to find what new surprises he has waiting, and they are never disappointed.

For Evan, alexandrite remains one of the world's most interesting gems. At the pinnacle of his long career, he is an authority on alexandrite and lectures on this and other gemstones.

Evan has recently been spending more time in Africa, sourcing gems and minerals for his business. He is involved in mining and spends even more time traveling to the African continent. He also spends a lot of time working to improve the lives of the East African people.

Evan is currently on the board of directors of both the American Gem Trade Association (AGTA) and the International Colored Stone Association (ICA). He has recently been named one of the two secretaries to the ICA. Many of the treasures he has sourced reside in museums and private collections around the world.



William Larson became interested in gems and minerals at a very early age when he combed the hills of San Diego County with his father and Josephine Scripps and John Sinkankas in search of fine crystals. He earned an advanced degree in geological engineering from the Colorado School of Mines.

In 1968, Bill and then-partner Ed Swoboda purchased three gem mines in the Pala mining district—the Tourmaline Queen, Stewart Lithia, and Pala Chief, whose histories date to the 1800s. Bill stepped onto the international stage in 1972 when an extraordinary strike established his company and the Pala mining district as one of the world's premier sources of tourmaline.

As president of Pala International Inc., Bill heads one of the industry's leaders among gemstone import, lapidary, and mining operations internationally. In a joint venture with his wife, Bill and Jeanne Larson own The Collector, a retail shop located in Fallbrook that showcases fine colored stones, jewelry, and *objets d'art*. Today, Bill travels the world as a guest lecturer, media spokesperson, and authority on minerals and gems, the mining industry, and colored stone pricing.



Dr. Çiğdem Lüle is a mineralogist and award-winning gemologist. She is the founder of Kybele LLC, a consulting firm based near Chicago. Çiğdem's scientific background and gem trade and market experience in Turkey, the United Kingdom, and the United States form the basis for the broad

range of services provided to clients. Çiğdem is considered one of the pioneers in archaeogemological research, with an emphasis on origin investigation. She lectures on various aspects of gemology, archaeogemology and mineralogy worldwide. She specializes in mineral and gem appraisal services as an independent appraiser. Her consultation services also include developing tailored education for the gem professionals, appraisers, gemologists, and gemology students. She is a contributing editor to the *GemGuide* and the technical advisor to the World of Color communication system. Çiğdem is also a consultant to the ColorCodex color referencing system developed by ColorCodex LLC in New York. In 2016, she was awarded the prestigious Antonio C. Bonanno Excellence in Gemology Award. She is also the proud recipient of the Catriona McInnes Medal of 2019.



Dr. Sally Eaton-Magaña has been at GIA for 16 years examining aspects of natural diamond color, diamond physics, and identification of treated and laboratory-grown diamonds. She began studying diamonds for her master's degree in engineering and performed her PhD work with Dr. John

Angus, one of the pioneers of diamond growth through chemical vapor deposition (CVD). She was intrigued by the alchemical aspects of the CVD process, which creates diamonds from methane gas, and thus she initially focused on engineering applications of diamonds. Her research efforts shifted during a collaboration with the Smithsonian National Museum of Natural History, which was studying phosphorescence properties of its blue diamonds, including the Hope diamond. She jumped at that exciting chance, which was her first foray into gem diamonds and naturally led her to GIA.



Niveet Nagpal has a deep history in the gem and jewelry industry dating back five generations. Attending his first gem show at six years old, Niveet discovered a great passion for the loose gemstone business from his parents, Omi and Preeti, who established Los Angeles-based Omi Gems in 1985. After earning a business degree from

the University of Southern California and a G.G. from GIA in 1997, Niveet joined his father at Omi Gems.

With an extraordinary love and appreciation for gemstones coupled with the company's accomplished reputation for sourcing the world's most valuable jewels, Niveet launched the award-winning Omi Privé jewelry collection in 2012. Today as president and head designer for Omi Privé fine jewelry, Niveet takes pride in providing the finest colored gemstones and jewelry to industry enthusiasts. This passion and focus on quality has garnered Omi Privé more than 40 design awards, including 18 AGTA Spectrum awards.

Niveet is deeply committed to the education and integrity of the industry and has contributed his business knowledge to many trade publications and events. Niveet has served on several trade organization boards, including the American Gem Society, American Gem Trade Association (AGTA), Women's Jewelry Association (WJA), JCK Luxury advisory committee, and Gem Legacy Leadership Council. Niveet is a past president of the 24K Club of Southern California. He volunteers as a career coach at GIA and is a participant in the GIA Leadership Program at the Harvard Business School.



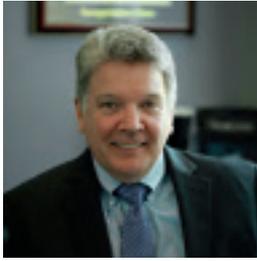
Dr. Aaron Palke developed an early interest in minerals and gemstones searching for agates and other minerals in eastern Montana. He was particularly struck by the geographic distribution of mineral and gem deposits and geological features—for instance, why were there mountains and an abundance

of mineral deposits in Montana but not in his home state of Oklahoma? These questions led Aaron to pursue a formal education in geology, obtaining a bachelor's degree from the University of Tulsa and a Ph.D. from Stanford University. Aaron began his geological career as a postdoctoral research associate at GIA, where he is now the senior manager of colored stone research. In this role, Aaron leads GIA's research efforts into geographic origin determination for rubies, sapphires, emeralds, and other colored stones as well as improving criteria for identifying treatments in colored stones. Aaron is a regular contributor to *Gems & Gemology* and serves on the journal's editorial review board.



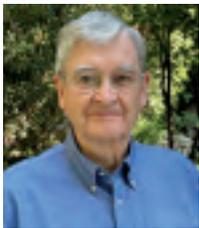
Nathan Renfro developed an interest in minerals during his teenage years in western North Carolina. He explored the rich geology of his home state, with particular interest in the pegmatite bodies of Mitchell County, searching for minerals such as beryl, kyanite, garnet, magnetite, feldspar, and mica.

In 2006, Nathan obtained a bachelor's degree in geology and education from Appalachian State University, where he was a recipient of the Outstanding Senior Teaching Geology Major award. In 2007, he received the William Goldberg Diamond Corporation scholarship and enrolled at GIA. As manager of identification (colored stones) at the GIA laboratory in Carlsbad, he has authored or coauthored several articles and served as a member of *Gems & Gemology's* editorial review board. Nathan is also a lapidary and designer, with a focus on contemporary cutting techniques, freeform shapes, and improving the optical performance of traditional cutting styles.



Stuart Robertson is an award-winning gemologist and appraiser. He is vice president of Gemworld International, Inc., and serves as research director for the company's *GemGuide* publication. Stuart is a senior member of the National Association of

Jewelry Appraisers and was appointed conference program content advisor to NAJA in 2020. He is also a former president of the Accredited Gemologists Association. Stuart is a 2011 recipient of the prestigious Antonio C. Bonanno Award for Excellence in Gemology. He received the AIJV Valuer of the Year Award in 2014 and the Scottish Gemmological Association's Catriona Orr McInnes Award in 2019.



Dr. George Rossman is Professor of Mineralogy in the Division of Geological and Planetary Sciences at the California Institute of Technology in Pasadena. His principal research interests deal with the use of spectroscopic probes to study minerals. His work addresses the origin of color in

minerals, methods for micro-phase identification, the long-term effects from the exposure of minerals to background levels of natural radiation, and X-ray amorphous minerals, including biominerals and weathering products. An important application of his studies concerns the role of low concentrations of water and hydroxide in nominally anhydrous solids.

He and his students develop analytical methods for OH analysis and examine the mode of incorporation of hydrous components in solids and their role in modifying physical and chemical properties. George was the recipient of the Mineralogical Society of America's inaugural Dana Medal in 2001, the Richard P. Feynman Prize for Excellence in Teaching at Caltech in 2004, and the Friedrich-Becke Medal of the Austrian Mineralogical Society in 2005. Rossmanite, a species of the tourmaline family, is named after him.

George joined the Caltech faculty in 1971. He received a B.S. in chemistry and mathematics from Wisconsin State University, Eau Claire, where he graduated summa cum laude. He holds a Ph.D. in chemistry from Caltech. George has authored or coauthored more than 320 publications in the mineralogical and chemical sciences.



Robert Weldon is director of GIA's Richard T. Liddicoat Library in Carlsbad, California, leading a team of librarians and subject matter experts. He is positioning the library to not only be a critical archive for researchers and students, but also a significant content producer for the Institute.

He pursues writing assignments at gem localities and often leads gem photography projects in those global locations. Robert has visited gem sites in Myanmar, India, East Africa and southern Africa, Colombia, Bolivia, Brazil, Russia, and other sources. He speaks Spanish and German fluently and is a well-known public speaker on gemological subjects. Robert is the recipient of the 2020 Antonio Bonanno Award for Excellence in Gemology. He has reported extensively on gemological issues for over three decades. He was a senior editor at *JCK*, and later *Professional Jeweler* magazines before returning to GIA in 2006.

Robert's photography is published in international gemological, jewelry, and consumer publications and in several books, including *Splendour & Science of Pearls*, which he co-authored and edited. *A Rough Guide for Artisanal Miners* is an educational booklet which he has also lectured on and delivered to artisanal miners in Tanzania and other East African countries. His photographs have appeared on more than 30 covers of GIA's scholarly publication, *Gems & Gemology*, where he has published a number of peer-reviewed articles on subjects such as the Museum of London's Cheapside Hoard, Botswana's diamond industry, the Chivor emerald mine, the gemstones of the Taj Mahal and the Mughals, and the extraordinary carvings from the Dreher family.



Wim Vertriest graduated from the Catholic University of Leuven (KULeuven) in Belgium. He obtained a masters in geology in 2014, specializing in geodynamics and geofluids and also gained his FGA and GG diplomas. Since joining GIA in 2015 at the Thailand laboratory, Wim has participated in GIA field expeditions on different

continents focusing on ruby, sapphire, and emerald mining areas. During these expeditions, samples are collected for GIA's research and the local situation is documented. He has authored articles on new gemstone localities, updates on existing mining localities, in-depth gemological studies, and treatment experiments. In his managerial role, Wim oversees the field gemology department and is in charge of GIA's colored stone research collection in Bangkok.



Above: Russian alexandrite crystal on fluorite. The alexandrite crystal approximately 15 mm x 8.5 mm. Courtesy of William Larson. Photos by Robert Weldon.



Alexandrite, Pricing Factors, and the Future Market

Evan Caplan

When I got out of the music business and into the gem business, the transition was not that difficult, because both types of clients enjoy beauty. I had never really thought about alexandrites, though, because the only ones I had ever seen were just not beautiful.

A friend of mine in the trade once said to me, “Look at this incredible stone! It changes color!” But what I saw was brown and had no color change that I could see. For me, brown was the kiss of death. So, I didn’t think about alexandrite again for many years, until I saw one at a major show in Hong Kong that just knocked my socks off. The intensity and vibration of this Brazilian gem—blue-green to purplish red—was absolutely incredible. Beyond the moon! Even today, when I think about that moment, it puts a smile on my face.

What to Look For

Alexandrites—the good ones—are special because of that color-change effect. And it is one of the rarest gems in the world. But even knowing that, I tend to look for perfection and my suppliers know it. Here is what I look for in an alexandrite:

- I look for complete and dramatic change of color. If I have to “imagine” the color change, the gem is not for me.
- I want loupe clean—that is, no visible inclusions and no distractions. Clean stones supercharge the rarity factor because most alexandrites are included (some heavily).
- I want the cut to be perfect. Not too deep or too shallow, and completely avoiding windows that just ruin a stone for me.
- I look for “magic” numbers in the sizes. Prices tend to leap dramatically at 2 ct, 5 ct, 10 ct. Anything over 10 ct is just astronomical.

- Cat’s-eye alexandrites need to have great color change and an eye that is sharp as a razor blade and doesn’t waver or wobble. The eye should extend from one girdle edge to the other.

Here is the problem with perfect stones: I don’t want to sell them. But obviously I want to stay in business. Ultimately, it is easy to sell a beautiful color-change gem because the “wow factor” is so dramatic, even with customers who may not be too familiar with alexandrites. Again, let’s not forget that these are truly rare! I have focused the color-change side of my business on alexandrites particularly, and not so much other color-change gemstones, though on occasion I will sell a color-change garnet from Africa or Madagascar. Those can be very, very beautiful also. Rarely, I have sold some sapphires that show color change (blue to purple) and spinel maybe only once or twice.

Sources

Regarding origin, the number one alexandrite source requested is generally Russia. However, they are often included and not always cut very well. In many instances the color change is not as dramatic, either—though they occasionally can be. Sri Lankan alexandrites tend to be asked for next. My problem with those is that they’re often brownish in color. My preference, and that of my customers, is Brazilian. I just love the vibrancy and intensity of the gems, particularly from the Hematita mine. In terms of Indian alexandrite, maybe three out of 100 will look like Brazilian stones, so that increases the rarity factor quite a bit. Though very rare, Tunduru (Tanzania) alexandrites can be extraordinary. I once owned a cat’s-eye alexandrite from Tunduru. I have never seen anything like that gem.

Facing page: 87.35 x 59.80 x 21.55 mm. Alexandrite crystal from the Hematita mine in Minas Gerais, Brazil, shown in both daylight and incandescent light, exhibits distinct color change. The oval cut alexandrite from the same source weighs 3.69 ct. Courtesy of Evan Caplan. Photo by Robert Weldon/GIA.



Above: Daylight and incandescent. This 3.49 ct Russian alexandrite is highly desirable because it is the classic source, though other sources consistently produce material that's less included and exhibits stronger color change. Courtesy of Evan Caplan. Photos by Robert Weldon.

The Alexandrite Suite and Other Important Gemstones

Over the years, based on my criteria, I began to assemble quite a collection of really nice alexandrites—matching—and all of them from Brazil. The largest of those was a 12-ct-plus gem. These were all in different papers, and I took them all out and began to play with them, arranging them by size, matching colors, etc. Next thing you know, I had assembled a 12-stone suite that included a necklace with a big center stone (the 12 ct centerpiece), matching earrings, and a ring stone. I showed it privately to many of my clients, but the value at the time was well over \$1 million, and I had to sell it. It wouldn't sell as a collection. At the time I was in a situation where one of my clients was begging me for the 12 ct gem, and even though it broke my heart, eventually it all had to be sold that way, piece by piece. I do dream about what an incredible suite that was, and it how it would have been extraordinary to keep them all together.

I have been able to sell many important gems to American museums. A 17-ct-plus gemstone went to the Smithsonian in Washington D.C., and just after that I was able to purchase a beautiful piece of rough that was 26 carats or so, and I believe those are now being exhibited together at the Smithsonian. Others went the Houston Museum of Natural Science. Perhaps the most important stone I've ever sold went to a royal family member in the Middle East. It was a 24 ct gem that required my personal travel there and waiting around in a hotel on the beach to make sure it was sold. I will say this: More than any other gemstone, alexandrite has taken me all around the world, and I've had the privilege of meeting some of the nicest people.

The Future

The future of alexandrites and other color-change gems is strapped and difficult for now, because not that much is being produced. The shortages are not just in color change—really all gemstones and all materials are suffering supply chain issues. Russia is at war in Ukraine, the Hematita mine in Brazil is closed, and the economic crisis in Sri Lanka has really brought production to a standstill.

Nonetheless, I remain optimistic. This is how our business is. There are production highs (even to the point that prices for a material may drop) and there are lows, which is what we are living in today. But I've been in the gemstone business long enough to understand that things are always changing: There are new sources we may not know about, existing sources may start producing again, and everything will look better once more.



Above: Sri Lankan alexandrites sometimes favor brownish colors, but this rare strong color-change alexandrite over 20 carats hails from Sri Lanka. Courtesy of Evan Caplan. Photo by Robert Weldon.



Above: Daylight and incandescent. A suite of fine Brazilian alexandrite exhibiting the finest color change seen in this material. The center stone is over 12 carats. The collection, which was too expensive to sell as a suite, eventually had to be broken up and sold individually. Courtesy of Evan Caplan. Photos by Robert Weldon.



Collecting Color-Change Minerals and Gemstones from World Localities

William Larson

My love of collecting began at a very young age when I was growing up in San Diego County. In fact, I went to the benitoite mine with John Sinkankas when I was just 14 years old. One doesn't start out collecting alexandrite. During my teens, I would see alexandrite displayed locally by another renowned figure, Dr. Peter Bancroft. They weren't all necessarily beautiful—to see a color change, you would need quite a bit of Photoshop.

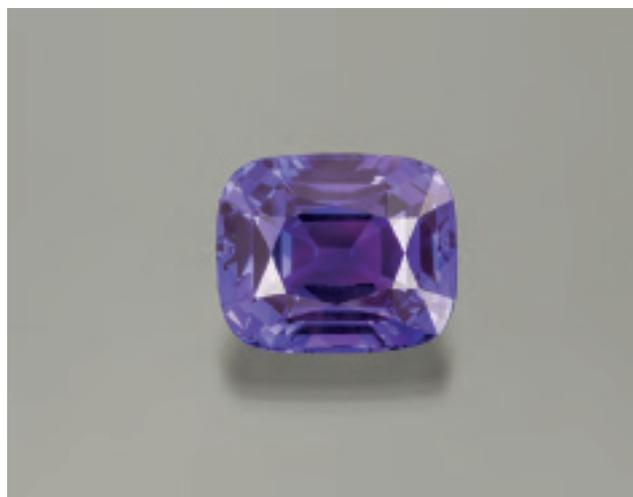
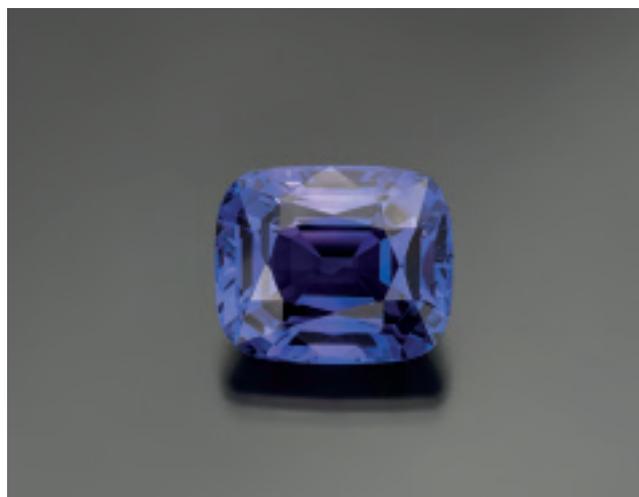
The mineral chrysoberyl is beryllium aluminum oxide. It's hard—the third hardest on the Mohs scale at 8.5. Only diamond and corundum are harder. One extraordinary chrysoberyl crystal from Brazil, a cyclic twinned crystal, was given to me by Dr. Edward Gübelin. But it's not alexandrite, because it doesn't contain the traces of chromium or vanadium needed for the color change.

As a young collector, I was fortunate to see small alexandrite crystals from what was then Rhodesia. My friend Jerry Rousseau and I used to go to the Girdlestone claims. Once a year we would drive up from Johannesburg and buy a shoebox of small alexandrite crystals. They were cyclic

twins and showed decent color change. The problem with Zimbabwean alexandrites, which come from a schist, is that they are full of inclusions and cracks. There is just no cutting in them whatsoever.

As a more advanced collector, I turned my eye elsewhere. Tanzania is another African source of alexandrite crystals. Moving across continents, Brazil is a major producer. The first beautiful crystals came from Bahia. Like the Zimbabwean material, they are too included for gem quality, but they do have lovely morphology. As we'll see, later Brazilian sources would yield some of the finest cut alexandrite ever seen.

I love Russian alexandrite, and over the years I've sold many of them. Usually I found them at the Munich or Sainte-Marie-aux-Mines shows. Many of these crystal specimens came from Malysheva and displayed beautiful morphology with a remarkable color change. The cyclic twin on the cover of this Sinkankas Symposium proceedings volume is my holy grail. I first saw it in the private collection of a major Czech dealer, not for sale, and chased it for more than a decade. I had to sell a lot of other things to acquire it.



Above: 76.61 ct color-change sapphire from Sri Lanka. Photos by Mia Dixon. **Facing page:** Color-change sapphire crystal 43 x 22 mm from Mogok, Myanmar. All stones courtesy of William Larson. Photo by Robert Weldon.

But when you're dealing with alexandrite, you have to become interested in the cut material, which does show a dramatic change of color. The effect is much easier to see in a clean faceted stone. I purchased a number of rough alexandrines in the Ural Mountains and had them cut locally. Sri Lanka has produced alexandrite almost as long as Russia, and the cut stones are famous. They tend to be somewhat brownish. India is also a notable producer, and some of them are quite good.

In the 1970s and 1980s, Brazil took over as the leading producer of fine gem-quality alexandrite. These came from two localities: Malacacheta and Hematita, both in the state of Minas Gerais. Both localities yield large, clean alexandrite, typically with a bluish green and a cherry pink red. These are very rare.

But the rarest of rare is cat's-eye alexandrite. One of the most amazing stones I ever encountered was a 6.74 ct Brazilian cat's-eye, purchased years ago in Tucson. The color change is ridiculously good, and the stone happens to be clean. The fibers are so fine that you don't even see them. This is what makes the eye amazingly sharp. It's a special stone.

While alexandrite is the foremost color-change stone, there are others. Color-change sapphires are well known, and the phenomenon is also displayed by pink pyrope garnet from Tanzania. A 15.25 ct round from Morogoro, cut by Meg Berry, was featured on the Winter 2015 cover of *Gems & Gemology*. Another color-change material I've collected is diaspore, from Turkey. These crystals are quite common on the market. And then there are photochromic gems such as hackmanite, which changes color dramatically in ultraviolet light. Over the years I've had thousands of carats of Burmese hackmanite from Mogok. These are quite fun.

Of course, alexandrite is quite rare and the exceptional ones are very difficult to obtain. But alexandrite crystals, especially small ones from Zimbabwe, are still being produced and you can find these at the Tucson shows. I encourage you to collect and enjoy color-change crystals and gemstones of all kinds.



Above: 2.61 ct round Russian alexandrite, purchased in rough form in the Ural Mountains by the author. Photos by Mia Dixon.



Above: 1.64 ct alexandrite from India. Photos by Mia Dixon.



Above: 1.85 ct Brazilian alexandrite. Photos by Mia Dixon.



Above: 18.73 ct alexandrite from Sri Lanka. Photos by Mia Dixon.



Above: This “Super Spiral cut” color-change pyrope garnet from Morogoro, Tanzania, weighs 15.25 ct. This stone was featured on the Winter 2015 cover of *Gems & Gemology*. Cut by Meg Berry. Courtesy of William Larson. Photos by Robert Weldon/GIA.



Diaspore from Turkey

Çiğdem Lüle

Diaspore, an aluminum hydroxide mineral, crystallizes in the orthorhombic system, usually in a thin and tabular habit. In fine-grained massive form, diaspore (alongside gibbsite) and boehmite make up “bauxite” as a major aluminum ore. Diaspore is mined in several different localities in the world, including Muğla, Turkey; Naxos, Greece; Postmasburg, South Africa; Pennsylvania, Massachusetts, and Colorado in the United States; and recently Nangarhar Province, Afghanistan. The unusual formation of gem-quality diaspore in Turkey, exclusively from a very small mine called Küçükçamlıktepe near Pınarcık village, has been an exciting find for the devoted mineral and gem collectors for decades. The latest finding in Afghanistan is now the second known source for the gem-quality material.

The earliest mention of mineral diaspore can be found in James Dwight Dana’s *System of Mineralogy*, published in 1837. The first detailed study of aluminum ores in western Turkey was presented as a PhD. thesis in 1949 by Togan Onay. Throughout the 1950s, the area was extensively researched and mapped by the Turkish government through its official Mineral Research and Exploration Institute (MTA). However, the gem-quality material was not reported until 1966. The first detailed geological and mineralogical survey of bauxite formations in Muğla region of Western Anatolia, Turkey indicates the large euhedral, transparent diaspore crystals within the bauxites. The mining operation started in the early 1970s and was carried out until the 1980s by the Turkish government. Once the ore was no longer economical within the Küçükçamlıktepe area, underground mining operation came to an end. Eventually the mining rights were sold through a privatization scheme of the Turkish government in 2005. The author studied Küçükçamlıktepe bauxite formations, mainly concentrated on gem-quality diaspore, as her MSc. thesis between 1996 and 1998 while the mines were abandoned.

Pocket and lens-shaped bauxite deposits, aka diasporites, are located in the marble cover (Menteşe Formation) of the Mendere Massif in southwestern Anatolia, Turkey (figure 1). Massive bauxite occurrences are fractured at the

late stage of diagenesis. Descending solutions rich in aluminum, silica, and iron form kaolinite+diaspore+hematite paragenesis at the footwall, hanging wall, and the cracks and fissures of bauxites (figure 2). This paragenesis constitutes further mineral formations of diaspore and chloritoid under greenschist metamorphism conditions (figures 3 and 4). Four different bauxite occurrences are distinguished on the basis of macroscopic and microscopic characteristics. Chemical analyses revealed that they also contain high amounts of chromium, nickel, cobalt, vanadium, and especially rare earth element enrichments at the massive bauxites. Based on all these features, bauxites appear to belong to the karstic class. In addition to early and late stages of diagenesis, metamorphism postdating the aforementioned processes led to the formation of syn-tectonic and post-tectonic growth of coarse grained diaspore, mostly in gem-quality crystals.

Diaspore is an unusual gemstone. The color-change and transparent crystals are only known from the Küçükçamlıktepe mine, despite the bauxite formation throughout western and southern Turkey.

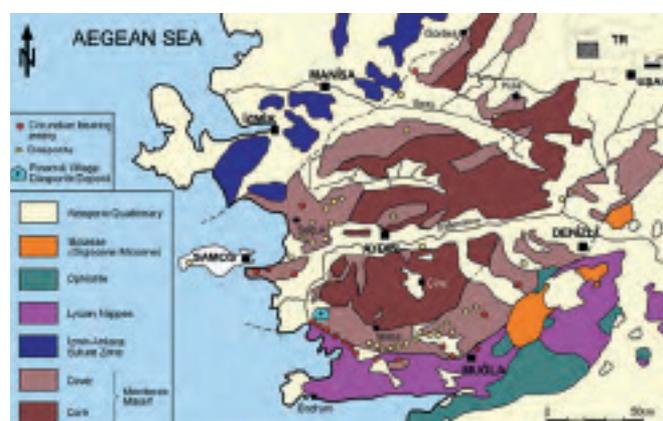


Figure 1. Geology of western Turkey and distribution of emery and diasporite occurrences. Modified from Dürr (1975). **Facing page:** Turkish diaspore, 25 mm. Stone courtesy of Will Larson. Photo by Robert Weldon.

Although it is mostly advertised as “color-change diaspore” and with a few trade names, diaspore from this area is almost always observed with color-change effect and sometimes with additional chatoyancy. While chatoyancy is caused by fine hollow tubular inclusions with post-crystallization two-phase fillings, the color-change effect is caused by chromium and rare-earth elements combinations. The bodycolor is a light to medium yellowish green in daylight and light to medium brownish pink in incandescent light. Recently, a new pocket in the area has been discovered with pink to red bodycolor in daylight.

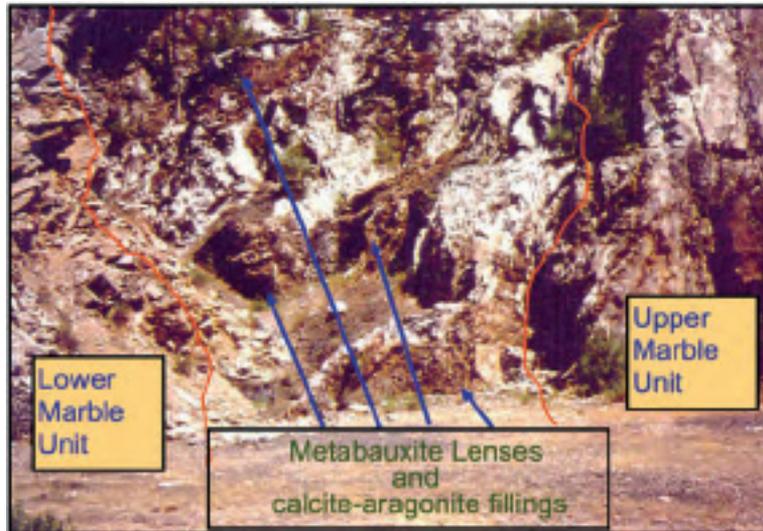


Figure 2. A view of the metabauxite lenses in between lower and upper marble units in the Küçükçamlıktepe mining area. From Lüle (1996).

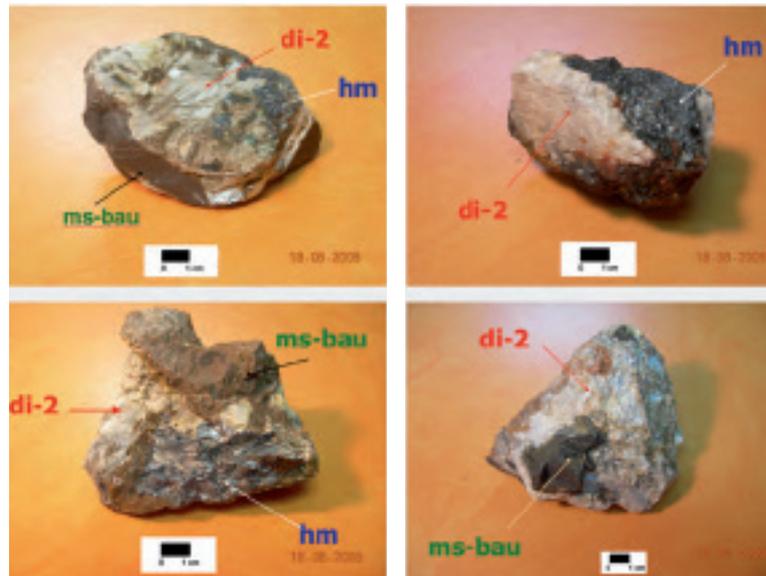


Figure 3. Second-generation diaspore (di-2) with hematite (hm) and massive bauxite (ms-bau) in hand specimens collected from the Küçükçamlıktepe mine. From Lüle (1996).

Pre-Metamorphism	Metamorphism 350-400 °C / 3-4 Kb		Post-Metamorphism
Accumulation of clay (mainly kaolinite) and iron oxides forming ooids and pisoids in karstic cavities on lower limestone member	Formation of fine grained diasporite and hematite Marble	Deformation-1	Deformation-2
		Due to preceding metamorphism and fracturing of bauxites Formation of curved Diasporite-2 and chloritoid	Brecciation of massive and all types formed before. Recognized by brecciated and fractured diasporite and chloritoid crystals. Calcite fillings

Figure 4. Stages of bauxite and diasporite formations caused by metamorphism. From Lüle (1996).

Gemological Properties of Diasporite

Chemical Formula: $AlOOH$

Crystal System: Orthorhombic

Color: Slightly brownish yellowish green and brownish pink.

Phenomenon: Color change (green variety) and chatoyancy

Refractive Index: 1.70–1.75

Pleochroism: Strong dichroism with yellowish green and brownish pink

Dispersion: 0.446

Hardness: 6.5–7

Cleavage: Perfect in one direction

Treatments: None known

Care Facts: Due to its perfect cleavage, cutting and setting can be a challenge. Cleaning should not involve steam pressure or an ultrasonic device.



Above left: Faceted diasporite under daylight. **Right:** Faceted diasporite under incandescent light. Photos by Göktürk Bircan.

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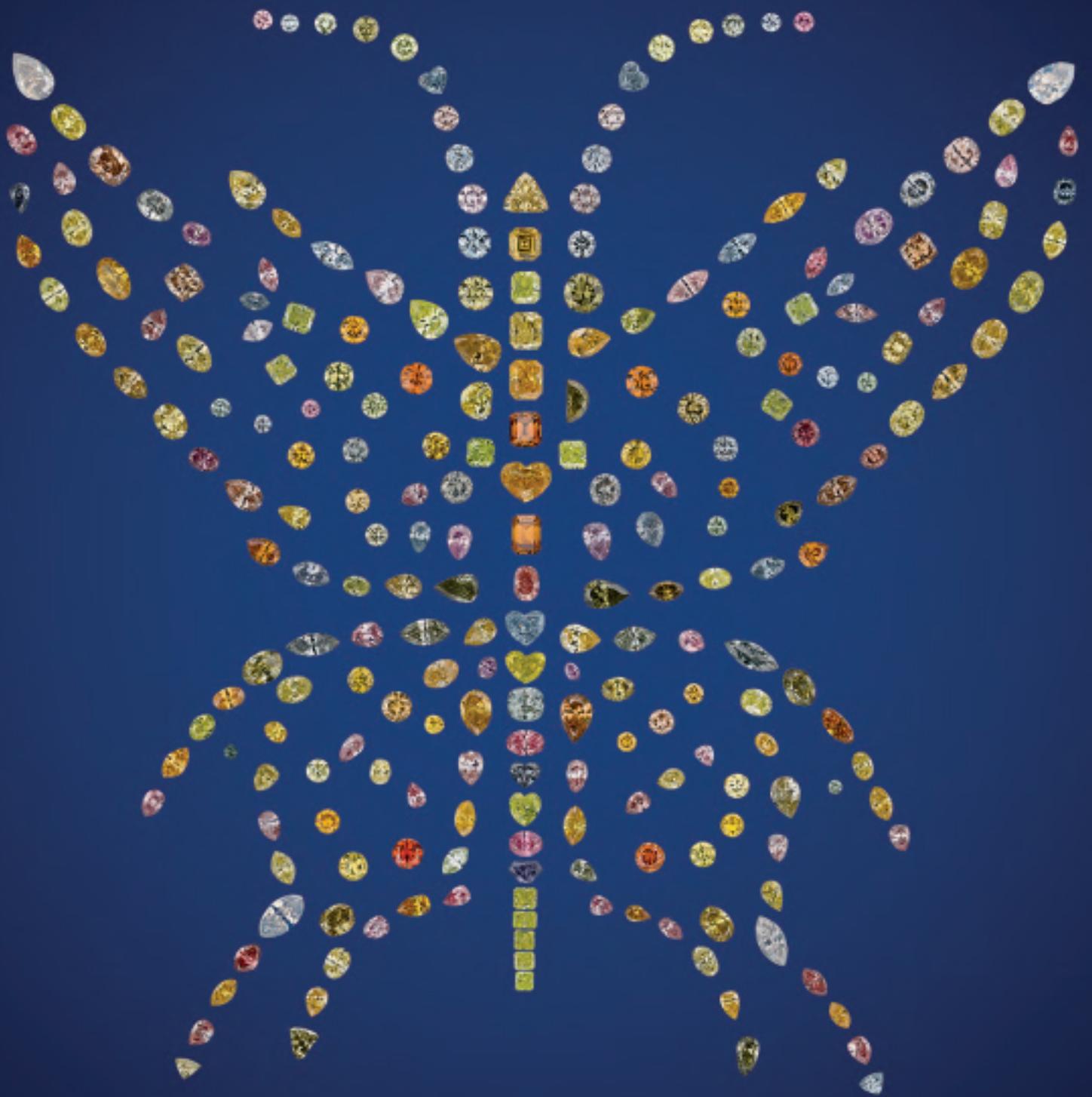
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Color-Change Phenomena in Diamond

Sally Eaton-Magaña

Among natural diamonds, observations of color-change phenomena are rare and typically limited to collector's stones. In treated and laboratory-grown diamonds, the ability to manipulate the concentration of color centers or to introduce them in concentrations not possible in their natural counterparts allows for the possibility of some interesting creations. This article is not intended to provide a complete picture of all diamonds that show a color-change (or a less dramatic "color-shift" in which the dominant color remains unchanged), but to provide an overview of the types of changes that are possible and occur by an array of different mechanisms.

Gübelin and Schmetzer (1982) defined the term *alexandrite effect* as "the apparent change of color in certain minerals from blue-green or greenish violet in daylight to red or reddish violet in incandescent light," adding that it was generally characterized by "transmission maxima in the blue-green and red regions and by a transmission minimum in the yellow region."

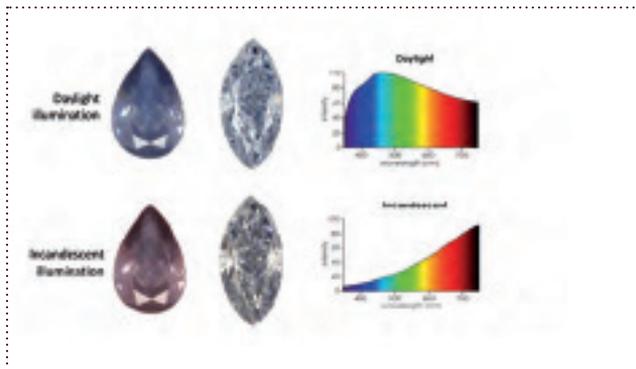
Here we will migrate far from that definition. We will also describe several examples that do not conform to these criteria, as they show distinct differences in appearance due to different light sources; in these, a pronounced impact of luminescence creates an apparent "alexandrite effect." Additionally, we will discuss other diamonds that show a color change that is not due to a difference in light source but instead have a reversible and temporary color change due to heating or light exposure.

Several distinctions about color grading procedures are important when discussing color-change phenomena in fancy colored diamonds. First, GIA color grading uses a lighting environment that approximates daylight (King et al., 1994)—that means that the lighting will include a UV component and an emphasis towards the blue end of the visible spectrum (e.g., figure 1, top right), whereas incandescent light shows a dominance towards higher wavelengths (figure 1, bottom right). Second, diamonds are color graded while in their stable state. Any diamond that is known to demonstrate photochromism or thermochromism will only be graded or released back to the client while appearing as its stable color.

ALEXANDRITE EFFECT

Blue-to-Gray Argyle Diamonds. This group of diamonds are colored by hydrogen-related defects, and their graded colors are typically gray to blue when observed in the standard GIA color-grading environment (King et al., 1994). However, they can appear violet in incandescent light (figure 1). The Argyle mine in Western Australia is the only known source for these diamonds. In these diamonds, the color is created by two broad absorption bands centered at ~530 and 720 nm (figure 2), which have been associated with hydrogen-related defects (Fritsch and Scarratt, 1992; van der Bogert et al., 2009). The specific configuration of the defects that creates these broad bands is unknown.

Figure 1. These gray-to-blue diamonds are colored by hydrogen defects, and the perceived color can vary with different light sources. Color grading proceeds under daylight conditions (top), which typically results in a blue-to-gray color grade, whereas incandescent lighting can permit these diamonds to appear as a violet hue (bottom). Left: Fancy Dark gray, 0.34 ct. Center: Fancy grayish blue diamond 0.33 ct. Right: These representative spectra show the variation in light output at different wavelengths is quite distinct between daylight and incandescent illumination. Photos by GIA staff.
Facing page: The 240 stones in this composite image (0.09-2.11 ct; total weight of 166.94 ct) show nearly the full spectrum of color and cut styles available in natural colored diamonds. The collection is shown here in standard daylight-equivalent illumination. The same collection is shown on page 27 in long wave UV illumination. Courtesy of Alan Bronstein. Photo by Robert Weldon/GIA.



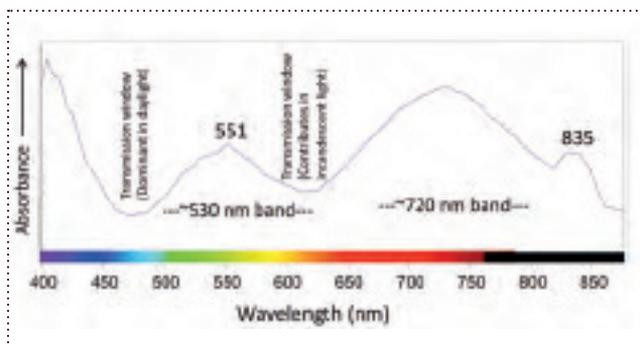


Figure 2. This representative visible-NIR absorption spectrum for a blue-to-gray type Ia diamond shows absorption bands centered at ~530 nm and ~720 nm. These diamonds often show a hydrogen-related absorption band at 835 nm as well.

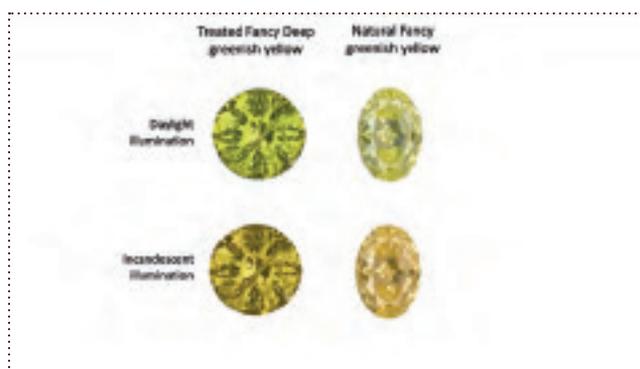


Figure 3. This treated-color, 0.70 ct Fancy Deep greenish yellow round brilliant (left) and natural-color, 0.62 ct, Fancy greenish yellow oval-shaped diamond (right) show color shifts between daylight and incandescent illumination. This “alexandrite effect” is not due to changes in multiple transmission windows, but due to the impact of greenish luminescence from the H3 ([NVN]⁰) defect that is excited by daylight wavelengths. Photos by Diego Sanchez.



Figure 4. This 4.29 ct type IIa color-treated diamond (Eaton-Magaña, 2016) has a Fancy brown-pink color grade when viewed under daylight conditions (left) and appears Fancy purplish gray under incandescent lighting (right). Photos by Robison McMurtry.

The two absorption bands in these Argyle blue-to-gray diamonds create two corresponding transmission windows (a transmission window is a wavelength region that has lower absorption and permits light of those wavelengths to be transmitted through the diamond; figure 2). The occurrence of these two windows can result in the alexandrite effect, in which a color change is observed under two different light sources. Very few Argyle diamonds with hydrogen impurities obtain a violet color grade (Eaton-Magana et al., 2018a); however, it is plausible that many of these diamonds appear violet under incandescent lighting conditions.

“Alexandrite Effect” Due to Influence of Fluorescence/Luminescence. H3 Center. Some natural and treated diamonds can appear green or, more commonly, greenish yellow due to the presence of H3 defects (e.g., Breeding et al., 2018). The H3 defect with principal absorption/emission at 503.2 nm is composed of a nitrogen-vacancy-nitrogen (or [NVN]⁰). H3 absorption can impart a yellow color to a diamond due to absorption within the blue wavelengths of ~420–500 nm. Additionally, H3 can also create fluorescence and add a greenish component to the diamond’s graded color. This greenish luminescence is observed in daylight due to excitation by the UV and blue components of daylight and under grading conditions (Luo and Breeding, 2013). This greenish component is not seen under incandescent light, as the fluorescence/luminescence is not activated under those conditions (figure 3); the transition is typically seen as a subtle color shift. The green luminescence is not seen in all diamonds with yellow color due to H3 absorption; if such diamonds also contain high amounts of other defects such as the nitrogen A aggregate (Collins, 2001), the H3 fluorescence will be quenched.

NV Centers. Color centers can be engineered by experienced treaters trying to create valuable colors. Sometimes, these efforts result in interesting diamonds demonstrating characteristics not seen in nature. Figure 4 shows a 4.29 ct treated diamond with a dramatic “alexandrite effect” due to nitrogen-vacancy (NV) and GR1 (neutral vacancy, V⁰) centers (Eaton-Magaña, 2016). The NV centers have negative and neutral charge states that can both be detected in the diamond; the principal absorption/emissions occur at 575 nm and 637 nm, respectively. The principal absorption/emission for the GR1 occurs at 741.2 nm and can impart a blue-to-green color to a diamond due to absorption within the yellow-to-red wavelengths. This 4.29 ct treated diamond is the only such example known to the author. This type IIa (i.e., no detectable nitrogen at the detection limits of IR absorption spectroscopy) diamond had been subjected to a sequence of high-pressure/high-temperature (HPHT) annealing, irradiation, and low-pressure annealing treatments, result-

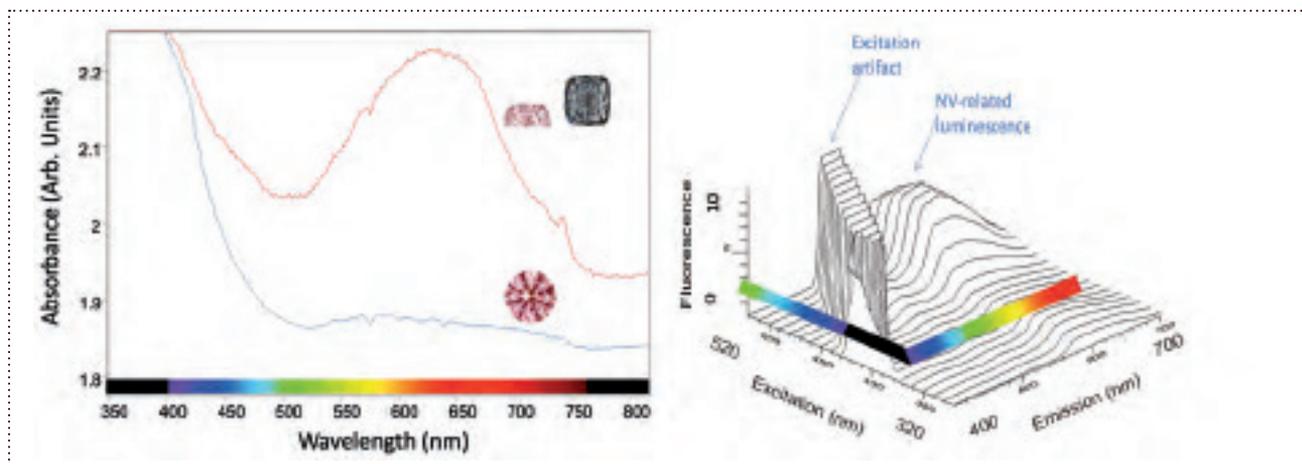


Figure 5. Left: The room temperature UV-Vis-NIR absorption spectrum under incandescent light illumination collected for the 4.29 ct treated sample shown in figure 4 (red trace) shows pronounced absorption within the red due to neutral vacancy (GR1) absorption, resulting in a Fancy purplish gray color. This indicates that the pink color enhancement observed under daylight illumination derives from the nitrogen-vacancy-related (NV) luminescence. The spectrum for a 0.48 ct treated CVD-grown diamond (blue trace) with a color grade of Fancy Vivid purplish pink is included for comparison. Although it has NV-related absorption (resulting in pink color) the absence of significant GR1 absorption meant that it did not show a dramatic change in color between daylight and incandescent light; the CVD showed a slight change with an equivalent color grade of Fancy Deep purplish pink in incandescent light. **Right:** Three-dimensional fluorescence spectra show the relationship between excitation wavelength, emission wavelength, and corresponding luminescence intensity. The excitation range is from the UV through the blue range of visible light (320–520 nm). The resulting luminescence is much higher when excited by wavelengths within the visible region than in the UV region; these data confirm that NV-related luminescence often enhances the color grade in pink diamonds that are colored by NV centers. The excitation artifact occurs when the emission spectrometer scans across the excitation wavelength.

ing in an unusual combination of both high NV and GR1 defect concentrations (figure 5, left). Typically this treatment sequence is used to create attractive pink colors stemming from NV center absorption. In daylight illumination, the diamond was color graded as Fancy brown-pink; however, it appeared as equivalent to Fancy purplish gray under incandescent light. When exposed to daylight, strong NV-related luminescence was stimulated by the UV and blue spectral components, creating red emission and, in conjunction with NV-center absorption, greatly enhancing the stone’s pink color (figure 5, right). In contrast, when the stone was illuminated by incandescent light, the NV-related red fluorescence was much diminished and the stone’s color was instead dominated by GR1-related absorption, forming a transmission window within the blue portion of the visible spectrum (figure 5, left). Consequently, the color changed to a purplish gray hue. In this treated diamond, the GR1 absorption intensity was comparable to that observed for irradiated green to blue diamonds. The GR1-related absorption is not detected in the vast majority of treated pink diamonds colored by NV centers, as it typically does not persist in sufficient concentrations following the treatment process. This suggests that the sample was irradiated to a far greater extent than most treated pink diamonds, resulting in a remarkably high GR1 concentration that is key to this “alexandrite effect.”

Other fluorescence-related “alexandrite effects” have been reported for diamonds. Such examples include the

56.07 ct Tavernier diamond, which shows a color change from light pink in daylight due to blue fluorescence created by the N3 defect; in incandescent light, this diamond appears light brown (Liu et al., 1998).

THERMOCHROMIC AND PHOTOCHROMIC EFFECTS

Chameleon Diamonds. Chameleon diamonds, similar to their namesake from the animal kingdom, show a reversible and temporary color change (figure 6). While some diamonds can show a change in color, the term *chameleon diamond* is exclusively reserved for those natural diamonds that change from a stable greenish hue to a temporary, unstable yellow-to-orange color due to temperature changes (i.e., thermochromism) or due to light exposure (i.e., photochromism). For chameleon diamonds, the thermochromic effect is observed when the diamond is heated and the photochromic effect is observed after the diamond is kept in the dark for an extended time. Upon returning to ambient lighting and temperature conditions, these diamonds quickly revert to their original greenish colors (figure 7). The precise mechanism of the color change remains unclear, but these noteworthy diamonds are often revered by collectors (Fritsch et al., 1995; Hainschwang et al., 2005; Fritsch et al., 2007; Byrne et al., 2018). Chameleon diamonds usually range in color from grayish yellow-green to brownish greenish yellow and generally occur as faceted stones under 2 carats (Breeding et al., 2018). The largest known faceted



Figure 6. Chameleon diamonds can change color from greenish (top left) to yellowish (bottom left) when heated or left in the dark. Like their animal namesake (right), these color changes are temporary and reversible. Photos on the left by GIA staff.

chameleon diamond is the 31.32 ct Chopard chameleon diamond.

The infrared absorption (IR) spectra of all chameleon diamonds show that they are type Ia, indicating measurable concentrations of aggregated nitrogen. The spectra also show that the majority of chameleons have the nitrogen impurities grouped as pairs (i.e., type IaA) and the presence of hydrogen-related impurities. The visible absorption spectra for chameleon diamond show broad absorption bands at ~480 nm and ~750–800 nm, as well as the common N3 ($[N_3V]^0$) peak at 415 nm (figure 8). The combined effect of these absorption features is the greenish color, often in conjunction with several modifying hues. The defect structures associated with the two broad bands are currently unknown. Prior research has correlated the 480 nm band with the presence of oxygen (Hainschwang et al., 2020) and the 750–800 nm band with hydrogen or nickel (Breeding et al., 2018). Additionally, photoluminescence spectra of many chameleon diamonds show features associated with nickel (Hainschwang et al., 2005), but its role has not been definitively established. Comparison between visible absorption spectra collected under ambient temperature and lighting conditions and spectra collected immediately following heating or storage in the dark reveal a reduction

in the 750–800 nm broad intensity for the latter, resulting in the temporary transition to a more yellow or orange color.

Another clue into their nature may be found by considering the spatial distribution of their defects. Deep UV (<230 nm) imaging has revealed that chameleon diamonds are characterized by highly heterogeneous growth zoning (figure 9), with distinct regions that fluoresce either green-to-yellow or blue. The patterns formed by the green-to-yellow and blue fluorescing regions are often unique to each chameleon diamond, and the boundaries between these regions can be linear or irregular, suggesting fluctuations in the diamond's growth environment. By performing photoluminescence spectroscopic mapping, which clearly distinguishes the spatial distribution of defect species, GIA has determined that the green-to-yellow fluorescing areas principally show features associated with the 480 nm absorption band (e.g., an associated and distinctive broad emission band centered at ~700 nm observed with PL spectroscopy; Eaton-Magana et al., 2018b); meanwhile, the blue fluorescing areas have high quantities of hydrogen- or nickel-related features associated with the 750–800 nm band (C.M. Breeding, unpublished results). The correlation of the green-to-yellow and the blue fluorescing zones with the bands associated with the chameleon color-change phenomenon implies that the changing growth conditions are an important ingredient for creating these captivating diamonds.

When this type of colored diamond is submitted to a GIA laboratory, the report includes an additional comment identifying it as a chameleon diamond, thus indicating the color-change observation (Breeding et al., 2018). There are three criteria for this comment on a GIA laboratory report: (1) the diamond has a green color component, either as the dominant hue or as a modifier; (2) the diamond shows phosphorescence to short-wave UV; and (3) the diamond changes color from greenish to yellow or orange when slightly heated or kept in the dark. Prior to heating a suspected chameleon diamond, it is important to verify by absorption spectroscopy that its green hue is not caused by GR1 centers. GR1 is the most common origin for green color (Breeding et al. 2018), and heating could permanently remove this valuable color.

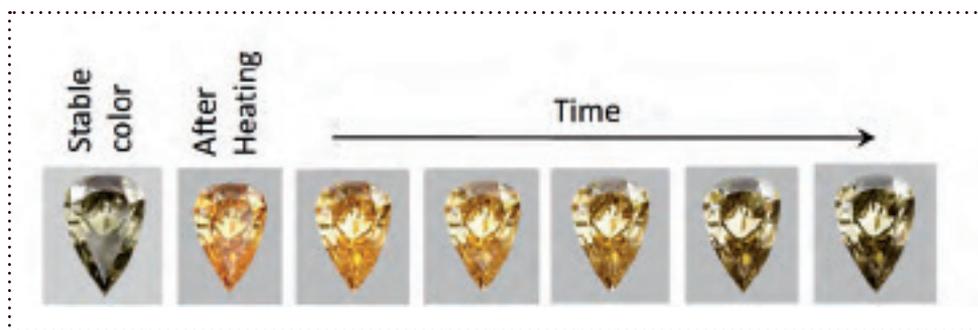


Figure 7. This series of images shows the change in color upon heating a chameleon diamond and the transition back to its stable color upon cooling and exposure to ambient lighting. Photos by GIA staff.

Temporary Color Changes in Natural Pink Diamonds.

There are two different defect-related origins for pink color in natural pink diamonds. The most commonly observed mechanism is a broad absorption band centered at around 550 nm; the composition of this defect has not yet been determined, but it has been shown to coincide with plastic deformation (Gaillou et al., 2010; Howell et al., 2015). While such pink diamonds have been mined from several localities throughout the world, the two dominant sources have been the Argyle mine in Australia (Shigley et al., 2001; Yakoubovskii K. and Adriaenssens, 2002) and several mines in the Siberian and Arkhangelsk regions of Russia (Smit and Shor, 2017).

Much more rare (~0.5% of natural pink diamonds; Eaton-Magaña et al., 2018b) are those colored by NV^{0/-} centers. They are often referred to as “Golconda pink” diamonds, after the historical mining region of Golconda in India (Fritsch, 1998). The 34.65 ct Fancy Intense pink cushion-cut Princie diamond is probably the most famous example. While records of the Princie diamond trace it back to an Indian origin, today the term “Golconda pink” no longer exclusively applies to this geographic location, as its diamond production was largely depleted by the early eighteenth century. Instead, the term is meant to signify NV centers as the cause of pink color. Although this color origin is extraordinary for natural diamonds, NV centers are straightforward to create within a laboratory and are thus almost exclusively the cause of color in treated and laboratory-grown pink diamonds.

Many natural pink diamonds, with color due to both the 550 nm band and NV centers, temporarily change color after exposure to UV light (figure 10). Although the most dramatic changes are induced by exposure to deep UV (< 225 nm excitation) illumination, changes can be also be observed, to a lesser extent, after exposure to short- and long-wave UV (254 nm and 365 nm, respectively) (Fisher

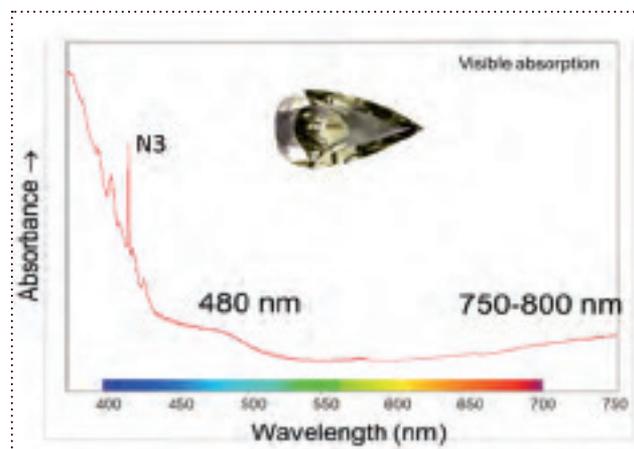


Figure 8. The visible absorption spectrum for a chameleon diamond in its stable state shows several features, including N3 absorption (a common feature in natural diamonds), the 480 nm absorption band, and a broad absorption at 750–800 nm. Its color grade is Fancy grayish yellowish green. Upon heating, the 480 nm band flattens and broadens, thus shifting the transmission window toward the yellow wavelength range.

et al., 2009; Byrne et al., 2012, 2014). After UV exposure, 550 nm band pink diamonds show a reduction of pink hue (sometimes referred to as “bleaching”), and the resulting temporary color can be yellow, brown, or near-colorless. These changes have been ascribed to charge-transfer processes associated with vacancy clusters found in brown diamonds (Byrne et al., 2014).

The effect is reversible, and the original stable color can be restored when exposed to an appropriate visible light source (Fisher et al., 2009; Byrne et al., 2014). Bright white light is known to accelerate the process, yet the illumination period may range from several minutes to more than a day, depending on the light’s emission wavelength composition and intensity. As a safeguard, GIA gemologists generally avoid collecting deep UV fluorescence images (such as those

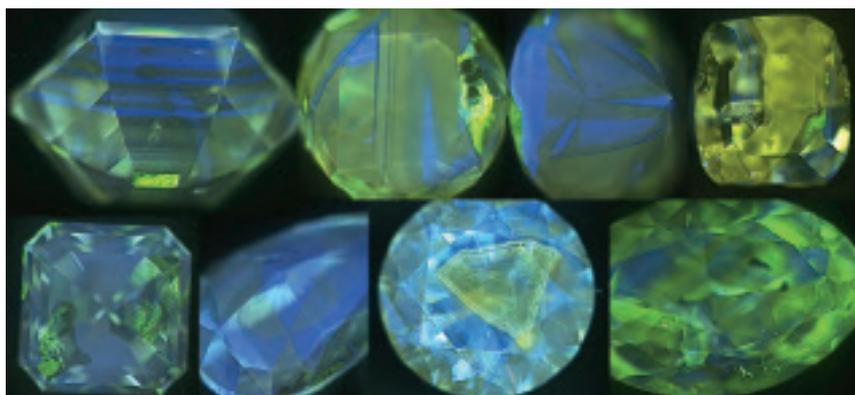


Figure 9. This compilation of deep UV fluorescence images shows the wide variety of possible growth morphologies for chameleon diamonds. Nevertheless, each diamond shows a combination of yellow-to-green and blue fluorescing regions. Photos by GIA staff.

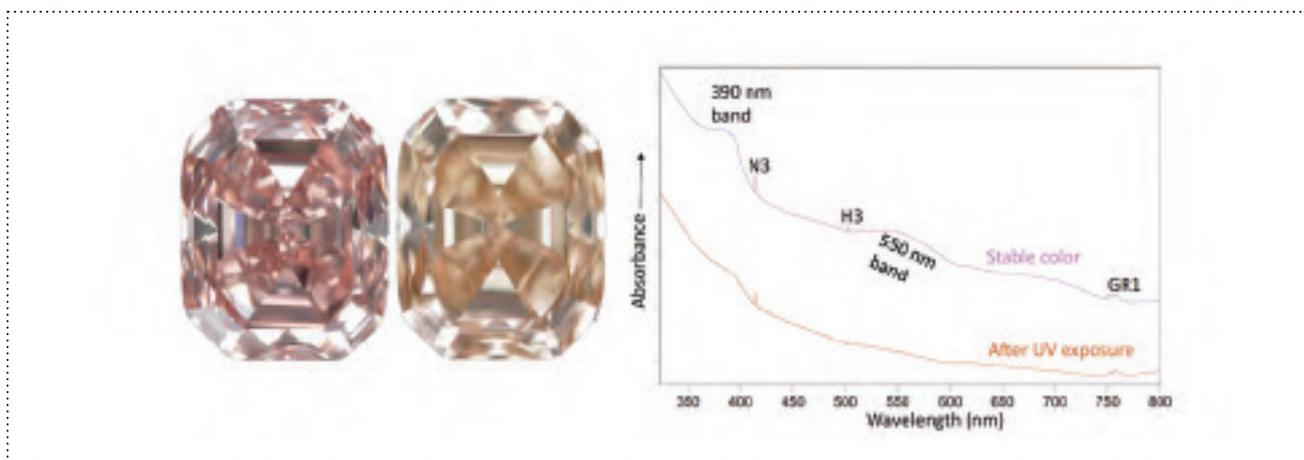


Figure 10. With deep UV exposure, this 9.35 ct Fancy Intense pink type IIa diamond showed a temporary color change to Fancy Intense brownish yellow (this unstable color grade was assessed for informational purposes only; diamond color grades are always determined and reported for the stable state). The UV excitation precipitated a decrease in the ~390 and ~550 nm absorption bands; 30 minutes of exposure to bright visible light restored the stable color.

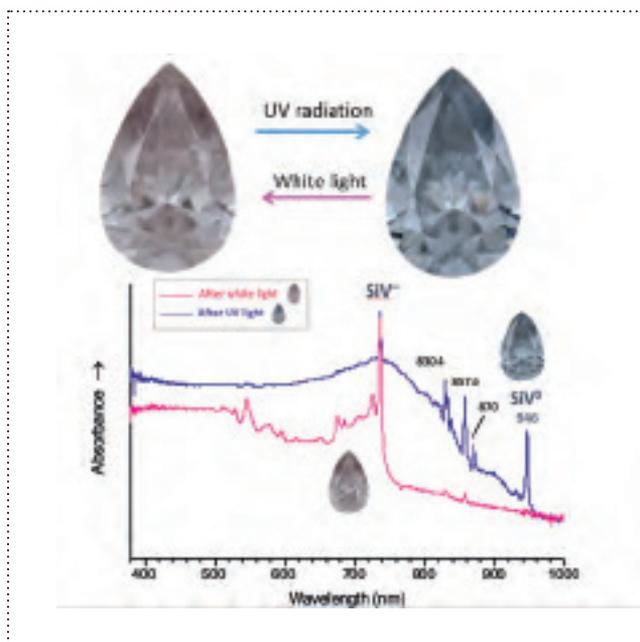


Figure 11. This 0.65 ct CVD-grown diamond has a color grade of Fancy brown-pink; however, it can temporarily appear as Fancy Intense blue after deep UV exposure. Bottom: The corresponding absorption spectra for this CVD diamond in its stable (pink trace) and unstable state (blue trace). A charge transfer between SiV^- (dominant in the stable state) and SiV^0 (dominant in the unstable state) assists in the observed color change.

from a DiamondView instrument) for pink diamonds unless necessary for treatment identification. Such images are only collected after color grading, and steps are in place to ensure that any pink diamonds that undergo this testing are always returned to their stable color.

As an example, figure 10 shows a type IIa Fancy Intense pink diamond that was exposed to deep UV in the DiamondView instrument. The color dramatically and temporarily changed to a color equivalent to a Fancy Intense brownish yellow grade. Absorption spectra illustrate how the color change corresponds with a decrease in the 390 nm and 550 nm absorption bands, while the other centers (e.g., N3, H3, and GR1) do not show any significant intensity changes.

Color Change in CVD-Grown Diamonds. Like treated diamonds, laboratory-grown diamonds manufactured by the chemical vapor deposition (CVD) method can create distinctive products not found within the natural world. One such example is intentional doping with high quantities of silicon. When incorporated into the diamond lattice, silicon can form silicon-vacancy defects that result in absorption and luminescence peaks at 737 nm (negative charge state, SiV^-) and 946 nm (neutral charge state, SiV^0). Depending on the relative concentrations of these states, highly silicon-doped CVD diamonds can have a stable pinkish brown, gray, or blue color. Exposure of such diamonds to UV creates a temporary charge transfer of SiV^- to SiV^0 , decreasing the concentration of the former while increasing that of the latter. Although the primary peak for SiV^0 is in the infrared, its photoconductivity spectrum causes absorption in the red visible range, hence this change introduces or intensifies blue color (figure 11; D’Haenens-Johansson et al., 2015; Breeze et al., 2020). These diamonds will return

to their original color with exposure to white light.

These high-silicon CVD-grown diamonds are also thermochromic. Heating at 550°C has been shown to decrease both SiV⁻ and SiV⁰ concentrations. Significantly, the SiV defect structure cannot be destroyed at this temperature, and instead the heating temporarily drives charge from electron donors to produce SiV²⁻, which has no optical absorption (Breeze et al., 2020). As a result, this charge transfer will temporarily decolorize the CVD diamond. The process is reversible, and the CVD diamond will return to its stable color when exposed to ambient lighting and temperature conditions. Strong white light will accelerate the return.

Another type of reversible color change can also be observed in as-grown nitrogen-containing CVD-grown diamonds (Khan et al., 2009, 2010, 2013). These diamonds often have a stable brown hue, which can be intensified by UV exposure. Conversely, heating to moderate temperatures (>450°C) can decolorize them, sometimes revealing an underlying pinkish hue. The responsible mechanism has been suggested as electron transfer from isolated nitrogen atoms to electron acceptor defects such as the nitrogen-vacancy-hydrogen center, NVH. Like the other charge transfer mechanisms, these transitions to an unstable color are temporary and reversible; the stable color returns with exposure to white light at room temperature.

CONCLUSIONS

Although color-change phenomena are not a widely known aspect of diamonds, there are rare natural diamonds along with some treated and CVD-grown diamonds that offer stunning and intriguing examples. In some instances, an alexandrite effect is observed where the color changes with different light sources due to multiple transmission windows or the impact of fluorescence. In other instances, the color change is created by a charge-transfer mechanism precipitated by light exposure (typically UV excitation) or temperature changes. These diamonds are certainly captivating not only to researchers as scientific curiosities but also to collectors, as their color change is both fascinating and beautiful.

ACKNOWLEDGMENTS

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Facing page: 166.94 total weight diamonds in long wave UV illumination. Courtesy of Alan Bronstein. Photo by Robert Weldon/GIA. See page 18 for more detail of this collection.





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Designing with Color-Change Gemstones

Niveet Nagpal

For Omi, gemstones have been at the heart of our business since the beginning. There is an art to everything we do, and our gemstones are the natural masterpieces. Each part of our process, from cutting the gemstones to devising the settings, is performed not only with skill but also with artistry. Beauty is our muse, and originality fuels us. We see it in our gemstones, in our work, and in the ways our customers express themselves through our pieces.

Alexandrite quickly became one of my favorite gemstones to design with and around. I've always found it so fascinating that a gemstone such as alexandrite can naturally come from the ground and possess a color-changing phenomenon. I like to call it the "perfect storm" of nature.

My obsession with alexandrite has grown so much over the years that we hand-set a small round alexandrite inside the shank of each one-of-a-kind design to signify the unique beauty each Omi Privé piece holds!

Due to our exceptional craftsmanship, dedication to design, and passion for colored gemstones, we have had the honor of being presented with numerous industry and consumer-voted awards since the launch of Omi Privé in 2012. We deeply appreciate and take pride in the recognition of our dedication to elevating rare and unique gemstones. In the years since we began, a varied group of our gemstone creations, all bearing masterful Omi Privé craftsmanship, have been recognized by the likes of *W* magazine, AGTA Spectrum Awards, JCK Jewelers' Choice Awards, and the Platinum Guild.

1. 18K white gold with black rhodium ring featuring a 1.07 ct emerald-cut alexandrite accented with 0.60 carat total weight of round diamonds and 0.08 carat total weight of round alexandrites. *2017 AGTA Spectrum Awards Manufacturing Honors in Men's Wear*

2. Platinum ring featuring a 3.87 ct emerald-cut purple spinel accented by 0.85 carat total weight of emerald cut blue tourmalines and 0.36 carat total weight of round alexandrites. *2017 Jewelers' Choice Awards Finalist in Platinum Jewelry*

3. Platinum ring accented with black rhodium featuring a 6.99 ct oval alexandrite accented by 1.67 carat total weight of round alexandrites and 0.91 carat total weight of round diamonds. *2016 AGTA Spectrum Awards 2nd Place in Classical and JCK Jewelers' Choice Awards 3rd Place in Colored Stone Jewelry*

4. Platinum ring featuring a 2.21 ct oval grandidierite accented by 1.18 carat total weight of round alexandrites and 0.34 carat total weight of round diamonds. *2020 AGTA Spectrum Awards Honorable Mention in Bridal Wear*

5. Platinum ring accented with black rhodium featuring a 10.62 ct oval alexandrite accented by 0.81 carat total weight of round alexandrites, 1.39 carat total weight of French-cut square diamonds, 0.80 carat total weight of epaulette-cut diamonds, and 1.17 carat total weight of round diamonds. *2021 AGTA Spectrum Awards 3rd Place in Classical*

6. Platinum with black rhodium ring featuring a 6.12 ct oval cabochon alexandrite accented with 0.28 carat total weight of pear-shaped alexandrites, 1.35 carat total weight of round alexandrites, and 0.21 carat total weight of round diamonds. *2018 AGTA Spectrum Awards 3rd Place in Bridal Wear*



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Other Stones Accented with Alexandrites

In addition to alexandrite, there are several other gemstones we use as the focal piece that can be highlighted with alexandrite. Some of our favorites include spinel, tourmaline, and sapphires. When accented with alexandrite, these gorgeous gemstones' colors can be multiplied and seen in a new light. For example, when we accent an alexandrite halo around a bi-color tourmaline, the natural blue and green hues are much more fully expressed.

7. 18K yellow gold pendant featuring a 16.91 ct pear-shaped blue-green tourmaline accented by 1.22 carat total weight of round alexandrites, 1.27 carat total weight of rose-cut diamonds, and 0.04 carat total weight of round diamonds.

8. 18K rose gold pendant accented with black rhodium featuring a 15.30 ct pear-shaped rainbow moonstone accented by a 0.88 ct oval cat's-eye alexandrite, 0.47 carat total weight of round alexandrites, and 0.15 carat total weight of round diamonds.

9. 18K rose gold earrings featuring 13.43 carat total weight of star sapphires accented by 0.83 carat total weight of round alexandrites and 0.13 carat total weight of round diamonds.

10. Platinum ring accented with black rhodium featuring an 8.64 ct emerald-cut bi-color tourmaline accented by 0.37 carat total weight of round alexandrites and 0.18 carat total weight of round diamonds.

11. 18K rose gold ring accented with black rhodium featuring a 12.17 carat oval rainbow moonstone accented by 0.57 carat total weight of round alexandrites and 0.24 carat total weight of round diamonds.

12. 18K rose gold ring featuring a 3.85 ct oval purple spinel accented with 0.46 carats of round alexandrites and 0.15 carats of round brilliant diamonds.



Causes of Color in Color-Change Gemstones

Aaron Palke and George R. Rossman

We begin by discussing the basic principles of what is responsible for color change in gems and minerals. There are a few important factors to consider. The first has to do with the intensity distribution of light across the different wavelengths that we humans can see. Historically, color change was often viewed as the difference in a stone's apparent color in ordinary daylight compared to illumination by an incandescent bulb. Particularly noteworthy is the significantly greater intensity of light in the purple, blue, and green regions of the spectrum coming from daylight compared to an incandescent bulb. Figure 1 presents the relative intensities of the different wavelengths across the visible spectrum of these two different sources.

From figure 1, it is obvious that daylight will have a relatively higher proportion of shorter wavelength components than an incandescent bulb.

Next, we need to consider the absorption spectrum of the stone; that is to say, we need to determine the wavelengths of visible light that the stone absorbs. Many color-change stones have a significantly greater amount of light absorption in the center of the visible spectrum than they do in the shorter wavelengths (blues and violets) and in the longer wavelengths (reds and orange). An example of such behavior is shown in the spectrum of a color-change garnet (figure 2), where significant absorption occurs in the 500–650 nm region. This results in bands of optimum transmission in the 450–500 nm region (blues) and in the 650–780 nm region (red). As a result, when the stone is illuminated by daylight, significant components in both the blue and green regions of the spectrum pass through the stone. But when the stone is illuminated with a tungsten filament bulb, significantly more red wavelengths pass through the stone than blue.

Because our eye is not uniformly sensitive to all wavelengths, its response is an additional factor that helps to determine the color-change behavior. Particularly interesting is the fact that dark-adapted eyes have a different color response than daylight-adapted eyes. Figure 3 shows that as we become adapted to dark, our peak vision sensitivity shifts to shorter wavelengths.

Modern lighting adds further complexity to the color-change story. Today, LED and fluorescent lighting are commonly used. But their spectral outputs can differ significantly from either daylight or incandescent illumination. Figure 4 shows the intensity spectrum of three different LEDs that are commonly sold as “white” LEDs. From the spectra, it should be obvious that the red-blue ratio of illumination depends upon the type of LED.

Figure 5 shows the intensity distribution of two common types of fluorescent lamp. From these, it can be seen that the proportion of yellow to orange light is quite different for the two different lamps. Depending on the type of illumination used, the exact color change observed between daylight and artificial illumination will vary somewhat depending on the light source.

Next we look at alexandrite, the best-known color-change stone. The most common color-change alexandrite contains chromium 3+, which is the origin of the broad absorptions near 425 and 600 nm (figure 6). These absorptions define regions of transmission in the blue-green and red portions of the spectrum. Depending on the type of light used for

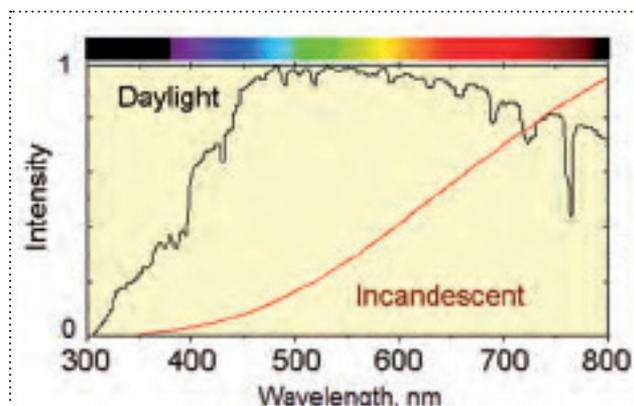


Figure 1. Comparison of the relative intensities of the wavelengths of daylight and an incandescent bulb. **Facing page:** Daylight view of a 4.88 ct alexandrite crystal from Mogok, Myanmar, measuring 12.50 x 6.90 mm; see page 39 for a photo of the same crystal in incandescent lighting. Courtesy of William Larson. Photo by Robert Weldon.

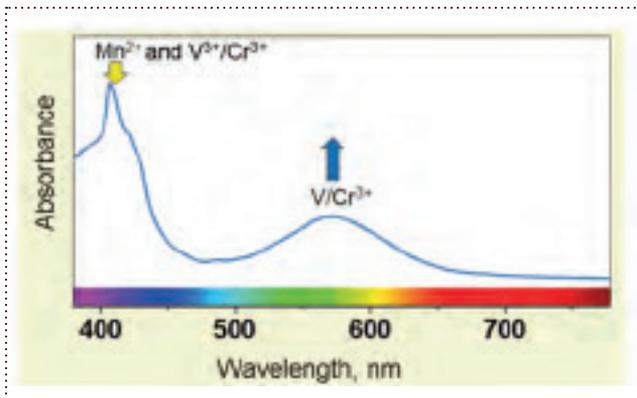


Figure 2. The optical absorption spectrum of a color change garnet.

illumination, the proportion of red to blue transmission will vary. With incandescent light, the sample primarily returns red-dominant wavelengths when illuminated and produces a reddish appearance. With daylight illumination, a much greater proportion of blue wavelengths are returned and the stone has a blue-dominant color (figure 7). The color-change behavior can be understood more fully by converting the absorption spectrum in figure 7 to transmission (figure 8). In the transmission spectrum, the parts of the spectrum with high transmission are the wavelengths of light that get preferentially passed through the stone and returned to the observer. Figure 8 also overlays the transmission spectrum of this alexandrite with the emission spectrum of a daylight-equivalent illuminant (called D65) and the emission spectrum of an incandescent illuminant. For the daylight illuminant, the peak emission exactly overlaps one transmission peak in the blue/green region of the spectrum while the maximum intensity of visible light in the incandescent illuminant exactly overlaps the transmission peak in the red region.

The behavior of alexandrite in the real world is complicated by the pleochroic nature of Cr-bearing chrysoberyl. The absorption spectrum of Cr varies significantly down the

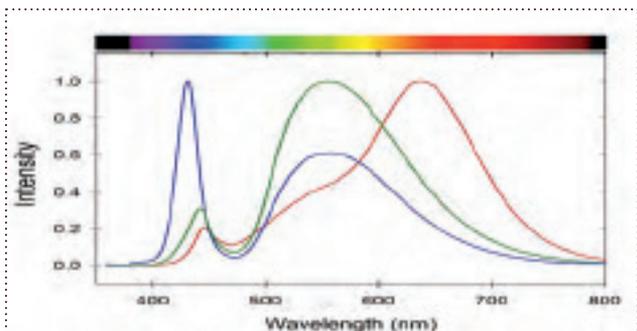


Figure 4. The relative spectral outputs of three different "white" LEDs.

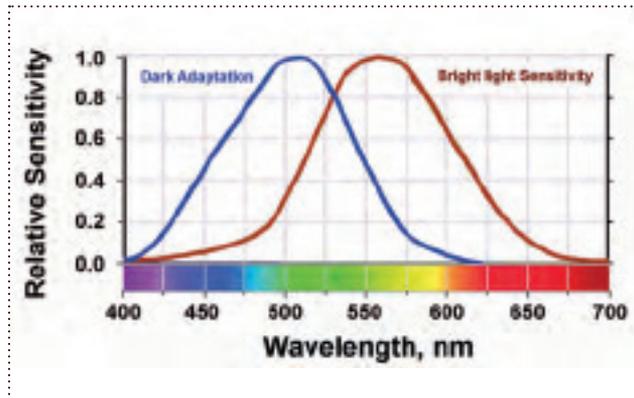


Figure 3. Comparison of the human color wavelength sensitivity when in bright light and when dark-adapted.

three different crystallographic axes of chrysoberyl (figure 9). Figure 10 shows photos of a synthetic alexandrite cut into a cuboid in both incandescent and daylight illuminants, illustrating the impact of this variation in absorption on the observed color and magnitude and nature of the color change.

Further complicating the situation is the potential presence of other chromophores in natural alexandrite and the varying concentration of chromium, which is responsible for the color change. Figure 11 shows representative examples of the range of expected color change for the main commercially important global sources of alexandrite (Russia, Brazil, Sri Lanka, and India). Alexandrite from the classic deposit in Russia tends to show pure green to green-blue in daylight and purple-red to purple in incandescent light, with medium to high saturation of these hues. Brazilian alexandrite typically has higher concentrations of chromium, which gives a generally higher color saturation and hues that tend to be more blue or purple from greenish blue to green in daylight and red-purple to purple in incandescent light. For an extreme example, Sri Lankan alexandrite tends to be lower in chromium, with generally lower saturation in color and

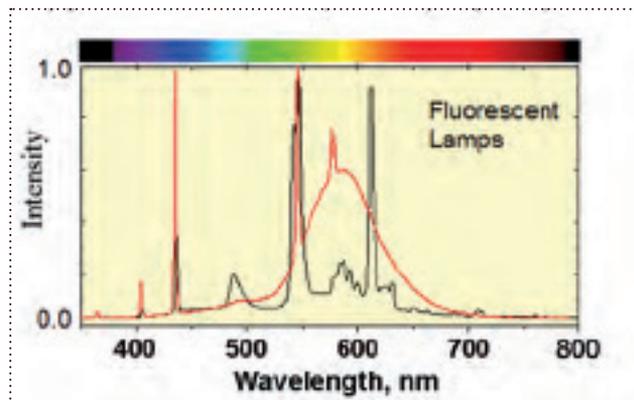


Figure 5. The relative intensity distribution across the visible spectrum of two common types of fluorescent lamp: a halophosphate bulb in red and the common compact fluorescent bulb in black.

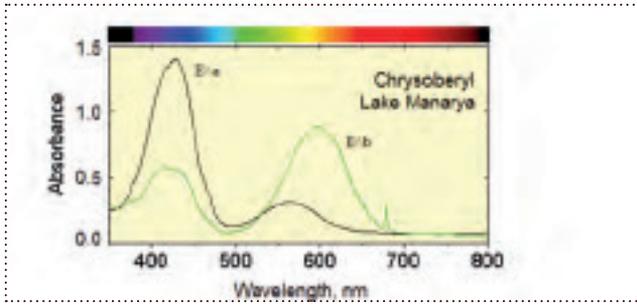


Figure 6. The spectrum of alexandrite, which contains Cr³⁺ as a minor component substituting for some of the aluminum.

brownish or grayish overtones. Due to the generally lower chromium content, iron is also an important chromophore in Sri Lankan alexandrite. Those stones from India typically range from green to bluish green in daylight and purplish violet to red-purple in incandescent light.

This color-change phenomenon is not unique to chromium-bearing chrysoberyl. In fact, the phenomenon is particularly common in gemstones with hues in the violet region of the color spectrum as seen often in some tanzanite, amethyst, copper-bearing tourmaline, and sapphires (figure 12). In many cases, as in many blue/violet to purple color-change sapphires, the color-change phenomenon is not caused by any single chromophore but only occurs with a combination of different chromophores in well-balanced proportions. The color change most commonly seen in sapphires is due to a delicate balance of Cr³⁺, producing a red transmission window and Fe²⁺-Ti⁴⁺ pairs, creating a blue transmission window, sometimes with additional color modification from Fe³⁺, which introduces a yellow color component.

The type of illuminant used can also be very important in observing color change in some minerals. The historical benchmarks for observing this optical phenomenon are actual daylight and candlelight. In the modern world, new

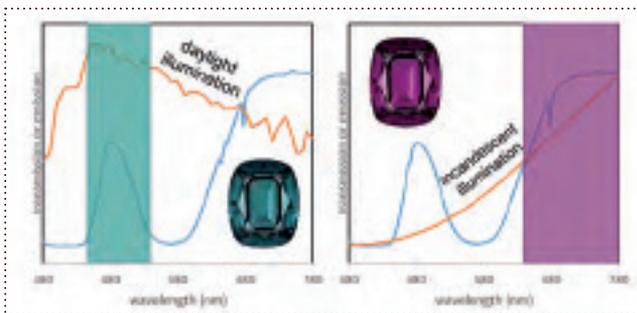


Figure 8. The spectrum from figure 2, converted to transmission (blue line). Also shown are the emission spectra of the daylight-equivalent D65 illuminant (orange line, left) and incandescent illumination (orange line, right). Daylight contains more blue and green wavelengths of light and enhances perception of these colors in alexandrite. Incandescent illumination contains more red wavelengths of light and enhances perception of red in alexandrite.

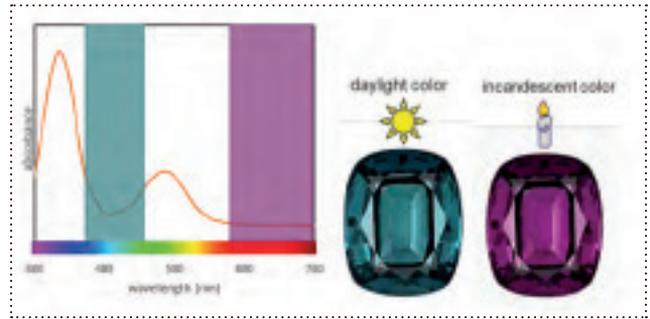


Figure 7. Typical absorption spectrum of an alexandrite. Cr³⁺ in alexandrite has two absorption bands in the visible region at about 410 nm and 570 nm. This creates two transmission windows in the blue/green and red regions of the visible spectrum that are selectively favored by daylight or incandescent light, respectively.

light sources have been developed to provide illumination for our increasingly indoors lifestyle. In particular, fluorescent and LED light sources are increasingly common. While our human eyes perceive these light sources to be white light similar to what would be observed from a black-body irradiator, these light sources often have emission curves with multiple spikes and narrow emission peaks that are unlike the smooth emission curves of black-body irradiators. In most cases this is not a problem for gemstones with broad absorption bands. However, some gemstones have narrow or sharp absorption features, which can result in unusual color-change behavior. Take, for instance, the zircon in figure 13. With a cool fluorescent light meant to approximate daylight the zircon has a green color that is almost indistinguishable from the color seen using an incandescent light. However, when taken outside in true daylight or when observed with a cool, daylight-approximating LED light, the color is grayish purple. The color change in this zircon can only be seen between incandescent light and either true daylight or cool LED light. The reason for this can be seen in figure 14

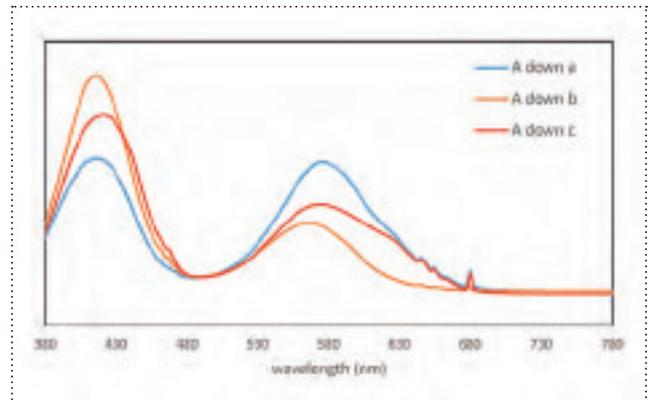


Figure 9. Visible absorption spectra (unpolarized) along the three crystallographic directions (a, b, and c) in lab-grown Cr-bearing alexandrite. The differences in absorption lead to significant pleochroism in Cr-bearing alexandrite. Modified from Sun et al. (2017a).

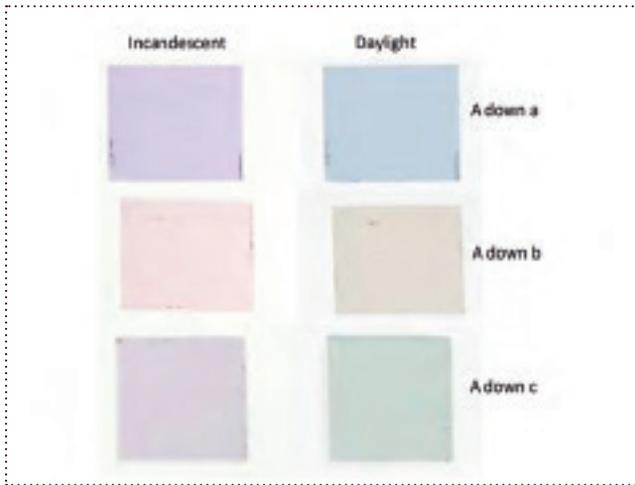


Figure 10. Photos of the oriented lab-grown alexandrite cube that produced the absorption spectra in figure 4 in both incandescent and daylight-equivalent illumination. Modified from Sun et al. (2017a).

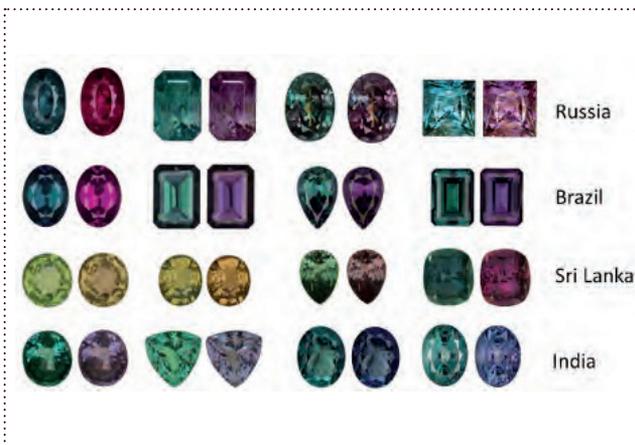


Figure 11. General ranges of colors seen from different alexandrite deposits. Modified from Sun et al. (2019).

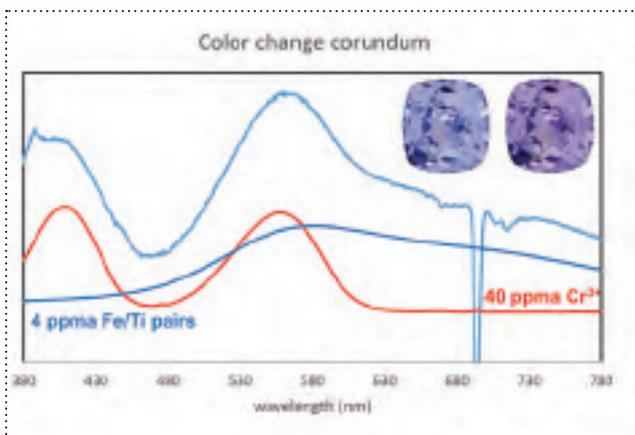


Figure 12. Visible absorption spectrum of a color-change sapphire going from violetish blue to purplish-violet due to the presence of both Cr^{3+} and $\text{Fe}^{2+}\text{-Ti}^{4+}$ pairs.

showing the absorption spectrum of the zircon as well as the emission profile of the cool fluorescent and cool LEDs used here. U^{4+} in the zircon lattice has several sharp absorption features including one at 434 nm that strongly overlaps with one of the major sharp emission features at 435 nm from the cool fluorescent light. The fluorescent light relies on this sharp emission feature in the blue to create the perception of this illuminant as a white light. The strong absorption of this blue emission throws off our perception of white balance and makes the zircon look the same as it would in incandescent light. The cool LED light is smoother with less sharp emission features and therefore it brings out more faithfully the color that is seen in true daylight.

One final example of the importance of illumination is seen with the holmium-bearing laboratory-grown cubic zirconia in figure 15. This stone showed multiple perceived colors in various illuminants, especially when different fluorescent lights are involved. Under standard daylight, the perceived color is green. In a fluorescent light rated at 4150 K, the stone is blue. Then, under a fluorescent light rated at 5000 K, the stone is violetish pink. The cause of the color change with 5000 K light is the strong absorption of one of the emission features at 545 nm, which emphasizes the emission features at 610 nm in the red and 435 and 405 nm in the blue/violet region.

Fluorescent lights in particular produce a varied effect, as the sharp emission bands from the fluorescent lights often overlap with sharp absorption bands from the holmium in the cubic zirconia. (a) shows the absorption spectrum and emission spectrum of a 4150 K fluorescent light, (b) shows

Apatite can have moderate color-change properties (figure 16). The optical spectrum of apatite (figure 17) shows numerous sharp features that originate from rare-earth elements, particularly neodymium (Nd^{3+}), that are minor components in the apatite. The Nd absorption will particularly absorb the emission from a common type of fluorescent lamp, which is why the sample in figure 16 illuminated by fluorescent light shows the greatest color change.

Some minerals change color when exposed to light of different wavelengths in a process known as *tenebrescence*. Sometimes the sample will return to its original color in a matter of minutes when put in darkness, and sometimes it takes days to months for the original color to return. One of the most famous examples of this property is the hackmanite variety of sodalite. One minute's exposure to sunlight can cause some samples to turn from nearly colorless or pale pink to a dark purple-red (figure 18). When placed in darkness, the return to the pale color may take weeks to months. But the process can be repeated time and time again.



Figure 13. The color of the 4.60 ct zircon is shown in LED illumination with cool white light at 6500 K (left) and in warm white light at 2700 K (right). Photos by Robert Weldon/GIA. Modified from Palke (2021).

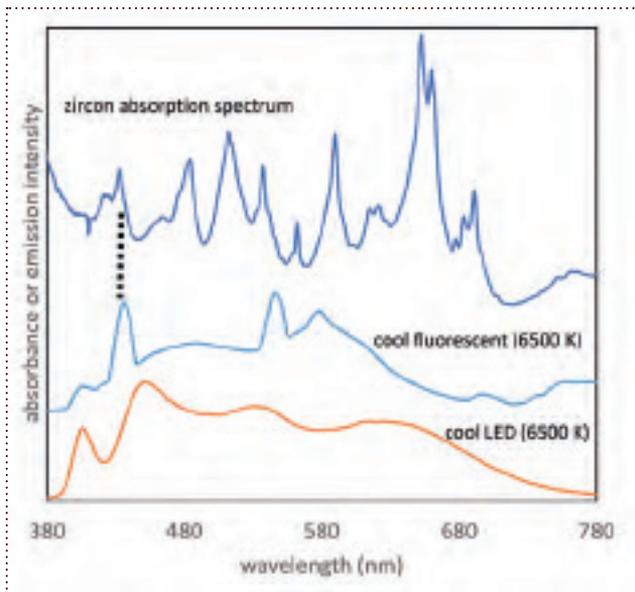


Figure 14. The visible absorption spectrum of the color-change zircon (top) compared to the emission spectrum of a standard cool (6500 K) fluorescent illuminant showing the overlap of sharp emission bands from the fluorescent light and sharp absorption bands in the absorption spectrum (see dashed line). Also shown is the emission spectrum of the cool (6500 K) LED used in GIA laboratories for color grading. From Palke (2021).

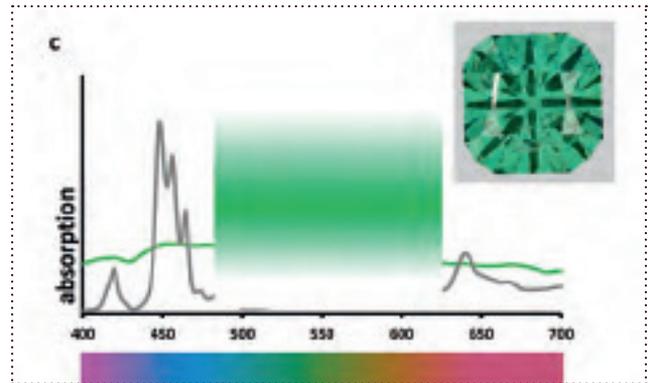
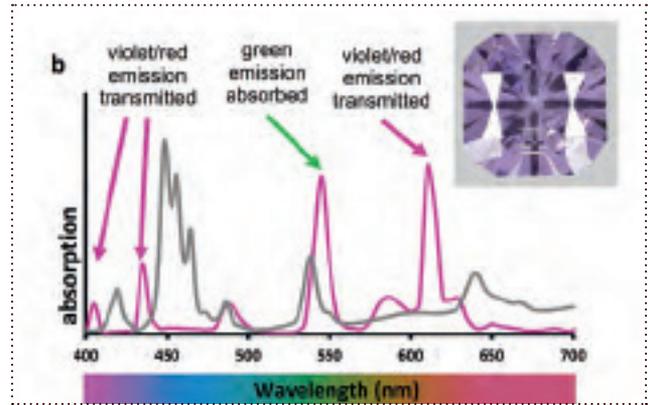
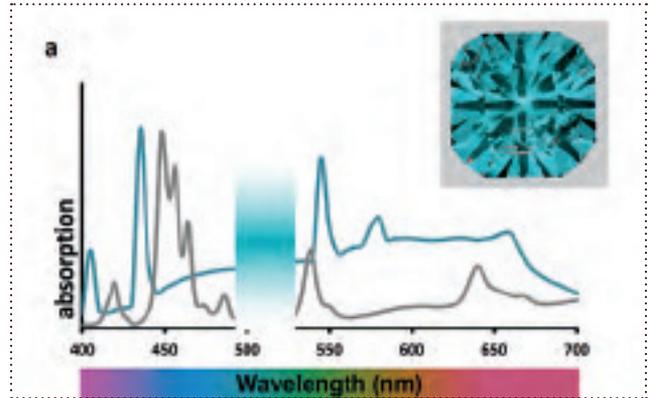


Figure 15. A.B.C. Holmium-doped cubic zirconia can show numerous different colors depending on the illuminant. Fluorescent lights in particular produce a varied effect, as the sharp emission bands from the fluorescent lights often overlap with sharp absorption bands from the holmium in the cubic zirconia. (a) shows the absorption spectrum and emission spectrum of a 4150 K fluorescent light, (b) shows the absorption spectrum against the emission spectrum of a 5000 K fluorescent light, and (c) shows the absorption spectrum against the emission of daylight-equivalent D65 illuminant. From Sun et al. (2017b).



Figure 16. An apatite crystal under different illuminations. Photos by John Rakovan.

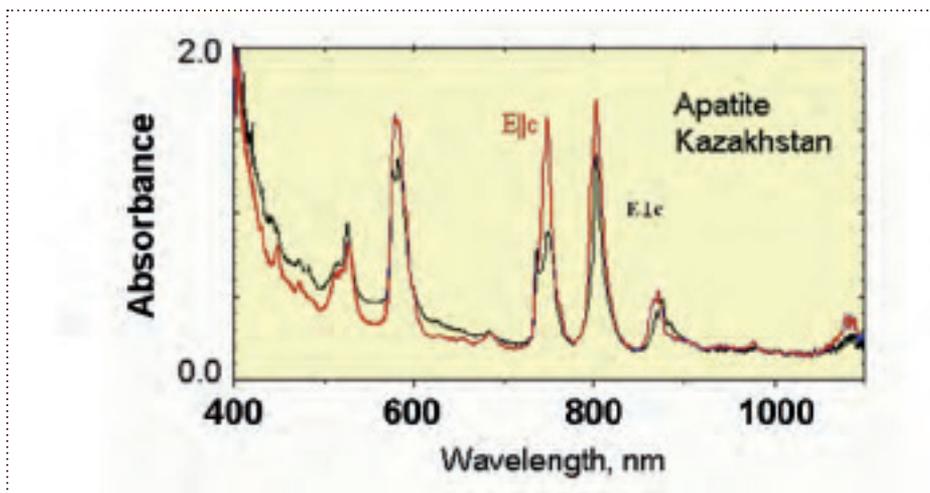


Figure 17. The absorption spectrum of an apatite showing strong absorption features from neodymium.



Figure 18. The color change in hackmanite (a variety of sodalite) when exposed to sunlight can be quite dramatic.

What causes this change in hackmanite? It is related to sodalite's sulfide content. A current model suggests that the S^{2-} ion is bound to sodium ions in a cage-like environment which must be next to a cage where the S^{2-} ion is missing. Light exposure transfers an electron from the S^{2-} ion turning it into the S^- ion and moves an electron into the adjacent site where the S^- ion is missing.

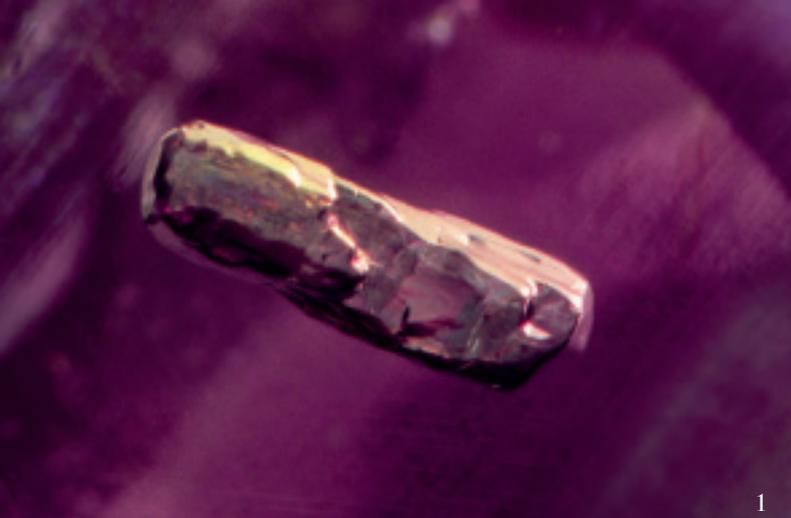
In addition to chameleon diamonds, which change color on exposure to light, some zircons also change color when exposed to intense incandescent light and others change color when exposed to ultraviolet light. Some blue zircons will turn black under ultraviolet light and only slowly revert back to blue when kept in darkness for extended periods of time.

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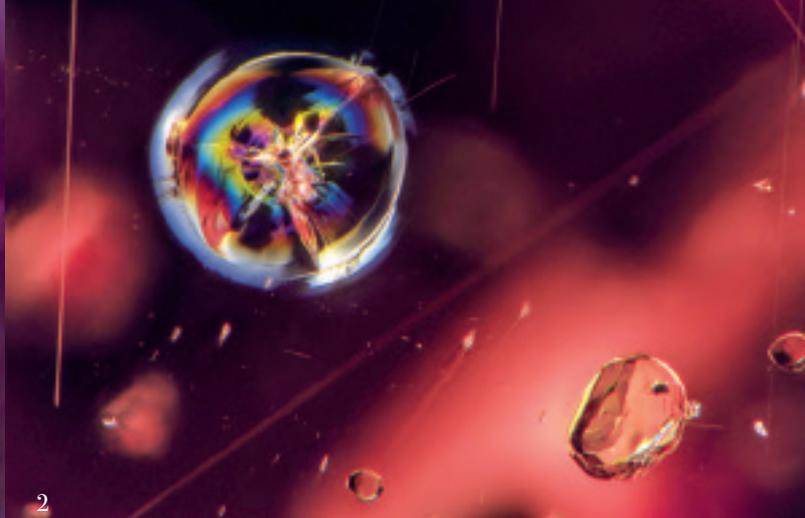
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Above: Incandescent light view of a 4.88 ct alexandrite crystal from Mogok, Myanmar, measuring 12.50 x 6.90 mm; see page 32 for a photo of the same crystal in daylight. Courtesy of William Larson. Photo by Robert Weldon.



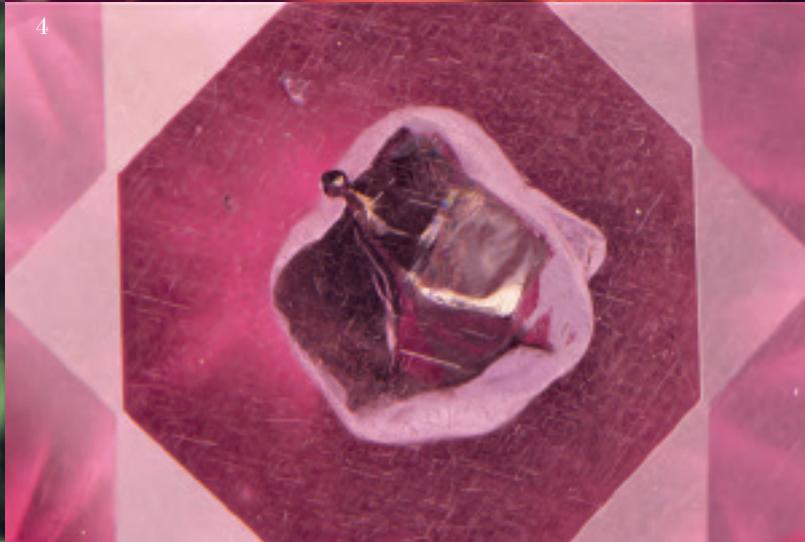
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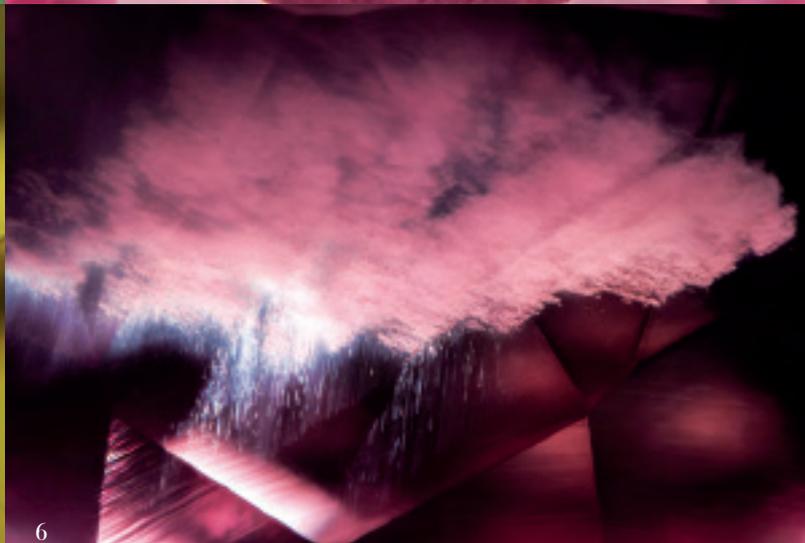
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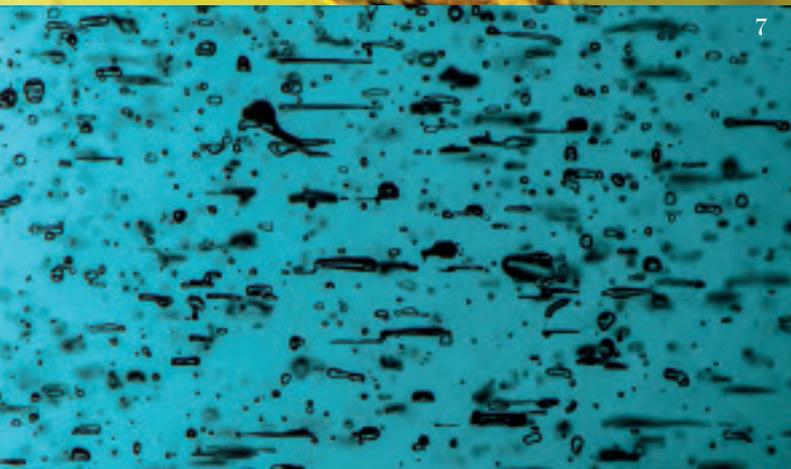
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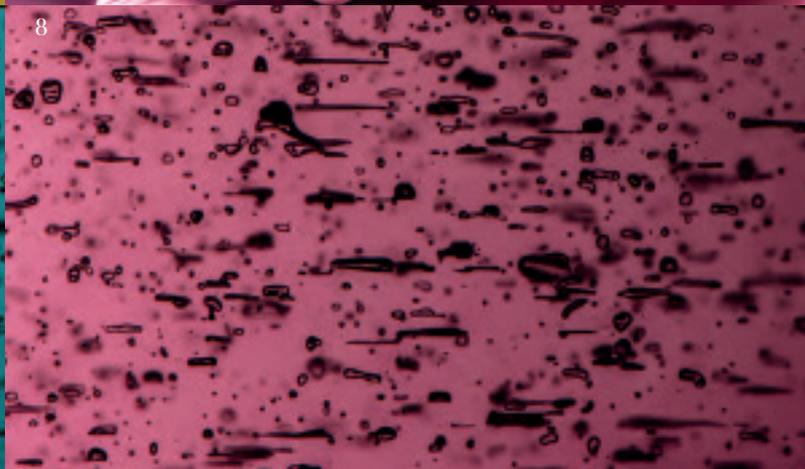
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The Micro-World of Alexandrite and Other Color-Change Gems

Nathan Renfro

While chrysoberyl generally forms in pegmatitic environments, the color-change variety alexandrite generally exists in metamorphic environments such as amphibolites and mica schists that resulted from pegmatitic influence. As a result, the types of mineral inclusions found in them are often reflective of both metamorphic and pegmatitic environments. Minerals such as amphiboles, micas, fluorite, and apatite are often found in alexandrite gems. Other color-change gems can showcase a wide array of inclusions, with garnets being host to rutile, metal sulfides, zircons, and many others.

Transparent color-change gems can showcase a wide range of interesting inclusions that tell the story of a gem. While the examples shown here are in no way comprehensive, they provide some reference to the range of inclusions that might be encountered in such stones.

1. Crystals such as this elongate apatite are occasionally seen in alexandrite. Photomicrograph by Nathan Renfro; field of view 2.56 mm. Stone courtesy of the John Koivula Inclusion Collection.

2. Radiation damage from a monazite inclusion has created a tension crack with vibrant interference colors in this color-change garnet from East Africa. Also present are apatite crystals. Photomicrograph by Nathan Renfro; field of view 2.27 mm. Stone courtesy of the John Koivula Inclusion Collection.

3. Fluorite inclusions in alexandrite are indicative of Brazilian origin. Photomicrograph by Nathan Renfro; field of view 2.79 mm. Stone courtesy of the John Koivula Inclusion Collection.

4. This color-change pyrope garnet colored by vanadium contains a large metal sulfide inclusion just under the table facet. Photo by Nathan Renfro; field of view 5.47 mm. Stone courtesy of the John Koivula Inclusion Collection.

5. Green pargasite and orange spinel are rare inclusions in this color-change sapphire colored by vanadium. Photomicrograph by Nathan Renfro; field of view 2.58 mm. Stone courtesy of the John Koivula Inclusion Collection.

6. This Russian alexandrite contains a dense particulate cloud of minute needle-like inclusions that is remarkably reminiscent of a raincloud. Photomicrograph by Britni LeCroy; field of view 2.90 mm.

7 and 8. A dense field of gas bubbles are seen in this pulled synthetic alexandrite. Photomicrographs by Nathan Renfro; vertical field of view 6.55 mm. Stone courtesy of the John Koivula Inclusion Collection.



Price Trends of Alexandrite and Other Color-Change Stones

Stuart Robertson

The presence of a phenomenon such as change color in a gemstone enhances its value relative to similar gemstones without such feature. In such gems, the keys to value are the vividness of each hue and the degree to which the color changes. And when it comes to color change, one gemstone is synonymous with this effect—alexandrite.

In the traditional sense of the term, alexandrite is among the rarest of all gems. This is due to the extent of its color change. In its finest specimens, the colors jump to opposite sides of the color wheel. For example, green (or bluish green) to red (or purplish red). Actually, the mystique of the “emerald green to ruby red” colors of the best Russian stones, which continues to be promoted to consumers by the industry, is in my opinion counterproductive to today’s gem trade. Extremely few alexandrites occur in these exceptional colors. As a result, most consumers inquiring about a fine alexandrite are not shown what they were expecting. And those who do see an “emerald green to ruby red” color change likely cannot afford the stone in front of them.

In my opinion, the more meaningful benchmark for alexandrite in the contemporary market is established by the material discovered in Brazil during the mid-1980s. The material exhibited a range of colors, but much of it had a bluish green to purplish red color change. The quantity of material produced over the initial three-month period of mining was substantial enough to generate strong international interest. This source really established the demand for all qualities of alexandrite observed during the past thirty years. More recent discoveries in East Africa and production from Sri Lanka have also supported the growth in demand of alexandrite.

Regardless of locality, the market for the finest alexandrites tends to be limited to collectors and gem aficionados. For this reason, truly exceptional stones always attract a buyer.

Price trends for alexandrite are influenced by factors similar to those that attract buyers to the finest natural rubies: promotion by high-end retailers and designers, as well as demand from collectors and sophisticated jewelry connoisseurs seeking extravagance or wealth preservation.

It is not unusual to encounter alexandrite stones that change color position between more closely aligned hues on the color wheel—for example, yellow to green-yellow. In more recent decades mass merchandisers and TV-based gem retailers have successfully cultivated a market for the more affordable pastel-colored or nontraditional-colored alexandrites. More pricepoint-conscious consumers responded to the emphasis on promoting the gem variety and its rare ability to change color than they did to the quality of the color change itself. Technically, any chrysoberyl that exhibits a color change is alexandrite. But many dealers relate the term only to those gems that change from some degree of green to some form of red. The term “color-change chrysoberyl” may be encountered among purists for those stones that exhibit a change among closely related hues. The lack of a uniform definition among gemologists and dealers must be considered when pricing and marketing these stones.

In addition to alexandrite, there are several other gem varieties that exhibit a true color change. Sapphire and garnet are the most notable in this group. Both have also been getting some attention from custom jewelers and designers in recent years.



Above: Pastel-colored alexandrite. Courtesy of Mayer & Watt.

Facing page: The frog in this Wallace Chan titanium pin features cat’s-eye alexandrite eyes; the leaf contains jadeite cabochons, green garnet, yellow and white diamonds, and emeralds. The jewel contains 16.66 g of titanium and 1.98 g of white gold. Courtesy of Wallace Chan. Photo by Robert Weldon/GIA.



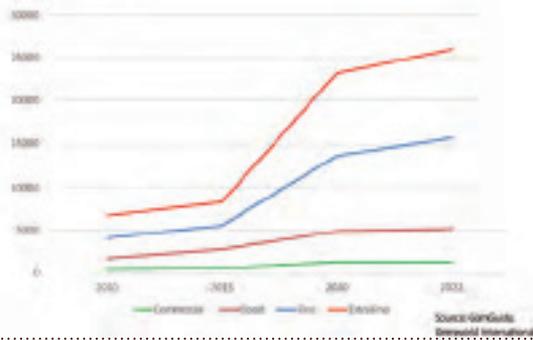
Above: 3.62 ct alexandrite from India. Courtesy of Tim Roark Inc. Photos by Orasa Weldon.



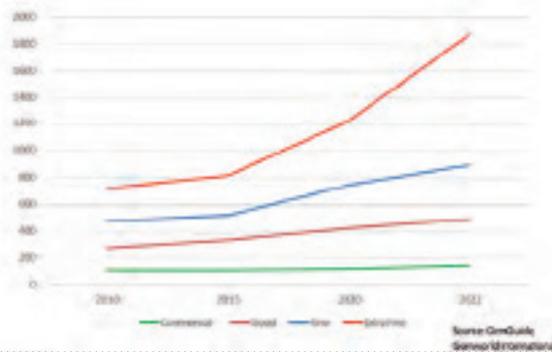
Above: This 12.18 ct color-change sapphire is from Sri Lanka. Courtesy of Pala International. Photos by Mia Dixon.
Below: 6.88 ct color-change pyrope garnet. Courtesy of Meg Berry. Photos by Orasa Weldon.



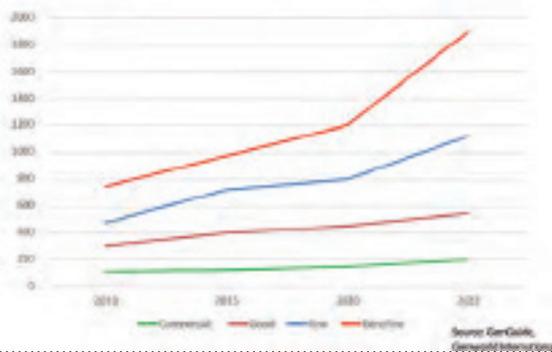
Alexandrite 1 ct
Prices are average per carat, wholesale



Color Change Sapphire 1 ct
Prices are average per carat, wholesale



Color Change Garnet 1 ct
Prices are average per carat, wholesale





Above: This color-change sapphire, 50.08 ct is from Sri Lanka. Courtesy of Edward Boehm. Photos by Robert Weldon/GIA

For garnet, this special member of the pyrope-spessartine series is often sought by collectors and gem aficionados for its vibrant colors. However, they are also occasionally featured in finished pieces by better-known jewelry designers. Although not inexpensive relative to alexandrite, it is an affordable alternative. Color-change garnet, like color-change sapphire, is certainly attractive enough to stand on its own merit. Too often, however, these stones are thought of as the “poor man’s alexandrite.” This is not the way to maximize the market potential for these special gems.

The production of color-change garnet is sporadic at best, and therefore not available in the quantities necessary to generate broader market attention. This is why it’s most often appreciated by designers and custom jewelers. Attention from the designer market has helped support long-term price growth during the past decade (as indicated in the accompanying chart). Emphasis is on the finer qualities, as demand is coming from more financially secure buyers.

Regarding color-change sapphire, there is less emphasis on the color change vs. color shift. It is more common to see subtle movement between adjoining hues on the color wheel as opposed to a dramatic leap across the wheel that can often be observed in alexandrite and also garnet. The influence of the color-change property can be less for sapphire than

for garnet. It is not uncommon for color-change sapphire to move through the market without emphasis on the phenomenon. This is especially true of some purple sapphires as well as some blue sapphires.

The market for color-change gems is experiencing growth of both demand and value. As with most gems of the finer grades, it is expected the current growth-favored trend for alexandrite, color-change garnet, and sapphire will continue but with some periods of pause as the global economies cope with a number of near-term issues that will stifle demand for all but the finest materials, where their role for wealth preservation will accelerate.

As the market for these rarities evolves, the gem trade would benefit from a clearer definition regarding variety names, especially in regard to what constitutes alexandrite vs. color-change chrysoberyl.



Above: A phenomenon known as “reverse” color change results when warmer light temperatures result in cooler colors observed in a gem material. Conversely, warmer colors are observed in daylight-equivalent lighting. These “Laurellite” tourmalines courtesy of the Bruce Fry collection exhibit such a color change. Photos by Robert Weldon/GIA.



Overview of the Geology and Mining of Alexandrite

Wim Vertriest

Alexandrite is a true miracle of nature, not only because of its phenomenal quality. The gem's natural formation itself is caused by a combination of various complex processes within the earth's crust.

The growth of minerals is dependent on the physical conditions, often simplified to the pressure and temperature, as well as the right chemical environment. While the presence of volatiles can be important, the most important factor is the availability of the correct ions.

The mineral chrysoberyl consists of beryllium, aluminum and oxygen. The color-changing variety is colored by chromium. These are the ingredients required to form alexandrite.

Oxygen and aluminum are widely available in the earth's crust, so these will not be the bottlenecks for chrysoberyl formation. Beryllium on the other hand is much rarer, but it tends to concentrate in certain rock types. Pegmatites are sometimes disrespectfully referred to as "the granites trashcan." All elements that don't fit in the most common minerals (quartz, feldspar, etc.) tend to concentrate in the leftovers, which eventually crystallize as pegmatite. This leads to increased concentrations of elements such as fluorine, boron, and lithium, as well as the minerals that include them in their structure. Most beryllium-rich minerals form in association with this type of rock, and chrysoberyl is no exception.

All our necessary ingredients are present in beryllium-rich pegmatites, but we also have to account for the presence of other elements that might prevent formation of chrysoberyl. These pegmatite rocks often have high concentrations of silicon. Under most physical circumstances, the combination of all these elements results in a whole different mineral: beryl.

Due to these similarities, we can draw many parallels between chrysoberyl and beryl formation. When we add the chromophore chromium into the mix, we are talking about emerald and alexandrite. We only have to account for that limited amount of silicon in the environment. Simply stated, we are looking for an environment where all the ingredients for an emerald are present but without any of the available silicon in most pressure-temperature environments.

The most common situation where this happens is when a pegmatite intrudes a mafic/ultramafic rock. Beryllium is supplied by the pegmatite, while the dark rock hosts some chromium. At the interface between those two rock types, a reaction zone develops. This is typically characterized by high concentrations of dark biotite mica as well as beryllium mineralization that has some chromium in it. Typically this would be emerald, but local depletion of the available silicon content could lead to mineralization of chrysoberyl/alexandrite (Martin-Izard, Paniagua et al. 1996). That does not mean that silicon availability is the only variable that influences this. At more extreme conditions (higher temperatures), chrysoberyl is actually the preferred mineral to form, even when sufficient Si is present to create beryl (Franz and Morteani 1984).

Either one of these reasons, or a combination of both, is responsible for the formation of the world's most famous alexandrite deposit: the Ural Mountains of Russia (Kiefert 2007, Burlakov and Burlakov 2019). It comes as no surprise that these color-change stones are intimately related with emerald formation; in fact, both materials are mined in the exact same mines. Similar geological formations are found near Lake Manyara in northern Tanzania, which is a known

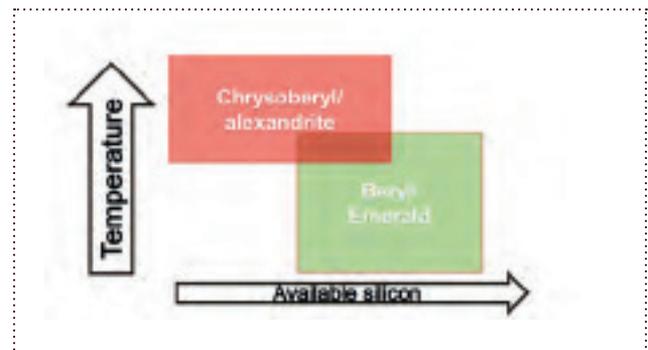


Figure 1. An approximate diagram of the required conditions to form chrysoberyl and beryl. **Facing page:** Tanzanian alexandrite crystal, 30.06 x 26.02 mm. Courtesy of William Larson. Photo by Robert Weldon.

producer of both gems, and in Mananjary, Madagascar, where crystals of alexandrite are found sporadically in the emerald mines (Schmetzer and Malsy 2011, Schmetzer 2012). These mineralizations are always associated with high volumes of dark mica, which is seen in matrix but also as inclusions in the gems (Schmetzer, Bosshart et al. 2010).

Most of these deposits are mined for the emeralds, with the alexandrites as a byproduct. Since emeralds are rather fragile crystals, they are mined almost exclusively directly from the host rock in primary deposits. This has some drawbacks since it requires more energy to extract the gems. Waste rock needs to be removed, often with the use of heavy equipment, and the gems need to be carefully extracted without too much damage. On top of that, natural action has not reworked this deposit, so the gems are sparsely dispersed throughout it and there is an entire range of qualities, sizes, and colors coming from these mines.

Alexandrite is also found in secondary deposits where they have been removed from their original host rock and are concentrated by natural forces. This has advantages for miners, who simply need to access the gravels where those gems are now found. There is no need for explosives or drilling. These deposits are typically richer in high-grade gem material as well. This kind of alexandrite deposit is well documented in Brazil, southern Tanzania, Madagascar, and Sri Lanka (Proctor 1988, Currie 1994, Johnson and Koivula 1996, Johnson and Koivula 1997, Milisenda, Henn et al. 2001).

In Sri Lanka, miners often construct deceptively simple constructions to descend into the earth and reach the gem-rich layers. In reality, these mines require a highly skilled team to operate and function well. While the actual diggers are critical, the importance of the supporting team cannot be overlooked. This crew of carpenters and engineers makes sure that the mine tunnels don't collapse. They do this by supporting the structures with custom-made wooden beams and keeping the water pumps running to prevent flooding of the tunnels. Working as such a tight-knit team, they are able to mine gems under flooded rice fields. Gem-rich gravel, locally referred to as *ilam*, is stockpiled and washed in the iconic conical baskets in the canals surrounding the rice paddies. This often results in a mix of gems, with sapphire being the most desired stone, but chrysoberyl and alexandrite are found alongside them.

In Madagascar, the risk of flooding is minimal since Ilakaka is located in an extremely arid zone. Miners can often dig more than 40 meters deep without encountering the water table. Many of the mines are open pits, but in some area they prefer to dig shafts to deeper gem-bearing layers. The lack of water might make mining easier, but it poses a challenge for washing the gravels and gems. Oftentimes they have to transport this to nearby rivers where huge washing

places are set up and many workers sift through bags of gravel in search of gems.

The disadvantage is that understanding the geological formation of these deposits is very complex since the tangle connection with the original host rocks has been cut by natural erosion. This leaves very little evidence of its geological formation apart from its chemical buildup and the inclusions that survived within the chrysoberyl crystals. At this time, our understanding of the formation of these stones is very limited.

We can, however, speculate on the mineralization that created these deposits. Is alexandrite the only beryllium mineral that formed? Perhaps the conditions where they formed simply didn't allow for minerals such as beryl to grow as well, due to higher P-T conditions or low silicon activity.

Is alexandrite the only beryllium mineral that survived and/or was concentrated? Of all beryllium-rich minerals, chrysoberyl is the hardest and has the highest density, which makes it an ideal candidate to survive the weathering process and be trapped in natural placer deposits. While beryl's hardness makes it suitable for jewelry, it is often too fragile to survive these natural weathering processes. This applies especially to emerald, which tends to have abundant natural fractures. Most other beryllium minerals have lower densities as well, so they are less likely to concentrate in secondary deposits.

While alexandrite has been studied extensively for its gemological phenomena, our understanding of its geological formation is limited. Only at a handful of locales are commercial mining operations taking place in hard rock. It is at these locations where we see a clear link with other beryllium mineralization in the form of emerald.

Most of the alexandrite/chrysoberyl gems are found in secondary deposits, where most links with the original host rock have been severed and the geological formation is not yet understood.

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Gem Photography's Biggest Challenge: Photographing Color-Change Gemstones

Robert Weldon

Photography of gemstones is a specialized art. It involves knowing a little about gemology—mainly how light reacts within a gemstone. Understanding the basics of reflection and refraction is valuable, and leveraging that knowledge to coax a gemstone subject to show its “best face forward” really helps with the photography.

Photographing the so-called alexandrite effect involves a slightly different process than what is used for most transparent gemstones. Capturing the color change requires specific color temperatures of light, much the way one views them in actual life. When we look at an alexandrite, for example, we tend to look at it in open shade on a sunny day to view the green to blue-green colors, then move it indoors, to incandescent light, to observe the color change shifting toward magenta and red.

Basic Tools: Lights, Camera, Action!

First, a bit of requisite information: My studio is about 20 feet square, with walls that are a neutral gray color, and I make sure the lights are of a single-color temperature. The one window I have is blocked out. The stage is centered in the room (so I can walk around it) and a desktop computer is tethered to my camera for near-instantaneous results. Using this method, I can compare the color I'm seeing in the actual gem and how it renders on a well-calibrated monitor. But even when lighting conditions are optimal, photographing color change is challenging. Often, what you see is not what you get. Back when film was used, color was even more demanding to get right. Because film often took a few days to develop, comparing the actual stone with the results was difficult.

Photography has also been made easier with LED lights that have variable color temperatures; this nuanced continuous light works well. However, the disadvantage of continuous light is that longer exposures are necessary, increasing the risk of camera shake—and a blurred image. A tripod is essential for these prolonged exposures. The tripod also helps to frame the picture and obtain critical focus. However, it is possible to use color gels (between the light source and the stage) to change the light's color temperature with strobe or flash

photography. This brief burst of powerful light eliminates the camera shake factor. Many camera brands are available (I use Nikon and Fujifilm). It is also possible in 2022 to take decent pictures with mobile phones, as resolution, color rendition, and optics have vastly improved. Ultimately, mobile phones are the cameras you always have with you! I use a dedicated macro lens on my DSLR and mirrorless cameras, such as the 105 mm Micro-Nikkor.

Finally, having a diffuser between the light source and a transparent gemstone helps minimize hot spots in the image. I use a soft light box attachment on my light unit. It scatters and softens light, eliminating bright hot spots in a gemstone. It also helps bring out the gem's color. Gems with two phenomena, such as cat's-eye alexandrite, are even more challenging.

Diffused light does not work with cat's-eye alexandrite! It is preferable to use a fine, pinpoint source of illumination. Because the cabochon dome shapes reflect everything in their vicinity, like a mirror, it is important to have an uncluttered working space. I have set up an improvised outdoor studio and shot a cat's-eye alexandrite in open sunlight at high noon. There is probably no better pinpoint of light than that! However, LED fiber-optic lighting, which has variable color temperature, would be wonderful. I don't have one. I use a clamped flashlight with gels in front of the light source to alter the color temperature.

Color Temperature

By now, you might gather that it's all about light. It is! With color-change gemstones, it's also about the color temperature of light, as I mentioned above. It is a characteristic of the visible light spectrum. Often this is expressed in Kelvin, or simply, “K.” This refers to light in a range going from red to orange (2700–3500 K) to yellow/white (5000–6500 K) to bluish white (6500–9500 K). The chart on this page gives us a sense of color temperature.

Facing page: 32.96 ct color-change zircon from Myanmar, exhibiting a deep blue to violet color in daylight and blue-green in incandescent. Courtesy of Mike Bowers. Photo by Robert Weldon.



Software to the Rescue

Even with studio lights that readily change color along the Kelvin chart—my Profoto lights go from 3000K–6500K—the resulting photograph on the monitor often is still not strong enough or does not show the colors we are seeing. This is when having the gemstone at your fingertips is very helpful. As all digital images go through software for post processing—I use Adobe Photoshop—it becomes a matter of routine to correct the color and bring it in line with what you are seeing in the actual gem. A serious note of caution: Photoshop is there to help us achieve what we are seeing, to remove bits of dust, or to accentuate a background. Moving beyond that, for example accentuating the colors of a gem to make them redder or greener than what we are seeing, or adding a cat’s eye that doesn’t exist, catapults us into an ethical dilemma. Think of it this way: A client may fall in love with the color change that’s achieved through Photoshop. But imagine their disappointment when the actual color change is not as dramatic as the one in the image. A gem—or jewelry for that matter—should be represented as closely as possible to what we see.

Now that we have those cautionary words out of the way, I’d like to show you how I adjust color in Photoshop with a series of visuals. This is more of an intermediate to advanced Photoshop lesson.



Above: This Brazilian alexandrite crystal and accompanying faceted gem, both from the Hematita mine in Brazil, exhibit a substantial color change between daylight-equivalent light and incandescent light. Photo by Robert Weldon; courtesy of William Larson. **Top left:** This cat’s-eye alexandrite was photographed in daylight, using the sun as a pinpoint light source.



Above: The Kelvin color range from warm to cool hues are used in a studio to photograph the alexandrite effect. The green arrow represents the area in the visible range that I use to photograph the color change. Diagram and garnet images by Robert Weldon.

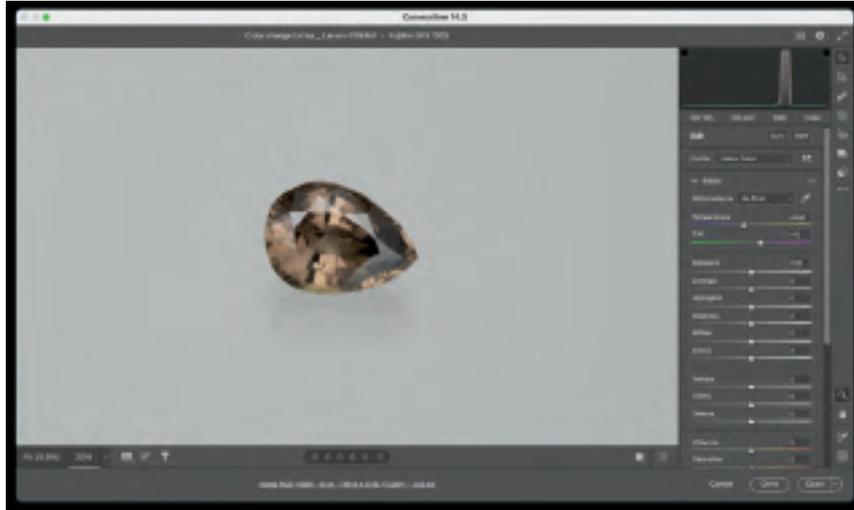


Figure 1. The image of the pear-shaped alexandrite appears an odd mix of yellow/pink/brown in daylight-equivalent light with no adjustments in Adobe Camera Raw. Camera Raw is where you can begin to affect the color before opening the image in Photoshop. However, the gem appears much greener to my eyes. Clearly, some adjustments in color are necessary.

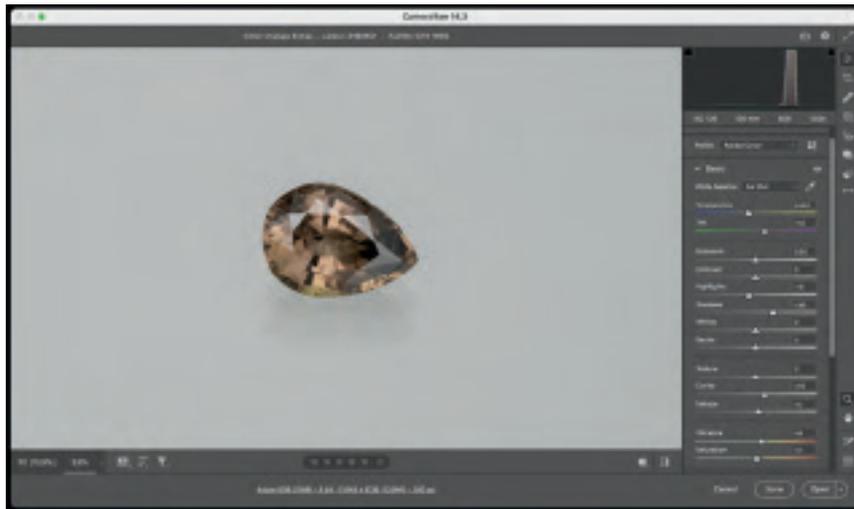


Figure 2. I can make some basic adjustments such as increasing the clarity, lightening some of the shadow areas, and minor adjustments in vibrance and saturation.

Once you have opened your image in Photoshop, you can begin to adjust. (Figure 1-4).

It is best to make these adjustments when your eyes are fresh, when you are viewing the gemstone in the correct lighting conditions, and when your monitor is fully calibrated.

Over the years I've had the privilege of photographing several color-change gemstones, and the gallery open for you here is based on those opportunities. But it would never have happened without the careful selection and curation of spectacular gems and mineral specimens by several different collectors, cutters, gem dealers, and jewelry designers. I thank them.

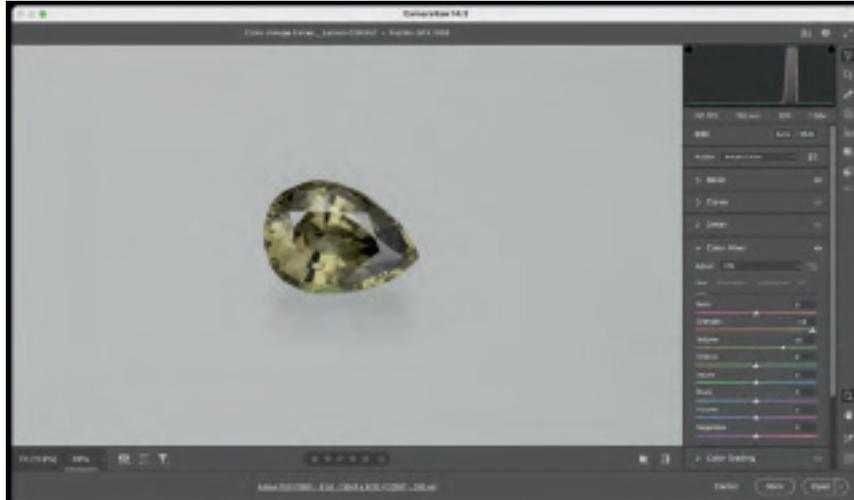


Figure 3a.

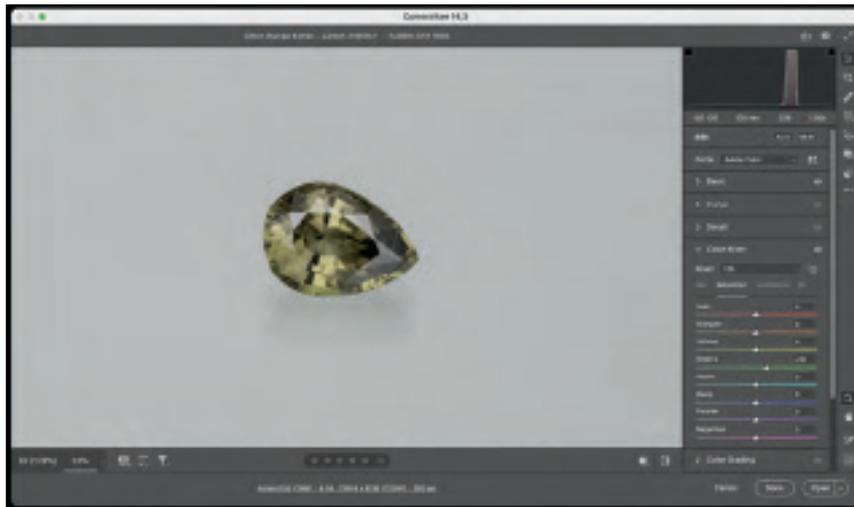


Figure 3b. To make initial adjustment to the bodycolor of the gem, I examine the gem itself in hand. I go to the "Color Mixer" adjustment tool, and in the "Hue" slider I move the color (in the orange slider) from the orange range toward the yellow-green range. I also move the yellow slider toward the greener side. The gem has changed color to a vague olive green before opening it in Photoshop. I then go to the "Saturation" tab and slide it toward a more saturated green. Now it is time to open the image in Photoshop. I click on "Open" in the bottom right.

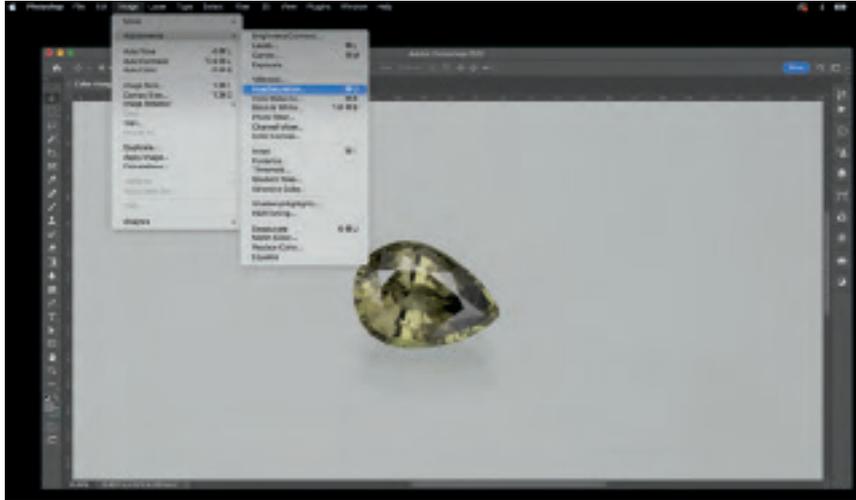


Figure 4a.

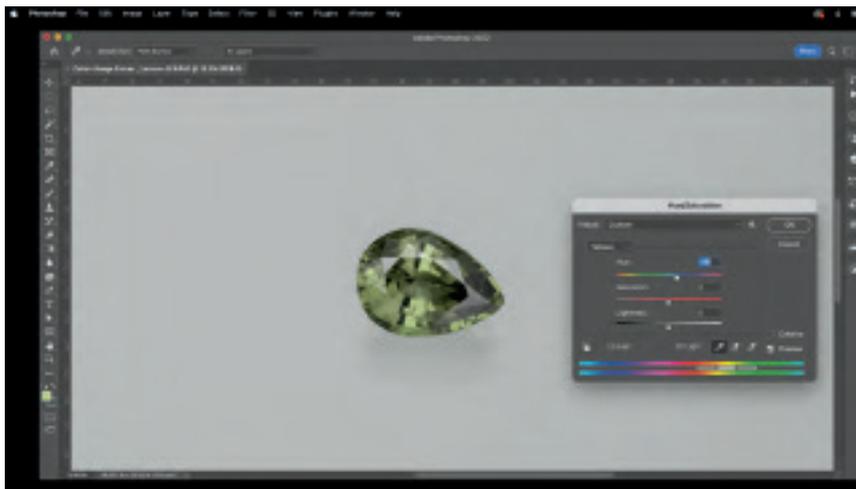


Figure 4b. In the Hue/Saturation dialog box, I choose yellow, as the image of the gem still appears yellowish. The slider range is in the yellow to green zone. Sliding the "Hue" slider slightly toward the right, the image appears much more the way I am seeing it with my eyes. The image color has been corrected from yellowish brown to green for the daylight-equivalent color.



Above and opposite page: While not a color-change gem in the classic sense, this 12.63 ct fluorescent hyalite opal from Zacatecas, Mexico changes dramatically under different lighting conditions. In daylight-equivalent studio lighting, the gem is a pale yellow color, with then fluoresces a vivid, neon green under UV; a few of the diamonds fluoresce as well. Designer Loretta Castoro takes advantage of the fluorescent effect in her design concept, which she says would be dramatic to wear in a nightclub, where “black light” would excite the vivid color. Courtesy of Loretta Castoro, photo by Robert Weldon/GIA.



Conclusion

While photographing color-change gemstones has its challenges, the joy of revealing a gemstone's true color and personality is more than ample payback. Remember that many of the same requirements for viewing color change in gems apply in photographing them. Those rigors often need to be followed with subtle color correction using post-processing photography software. Go forth and conquer!



Geographic Origin Determination of Alexandrite

Ziyin Sun, Aaron C. Palke, Jonathan Muyal, Dino DeGhionno, and Shane F. McClure

Abstract: The gem and jewelry trade has come to place increasing importance on the geographic origin of alexandrite, as it can have a significant impact on value. Alexandrites from Russia and Brazil are usually more highly valued than those from other countries. In 2016, GIA began researching geographic origin of alexandrite with the intent of offering origin determination as a laboratory service. Unfortunately, collecting reliable samples with known provenance can be very difficult. Alexandrite is often recovered as a byproduct of mining for other gemstones (e.g., emerald and corundum), so it can be difficult to secure reliable parcels of samples because production is typically erratic and unpredictable. The reference materials studied here were examined thoroughly for their trace element chemistry profiles, characteristic color-change ranges under daylight-equivalent and incandescent illumination, and inclusion scenes. The data obtained so far allow us to accurately determine geographic origin for alexandrites from Russia, Brazil, Sri Lanka, Tanzania, and India. Future work may help to differentiate alexandrites from other localities.

In Brief

- Geographic origin can significantly affect alexandrite's value.
- Collecting reliable alexandrite samples with known provenance can be very difficult because production is typically erratic and unpredictable.
- Trace element chemistry data obtained from LA-ICP-MS are the primary consideration in determining its geographic origin.
- Color-change behavior and inclusions are used as secondary factors to support the geographic origin determination.

After the discovery of a gem mineral with unusual color-change behavior in the Russian Ural Mountains during the early 1830s, Swedish mineralogist Nils Adolf Erik Nordenskiöld named this new gem alexandrite in 1834 in honor of the future Czar Alexander II (Kozlov, 2005). This immediately created a royal and romantic aura around this variety of chrysoberyl. The most coveted alexandrites exhibit a lush green to greenish blue color in daylight and a warm, bright red shade in candlelight (Levine, 2008); some fine Brazilian and Indian alexandrite examples are shown in figures 1–3 and 6. This phenomenal color change is caused by the presence of trace Cr^{3+} substituting for Al^{3+} in the chrysoberyl crystal structure. Alexandrite is routinely described as “emerald by day, ruby by night.” It is a stone of duality—green or red, cool or warm, day or night (Levine, 2008). Because of its rare and attractive color-change phenomenon, alexandrite has been highly sought after and is one of the most valuable gemstones in the trade.

Alexandrite, particularly fine-quality material, is also very scarce; it has generally been a byproduct of mining other major colored stones. Overall production statistics are hard to evaluate. It has been mined in Russia (Kozlov, 2005; Schmetzer, 2010), Tanzania (Gübelin, 1976; Schmetzer and Malsy, 2011b) and Zimbabwe (Brown and Kelly, 1984; Schmetzer et al., 2011) as a byproduct of emerald mining, and in Brazil (Proctor, 1988; Cassedanne and Roditi, 1993; Voynick, 1988) and India (Newlay and Pashine, 1993; Patnaik and Nayak, 1993; Panjekar and Ramchandran, 1997; Voynick, 1988; Valentini, 1998) along with cat's-eye and nonphenomenal chrysoberyl, as well as other pegmatitic minerals. In Sri Lanka (Zwaan, 1982; Zoysa, 1987, 2014), it is mined as a byproduct of corundum, cat's-eye and nonphenomenal chrysoberyl, and other minerals. The supply of alexandrite in the U.S. market has been low since the 1990s, as the supplies from the initial rush in Brazil presumably started drying up (Costanza, 1998). However, demand for the gemstone has

Facing page: A group of rings featuring alexandrite from Brazil. Showing daylight and incandescent (see page 62, figure 1 for more detail). Courtesy of Omi Privé. Photos by Robert Weldon/GIA.



Figure 1. A group of rings featuring alexandrite from Brazil. Top row, left to right: A three-stone alexandrite ring with a 1.35 ct center oval flanked by two smaller ovals with a combined weight of 1.29 carats and a ring with a 1.32 ct kite-shaped center stone flanked by two kite-shaped diamonds weighing a total of 0.32 carats. Bottom row, left to right: Rings featuring a 1.71 ct oval and a 0.72 ct cushion-cut alexandrite. The designs also feature melee-cut alexandrites of unknown provenance and diamonds. The image on the left was photographed in daylight-equivalent lighting, the image on the right in incandescent light. Detailed procedures for photographing the alexandrites shown in this article are provided in appendixes 2 and 3, online at <https://www.gia.edu/doc/WN19-Alexandrite-Appendixes2-3.pdf>. Photos by Robert Weldon/GIA; courtesy of Omi Privé.



Figure 2. This ring features a 0.72 ct Brazilian cushion-cut alexandrite with a strong color-change effect, and the design uses additional alexandrite melee and diamonds as accents. The loose oval alexandrite below the ring weighs 4.13 ct and hails from India. The image on the left was photographed in daylight-equivalent lighting, the image on the right in incandescent light. Photos by Robert Weldon/GIA; courtesy of Omi Privé.



Figure 3. This matched pair of cat's-eye alexandrites from Brazil exhibits double phenomena (color change and chatoyancy) and weighs a total of 2.43 carats. The design also features alexandrite and diamond melee accents. The image on the left was photographed with daylight-equivalent lighting and the image on the right with incandescent light. Pinpoint light was used to reveal the stones' chatoyancy. Photos by Robert Weldon/GIA; courtesy of Omi Privé.



Figure 4. The ring on the far left features a heart-shaped alexandrite from India. The second ring is mounted with an oval-shaped alexandrite—possibly from Madagascar—and melee-cut diamonds. All loose faceted stones are from Sri Lanka. The stones range from 4.01 to 22.99 ct. The image on the left was taken under an LED light source simulating daylight-equivalent lighting, while the right-hand image was taken under an LED light source simulating incandescent illumination. Photos by Kevin Schumacher; courtesy of LC Gem Collection Inc.

stayed high in the U.S., especially for large stones with high clarity and intense and distinctive color change (again, see figures 1–3 and 6). The situation has changed somewhat recently, with new production from Sri Lanka, Brazil, and Tanzania (Jarrett, 2015).

With the development of these modern sources and the subsequent rapid changes in the alexandrite supply chain, there is growing demand from the gem trade for geographic origin determination for fine alexandrite. Origin is increasingly important, as it is often used as a factor in establishing a stone’s value. Stones from Russia or Brazil can easily command a higher price than alexandrite from Tanzania and Zimbabwe with the same attributes. Because of all of these market factors, in 2016 GIA initiated a research project centered around alexandrite geographic origin determination. Since then, many samples have gone through the laboratories and had their characteristic chemistry, colors, and inclusions carefully documented. Reference stones with reliable provenance were obtained from multiple sources. The data collected on stones from a single country from various sources were generally found to be self-consistent, which corroborates the validity of the origin determination criteria developed. GIA announced the origin determination service in early 2019 and will continue to develop its alexandrite database to ensure the most accurate identification and origin reporting for the jewelry trade.

ALEXANDRITE GEOGRAPHIC LOCALITIES: A BRIEF SUMMARY

Russia. The original locality for alexandrite remains one of the most highly valued sources (Kozlov, 2005; Schmetzer, 2010). Alexandrites from Russia are generally a byproduct of emerald mining from metamorphic mica-schist veins in ultramafic host rocks. The micaceous rocks are called “glimmerites” because of the glowing sheen of the micas.

Russian production began in the 1830s but waned in the twentieth century when mining emphasis shifted to beryllium, and it lapsed with the fall of the Soviet Union in 1991. Recent efforts have been undertaken to increase Russian alexandrite production. There are a few important deposits: Mariinskoye (Malyshevskoye); Cheremshanskoye; Sretenskoye (Sverdlovskoye), where the first Russian emeralds were discovered; Krasnobolotnoye, where the largest and most beautiful Russian alexandrites were found in 1839; and Krasnoarmeiskoye. Of these, the Mariinskoye deposit has historically had the largest mining operation.

Sri Lanka. Sri Lanka is one of the world’s most important gemstone localities (Zwaan, 1982; Zoysa, 1987, 2014). The main gem-bearing areas are the Ratnapura district in Sabaragamuwa Province, Elahera in Central Province, Okkampitiya in Uva Province, and the Kataragama area in Southern Province. The chrysoberyl occurrences are more frequently found in and around Morawaka and Deniyaya in Southern Province. All of these gems occur in alluvial deposits underlain by Precambrian metamorphic rocks, and their original source remains unknown. There was little reliable information available on the amount and value of the gem material recovered in Sri Lanka until 1923, when the discovery of fine-quality alexandrites in Ratnapura’s Pelmadulla deposits was reported. There was a constant supply of Sri Lankan alexandrite in the market until the end of the 1980s, when production dropped (Proctor, 1988).

Most Sri Lankan alexandrites have a weaker color change than Russian and Brazilian stones (see the loose stones in figure 4), although finer-quality material can show color change from saturated green to red. However, Sri Lankan alexandrites often achieve large sizes with high clarity, and stones up to 600 ct have been examined by GIA.



Figure 5. A cyclical twinned Brazilian alexandrite mineral specimen, 4.13 cm in the longest dimension, shows distinct color change from green to red under daylight-equivalent lighting and incandescent illumination, respectively. The image on the left was taken under an LED light source simulating daylight-equivalent lighting, while the image on the right was taken under an LED light source simulating incandescent illumination. Photos by Kevin Schumacher; courtesy of John I. Koivula.

Brazil. In the 1980s, as Russia’s Uralian deposits were producing little and supplies from Sri Lanka were drying up, the pegmatite district in Minas Gerais, Brazil, became for a time the world’s major alexandrite producer (Koivula, 1987a,b; Proctor, 1988; Cassedanne and Roditi, 1993).

From 1846 until the 1980s, the Americana and Santana Valleys, near the city of Padre Paraíso in the Teófilo Otoni–Marambaia pegmatite districts, accounted for approximately 95% of the chrysoberyl and cat’s-eye chrysoberyl found in Minas Gerais. But fine alexandrites from the Americana, Santana, Gil, and Barro Preto Valleys were rare. Brazil’s foremost source of fine alexandrite was the Malacacheta region in the northeast of Minas Gerais State. Alexandrite was mined there from 1975 to 1988, with peak production in the early 1980s. In 1987, the Lavra de Hematita alexandrite deposit was discovered. This marked the greatest discovery of Brazilian alexandrite. To date, Hematita has yielded tens of kilos of alexandrite that are generally larger and cleaner than those from Malacacheta, including some faceted gems weighing up to 30 ct that exhibit extraordinary color change. A few locations in the adjacent states of Bahia and Espírito

Santo also produce alexandrite, albeit with an overall lower quality in terms of color, clarity, size, or some combination.

Most of the finest cyclical twinned alexandrite mineral specimens in today’s market come from Brazil (see figure 5). Brazilian alexandrites have a distinct color change that is often comparable to that of the finest Russian stones (see figure 6), but with a higher clarity, larger size, and much greater availability. Brazil also produces some of the world’s finest cat’s-eye alexandrite, such as the pair in figure 3 that exhibit a distinct color change and a sharp eye.

India. In the religions associated with Southeast Asia and the Indian subcontinent—Hinduism, Jainism, and Buddhism—cat’s-eye chrysoberyl holds a place of distinction among the Navratnas (a combination of nine sacred gemstones) (Brunel, 1972). Chrysoberyl has been mined in five Indian states—Kerala, Madhya Pradesh, Odisha (formerly Orissa), Andhra Pradesh, and Tamil Nadu—since the 1980s and ’90s. Alexandrite is found there either in pegmatites intruding granitic rock or in biotite schists developed along the contact zone of pegmatites and peridotites (Soman and Nair, 1985; Patnaik



Figure 6. A suite of fine Brazilian alexandrite exhibiting the finest color change seen in this material. The left image was taken under an LED light source simulating daylight-equivalent lighting, while the right photo was taken under an LED light source simulating incandescent illumination. Photos by Robert Weldon/GIA; courtesy of Evan Caplan.

and Nayak, 1993; Newlay and Pashine, 1993; Panjekar and Ramchandran, 1997; Valentini, 1998).

Indian alexandrines usually have a weaker color change than Russian and Brazilian material (see the ring mounted with a heart-shaped stone in figure 4). However, stones with good color change and clarity are comparable to the finest Russian and Brazilian specimens. The 4.13 ct loose oval in figure 2, representing top-quality Indian alexandrite, exhibited saturated blue-green color under daylight and saturated red under incandescent light. Many small Indian cat's-eye alexandrines with weak color change are fairly common in today's market, but Indian cat's-eye alexandrite with distinct color change and sharp eyes are rare.

Tanzania. Alexandrite has come mainly from two mining areas in Tanzania: Lake Manyara in the north and Tunduru in the south (Gübelin, 1976; Johnson and Koivula, 1996, 1997; Henricus, 2001; Schmetzer and Malsy, 2011b; Jarrett, 2015). Lake Manyara is a primary deposit where alexandrite has been found in a phlogopite-bearing schist. Alexandrite from Tunduru has been mined from a secondary alluvial deposit. Alexandrite from Lake Manyara (figure 7) entered

the market in the 1960s, with significant production into the early 1980s. Johnson and Koivula reported a wide variety of gem materials, including alexandrite, from Tunduru at the Tucson show in 1996. Since then, the area has been known for producing large quantities of alexandrite, and material from Tunduru was available in the U.S. market in 2015 according to Michael Couch of Michael Couch & Associates (Jarrett, 2015). In the early 2000s, emerald and alexandrite were reported from Mayoka, just outside Manyara National Park, by Abe Suleman, a director of the International Colored Gemstone Association and a member of the Tanzania Mineral Dealers Association (Henricus, 2001), but environmental concerns stopped mining activities in late 2000 and little material was produced.

A chameleon brooch mounted with beautiful rough alexandrite crystals from Lake Manyara on its back and small faceted alexandrines on its legs and tail changes from blue green to violet when viewing under daylight and incandescent light, as seen in figure 7.

Minor Alexandrite Geographic Localities. *Zimbabwe.* Alexandrite has been recovered from the Novello deposit



Above: Figure 7. Rough and faceted alexandrite from Lake Manyara, Tanzania. The left image was taken under an LED light source simulating daylight-equivalent lighting, while the right photo was taken under an LED light source simulating incandescent illumination. Photos by Robert Weldon/GIA; courtesy of Omi Privé.

of Zimbabwe’s Masvingo district (Schmetzer, 2011). It is located in a phlogopite-bearing host rock with surrounding serpentinite. Peak production was in the 1960s and 1970s and yielded larger, mostly non-facet-grade material. The material is considered very dark and only suitable for faceting small stones with intense color change. The deposit is believed to still produce alexandrite.

Madagascar. Alexandrite originating from phlogopite-bearing host rocks comes from primary emerald deposits in the Mananjary region of Madagascar (Schmetzer and Malsy, 2011a). The other deposit, in the Ilakaka region (Hänni, 1999; Milisenda et al., 2001), is a secondary deposit where different varieties of chrysoberyl—including alexandrite—have been found. Occasionally, large alexandrite crystals of gem quality have been recovered in the Lake Alaotra region.

Myanmar. In Myanmar (formerly Burma), the pegmatites in the western part of the Mogok Valley in Sakangyi or Barnardmyo, and the alluvial placers in the Mogok Stone Tract near Mogok, Kyatpyin, and Barnardmyo, have produced gem-quality alexandrite (“Alexandrite world occurrences...,” n.d.). Burmese alexandrites usually fluoresce intense red under long- and short-wave UV radiation due to lack of iron.

Australia. Dowerin is the first recorded alexandrite occurrence in Western Australia, known since 1930. The deposit has yielded many small crystals (Bevan and Downes, 1997; Downes and Bevan, 2002).

United States. In recent years, small chrysoberyl crystals with weak color change were reported from a mine at La Madera Mountain in Rio Arriba County, New Mexico (“Alexandrite world occurrences & mining localities,” n.d.).

Zambia. Some Zambian alexandrite with similar characteristics to Zimbabwean stones has appeared in the market. No reliable information is currently available.

MATERIALS AND METHODS

Reference Samples. GIA’s research project on alexandrite origin started in early 2016, with suites of alexandrites from both Russia and Brazil. Almost all Russian material came from Warren Boyd, who acquired them as a mining consultant at the Malysheva emerald and alexandrite mine from 1992 to 2007. There are four different sources for the Brazilian alexandrites. Seventeen specimens came from Evan Caplan, who acquired them from a source directly connected to a mine owner in Brazil. Fifteen of the Brazilian gems came from Nilam Alawdeen, who later provided three Sri Lankan and two Indian stones during this project. Spectrum Fine Jewelry & Exotic Gems supplied 140 Brazilian alexandrites. Four additional samples came from the GIA Museum. It is very likely that all the Brazilian material came from the Hematita deposit in Minas Gerais.

A few months later, eight Sri Lankan, twenty-one Tanzanian, and two Indian alexandrites were provided to the lab by LC Gem Collection Inc., a Sri Lanka-based gem company. Gem dealer Chandika Thambugala submitted nine Sri Lankan stones to the lab. The GIA Museum was also able to provide thirteen Sri Lankan, four Indian, and five Tanzanian gems. In some cases, all that was known about a specimen was the country of origin; specific mines were unknown. However, the Tanzanian stones were very likely from Lake Manyara. An additional 18 Indian stones were provided by Lance Davidson. Field gemologist Vincent Pardieu provided us with some stones from his personal collection: three Madagascar alexandrites bought in Madagascar; nine Zambian stones bought in Mahesak, Thailand, from a trustworthy source; and one Burmese sample purchased from the trade

TRACE ELEMENT DISCRIMINATION

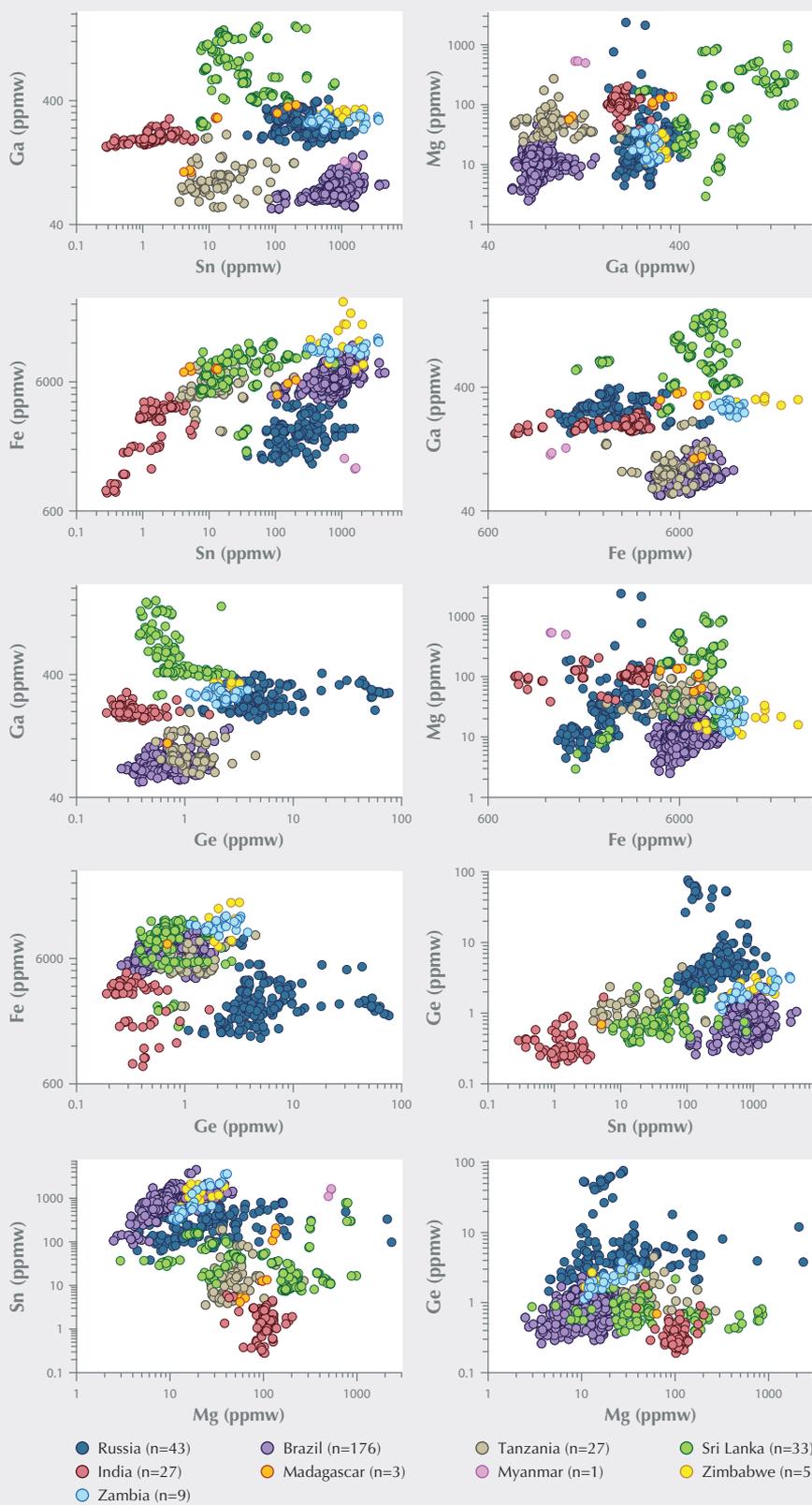


Figure 8. Plots of Mg, Fe, Ga, Ge, and Sn concentration in alexandrite reference stones from different countries. Ten plots were generated by plotting any two elements against each other. The origin of most alexandrite samples can be confidently ascertained using these 10 plots.

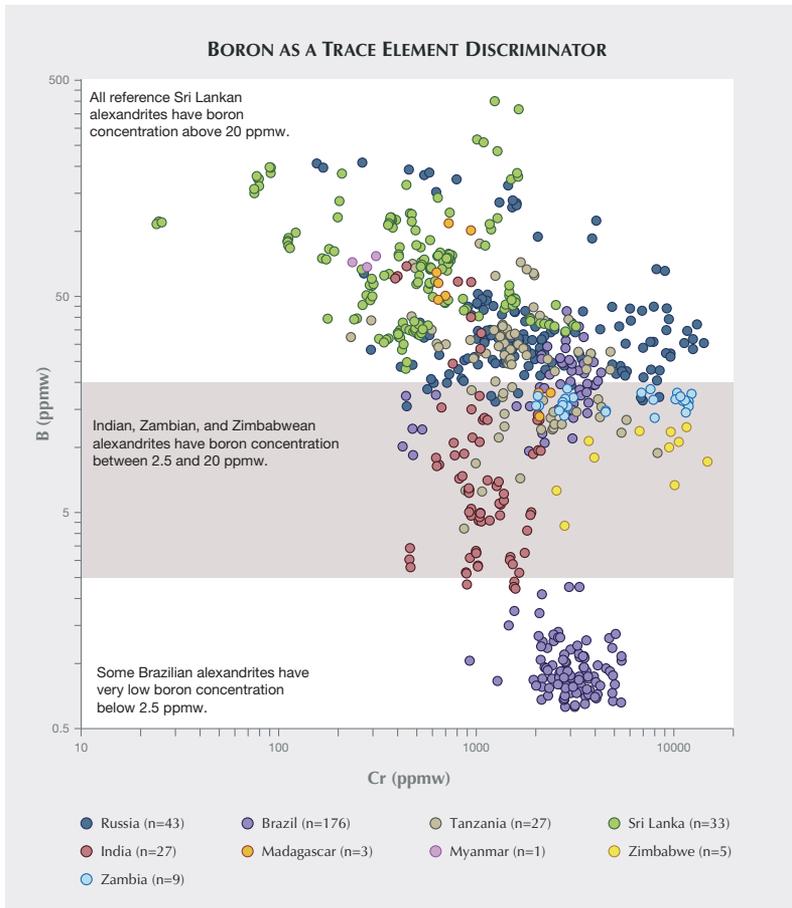


Figure 9. Boron can be used to separate Sri Lankan alexandrite from Indian, Zambian, and Zimbabwean samples. Some Brazilian stones have the lowest boron concentrations among all countries.

in Mogok. Five Zimbabwean stones came from two different sources: Two were borrowed from the personal collection of Yusuke Katsurada, a senior gemologist and scientist in GIA’s Tokyo laboratory, and the GIA Museum provided the other three. Detailed reference sample provenance is listed in appendix 1, table 1, online at <https://www.gia.edu/doc/WN19-Alexandrite-Appendix1.pdf>.

Procedures for Alexandrite Identification in GIA Laboratories. When an alexandrite first arrives at the GIA laboratory, we ask a question even more fundamental than geographic origin: Is this a natural alexandrite? Fourier-transform infrared spectroscopy (FTIR) is performed on every alexandrite to distinguish natural from synthetic material (Stockton and Kane, 1988) and to identify imitations. Natural alexandrites are then sent for laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS); see Groat et al. (2019), pp. 512–535 of this issue. This method is used to acquire trace element chemistry for geographic origin determination, if origin service is requested by the client.

After advanced analysis, the stone is given to a preliminary gemologist for standard gemological testing and iden-

tification. The stone is examined under a standard GIA desktop microscope for inclusions that would be indicative of a natural or synthetic origin. Photomicrographs are taken and Raman spectroscopy is performed if there are crystalline inclusions that might aid in origin determination (see Groat et al., 2019, pp. 512–535 of this issue). The colors exhibited by the alexandrite are also considered as possible evidence of origin. A stone’s warm and cool colors are also recorded in GIA’s database with careful photographic documentation under standardized conditions (see below). The stone is then sent to a more senior gemologist to further check all the physical and chemical properties to confirm the stone’s identity and complete the identification and origin determination.

Photography. *GIA Digital Imaging for Color-Change Stones.* GIA has a set of standardized procedures for photographing color-change stones to ensure consistency in appearance reproduction. The image of an alexandrite is captured using a variety of high-quality cameras and lenses in a specially made light box produced by the GIA instrument department. An LED light with a color temperature around 6500 K is used as a daylight-equivalent light source, while an LED light with a color temperature around 2700 K is used as

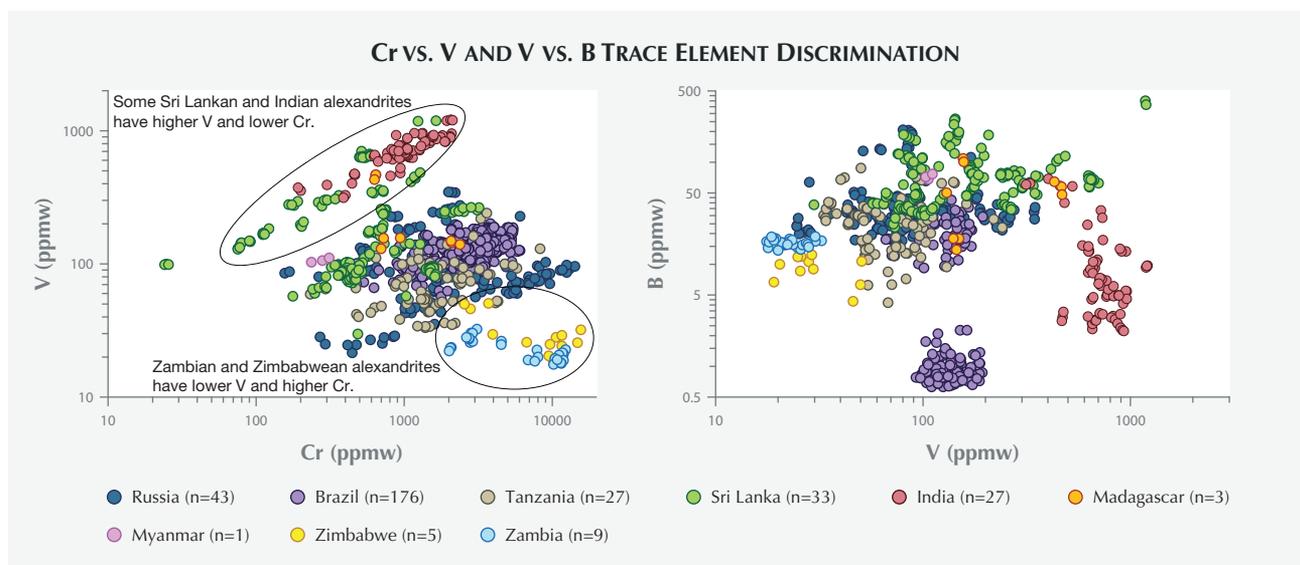


Figure 10. Cr-V and V-B plots prove very useful in validating the origin of Indian, Zambian, and Zimbabwean alexandrites. The Indian stones, along with some of the Sri Lankan specimens, have the highest V/Cr ratios. The Zambian and Zimbabwean stones have the lowest V/Cr ratios.

an incandescent light source. The final printed images are viewed in a controlled lighting environment and compared to the actual stone. Slight color adjustments are made with Adobe Photoshop software if needed, using a monitor that is maintained and color calibrated using GretagMacbeth calibration software.

Photomicrography of Inclusions. Photomicrographs are taken using various Nikon microscopes, including an Eclipse LV100, SMZ1500, and SMZ10 (Renfro, 2015a,b). Photographs of the inclusion scenes are captured using Nikon DS-Ri2 digital cameras. Various lighting environments including darkfield, brightfield, and fiber-optic illumination are used to highlight specific internal features. Image stacking (Renfro, 2015a) is sometimes employed to maximize the depth of field of an image.

Raman Spectroscopy. Raman spectra are collected with a Renishaw inVia Raman microscope system. The Raman spectra of the inclusions are collected using a Stellar-REN Modu Ar-ion laser producing highly polarized light at 514 nm at a nominal resolution of 3 cm^{-1} in the $2000\text{--}200 \text{ cm}^{-1}$ range. Each inclusion spectrum is accumulated three times at 20x or 50x magnification. In many cases, the confocal capabilities of the Raman system allow inclusions beneath the surface to be analyzed.

FTIR. Fourier-transform infrared spectra are collected using a Thermo Fisher Nicolet 6700 FTIR spectrometer equipped with an XT-KBr beam splitter and a mercury-cadmium-telluride (MCT) detector operating with a 4x beam condenser

accessory. The beam is transmitted through the stone. The spectra are collected at a nominal resolution of 4 cm^{-1} with 1.928 cm^{-1} data spacing. Each stone is scanned 128 times to achieve a high signal-to-noise ratio.

LA-ICP-MS. Trace element chemistry is acquired using a Thermo Fisher iCAP Qc ICP-MS coupled with an Elemental Scientific Lasers NWR213 laser ablation system. It incorporates a Nd:YAG laser rod that emits light with a wavelength of 1064 nm in the infrared and a frequency quintupler system to generate a 213 nm ($1/5$ of 1064 nm) ultraviolet wavelength that is used to ablate samples. Ablation is achieved using a 55 μm diameter circular spot size, a fluence (energy density) of approximately 10 J/cm^2 , and a 20 Hz repetition rate. National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 610 (http://georem.mpch-mainz.gwdg.de/sample_query.asp; Jochum et al., 2005) is used as an external standard. ^{27}Al is used as an internal standard, with a value of 425000 calculated and rounded from pure chrysoberyl. A similar method was used in works done by Malsy and Schmetzer (Schmetzer, 2010; Schmetzer and Malsy, 2011b; Schmetzer et al., 2011).

RESULTS AND DISCUSSION

Trace Element Chemistry of Alexandrite from Different Countries. In general, trace element chemistry is the most important factor in determining a geographic origin for alexandrite. By carefully examining our reference datasets, we concluded that Mg, Fe, Ga, Ge, and Sn are the five best discriminators to distinguish different geographic locations (figure 8). B, V, and Cr were also good discrimina-

TABLE 1. Generalized trace element profiles of alexandrite samples in ppmw.

Russia								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	15.5–208	4.47–3140	21.5–347	156–14200	1390–8610	171–406	1.08–76.4	37.9–1550
Average	45.0	93.0	102	3090	2780	263	10.3	324
Median	31.4	26.1	84.0	1640	2480	255	4.55	244
Sri Lanka								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	23.1–400	2.95–987	29.8–1190	24.1–3200	1720–12200	246–1580	bdl–2.70	7.35–785
Average	81.6	170	211	702	7680	731	0.55	57.9
Median	68.5	123	146	526	8090	638	0.55	29.3
Brazil								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	bdl–42.7	2.50–46.7	56.8–201	424–6050	4180–11500	53.3–145	bdl–2.55	87.4–4470
Average	2.17	11.9	136	2960	6350	72.8	0.70	871
Median	bdl	11.1	137	2870	6270	69.9	0.69	821
India								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	bdl–68.9	38.4–203	314–1210	192–2120	829–4610	168–284	bdl–1.68	0.28–6.01
Average	10.8	104	722	1090	2900	199	0.30	1.89
Median	5.68	102	714	1020	3250	195	0.28	1.33
Tanzania								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	4.21–87.8	24.0–270	33.2–241	232–8270	2470–9210	54.9–212	bdl–4.48	3.56–192
Average	28.3	53.3	76.1	1990	5620	94.1	0.84	22.9
Median	26.7	47.1	69.2	1500	5390	85.8	0.79	14.2
Zimbabwe								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	bdl–12.4	10.9–38.3	19.1–50.6	2550–15600	7480–25000	269–343	bdl–3.19	338–2110
Average	7.87	20.5	31.2	8700	14100	313	1.78	1200
Median	8.97	19.4	28.1	9650	12700	317	2.04	1080
Zambia								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	13.7–18.7	10.6–40.9	17.6–32.4	2010–12300	9050–13100	228–317	1.12–3.8	305–3630
Average	16.2	21.5	23.2	6720	11000	276	2.19	1270
Median	16.3	18.0	22.6	6860	10900	277	2.04	668
Madagascar								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	13.9–109	56.2–136	130–468	630–2380	4770–7840	106–338	bdl–0.69	4.16–205
Average	53.4	97.4	249	1200	6850	248	0.077	57.7
Median	50.3	97.2	156	726	7280	289	bdl	12.7
Myanmar								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	68.3–76.8	495–531	103–111	236–311	1270–1530	114–129	bdl–bdl	1100–1640
Average	72.3	519	107	276	1360	120	bdl	1440
Median	71.9	530	106	280	1290	118	bdl	1580
Detection limits (ppmw)								
	B	Mg	V	Cr	Fe	Ga	Ge	Sn
Range	0.091–0.15	0.014–0.034	0.008–0.021	0.15–0.26	0.87–1.63	0.007–0.031	0.037–0.11	0.026–0.065

*bdl = below the detection limit of the LA-ICP-MS analysis

Sn vs. Mg TRACE ELEMENT DISCRIMINATION

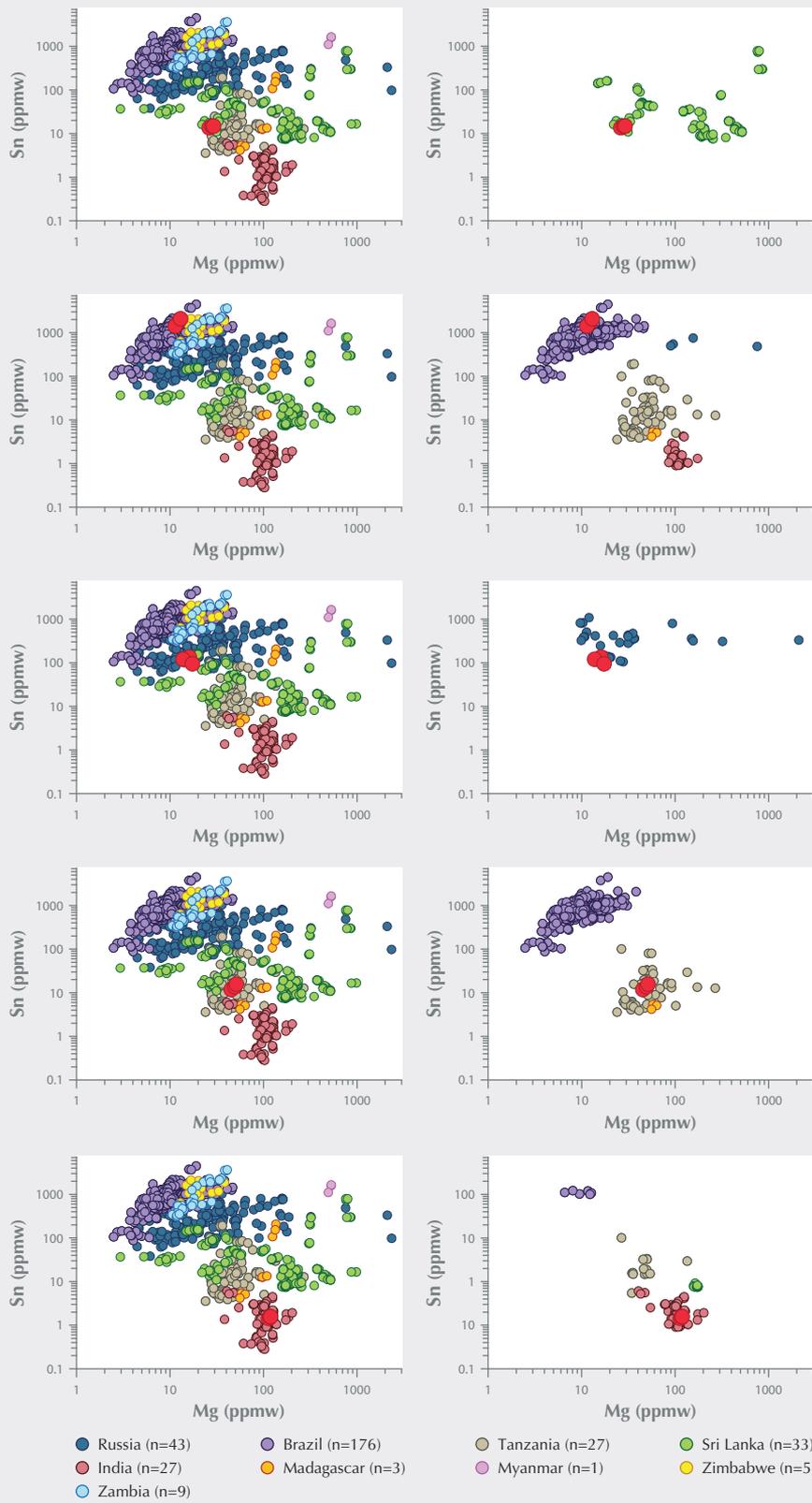


Figure 11. The left column shows Sn-Mg plots before discrimination for alexandrite from (top to bottom) Sri Lanka, Brazil, Russia, Tanzania, and India. The right column shows the same Sn-Mg plots after application of the selective plotting method. This method leaves in reference data that are similar to unknown stones and filters out irrelevant information, making these plots much easier to interpret accurately.



Figure 12. Characteristic color-change pairings of alexandrite from different countries. The photos were selected from GIA’s digital imaging database of production stones, which were taken using GIA digital imaging procedures and printed on GIA alexandrite reports.

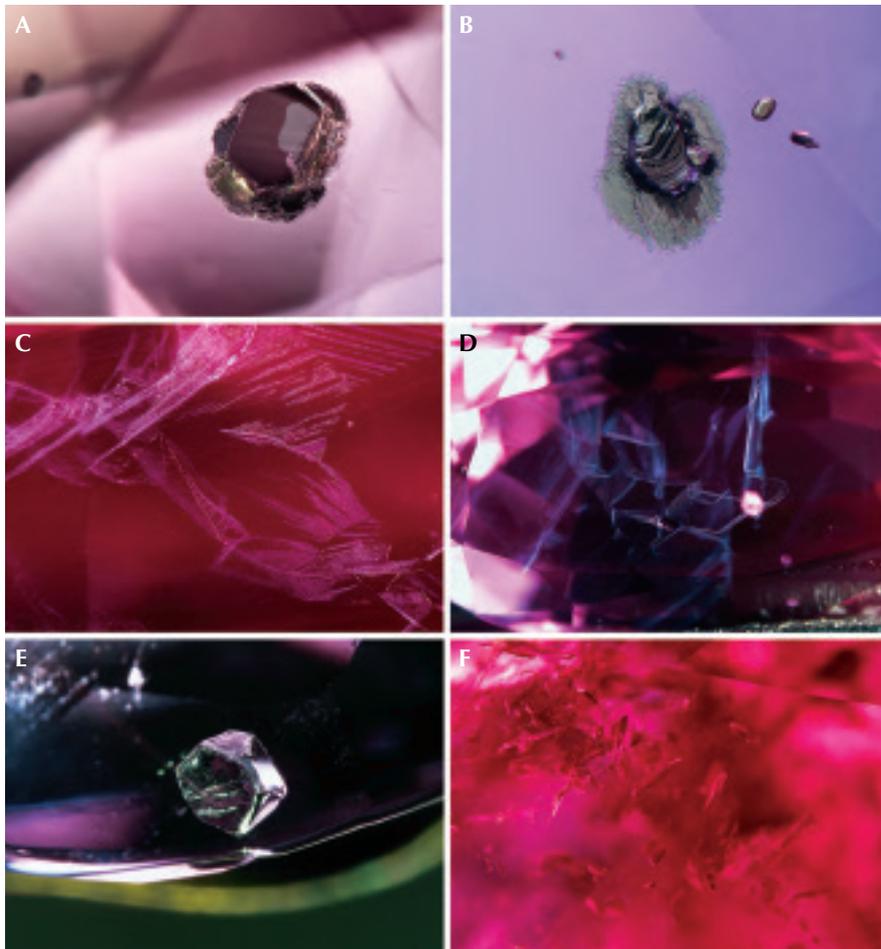


Figure 13. Inclusions in Brazilian alexandrite. A: A metal sulfide crystal inclusion surrounded by a melted/ decrepitated halo under diffused fiber-optic illumination. B: Chalcopyrite crystal surrounded by melted/decrepitated halo under darkfield and oblique fiber-optic illumination. C: Silk, bands, and fingerprints composed of minute particles under oblique fiber-optic illumination. D: Clouds/fingerprints composed of minute particles under darkfield and oblique fiber-optic illumination. E: Rounded fluorite crystal inclusions under diffused illumination. F: Mica crystals under darkfield illumination. Fields of view: 1.99 mm (A), 1.42 mm (B), 2.34 mm (C), 7.19 mm (D), 0.55 mm (E), and 2.00 mm (F). Photomicrographs by Jonathan Muyal (A, C), Tyler Smith (B, D, E), and Makoto Miura (F).

tors for separating alexandrites among some countries (see figures 9 and 10), but must be considered as an addition to the first five with specific criteria. The generalized trace element profiles are listed in table 1. The results described herein and shown in figures 8–10 are generally consistent with the results previously reported by Malsy and Schmetzer.

Using any two of the five discriminators (Mg, Fe, Ga, Ge, and Sn) to plot against each other, 10 plots can be generated (figure 8). Alexandrites from different countries have their own characteristic chemistry.

Mg—Indian and Tanzanian alexandrites have high Mg concentrations, while Brazilian, Zambian, and Zimbabwean stones have low Mg concentration. Russian and Sri Lankan stones have wide ranges of Mg concentrations that overlap with every other source.

Fe—Zambian and Zimbabwean stones have relatively high Fe concentration, while Tanzanian, Brazilian, and Sri Lankan specimens have medium Fe concentration. Russian and Indian stones have the lowest Fe concentrations.

Ga—Sri Lankan stones have the highest gallium concentration. Indian, Russian, Zambian, and Zimbabwean material falls in a middle range, while Tanzanian and Brazilian alexandrites have the lowest Ga concentrations.

Ge—Russian alexandrites have the highest germanium concentrations, while Sri Lankan, Indian, Brazilian, and Tanzanian stones have the lowest. Zambian and Zimbabwean stones have medium Ge concentrations.

Sn—Russian, Brazilian, Zambian, and Zimbabwean alexandrites have higher Sn concentrations, while Indian specimens have lower amounts. Sri Lankan and Tanzanian stones have similar Sn concentrations in the middle range.

In addition to these five discriminators, B, V, and Cr are very useful for some specific cases. These three elements can further validate geographic origin conclusions (figures 9 and 10). Boron can be used to distinguish Sri Lankan alexandrite from Indian, Zambian, Zimbabwean, and some of the low-boron Brazilian stones (figure 9). According to our

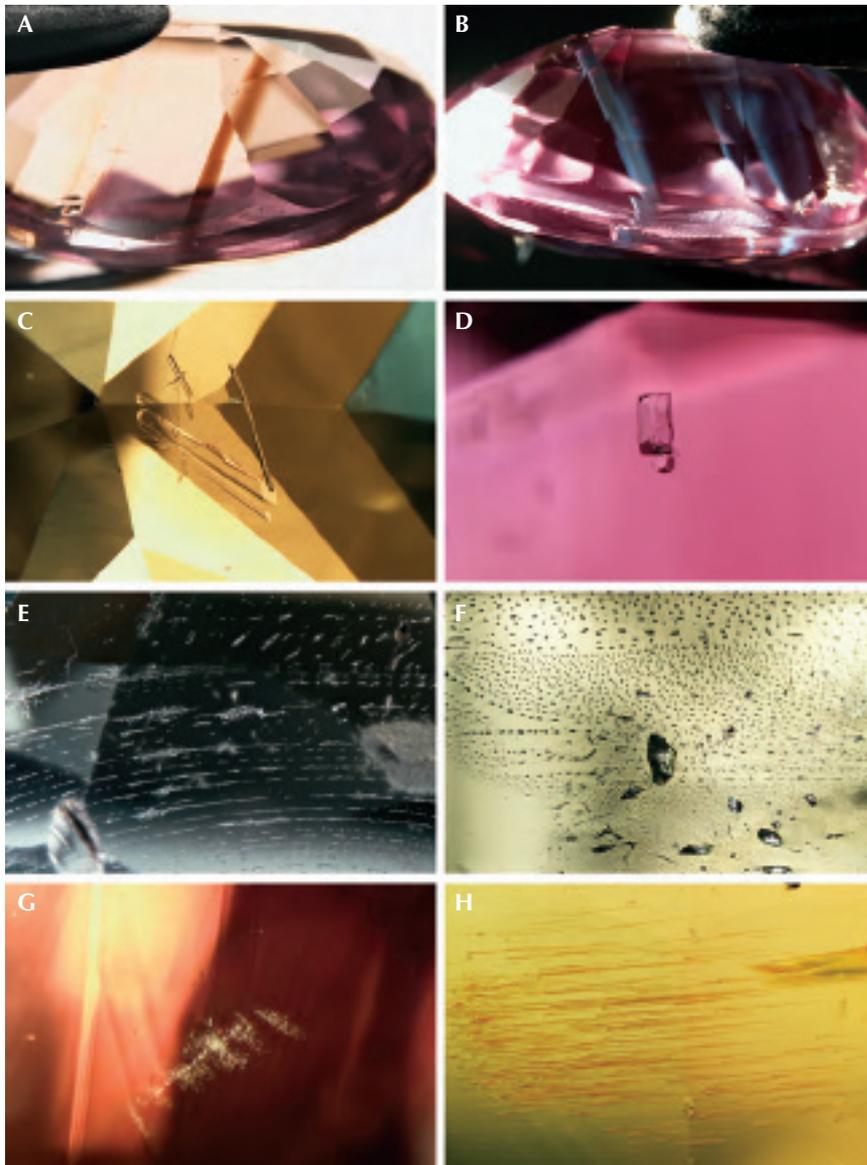


Figure 14. Inclusions in Sri Lankan alexandrite. A: Brown color zoning and strong parallel graining under brightfield illumination. B: The same brown color zoning in (A) becomes milky bands under darkfield and oblique fiber-optic illumination. C: Well-formed prismatic sillimanite crystals under darkfield and oblique fiber-optic illumination. D: Euhedral feldspar crystal under diffused illumination. E: Fingerprints formed by parallel lines of fluids and tiny crystals under darkfield and diffused fiber-optic illumination. F: Irregularly shaped crystals and fingerprints composed of two-phase and multiphase fluid inclusions under darkfield illumination. G: Flake-like cloud of particles under oblique fiber-optic illumination. H: Tubes with brownish oxide stains under diffused fiber-optic illumination. Fields of view: 7.19 mm (A), 7.19 mm (B), 2.90 mm (C), 1.99 mm (D), 2.90 mm (E), 3.57 mm (F), 1.44 mm (G), and 1.99 mm (H). Photomicrographs by Tyler Smith (A–D) and Jonathan Muyal (E–H).

reference database, all Sri Lankan alexandrites collected so far have boron concentrations above 20 ppmw, while almost all Indian, Zambian, and Zimbabwean alexandrites have boron concentrations between 2.5 and 20 ppmw, and some Brazilian alexandrites have the lowest boron concentrations, below 2.5 ppmw (figure 9). Besides boron, the chromophores vanadium and chromium are also very important in separating Indian, Zambian, and Zimbabwean alexandrites from material from other localities (figure 10). According to our reference database, some Sri Lankan and all Indian alexandrites have the highest V/Cr ratio among all reference stones (indicated by the black oval in the top left of the plot in figure 10). Zambian and Zimbabwean alexandrites have the lowest V/Cr ratio among all reference stones (indicated by the black oval in the bottom right of the plot in figure 10).

Selective Plotting for Alexandrite Geographic Origin Determination. We have found that the use of the “selective plotting” method can greatly enhance the accuracy of origin determination for alexandrite (figure 11). The method essentially involves plotting data for the unknown client stone only against reference data with similar full trace element profiles; see Palke et al. (2019), pp. 536–579 of this issue. In this method, discrete “windows” are selectively created around the trace element data of the client stone, and only reference data within these windows are plotted while everything else is filtered out. This results in plots that are much easier to read and accurately interpret. A few examples are shown in figure 11. The plots after discrimination usually point to simple and definite results.

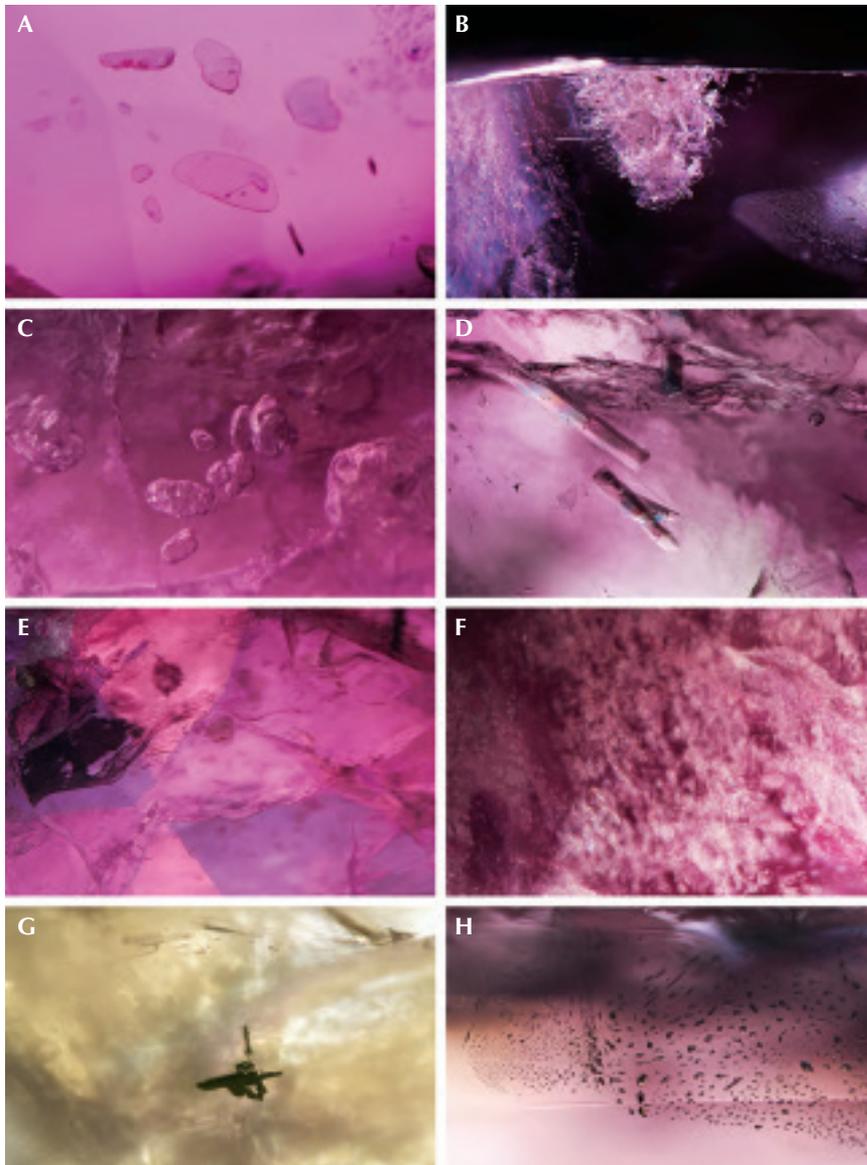


Figure 15. Inclusions in Russian alexandrite. A: Rounded, unevenly shaped flat transparent phlogopite crystals under darkfield illumination. B: A dense cluster of colorless, bladed phlogopite crystals breaks the surface of the stone under darkfield and oblique fiber-optic illumination. C: Corroded and rounded fluorite crystals under diffused illumination. D: Prismatic rod-like tourmaline crystals under brightfield illumination between crossed polarizers. E: Pseudo-hexagonal growth sections shown in different colors under brightfield illumination between crossed polarizers. F: Graphite film under darkfield illumination. G: Rounded cotton-like clouds under oblique fiber-optic illumination. H: Minute two-phase and multiphase fluid fingerprints under diffused illumination. Fields of view: 0.80 mm (A), 1.99 mm (B), 1.26 mm (C), 1.44 mm (D), 3.57 mm (E), 0.72 mm (F), 4.79 mm (G), and 1.44 mm (H). Photomicrographs by Makoto Miura (A), Tyler Smith (B), and Jonathan Muiyal (C–H).

Characteristic Color Change of Alexandrite from Different Countries. Anyone who is familiar with alexandrite is well aware that material from different countries has different characteristic color-change behaviors. Many dealers have a good sense of where a specimen comes from through visual observation under daylight and incandescent lighting conditions. After examining hundreds of alexandrites, we can provide some examples of typical color-change pairings of alexandrite from different countries (figure 12). The images are from stones submitted to GIA at the five different global identification laboratories; each origin was confirmed by analyzing their trace element profiles as measured by LA-ICP-MS. While there is usually a range in the warm/cool color pairs seen for alexandrite from a single locality, each locality does tend to have its own specific range, and

the different colors seen are generally helpful in narrowing down the origin. The color types for each country in figure 12 were determined based on both colorimetric analyses of the images and visual observations by gemologists.

Sri Lankan alexandrites usually have a yellowish green component in daylight-equivalent lighting and a brownish or orangy component with incandescent illumination. Brazilian alexandrites tend to have a bluish green component in daylight-equivalent lighting and a reddish purple to purple component under incandescent light. The color-change characteristics of alexandrites from other countries are not as well known, because of the limits of our current image database.

Geographic origin determinations should never be based on color alone; trace element chemistry is the primary factor

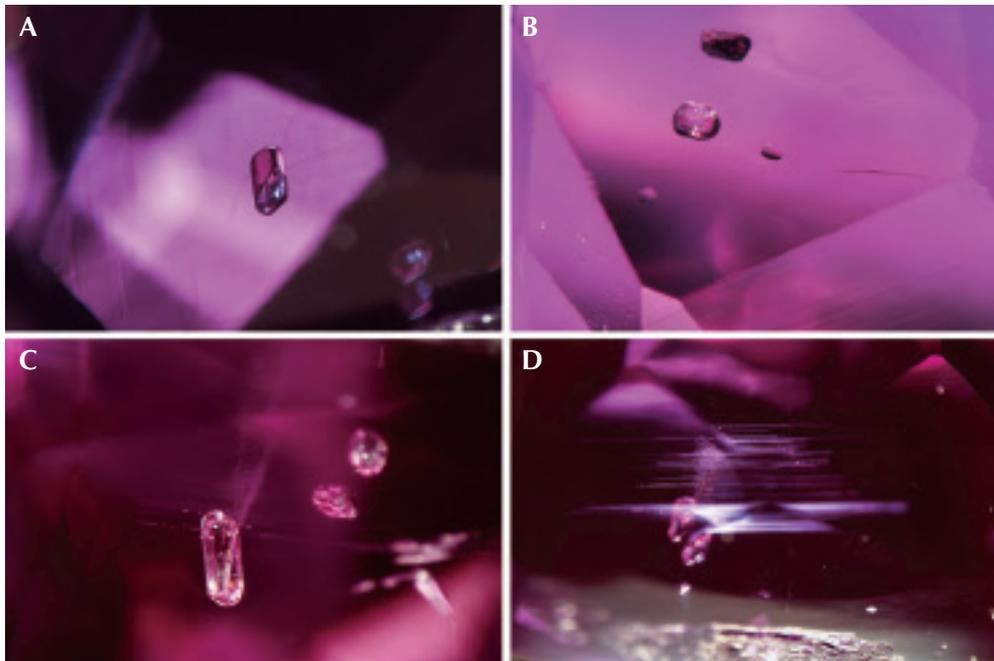


Figure 16. Inclusions in Tanzanian alexandrite. A: Prismatic apatite crystal with slightly rounded edges and uneven termination. B: Large colorless apatite crystal on the left and smaller, slightly tapered phlogopite crystal on the right. C: Apatite crystal with faint needles and particles. D: Nest of fine silk and small platelets. The "X" is an artifact from the facet junctions. Fields of view: 1.99 mm (A), 1.76 mm (B), 1.76 mm (C), and 2.90 mm (D). Photomicrographs by Tyler Smith; oblique fiber-optic and darkfield illumination.

in establishing origin. However, color can support the origin determination derived from trace element chemistry. The authors grouped all types of alexandrite color-change pairings into the following general categories (corresponding to types in figure 12):

1. Sri Lanka – Cool

Even though Sri Lankan alexandrines typically have brownish to grayish overtones, some lack these overtones and fall into the Cool category. In lighter-toned stones, hue changes from green or bluish green in daylight to purplish red or grayish purple in incandescent light. Saturation is low to medium in fine-quality stones, with a medium to dark tone.

2. Sri Lanka – Warm

Specimens in the Warm category exhibit the typical brownish to grayish overtones that characterize many Sri Lankan alexandrines. Daylight hues are generally yellowish compared to other alexandrines, ranging from yellowish green to brownish yellow to the occasional pure green. In incandescent light, they usually appear brownish, with yellowish brown, orangy brown, brownish pink, brownish purple, brownish yellow, and brownish red hues. Saturation is generally low to medium, with medium to dark tones.

3. Brazil

Top Brazilian stones are generally considered to exhibit the finest color change of any alexandrines. Most tend

to have a bluish component to their daylight color. Their hues are greenish blue to blue-green to pure green in daylight and red-purple to purple in incandescent light. These colors are often vivid, with medium to high saturation and medium to dark tone.

4. Russia

Russian alexandrite can exhibit some of the finest colors in top-quality material. Hues are generally pure green to bluish green to green-blue in daylight and purple-red to purple in incandescent light. Stones tend to have medium to high saturation, with medium to dark tone.

5. Tanzania

Tanzanian alexandrite is capable of producing superb color change. Hue tends to range from bluish green to greenish blue in daylight and red-purple to purple in incandescent light. Tanzanian stones typically have medium to high saturation and medium to dark tone.

6. India

Hue for Indian alexandrite tends to range from green to bluish green in daylight, changing to purplish violet, purple, brownish purple, or red-purple in incandescent light. Indian stones typically have low to medium saturation and medium to dark tone.

Inclusions in Alexandrite from Different Countries.

Geological environment not only controls the presence of certain trace elements and their concentration but also

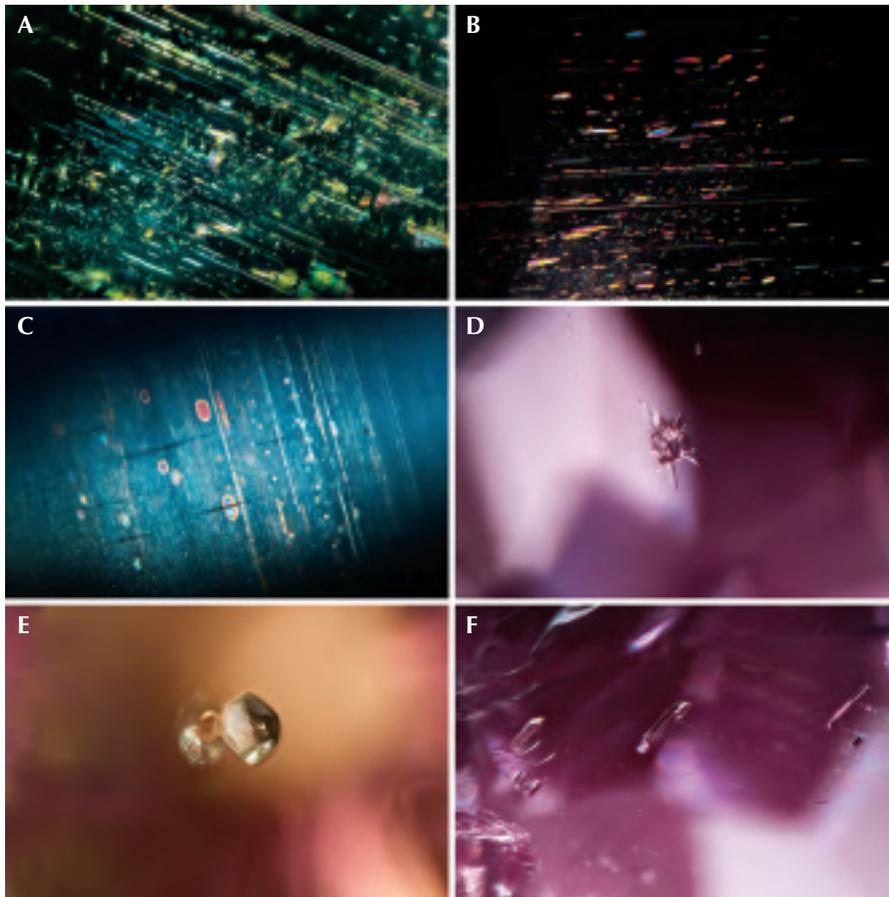


Figure 17. Inclusions in Indian alexandrite. A: Needles and tiny oval-shaped reflective particles under oblique fiber-optic and darkfield illumination. B: Needles and tiny oval reflective particles under darkfield illumination. C: Needles, a minute and large reflective oval, and round particles under darkfield illumination. D: Zircon crystal inclusion surrounded by tension fissures under darkfield illumination. E: Large unknown crystal with metallic luster and adjacent small crystal with halo-like tension fissure under darkfield illumination. F: Elongate negative crystals under diffused illumination. Fields of view: 0.72 mm (A), 1.26 mm (B), 2.41 mm (C), 1.26 mm (D), 1.44 mm (E), and 1.58 mm (F). Photomicrographs by Jonathan Muyal (A, B, D, E, F) and Makoto Miura (C).

impacts the inclusions an alexandrite contains. GIA has captured photomicrographs of inclusions in alexandrite and is using them to support the origin determinations made by chemistry and color.

Brazil. Metal sulfides have frequently been found in Brazilian alexandrines (figure 13A and B) and are almost diagnostic for this origin in the authors' opinion, although alabandite, a metal sulfide with similar appearance to the inclusions in figure 13A and B, was reported by Gübelin and Koivula (1986) in a non-color-change Sri Lankan chrysoberyl. Minute particles sometimes group together to form fingerprints (figure 13C) and wispy clouds (figure 13D). Crystals of fluorite (figure 13E) and mica crystals and flakes (possibly phlogopite or biotite, figure 13F) are also observed occasionally. Other researchers have also reported fluorite, phlogopite, and biotite and additionally calcite, apatite, albite, and two-phase and multiphase fluid inclusions in Brazilian alexandrines (Gübelin and Koivula, 1986; Proctor, 1988; Koivula and Kammerling, 1988).

Sri Lanka. Sri Lankan stones submitted to GIA are usually clean, but the identification team has still documented

many inclusions. Strong brown color zoning has only been observed in Sri Lankan stones and may be diagnostic of this origin (figure 14A), although additional observations are needed to confirm this. Under fiber-optic illumination, these brown color zones are populated with reflective milky clouds (figure 14B). Very rarely, elongate prismatic sillimanite crystals (figure 14C) and euhedral feldspar crystals (figure 14D) have been observed. Fingerprints (figure 14E and F) formed by two-phase and multiphase fluid inclusions are normal. Minute particles may group together to form flake-like clouds (figure 14G). Occasionally, tubes with brownish oxide stains (figure 14H) can also be observed. Additionally, green mica, quartz crystals, and slender rod-like crystals of columbite, spessartine, ilmenite, and alabandite have previously been observed in Sri Lankan alexandrines and non-color-change chrysoberyls (Gübelin and Koivula, 1986).

Russia. In our limited observations of inclusions in Russian alexandrite, phlogopite mica has been seen forming flattened, rounded, unevenly shaped crystals (figure 15A) and clusters of cotton-like inclusions (figure 15B). Very rarely, corroded and rounded fluorite crystals (figure 15C) and prismatic rod-like tourmaline crystals (figure 15D) have been observed.



Figure 18. Russian alexandrite in daylight-equivalent light (left) and incandescent light (right). The twinned crystal from Malysheva measures 32.35 mm, and the faceted stone weighs 2.61 ct. Photos by Robert Weldon/GIA; courtesy of William Larson.

Both inclusions were first reported in Russian alexandrites. Tourmaline crystals, chemically identified as dravite by LA-ICP-MS (Sun et al., 2019), may be diagnostic of the origin, although additional observations are needed to confirm this. Sometimes it is not difficult to see pseudo-hexagonal growth sections shown in different colors under brightfield illumination between crossed polarizers (figure 15E). Graphite film, resembling a spaceship in figure 15F, has been occasionally observed in Russian material. Rounded cotton-like clouds composed of tiny particles (figure 15G) show unique texture and may be diagnostic. Planes of fluid inclusions (figure 15H) have also been observed. Further work is underway to collect additional information on reliably sourced Russian alexandrite. Mica (e.g., phlogopite and biotite) and amphibole inclusions are most commonly observed in Russian alexandrites (Gübelin and Koivula, 1986).

Tanzania. For alexandrite from Tanzania, inclusions of actinolite crystals, mica, monazite, xenotime, and rounded metamict zircon have been observed (Gübelin and Koivula, 1986). Currently, there are only a few images of crystals and fingerprint-like inclusions in GIA's production database. Groups of prismatic apatite crystals (figure 16A, B, and C) and nests of fine silk (figure 16D) have been observed in one Tanzanian alexandrite.

India. Fingerprint-like inclusions in Indian alexandrite are usually composed of tiny needles and oval and round reflective particles (figure 17A, B, and C). This feature may be diagnostic of the origin, although additional observations are needed to confirm this. Occasionally, zircon crystals (figure 17D) with tension fissures have been observed. Figure 17E shows two adjacent crystals with unknown identity; the larger one shows a metallic luster. Groups of elongate negative crystals (figure 17F) are also observed sometimes in Indian alexandrite. Additionally, mica flakes (biotite, muscovite,

etc.) are often observed (Panjekar and Ramchandran, 1997). Quartz and apatite crystals (Patnaik and Nayak, 1993) are sometimes randomly scattered or in isolation. Needles of rutile and colorless sillimanite can also be observed (Panjekar and Ramchandran, 1997).

Other Localities. GIA lacks inclusion information on alexandrite from Madagascar, Zimbabwe, Zambia, and Myanmar. The field gemology team is actively working to expand GIA's reference collection for these stones.

CONCLUSIONS

Determining alexandrite's geographic origin is a complicated process that requires careful examination of a wide range of physical and chemical properties. In order to make a final determination, we evaluate a combination of the three most important characteristics: trace element chemistry, color-change behavior under daylight-equivalent lighting and incandescent illumination, and inclusions. Of these three characteristics, trace element chemistry obtained from LA-ICP-MS is the primary consideration. Color and inclusions are used as secondary factors to support the origin determination derived from trace element chemistry.

The trace elements Mg, Fe, Ga, Ge, and Sn are the five best discriminators to distinguish alexandrite from the major producing countries of Russia (figure 18), Sri Lanka, Brazil, India, and Tanzania. B, V, and Cr are good discriminators for separating alexandrites among some countries, but they must be considered as a complement to the first five trace elements with specific criteria, rather than on their own.

Most Sri Lankan alexandrites have a yellowish green component in daylight-equivalent lighting and a brownish or orange component in incandescent illumination. Brazilian alexandrites have a bluish green component in daylight-equivalent lighting and a purple to purplish red component in incandescent illumination. The color char-

acteristics of alexandrites from other sources are less well known at the moment, but this remains an area of active research.

Sulfides with metallic luster may be diagnostic inclusions for Brazilian alexandrites. Prismatic rod-like tourmaline crystals and rounded cotton-like clouds composed of tiny particles may be diagnostic for Russian alexandrites. Fingerprint-like inclusions composed of tiny needles and oval and round reflective particles may be unique to Indian alexandrites. Strong brown color zoning is a good indication of Sri Lankan origin. Characterization of inclusion scenes in alexandrite from the various localities is an active area of research in this project, and future work may help identify additional microscopic indicators of a stone's origin.

Alexandrite origin is an ongoing project for the GIA research and identification department. One of the largest efforts on this front is to add samples obtained by GIA's field gemology team to our reference database. It can be difficult to find reliable alexandrite samples from secondary deposits such as Sri Lanka, Tunduru in Tanzania, or Ilakaka in Madagascar. That is why our reference data were obtained from trusted members of the trade or the GIA Museum. As this new origin service evolves, future efforts of the field gemology team will focus on obtaining samples from these sources as material becomes available. Additionally, the internal crystal growth pattern and morphology of rough crystals have been used as factors for geographic origin determination by other researchers (Schmetzer, 2011; Schmetzer and Malsy, 2011a,b). These two areas can enhance our current methods and are worth investigating. Third, different deposits within a country can contain crystals with very different morphologies, producing material with varying trace element chemistries that show different colors and inclusions. Further work will be needed to collect additional data on stones from all major locations in order to delineate the differences, not only for alexandrite from different geographic locations but also for alexandrite from a single source. In this there is a truth that applies to all gemological laboratories, no matter how mature and well established: We must remain vigilant and continue expanding the state of our gemological knowledge if we are to uncover the story of any precious stone that passes through our hands.

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Mr. Sun is a research associate, Dr. Palke is a senior research scientist, Mr. Moyal is a former staff gemologist, Mr. DeGhionno is senior manager of colored stone services, and Mr. McClure is global director of colored stone services at GIA's laboratory in Carlsbad, California.

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Pleochroism and Color Change in Faceted Alexandrite: Influence of Cut and Sample Orientation

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Abstract: The color appearance of faceted gemstones is a complex subject, and the challenges are increased if the material is biaxial and pleochroism is added to the considerations. For alexandrite in particular, the quest for a beautiful cut gem is further intensified by efforts to achieve the “best” color change. As an optically biaxial material, alexandrite possesses three different vibration directions X, Y, and Z. These are parallel to the three crystallographic axes a, b, and c, each of which has a distinct pleochroic color.

The present study seeks to evaluate the effect of various factors on color and color change using two groups of faceted synthetic alexandrites of comparable sizes and cuts with table facets oriented perpendicular to one of the three crystallographic axes. If the faceted gemstones are examined in transmitted light in immersion with a polarizer between the sample and the observer, the basic pleochroic colors can be separated and seen individually. For the synthetic alexandrites, if the faceted gemstones are examined in reflected light, this study demonstrates that the mixing of the three colors X + Y + Z, caused by multiple reflections of light within the faceted stones, greatly diminishes the role of table facet orientation on the quality of color and color change in well-cut gems. Likewise, for other biaxial stones it is expected that the effects of pleochroism will also be reduced in faceted stones to some extent.

Alexandrite, the chromium-bearing variety of chrysoberyl, shows distinct pleochroism and a signature color change between daylight (or daylight-equivalent fluorescent light) and incandescent light, referred to as the alexandrite effect. A similar color change is also observed for other varieties of gem minerals such as garnet, sapphire, spinel, kyanite, fluorite, and diaspore (Bosschart et al., 1982; Gübelin and Schmetzer, 1982; Schmetzer et al., 2009).

Chrysoberyl, belonging to the orthorhombic crystal system, is birefringent and optically biaxial. If unpolarized

light enters a birefringent crystal, the beam is split into two polarized waves in all directions not parallel to an optic axis. These two waves leave the crystal in polarized form and can be separated, and seen individually, by rotating a polarizer (i.e., a polarizing filter) located between the sample and the observer. The optically biaxial nature of chrysoberyl further means that the optical indicatrix has three different vibration directions X, Y, and Z, which are parallel to the three crystallographic axes a, b, and c (Bloss, 1961; Wahlstrom, 1969; Kerr, 1977). In the three vibration directions, light can be differentially absorbed, and an absorption spectrum

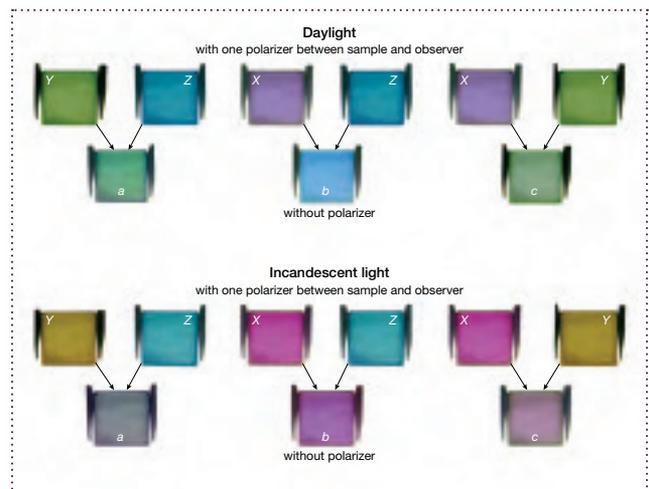


Figure 1. Color of a synthetic Czochralski-grown alexandrite cube with edge lengths of 9.0 to 9.2 mm, shown in daylight and incandescent light. In a view parallel to one of the crystallographic axes a, b, and c, the color is always a mixture of two of the three basic components X, Y, and Z, which can be separated and observed individually by using a polarizer (polarizing filter) between the sample and the observer. All photos and drawings are by the author.

Facing page: Alexandrite ring (shown in daylight and incandescent lighting) featuring a 4.27 ct alexandrite center stone and 1.00 ct total weight in diamonds. The gems are set in a multi color gold setting. Courtesy Kremetz & Co. Photo by Robert Weldon/GIA.

TABLE 1. Properties of synthetic alexandrites.

Growth method	No.	Orientation of seed	Orientation of table facet	Cut	Size (mm)	Weight (ct)	Color observed through table facet in reflected light	
							Daylight	Incandescent light
Flux growth by Creative Crystals Inc. (San Ramon, California) ^a	1	b (010)	a (100)	Step cut	8.7 × 7.8 × 7.8	5.11	Green	Red-purple
	2		b (010)	Step cut	9.1 × 8.6 × 8.2	5.83	Intense blue-green	Intense purple
	3		c (001)	Step cut	8.3 × 8.1 × 7.0	4.42	Green	Red-purple
HOC growth by V.V. Gur'ov (Novosibirsk, Russia) ^b	4	b (010)	a (100)	Oval mixed	8.0 × 6.0 × 4.2	1.63	Blue-green	Purple
	5		b (010)	Oval mixed	8.1 × 6.1 × 4.2	1.74	Blue-green	Purple
	6		c (001)	Oval mixed	8.1 × 6.0 × 4.1	1.66	Blue-green	Purple

^aSee Schmetzer et al. (2012)

^bSee Schmetzer et al. (2013)

can be measured for each direction. These three directions thus generate three basic pleochroic colors (Burns, 1993; Schmetzer and Bosshart, 2010; Schmetzer et al., 2012, 2013; Sun et al., 2017; see also Devouard and Notari, 2009).

In views parallel to one of the three a, b, or c¹ crystallographic axes in alexandrite, two vibration directions and two of the three basic colors are always present simultaneously, i.e., X + Y, X + Z, or Y + Z (figure 1). Stated otherwise, the color seen with the unaided eye when looking parallel to any of the three crystallographic axes is always a mixture of two of the X, Y, and Z basic color components (Schmetzer and Bosshart, 2010; Schmetzer and Malsy, 2011).

The specific colors observed (and the spectra produced) are in turn dependent in large part on the concentrations of color-causing trace elements and the path length of light through the crystal. Principal trace elements affecting color in alexandrite are chromium, vanadium, and iron. Variations in path length result in the optical phenomenon referred to in gemology as the Usambara effect, with color changing or shifting as the path length increases (Halvorsen and Jensen, 1997; Halvorsen, 2006).

The color impressions just described, based on visual appearance and examination, have also been evaluated and verified through colorimetric measurement of natural alexandrite crystals, natural alexandrite cubes, and synthetic alexandrite cubes with different trace-element contents (Schmetzer and Bosshart, 2010; Schmetzer and Malsy, 2011; Schmetzer et al., 2012, 2013). For instance, colorimetric measurements using oriented cubes of synthetic alexandrite with edge lengths from 2 to 10 mm (Schmetzer et al., 2013) demonstrated that, regardless of size, for all three different orientations parallel to the a-, b-, and c-axes, changing between daylight and incandescent light resulted in a respective increase or decrease in blueness and redness (the alexandrite

effect). With increasing cube size, a color shift was visible. The larger the cube, the redder the alexandrite appeared in both daylight and incandescent light (the Usambara effect).

The foregoing optical characteristics and phenomena have long spawned efforts to ascertain preferred orientations for fashioned alexandrites (and pleochroic materials more broadly). For alexandrite in particular, the goal of gem cutters and merchants for decades has been the “best” color change, defined as a green or bluish green to blue-green color in daylight and a red-purple or reddish purple to purple color in incandescent light. Conventional wisdom among cutters has traditionally held that this favored color change is obtained if the table facet is oriented perpendicular to the b-axis (Fischer, 1954). In practical terms, however, cutting in such a direction could prove problematic at times on account of the cyclic twinning commonly seen in natural alexandrites.

The above-noted work with oriented crystals and cubes has also lent scientific support to the traditional understanding, concluding on the basis of visual inspection in transmitted light and colorimetric measurements that the “best” and most highly desired color change between daylight and incandescent light was observed in a direction of view parallel to the b-axis (Schmetzer and Bosshart, 2010; Schmetzer and Malsy, 2011; Schmetzer et al., 2012).

Hughes (2014) described pleochroism using a simplified theoretical model for light behavior in optically biaxial faceted gemstones. That model was based upon a single light beam entering the crystal perpendicular to the table facet. If the table facet were oriented perpendicular to one of the crystallographic axes, that beam would be split into two of the three basic components X, Y, and Z. If next reflected from pavilion facets, the light beam would travel through the crystal in a direction parallel to another of the three crystallographic axes and, consequently, would contain the third basic color component. After another reflection at the pavilion, the light leaving the faceted gemstone would be a mixture of all three components X, Y, and Z.

¹The present study refers to parameters based on the traditionally used morphological cell with a = 4.42, b = 9.33, c = 5.47 and X || a, Y || b, Z || c.

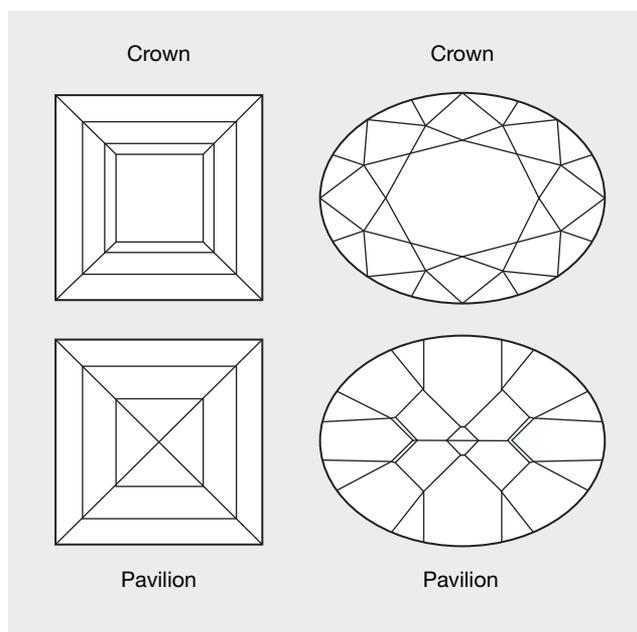


Figure 2. Diagram showing the cuts of the two groups of synthetic alexandrites examined in this study. Three samples were faceted with a simple step cut (emerald cut) with a nearly square table and three rows of facets on both the crown and the pavilion (left). The other three samples were faceted with an oval brilliant cut on the crown and a mixed cut (brilliant and step) on the pavilion (right).

Hughes (2014) further noted that, depending on the cut of the sample, the light path length could vary based on whether the beam entered the faceted gemstone near the center of the table facet or near the girdle. Hence, the mixture of light reflected from different pavilion facets would show different percentages of X, Y, and Z, thereby generating different colors. Unfortunately, however, no faceted biaxial gemstones with known orientations were presented to support the theoretical model.

More recently, Sun et al. (2017) both inspected visually and measured colorimetrically a solely Cr-bearing Czochralski-grown synthetic alexandrite cuboid with edges between 2.65 and 3.18 mm and also calculated colorimetric data maps detailing color, chroma, chroma difference, hue angle difference, and color difference for wafers in various orientations and with path lengths between 1 and 25 mm. One point explicitly highlighted was that areas with large values for hue angle difference or color difference did not necessarily show the “best” orientation for the desired color change.

Maps of colorimetric data were likewise calculated for faceted alexandrites. Based upon the general considerations of Hughes (2014) for optically biaxial gemstones, Sun et al. computed parameters for color and color change for a hypothetical faceted stone with a 10 mm light path length. Using preferred ranges for hue angle for daylight versus incandescent light and large chroma values for both light sources for

alexandrite, these authors tried to find the “best” orientation of the table facet or, in their own words, to “orient a stone along the ‘best’ direction.” It was concluded “that pleochroism in a faceted gemstone serves to smear out the “best” direction for color change.” Furthermore, it was found “that stones cut with their table to culet direction oriented perpendicular to the b-axis show the best color change, while orientation parallel to the b-axis produces weaker color change” (Sun et al., 2017; Z. Sun pers. comm., 2018).²

Again, however, no faceted stones were examined and compared with the results obtained by theoretical calculations of colorimetric parameters.

Thus, with regard to faceted alexandrites found in the trade, the current situation remains one where questions abound. Due to differences in trace-element content, sample orientation, size, and cut, numerous parameters exist that might influence color and color change. The present study therefore attempts to address queries involving the influence of these factors using carefully prepared samples of faceted material.

SAMPLES

The high value of facet-quality natural alexandrite material renders it nearly impossible to obtain suitable rough for cutting several small samples with different known orientations from the same large rough crystal. Hence, the present study was performed with synthetic gem material. Two groups of three samples each were cut from two synthetic crystals. An overview is provided in table 1.

One group consisted of three samples cut from a flux-grown synthetic alexandrite produced by Creative Crystals Inc. in San Ramon, California (see Schmetzer et al., 2012). The crystal was grown with a seed oriented parallel to b (010), and square or almost square table facets were cut parallel to either a (100), b (010), or c (001). Simple step cuts (emerald cuts) were fashioned with a table facet, three rows of crown facets, and three rows of pavilion facets (figure 2). Sizes ranged from 8.3 x 8.1 x 7.0 mm to 9.1 x 8.6 x 8.2 mm.

The other group comprised three synthetic alexandrites faceted from a crystal grown by the HOC technique in Novosibirsk, Russia, by V.V. Gurov (see Schmetzer et al., 2013). Starting with pieces sawn from the rough crystal, likewise produced with a seed parallel to a (010), table facets were again oriented parallel to either a (100), b (010), or c (001). An oval brilliant cut was used for the crown, with a mixed cut

²Sun et al. (2017) presented results using the cell applied for crystal structure refinement in 1962 with $a = 9.404$, $b = 5.476$, $c = 4.427$ and $X \parallel c$, $Y \parallel a$, $Z \parallel b$. For comparison purposes, those results have been converted to correspond with the morphological cell used here. See again footnote 1.

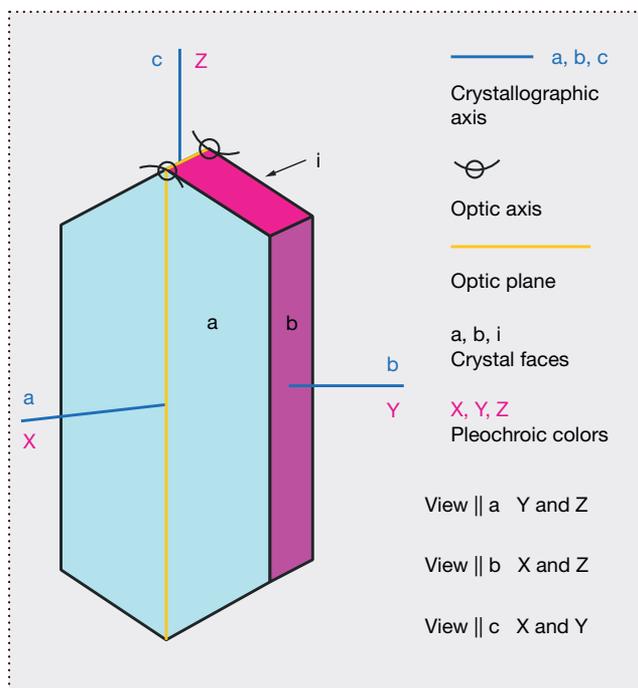


Figure 3. Schematic diagram demonstrating the orientation of the optic plane and the two optic axes relative to the crystallographic axes *a*, *b*, and *c* in alexandrite. The optic plane with both optic axes is the *ac*-plane. The three basic vibration directions *X*, *Y*, and *Z*, which also represent the three basic color components, are oriented parallel to the *a*-, *b*-, and *c*-axes. In views parallel to one of the crystallographic axes, two basic vibrations and their color components are always present.

of brilliant and step facets for the pavilion (figure 2). Sizes spanned from 8.0 x 6.0 x 4.2 mm to 8.1 x 6.1 x 4.2 mm.

Within each group, the identical cuts and similar dimensions enabled a direct comparison of the influence of cut orientation upon color and color change.

CHEMICAL PROPERTIES

The flux method employed by Creative Crystals for the alexandrites examined here used a series of several sequential growth cycles. As a result, the amount of chromium and iron, the principal color-causing trace elements in these samples, incorporated in each growth layer was variable. Mean values ranged from 0.18 to 0.26 wt.% Cr_2O_3 and from 0.86 to 1.14 wt.% Fe_2O_3 . Vanadium contents were approximately 0.01 wt.% V_2O_3 (Schmetzer et al., 2012).

The synthetic alexandrites grown by the HOC technique, in contrast, were more homogeneous in chemical composition, with chromium measuring from 0.30 to 0.43 wt.% Cr_2O_3 and vanadium ranging from 0.07 to 0.14 wt.% V_2O_3 . Iron levels were at 0.01 wt.% Fe_2O_3 or below (Schmetzer et al., 2013).

VERIFICATION OF SAMPLE ORIENTATION

The orientation of the table facets, which were cut according to morphological features of the rough gem alexandrites, was verified by ascertaining the positions of the optic axes in each stone. The optic axes lie in the optic plane, which in chrysoberyl is the *ac*-plane, and the *c*-axis is located exactly between the two optic axes (figure 3). The *b*-axis is perpendicular to the optic plane. Consequently, by viewing in a direction parallel to the optic plane and rotating a sample about the *b*-axis, both optic axes may be brought parallel to the direction of view.

In applying this information to the flux material grown by Creative Crystals, the task was aided by growth planes visible in immersion parallel to the seed (010) and, in one sample, additional growth planes parallel to the prism *k* (021) (figure 4). By using that insight (in conjunction with the observed pleochroism; see below), it was possible with reasonable ease to find the *b*-axis of the crystals and to use that axis for rotation in the immersion microscope. In so doing, an interference pattern consisting of several rings would be obtained if an optic axis were slightly inclined to the direction of view. Tilting the faceted alexandrite toward a position in which the optic axis was parallel to the direction of view would then move the interference rings toward the center of the sample. The positions of both optic axes in the optic plane of the gemstone could thus be located, leading directly to the positions of the crystallographic axes *a*, *b*, and *c* and making apparent the orientation of the table facet relative to the crystallographic axes. The practical measurements were made by means of two- and three-axial sample holders with attached dials to measure angles. For all three step-cut samples, the deviation of the table facets from the intended orientation was below 5°.

The same procedure was applied for the three oval samples cut from a crystal grown by the HOC technique. Because these crystals, in general, did not show distinct growth planes, finding the proper orientation for the sample in the immersion microscope with the *b*-axis as the rotation axis was somewhat more time consuming. However, after locating both optic axes through observation of interference patterns (figure 5), the positions of the three crystallographic axes were determined, and the inclination of the table facet to the relevant crystal axis was measured. It was again found that the deviation of the table facets from the intended orientation was below 5° for all three mixed-cut gemstones.

COLOR BEHAVIOR OF FACETED GEMSTONES IN TRANSMITTED LIGHT

As noted at the outset, unpolarized white light in birefringent chrysoberyl crystals is split into two polarized waves, which can in turn be separated and seen individually by rotating a polarizer placed between the sample and the observer. For

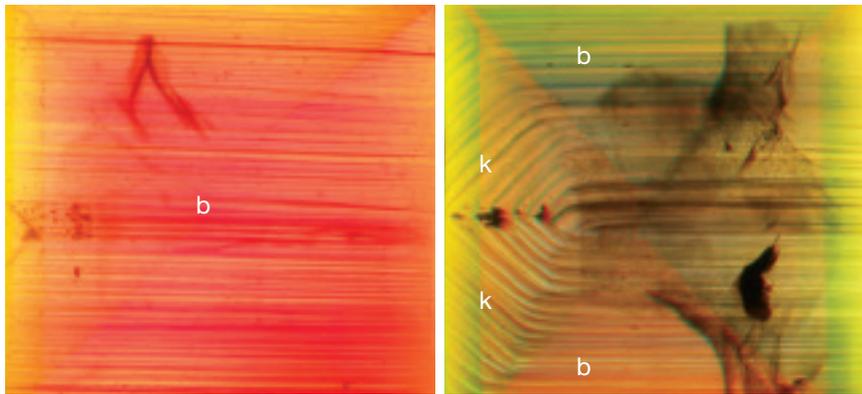


Figure 4. In faceted alexandrites produced using the flux method by Creative Crystals Inc., growth planes parallel to the pinacoid b (010) and the prism k (021) are observed in the immersion microscope. The b -axis runs north-south in both examples. These growth structures aid in locating the positions of the b -axis and the optic plane. Viewed in immersion with polarized light, field of view 7.5 x 7.5 mm.

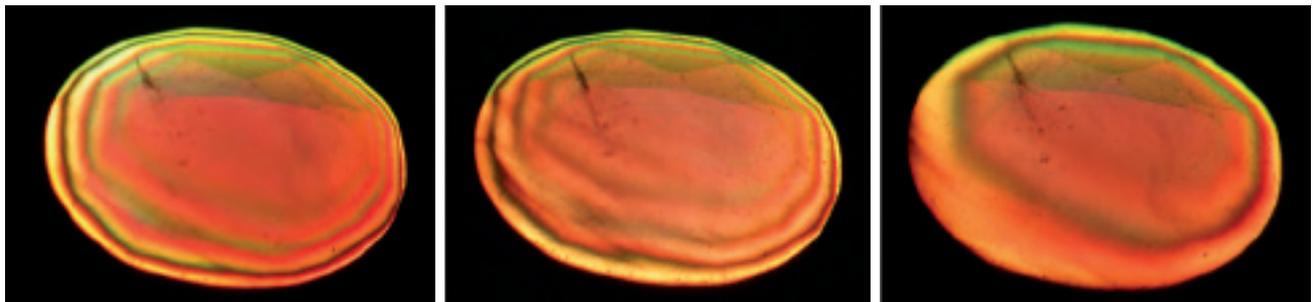


Figure 5. Interference figures of an 8 x 6 mm faceted alexandrite grown by the HOC technique in Novosibirsk, Russia. In all three images, the optic axis is inclined to the direction of view. Tilting the crystal toward a position in which the angle between the optic axis and the direction of view is decreased (shown from left to right) moves the interference rings toward the center of the sample. Upon rotating the crystal about the b -axis, both optic axes can be observed. The locations of both optic axes determine the positions of the optic plane and of the a - and c -axes. With this information, the angle between the table facet and the relevant crystallographic axis can be verified. Viewed in immersion with crossed polarizers.

purposes of evaluating this phenomenon in faceted alexandrites in transmitted light, the samples were observed in immersion. By doing so, reflection of light at the pavilion facets and the corresponding mixing of different color components could be largely avoided. The only minor side effect of the methodology was a slight shift in color toward yellow on account of the immersion liquid.

All six oriented samples displayed the pleochroic behavior and colors commonly seen in alexandrites of similar size in both daylight and incandescent light, as follows (figure 6):

Daylight: X || a = violet-purple, Y || b = yellow-orange, Z || c = intense blue-green

Incandescent light: X || a = reddish purple, Y || b = orange, Z || c = green

The results were consistent with the established orientation of the table facets of the six samples as described above. The colors of X, Y, and Z observed visually were almost identical for the different samples of each group (flux-grown and HOC-grown synthetic alexandrites), with no distinct differences. Likewise demonstrated was the effect of differences in light path length and stone thickness, insofar as a fading

of the color from the center of the table (or the culet) to the girdle was seen, especially in the step-cut samples grown by Creative Crystals.

Still in transmitted light but without a polarizer, two of the three basic colors previously separated by means of the filter were mixed in each direction of view. In all three directions, a color change between daylight and incandescent light was perceived (figure 7):

Daylight: view || a = green, view || b = blue-violet, view || c = greenish yellow

Incandescent light: view || a = red-purple, view || b = reddish purple, view || c = red-purple

Again, no distinct differences were seen when comparing samples with the table facets in the same orientation, regardless of the cut.

Thus, to summarize, in transmitted light and especially in immersion, it was possible to observe different colors in views parallel to one of the three crystallographic axes and, by means of a polarizer, to separate the three basic colors of X, Y, and Z.

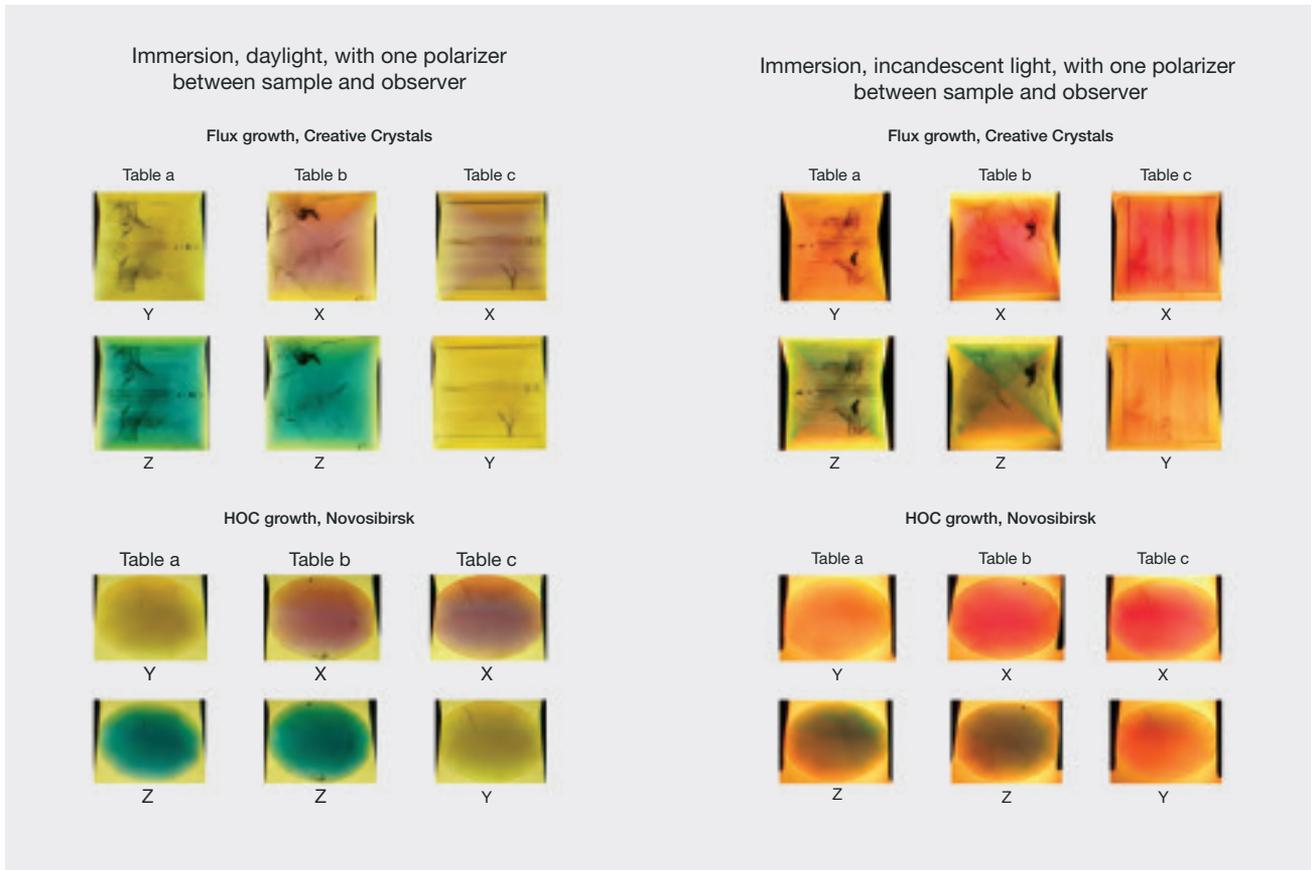


Figure 6. Pleochroism in faceted alexandrites cut with table facets perpendicular to the three crystallographic axes a, b, and c, in daylight (left) and incandescent light (right). The three basic colors of X, Y, and Z are observed by using a rotatable polarizer between the sample and the observer. The colors seen are nearly identical for all six alexandrite samples, regardless of differences in cuts and sizes. Use of immersion liquid reduces the influence of reflections from the facets. Field of view 7.5 x 7.5 mm (flux-grown samples) and 8 x 6 mm (HOC-grown samples).

COLOR BEHAVIOR OF FACETED GEMSTONES IN REFLECTED LIGHT

Turning to the scenario in reflected light, the impression was one of a mixture of all three color components. To evaluate the general underpinnings of this situation, the simplified model presented by Hughes (2014) for biaxial gemstones in general was applied to the synthetic alexandrites examined.

With regard to the samples faceted with a relatively simple step cut (emerald cut), and by neglecting the refraction of light entering the crown facets and assuming a pavilion angle (the angle between the table and a pavilion facet) of 45°, a similarly simplified model for the path of light could be drawn. An example is given in figure 8 for an alexandrite cut with the table facet perpendicular to the b-axis. Unpolarized white light entering the sample at (1) through the table and crown facets would travel along the b-axis and split in the sample into X and Z color components. After reflection at the pavilion, light would travel along the c-axis, with X and Y color components. After a further reflection at the opposite side of the pavilion, the light beam would again travel along

the b-axis. Light leaving the sample at (3) would thus contain X, Y, and Z color components. Reversing the scheme, light entering the sample at (3) would traverse along analogous paths, leaving the sample at (1). Light paths are not shown for this example.

If the starting point is shifted by 90°, light entering the sample at (2) through the table and crown facets would travel along the b-axis and split in the sample into X and Z color components. After reflection at the pavilion, the beam would travel along the a-axis, with Y and Z color components. Following a second reflection opposite, the beam would return to traveling along the b-axis. Upon exit at (4), the light would consist of two polarized waves with each wave showing X, Y, and Z color components. A reversed scenario for light entering at (4) would display a similar route, leaving the sample at (2). Again, light paths are not shown for this example.

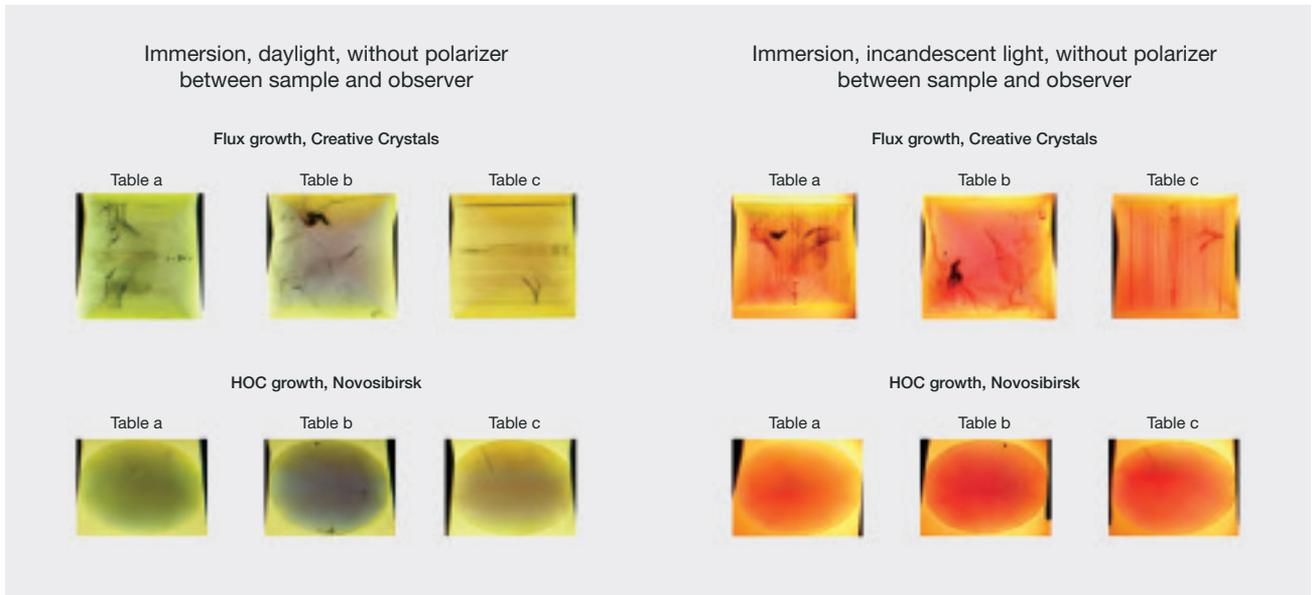


Figure 7. Pleochroism in faceted alexandrites cut with table facets perpendicular to the three crystallographic axes a, b, and c, in daylight (left) and incandescent light (right). The different colors are observed in views parallel to the crystallographic axes without using a polarizer. The colors seen are nearly identical for all six alexandrites, regardless of differences in cuts and sizes. Use of immersion liquid reduces the influence of reflections from the facets. Field of view approximately 7.5 x 7.5 mm (flux-grown samples) and 8 x 6 mm (HOC-grown samples).

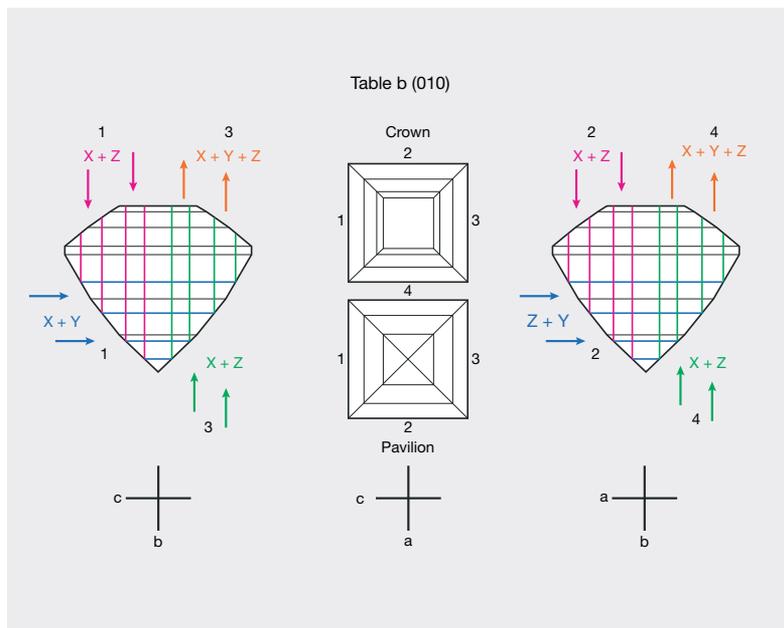


Figure 8. Schematic representation of simplified light paths through a faceted biaxial alexandrite cut with a table facet perpendicular to the b-axis. Views perpendicular to the table facet—i.e., parallel to the b-axis (center) and parallel to the table facet (right and left); a, b and c represent the directions of the crystallographic axes. Light entering the crown at (1) is reflected at pavilion facets at (1) and (3), leaving the crown at (3). Light entering the crown at (2) is reflected at pavilion facets at (2) and (4), leaving the crown at (4). Light is absorbed along the different light paths, and a complex mixture of the three basic color components X, Y, and Z exits the crown of the gemstone.

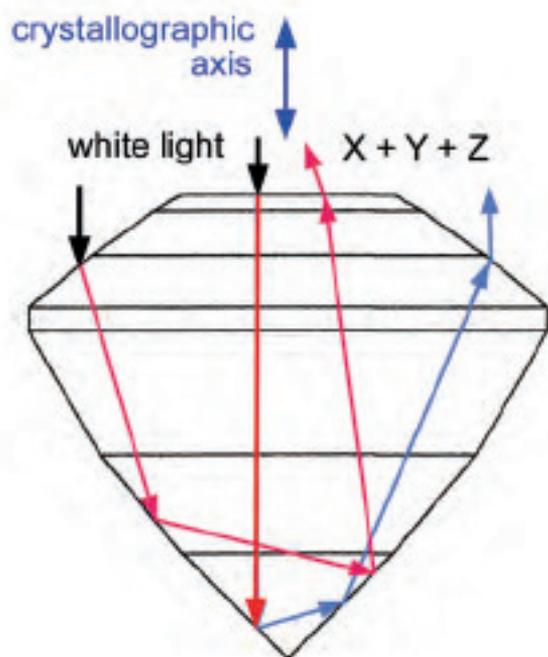


Figure 9. Schematic representation of light paths through a faceted biaxial alexandrite. Light is refracted at the crown facets and reflected from the pavilion facets. If the table facet is oriented perpendicular to a crystal axis, only the beam shown in red would consist of just two color components. All light beams inclined to this beam would be composed of all three color components X, Y, and Z. Therefore, light traveling through the faceted sample leaves the gemstone as a complex mixture of the X, Y, and Z color components.

Hence, application of the simplified model reveals that for each light path just described, the beam leaving the sample at the table or crown facets would have X, Y, and Z color components. If the simplifying assumptions are removed from the equation, light entering the alexandrite would be refracted at the crown facets, and the beam traveling

through the sample would be reflected at facets with pavilion angles other than 45° (figure 9). For example, the three pavilion angles of the step-cut alexandrites examined here measured 62°, 54°, and 42°, respectively. The actual behavior in the faceted step-cut alexandrites would therefore entail a far more diverse collection of beams, path lengths, and oblique directions through the sample. Such oblique directions, in turn, would alter the absorptions and corresponding mixtures of X, Y, and Z color components present in each beam exiting from the faceted gemstone. As a result, the light leaving the sample would show a more complex mixture of X, Y, and Z components than calculated on the basis of the simplified model.

Analogous theoretical considerations would pertain for samples cut with the table facets in other directions (i.e., perpendicular to the a- and c-axes). Similarly pertinent, if the cut is more complicated, such as that of the three HOC alexandrites with an oval brilliant-cut crown and a mixed-cut pavilion, more reflections would be generated, with light passing through the samples in an even greater number of different directions.

The foregoing theories suggesting extensive color mixing were tested on a practical basis using the six faceted samples in both daylight and incandescent light. The alexandrites of the two groups were placed table-up on a grooved plastic tray, which made it possible to view all six simultaneously while the light of a single lamp was reflected from their table facets. As such, the color impression given by each of the samples was quite similar, notwithstanding the different cut orientations for the table facets. This similarity thus corroborated the mixing of all three colors in faceted stones due to multiple reflections.

More specifically, with respect to the three step-cut alexandrites, some minor differences in color could be discerned. In daylight, the sample cut with the table facet perpendicular to the b-axis was blue-green, while the other two were less

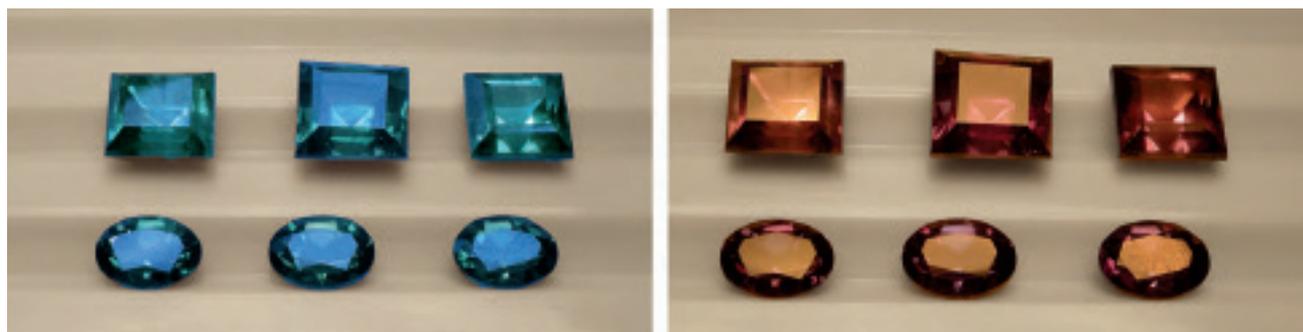


Figure 10. The six examined alexandrites in daylight (left) and incandescent light (right). These images have been corrected to represent the colors perceived by the eye. The samples, faceted with tables perpendicular to the a-, b-, and c-axes, are positioned face-up on a grooved plastic tray and illuminated with a light source placed directly above. The step-cut stones in the top row are in the range of 8 to 9 mm; the oval samples in the bottom row are approximately 8 x 6 mm.

blue, more green, or even slightly yellowish green (figure 10). In incandescent light, the sample with the table perpendicular to the b-axis was intense purple, while the two other two were less intensely colored, somewhat more reddish purple or red-purple.

When using the stone tray arrangement, the colors of the three samples with a more complex cut and a greater number of crown and pavilion facets were equivalent to each other in daylight and incandescent light. No visual color differences were observed. Moreover, if the alexandrites were placed on a glass plate, with several light sources illuminating them from different directions through the table and crown facets, or if the alexandrites were observed in diffused daylight, the differences in visual impression for even the step-cut samples became almost indistinguishable.

The divergence of the above results from the colors calculated by Sun et al. (2017) for alexandrites of various orientations are potentially explained by the simplifications employed for the model used there. In particular, the calculations neglected refraction of light at the crown facets, reflection of light from pavilion facets at angles of other than 45° , and especially multiple reflections from light entering the stone at directions oblique to the table facet. As a consequence, oblique directions of travel were not taken into account, yet these contribute significantly to the lively appearance of a faceted gemstone. It would be interesting to see if an augmented, more complex model incorporating a more realistic group of reflections and light paths within the sample would yield a closer approximation of reality.

In summary, the practical observations in the present study indicate that the cut and the orientation of the table facets play some role in achieving the desired colors in daylight or incandescent light. Nonetheless, all three simple step-cut alexandrites showed the “desired” color change. For samples with a more complex cut, such as a brilliant or mixed cut with numerous reflecting pavilion facets, the orientation of the table facet in such alexandrites is an almost negligible factor in determining color and color change.

CONCLUSIONS

Examination of two groups of faceted synthetic alexandrites with three known specific orientations of the table facets confirmed the general applicability of widely held tenets regarding color in the gemstone and also showed that as the cuts become more complex, such considerations have a diminishing effect on the actual appearance. In alexandrite, the three main color components of X, Y, and Z are quite different, but their visual impact can depend heavily on the viewing scenario.

When faceted samples are observed in transmitted light, with or without the use of a polarizer, distinct color differences dependent on the orientation of the table facets can be

perceived. Conversely, in reflected light, the color differences become less discernible. More particularly, the differences are weaker in samples with a simple step cut and nearly nonexistent with a complex cut.

Thus, to summarize the progression in moving from basic cases to the more complicated (see also Schmetzer et al., 2013):

- Cubes of different sizes viewed in transmitted light parallel to the a- and c-axes are green or even slightly yellowish green in daylight and red-purple or reddish purple in incandescent light. Cubes viewed parallel to the b-axis are more blue-green, blue, or even violet in daylight and more purple or purplish violet in incandescent light. In other words, parallel to the a- and c- axes there is a stronger yellow component in daylight and a stronger red component in incandescent light, while parallel to the b-axis there is a stronger blue component in both daylight and incandescent light.
- Faceted alexandrites with a simple cut such as a step cut exhibit, when viewed in reflected light, behavior similar to that of the cubes, albeit potentially weaker. Those with table facets perpendicular to the a- and c-axes are green or even slightly yellowish green in daylight and red-purple or reddish purple in incandescent light. Those with table facets perpendicular to the b-axis are more blue-green, blue, or even violet in daylight and more purple or purplish violet in incandescent light. The differences diminish with multiple light sources at a variety of angles, or with diffused light.
- Faceted alexandrites with a complex cut—such as a modern brilliant or mixed cut—display, when viewed in reflected light, almost no discernible color difference dependent upon table facet orientation.

The faceted samples studied here also demonstrated the interrelated effect of trace-element concentration and light path length. To wit, although the flux-grown alexandrites were larger than those grown by the HOC technique, the intensity of their colors was similar because the sum of color-inducing trace elements in the HOC material—primarily chromium and vanadium—was approximately double that in the flux material. The longer light path lengths in the three larger flux-grown samples (between 7.0 and 8.2 mm from table to culet) broadly compensated for the higher concentration of chromium and vanadium in the smaller HOC-grown synthetic alexandrites (between 4.1 and 4.2 mm from table to culet). Any influence on color-

ation from the iron measured in the flux-grown samples was minimal.

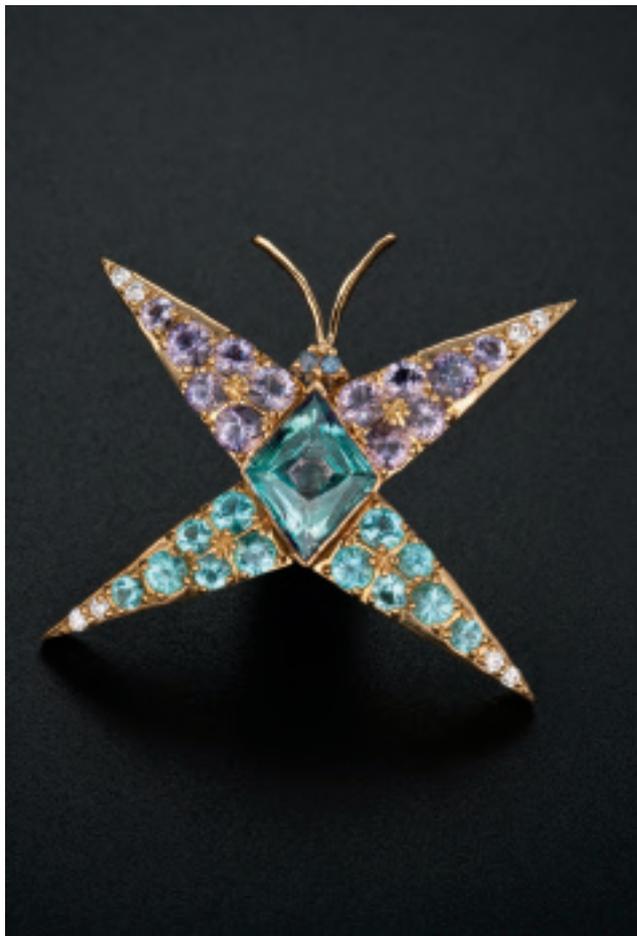
All six samples would be classified as showing the “desired” alexandrite color-change effect from daylight to incandescent light. In general, due to the mixing of colors by light traveling through the samples in different directions, alexandrites with appropriate sizes having the necessary amounts of color-causing trace elements, especially chromium or both chromium and vanadium, display good or at least acceptable color change regardless of cut orientation. For the synthetic alexandrite studied here, the risk of an unfavorable orientation of the table facet—again for stones of adequate sizes and concentrations of trace elements—is negligible. For other biaxial stones, it is expected that the effects of pleochroism in faceted stones will be reduced to some extent.

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Above: Butterfly pin. Body: 3.58 ct Russian alexandrite. Wings: diamond and purple scapolite from Tanzania, blue apatite from Madagascar. Eyes: alexandrite from Tanzania. Courtesy of Buzz Gray and Bernardine Johnston. Photos by Robert Weldon.

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Facing page: This 14.62 ct "reverse" color-change gem is a zircon—very few such stones from the Mogok region of Myanmar exhibit the phenomenon. This image is photographed in daylight; to view it in incandescent light, see page 106. Courtesy of Bryan Lichtenstein, 3090 Gems, Ltd. Photo by Robert Weldon/GIA.

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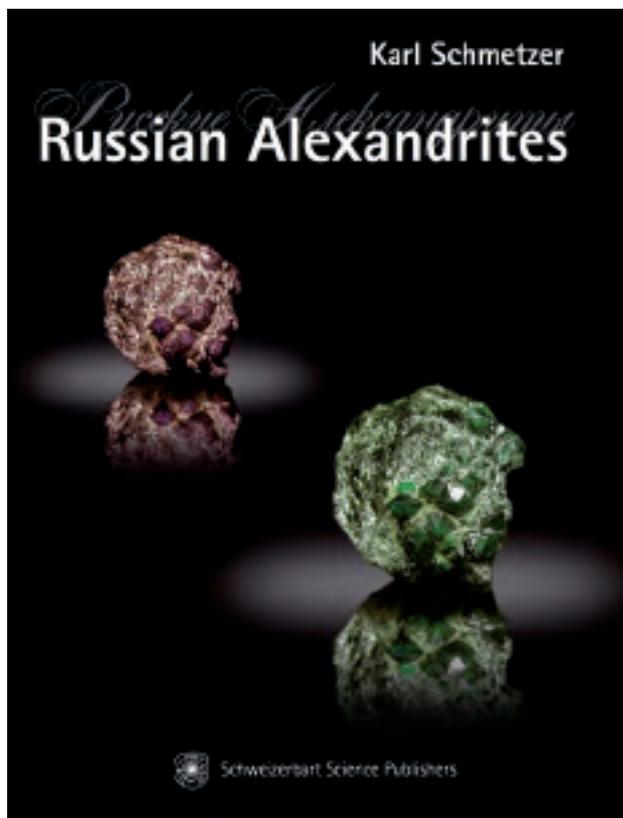
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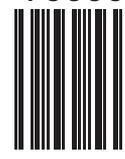


Above: Zircon, 14.62 ct incandescent (see p. 95 for more detail and to view daylight version of the same stone). Courtesy of Bryan Lichtenstein, 3090 Gems, Ltd. Photo by Robert Weldon/GIA.



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