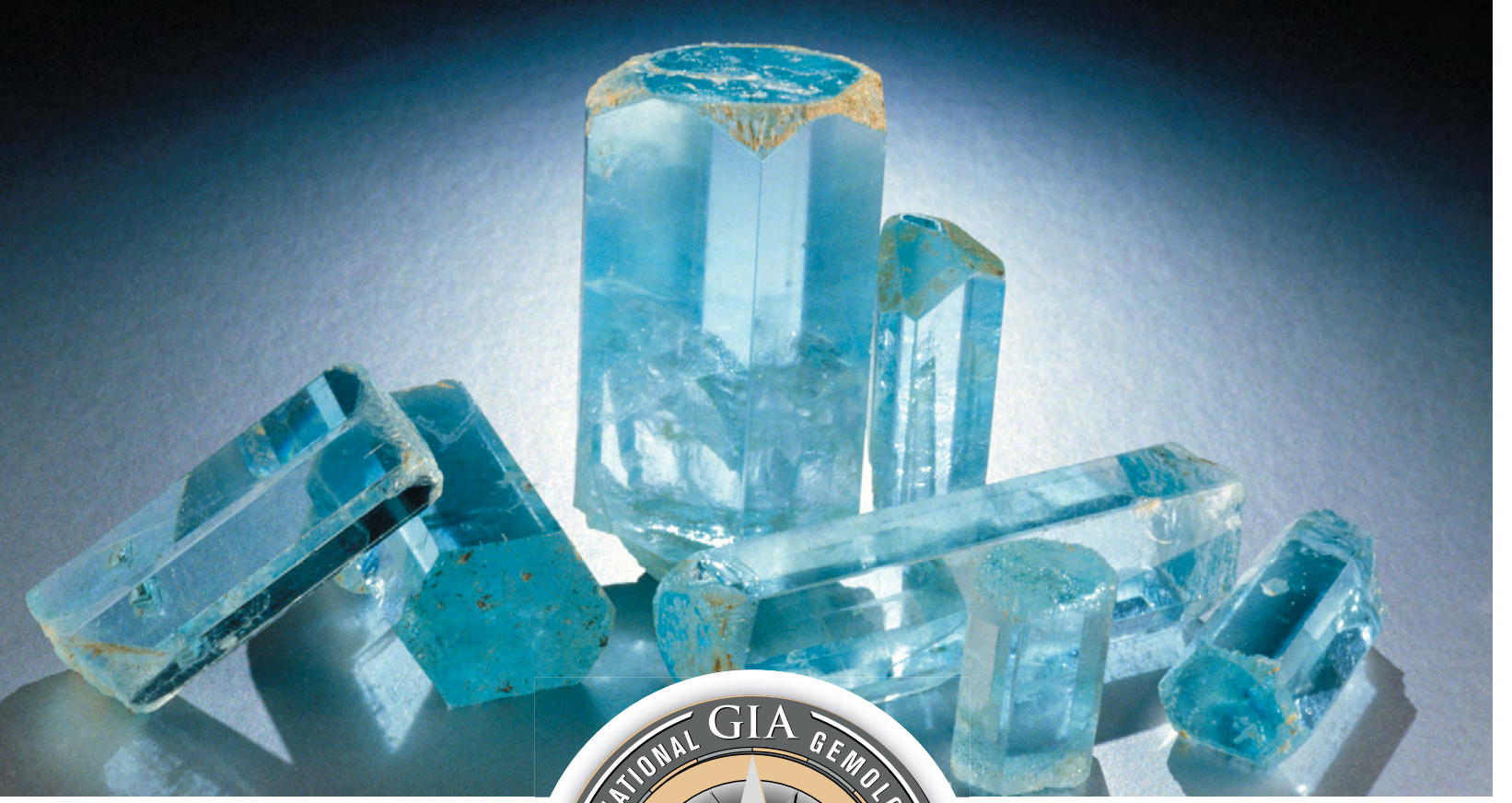
VOLUME XLVI

GEMS & GEMOLOGY

FALL 2010

Special Issue:
Retrospective of the 2000s

THE QUARTERLY JOURNAL OF THE GEMOLOGICAL INSTITUTE OF AMERICA



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DATABASE COVERAGE

Gems & Gemology's five-year impact factor (for 2004–2008) is 1.197, according to the 2009 Thomson Reuters Journal Citation Reports (issued July 2010). The journal ranked 17th out of 27 titles in the mineralogy category. *Gems & Gemology* is abstracted in Thomson Reuters products (*Current Contents: Physical, Chemical & Earth Sciences* and Science Citation Index—Expanded, including the Web of Knowledge) and other databases. For a complete list of sources abstracting *G&G*, go to gia.edu/gandg.

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Gems & Gemology is published quarterly by the Gemological Institute of America, a nonprofit educational organization for the gem and jewelry industry.

Postmaster: Return undeliverable copies of *Gems & Gemology* to GIA, The Robert Mouawad Campus, 5345 Armada Drive, Carlsbad, CA 92008.

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Color separations for *Gems & Gemology* are by Pacific Plus, Carlsbad, California.
Printing is by Allen Press, Lawrence, Kansas.

 ISSN 0016-626X

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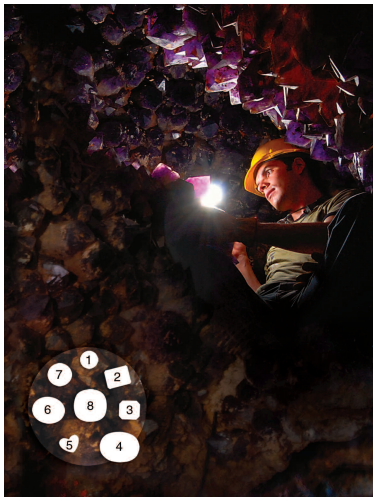
EDITORIAL

FEATURE ARTICLES

REGULAR FEATURES



About the Cover: The first decade of the 2000s saw dramatic changes in the diamond and colored stone industries, as established conventions in production, distribution, and marketing were upended by new sources, new gem treatments, and new methods of moving products from mine to consumer. The main cover image was taken at the Anahí mine in Bolivia, a major producer of ametrine. Fernando Arrien of Minerales y Metales del Oriente examines some of the larger amethyst specimens. The gems in the foreground are: (1) a 1.01 ct diamond, GIA Collection no. 37583 (2) a 4.50 ct emerald from Chivor, courtesy of Equatorian Imports; (3) a 1.53 pink diamond from Argyle, courtesy of Rio Tinto; (4) an 11.16 ct sapphire from Madagascar, GIA Collection no. 31618; (5) a 1.01 ct yellow diamond from the Aurora Butterfly of Peace collection, courtesy of Aurora Gems; (6) a 9.15 ct ruby from Winza, Tanzania, courtesy of Hakimi & Sons; (7) a 14.80 ct "golden" cultured pearl, gift of Tiffany & Co., GIA Collection no. 32510; and (8) a 13.94 cuprian elbaite tourmaline from Mozambique, courtesy of Pala International and Barker & Co. All images in this composite photo are by Robert Weldon.

Retrospective of the First Decade of the 2000s: Looking Back as We Move Ahead

Another decade, another period of sweeping change in the gem industry. . . . The articles in this retrospective offer four distinct perspectives on the developments of this tumultuous period, from the points of view of industry analysts Russell Shor and Robert Weldon; geologist James Shigley and colleagues; seasoned gemologists Shane McClure, Robert Kane, and Nicholas Sturman; and research scientist Christopher (Mike) Breeding and coauthors.

The content of this issue has been meticulously researched over the last several years. Russ Shor has been reporting on the business of diamonds and other gems for three decades now, and Robert Weldon has been doing the same for colored stones for nearly as long. Dr. Shigley and his coauthors started researching gem deposits for this retrospective issue almost as soon as they published the localities article in the Winter 2000 retrospective—which built on the Spring 1990 retrospective article. Shane McClure has lived and breathed gem identification in the GIA Laboratory for more than 30 years, with his two colleagues providing in-depth experience from both the lab and the industry. Dr. Breeding and his coauthors are experienced researchers tasked with applying the instruments and techniques described in their article to the gemological challenges of the 21st century.

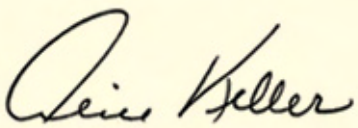
Certain developments dominated gemology in this first decade of the 2000s. High-pressure, high-temperature treatment of diamonds augured chaos as we entered the century, but researchers around the world mobilized to find identification clues through traditional gemological observation as well as new technologies adapted from other fields. Likewise, beryllium diffusion of ruby and sapphire brought together geologists, gemologists, and physicists to determine the starting material used, the techniques being applied, and the instrumentation needed to identify the treatment. Little-known acronyms such as SIMS and LIBS permeated the gemological lexicon, and instrumentation such as LA-ICP-MS—once primarily the province of academia—became a fixture in many gemological labs.

All these developments took place, as the lead article points out, during a period of profound changes in the diamond and colored stone industries. The traditional single-channel diamond distribution system morphed into many channels, TV shopping and the meteoric rise of the Internet created new challenges for the brick-and-mortar retailer, and new attention to social and political issues in gem production radically transformed the supply chain.

Amid all this change there was one constant that became ever more important as the decade progressed: the need for cooperation, to work together to tackle these issues with our colleagues—not alone. Researchers from laboratories around the world furnished pieces to the puzzle that led to the identification of HPHT treatment of diamonds. Likewise, colored stone dealers, scientists, and laboratory gemologists contributed to the understanding and identification of beryllium diffusion. This decade also witnessed the creation of the Kimberley Process Certification Scheme, which brought together nations, nongovernmental organizations, and diamond industry leaders to stop the trade in conflict diamonds.

We at *Gems & Gemology* hope that you enjoy this valuable compendium, digest the wealth of information, and recognize the contributions made by so many individuals, companies, and organizations to move gemology forward in this first decade of the new millennium.

One last note: Throughout the issue, you will see references to information available in our online *G&G* Data Depository (gia.edu/gandg). We urge you to visit the Depository for the additional information it provides, especially the tables of diamond and pearl localities active during the decade. Note, too, that a retrospective article on synthetics and simulants will appear in our upcoming Winter 2010 issue. We are grateful to all of our authors for the vast amount of knowledge and research they brought to this endeavor—and their willingness to share so much with the greater gemological community.



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AN ERA OF SWEEPING CHANGE IN DIAMOND AND COLORED STONE PRODUCTION AND MARKETS

Russell Shor and Robert Weldon

The diamond, colored stone, and pearl businesses have witnessed unprecedented change since the turn of the 21st century. Not only have new markets for gems emerged around the world, but channels of distribution have also changed dramatically as a result of economic forces and political pressures. De Beers abandoned its single-channel seller role, which created—for the first time in over a century—a competitive rough diamond market. Political problems in Madagascar and a ban on gem exports from Myanmar disrupted supply channels for sapphire and ruby. And the proliferation of new sales avenues, through the Internet and TV, has given consumers much more information about gems and forever changed the way they buy them. The use of gems to subsidize bloody conflicts and repressive regimes has moved the trades to become more accountable, as concerns over terrorism and illicit trading have created a new legal environment. At the same time, a new class of consumers who value ethically, socially, and environmentally friendly products are making their demands known in the gemstone business.

The last decade was bookended by its two defining events: the September 11, 2001, terrorist attacks on the U.S and the world financial crisis that struck in September 2008. The 2001 attacks, which were followed by a terror attack on the Indian parliament in December, brought far-reaching international reviews of financial and security activities, while the crisis of 2008 placed much of the world’s financial institutions in jeopardy. In between, however, the decade saw substantial increases in wealth, both in most developed nations and in some developing nations, particularly India and China.

For the diamond industry, this article will address the radical transformation it underwent on many levels during the last 10 years. The most significant event was the dissolution of the once tightly controlled rough distribution channel into a more competitive market. In addition, producing nations, particularly in Africa, moved to derive greater economic benefits from their diamonds (figure 1). And social and political issues, from the Kimberley Process to anti-terrorist legislation, became a critical part of doing business, as the industry was subjected to close scrutiny from various government and law-enforcement agencies around the world.

The traditional art of diamond cutting also was revolutionized by technology, which brought new cuts and greater demand for precision cuts. In diamond retailing, the Internet became the fastest-growing sector in the U.S., while India and China became important consumer markets.

The colored gemstone industry also witnessed significant changes. It saw an evolution in the way gems are mined and the manner in which they are then distributed through the supply chain. The development of large-scale mining operations for colored gems has been in the news for the entire decade (Robertson, 2009). Nevertheless, it is believed

See end of article for About the Authors and Acknowledgments.
GEMS & GEMOLOGY, Vol. 46, No. 3, pp. 166–187.

Figure 1. Some of the most important developments of the decade were in the way rough diamonds were distributed and the efforts of producing countries to gain greater economic benefits from their deposits. These rough diamonds are all ~1 ct in weight. GIA Collection no. 24648; photo by R. Weldon.

that about 80% of the world's supply of colored gems still come from small-scale artisanal miners (Michelou, 2010; figure 2).

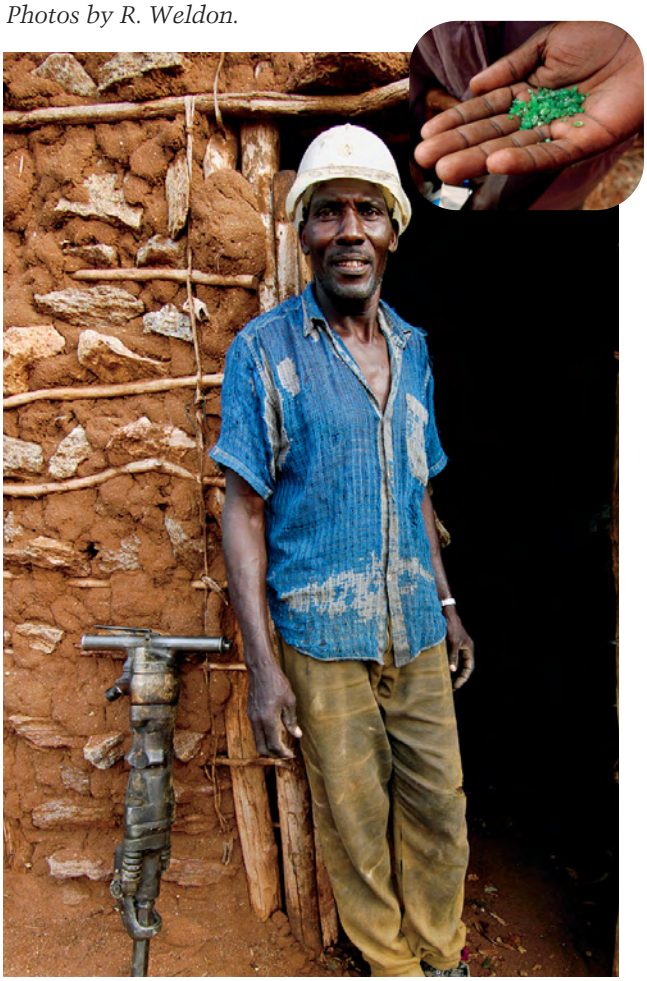
The financial crisis at the end of the decade forced major cutbacks in diamond mining and prompted industry banks to re-evaluate long-accepted credit practices, with the result that supplies and distribution began changing in ways that still have not fully played out. Colored stone mining and cultured pearl farming also experienced severe cutbacks, while prices and demand grew increasingly volatile.

PRODUCERS

Diamond—From Supplier of Choice to Multiple Suppliers. *De Beers.* In 2000, the De Beers Diamond Trading Company (DTC), which then controlled about 64% of the world's rough diamond output by value (Even-Zohar, 2007) and 50% by volume (Shor, 2005), announced an ambitious plan to revamp its 65-year-old sales structure. The initiative was called Supplier of Choice (SOC). The main components were designed to shift the burden of consumer advertising of diamond jewelry onto DTC clients; reset the client selection system to one based on a set of "objective criteria" determined through detailed company profiles; and implement "best practice" policies that required clients to source all of their rough from nonconflict producers, pay fair wages, ensure safe working conditions, and follow ethical trading practices (Shor, 2005; figure 3).

Coinciding with the launch of SOC, the DTC also announced that it would abandon its traditional

Figure 2. Small-scale artisanal miners, such as this tsavorite miner near Voi, in Kenya, are estimated to supply some 80% of the world's gems. Photos by R. Weldon.



role of stockpiling diamonds during periods when demand was reduced or when production from particular sources threatened to destabilize the market. This strategy had consumed considerable cash reserves and generated a great deal of controversy during the 1990s (Even-Zohar, 2007). When the DTC announced Supplier of Choice in 2000, it controlled an enormous rough stockpile, held by corporate parent De Beers, that was valued at more than $4.8 billion and drawn from all producers in its network (Even-Zohar, 2007). The DTC's overall aim, in addition to freeing itself of the burden of stocking rough diamonds, was to comply with the European Union's regulations regarding anti-competitive activity (Shor, 2005; Even-Zohar, 2007) and more tightly focus marketing and sales efforts on its own production.

While Supplier of Choice was the most significant shift in De Beers's operations, it also embarked on several major changes that affected the rough and, ultimately, polished diamond market. In 2001, De Beers converted from a publicly traded corporation to a privately held company. The main shareholders were Anglo-American Group, 45%; Central Holdings, the Oppenheimer family trust, 45%; and Debswana, the De Beers–Botswana government partnership that operates the country's diamond mines, holding the remaining 10% (Shor, 2005). The deal cost $18.7 billion, financed mainly through sale of Anglo-American stock. However, the company also borrowed $3.35 billion from a consortium of banks, which transformed it from one with ready cash reserves to one carrying a significant debt. To pay down this debt, De Beers significantly reduced its workforce and sold the bulk of its diamond stockpile in an orderly fashion during the following two years.

At the same time, De Beers sought (and in late 2002 received) legal approval of its SOC initiatives from the European Commission (EC), which oversees competitive issues in the EU. However, its June 2003 announcement that it would drop one-third of its existing sightholders touched off several lawsuits in the U.S. and Europe from clients claiming they were unfairly removed (Shor, 2005).

De Beers ran into other legal problems in the U.S. A number of class-action suits were filed during the early 2000s, alleging that the company had, over the years, violated anti-trust, unfair competition, and consumer protection laws in order to fix and raise diamond prices. The suits were combined under the jurisdiction of the U.S. District Court of New Jersey

Figure 3. Gareth Penny, outgoing managing director of De Beers Group, was the principal architect of the Supplier of Choice program. Photo by R. Weldon.

(Diamond Class Action Settlement, 2010). De Beers initially declined to appear, leading to default judgments against it. After launching SOC, and with an aim of returning to the U.S., De Beers eventually negotiated a combined settlement that was approved in April 2008—though it admitted no wrongdoing. Of the total settlement, $22.5 million would go to "direct" purchasers (DTC clients) between 1997 and 2006, while $272.5 million would be split by an "indirect purchaser" class, which included diamond wholesalers and retailers—who would divide half that amount—and consumers, who would share the second half. Although the court approved the settlement in August 2008, a number of claimants filed appeals contesting it (Diamond Class Action Settlement, 2010). In July 2010, the U.S. Second Circuit Court of Appeals overturned the settlement, holding that the indirect purchaser class had been improperly certified. Then, in August, a panel of judges from that same court vacated that ruling, primarily on the grounds that both sides had agreed to the settlement, and referred the case to review by the full 15-judge panel of the court. At this writing, the case remains in limbo.

De Beers faced legal challenges from another front: EU approval of Supplier of Choice. Various parties claimed that the company's relationship with Russia's Alrosa, the world's second largest diamond producer, was anti-competitive. Again, De Beers did not contest the challenge; and in 2004 it agreed to gradually scale down its rough diamond purchases from approximately $1.2 billion yearly, to $700 million in 2005, and by $75 million increments thereafter until 2009, with the maximum set at $275 million (De Beers/ALROSA Trade Agreement, 2004).

By 2008, the last "normal" year before the economic crisis forced major changes in mining operations, the DTC's share of the rough market was down to 42% by value and 29% by volume (Rio Tinto Diamonds, 2008). It had unloaded its diamond stocks and a number of its South African mines, and was making plans to shift the bulk of its operations to Botswana, which had acquired a significant share of the company (Even-Zohar, 2007). Because of the mine closures, De Beers's market share by volume fell to just under 20% in 2009 (24 million carats against a world total of 125 million). The company expected to produce 31 million carats in 2010 and revive to 40 million carats in 2011, compared to 48 million carats in 2007 (Penny, 2010). De Beers announced it would cap production at 40 million carats yearly after 2011 in order to extend the lives of its existing mines.

Beneficiation. The 2000s also saw diamond-producing counties begin to assert more control over the disposition of their resources. The "beneficiation" movement, creating added-value activities such as rough sorting and cutting in producer countries, also forced De Beers and the DTC to greatly restructure operations away from their traditional headquarters on London's Charterhouse Street (Even-Zohar, 2007). Botswana, which produces two-thirds of De Beers's output (De Beers, 2009), used that leverage to create a separate DTC Botswana in 2006. By the following year, it had issued diamond manufacturing licenses to 16 companies—mostly Indian and Israeli—that agreed to establish cutting operations supplied from local production. The government also mandated that much of the sorting from its mines be done locally instead of in London. Both of these actions represented a drastic break from the long-standing DTC policy of integrating production from all of its sources and sorting it at its London headquarters (Even-Zohar, 2007). Still, the DTC formalized the process when it appointed these 16 companies sightholders.

Beneficiation efforts have also led to 11 DTC-sightholder manufacturing facilities in Namibia. However, these are supplied from all DTC sources, not just local Namibian production.

South Africa launched similarly ambitious efforts, beginning with amendments to the Diamond Act in November 2005. It also embarked on a plan to promote black businesses under a series of Black Economic Empowerment (BEE) initiatives. The BEE laws required all diamond mining companies, including De Beers, to have a minimum of 26% black equity within five years. The diamond portion of BEE also required that local diamond polishing operations would be offered first refusal for all diamonds mined in the country. The process was supervised by a government-appointed State Diamond Trader, which was mandated to buy up to 10% of the nation's output for resale to cutting operations (Hill, 2008).

The State Diamond Trader's office opened in June 2007 with the professed goal of buying $140 million worth of rough. While the policy did result in an increase in the number of diamond manufacturing operations in the country (e.g., figure 4), including 19 newly appointed DTC sightholders, the office was never sufficiently funded to purchase more than a tiny fraction of South Africa's rough

Figure 4. A renewed desire for black empowerment and beneficiation took root in the southern African diamond business at the beginning of this century, with the establishment of cutting factories throughout South Africa, Namibia, and Botswana, such as this facility in South Africa. Photo by R. Weldon.

Figure 5. These two pink diamonds (0.51 and 0.55 ct) from the Argyle mine in Australia were part of the 2007 Argyle pink diamonds tender. Photo by R. Weldon.

production. At this writing, it has made little impact on the nation's diamond industry (Creamer, 2009; "South Africa's state diamond trader. . . ," 2010).

De Beers also commissioned two new mines in Canada: Snap Lake and Victor. Snap Lake was initially projected to yield 1.4 million carats yearly of primarily smaller diamonds; Victor's production, estimated to be about half of that, was somewhat higher quality. The company appointed three Ontario sightholders to polish 10% of its locally mined production (Golan, 2010). However, just as the mines became fully operational in the fall of 2008, the market went into a severe decline (Hill, 2009).

Alrosa. After it was required—not without some objections—to scale back its rough sales to the DTC, Russia's Alrosa developed its own client base, which included a number of major DTC sightholders. Alrosa had acquired a 32.8% interest in Angola's Catoca mine in the early 1990s. Commissioned in 1997, Catoca was producing just over 3 million carats yearly by 2003 (Even-Zohar, 2007) and 6 million carats by 2009, representing about 70% of the country's diamond output (Nyaungwa, 2010). During the economic crisis of 2009, Alrosa began changing its rough sales policy from a DTC-like system of supplying several dozen firms, toward one that allotted much greater quantities to comparatively few major buyers. In 2010, the company announced it would earmark a minimum of $500 million worth of rough to four Indian companies over the following three years, contracting an additional $300 million to a consortium of Israeli manufacturers and $1.4 billion to Russian cutting operations over the same period (Kravitz, 2010; Goldstein, 2010).

Rio Tinto. In 2003, London-based mining giant Rio Tinto opened Canada's second diamond mine, Diavik, with 60% ownership. Rio Tinto had established its own rough diamond sales channel in 1996, when its Argyle operation in Australia ended its sales agreement with the DTC (Shor, 2005). Diavik produced 3.8 million carats in its first year of operation and more than 8 million carats over the following several years (Rio Tinto Diamonds, 2006). Rio Tinto marketed its share and its Argyle production through a sight system similar to the DTC's, though it claimed its pricing would be more flexible than its rival's (Even-Zohar, 2007). The company also adopted a series of sustainable mining initiatives for its own operations and, like De Beers, developed a code of best business practice requirements for its clients. It also helped develop Canada-branded diamond programs in cooperation with local diamond cutting operations (Rio Tinto Diamonds, 2004–05).

Argyle, at its peak, was the world's largest diamond producer by volume, yielding over 40 million carats yearly of predominantly near-gem diamonds during the 1990s. The majority of its cuttable output went to feed the discount diamond jewelry markets (Shor, 2005). As the millennium opened, however, Rio Tinto faced a decision over whether to convert Argyle to an underground mine. The project was estimated to cost $1 billion, and Rio Tinto studied it for five years before making the decision to go ahead in 2005 (Rio Tinto Diamonds, 2006; Bosshart, 2010). The construction underground and reduction in the open-pit operations cut Argyle's yearly production to some 29 million carats in 2006, 20.5 million in 2007, and 15 million in 2008 (Janse, 2007, 2008, 2009).

Because Argyle produces a significant amount of yellowish brown and brown diamonds (which it calls "Champagne" and "Cognac"), Rio Tinto was a charter member of the Natural Color Diamond Association, through which it promoted the $150 million worth of those stones it mined each year. Argyle also produces several hundred carats of pink diamonds each year, which it markets at special tender auctions in Geneva, Switzerland (e.g., Rio Tinto Diamonds, 2008; figure 5).

BHP Billiton. Canada's first diamond mine, Ekati, was developed by BHP Billiton during the late 1990s. The company set aside 10% of its production by value, in specific qualities, for local polishing operations (BHP Billiton, 2010). Unlike the DTC or Rio Tinto, BHP markets most of its production, current-

ly $40–$50 million monthly, by tender auctions through an Antwerp sales office. While this system has resulted in fluctuating prices, the BHP rough is so competitive that these are regarded by some observers as closest to true market prices (Even-Zohar, 2009).

Other Producers. In the meantime, a number of junior producers developed smaller mines that large firms such as De Beers or Rio Tinto had withdrawn from or declined to exploit. The most significant was the Letšeng-la-Terae mine in the small nation of Lesotho. Originally operated by De Beers in the 1970s, Letšeng closed in 1982 during a major industry slump and remained inactive for almost two decades. In 1999, two South African investment groups, JCI and Matodzi, acquired the property, restarting operations in 2004. In 2006, they sold a controlling interest to Gem Diamonds of South Africa (Gem Diamonds, 2010a).

Soon after, the company unearthed the 603 ct "Lesotho Promise," the 15th largest diamond ever found. A year later, it came up with the 493 ct Letšeng Legacy (figure 6), which Laurence Graff purchased for $10 million, as well as several other diamonds weighing over 100 ct. The stream of huge stones continued: In 2008, Letšeng yielded a 478 ct stone that also went to Graff, and in 2010, it announced a 196 ct diamond that drew estimates of over $11 million (Gem Diamonds, 2010b). While Letšeng's production was relatively small—less than 100,000 carats yearly—its average price per carat was nearly $1,900, compared to an industry average of $71 (Brough, 2007; Letšeng Diamonds, 2010).

Figure 6. The 493 Letšeng Legacy is one of several 100-ct-plus diamonds recovered from the Letšeng-la-Terae mine in the last few years. Photo courtesy of the Antwerp World Diamond Centre.

In 2007, Gem Diamonds acquired Australia's Ellendale mine, the source of about half the fancy yellow diamonds entering the market; and by the end of 2009, it had completed a deal with Tiffany & Co. to supply a collection of fancy yellow diamond jewelry (Allen, 2009; Gem Diamonds, 2010c).

As De Beers sold off some of its older operations in the middle of the decade, Petra Diamonds of South Africa acquired its Cullinan (formerly Premier) and Koffiefontein mines, both in South Africa, and its interest in the Williamson mine of Tanzania. Soon after the Cullinan deal went though (July 2008), Petra recovered a 26 ct stone that was cut to a 7.03 ct Fancy Vivid blue diamond that sold for $9.4 million ($1.35 million per carat). In 2009, Petra recovered a 507 ct diamond, which it named the Cullinan Heritage and sold to Hong Kong diamond trader Chow Tai Fook for $35.3 million, the highest known price ever paid for a rough diamond (Petra Diamonds, 2010).

By the end of 2007, diamond production had climbed to an estimated 168.1 million carats (Kimberley Process, 2008), while prices for top-quality and large stones soared, both on the prospect that an increasingly affluent world would generate greater demand (Shor, 2008b). Events were in the offing, however, that would soon upend these assumptions.

Colored Stones. In 2007, worldwide demand for all colored stones was about $10 billion, 7% of the total jewelry market according to a 2009 survey (BUZ Consulting, 2009). Broken down further, ruby and sapphire accounted for 30% ($3 billion) and emerald 12% ($1.2 billion), with all other gemstones constituting the remainder. The study, completed before the 2008 economic crisis, predicted a 5.2% average annual growth rate in worldwide demand for colored gems through 2020, largely from emerging markets such as India and China that have cultural affinities for gemstones.

New Deposits and New Operations. *Madagascar.* Much of the global gem business for well over three years in the middle of the decade was dominated by Madagascar. This was due in part to the Malagasy

Figure 7. Madagascar produces rubies and sapphires of many colors, and production of these and other gems drove the global gemstone market for much of this decade. The orange-pink sapphire in the ring weighs 3.15 ct; the loose stones are 2.11–4.13 ct. Courtesy of Omi Gems, Los Angeles; photo by R. Weldon.

government's decision to liberalize its mining sector (beginning in 2005) and in part to a historic financing scheme sponsored by the World Bank to help develop mining, gemology, and other value-added initiatives in the island nation. Most of the production was in tourmalines, sapphires (e.g., figure 7), and rubies, but a new gem mineral—pezzottaite—was also introduced. At its peak in 2007, the sector employed close to 100,000 people (Shor and Weldon, 2009).

However, Madagascar's gemstone production suffered a serious setback in 2008, when the country's then-president, Marc Ravalomanana, reversed some of his own liberalization policies by placing a ban on rough gemstone exports. His decision to clamp down followed the export of the 536 kg emerald-in-matrix specimen "Heaven's Gift Emerald," which Ravalomanana claimed had been illegally taken from the country (Yager, 2008). Even though the ban on exports ended in July of 2009, the mining sector in Madagascar failed to get jump-started as a result of the global economic slump.

Myanmar. Production at various Burmese corundum mines slowed considerably in the latter part of the decade, as trade sanctions deterred exports of rough material. The sanctions enacted by the U.S. and EU—among the world's largest consumer markets for gems—cut supplies of Myanmar's ruby and jade in Western markets to virtually nothing. This was particularly true after the U.S. Tom Lantos Block Burmese JADE Act, banning the importation of all ruby and jadeite mined in Myanmar, was signed into law in July 2008. The previous ban, enacted in 2003, did not cover Burmese gems that were cut in a third country. The cumulative sanctions caused Burmese ruby production to drop by an estimated 50% (Shor and Weldon, 2009).

Figure 8. Affluent Chinese consumers are avid collectors of Burmese jadeite, and much of the production of jadeite in Myanmar is exported to China. This upscale jadeite shop in Guangzhou caters to jadeite connoisseurs. Photo by R. Weldon.

Because Myanmar produced an estimated 90% of fine- and commercial-quality ruby, while Madagascar embargoed exports as noted above, supplies of ruby and sapphire slowed greatly. This not only created worldwide shortages of gem corundum, but it also proved devastating to Thailand's gemstone cutting industry (Shor and Weldon, 2009).

One new source of corundum, Winza in Tanzania, began yielding some fine-quality ruby in 2007 (Schwarz et al., 2008), but the quantities produced could not begin to compensate for the loss of Myanmar and Madagascar goods. As supplies of fine and commercial qualities dwindled after 2008, a flood of nongem material entered world markets, especially the U.S., to fill the void. In its natural state, much of this material was infused with a lead-based glass to render it stable and attractive enough for jewelry use. This treated material, which traded for extremely low prices in gem markets, touched off two major controversies: (1) whether it was actually "ruby" (because some material was more filler than ruby, or was assembled from multiple pieces of corundum); and (2) how to describe it, with terms such as *composite*, *filled*, *stabilized*, and *treated* being used (Robertson, 2010). Lack of proper disclosure at retail also created controversy and brought on a number of press reports warning consumers about such stones (Wouters, 2010).

Jadeite jade, an important gem in Chinese culture, continued to be heavily mined in Myanmar. Between June 2009 and June 2010, more than 22,600 metric tons of jade were produced ("Over 10,000 jade lots. . . ," 2010), with much of that destined for China (Palagems, 2010; figure 8). Most was sold at official government Myanma Gems Enterprise gem auctions, though much was also distributed by other means, mainly through illicit smuggling into Thailand.

Other Producers. Colombia remained the major producer of emeralds; about 60% by quantity and 80% by value (Kuri and Ramirez, 2008), but problems in the form of market decline, guerilla activities, and ongoing conflicts with drug cartels led to a precipitous drop in official exports, from a peak of $452.4 million in 1995 to a reported $75 million by 2005 (Kuri and Ramirez, 2008). A major new source of fine emeralds called La Pita, located in Colombia's Boyacá Department, was developed in the late 1990s (Fritsch et al., 2002). By mid-decade, La Pita had produced hundreds of thousands of carats—some 40% of the output of Colombian emeralds—as production from other mines in the area slowed (Weldon, 2006).

Figure 9. Near Nova Era in Minas Gerais, Brazil, the Belmont mine operates using sophisticated optical sorters and other machinery to ensure an efficient and steady supply of rough (photo by Eric Welch). In the inset are two emeralds (17.4 g crystal and ~5 ct faceted stone) from the Belmont mine (photo by R. Weldon).

Brazil witnessed a sustained slump in overall gemstone production, in part due to the enforcement of minimum wage and environmental protection laws. However, its production of emeralds has reportedly increased with the opening of a new mine in the Nova Era region and technological developments at established mines such as the Belmont (ICA, 2006; figure 9). Toward the end of the decade, Pakistan's emeralds became embroiled in controversy over allegations that members of the militant Taliban were forcing residents of the Swat Valley, which had been closed for nearly a decade, to mine the material. It was reported that the proceeds were being used to finance terrorist activities ("Emeralds from Swat Valley. . . ," 2009).

The decade also saw the rise in popularity of garnets such as spessartine (e.g., Laurs, 2002b), demantoid (Laurs 2002a; Eddins 2010), and tsavorite (Mayerson and Laurs, 2004), as well as cuprian tourmaline (from Africa), thanks to the discovery of new sources (see, e.g., Laurs et al., 2008).

And as fine ruby gained in price and grew ever scarcer in world markets, red spinel and pink-to-red tourmaline became sought-after alternatives. In

Figure 10. TanzaniteOne, formerly Afgem, is licensed to mine tanzanite at Block C in Merelani, Tanzania. This high-security screen enclosure (designed to prevent theft) guides miners to different shafts at the mine. Photo by R. Weldon.

addition to the traditional spinel sources of Sri Lanka, Pakistan, and Myanmar (spinel, if polished elsewhere, is not included in the sanctions against the country), a new deposit was located in Tanzania in 2005 (Laurs, 2006), while Nigeria developed into an important source for pink tourmaline (Laurs, 2009) following a 1999 discovery in the western part of that country.

Large-Scale Mining Operations. Despite the recent economic downturn, global demand for gems grew over most of the decade. As a result, several corporations have begun large-scale colored stone mining projects in the last 10 years. (By "large-scale," we mean here that such a company is publicly traded, uses geophysical techniques to identify and analyze suitable deposits, and employs heavy machinery such as backhoes, bulldozers, pneumatic drills or jackhammers, explosives, and trucks to move large quantities of overburden to extract and presort gem materials.) In recent years, large-scale miners have also launched corporate social and environmental responsibility programs.

We review some of the most notable companies here.

Afgem and TanzaniteOne. Merelani, Tanzania, is the world's sole commercial source for tanzanite. In 2001, South Africa–based Afgem obtained government licensing to mine tanzanite and commenced operations at Block C in Merelani, which contains several other blocks that are primarily worked by small-scale miners. Afgem soon modeled their production and marketing strategy after De Beers's historical approach to the diamond business (Weldon, 2001a). It did so by attempting to control output of the rare blue-to-violet gem through their mining operations (figure 10) and by purchasing tanzanite from local producers. Distribution was handled through a series of "sightholders," or preferred dealers. Its primary aim was to stabilize what had been a highly volatile pricing structure for tanzanite since its discovery in 1967. TanzaniteOne Mining Ltd. acquired Afgem's business and assets in 2004. Other colors of zoisite, including green (e.g., figure 11) and pink, have been mined in the Merelani area, though production remains sufficiently rare for them to be deemed collectors' stones.

At the height of tanzanite's popularity, in 2000, it was named a birthstone for the month of December, ascension to a status that ranked it among the world's most popular gems (Federman, 2006). However, according to *The Guide*, which has monitored the value of tanzanite for several decades, prices dipped during the early-to-mid 2000s. In an extensive report on tanzanite values, Robertson (2006) attributed the dip to a combination of factors, including market saturation in the U.S. He and others also reported on a decline in price for blue sapphires, which provided the buying public with far greater choices when selecting blue stones (Weldon, 2001b). TanzaniteOne has sought to diversify its portfolio of gem offerings, and in 2009 it announced the acquisition of the "Tsavorite Project" from Green Hill Mining Ltd. and

Figure 11. This 8.72 ct green zoisite and 11.30 ct tanzanite are from Merelani, Tanzania. Faceted by Meg Berry, Fallbrook, California; photo by R. Weldon.

Kirkwood Resources Ltd., a license covering a 100 km^2 area not far from Merelani.

Gemfields. A gemstone exploration and mining company based in London, Gemfields began exploration and small-scale mining of emeralds in Zambia in 2000. In 2008, it was invited to start operations at the Kagem mine in the Kafubu District, historically Zambia's largest source of emeralds, which reportedly produces about 20% of the world's supply (Zwaan et al., 2007; "Acquisition of the Kagem mine," 2008). At the time, heavy financing for emerald promotion came from Pallinghurst Resources, which with other parties became a major shareholder in Gemfields.

Gemfields also holds exploration licenses for emerald, ruby, and sapphire in Madagascar; owns the Kariba amethyst mine in Zambia; and has cutting facilities in Jaipur, India, where it auctions its production. With a view toward furthering its mine-to-market strategy, Pallinghurst has negotiated a 15-year license to use the Fabergé name in its brand-building efforts (Kurian, 2008).

True North Gems. Canada-based True North Gems has been actively exploring and mining for emeralds, rubies (e.g., figure 12), and sapphires for about a decade. Its biggest investment is the Fiskenaesset Ruby Project in Greenland. While the company remains in the exploration phase of its ruby operation in Greenland, it says it has identified some 30 occurrences there. However, none of the material True North has sampled so far has reached the market (Shor and Weldon, 2009).

Cultured Pearl Production. By 2000, pearl producers in Australia, Indonesia, French Polynesia (Tahiti), and China were in the process of breaking the century-long domination of pearl culturing by the Japanese pearl industry (figure 13). The result brought a much more diverse array of products and prices to the pearl market in the first decade of the new century, with Australian South Sea cultured goods at the high end for white pearls and Chinese freshwater cultured pearls, many of which resembled more expensive Japanese akoyas, in very low price points (Shor, 2007). The decade also saw the acceptance into fashion of fancy-colored cultured pearls: "goldens" from the Philippines, and greens and browns from French Polynesia. This broad array of goods was well promoted by large producers such as Paspaley in Australia, Jewelmer in the Philippines, and Perles de Tahiti, the marketing consortium funded by the Polynesian government and local producers (Shor, 2007).

Even so, from 1999 to 2009 the combined estimated value of the three major groups of saltwater cultured pearls—akoya, South Sea, and Tahitian—decreased from $489 million to $367 million. The reasons for this shift were greatly increased production of South Sea (some say overproduction) and Tahitian goods, while akoyas declined (Müller, 2009). An estimated 25 metric tons of white South Sea and black Tahitian cultured pearls were produced in 2009, compared to 8.7 metric tons for both in 1999, at a lower per-pearl value as a result of the global economic downturn at the end of the decade.

Production of Chinese freshwater cultured pearls stabilized at about 1,500–1,600 tons in 2006 (Shor, 2007), but it declined sharply in 2009 to an estimated 1,200 tons as many farms cut back (A. Müller, pers. comm., 2010). While China's cultured pearl production is 20 to 30 times greater than other producers in volume, the percentage of high-quality goods is extremely low, with the result that by mid-decade the total value was only about 20% of the saltwater pearl market (Shepherd, 2007).

Figure 12. True North Gems has performed gem exploration and feasibility studies on various localities in the northern hemisphere. This pink sapphire and ruby sample comes from their Fiskenaesset Ruby Project along the southwest coast of Greenland. Courtesy of True North Gems; photo by R. Weldon.

Figure 13. These two South Sea necklaces typify fine quality in multi-color (inside, 12–15 mm) and white (outside, 11–16 mm) cultured pearls, which were fashionable throughout the decade. Courtesy of Armand Asher Pearls, New York. Photo by R. Weldon.

MARKETING AND DISTRIBUTION

Globalization has affected the gemstone business by making the world "smaller" through enhanced and easier communication by telephone, the Internet, and digital photography—but it has also made it far more complex. New selling channels have emerged. New gem sources have appeared, in some cases confusing established supplies and nomenclature. New treatments, some sophisticated, some deceptively simple, have been introduced. As the market has become global, an increased need for vigilance regarding the sourcing of gems has become required.

New Channels Provide Strong Competition. *Diamonds.* The 1990s brought the Internet business boom, which saw the rise of the "e-tailer," including jewelry sellers. The bust in late 2000 ended many of these ventures, but Internet retailing regrouped during the 2000s to become a solidly growing force, while the number of brick-and-mortar jewelers declined from 26,200 at the start of the decade to 22,100 by June 2010 (Jewelers Board of Trade, 2010a). The growth in Internet sales can be gleaned from the sales results of the largest online diamond seller, Blue Nile. In 2000, its first full year of operation, the company reported sales of $44 million. By 2003, sales had almost tripled to $128.9 million, and they reached $319.3 million by 2007. The 2008 economic crisis caused a dip, but sales rebounded in 2009 to $302.1 million, and by the second quarter of 2010, Blue Nile had posted an industry-leading 9.7% year-over-year sales increase (Blue Nile, 2010).

Many traditional jewelers added online sales channels as well, so that by 2004 an estimated 2% of all diamond sales in the U.S. were made online (Shor, 2005). By 2009, that share had more than doubled to 4.6%, or $2.7 billion, 70% of which were diamond-set pieces (Blue Nile, 2009b; Gassman, 2010).

Demand for diamond grading reports soared during the decade, with every major gemological lab reporting strong intake gains. The reasons were rooted in the proliferation of older treatments such as fracture filling, and development of new gem treatments such as HPHT color enhancement, combined with the rise of electronic diamond trading, which facilitated the sale of diamonds sight unseen (Bates, 1998; Reiff and Rapaport, 1998; Halevi, 2004). As consumers grew more educated about diamonds, demand for grading reports increased yet again (Dobrian, 2006). One industry expert noted that GIA's lab business increased 20% yearly between 2001 and 2005 (Even-Zohar, 2005).

Quality issues—especially those related to cut—also changed how diamonds were sold during the decade. By 2000, engineers and laser experts had devised equipment that could model and cut rough diamonds much more precisely than human labor, and consumers in Japan, a key diamond market, were demanding stones cut to very exacting standards. The facet arrangements of such diamonds often formed what was called a "hearts and arrows" pattern (Shor, 2005; figure 14). In the U.S., a number of diamond manufacturers created successful brands by promoting round brilliants precision-cut for both proportions and facet placement.

Yet cut grading had been the subject of considerable controversy during the 1990s, when some (mostly opponents of online diamond trading) argued that such a grade would fully commoditize diamonds, while others argued that it would prevent vendors from misrepresenting poorly cut stones with high color and clarity grades as top quality (Shor, 1997). The American Gem Society (AGS) grading lab, which opened in 1996, began issuing reports

with cut grades based on the system AGS had developed in 1966 that, in turn, was based on proportions devised by Marcel Tolkowsky in 1919. The AGS was the first lab to adopt a detailed cut grade system. The lab revised the system in 2005 to include light performance (how well a diamond refracts light from the crown and table) and add a grade for princess-cut diamonds (P. Yantzer, pers. comm., 2010).

In 2004, GIA completed a 15-year study of diamond cut, which found that an excellent balance of fire and brilliance could be achieved by a number of proportion combinations beyond the traditional Tolkowsky "ideal" that had formed the basis for most diamond cut grades (Moses et al., 2004). The following year, those findings were incorporated into a cut grading system subsequently used on all GIA round-brilliant-diamond grading reports (Luke, 2006). Other labs, including Hoge Raad vor Diamant (HRD) and the International Gemological Institute (IGI), also began adding more cut information

Advances in cutting technology also gave diamond manufacturers greater opportunities to design new, proprietary cuts that would offer differentiation at retail—important for branding initiatives—and, it was hoped, garner premium prices in a market where traditional cuts were commoditized in price lists. While some cuts never gained a foothold in the market, others, such as the Signet Corp. (Kay Jewelers) 66-facet Leo Cut, became an integral part of the retailer's marketing efforts (Kay Jewelers, 2010). At the same time, a new take on an older cut—the Asscher cut—entered the market as an alternative to traditional shapes (Shor, 2005). By greatly speeding up and expanding the diamond cutting process, technology also put many more diamonds into the marketplace, creating larger inventories and more price competition. This favored volume buyers like the large retail chains and mass merchandisers and, in turn, led to an increase in memo deals and extended payment terms.

Figure 14. In efforts to differentiate themselves, and because of increasing demand for precision in cutting, many manufacturers fashioned diamonds to exacting standards throughout the decade. Note the precise arrow pattern in this 1.54 ct diamond, courtesy of Crossworks Manufacturing, member of the HRA Group, Vancouver, British Columbia. Photo by R. Weldon.

Colored Stones. The U.S. market accounts for 35% of global sales of colored stones at retail, a position of dominance it has held for several decades. Worldwide in 2007, sales of colored gemstones were estimated to be about $12 billion at retail, or 7% of total jewelry sales (BUZ Consulting, 2009). The U.S. also crossed the important billion-dollar benchmark in imports of unmounted colored stones, growing in size from almost $875 million in 2004 to $1.15 billion by 2008, according to the U.S. Geological Survey (Olson, 2009). Globalization has also made colored stones more accessible to newly affluent consumers in places like the United Arab Emirates, Russia, Brazil, India, and China—locations that would not have been considered significant markets for gemstones during the 20th century ("India's 9.6 billion . . . ," 2008).

Television shopping and Internet sites have increased the market for previously little-known gems, such as iolite, sunstone, and others. One such stone, sold almost exclusively through TV shopping channels, was red andesine feldspar, which caused a considerable controversy when undisclosed treatment came to light (Roskin, 2008; see below).

The online auction site eBay grew into a major sales outlet for vendors who wanted to reach the public directly. A recent (September 2010) search of the site found nearly 285,000 individual colored stones of all types, ranging from a 69 ct sapphire with a reserve of $1 million, to bead material at an initial offering price of one cent. The site's ease of access for vendors also brought controversy over alleged fakes. In 2004, Tiffany & Co. sued the company over alleged counterfeit merchandise sold via eBay auctions and the misuse of its trademark. The case, which took four years to litigate, was ultimately decided in eBay's favor when the U.S. District Court of New York determined that the burden of protecting the brand

Figure 15. The historic Wittelsbach Blue diamond was sold for a record-breaking $24.3 million to London jeweler Laurence Graff at Christie's in December 2008. It was subsequently recut to 31.06 ct, as shown here, and renamed the Wittelsbach-Graff. Photo by R. Weldon.

fell on Tiffany, not the online auction seller. The court noted that eBay did make considerable effort to police its site for counterfeit goods (Clark, 2008).

Nomenclature Issues. Differences of opinion about gemstone nomenclature have had an effect on the gem business in the last decade—particularly felt at the collector and dealer level. One of the most contentious examples involved violet-to-blue-to-green copper-bearing (cuprian) tourmalines, which were first discovered in Paraíba and Rio Grande do Norte states in Brazil in 1989 (Fritsch et al., 1990) and became known as *Paraíba tourmaline* in the trade. Their vibrant "electric" colors were distinctive and had not been observed in tourmaline from other localities. In a few years, as production tapered to a trickle, prices for this material soared wildly.

Around 2001, a new deposit of cuprian tourmaline was discovered near Edeko, Nigeria, though this material did not have quite the same color saturation as the original Brazilian stones (Smith et al., 2001). In 2005, another deposit was discovered in Mozambique (Laurs et al., 2008), and some of this new material approached the appearance of the best Brazilian tourmaline. Many dealers used *Paraíba* (or *Paraíba-type*, or *Paraíba-like*) as a general descriptor for cuprian tourmaline. In the absence of a recognized naming committee for gemstones, the Laboratory Manual Harmonisation Committee (LMHC; a panel composed of representatives from major gem labs in Europe, the U.S., and Asia) issued a statement supporting the use of the term *paraíba* to refer to blue (electric blue, neon blue, or violet blue), bluish green, greenish blue, or green colors (of medium-to-high saturation and tone) of elbaite tourmaline, whatever its geographic origin (LMHC, 2010).

Auctions. The last decade brought the first $1 million-per-carat fancy-colored diamond, the $100,000-per-carat colorless diamond, and extraordinary prices for top colored gems. These steep increases began in 2005, when precious materials began inflating quickly in price, fueled by a decline in the U.S. dollar (in which gold and diamonds have been historically traded) and a rise in the numbers of very wealthy people around the world. Some of this action was played out in public, primarily at auctions conducted by Christie's and Sotheby's. The colored stone world was stunned in February 2006 when an 8.62 ct Burmese ruby sold at Christie's Geneva for $3.64 million, or $422,000 per carat—a record per-carat price for any colored stone. In October 2007, a 6.04 ct Fancy Vivid blue diamond sold for $7.98 million at a Sotheby's auction in Hong Kong, the first gemstone to ever break the $1 million-per-carat mark, at $1.32 million. The buyer was London jeweler Alisa Moussaieff (Hines, 2007).

A year later, another blue diamond shattered the record for the most expensive gemstone ever sold at auction, when the historic 35.56 ct Wittelsbach Blue, graded Fancy Deep grayish blue, sold to jeweler Laurence Graff for $24.3 million at a Christie's auction in London (Christie's, 2008). Graff had the stone recut in a shape similar to the original (figure 15), losing 4.5 ct but shifting the color grade to Fancy Deep blue (Gaillou et al., 2010).

While auction offerings and sales were restrained during the spring of 2009, sales of million-dollar-plus-per-carat blue diamonds and $100,000-plus per-carat D-flawless stones resumed a year later. At Sotheby's April 7, 2010, Hong Kong sale, the De Beers Millennium blue diamond—a 5.16 ct Fancy Vivid blue IF—sold for $6.4 million to Moussaieff of London. The $1.24 million per-carat price was some 20% over estimate. A month later in Geneva, a Swiss retailer paid $162,000 per carat for a D-flawless round brilliant of 16.92 ct. Also in April, Sotheby's New York sold an 8.66 ct Burmese ruby for $2.1 million and a Kashmir sapphire bracelet for $2.85 million ("Magnificent Jewels. . . ," 2010). At the Hong Kong

sale that same month, an unidentified bidder paid $5.54 million for a jade necklace.

Treatments. Methods of enhancing the appearance of natural gemstones have been practiced for centuries, but the decade saw a number of new techniques and the inevitable controversy over nondisclosure.

The 1999 announcement of a new, difficult-to-detect process of improving the color of type IIa diamonds by high-pressure, high-temperature annealing rocked the industry and threatened to undermine confidence in those stones until a reliable means of detection was discovered shortly thereafter (see., e.g., Smith et al., 2000).

In 2002, the sapphire market received a jolt of its own from a previously unknown treatment that added traces of beryllium to the heating process and thereby altered the color of plentiful light pink sapphire to a more marketable pinkish orange ("padparadscha"). Later the treatment was applied to create other sapphire colors (see, e.g., Emmett et al., 2003. The result caused confidence and prices to drop, in some cases to extremely low levels, and led to press reports warning consumers about the process (Mazurkiewich, 2003).

An old treatment of a popular gemstone received a new hearing in 2007 when the U.S. Nuclear Regulatory Commission (NRC) contacted retailers and wholesalers to determine whether their stocks of irradiated "London Blue" topaz had come from NRC-licensed suppliers. Because there *were* no licensed distributors in the U.S. at the time, many retailers and wholesalers temporarily removed the gems from their inventory. The NRC continues to require proper licensing, though it has since been determined that the material on the market is safe to wear (Weldon, 2007).

Figure 16. Gems that are traditionally not treated, such as this 3.47 ct tsavorite from Kenya, were in high demand throughout the decade. Courtesy of RareSource, Chattanooga, Tennessee; photo by R. Weldon.

Nondisclosure of treatment led to a class action lawsuit against a major TV retailer who allegedly sold andesine feldspar that was altered to look like Oregon sunstone. The case created a major controversy within the gem industry (see, e.g., Graff, 2008). Likewise the proliferation of lead glass–filled rubies led to a number of televised exposés that publicized incidents of nondisclosure at retail.

As education about gemstones has expanded, there has also been a resurgence of appreciation for less traditional gems that are more likely to be untreated (Robertson, 2009). For example, as more information became available about lead glass–filled rubies, buyers chose alternatives such as red spinel. As lawsuits concerning emerald treatments were disclosed in the press, demand grew for alternative green stones such as tsavorite or demantoid garnets (figure 16).

In 2008, a controversial new treatment of tanzanite surfaced, affecting its perceived value and undoubtedly hampering the gemstone's recovery in value (McClure and Shen, 2008). While the market has largely understood and accepted that most tanzanite must be heat treated to achieve the colors associated with the gem, it does not readily accept impermanent surface coatings.

India and China. Two powerhouses, India and China, became the world's fastest-growing consumer markets for diamond jewelry during the decade. India grew rapidly in the 1980s and 1990s as a diamond manufacturing center, but it also saw an exponential rise in affluence within the country as a whole. The result was a growing middle class that began buying diamond jewelry. One study reported that from 2000 to 2005, consumer demand for diamonds in India increased at an annual rate of 43.5%, to $1.5 billion, about 2% of world diamond consumption. By 2009, India's market share was about $5.5 billion, about 8% of the world market. Diamond sales in China, excluding Hong Kong, grew at 9.15% yearly between 2000 and 2005, to about $1.32 billion, slightly lower than India. By 2009, diamond sales had reached $6

billion, about 9% of the world total. One study predicted that by 2015, India and China together would account for a world market share equal to that of the U.S. (KPMG, 2006).

THE ECONOMIC CRISIS OF 2008–2009

Retail. As the U.S. economy began slowing in late 2007 and 2008, a number of large retail jewelry chains found themselves in difficulty and, ultimately, liquidation. These included Friedman's Jewelers, a 388-store chain (Graff, 2009); Fortunoff, a 20-store chain; and the 375-store Whitehall Jewellers (figure 17). Several other jewelry chains also filed bankruptcy during this period, the 23-store Shane & Co. and the 15-store Christian Bernard stores.

A key reason behind the liquidations of such large firms was that diamond suppliers, who had millions of dollars in outstanding invoices, feared that the equity capital firms that held large shares in these companies would get their money out through Chapter 11 reorganizations at the expense of the trade (White, 2008). The Whitehall bankruptcy and liquidation also presented a crucial legal test of memo (consignment) agreements, commonly used by most large diamond companies to supply major accounts. In July 2008, a U.S. bankruptcy court judge ruled that Whitehall could not sell $63 million worth of properly identified consigned merchandise because it had no legal title to it (Memorandum opinion, 2008; White, 2008).

In late September 2008, the collapse of investment banker Lehmann Brothers set off a chain reaction that rippled through the global economy, as once-solid financial houses now seemed vulnerable. The holiday season of 2008 was a retailing disaster, even for strong firms. Signet, parent company of Kay Jewelers, reported that its fourth quarter same-store worldwide sales fell by 14.9% compared to the previous year; Zale Corp. charted a decline of 22%; Tiffany & Co. noted a same-store fall-off of 23% worldwide; and Finlay Enterprises, which owned Carlyle & Co., Congress Jewelers, and Bailey Banks & Biddle, as well as operating a number of leased jewelry departments, reported that its same-store sales for the last quarter of 2008 fell 20% (Shor, 2009a; Tiffany & Co., 2009; Signet Jewelers, 2009).

Even the Internet was not spared. Blue Nile reported that its holiday season/fourth quarter sales fell to $85.8 million from $111.9 million a year earlier (Blue Nile, 2009a), after five years of double-digit growth.

The second half of 2009 brought a slow recovery, with mixed U.S. holiday sales results that generally exceeded economists' forecasts. Several large chains fared well—Signet and Tiffany reported same-store sales gains of 6.8% and 11%, respectively. However, others battled strong competitive pressures, such as Zale Corp., which suffered a decline of 15%. The big winner in diamond sales was the Internet, with Blue Nile, for example, reporting a 23% sales gain.

By the second quarter of 2010, the number of stores operated by the top 10 U.S. retailers had dropped to 4,518, down from 5,978 at the beginning of 2008 (Jewelers Board of Trade, 2010b).

Diamond Production. As the global crisis took hold, diamond manufacturers asked the DTC and other producers to cut back rough sales (Shor, 2008c). At the September 2008 DTC sight, held a week after the Lehman Brothers news, clients declined to buy some $60 million worth of rough—about 10% of the value of that month's allocation.

As 2009 opened, diamond trading was nearly paralyzed at the wholesale level. The DTC allocated its smallest sight in many years, an estimated $108 million, and instituted a series of unprecedented nonprescheduled rough sales. Alrosa announced it would divert all its rough sales to the state stockpile Gokhran (Golan, 2009c; "Alrosa: $35 million. . . ," 2009). The value of worldwide mining output plummeted from $14.3 billion in 2008 to $8.4 billion in 2009. By weight, total production (including industrial qualities) dropped from 165 million to 124 million carats (Even-Zohar, 2010).

The crisis created havoc in India, particularly Gujarat State, where an estimated 200,000 diamond workers—25% of the country's diamond workforce—were furloughed ("'Rough' times ahead. . . ," 2009). The central and state governments, fearing that such a large number of unemployed workers created potential for unrest in an already volatile region of the country, formulated a stimulus package (Golan, 2009a). In June, the central government offered India's 53 industry banks more than $4 billion in credit guarantees to enable diamond manufacturers to resume operations (Kazi, 2009). Within one month, as many as half of the idled workers were rehired (Polished Prices, 2009).

In other diamond centers, banks were keeping a close watch on credit, but supported almost one-third of major diamond companies that, otherwise, might have collapsed (Segal, 2009). This prevented a

Figure 17. Whitehall Jewellers was one of the many large chains that was forced to liquidate during the economic recession of 2008–2009. Photo © Najlah Feanny/Corbis.

run of bankruptcies and inventories coming into the market.

By early summer, the rough market had stabilized, with inventories at very low levels because of the cutbacks in mining and producer sales (Shor, 2009b). Demand for rough now rose sharply as diamond manufacturers were getting back to work and needed goods. The DTC sold nearly $550 million at its June 2009 sight. Alrosa slowly resumed sales into the market in July, allocating about $150 million worth of rough to long-term clients (Golan, 2009b). In August, the operation's new president, Fyodor Andreyev, announced a much more aggressive sales policy ("Alrosa: $35 million. . . ," 2009), which eventually saw some $900 million worth of rough going to the market during the second half of 2009.

By October, banks and some diamond analysts were warning that the rising rough prices—which had recouped all of the early-year declines—were not warranted by still-sluggish demand for polished goods ("ABN Amro sees no recovery yet," 2009). As a result of the precipitous rise in rough prices, the DTC stepped up rough sales during the first quarter of 2010, dealing a total of about $1.5 billion worth. During the same period, Alrosa sold $925 million in diamond rough while suspending all sales to the government stockpile. Polished prices, however, recovered much more slowly, even as diamond centers reported encouraging pre-holiday orders from retailers in the U.S. and other markets (Polished Prices, 2010).

Colored Stones. The economic crisis exacerbated problems in the colored stone market that had adversely affected it for several years. The skyrocketing cost of gasoline and diesel fuel in the late 2000s had already curtailed mining activities in many countries by making them too expensive to be economic. As noted earlier, mid-2008 brought a U.S. and European Union ban on all ruby and jadeite from Myanmar, while Madagascar suddenly imposed a ban on rough gem exports.

As the economic crisis took hold and sales plummeted, mining operations in key centers such as Brazil and Zambia curtailed or ceased production, though reports were anecdotal and offered no specifics (ICA Mining Report, 2006). Exploration also halted in many locales (Robertson, 2009). The depth of the problem was evident in the weak retail sales reported above for the 2008 holiday season. As a result, at the February 2009 gem shows in Tucson, reports estimated that buying was down 30%–50% from 2008, and attendance at the American Gem Trade Association show was down 19% (Weldon, 2009).

Thailand, which accounts for 70% of the world's polished sapphire exports and 90% of polished ruby exports, was hard hit. By the time the global economy plunged into crisis in September 2008, numerous cutting firms had already closed or suspended operations (Shor, 2008a). In 2009, exports of "precious" stones dropped 29.9% to $178.74 million compared to 2008. Exports of "semi-precious" stones (the term used by Thai customs for all colored stones other

Figure 18. Swala Gem Traders, based in Arusha, Tanzania, works a tsavorite mine in the rural region of Lemshuko. To serve the needs of the miners' children, the company constructed a schoolhouse and hired a schoolmaster. This is an effort to provide learning opportunities for people in the area. Photo by R. Weldon.

than ruby, sapphire, and emerald) fell 17.5% to $201.5 million (Gem and Jewelry Institute of Thailand, 2010).

By late 2009, colored stone dealers were noting a mild recovery, though supplies of many types of stones had become scarce because of reduced production and the Myanmar trade bans (Robertson, 2010), in spite of the fact Madagascar had lifted its export ban in July. Thai exports of colored stones increased 6.28% to $137.9 million during the first quarter of 2010. However, the political unrest that paralyzed Bangkok and several other cities in Thailand that spring kept buyers away from the country for part of the second quarter.

Pearl production was also greatly affected by the economic crisis. Nearly half (300 of 650) of the farms in French Polynesia ceased operations in 2008 and 2009. In addition, Perles de Tahiti ended its $1–$2 million yearly promotions early in 2008, and the government abolished the export duty that had funded them (Müller, 2009). According to N. Paspaley (pers. comm., 2010), about 700,000 shell operations are expected in Australia in both 2010 and 2011—a considerable decrease from peak operations in 2007–2008. To deal with the downturn in the market in 2009, most Australian pearl producers reduced production or closed operations. Akoya production continued its decline, falling from 25 metric tons in 2007 to an estimated 15 metric tons in 2009 (Müller, 2009). Chinese freshwater pearl production plunged 25%–30% from the high at mid-decade.

SOCIAL ISSUES, A NEW INDUSTRY FORCE

As the decade opened, brutal civil wars in Africa and terrorist attacks against targets in the U.S., India, and Europe created demand for greater accountability in the diamond and gem trades, while growing concerns over corporate governance issues in the wake of major business scandals such as Enron and WorldCom generated public calls for increased transparency and ethics. These developments led to greater consumer attention to how and where gems were sourced and manufactured. In many cases, the buying public began asking if the gems they purchased were products of fair trade; that is, if they provided a living wage throughout the supply chain (including at the source), fostered gender equality and opportunity, and were mined in a socially and environmentally friendly manner (e.g., figure 18). Increasingly, consumers expected independent verification of the claims—a dealer or retailer saying it was so was no longer enough (Weldon, 2008).

The Kimberley Process. The issue of conflict, or "blood," diamonds reached critical mass in 2000, while civil wars—funded primarily by diamonds—raged in Sierra Leone and Angola. As images of atrocities from these conflicts began appearing in the media, pressure built on the industry to stop the trade in conflict stones and thus help stem the violence. An estimated 3% of world diamond production came from these sources that year, though some non-governmental organizations (NGOs), wanting to draw attention to the larger issue of illicitly traded diamonds, reported estimates as high as 25% (Smillie, 2010). In July 2000, representatives of various industry organizations convened in Antwerp to propose a system of monitoring and certifying legitimate rough diamond exports, which would help the United Nations and governments end the illicit trade.

In December of that year, representatives from diamond producing and processing countries met in Kimberley, South Africa, to put together the formal policies and procedures of that system, known afterward as the Kimberley Process.

Two years later, 53 nations ratified the Kimberley Process Certification Scheme (KPCS), which took

effect January 1, 2003 (Shor, 2005). The KPCS required that all rough diamond imports carry certificates indicating they were exported through legitimate, official channels. By the end of 2003, Angola and Sierra Leone had regained sufficient control over their diamond production to be admitted as KPCS members, allowing their diamonds to be sold on world markets. The following year, the KPCS reported that it covered 99.8% of world diamond production. By that time, the conflicts responsible for the KPCS's creation had ended and the body now took a role in ensuring diamonds remained in legitimate channels, preventing their use to fund wars or criminal activity. While KPCS was generally regarded as successful in greatly reducing the flow of illicit diamonds into the trade, a number of NGOs criticized it for being too dependent on voluntary compliance, the lack of independent monitoring, and a lack of resolve in dealing with alleged violators.

By 2008, the KPCS had 75 member nations, but a new issue thrust it once again back into the news: Zimbabwe's Marange diamond fields, also known as Chiadzwa, near the Mozambique border. Since KPCS regulators determined that the government controlling the diamond area was also responsible for killing more than 180 miners during a 2008 eviction action, the Kimberley Process was unable to take decisive action. This paralysis drew renewed criticism from both NGOs and the diamond industry (Dugger, 2009; "Zimbabwe's diamond controversy. . . ," 2010). In July 2010, the Kimberley Process, after conducting an investigation into Marange diamond production, agreed to permit exports from two of the mining sites ("World Diamond Council concludes. . . ," 2010). In August, the government sold 900,000 carats from the concessions, and an additional 500,000 carats in September.

The decade also saw the rise of several initiatives designed to improve working conditions and returns for miners of alluvial deposits in West Africa (see, e.g., figure 19). One, the Diamond Development Initiative, founded in 2005, was an outgrowth of a collaboration involving several NGOs, De Beers, the Rapaport Group, and the World Bank. The DDI has conducted several studies tracking how alluvial diamonds get to market, and the prices paid at each step of the pipeline in Sierra Leone and Democratic Republic of Congo (DRC), as well as ways of ending child labor in DRC diamond deposits.

The studies will be used to develop sustainable, repeatable programs to help improve the lives of alluvial miners and their families (Diamond Development Initiative, 2010). Another organization, the Diamond Empowerment Fund, was established in 2007 by the diamond and jewelry industry to improve educational opportunities and living conditions in diamond-producing African nations (Diamond Empowerment Fund, 2010).

Figure 19. Most of the diamonds in Sierra Leone are found in alluvial deposits by independent miners. These men are panning for diamonds in one of Sierra Leone's many rivers and streams. Photo taken in 2006 by Ric Taylor.

Terrorism and PATRIOT Act Restrictions. Illicitly mined and exported diamonds also became the focus of attention following the September 11 terrorist attacks. Allegations that terrorists had used diamonds, tanzanite, and other gems to raise and launder funds for al Qaeda and other terrorist groups prompted the U.S. government to examine industry dealings more closely.

As a result, a provision was added to the PATRIOT Act, passed five weeks after the attacks, to designate all dealers of diamonds, gems, and jewelry as "financial institutions" and subject them to much more detailed financial reporting requirements. These included reporting all large cash transactions, obtaining valid identifications and addresses for both suppliers and clients, maintaining transaction records, and briefing staff on PATRIOT Act procedures. The European Union and other countries adopted similar measures in tandem with the U.S.

Then, in November 2001, the *Wall Street Journal* reported that an al Qaeda operative named Wadih el Hage—who had been linked to the 1998 U.S. Embassy bombings in Kenya and Tanzania—had sold tanzanite to fund terrorism in East Africa (Block and Pearl, 2001). A notebook found among his possessions when he was captured mentioned his attempts to sell a parcel of tanzanite. Print, radio, and television media soon broadcast similar stories, and the repercussions for tanzanite were immediate and devastating (Drucker, 2002). Tiffany & Co., Zales, Walmart, and QVC all pulled tanzanite from their inventories, and they and other manufacturers canceled outstanding orders. Sales of the gem plummeted to virtually nothing overnight (M. Avram, pers comm., 2001).

However, the details in el Hage's notebook sketched a different story. El Hage had tried to sell a parcel of tanzanite, but his notes also showed how little he knew about tanzanite or the gem market—such as where to sell it, or for how much. He chronicled his unsuccessful attempts to sell the material in London and San Francisco, and at trial it was revealed he actually had to borrow money from a friend to complete his fruitless trip (Weldon, 2002). No actual sale of tanzanite by him or any other operative was ever confirmed. In February 2002, the U.S. State Department declared that it did not consider tanzanite to have been used to raise funds for al Qaeda (Gomelsky, 2002).

The diamond industry also came under suspicion in the aftermath of the September 11 attacks. In November of that year, *Washington Post* reporter Douglas Farah reported that diamond dealers, working through alleged al Qaeda operatives, had purchased diamonds from Sierra Leone rebels at below-market prices. The report also alleged that the diamond trade helped al Qaeda avoid a freeze of its bank assets (Farah, 2001). A staff report to the National Commission on Terrorist Attacks upon the United States (the "9/11 Commission") later concluded that there was insufficient evidence to tie al Qaeda to the diamond trade (Roth et al., 2004), though some NGOs objected to its conclusions (Global Witness, 2004).

Responsible Jewelry. During the early part of the decade, a number of industry organizations independently drafted standards for responsible business practices. To establish sets of commonly agreed-upon standards, 14 of the industry's largest players—including diamond miners (De Beers, Rio Tinto, BHP Billiton), several diamond manufacturers, ABN Amro Bank, and major retailers such as Tiffany & Co. and Signet Group—formed the Council for Responsible Jewellery Practices (now called the Responsible Jewellery Council) in 2005 to create minimum standards regarding fair labor practices, environmental sustainability, ethical trading, and transparent business dealings (Responsible Jewellery Council, 2010). By the following year, membership had reached 33 after the council adopted a formal structure, was chartered in London, and promulgated a detailed set of standards in business, environmental, and social areas (Council for Responsible Jewellery Practices, 2006).

In December 2008, with codes of practice in place, the council moved into a new phase certifying members' compliance to its best practice standards.

CONCLUSION

The first decade of the 2000s witnessed the fragmentation of the rough diamond market, greater financial scrutiny of colored stone and diamond dealers, and the rise of social concerns. Today, consumers are much more aware of these issues as well as treatments, quality, and pricing, thanks in great part to widespread information on the Internet, a situation that will certainly improve as new ways of delivering information proliferate.

For diamonds, the fragmenting of the rough diamond market will probably continue, as De Beers

recently announced it would keep mining at a reduced rate (about 40 million carats yearly, compared to 48 million before the economic crisis) while newer producers pursue independent sales channels. New estimates about Zimbabwe peg its diamond production at 40 million carats yearly, making it potentially the world's largest by volume, yet not under the control of any single marketing channel (Thomas, 2010). The country's uncertain political situation may lead to more changes in the near future.

Politics in producing and processing nations will continue to affect the colored gemstone market. Ongoing sanctions against Myanmar by the U.S. and EU will keep a large percentage of ruby and jade from reaching those markets, while difficulties in other producing countries will create spot shortages of gem-quality material. We do not know what new treatments are on the horizon, only that they are inevitable. In pearls, the majority of the industry is still working through the double challenge of overproduction and diminished demand.

The world economic crash of 2008 also brought changes in the ways the diamond and colored stone industries conduct business, particularly in financing and retail consolidation in the U.S., though the long-term effects are still far from being understood. However, the industries appear to have regained solid footing in recovery, aided greatly by two powerful emerging consumer markets in India and China—which promise to be even more important in the decade to come.

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ACKNOWLEDGMENTS

The authors would like to thank Andy Müller of Hinata Trading and Jeremy Shepherd of Pearl Paradise for their insights into the pearl business. Stuart Robertson of The Guide *and Evan Caplan of Omi Gems provided fresh perspectives on the business of colored gemstones. Finally, we would like to thank Dona Dirlam, Caroline Nelms, and Cathy Jonathan from GIA's Richard T. Liddicoat Gemological Library and Information Center, who helped compile vast amounts of information and references.*

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ERRATUM

While every effort is expended to ensure the accuracy of the information printed in *Gem & Gemology*, on page 156 of the Summer 2010 issue an error occurred in, and was not corrected during, the editing process. In the report titled "'Nanogems' – A new lab-grown gem material," the part of the title reading "A new lab-grown gem material" should have read "A new glass-ceramic material," and this correction should also be reflected throughout the rest of text. We recognize we improperly used the terms lab-grown and gem material when referring to what is essentially a glass. We have corrected the online version of the issue, and ask that you make a note correcting this in your copy.

’10

GEM LOCALITIES OF THE 2000S

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Sheryl Elen, and Dona M. Dirlam

While the past decade saw some impressive discoveries of diamonds and colored stones (such as corundum, spinel, garnet, and tourmaline), it also witnessed reduced gem production in many areas as a result of high development costs, environmental considerations, and the downturn in the global economy. With legal and ethical restrictions on the trade in gems from some nations, and with premium market values paid for certain stones from particular sources, “locality of origin” determinations took on increased importance for some colored stones such as ruby, sapphire, emerald, and copper-bearing tourmaline. This article reviews the geographic sources of diamonds and colored stones, as well as the areas of production for both natural and cultured pearls, that were commercially important during the years 2001–2010. Maps of most of the important gem-producing regions of the world are included on an accompanying wall chart.

New finds of both diamonds and colored stones, along with increased production of natural and cultured pearls, have characterized the last decade. Canada rose from virtually no diamond production in 1998 to rank second in value of global production in 2009. Existing diamond mines in Botswana and Russia were expanded, and in South Africa new mines opened. A number of the old De Beers mines in South Africa were closed, but later reopened under a new operator. Some important colored stones included emeralds from Zambia, rubies from Madagascar and Tanzania, sapphires from Madagascar (e.g., figure 1), spinels from Tanzania and Myanmar, opals from Australia and Ethiopia, and copper-bearing tourmalines from Brazil as well as new sources in Mozambique and Nigeria. In cultured pearls, Chinese products have come to dominate global production by quantity and variety of new items being farmed. For most of the decade, there were significant increases in the culturing of large white pearls from Australia, “golden” pearls from Indonesia and the Philippines, and black pearls from French Polynesia, the Cook Islands, and Mexico—although the global recession at the end of the decade has had a dampening effect on prices and production.

Following the format established in the two previous 10-year retrospective issues of this journal (see Shigley et al., 1990, 2000), this article identifies localities throughout the world that produced diamonds, colored stones, and pearls on a commercial scale during the past decade. The selection of localities included in this article was based on the published literature, Internet sources, and geologic resource maps, as well as on personal communications provided by a number of experts on particular countries (see Acknowledgments in the *G&G* Data Depository at gia.edu/gandg). The lack of gem production information, especially for colored stones, complicates the task of identifying which localities were significant during the past 10 years, as well as which are still active. Table 1, at the end of the article, lists major colored stone localities. Tables for key diamond and pearl localities can be found in the Data Depository, along with a list of sources of

See end of article for About the Authors and Acknowledgments.
GEMS & GEMOLOGY, Vol. 46, No. 3, pp. 188–216.

Figure 1. Madagascar was one of the largest producers of sapphires—in a variety of colors—in the 2000s. The stones shown here weigh ~3–5 ct. Courtesy of Menavi International; photo by Robert Weldon.

minor colored gemstones, and a comprehensive list of all references cited in the article and tables. Many of the key diamond and colored stone localities are plotted on several regional maps that comprise an accompanying wall chart.

While the larger gem deposits are generally well known, information on some smaller sites is less certain because no recent published reports on them could be found. Although we have attempted to make this article as complete as possible, in some cases minor productive localities may have been overlooked. The spelling of locality names is taken whenever possible from the Microsoft Encarta World Atlas and maps.nationalgeographic.com. References for specific statements made in the text below can be found where the corresponding localities are listed in the tables.

DIAMOND

The highlights of the decade were the emergence of Canada as a major diamond producer and the continued strength of diamond production in general, prior to the global financial crisis of 2008–2009. Annual rough diamond production worldwide rose from 117 million carats (Mct) in 2000, worth US$7.9 billion, to a peak of 176 Mct in 2006, worth $12 billion. Then, rough production declined slightly in 2007–2008 before falling sharply in 2009 to 125 Mct, worth $8.6 billion (for data covering 2000–2005, see Janse, 2006; for 2006–2009, see Janse, 2007–2010). The increase was due to newly discovered Canadian deposits coming to market and greater production from Botswana and Russia. The decline was due to reduced production from the Argyle mine in Australia, where mining of the large open pit was coming to an end. During the past decade, 20 mines entered full production (Read and Janse, 2009), of which two (Catoca in Angola and Ekati in Canada) already had initial production at the end of the 1990s.

During the first decade of the 2000s, diamonds were mined on every continent except Antarctica, from three types of sources: (1) primary deposits developed in kimberlite pipes and dikes, and in some instances in lamproite pipes; (2) alluvial deposits, mainly from sand and gravel in river beds and river terraces; and (3) coastal deposits, from onshore beach sands and gravels and from offshore marine sediments. The *G&G* Data Depository table

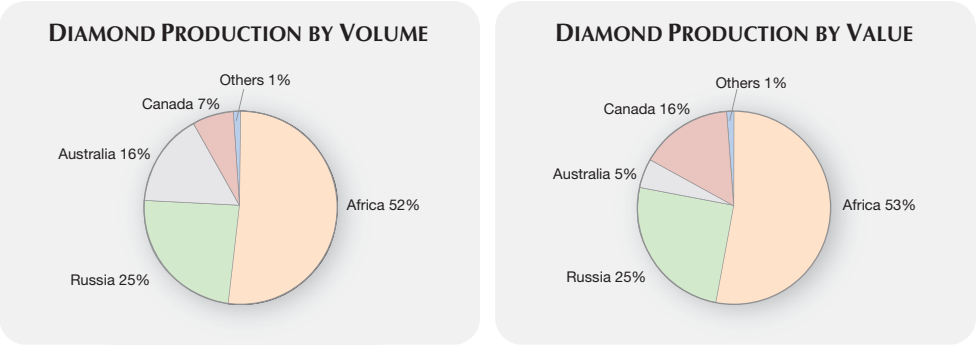


Figure 2. Average global diamond production for the period 2001–2008 is reported by volume (left) and by value (right). Sources: U.S. Geological Survey, Mining Journal*, and (since 2004) Kimberley Process data.*

lists the commercial deposits that were active during this decade, along with an indication of their annual diamond production (ranging from "small" to "huge"; see table footnote for definitions of the size classifications) and the company responsible, as appropriate.

Diamond exploration remained vibrant until 2009, when the global financial crisis virtually eliminated such activity in most countries. Nevertheless, exploration continued at a reduced rate in the region around Canada's Hudson Bay, resulting in the development of the Chidliak kimberlite field on southeastern Baffin Island, and in the discovery of kimberlites at Aviat, Amaruk, Nanuq North, and Churchill. Another area of interest is in the Bundelkhand region of India, where a promising lamproite field has been discovered (Janse, 2010).

Africa. During the 2000s, the African continent remained the major producer of diamonds by volume and by value (figure 2).

In **southern Africa**, *Angola* produced medium-quality diamonds from the very large Catoca kimberlite (Robles-Cruz et al., 2009) and four smaller mines. In addition, high-quality diamonds came from 12 alluvial deposits that were for the most part developed by expatriate companies and co-owned with Endiama, the national diamond company of Angola, as well as from many small deposits worked by artisanal miners (Gordon, 2004). Because of the global financial crisis, two alluvial deposits (Luarica and Faucama) stopped operating in 2009, but two others (Luana and Cassanguidi) opened in 2009–2010. The continued operation of many other alluvial deposits is uncertain. The Russian parastatal managing company, Alrosa, planned to withdraw from Angola except for their participation in Catoca.

During most of the decade, *Botswana* ranked first by value and second or third by volume (after Russia and the Democratic Republic of the Congo [DRC]) in global diamond production. There were three kimberlite mines with large-to-huge production, one with medium production (Damtshaa) that was closed in 2009 because of the global financial crisis, and one (Lerala) that produced relatively little and closed after only a few months due to low diamond value. Because De Beers shut its mines down for four months in 2009 to help stabilize diamond prices during the global financial crisis, and Russia did not, Botswana is now ranked third by value (after Russia and Canada) and also third by volume (after Russia and the DRC; Janse, 2010).

Although production from the kimberlites in *Lesotho* is relatively small, the mines are renowned for their large (several over 100 ct) high-quality diamonds (Bowen et al., 2009). Three kimberlites were mined: Letšeng-la-Terae since 2004, and Kao and Liqhobong intermittently during the decade. Kao was reopened in 2010, and Liqhobong is scheduled to reopen in 2012. The Mothae pipe is being developed for future production.

The main production from *Namibia* was derived from two coastal onshore mines operated by Namdeb and one offshore mine operated by De Beers Marine. However, there were also two small alluvial mines and several small coastal offshore producers.

Diamonds in *South Africa* were mainly derived from six large kimberlite pipes, while 15 other small pipes were operated intermittently during the decade and had relatively small production of 10,000–100,000 carats annually; the latter were all closed by 2009 because of the global financial crisis. The main producer was De Beers Consolidated Mines, which operated all five of the largest mines until mid-decade, when it sold three of them (Koffiefontein, Cullinan, and Kimberley; the latter includes the Bultfontein, Dutoitspan, and Wesselton pipes) to Petra Diamonds, and opened one new mine (Voorspoed). Four small kimberlite dike mines (Helam, Sedibeng, Star, and Klipspringer) survived the global financial crisis, but all others were closed in 2009. All 18 alluvial deposits were closed in 2009, and only those operated by

Rockwell, Trans Hex, Firestone, and Namakwa have been reopened. Four coastal offshore operations are still active, as are three onshore ones.

Zimbabwe derived its diamonds from one kimberlite mine at Murowa managed by Rio Tinto, and one alluvial deposit at Marange mined by local artisanal workers of disputed legal status. The Marange operation is overseen by military and police forces, who have been accused of numerous human rights abuses (Elliott, 2009), but so far the production is recognized by the Kimberley Process (KP).

In **Central Africa**, the *Central African Republic* produced only alluvial diamonds, recovered by artisanal miners. Attempts by expatriate companies to develop these deposits have failed (Dietrich, 2003). The *Democratic Republic of the Congo* derived most of its diamonds from high-quality alluvial deposits in the western Kasai worked by artisanal miners. In the eastern Kasai, medium- to low-quality alluvial diamonds have been mined by dredging the Bushimaie river by the parastatal Société Minière de Bakwanga (MIBA), and by Sengamines (now Emikor). Mwana Africa owns 20% equity in each company. Both MIBA and Emikor also recovered diamonds from kimberlite fields at Mbuji Mayi and Tschibwe in eastern Kasai (Long, 2007). Diamond exports from the *Republic of the Congo* for many years were believed to be derived from diamonds smuggled from the neighboring Democratic Republic of the Congo, but since 2007 the KP has recognized a small production from an as-yet-unidentified alluvial deposit in the western part of the country.

In **West Africa**, diamond production in *Ghana* was derived only from alluvial deposits (Asiedu et al., 2004) that were mainly worked by licensed artisanal miners; the parastatal Ghana Consolidated Diamonds finally stopped production in 2007 because of outdated and worn mining equipment. Although many kimberlite dikes and several small pipes are known in *Guinea*, production was derived from high-quality-diamond alluvial deposits primarily worked by artisanal miners, with four small operations run by expatriate companies. Diamond production from the *Ivory Coast* derived only from unlicensed artisanal workers, and is not recognized by the KP. Diamonds from *Liberia* were mined artisanally from alluvial deposits. Sanctions on Liberian diamonds imposed by the KP from the end of 2001 to the end of 2007 have now been lifted. Although three small kimberlite pipes and several dikes are known in *Sierra Leone*, about 80–90% of the diamond production came from alluvial deposits in the southeastern part of the country. These were mined by artisanal workers and by two expatriate companies. Koidu Pipes 1 and 2 were mined by Koidu Diamond Holdings, which is 80% owned by the Steinmetz Group. Koidu Pipe 3 was mined by West African Diamonds (Gberie, 2004, 2006). Since 2004, the KP has recognized a small annual production from *Togo*. The diamonds allegedly come from small artisanal workings exploiting alluvial deposits, but their location is still uncertain.

In **East Africa**, numerous kimberlite pipes are known in *Tanzania*, but only the Williamson mine at Mwadui was developed by De Beers into a major operation (Stiefenhofer and Farrow, 2004). It was recently sold to Petra Diamonds, with the Tanzanian government holding a 25% equity. Local people mine alluvial deposits around the Williamson mine (Mutagwabe et al., 2007; Scalie et al., 2007).

Asia. Small quantities of diamonds have been recovered from various deposits in China, India, and Indonesia, but the giant in the area is eastern Russia.

The main producer in *China* appeared to be the small Shengli mine (also called the 701 mine; Wang et al., 2010) in the Mengyin area, though its production is not recognized by the KP. The diamonds that are recognized by the KP are of low quality and appear to come from dredging operations in the Yuan River in Hunan Province. One kimberlite with an adjacent alluvial placer in Liaoning Province also produced small quantities of low-quality diamonds (Tompkins et al., 1999). The only official diamond production in *India* during the decade came from the Majhgawan open-pit lamproite mine (Chalipathi-Rao, 2006), which was closed for environmental reasons in 2006 and reopened in 2009 (Janse, 2010). In *Indonesia*, the only diamond production recognized by the KP was derived from the Cempaka mine in southeastern Kalimantan, which is now closed and for sale. Additional small production from Kalimantan was derived from artisanal miners in the Martapura and Landak areas (Smith et al., 2009).

About 20 kimberlite fields are known in the Siberian Platform of *Eastern Russia*, in the Sakha Republic (formerly Yakutia). They contain at least 1,000 kimberlite pipes and dikes. Of this total, a dozen were developed by Russian parastatal managing company Alrosa into mines located in three fields (Anastasenko and Leybov, 2008). Most of the large,

Figure 3. Australia's Argyle mine is the world's largest single diamond producer by volume. Since the 1980s, the deposit has been mined in a large open pit; the processing plant and west pit wall are shown here. Over the next few years, mining will move underground. This 2009 photo is courtesy of Rio Tinto Diamonds.

old open-pit mines—including Mir, Internationalaya, Udachnaya, Aikhal, Zarnitsa, and Sytykanskaya—have transitioned into underground mining, entailing higher costs and lower output. The newer mines, Jubileynaya and Nyurba, are still open pits. In May 2009, Alrosa announced they were opening a large mine on a cluster of three pipes in the Upper Muna area (Janse, 2010). Kimberlites there were discovered in the late 1960s, but until now Alrosa has avoided development above the Arctic Circle.

The deposits in *Western Russia* (actually in Europe) continue to yield large quantities of diamonds. Most come from the Arkhangelskaya kimberlite pipe, the first in the Lomonossov cluster of five pipes to be developed into a very large mine (Verzhak and Garanin, 2005; Palazhchenko et al., 2008). Development of the rest of the Lomonossov cluster is planned for the future, with projected reserves of ~200–230 Mct. Small quantities of diamonds were produced intermittently from scattered alluvial deposits in the Ural Mountains (Laiginhas, 2008).

Australia. Two lamproite mines—Argyle and Ellendale—were the main producers. A small quantity of diamonds also came from the Merlin kimberlite, which closed in 2004 as Rio Tinto decided it was not economic. It is expected to be reopened in 2012 by its new owner, North Australian Diamonds (Janse, 2010).

When the Argyle mine (figure 3) began production in 1986, the open-pit reserves were calculated to last 20 years. Its life has now expired, but to keep the Indian diamond cutting industry buoyant, Rio Tinto decided in 2005 to continue mining by going underground. Rising prices for energy, steel, and labor caused cost overruns and delays, so the open-pit mine was extended initially to the end of 2008, then to 2010, and most recently to 2012. The open pit was expanded northward into lower-grade ore, resulting in a production decline from ~30 Mct for 2005 to 15.4 Mct in 2009. Underground operations are scheduled to commence in mid-2012 and last for at least six years (Janse, 2010).

In September 2007, Gem Diamonds purchased the Ellendale mine from Kimberley Diamond Co.; the deposit has produced a total of just over 1 Mct since 2002. This included some high-quality yellow diamonds (about 7% of total production), which in 2009 sold for $2,480/ct. In December 2009, Gem Diamonds signed a long-term contract to sell the yellows to Laurelton Diamonds, an Antwerp subsidiary of Tiffany & Co. (Janse, 2010).

All the activities mentioned above concern "old" prospects, and no new promising discoveries have been made in Australia in the last 20 years. The "Big Three" companies—De Beers, Rio Tinto, and BHP—have withdrawn from diamond prospecting there, but a few junior companies still continue to search.

North America. The 2000s marked the first full decade of Canada's position as a major diamond producer. In fact, in 2009 Canada globally ranked second in value and sixth in volume. The quality of the Canadian diamonds is high (see, e.g., figure 4), and they are not tainted by the "conflict diamond" issue. Production came from four kimberlite mines, three located in the Northwest Territories (Ekati, Diavik, and Snap Lake) and one in Ontario (Victor). A fifth kimberlite mine (Jericho, located in Nunavut) closed after an 18-month operation because the actual production was well below projections made in economic feasibility studies (Read and Janse, 2010).

South America. Although South America, especially *Brazil*, has great historical significance as a diamond producer, most of the deposits produce small quantities. All Brazilian diamonds were mined from alluvial deposits, located in many areas (Blore, 2005). About 80% were mined by local artisanal miners (*garimpeiros*), while Elkedra Diamonds and Vaaldiam Resources were the only major (foreign) companies involved. Hundreds of kimberlites are known in Brazil, but none has a producing mine.

Figure 4. The most important diamond production event of the decade was the emergence of Canada as a significant source. The diamonds shown here are from the Ekati mine in the Northwest Territories, and weigh a total of 6.73 ct (round brilliants) and 14.25 ct (crystals). Courtesy of BHP Billiton Diamonds; photo © GIA and Harold & Erica Van Pelt.

All diamond deposits in *Guyana* are also alluvial, mined by local artisanal workers. No kimberlite or other primary host rock has been found there (Blore, 2006a). Until the end of 1982, when kimberlitic dikes and sills were discovered at the Guaniamo field, all diamond production from *Venezuela* was from alluvial deposits (Blore, 2006b). Canada-based Kansai Mining Corp. tried to develop a kimberlite mine at Guaniamo, but in 2008 the Venezuelan government canceled all diamond mining concessions held by foreigners and brought all development to a halt. Recent (artisanal) production from Venezuela is not recognized by the KP.

COLORED STONES

Although Brazil remained an important gem source during the decade, most new discoveries of the major colored stones took place in two other regions. One consists of areas around the present-day Indian Ocean, consisting of East Africa and Madagascar, India, Sri Lanka, and Southeast Asia. In the geologic past, these areas were either juxtaposed or closer to one another due to plate tectonics, and they share some similar geologic environments that were conducive to gem formation. The other important region extends from Afghanistan and Pakistan in the west through northern India and Nepal to Myanmar and Vietnam in the east, along the major geologic boundaries where the Indian and Asian continental plates collided.

Some deposits were exploited by mining concerns using mechanized equipment, but many others were worked by local people using very basic tools and techniques. Localities for the major colored stones are listed in table 1 according to gem material, while the *G&G* Data Depository lists these sources according to their geographic location by country. The Depository also includes separate listings for minor colored stones, sorted by gem material and location. The tables provide literature references (where available) for the individual deposits.

Emerald and Other Beryls. As with rubies, sapphires, and some other gem materials, determination of the country of origin was a lab service for emeralds during this decade, and many localities continued producing this popular gem. Accurate production figures are not available, but the most important sources were Colombia, Brazil, Zambia (figure 5), and Zimbabwe, which each produces commercial- to fine-quality material. Other sources included eastern Madagascar, the Panjshir Valley of Afghanistan, and the Swat Valley of Pakistan.

Brazil remained an important source for aquamarine, mainly from granitic pegmatites in the states of Minas Gerais, Bahia, and Espírito Santo. Additional sources were Malawi (mainly around Mzimba), Mozambique (Nampula and Zambézia provinces),

Figure 5. Large-scale open-pit mining in Zambia, as shown here at the Grizzly mine near Kafubu, yielded major quantities of emerald during the 2000s. Photo by B. M. Laurs, August 2004.

Figure 6. Along with Russia, Namibia remained an important source of demantoid, as shown by the stones from the Green Dragon mine in this fine jewelry. The bracelet (donated to the Smithsonian Institution) contains 104 demantoids weighing a total of 18.25 ct (3.0 and 3.5 mm diameter). The brooch (from a private collection) features three demantoids with a total weight of 2.71 ct set with 100 pieces of demantoid melee (1.5–2.1 mm). Photo by Robert Weldon.

Nigeria, and Zambia. Production of morganite continued at previously known localities (e.g., Afghanistan and Brazil), and large crystals of heliodor were recovered occasionally from Volodarsk-Volynskiy in the Ukraine.

Chrysoberyl and Alexandrite. These gems were mined in Brazil, India (particularly Orissa), Madagascar, Sri Lanka, and Tanzania from primary deposits in pegmatites and associated metamorphic rocks, or from secondary alluvial deposits. The most important source of alexandrite was probably the Hematita mine in Minas Gerais, Brazil. No important new chrysoberyl or alexandrite deposits were reported during the past decade.

Garnet. Many countries produced various species and varieties of gem garnet, including India (from Andhra Pradesh, Orissa, and Rajasthan) and Sri Lanka. In Namibia, production of fine spessartine decreased from the Kunene area, while the Green Dragon mine in the Tubussis area yielded commercial amounts of demantoid (figure 6). The Taita-Taveta region of Kenya (Coast Province, near Voi) produced color-change garnets as well as tsavorite. Additional major garnet sources include Madagascar (mainly around Ilakaka and a new deposit of demantoid at Antetezambato), Nigeria (spessartine from Oyo State), and Tanzania (tsavorite or green grossular from around Arusha and Merelani, and various garnets from the Tunduru region and Umba Valley). A significant new spessartine deposit was found in Tanzania near the Kenyan border at Loliondo (figure 7). Both Japan and Mexico produced some interesting andradite showing iridescence.

Jade. For the most part, major sources of both jadeite and nephrite remained the same as in the previous decade. The traditional sources of jadeite in northern Myanmar (mainly around Hpakant and Hkamti) were joined by the rediscovery of jadeite deposits in the Motagua Valley of Guatemala that had archaeological significance for the ancient inhabitants of Central America. Nephrite continued to be produced from various localities in China, in Canada (mainly in British Columbia), near Cowell on Australia's Eyre Peninsula, and on the South Island of New Zealand.

Opal. Deposits in the Australian states of New South Wales, Queensland, and South Australia continued to be the main sources of play-of-color white and black opal, although overall production declined somewhat due to increased mining costs and government regulations. Classic localities in Mexico (Querétaro area) and Brazil (Piauí State) were important producers of "fire" and white opal, respectively. Commercial quantities were also mined in Ethiopia (including the large new deposit in Wollo Province; figure 8), central Europe, Honduras, Indonesia, Madagascar, Peru, Turkey, and the United States. The low cost and availability in numerous colors attracted jewelry designers to common opal from several sources.

Peridot. Gem-quality olivine continued to be produced in China, with significant amounts sold at below-market values that challenged producers of this material from the United States (Arizona). There

Figure 7. Bright orange spessartine was recovered from a new deposit near Loliondo, Tanzania. The crystal measures 27 × 23 × 19 mm, the carving is 30 × 16 × 11 mm, and the cut stone weighs 1.95 ct. Specimens and photo courtesy of Jason Stephenson.

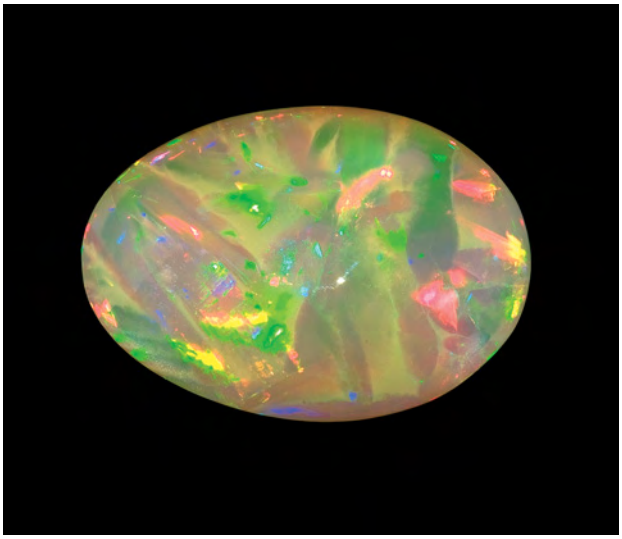


Figure 8. The Wollo Province of Ethiopia is the source of this fine 23.48 ct opal. Courtesy of Opalinda (Paris) and EyaOpal (Addis Ababa, Ethiopia); photo by Robert Weldon.

was occasional production of large peridot crystals from Bernardmyo in Myanmar. Kohistan, an important source of large, high-quality peridot in northern Pakistan, saw decreased production in the latter part of the decade due to depletion of the source.

Quartz—Amethyst, Citrine, and Rose. The states of Minas Gerais, Pará, and Rio Grande do Sul in Brazil, and the Kalomo region of Zambia (figure 9), continued to supply significant quantities of amethyst. Additional sources included the Thunder Bay region of Ontario in Canada, and the Artigas region of Uruguay. The Anahí mine near Sandoval in Bolivia was still the main producer of ametrine, while pegmatite deposits in Brazil, Madagascar, and elsewhere produced bulk rose quartz.

Ruby and Sapphire. The major sources of gem corundum were Madagascar (various localities including Ilakaka and Sakaraha for sapphire, and Andilamena [figure 10] and Vatomandry for ruby), Mozambique (new deposits in Montepuez and Niassa/Lichinga), Tanzania (a new occurrence at Winza [figure 11], as well as previous deposits), Kenya (John Saul mine and a new deposit at Baringo), India, Sri Lanka, Myanmar (Mogok and, for a period of time, at Nanyaseik), Thailand, Cambodia (Pailin), and Australia (mainly areas in New South Wales and Queensland).

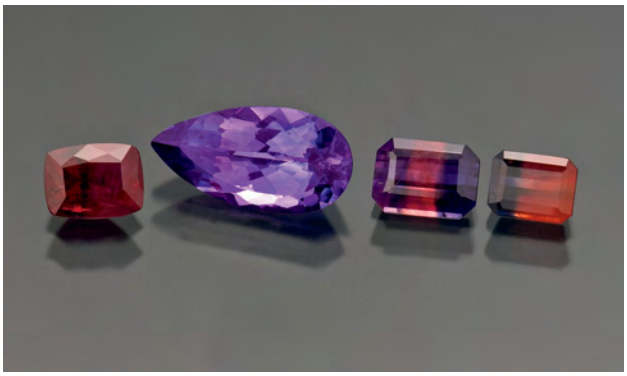
A decline in production of ruby from Mong Hsu

Figure 9. Zambia remains one of the most important localities for fine amethyst, as shown by these stones (4.59–14.07 ct). Courtesy of Guy Clutterbuck; photo by Robert Weldon.

Figure 10. Andilamena, Madagascar, was the site of a major ruby rush, as shown here in 2005 when about 15,000 people were living and working at the deposit. Photo by Vincent Pardieu.

in Myanmar due to decreased reserves was offset by discoveries of additional deposits in Madagascar, northern Mozambique, and central Tanzania. Production of geuda corundum in Sri Lanka continued mainly as a source of material for heat treatment,

Figure 11. Winza, Tanzania, has produced fine rubies as well as gem corundum in a variety of colors (including the rare color-zoned stones shown on the right). The sapphires shown here are heat treated and weigh 0.88–3.12 ct; the purple pear shape reportedly came from the Dodoma area (Winza region) in 2000, before the Winza deposit was discovered. The ruby is unheated and weighs 1.09 ct. Courtesy of Michael Nemeth; photo by Robert Weldon.



but the recovery of high-quality sapphires decreased because of exhaustion of some deposits and mining restrictions. A similar situation of diminished supply, government regulations, and no new ruby/sapphire discoveries occurred in Thailand, Vietnam, and Australia. For more on gem corundum localities in the 2000s, see Shor and Weldon (2009).

Spinel. Given the proliferation of ruby and sapphire treatments (e.g., beryllium diffusion and lead-glass fracture filling), spinel witnessed a surge in popularity during the 2000s with its attractive range of colors and lack of treatments except for occasional heating. Significant producers included the Mogok and Nanyaseik areas of Myanmar, the Luc Yen area of Vietnam, the Ilakaka region of Madagascar, and the Pamir Mountains in Tajikistan. In addition, the early

Figure 12. At Mahenge, Tanzania, spinel is recovered from a series of hand-dug pits that explore primary and secondary deposits. Photo by Vincent Pardieu.

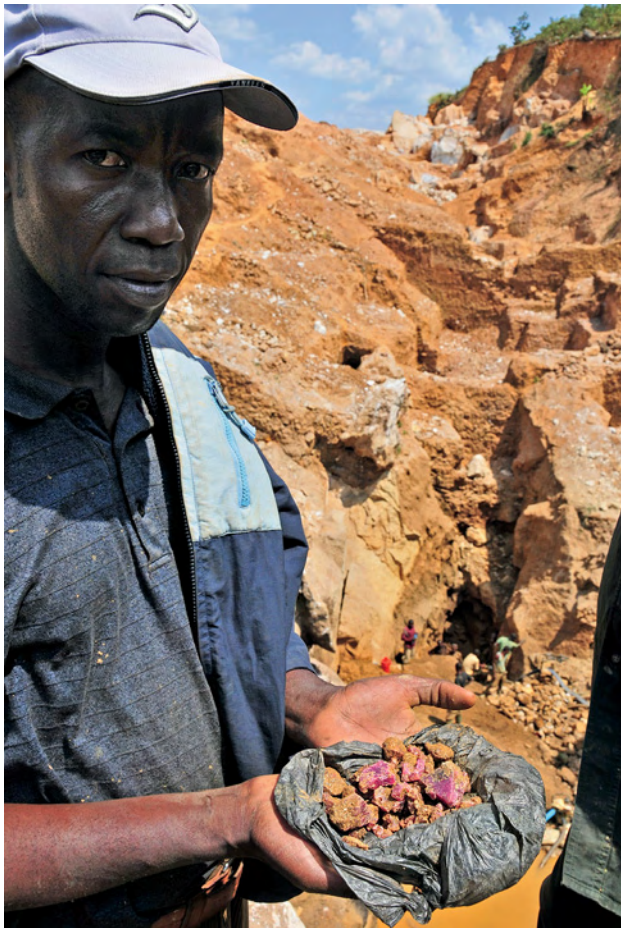


Figure 13. An important deposit of Cu-bearing tourmaline near Mavuco, Mozambique, yielded a wide variety of colors. These tumbled pieces of unheated tourmaline rough were compiled for a colorful necklace and bracelet suite; the yellow-green stone at the top weighs 23.25 ct, and the largest piece at the bottom is 61.88 ct. Courtesy of Mozambique Gems; photo by Robert Weldon.

2007 discovery of a number of large, high-quality, red-to-pink spinel crystals (some weighing 20+ kg) in the Mahenge region of east-central Tanzania (figure 12) brought renewed interest in this gem mineral.

Topaz. Pegmatite deposits in Brazil, Madagascar, Namibia, and Pakistan were the main sources of transparent colorless and blue topaz. Imperial topaz continued to originate from the Ouro Preto region of Minas Gerais in Brazil.

Tourmaline. The most significant tourmaline development was the production of copper-bearing elbaite from Mozambique (figure 13) and Nigeria (figure 14) that in some cases rivaled the "neon" blue-to-green tourmalines from Brazil's Paraíba State. Major sources of non-Cu-bearing tourmaline were Brazil (although the production there was smaller than in the previous decade), Afghanistan (Kunar and Nuristan provinces), Mozambique (mainly Nampula and Zambézia provinces), Namibia (Karibib area), Nigeria (Kaduna, Kwara, Nassarawa, and Oyo States; see figure 15), and Zambia (Mkushi and Lundazi; the latter was a source of distinctive "canary" yellow tourmaline).

Zoisite and Tanzanite. Underground workings in the Merelani Hills area of Tanzania remained the world's only commercial source of tanzanite, with production increasingly coming from the TanzaniteOne mines (Block C) and from numerous smaller workings in the nearby area.

Other Gemstones. Several less-common colored stones became more prominent in the marketplace during the past decade. Gem-quality diaspore crystals were mined in the Ibir Mountains in Turkey and sold under the trade name Zultanite. Controversy over the source—and chemical diffusion color treatment—of andesine-labradorite feldspar put a spotlight on the world deposits reported for this material, especially in China. Sodalite was produced in several colors, particularly from Afghanistan (figure 16) and Myanmar. Continued production of various colors of zircon from

Figure 14. These heated Cu-bearing tourmalines from Nigeria (2.42–52.13 ct) show a range of blue-to-green colors. Courtesy of Hussain Rezayee, Rare Gems & Minerals; photo by Robert Weldon.

Figure 15. The Komu area of Nigeria produced gem tourmaline from several small pegmatite pits, such as this one near the Abuja Leather mining camp in Oyo State. Photo by Jean Claude Michelou.

Myanmar, Sri Lanka, Tanzania, Cambodia, and Thailand combined with demand from designers to raise the profile of this gem. Significant quantities of attractive, highly dispersive sphene were produced from Madagascar and elsewhere. Various transparent gems featuring unusual inclusions also gained popularity with collectors and designers, spurring demand for these products. Production of benitoite in California, rhodochrosite in Colorado, and red beryl in Utah ended, and the mine sites were closed and reclaimed.

Figure 16. Less common gem materials such as sodalite (here, from Badakhshan, Afghanistan) gained prominence as mining and exploration extended into more remote areas. Shown here are a 0.68 ct hackmanite, a 19.54 ct pale blue sodalite, and a 2.08 ct yellow sodalite. Courtesy of Herb Obodda; photo by Robert Weldon.

PEARLS

In the Winter 2000 *Gems & Gemology* retrospective gem localities article (Shigley et al., 2000), the decade of the 1990s was described as the "pearl era," with its dramatic increase in production and diversity of cultured pearls. That diversity dominated pearls in the past decade as well (e.g., figure 17), which witnessed dramatic fluctuations in both production and pricing. Shor (2007) documented these changes in his comprehensive article. Another important pearl reference is Strack (2006), an expansion in English of the author's German book *Perlen* from 2001. *Pearls*, by H. Bari and D. Lam (2009), is a valuable new resource.

Here we will highlight the changes in cultured pearl production during the past few years since Strack (2006) and Shor (2007). In addition, the pearls table in the *G&G* Data Depository shows sources for the major types of pearls according to their locality, and they are also listed by type of mollusk.

Saltwater Cultured Pearls. During 1999–2009, the combined value of the three major groups of saltwater cultured pearls—white South Sea (includes "golden"), black South Sea, and akoya (from China as well as Japan)—decreased from $489 million to $367 million, and the relative percentages of each group changed (see figure 18 and Müller, 2009). In addition, more cultured pearls (particularly South Sea) were being produced at a lower per-pearl value as a result of the global economic downturn at the end of the decade.

South Sea – Australia. In the waters around Australia, five mollusks produce natural and cultured South Sea pearls in white, "golden," black, and other colors. The pearling area extends from north of the Tropic of Capricorn along the northern and western coasts (a distance of 3,500 km [2,150 mi.]), from the Northwest Cape in the west to Cape York in the east, and from there along the eastern coast to Cooktown (Strack, 2006).

To protect the mollusks from overharvesting, Western Australia's Department of Fisheries established a quota system to regulate both the number of wild mollusks that could be collected for culturing and the number of licenses issued to pearl culturers. According to N. Paspaley (pers. comm., 2010), about 700,000 shell operations are expected in Australia in both 2010 and 2011—a considerable decrease from the peak operations in 2007–2008. To deal with the downturn in the market in 2009, most Australian pearl producers reduced production while some with-

Figure 17. The 2000s witnessed the popularity of multi-species cultured pearl necklaces. The natural-colored cultured pearls (8–10 mm) in this strand include pastel freshwaters from China, grays from French Polynesia, "goldens" from the Philippines, and whites from Australia. Courtesy of King's Ransom; photo by Robert Weldon.

drew from the industry. Consequently, there may be a shortage of high-quality cultured pearls when the oysters seeded in 2009–2010 are harvested.

South Sea – French Polynesia. Since the late 1970s, French Polynesia has been the predominant producer of black South Sea cultured pearls. By the early 2000s, the government had issued about 1,500 farming licenses (Shor, 2007), but today there are fewer than 800 licenses as a result of the overproduction of lower-quality pearls, the loss of funds for marketing, and declining sales (E. Strack, pers. comm., 2010).

However, the *Pinctada margaritifera* mollusk can be found in waters throughout the Indo-Pacific, and there are also pearl farms in the Cook Islands, Fiji, New Caledonia, Marshall Islands, and Ryukyu Islands, as well as in the Taiwan Strait (A. Müller, pers. comm., 2010).

South Sea – Southeast Asia. In Indonesia, the biggest producers are in the west Nusa Tenggara region around Lombok, which is known for its "golden" cultured pearls from *Pinctada maxima*. The popularity of this product increased dramatically over the decade ("Pearl farm information . . . ," 2009).

Through its Indonesian subsidiary, PT Cendana Indopearls, Atlas Pacific Ltd. operates pearl farms in Bali, Lombok, and West Timor. However, its main culturing operation is in Aluyi Bay on Waigeo Island near New Guinea. They produce about 240,000 white-to-"silver" cultured pearls annually (Bari and Lam, 2009).

Jewelmer International Corp. continues to dominate the culturing of pearls in the Philippines, with six farms around the island of Palawan (Bari and Lam, 2009). Recently, however, the company predicted a 30% decrease in production over the next 12–18 months ("Jewelmer gets focused," 2010).

In Myanmar, three foreign (down from six earlier in the decade) and two local companies are conducting pearl culturing on eight islands. During the decade, the cultured pearls were sold at the Myanmar Gems, Jade and Pearl Emporium to connoisseurs

Figure 18. These pie charts show the dramatic shift in production by value of the three main saltwater cultured pearl categories. Adapted from Müller (2009).

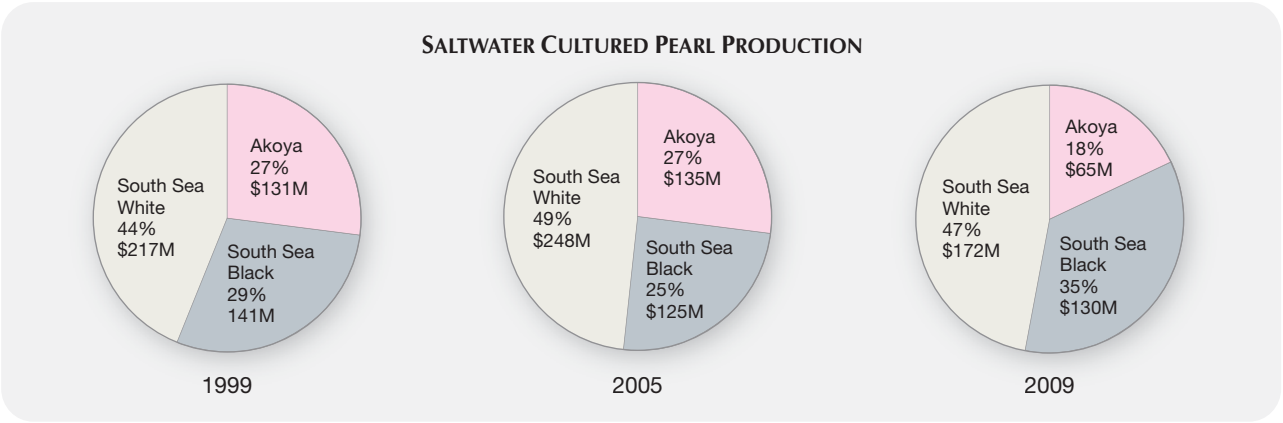


Figure 19. Hundreds of larger industrial freshwater pearl farms along with thousands of smaller family pools are active in China. The plastic bottles are used to suspend the growing mussels in the lakes. Photo taken in Zhuji, 2007, by Valerie Power.

from around the world. Myanmar produced 754 kg (201,081 mommes) of cultured pearls during the 2008–2009 fiscal year (Central Statistical Organization, 2010).

Akoya. After reaching a peak of 230 tons in 1966, disease and competition from Chinese freshwater products have reduced the current estimate for akoya cultured pearls in 2010–2011 to 12 tons (and possibly to as low as 8 tons by 2012; Müller, 2009). Müller believes that at least some of Japan's akoya farms will survive as the sale of these cultured pearls becomes a niche business.

Akoya cultured pearls also come from China, South Korea, and Vietnam. A new farm in northeastern Australia (Queensland) employs state-of-the-art environmental practices and has cultivated 20,000 pearls averaging 10 mm in diameter, with plans to increase the size to 12 mm.

Mexico. A pearl farm in Guaymas continues to produce commercial quantities of mabe as well as bead-nucleated full-round cultured pearls from the indigenous pearl oyster *Pteria sterna*. One indication of their natural color (and their Mexican provenance) is a red fluorescence to long-wave UV radiation (Bari and Lam, 2009). The Guaymas Pearl Farm produces about 8,000 cultured pearls per year (McLean, 2010).

Freshwater Cultured Pearls. *China.* Most of China's freshwater pearl farms can be found within 300 miles (483 km) of Shanghai, in ponds and lakes (e.g., figure 19) within the valleys of the Yangtze River and its tributaries. The total production was 900 tons in 2000, and peaked in 2008 at 1,500 tons (Nucleated pearls, 2008; Bari and Lam, 2009; Canning, 2010). Since 2008, the number of farms dropped, as some went out of business and others were consolidated, resulting in about 500 large industrialized farms currently in operation (J. Shepherd, pers. comm., 2010).

Especially noteworthy during this decade are the experiments that have produced dramatically new cultured pearls. There are the colorful bead-nucleated cultured pearls called "fireballs," which are noted for their tail. Another fascinating new product debuted in 2009 as "hollow keshi," also referred to as "Soufflé pearls" (Sturman and Strack, 2010). By matching the implanted bead to the form of the pearl sac, farmers are better able to control the shape of the resulting cultured pearl. As a result, they are producing significant numbers of bead-nucleated rounds.

Other Freshwater Cultured Pearls. In North America, freshwater pearls are cultured in the Tennessee River in an operation that now centers on one location in Birdsong Creek (Tennessee River Pearls, 2009). The last major production was in 2002, but substantial stock remains of fancy-shaped cultured pearls—from bars and buttons to coins and crosses.

Vietnam is experimenting with some freshwater bead-cultured pearls of various hues. It is interesting to note that freshwater shells from Vietnam are also providing the bead nuclei for their domestic saltwater cultured pearls (Pardieu and Vannaxay, 2010).

In 2004, Chi Huynh, a California jewelry designer and holder of the patent on a new pearl cultivation process, developed the idea of transplanting mantle tissue along with a bead made from a gem material such as coral or turquoise into a mollusk while culturing black pearls off the coast of his homeland, Vietnam. After the cultured pearls were recovered, they were carved down to reveal the gem bead in places below. In 2010, his first crop of the summer yielded 10,000 cultured pearls. Named the "Galatea pearl," he has also cultivated them in French Polynesia (Roskin, 2007).

Cultured Conch Pearls. For more than 25 years, attempts at culturing pearls from the queen conch (*Strombus gigas*) had been unsuccessful. In 2009, scientists at Florida Atlantic University's Harbor

Figure 20. This two-strand necklace, which was owned by the Maharajas of Baroda in western India, consists of 68 natural pearls from 9.47 to 16.04 mm. At the April 2007 Christie's New York auction, the necklace and its accompanying ear pendants, brooch, and ring sold for $7,096,000, setting a world auction record for natural pearl jewels. Courtesy of Christie's Images Ltd. 2010.

Branch Oceanographic Institute developed proprietary techniques to produce beaded and non-beaded cultured pearls from the queen conch. Identification criteria are being compiled to separate the cultured conch pearls from their natural counterparts (Wang et al., 2009), although this is not yet a commercial product.

Cultured Abalone Pearls. Jewelry made with cultured abalone pearls is very popular in New Zealand and Australia, in part due to the farming efforts of the Eyris Blue Pearl Co. in New Zealand. Mabe cultured pearls have been farmed in red abalone by the U.S. Abalone Co. since 2000. Other farms have been attempted in Canada and along the Pacific coast of Baja California, but they are not currently in commercial production (E. Strack, pers. comm., 2010).

Natural Pearls. The popularity of natural pearls has generated a global effort to recover them. While the mollusks that produce these pearls have suffered from overfishing, temperature changes, and pollution, protective measures have been put in place, and some areas (e.g., Arabian Gulf, Red Sea, Indian Ocean, and Guaymas and the Sea of Cortez in Mexico) are beginning to see an increase in wild mollusk populations as well as finding more natural pearls from the existing mollusks (K. C. Bell and E. Strack, pers. comms., 2010).

During the past decade, there has been greater awareness of non-nacreous natural pearls from mollusks such as *Strombus gigas* (conch), *Melo melo* (melo), *Mercenaria mercenaria* (quahog or common hard-shelled clam), and the nautilus (K. C. Bell, pers. comm., 2010). Conch pearls are found in the waters of the Caribbean Sea from southern Florida to the northern coast of Colombia. Melo pearls are found in the South China Sea along the coasts of Vietnam, China, Myanmar, and the Philippines (Htun, 2006; Strack, 2006). According to F. Barlocher (pers. comm., 2010), during the decade about 30 melo pearls were recovered annually, but very few were perfectly round with top orange color. Quahog pearls are mainly found in waters along eastern Canada and down the eastern U.S. coast (Strack, 2006). The rarest may be nautilus pearls ("Nautilus pearls," 2010), which are reportedly found off the coast of the Philippines (Bari and Lam, 2009).

Recent sales of natural pearls reflect their high value and growing popularity. For example, on April 25, 2007, the Baroda suite of natural pearls sold for nearly $7.1 million at the Christie's New York auction (figure 20).

CONCLUSIONS

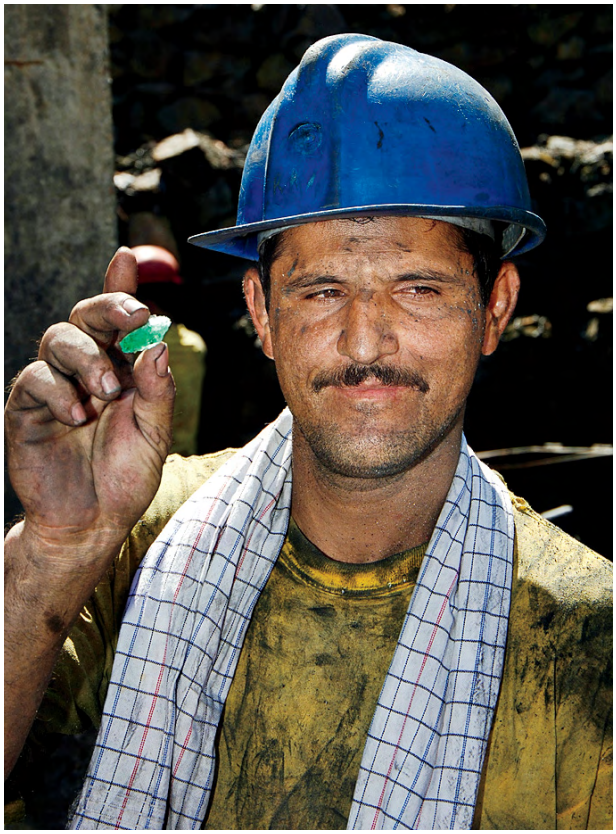
The past decade witnessed the continued production of diamonds and colored stones primarily from the geographic sources that had been important in the 1990s. The main diamond developments centered around the new prominence of Canadian deposits, increased production from Botswana and Russia, and a decline in output from the Argyle mine in Australia. There continued to be discoveries of colored stones, mainly in East Africa and Southeast Asia, but overall gem mining was somewhat limited by the lack of easily worked deposits, governmental restrictions, exploration and exploitation costs, and—increasingly in many countries—environmental concerns. The most notable colored stone discoveries were rubies in Tanzania and Mozambique, Cu-bearing tourmaline in Mozambique and Nigeria, spinel in Tanzania, and high-quality opal in Ethiopia. Cutbacks in pearl culturing in response to the global economic downturn will result in lower production during the early years of the next decade. An expanded awareness of the diversity of natural pearls will contribute to their popularity.

TABLE 1. Active gem localities of the 2000s for major colored stones.[a]

Gem material/locality	Reference
BERYL—Emerald	
♦ **Africa**	Schwarz and Giuliani (2001), Gründmann and Giuliani (2002), Groat et al. (2008)
Madagascar	Kanis and Schwarz (2002), F. Danet (pers. comm., 2009)
Fianarantsoa—**Mananjary:** *Ambodibakoly, Ifanadiana, Irondro, Kianjavato, Morafeno*	Henn and Milisenda (2001), Moine et al. (2004), Vapnik et al. (2006)
Toliara—Ianapera: *Sakalava*	Vapnik et al. (2005), Andrianjakavah et al. (2009)
Mozambique	Kanis and Schwarz (2002), J. Marques (pers. comm., 2009)
Zambézia—Gilé: *Niane, Rio Maria*; Ile: *Maria III*; Uape: *Maria Norte*	Bettencourt-Dias and Wilson (2000), Kanis and Schwarz (2002), Vapnik and Moroz (2002), Schappmann (2005)
Nigeria	Kanis and Schwarz (2002), J. C. Michelou (pers. comm., 2009)
Nassarawa—Nassarawan Eggon	Michelou (2007)
Kaduna—Gwantu: *Ankara*; Nandu: *Nandu*	Vapnik and Moroz (2000)
Somalia	
Awdal—Alihiley, Simodi	Kinnard (2001)
South Africa	
Limpopo—Gravelotte	Kanis and Schwarz (2002)
Tanzania	Kanis and Schwarz (2002), M. Saul and W. Balmer (pers. comm., 2009)
Manyara—Mangola, Mayoka	Moroz et al. (2001), Cairncross (2005a), Michelou (2006)
Rukwa—Sumbawanga	Moroz et al. (2001), Michelou (2006)
Zambia	Kanis and Schwarz (2002)
Copperbelt—**Luanshya-Kafubu:** *Chantete, Grizzly, Kagem*	Milisenda et al. (1999), Taupitz (2003a), Laurs (2004c), Seifert et al. (2004), Cairncross (2005a), Zachariáš et al. (2005), Zwaan et al. (2005), Lees (2009b), Behling and Wilson (2010), Cook (2010a)
Zimbabwe	Kanis and Schwarz (2002), L. F. Marsh and F. Mugumbate (pers. comm., 2009)
Mashonaland West—Karoi: *Rukomechi*; Mwami: *Simu, Swallow*	
Midlands—Somabhula, **Mberengwe:** *Hyabert, Khanya Hlaza, Lodge, Machingwe, Mtombeni, Pandora, Pearzam, Sihande, Vidan East, Venus, Zeus (Sandawana)*	Zwaan and Touret (2000), Taupitz (2003b), Zwaan et al. (2004), Zwaan (2006)
Masvingo—Masvingo: *Brentwood, Mayfield;* Guta: *Chikwanda, Novello*	
♦ **Asia**	
Afghanistan	Schwarz and Giuliani (2002c), Kalukiewicz (2005), D. Blauwet (pers. comm., 2009)
Badakhshan—Khash	
Laghman—Shamya	Laurs (2001a)
Nuristan—Gamitha, Korgun, Lamonda, Titin	Laurs (2001a)
Panjshir—**Panjshir Valley:** *Bismal*	Sachanbinski et al. (2003), Fijał et al. (2004), Pardieu and Soubiraa (2006a)
China	Ou Yang (2005), Smith et al. (2005), X. Yuan (pers. comm., 2009)
Heilongjiang—Boli, Hehe, Jiamusi	B. Ottens (pers. comm., 2009)
Yunnan—Maguan-Malipo: *Dayakou Mountain, Nan-Jiang, Wenshan*	Wu (2004), Liu (2005), Li (2009), Marshall et al. (2009)
Xinjiang Uygur—Taxkorgan: *Davdar*	Blauwet et al. (2005), Michelou and Pardieu (2009), Schwarz and Pardieu (2009)
India	Schwarz and Giuliani (2002c), G. Choudhary, J. Panjikar, and A. Dholakia (pers. comm., 2009)
Orissa—Balangir, Phulabani, Sambalpur	Michelou (2006)
Rajasthan—Ajmer, Kaliguman, Rajgarh, Udaipur	Michelou (2006)
Tamil Nadu—Salem	
Pakistan	Schwarz and Giuliani (2002c), D. Blauwet (pers. comm., 2009)
Federally Administered Tribal Areas—Bajaur, Mohmand: *Gandao*	Einfalt (2002), Hammer (2004a)
Gilgit-Baltistan—Basha Valley: *Doko*	Hammer (2004a,d)
North-West Frontier—**Swat Valley:** *Charbagh, Gujar Kili, Makad, Mingora*	Einfalt (2002), Hammer (2004a), Pardieu and Soubiraa (2006b), Arif et al. (2010)
Russia	
Middle Ural Mountains—Asbest: *Marinskiy*; Izumrudnye Kopi: *Cheremshansk, Krasnobolotnoe, Malyshevsk, Sverdlovsk*	Zolotukhin (1999), Kupriyanova (2002), Hochleitner (2005a), Kozlov (2005), Lyckberg (2005a), P. Lyckberg (pers. comm., 2009)

[a] *This table lists active mining localities of the decade for the more important colored stones, with references to publications in the contemporary literature and personal communications. The country name is followed by the province/state/region, then the district or mining area, and finally (in italics) the name of the closest town or mine/deposit/occurrence when known. Towns or mines that the authors believe were important producers during the past decade are shown in boldface text. The references cited can be found in the G&G Data Depository at gia.edu/gandg. Tables for the localities of diamonds, minor colored stones, and pearls can be found in the G&G Data Depository.*

A miner at La Pita in Colombia displays a newly discovered emerald crystal. Photo by Robert Weldon.



Gem material/locality	Reference
♦ Australia	Henry (2005), Sutherland (2006)
New South Wales—New England Range: Emmaville, Torrington	
Queensland—Mount Surprise	
Western Australia—Menzies, Pilbara, Poona, Wodgina	
♦ North America	
Canada	Wilson (2007,2010)
Northwest Territories—Tungsten: *Lened*	Marshall et al. (2004), Groat et al. (2008)
Ontario—Dryden: *Taylor*	
Yukon Territory—Finlayson Lake: *Tsa da Glisza (Regal Ridge)*	Groat et al. (2002), Rohtert (2002b), Marshall et al. (2003), Wight (2003), Groat (2005)
United States	
North Carolina—Alexander: *Hiddenite*	Wise (2002, 2009), Potucek (2005), Wise and Anderson (2006), Cook (2007), Mychaluk (2008), Speer (2008), White (2010)
♦ South America	
Brazil	Pinto and Pedrosa-Soares (2001), Schwarz and Giuliani (2002b)
Bahia—Anajé, Brumado: *Serra das Eguas*, **Campo Formoso:** *Socotó*; Pilão Arcado: *Salininha*, **Pindobaçu:** *Carnaiba*	Couto (2000)
Goiás—Pirenópolis, **Santa Teresinha:** *Campos Verdes, Santa Teresinha*	D'el-Rey Silva and Neto (2002)
Minas Gerais—Conselheiro Pena: *Itatiaia, Hematita, Itinga*; **Itabira:** *Belmont, La Rocha, Nova Era, Piteiras*	Kanis (2001,2002), Levinson et al. (2001a), Mossman (2001), Preinfalk et al. (2002), Rondeau et al. (2003)
Rio Grande do Norte—Lajes	Milisenda (2007)
Tocantins—Monte Santo, Paraiso do Tocantins	J. Hyršl (pers. comm., 2009)
Colombia	Banks et al. (2000), Giuliani et al. (2000), Schwarz and Giuliani (2002a)
Boyacá—**Chivor**, **Cosquez**, **Muzo**, Pava; **Maripí (La Pita):** *Polveros*; San Pablo de Borbur: *Peñas Blancas*	Johnson et al. (2000a), Michelou (2001,2005,2006), Boehm (2002a), Fritsch et al. (2002a), Vuillet et al. (2002), Campos-Alvarez and Roser (2007)
Cundinamarca—Gachalá, Yacopí	

BERYL—Aquamarine/Heliodor/Morganite

♦ Africa	
Kenya	
Eastern—Embu	Cairncross (2005a)
Madagascar	Henn and Milisenda (2001), F. Danet and F. Pezzotta (pers. comm., 2009)
Antananarivo—Ambohidrano, Anjanabonoina, Ankazobe, Antsirabe, Betafo, Mahaiza, Mount Bity, Vohitrakanga	Pezzotta (2001b), Danet (2007)
Antsiranana—Andapa	Pezzotta (2001b)
Fianarantsoa—Ambatovita, Isahara, Voandambo	Laurs and Quinn (2002a)
Mahajanga—Andriamena, Boriziny, Mahajamba	Pezzotta (2001b)
Toamasina—Ambatondrazaka	
Toliara—Amboasary	
Malawi	
Northern—**Mzimba**	Cairncross (2005a), Michelou (2006), Dill (2007)
Mozambique	J. Marques (pers. comm., 2009)
Nampula—Chalaua (Moma), Lalaua: *Lalaua*; Malema: *Mutuáli*	
Tete—Marávia: *Marironguè*; Mutarara: *Nhaphali*; Zumbo: Mese River	
Zambézia—Alto Molócuè: *Namacotche*; Gilé: *Marropino*, *Muiane*, *Naipa*; Milange, Mocuba, Murrua	Bettencourt-Dias and Wilson (2000), Schäfer and Arlt (2000), Schappmann (2005), Cairncross (2005a)
Namibia	G. Schneider (pers. comm., 2009)
Erongo—Erongo Mountains, Klein and Grosse Spitzkoppe, Rössing Mountain	Jahn (2000), Jahn and Bahmann (2000), Glas (2002), Laurs (2002a), Cairncross (2005a), Cairncross and Bahmann (2006a)
Nigeria	Michelou (2006, 2007), J. Michelou (pers. comm., 2009)
Kaduna—Kwoi	
Kogi—Egbe, Okene	
Nassarawa—Akwanga	
Niger—Paikolo	
Ogun—Ijebu Igbo, Igbo Ora	
Oyo—Olonde: *Concord, Gbayo*	
Plateau—Bomo	
South Africa	
Northern Cape—Keimoes	Cairncross (2005a)
Tanzania	Michelou (2006), D. Mantheakis (pers. comm., 2009)
Arusha—Loliondo	
Rukwa—Sumbawanga	
Ruvuma—Nyamtumbo, Songea, Tunduru	Laurs (2002b)
Zambia	C. Milisenda (pers. comm., 2009)
Central—Mkushi	
Eastern—Chama, Lundazi	Milisenda et al. (2000), Carranza et al. (2005)
Southern—Itezhi-Tezhi	
Zimbabwe	Cairncross (2005a), L. F. Marsh and F. Mugumbate (pers. comm., 2009)
Mashonaland Central—Rushinga: *First Try, God's Gift*	
Mashonaland East—Mutoko: *Benson*	
Mashonaland West—Mwami: *Baboon Hill, Gwati, JLM, Saint Ann's, Simu, Swallow, Green Walking Stick*	Milisenda et al. (2000), Cairncross (2005b), Wise (2005)
Matabeleland South—Filabusi, Zvishavane	Cairncross (2005a)
Masvingo—Gutu: *Novello*	Cairncross (2005a)
♦ Asia	
Afghanistan	D. Blauwet (pers. comm., 2009)
Kunar—Darra-i-Pech, Kala	Glas (2002)
Nuristan—Grangal, Mawi, Papra, Paprowk, Waigon, Watata	
China	Ou Yang (2005), Smith et al. (2005), Michelou (2006), X. Yuan (pers. comm., 2009)
Sichuan—Pingwu: Xuebaoding Mountain	Liu (2005)
Yunnan—Yingjiang: Ailaoshan Mountains, Gaoligongshan Mountains	Wu (2004), Liu (2005), Marshall et al. (2009)
Xinjiang Uygur—Altai Mountains: *Koktokay*	Tang et al. (2004), Liu (2005), Li (2009)
India	Quinn-Darenius (2008), G. Choudhary and J. Panjikar (pers. comm., 2009)
Jammu and Kashmir—Sunjam, Zanskar	
Jharkhand—Hazaribag	
Orissa—Balangir, Kantabanji, Phulabani, Sambalpur, Subarnapur	Boehm (2000)
Rajasthan—Ajmer, Panwar, Sarwad, Shahpura, Tonk	Michelou (2006), Win (2009)
Tamil Nadu—Coimbatore, Dindigul, Kadavur, Kangayam, Kanniyakumari, Karur, Kurumbapatti, Madurai, Padiyur, Salem, Sivapuram, Tarapuram, Tharagampatti, Tiruchchirappalli, Tiruppur, Varusha Nadu	Boehm (2000), Michelou (2006)
Myanmar	M. Smith, K. Thu, and T. Hlaing (pers. comm., 2009)
Karen	
Mandalay—Kabaing, Kume, Mogok: *Sakhangyi*	Kyi et al. (2005), Hlaing (2009a)

Gem material/locality	Reference
Shan—Molo: *Katchay*; Momeik	Kyi et al. (2005)
Pakistan	D. Blauwet (pers. comm., 2009)
Gilgit-Baltistan—Basha Valley: *Bien, Biensla, Dogoro, Sibiri, Thorgu*; Braldu Valley: *Apo Ali Gun, Baha, Byansahpi, Chhappu, Dassu, Foljo, Gone, Hoh Nala, Nyet, Nyet Bruk, Teston, Tosho*; Hunza Valley: *Chumar Bakhoor, Nagar*; Indus Valley: *Baluchi, Baralooma, Dassu, Drot, Haramosh, Khargulook, Raikot, Rhondu, Sabsar, Saichais, Sassi, Shengus*; Shigar Valley: *Haiderabad, Mungo, Sildi, Yuno*	Hammer (2003a,2004d), Hammer and Muhammad (2004), Blauwet (2004), Blauwet and Muhammad (2004)
Russia	
Middle Ural Mountains—Asbest: *Marinskiy*; Yekaterinburg: *Aduy, Alabashka*	P. Lyckberg (pers. comm., 2009)
Transbaikalia—Borzya: *Sherlova Gora*; Chita: *Adun-Chilon*; Krasnyy Chikoy: Malkhan Mountains	Hochleitner (2005a,b), Lyckberg (2005a), Badanina et al. (2008), P. Lyckberg (pers. comm., 2009), Zaraisky et al. (2009)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Hatton, Nawalapitiya, Rattota	
Sabaragamuwa—Balangoda, Opanayaka, Ratnapura	Dissanayake et al. (2000)
Southern—Hambantota, Lunugamwehera, Mitiyagoda	Laurs et al. (2006b), Michelou (2006)
Ukraine	
Zhytomyr—Zhytomyr: **Volodarsk-Volynskiy**	Lyckberg (2005a), Lyckberg et al. (2009)
Vietnam	Pham et al. (2004a), D. Blauwet (pers. comm., 2009)
Nghe An—Qui Phong, Qui Vinh	Michelou (2006)
Phu Tho—Lu Phu, Phu Tho	
Thanh Hoa—Xuan Loc	
Yen Bai—Minh Tien, Luc Yen	
♦ Europe	
Finland	
Kymi—Luumäk	Lyckberg (2004a,b,2005b), Wise (2005)
♦ North America	
Canada	Wilson (2010)
British Columbia—Atlin, Bennett: *Mount Foster*, Passmore: *B-Q Claim*	Groat (2005), Wilson (2007)
Ontario—Quadeville	Wilson (2007)
Yukon Territory—Watson Lake: *True Blue*	Groat (2005), Turner et al. (2007)
United States	White (2010)
California—Riverside: Chihuahua Valley; San Diego: Jacumba, Mesa Grande, Pala, Ramona, Rincon	Fisher (2005), Mauthner (2008)
Colorado—Chaffee: Mount Antero	Jacobsen (2005), Potucek (2005)
Connecticut—Middlesex (East Hampton): *Slocum*	Jarnot (2005), Wise (2005)
Idaho—Sawtooth Mountains	Potucek (2005)
Maine—Oxford-Sagadahoc: *Buckfield, Mount Mica, Oxford, Stoneham, Topsham*	Jarnot (2005)
New Hampshire—Grafton (Groton): *Palermo*; Sullivan-Cheshire: *Keene*	Wise (2005)
♦ South America	
Brazil	César-Mendes et al. (2001), Pinto and Pedrosa-Soares (2001)
Bahia—Alcobaça: *Juerana*; Itambé: *Morro da Gloria, Paraíso*; Itanhém: *Jaquetô*; Macarani: *Lajedinho*; Maiquinique: *Jagarauna*; Vitória da Conquista: *Cercadinho*	Couto (2000), Menezes (2005)
Espírito Santo—Baixo Guandu: *Santa Cruz (Itapina)*; Castelo: *Forno Grande*; Itaguaçu: *Boa Vista*; Mimoso do Sul: *Concórdia*; Muqui: *São Domingos*; Pancas	Menezes (2005)
Minas Gerais—Conselheiro Pena-Galiléia-Resplendor; Medina-Pedra Azul; Santa Maria de Itabira-Ferros; Teófilo Otoni-Topázio-Catuji-Padre Paraíso-Caraí; Coronel Murta: *Paineira, Pau Alto, Terra Corrida*	Mossman (2001), Viana et al. (2002), Laurs (2004a), Ferreira et al. (2005), Menezes (2005), Millisenda and Bank (2005), Steger (2006), L. Barbosa (pers. comm., 2009)
Rio Grande do Norte—Acari, Lajes Pintadas, São João do Sabuji, Tenente Ananias	Bhaskara-Rao (2002), Bhaskara-Rao et al. (2004), B. Cook (pers. comm., 2009)

CHRYSOBERYL (Including cat's-eye)

♦ Africa	
Madagascar	F. Danet (pers. comm., 2009)
Antananarivo—Ankazobe	Henn and Milisenda (2001)
Fianarantsoa—Ambositra, **Ilakaka**	Milisenda et al. (2001b), Pezzotta (2001f,g,h), Schmetzer et al. (2002b)
Toamasina—Ambatondrazaka	Pezzotta (2001b)
Tanzania	Michelou (2006), W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009)
Manyara—Mayoka	
Mtwara—Lumesule River	
Ruvuma—Muhuwesi River, Mtetesi River, **Tunduru**	Pardieu (2007a)
Zambia	
Eastern—Muyombe: Kalanga Hill	Žáček and Vrána (2002)
Zimbabwe	L. F. Marsh and F. Mugumbate (pers. comm., 2009)
Mashonaland West—Kadoma: *Rattis*; Mwami: *Green Walking Stick, Haslemere, Pearl, Spider*	
Midlands—Somabhula	
Masvingo—Gutu: *Novello*; Masvingo: *Brentwood*	
♦ Asia	
India	G. Choudhary and J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Addatigala, Araku Valley, Chintapalli, Godavari, Khammam, Paderu, Srikakulam, Vizianagaram	Michelou (2006), Sarkar and Guru (2010)
Kerala—Quilon	Michelou (2006)
Orissa—Balangir, Kalahandi, Kantabanji, Koraput, Rayagada, Sambalpur	Michelou (2006), A. Dholakia (pers. comm., 2009)
Tamil Nadu—Dindigul, Kangayam, Kanniyakumari, Karur, Madurai, Tirunelveli	Michelou (2006)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Sabaragamuwa—Kalawana, Niwitigala, Pelmadulla, Rakwana, **Ratnapura**	
Southern—Akuressa, Deniyaya, Morawaka, Pattara	Michelou (2006)
♦ Australia	
Western Australia—Dowerin	Downes and Bevan (2006)
♦ South America	
Brazil	Pinto and Pedrosa-Soares (2001)
Espirito Santo—Colatina: *Pancas*	J. Hyršl (pers. comm., 2009)
Minas Gerais—Padre Paraíso	L. Barbosa (pers. comm., 2009)

CHRYSOBERYL—Alexandrite

♦ Africa	
Madagascar	F. Danet (pers. comm., 2009)
Fianarantsoa—**Ilakaka**	Milisenda et al. (2001b), Pezzotta (2001f,g,h), Schmetzer (2002)
Tanzania	
Manyara—Mayoka	Michelou (2006), D. Mantheakis (pers. comm., 2009)
Zimbabwe	L. F. Marsh and F. Mugumbate (pers. comm., 2009)
Midlands—Somabhula	
Masvingo—Gutu: *Novello*	
♦ Asia	
India	G. Choudhary and J. Panjikar (pers. comm., 2009)

Gem material/locality	Reference
Andhra Pradesh—Addatigala, Araku Valley, Godavari, Khammam, Srikakulam, Vizianagaram	Michelou (2006)
Chattisgarh—Raipur	
Kerala—Aruvikkara, Kolattupuzha, Ooruttambalam	Michelou (2006)
Madhya Pradesh—Deobhog	
Orissa—Sambalpur	
Tamil Nadu—Dindigul, Kangayam, Kanniyakumari, Karur, Madurai, Palni, Tirunelveli	Sarkar and Guru (2010)
Russia	
Middle Ural Mountains—Izumrudnye Kopi: *Malyshevsk, Sverdlovsk*	Hochleitner (2005a), Kozlov (2005), Lyckberg (2005a)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Sabaragamuwa—Kalawana, Niwitigala, Pelmadulla, Rakwana, Ratnapura	Dissanayake et al. (2000)
Southern—Akuressa, Deniyaya, Morawaka, Pattara	
♦ Australia	
Western Australia—Dowerin	Downes and Bevan (2006)
♦ South America	
Brazil	Pinto and Pedrosa-Soares (2001)
Bahia—Pindobaçu: *Carnaíba*	
Goías—Minaçu: *Pela Ema*	Petersen et al. (2002)
Minas Gerais—**Hematita**, Malacacheta, Manhuaçu	Mossman (2001), Michelou (2006), L. Barbosa and J. Hyršl (pers. comm., 2009)

CORUNDUM—Ruby

Gem material/locality	Reference
♦ Africa	
Kenya	Garnier et al. (2004a), C. Simonet (pers. comm., 2009)
Coast—Kuranze: *Ushindi*; **Mangare:** *John Saul (Rockland)*	Mercier et al. (1999), Pardieu and Senoble (2005d), Michelou (2006), Laurs (2008), Pardieu (2008)
Rift Valley—**Eldoret:** *Baringo*; West Pokot: *Alale*	Laurs (2002c), Blauwet and Laurs (2005), Pardieu and Senoble (2005d), Pardieu (2008)
Madagascar	Giuliani et al. (2007a,b), Rakontondrazafy et al. (2008), F. Danet (pers. comm., 2009)
Antananarivo—Antanifotsy, Antsahanandriana, Faratsiho, Soamiakatra	Pardieu and Senoble (2005c), Rakotosamizanany et al. (2009)
Antsiranana—Ambondromifehy	Rakotosamizanany et al. (2009)
Fianarantsoa—Marosely, Miarinarivo, Sakeny	Laurs (2000), Cartier (2009)
Mahajanga—Andriba	
Toamasina—Ambatondrazaka, Ambodilalona, Amboditavolo, Ambodivandrika, **Andilamena**, Beforona, Didy, Moramanga, Tetezampaho, **Vatomandry**	Hänni (2001), Hänni et al. (2001), Leuenberger (2001), Schwarz and Schmetzer (2001), Pardieu and Senoble (2005c), Rakotosamizanany et al. (2009)
Toliara—Anavoha, Ambatomena, Ejeda, Fotodrevo, Gogogogo, Maniry, Vohitany	
Malawi	
Southern—Ntcheu: *Chimwadzulu Hill*	Emmett (2000), Boehm (2004), Laurs (2004c), Dill (2005,2007), Michelou (2006), Dill and Ludwig (2008)
Mozambique	J. Marques (pers. comm., 2009)
Cabo Delgado—Montepuez: Namahaca, Namahumbire	Hänni and Krzemnicki (2009), Pardieu et al. (2009b,c,e)
Niassa—Marrupa: Luambéze River; Mavango: M'Sawize	McClure and Koivula (2009), Pardieu et al. (2009b,c,e)
Tete—Changara: Dombe Mountain, Nhaponzo	
Tanzania	Garnier et al. (2004a,b), W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009)
Arusha—Landanai, Lossogonoi, Wundarara	Pardieu (2007b), Le Goff et al. (2008)
Dodoma—Winza	Hänni (2008), Laurs and Pardieu (2008), Schwarz et al. (2008), Schmetzer et al. (2010)
Kilimanjaro—Longido: *Mundarara*	Pardieu and Senoble (2005e), Michelou (2006), Le Goff et al. (2010)
Morogoro—Epanko, Lukande, **Mahenge**, **Matombo**, Uluguru Mountains	Pardieu and Senoble (2005e), Michelou (2006), Pardieu (2007a)
Rukwa—Chala	
Ruvuma—Amanimakoro, Masuguru, Mtetesi River, Muhuwesi River, Ngapa, **Songea**, **Tunduru**	Hamid et al. (2000), Pardieu and Senoble (2005e)
Tanga—Kalalani, **Umba Valley**	
Zimbabwe	L. F. Marsh and F. Mugumbate (pers. comm., 2009)
Midlands—Somabhula	
♦ Asia	
Afghanistan	Hammer (2003b), Garnier et al. (2008)
Badakhshan—Khash	Laurs (2007b), D. Blauwet (pers. comm., 2009)
Kabul—Jegdalek: *Mirkhalwat, Warmankai*	Bowersox et al. (2000), Garnier et al. (2006), Pardieu and Soubiraa (2006a)
Cambodia	
Pailin—Pailin	Pardieu (2009), Sutherland et al. (2009a)
China	Ou Yang (2005), Smith et al. (2005), Michelou (2006), B. Ottens and X. Yuan (pers. comm., 2009)
Yunnan—Ailaoshan Mountains, Jingping, Yuanjiang, Yuanyang	Wu (2004), Li (2009)
India	G. Choudhary and J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Anantapur, Chittoor, Guntur, Khammam, Nalgonda, Vishakhapatnam, Warangal	Michelou (2006)
Chattisgarh—Bastar, Raipur	Michelou (2006)
Karnataka—Channapatna, Chikmagalur, Coorg, Durgadahalli, Hassan, Somvarpet, Maddur, Madikeri, Mysore, Pavagada, Subrahmanya (Puttur), Ramanahalli, Tumkur	Michelou (2006)
Kerala—Kolattupuzha	

The Mogok Stone Tract in Myanmar is the source of this 9.28 ct star ruby. Courtesy of Hussain Rezayee, Rare Gems & Minerals; photo by Robert Weldon.

Gem material/locality	Reference
Orissa—Angul, Balangir, Hinjlibahal, Kalahandi	Michelou (2006)
Tamil Nadu—Kangayam, Karur, Namakkal, Padiyur, Palni, Paramatti, Salem, Vellore	Sartar and Guru (2010)
Laos	Michelou (2006), Graham et al. (2008)
Bokeo—Ban Houayxay	Sutherland et al. (2002)
Myanmar	Barley et al. (2003), Garnier et al. (2004b,2008), Thein (2008), M. Smith, K. Thu, and T. Hlaing (pers. comm., 2009)
Kachin—Nanyaseik, Nam Phyu	Smith and Bosshart (2001), Hlaing (2008), Hlaing and Win (2008)
Mandalay—**Mogok**, Thabeikkyin	Garnier et al. (2006), Mitchell et al. (2007), Searle et al. (2007), Yui et al. (2008)
Shan—**Mong Hsu**	
Nepal	
Gandaki—Ganesh Himal: *Dhading*	Garnier et al. (2006,2008)
Pakistan	Hammer (2003b,2004d), Garnier et al. (2005a,2008), Laurs (2007b), D. Blauwet (pers. comm., 2009)
Azad Kashmir—Neelum Valley: *Nangimali*	Pêcher et al. (2001,2002), Chamberlain et al. (2002), Beesley (2004), Garnier et al. (2004), Pardieu and Soubiraa (2006b)
Gilgit-Baltistan—Basha Valley: *Bisil*; Hunza Valley: *Ahmedabad, Bajouri, Ganesh, Hachindar, Hassanabad*	Hammer (2004a), Garnier et al. (2006)
North-West Frontier—Bashi Valley, Battakundi	Pardieu et al. (2009f)
Russia	P. Lyckberg (pers. comm., 2009)
Northern Ural Mountains—Polyarnyy: *Rai-Iz*	Grygoriev et al. (2000)
Middle Ural Mountains—Yekaterinburg: *Alabashka, Lipovka*	
Southern Ural Mountains—Plast: *Svetloe*	
Tajikistan	
Kuhistoni-Badakhshon—Pamir Mountains: Murgab, Muzkol	Dufour et al. (2007)
Thailand	Sutthirat et al. (2001), Garnier et al. (2004b), Graham et al. (2008), P. Wathanakul (pers. comm., 2009)
East—Bo Rai, Bo Waen, Khao Ploi Waen, Khao Saming, Welu Klang, Nong Bon, Tok Phrom	Yui et al. (2006)
North-East—Nong Khon, Nam Yuen	
Vietnam	Garnier et al.(2002,2004a,2005b, 2005c,2006,2008), Giuliani et al. (2003), Pham et al. (2004a,b,c), Michelou (2006), Graham et al. (2008), D. Blauwet (pers. comm., 2009)
Binh Thuan—Da Ban, Dak Ton, Ma Lam	Nguyen et al. (2007)
Nghe An—**Qui Chau**, Qui Hoop	Pham et al. (2004d)
Quang Nam—Phuoc Hiep	Nguyen et al. (2007)
Yen Bai—An Phu, **Luc Yen**, Minh Xuan, Tan Huong, Thac Ba, Truc Lau, Yen Bai	Pardieu and Senoble (2005a), Blauwet (2006a)
♦ Australia	Brown (2002), Sutherland (2006), Sutherland and Webb (2007), Graham et al. (2008)
New South Wales—Barrington, Bingara, Cudgegong and Macquarie Rivers, **Gloucester**, Swanbrook, Tumbarumba	McClure and Smith (2001), Sutherland and Fanning (2001, 2007), Sutherland et al. (2003, 2009b), Roberts et al. (2004), Webb (2007), Graham et al. (2008), B. Birch (pers. comm., 2009), Sutherland and Abduriyim (2009)
Victoria	Sutherland and Abduriyim (2009)
♦ South America	
Brazil	
Minas Gerais—Indaiá, Malacacheta, Palmeiras, Sapucaia	Liccardo et al. (2005)

CORUNDUM—Sapphire

Gem material/locality	Reference
♦ Africa	
Kenya	Garnier et al. (2004a), C. Simonet (pers. comm., 2009)
Coast—Kisoli	
Eastern—Garba Tula (Dusi), Kitui: *Kisou*	Sutherland and Schwarz (2001), Simonet et al. (2004)
Rift Valley—**Eldoret:** *Baringo*; Turkana: *Kanakurdio*	Blauwet and Laurs (2005)
Madagascar	Garnier et al. (2004a,b), Giuliani et al. (2007a,b), Rakontondrazafy et al. (2008), F. Danet (pers. comm., 2009)
Antananarivo—Anjomakely, Antanifotsy, Mandrosohasina	Rakotosamizanany et al. (2009)
Antsiranana—Amboahangimamy, **Ambondromifehy**, Antserasera, Anivorano, Befotaka	Laurs (2000, 2003a), Schwarz et al. (2000), Pardieu and Senoble (2005c), Rakotosamizanany et al. (2009), Ramdohr and Milisenda (2004, 2006)
Fianarantsoa—Ambinda, Andranolava, **Ilakaka**, Marosely, Sahambano, Sakalalina, Zazafotsy	Laurs (2000, 2003a), Milisenda et al. (2001b), Pezzotta (2001f,g, h, 2006), Pardieu and Senoble (2005c), Ralantoarison et al. (2006), Cartier (2009)
Toamasina—**Andilamena**, **Vatomandry**	Pardieu and Senoble (2005c), Rakotosamizanany et al. (2009)
Toliara—Amboasary, **Andranondambo**, Bekily, Betroka, Iankaroka, **Sakaraha**, Voronkafatra	Milisenda et al. (2001a), Pardieu and Senoble (2005c)
Malawi	
Southern—Ntcheu: *Chimwadzulu Hill*	Emmett (2000), Rankin (2002), Laurs (2004c), Dill (2005,2007), Michelou (2006), Dill and Ludwig (2008)
Mozambique	J. Marques (pers. comm., 2009)
Manica—Chimoio: *Chimoio*	
Tete—Mutarara: *Nhaphali*	
Nigeria	Michelou (2006,2007), J. Michelou (pers. comm., 2009)
Bauchi—Tafawa Balewa	
Borno—Biu-Gunda	
Kaduna—Antang, Gidan Waya, Godogodo	Sutherland and Schwarz (2001)
Taraba—Adamawa: *Ganye*; Gembu: *Karim Lamido*	
Tanzania	Garnier et al. (2004a,b), W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009, 2010)
Dodoma—**Winza**	Laurs and Pardieu (2008), Schwarz et al. (2008), Schmetzer et al. (2010)
Morogoro—Lukande, Mahenge, Matombo, Uluguru Mountains	Pardieu and Senoble (2005e), Michelou (2006), Pardieu (2007a)
Ruvuma—Amanimakoro, Masuguru, Mtetesi River, Muhuwesi River, Ngapa, **Songea**, **Tunduru**	Pardieu and Senoble (2005e), Michelou (2006), Pardieu (2007a)
Tanga—Kalalani, Kigwase, **Umba Valley**	Michelou (2006)
Zimbabwe	
Midlands—Somabhula	L. F. Marsh and F. Mugumbate (pers. comm., 2009)
♦ Asia	
Afghanistan	Hammer (2003b), Garnier et al. (2008), D. Blauwet (pers. comm., 2009)
Kabul—Jegdalek	Bowersox et al. (2000)
Wardak—Maidan Shahr	Laurs (2002d), Quinn and Laurs (2004a)

Gem material/locality	Reference
Cambodia	Sutherland and Schwarz (2001)
Pailin—Pailin	Sutherland et al. (2009a)
China	Sutherland and Schwarz (2001), Liu (2004), Ou Yang (2005), Smith et al. (2005), Michelou (2006), X. Yuan (pers. comm., 2009)
Fujian—Mingxi: *Gaiyang*	Li (2009)
Hainan—Wenchang: *Penglai*	Li (2009)
Jiangsu—Liuhe: *Lianshan*	Li (2009)
Shandong—Changle: Wutu	Li (2009)
Xinjiang—Taxkorgan	Tang et al. (2004)
India	Garnier et al. (2004a,2008), G. Choudhary and J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Anantapur, Hindupur, Ratnagiri Hills	
Jammu and Kashmir—Doda, Sunjam	Michelou (2006)
Kerala—Quilon, Trivandrum	Santosh et al. (2002)
Orissa—Balangir, Nawapara, Sambalpur	
Tamil Nadu—Kangayam, Kanniyakumari, Karur, Padiyur, Venkatpuram	McClure et al. (2005a), Michelou (2006)
Laos	Sutherland and Schwarz (2001), Garnier et al. (2004a), Michelou (2006)
Bokeo—Ban Houayxay	Sutherland et al. (2002a)
Myanmar	Barley et al.(2003), Garnier et al. (2004b,2008), Thein (2008), M. Smith. K. Thu, and P. Hlaing (pers. comm., 2009)
Kachin—Nanyaseik	
Mandalay—Kyauksin, **Mogok**, Thabeikkyin	Mitchell et al. (2007), Searle et al. (2007)
Shan—Mong Hkak, Mong Hsu	Hlaing (2008)
Nepal	Garnier et al. (2008)
Gandaki—Ganesh Himal: *Dhading*	
Pakistan	Hammer (2003b,2004d), Henn and Milisenda (2005), Garnier et al. (2008), D. Blauwet (pers. comm., 2009)
Gilgit-Baltistan—Astore Valley: *Batwash Gah*; Hunza Valley: *Ganesh*	Hammer (2004a)
North-West Frontier—Battakundi, Kohistan: *Sapat*	Quinn and Laurs (2004a), Pardieu et al. (2009f)
Russia	
Far East—Primorsky: *Kedrovka River, Krasnoarmeisky, Nezametnoye*	Khanchuk (2002), Pakhomova et al. (2006), Nechaev et al. (2009)
Sri Lanka	Dharmaratne (2003), Garnier et al. (2004a,b), Pardieu and Senoble (2005b), G. Zoysa (pers. comm., 2009)
Central—Elahera, Lunugala, Passara, Polonnaruwa	Dissanayake et al. (2000), Pardieu and Senoble (2005b)
Sabaragamuwa—Balangoda, Eheliyagoda, Embilipitiya, Niwitigala, Pelmadulla, Rakwana, **Ratnapura**	Dissanayake et al. (2000), Pardieu and Senoble (2005b)
Southern—Kataragama, Matara, Ridiyagama	
Uva—Bibile, Haputale, Moneragala, Okkampitiya, Wellawaya	
Western—Akurana, Horana, Ingiriya, Kiriella, Pelpola, Pugoda	
Thailand	Sutherland and Schwarz (2001), Garnier et al. (2004a,b), Graham et al. (2008), P. Wathanakul (pers. comm., 2009)
East—Khao Ploi Waen	Promprated et al. (2003), Yui et al. (2006)
North-East—Nong Khon, Nam Yuen	Wathanakul et al. (2007)
North—Chiang Khong, Den Chai, Wang Chin	Limtrakun et al. (2001), Yui et al. (2003)
West—Bo Phloi, Kanchanaburi	Choowong (2002)
Vietnam	Sutherland and Schwarz (2001), Garnier et al. (2004a,b,2005b, 2005c,2008), Pham et al. (2004a,b), Michelou (2006), Graham et al. (2008), D. Blauwet (pers. comm., 2009)
Binh Thuan—Da Ban, Dak Ton, Ma Lam, Phan Thiet	Nguyen et al. (2007)
Dak Lak—Dak Nong	
Dong Nai—Xa Gia Kiem, Xuan Loc	
Lam Dong—Bao Lac, Di Linh	
Nghe An—**Qui Chau**, Qui Hoop	
Quang Nam—Phuoc Hiep	Nguyen et al. (2007)
Yen Bai—An Phu, Bai Da Lan, **Luc Yen**, Yen Bai	Pardieu and Senoble (2005a), Blauwet (2006)
♦ **Australia**	Sutherland and Schwarz (2001), Brown (2002), Garnier et al. (2004a,b), Jaques and Milligan (2004), Sutherland (2006), Sutherland and Webb (2007), Graham et al. (2008)
New South Wales—Barrington, Bingara, Cudgegong and Macquarie Rivers, **Gloucester**, New England Range: *Glen Innes, Inverell, Tumbarumba, Yarrowitch*; Oberon, Vulcan State Forest	McClure and Smith (2001), Sutherland and Fanning (2001), Sutherland et al. (2002b, 2003, 2009b), Roberts et al. (2004), Zaw et al. (2006), Webb (2007), Sutherland and Abduriyim (2009)
Queensland—Anakie, Rubyvale	Sutherland and Abduriyim (2009)

These sapphire crystals from Sri Lanka (yellow 6.8 g, blue 8.4 g) show a typical bipyramidal habit. Courtesy of Bill Larson, Palagems.com; photo by Robert Weldon.

Gem material/locality	Reference
Tasmania—Weldborough	Zaw et al. (2006), Sutherland and Abduriyim (2009)
Victoria	Sutherland and Abduriyim (2009)
New Zealand	
South Island—Dunedin	Kiefert et al. (2006)
♦ North America	
Canada	Wilson (2010)
British Columbia—Slocan Valley near Passmore: *Blu Moon, Blu Starr, Sapphire Hill*	Coenraads and Laird (2000), Wilson (2007)
Nunavut—Baffin Island: Kimmirut	LeCheminant et al. (2004), Wilson (2007)
Ontario—Bancroft	Wight (2004)
United States	
Montana—Deer Lodge: *Dry Cottonwood Creek*; Granite: *Rock Creek*; Judith: *Yogo Gulch*; Lewis and Clark: *American Bar, Dana Bar, Eldorado Bar, Emerald Bar, French Bar, Magpie Gulch, Metropolitan Bar*, and *Spokane Bar* along the Missouri River	Mychaluk (2001), Berg (2004), Garnier et al. (2004a), Berger and Berg (2006), White (2010)
♦ South America	
Brazil	
Minas Gerais—Indaiá, Malacacheta, Manhuaçu, Palmeiras, Sapucaia	Henn and Petsch (2000), Liccardo et al. (2005)
Colombia	
Cauca—Mercaderes: Rio Mayo	Johnson et al. (2000c), Romero-Ordóñez and Rodriguez-Vargas (2002), Duroc-Danner (2003), Sutherland et al. (2008)
GARNET—Almandine/Rhodolite	
♦ Africa	
Ethiopia	
Sidamo—Agere Maryam, Chumba	Quinn and Laurs (2005a)
Kenya	C. Simonet (pers. comm., 2009)
Coast—Chawia, Kamtonga, Kisoli, Kuranze, Mangare, Manoa, Mgama, Mukongonyi, Mwachango: *Kambanga*	
Rift Valley—Kajiado	
Madagascar	Henn and Milisenda (2001), F. Danet (pers. comm., 2009)
Antananarivo—Betafo	
Fianarantsoa—Ambositra, Ankaditany, **Ilakaka**, Ranohira	
Toamasina—Ambatondrazaka, Andreba, Marolambo	Schmetzer et al. (2002c)
Toliara—Ambovombe, Ampanihy, Bekily, Betioky, Betroka, Fotodrevo, **Sakaraha**, Taolagnaro, Tranoroa	Schmetzer et al. (2001,2002b)
Mozambique	J. Marques (pers. comm., 2009)
Niassa—Cuamba: *Cuamba*	
Tanzania	W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009, 2010)
Arusha—Komolo, Merelani Hills	
Kilimanjaro—Hedaru, Mwembe	
Lindi—Namungo	Quinn-Darenius and Laurs (2008)
Manyara—Lelatema Mountains	
Morogoro—Mahenge, Matombo, Mvuha, Uluguru Mountains	
Mtwara—Namaputa	
Ruvuma—Mtetesi River, Muhuwesi River, **Tunduru**	
Tanga—Kalalani, Kigwase, Mwakijembe, **Umba Valley**	Blodgett et al. (2007)
♦ Asia	
Afghanistan	
Kunar—Darra-i-Pech	Quinn and Laurs (2004b)
India	G. Choudhary and J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Bhadrachalam, Chittoor	
Orissa—Angul, Balangir, Deogarh, Kalahandi, Koraput, Phulabani, Nuapada, Sambalpur, Subarnapur	
Rajasthan—Ajmer, Bendria, Bhilwara, Kakaoria, Sangwa, Sarwad, Tonk, Udaipur	
Tamil Nadu—Karur, Madurai, Nilgiri, Salem, Tiruchchirappalli	
Myanmar	
Shan—Mong Hsat	T. Hlaing (pers. comm., 2009)
Russia	
Karelia—Sortavala: *Kitelskoe*	P. Lyckberg (pers. comm., 2009)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Elahera, Kongahawela, Maskeliya, Polonnaruwa	
Sabaragamuwa—Ratnapura	
♦ Europe	
Austria	
Tirol—Ziller Valley	Staebler and Pohwat (2008)
♦ Oceania	
Solomon Islands	
Malaita	Thirangoon (2010)
♦ North America	
Canada	Wilson (2010)
British Columbia—Passmore: *B-Q Claim*	Wilson (2007)
Nunavut—Baffin Island	Wilson (2007)
United States	White (2010)
Alaska—Wrangell Mountains: *Wrangell*	Crawford et al. (2005), Staebler and Pohwat (2008)
Idaho—Benewah: *Emerald Creek*	Ream (2000), Gunter (2008)
♦ South America	
Brazil	
Rio Grande do Norte—Carnaúba dos Dantas: *Marimbondo*	Ferreira et al. (2007)
Tocantins—Peixe: *Fazenda Balisto*	Eeckhout et al. (2004)
GARNET—Andradite/Demantoid	
♦ Africa	
Eritrea	
Northern Red Sea—Sciumagalle	Milisenda and Hunziker (1999), Furuya (2007b)
Madagascar	F. Danet (pers. comm., 2009)
Antsiranana—**Antetezambato**	Danet (2009a), Mocquet et al. (2009), Rondeau and Fritsch (2009), Rondeau et al. (2009b), Schmetzer and Karampelas (2009), Pezzotta (2010), Praszkier and Gajowniczek (2010)
Namibia	
Erongo—near Erongo Mountain, Tubussis: *Green Dragon*	Laurs (2002e), Cairncross and Bahmann (2006a), Fritz et al. (2007c), Furuya (2007b), Stephenson and Kouznetsov (2009)
♦ Asia	
China	Renfro and Laurs (2010)
Iran	
Kerman—Jiroft: *Sogdan*	Laurs (2002f), Douman and Dirlam (2004), Furuya (2007b), Karampelas et al. (2007), Zang (2008a), Stephenson and Kouznetsov (2009)
Japan	
Nara—Tenkawa: *Kouse*	Hainschwang and Notari (2006)
Pakistan	D. Blauwet (pers. comm., 2009)
Baluchistan	Fritz and Laurs (2007b)
Federally Administered Tribal Areas—Bajaur: *Mana*	Milisenda et al. (2001a), Quinn and Laurs (2005b)
Gilgit-Baltistan—Nanga Parbat	Furuya (2007b)
North-West Frontier—Kaghan Valley	Milisenda et al. (2001a), Quinn and Laurs (2005b)

Gem material/locality	Reference
Russia	
Middle Ural Mountains—Nizhniy-Tagil: *Bobrowka River*; Verkhniy Ufaley: *Karkodino, Kladovka, Poldenevaya*	Laurs (2003b), Hochleitner (2005a), Korchevskaya (2006), Furuya (2007b), Zang (2008a), P. Lyckberg (pers. comm., 2009), Stephenson and Kouznetsov (2009)
Turkey	
Erzincan—Erzincan	Inns and Laurs (2009)
♦ Europe	
Italy	
Lombardy—Sondrio: *Malenco Valley*	Zang (2008a), Adamo et al. (2009b), Stephenson and Kouznetsov (2009)
♦ North America	
Canada	Wilson (2010)
Quebec—Black Lake: *Lac D'Amiante*	Wilson (2007), Amabili et al. (2009)
Yukon Territory—Swift River	Wilson (2007)
Mexico	
Sonora—Hermosillo	Boehm (2006)
GARNET—Grossular/ Hessonite/Tsavorite	
♦ Africa	
Kenya	C. Simonet (pers. comm., 2009)
Coast—Chawia, Kamtonga, Kisoli, Kuranze, Mangare, Manoa, Mgama, Mukongonyi, Mwachango: *Kambanga*	Levinson et al. (2001d), Pardieu and Senoble (2005d), Michelou (2006), Pardieu (2008), Pardieu and Hughes (2009), Jang-Green and Beaton (2009)
Rift Valley—Kajiado	
Madagascar	F. Danet (pers. comm., 2009)
Toliara—Behara, Bekily, Berenty, Ejeda, Gogogogo	Henn and Milisenda (2001), Laurs (2003a), Pardieu and Hughes (2009)
Mali	
Kayes–Sandaré	Dameron (2008)
Nigeria	J. Michelou (pers. comm., 2009)
Cross River	
Kogi–Makutu	
Kwara–Babana	
Plateau	
Tanzania	Levinson et al. (2001d), W. Balmer, D. Mantheakis, S. Merisheki, and M. Saul (pers. comm., 2009)
Arusha—Komolo: *Lemeshuko*; Loliondo, Merelani Hills	Pardieu (2007b), Pardieu and Hughes (2009)
Lindi—Mbekenyera, Namungu Hill	Pardieu (2007a), Pardieu and Hughes (2009)
Manyara—Lelatema Mountains, Naberera, Namalulu	Mayerson and Laurs (2004), Pardieu and Hughes (2009), Zang (2008b), Beaton (2009c), Pardieu et al. (2010)
Ruvuma—Mtetesi River, Muhuwesi River, **Tunduru**	Pardieu and Hughes (2009)
Tanga—Kalalani	
♦ Asia	
Afghanistan	
Nuristan—Kantiwa, Munjagal	Laurs and Quinn (2004), Blauwet (2008)
India	J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Nellore	
Jharkhand—Hazaribag	
Karnataka—Hassan, Mysore, Shimoga	
Orissa—Angul, Balangir, Deogarh, Ghatpara, Jharposi, Kalahandi, Koraput, Phulabani	
Rajasthan—Ajmer, Shahpura	
Tamil Nadu—Nilgiri	
Myanmar	
Mandalay—Kume	T. Hlaing (pers. comm., 2009)
Pakistan	
North-West Frontier—Mohmand: *Ungade*	D. Blauwet (pers. comm., 2009)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Sabaragamuwa—Eheliyagoda, Ratnapura	
Southern—Kamburupitiya, Kataragama, Lunugamwehera, Matara, Tanamalwila, Thelioya, Tissamaharama	
Uva—Okkampitiya	
♦ North America	
Canada	Wilson (2010)
Quebec—Asbestos: *Jeffrey*; Bancroft: York River, Black Lake: *Lac d'Amiante*; St.-Denis-de-Brompton: *Orford*	Amabili et al. (2004,2008), Wilson (2007), Horváth and Spertini (2008), Zang (2008b)
♦ South America	
Brazil	
Minas Gerais—Galiléia: *Barra do Cuieté*	Eeckhout et al. (2004)
Paraíba—Santa Luzia: *Água Fria*	Eeckhout et al. (2004), Ferreira et al. (2006)
GARNET—Pyrope	
♦ Africa	
Madagascar	F. Danet (pers. comm., 2009)
Toamasina—Marolambo	
Toliara—Ampanihy, Antaratra, Bekily, Fotodrevo, Sakoandroa, Tranoroa	Schmetzer et al. (2001,2002b), Krzemnicki et al. (2001), Laurs (2003a), Schmetzer (2003)
Tanzania	
Lindi—Namtamba	Laurs and Quinn (2006a)
Tanga—**Umba Valley**	Blodgett et al. (2007)
Zambia	
Eastern—Sangu	Seifert and Vrána (2003)
♦ Asia	
China	Ou Yang (2005)
Heilongjiang—Shuangyashan	Li (2009)
India	J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Bhadrachalam, Chittoor	
Orissa—Angul, Balangir, Deogarh, Kalahandi, Koraput, Phulabani, Sambalpur	
Rajasthan—Bendria, Kakaoria, Sangwa, Sarwad, Udaipur	
Tamil Nadu—Karur, Madurai, Nilgiri, Salem, Tiruchchirappalli	
Mongolia	
Khangai Mountains—Shavryn Tsaram	Dill et al. (2004,2006)
Russia	
Yakutia: Sakha Republic—Mirnyy: *Mir*; Udachnyy: *Udachnaya*	P. Lyckberg (pers. comm., 2009)
♦ Europe	
Czech Republic	Novák (2001), Seifert and Vrána (2005), Kouřimský and Hyršl (2008), Zang and Gilg (2008)
Bohemia—Český Středohoří Mountains: Podsedice	
Moravia—Krkonoše Mountains: Vestřev	
Italy	
Piedmont—Ala Valley, Varaita Valley	Guastoni et al. (2001), Simon (2008)
GARNET—Spessartine	
♦ Africa	
Kenya	
Coast—Kamtonga	Beaton (2009a)
Madagascar	F. Danet (pers. comm., 2009)

Gem material/locality	Reference
Fianarantsoa—Ilakaka	
Mahajanga—Ambohimaranitra	
Toliara—Antaratra, Sakoandroa	
Namibia	
Kunene—**Hartmann Mountains:** *Marienfluss*	Palfi (2005), Staebler (2008), Cook (2010b), Milisenda et al. (2010)
Nigeria	Lind and Henn (2000), J. Michelou (pers. comm., 2009)
Oyo—Komu, Ogbomosho, Iseyin	Michelou (2007), Staebler (2008), Milisenda et al. (2010)
Tanzania	D. Mantheakis and W. Balmer (pers. comm., 2009)
Arusha—Loliondo: *Nani*	Pardieu (2007b), Chadwick et al. (2008a), Staebler (2008), Milisenda et al. (2010)
Iringa	Laurs (2002b)
Lindi—Namtamba	Laurs and Quinn (2006a), Quinn-Darenius and Laurs (2008)
Tanga—Kalalani, Umba Valley	Staebler (2008)
♦ Asia	
Afghanistan	
Kunar—Darra-i-Pech	Quinn and Laurs (2004b)
China	Ou Yang (2005)
Fujian—Tongbei: *Wushan*	Ottens (2004)
Myanmar	
Mandalay—Mogok: *Sakhangyi*	Kyi et al. (2005), N. and R. Schlussel (pers. comm., 2009)
Pakistan	D. Blauwet (pers. comm., 2009)
Azad Kashmir—Neelum Valley: *Donga Nar*	Beesley (2004), Blauwet (2008), Milisenda et al. (2010)
Federally Administered Tribal Areas—Bajaur: *Mana*	Milisenda et al. (2001a), Quinn and Laurs (2005b)
Gilgit-Baltistan—Braldu Valley: *Byanno, Hoh Nala*; Indus Valley: *Shengus*	Blauwet (2008)
♦ North America	
United States	White (2010)
California—San Diego (Ramona): *Little Three*	Laurs and Knox (2001), Staebler (2008), Milisenda et al. (2010)
♦ South America	
Brazil	
Minas Gerais—Conselheiro Pena: *Navegador*; Galiléia: *Barra do Cuieté, Escondido*; São José da Safira: Poaia	Eeckhout et al. (2002, 2004), L. Barbosa and J. Hyršl (pers. comm., 2009), White (2009)
Rio Grande do Norte—Carnaúba dos Dantas: *Alto Mirador, Pedra Bonita*; Marimbondo	Eeckhout et al. (2002, 2004), Ferreira et al. (2007)
Tocantins—Peixe: *Fazenda Balisto*	Eeckhout et al. (2004), L. Menezes (pers. comm., 2009)
GARNET—Uvarovite	
♦ Asia	
China	
Tibet—Bo Mi: *Yi Gong*	He et al. (2000)
Russia	
Middle Ural Mountains—Perm: *Saranovskoye*	Burlakov and Avdonin (2006), P. Lyckberg (pers. comm., 2009)
JADE—Jadeite	
♦ Asia	
Iran	
Hormozgan—Sorkhan	Oberhänsli et al. (2007)
Japan	
Niigata—Omi: Himekawa, Kotaki, and Omi Rivers	Chihara (1999), Harlow and Sorensen (2001), Morishita et al. (2007)
Myanmar	Hughes et al. (2000), Qiu et al. (2008), Shi et al. (2009a,b,2010)
Kachin—**Hpakant**	Harlow and Sorensen (2001), Levinson et al. (2001b), Ou Yang (2001a,b), Shi et al. (2003, 2005), T. Hlaing (pers. comm., 2009)
Sagaing—**Hkamti**	Levinson et al. (2001b), P. Hlaing (pers. comm., 2009)
Russia	V. Zboykov (pers. comm., 2009)
Northern Ural Mountains—Ketchpel River	Harlow and Sorensen (2001)
Siberia—Sayan Mountains: *Borusskoye*; Vitim River	Harlow and Sorensen (2001), Adams and Beck (2009)
Turkey	
Bursa—Orhaneli	Okay (2002)
♦ Europe	
Italy	
Piedmont—Po Valley	Adamo et al. (2006)
♦ North America	
Cuba	
Guantanamo—Sierra del Convento	García-Casco et al. (2009)
Guatemala	
El Progreso—**Motagua Valley:** *Manzanal*	Harlow and Sorensen (2001), Cleary and Rohtert (2002), Gendron et al. (2002), Miller (2002), Sisson (2002), Harlow et al. (2004), Marroni et al. (2009), Simons et al. (2010), Yui et al. (2010)
JADE—Nephrite	
♦ Asia	
China	Harlow and Sorensen (2001), He (2001), Ou Yang (2005), Smith et al. (2005), Michelou (2006), Li (2009), X. Yuan (pers. comm., 2009)
Jiangsu—Suyang	
Liaoning—Xiuyan	
Qinghai/Gansu—Qilian Mountains	Li (2005)
Sichuan—Wenxi	
Xinjiang Uygur—**Kunlun Mountains:** Yutian	Harlow and Sorensen (2001), Li (2005)
Taiwan—**Fengtien**	Adams and Beck (2009)
Russia	V. Zboykov (pers. comm., 2009)
Siberia—**Sayan Mountains**, Vitim River, Zakamensk	Harlow and Sorensen (2001), Lapot (2004)
South Korea	
Chuncheon	Yui and Kwon (2002), Kim (2007)
♦ Australia	Brown (2002), Sutherland (2006)
South Australia—**Cowell**	Nichol (2000), Harlow and Sorensen (2001), Adams and Beck (2009)
New Zealand	Harlow and Sorensen (2001)
South Island—Arahura River, Caples, Dun Mountain, Maitai River, Mount Torlesse, Taramakau River	Wilkins et al. (2003), Adams et al. (2007)
♦ Europe	
Finland	
Itä-Suomen—Paakkila	Nichol (2004)
Etelä-Suomen—Hakkila, Stansvik	Nichol (2004)
Italy	
Liguria—Sestri Levante	Nichol (2003)
Lombardy—Mastabia	Nichol and Giess (2005a)
Poland	
Wroclaw—Jordanów Slaski	Nichol (2001)
Switzerland	
Graubünden—Faller Valley: *Mulegns*; Poschiavo Valley: *Scortaseo*	Nichol and Giess (2005b,c)

Gem material/locality	Reference
♦ Oceania	
New Caledonia—Tiwaka River	Adams and Beck (2009)
♦ North America	
Canada	Wilson (2010)
British Columbia—Cassiar, Cry Lake, Dease Lake, Mount Ogden	Nichol (2000), Harlow and Sorensen (2001), Simandl et al. (2001), Makepeace and Simandl (2004), Kim (2007), Adams and Beck (2009)

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♦ Africa	
Ethiopia	Gaillou et al. (2008)
Shewa—Mezezo	Mazzero (2003), Gauthier et al. (2004a), Tucci (2005), Staebler and Neumeier (2007)
Wollo—Wegel Tena	Mazzero et al. (2009), Rondeau et al. (2009a)
Madagascar	Simoni and Caucia (2009)
Toliara—Beraketa, Tsivory	Holzhey (2000), Henn and Milisenda (2001)
Somalia	
Jodha—Qabri Baxar	Kinnaird (2002)
♦ Asia	
Indonesia	
Java—Jawa Barat: *Banten, Labak*	Laurs (2001b), Milisenda and Wild (2004), Sujatmiko et al. (2004,2005), Staebler and Neumeier (2007), Sun et al. (2009)
Iran	
Kerman—Shahr-e-Babak	Nagle (2007)
Myanmar	
Mandalay—Natogyi	T. Hlaing (pers. comm., 2009)
Sri Lanka	
Uva—Wellawaya	G. Zoysa (pers. comm., 2009)
Turkey	
Anatolia—Kütahya: *Simav*	Esenli et al. (2001,2003), Mutlu et al. (2005), Fischer (2007), Hatipoğlu (2009)
♦ Australia	Townsend (2001), Brown (2002), Horton (2002), Sutherland (2006), Thiry et al. (2006), Pecover (2007), Gaillou et al. (2008)
New South Wales—**Lightning Ridge**, **White Cliffs**	Thomas et al. (2006), Frasier and Frasier (2007), Smith (2007), Roskin (2008)
Queensland—Bulgroo, Davenport-Palpara, Eromanga, Jundah, Koroit, Kynuna, **Opalton**, **Quilpie**, Toompine, Yaraka, **Yowah**	Cooper and Neville (2007)
South Australia—**Andamooka**, **Coober Pedy**, **Lambina**, **Mintabie**, Stuart Creek	Townsend (2006,2009), Cody (2007), R. Coenraads (pers. comm., 2009)
♦ Europe	
Hungary	
Zemplén Mountains	Rondeau et al. (2004)
Slovakia	
Košice—Prešov: *Dubník*	Huber (2007)
♦ North America	
Canada	Wilson (2010)
British Columbia—Vernon: *Klinker*	Downing (2003), Wilson (2005), Michelou (2006), Gaber (2007)
Honduras	Banerjee and Wenzel (1999), Vogt (2004), Michelou (2006), Dabdouh (2007), Gaillou et al. (2008)
Gracias—San Antonio	Viti and Gemmi (2009)
Lempira—Erandique: *San Andres, Tablon*; Sosual: *Las Colinas*	
Mexico	Fritsch et al. (2002b), Cruz-Ocampo et al. (2007), Schütz (2007), Gaillou et al. (2008)
Hidalgo—Zimapán: *Leopard*	Coenraads and Zenil (2006)
Jalisco—Magdalena	Michelou (2006)
Querétaro	Michelou (2006)
United States	Gaber (2007), White (2010)
Louisiana—Vernon	
Mississippi—Claiborne	
Nevada—Humboldt: *Virgin Valley*; Pershing: *Black Rock Desert*	Castor and Henry (2000), Clark (2005), Huber (2008)
Oregon—Lake: *Juniper Ridge*; Morrow: *Opal Butte*	Laurs and Quinn (2003)
Wyoming—Granite Mountains	
♦ South America	
Argentina	Fritsch et al. (2009)
Brazil	Pinto and Pedrosa-Soares (2001), Caucia et al. (2008b), Gaillou et al. (2008)
Bahia	Hyršl (2002a)

The diversity of colored stones mined during the 2000s is shown in these butterfly brooches. Top—Vietnamese spinel (8.47 ct in body) with Namibian jeremejevite for the eyes; center—natural pearls from Mexico's Sea of Cortez (11.77 ct), with "rainbow" feldspars from Madagascar and diamonds in the wings, and Colombian emeralds for the eyes; and bottom—sphene from Madagascar (center stone 13.83 ct) with haüyne from Germany for the eyes. Courtesy of Bernadine Johnston and Buzz Gray; photo by Robert Weldon.

Gem material/locality	Reference
Pará—São Geraldo do Araguaia	Collyer and Kotschoubey (2000), Gauthier et al. (2004b), Farrar (2007)
Piauí—**Pedro II:** *Boi Morto*	Hyršl (2002a), Laurs (2007a), Caucia et al. (2009)
Peru	Gaillou et al. (2008)
Arequipa—Nazca: *Acari*	Hyršl (2001a,2007), Quinn and Laurs (2003), Henn (2006a), Brajkovic et al. (2007), Caucia et al. (2008a)
Ica—Ica: *Monte Rosa*	Hyršl (2006)
PERIDOT (Olivine)	
♦ **Africa**	
Egypt	
Red Sea—Zabargad Island	Brooker et al. (2004)
♦ **Asia**	
China	Liu (2004), Ou Yang (2005), Smith et al. (2005), Michelou (2006), X. Yuan (pers. comm., 2009)
Hebei—Zhangjiakou: *Damaping*	Henn (1999), Li (2009)
Jilin—Jiaohe	
Mongolia	
Khangai Mountains—Shavryn Tsaram	Dill et al. (2004,2006)
Myanmar	
Mandalay—**Bernardmyo**	Krzemnicki and Groenenboom (2008), T. Hlaing (pers. comm., 2009)
Pakistan	
North-West Frontier—**Kohistan:** *Sapat*	Hammer (2004c), Bouilhol et al. (2009)
Russia	
Kola Peninsula—Kovdor	Sokolov et al. (2006)
Sri Lanka	
Sabaragamuwa—Kolonne	Graziani et al. (2002), G. Zoysa (pers. comm., 2009)
Tajikistan	
Kuhistoni-Badakhshon—Pamir Mountains: *Kuh-i-Lal*	Kondo (2008)
Vietnam	
Gia Lai—Bien Ho, Ham Rong	Pham et al. (2004a), D. Blauwet (pers. comm., 2009)
♦ **Europe**	
Italy	
Sardinia—Pozzomaggiore	Adamo et al. (2009a)
♦ **North America**	
Canada	Wilson (2010)
British Columbia—Cherryville, Hendrix Lake, Lumby, Williams Lake	Wilson (2005, 2007)
United States	
Arizona—**Gila:** *San Carlos*	White (2010)
QUARTZ—Amethyst/Citrine/Ametrine	
♦ **Africa**	
Democratic Republic of the Congo	Fritz and Laurs (2007a)
Kenya	
Eastern—Kitui	C. Simonet (pers. comm., 2009)
Madagascar	Henn and Milisenda (2001), F. Danet (pers. comm., 2009)
Antananarivo—Andongologo, Bevitsika Mountain, Mahasolo, Soavinandriana	Danet (2009)
Antsiranana—Ambakirano, Andapa	
Fianarantsoa—Ambatofinandrahana, Ambositra, Isahara, Mangataboahangy, Vondrozo, Vorondolo	Pezzotta (2001e)
Mahajanga—Boriziny, Tsaratanana	
Toamasina—Antanimbohibe, Didy, Vatomandry	
Toliara—Ifotaka	E. Granon (pers. comm., 2009)
Morocco	
Tata—Tata	Beaton (2009b)
Mozambique	J. Marques (pers. comm., 2009)
Nampula—Namapa: *Namapa*	
Tete—Zumbo: *Catizane River*	
Zambézia—Alto Molócuè: *Molócuè*; Milange: *Milange*; Murrua	Bettencourt-Dias and Wilson (2000)
Namibia	G. Schneider (pers. comm., 2009)
Erongo—Erongo Mountains, Goboboseb Mountains, Otjiwarongo: *Platveld*	Cairncross and Bahmann (2006a), Michelou (2006)
Kunene—Namib Desert: *Sarusas*	Laurs (2005a)
Nigeria	Michelou (2006,2007)
Bauchi	
Cross River	
Gombe	
Kaduna	
Kano	
Oyo	
Taraba—Jalingo	Laurs and Koivula (2003)
Zambia	C. Milisenda (pers. comm., 2009)
Central—Mumbwa	
Southern—**Kalomo:** *Mapatizya*	Milisenda et al. (2001c), Anckar (2006)
Zimbabwe	
Bulawayo—Nyamandlovu: *Chikodzi, Manzinyama*	L. F. Marsh and F. Mutugumbate (pers. comm., 2009)
♦ **Asia**	
Afghanistan	
Ghazni—Zarkishen Mountain: Moqor	Laurs (2002g)
Russia	P. Lyckberg (pers. comm., 2009)
Far East—Magadan: *Kedon*	
Northern Ural Mountains—Khasavarka	
Middle Ural Mountains—Yekaterinburg: *Aduy*	
Yakutia (Sakha Republic)—Aldan: *Obman*	
South Korea	
Kangwŏn—Eonyang	Yang et al. (2001)
♦ **North America**	
Canada	
Ontario—**Thunder Bay**	Garland (2004), Kerr (2006), Wilson (2007,2010)
Mexico	
Guerrero—Amatitlan	Ontiveros et al. (2004)
United States	White (2010)
Arizona—Maricopa: *Four Peaks*	Lowell and Koivula (2004)
Georgia—Wilkes: Jackson's Crossroads	Laurs (2005b), Bowling et al. (2005)
♦ **South America**	
Bolivia	
Santa Cruz—**Sandoval:** *Anahí, Ayoreita, Mina Pobre*	Laurs (2001g,2010a), Hyršl and Petrov (2009), Weldon (2009)
Brazil	Pinto and Pedrosa-Soares (2001)
Bahia—Caetité: *Brejinho das Ametistas*	Couto (2000)
Minas Gerais—Coronel Murta-Itinga: *Jenipapo, Morro Redondo, Piauí*; Galiléia-Conselheiro Pena-São Geraldo do Baixio: *Macaco, Sapo*	Macrì et al. (2006)
Pará—**Marabá:** *Alto Bonito*; **Pau d'Arco:** *Villa Esperança*	
Rio Grande do Sul—**Paraná Basin**	Mossman and Juchem (2000), Gilg et al. (2003), Proust and Fontaine (2007a,b), Duarte et al. (2009), Commin-Fischer et al. (2010)

Gem material/locality	Reference
Uruguay	
Artigas—**Artigas**	Gilg et al. (2003), Michelou (2006), Duarte et al. (2009), Morteani et al. (2009)

QUARTZ—Rose

♦ Africa

Madagascar	Henn and Milisenda (2001), F. Danet (pers. comm., 2009)
Antananarivo—Ambohimanitra, Antsirabe, Betafo, Faratsiho, Mahaiza, Tsiroanomandidy	Pezzotta (2001c)
Fianarantsoa—Ambositra	
Toamasina—Ambatomafana, Ambatondrazaka, Analangoaika, Antanimenabaka, Didy, Lakato, Moramanga, Ranomafana, Sahaviavy Fito	E. Granon (pers. comm., 2009), R. Gobert (pers. comm., 2009)
Mozambique	
Zambézia—Alto Molócué: *Naquilite, Naquissupa, Nuaparra*	Bettencourt-Dias and Wilson (2000)

♦ Asia

India	J. Panjikar and A. Dholakia (pers. comm., 2009)
Chhattisgarh—Raipur	
Maharashtra—Aurangabad	
Rajasthan	
Tamil Nadu—Kangayam, Karur, Salem	
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Kaikawala, Matale	
Southern—Galle	Schmetzer and Glas (2003)

♦ South America

Brazil	Pinto and Pedrosa-Soares (2001)
Minas Gerais—Sapucaia	Wilson (1999)
Rio Grande do Norte—Carnaúba dos Dantas: *Taboa*; Parelhas	Barreto et al. (2009), B. Cook (pers. comm., 2009)

SPINEL

♦ Africa

Kenya	
Coast—Rukanga	C. Simonet (pers. comm., 2009)
Madagascar	Henn and Milisenda (2001)
Fianarantsoa—**Ilakaka**	Schmetzer (2000), Milisenda et al. (2001b), Pezzotta (2001f,g,h)
Tanzania	Michelou (2006), W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009, 2010)
Arusha—Komolo	S. Merisheki (pers. comm., 2009)
Morogoro—Chipa, **Epanko**, **Kituti**, **Mahenge**, Matombo, **Mbarabanga**, Mvuha, Uluguru Mountains	Hyršl (2001b), Quinn and Laurs (2004d), Pardieu and Senoble (2005e), Laurs (2006), Pardieu and Hughes (2008)
Mtwara—Lumesule River	
Ruvuma—Mtetesi River, Muhuwesi River, Tunduru	Pardieu and Senoble (2005e), Pardieu (2007a)

♦ Asia

Afghanistan	Hammer (2003b)
China	Liu (2004), Ou Yang (2005)
Yunnan—Ailaoshan Mountains, Jingping, Yuanjiang, Yuanyang	Laurs and Shigley (2005), B. Ottens (pers. comm., 2009)
India	
Orissa	
Tamil Nadu—Kangayam, Karur, Tiruchchirappalli	G. Choudhary (pers. comm., 2009)
Laos	
Bokeo—Ban Houayxay	Michelou (2006)
Myanmar	M. Smith, K. Thu, and T. Hlaing (pers. comm., 2009)
Kachin—**Nanyaseik**	Smith and Bosshart (2001), Hlaing and Win (2008), Pardieu and Hughes (2008)
Kayah—Pawn Chaung	Hlaing (2004)
Mandalay—**Mogok**	Pardieu and Hughes (2008)
Pakistan	D. Blauwet (pers. comm., 2009)
Gilgit-Baltistan—Hunza Valley: *Ganesh, Hassanabad, Muchara Nala*	Hammer (2004a)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Elahera	Dissanayake et al. (2000)
Sabaragamuwa—Balangoda, Eheliyagoda, Embilipitiya, Kuruwita, Rakwana, Ratnapura	Dissanayake et al. (2000)
Southern—Kataragama	
Uva—Okkampitiya	
Western—Kiriella, Horana	
Tajikistan	
Kushistoni-Badakhshon—**Pamir Mountains:** Kuh-i-Lal	Pardieu and Hughes (2008), P. Lyckberg (pers. comm., 2009)
Vietnam	Pham et al. (2004a), D. Blauwet (pers. comm., 2009)
Nghe An—Qui Chau	
Yen Bai—An Phu, **Luc Yen**, Tan Huong, Thac Ba, Truc Lau	Pardieu and Senoble (2005a), Blauwet (2006a), Pardieu and Hughes (2008

♦ North America

Mexico	
Nayarit—Acaponeta	Rohtert (2002a)

TOPAZ

♦ Africa

Madagascar	Henn and Milisenda (2001), F. Danet (pers. comm., 2009)
Antananarivo—Faratsiho	
Antsiranana—Andapa	
Fianarantsoa—Ambositra, Ilakaka, Isahara	Milisenda et al. (2001b), Pezzotta (2001f,g,h)
Mozambique	J. Marques (pers. comm., 2009)
Tete—Marávia: *Marironguè*	
Zambézia—Gilé: *Naipa*	
Namibia	
Erongo—Klein Spitzkoppe	Cairncross (2005b), Haapala et al. (2007), G. Schneider (pers. comm., 2009)
Nigeria	Michelou (2006,2007), J. Michelou (pers. comm., 2009)
Bauchi—Magama	
Plateau—Bomo	
Nassarawa—Shabu	
Zambia	
Copperbelt—Karengerenge	S. Vrána (pers. comm, 2009)
Zimbabwe	L. F. Marsh and F. Mutugumbate (pers. comm., 2009)
Mashonaland West—Guruwe: *Dungusha*; Mwami: *Gwati, Saint Ann's, Topaz*	
Midlands—Somabhula	

♦ Asia

Afghanistan	D. Blauwet (pers. comm., 2009)
Nuristan—Paprowk	
China	Liu (2004), Ou Yang (2005), Smith et al. (2005)
Inner Mongolia—Alaxianzuanqi	Li (2009)
Jiangxi—Dayu: *Piaotang*	B. Ottens (pers. comm., 2009)
Yunnan—Yingjiang: Gaoligongshan Mountains	Wu (2004), X. Yuan (pers. comm., 2009)

Gem material/locality	Reference
Xinjiang—Altai Mountains: *Koktokay*	B. Ottens (pers. comm., 2009)
India	G. Choudhary and J. Panjikar (pers. comm., 2009)
Orissa—Balangir, Boudh, Subarnapur	
Tamil Nadu—Kangayam, Kanniyakumari, Karur, Tirunelveli	Sarkar and Guru (2010)
West Bengal—Singhbhum	
Myanmar	M. Smith, K. Thu, and T. Hlaing (pers. comm., 2009)
Mandalay—Kume, Mogok: *Sakhangyi*	Kyi et al. (2005), Hlaing (2009a)
Shan—Molo: *Katchay*	
Pakistan	D. Blauwet (pers. comm., 2009)
Gilgit-Baltistan—Basha Valley: *Sibiri*; Braldu Valley: *Apo Ali Gun, Baha, Chhappu, Dassu, Goiyngo Foljo, Gone, Nyet, Nyet Bruk, Teston*; Hunza Valley: *Hassanabad*; Indus Valley: *Baluchi, Chhamachhu, Drot, Ishkapul, Kaotoonery, Khargulook, Sabsar, Saischais, Sassi, Shengus*; Shigar Valley: *Haiderabad, Mungo, Yuno*	Hammer and Muhammad (2004), Blauwet (2004), Blauwet and Muhammad (2004)
North-West Frontier—Katlang: *Ghundao Hill*	Einfalt (2002), Hammer (2004c), Morteani and Voropaev (2007)
Russia	P. Lyckberg (pers. comm., 2009)
Middle Ural Mountains—Yekaterinburg: *Alabashka*	
Southern Ural Mountains—Plast: Kamenka and Sanarka Rivers	
Transbaikalia—Borzya: *Sherlova Gora*	
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Elahera, Nawalapitiya, Polonnaruwa, Rattota	
Sabaragamuwa—Balangoda, Ratnapura	
Vietnam	Pham et al. (2004a), D. Blauwet (pers. comm., 2009)
Lam Dong—Bao Lac	
Thanh Hoa—Xuan Le	
Yen Bai—Tu Le	
♦ North America	
Canada	
British Columbia—Atlin, Mount Foster	Wilson (2007,2010)
Yukon Territory—Swift River, Teslin	Wilson (2007,2010)
United States	White (2010)
California—San Diego (Ramona): *Little Three*	Fisher (2002,2008)
Colorado—Park: *Topaz Mountain*	
New Hampshire—Carroll, Coos	
♦ South America	
Brazil	Pinto and Pedrosa-Soares (2001), L. Barbosa and J. Hyršl (pers. comm., 2009)
Minas Gerais—Caraí, Itinga, Medina, Nova Era, **Ouro Prêto:** *Antonio Pereira, Boa Vista, Capão, Dom Bosco, Vermelhão*; Catuji-Padre Paraíso: *Marambaia*; Pedra Azul, Virgem da Lapa	Mossman (2001), da Costa et al. (2000), Morteani et al. (2002), Schott et al. (2003), Ferreira et al. (2005), Sapalski-Roselló (2005)
Rondônia—Massangana River	

TOURMALINE

Gem material/locality	Reference
♦ Africa	
Democratic Republic of Congo	
Nord-Kivu—Virunga, Walikale	Laurs et al. (2004), Michelou (2006)
Kenya	C. Simonet (pers. comm., 2009)
Coast—Kamtonga, Kisoli, Kuranze, Lasamba Hill, Mangare: *Rockland (John Saul), Yellow*; Mgama, Mukongonyi, Mwachango: *Kambanga*; Mwakinsunzuru, Ngombeni	Simonet (2000,2006)
Rift Valley—Narok: *Osarara*	
Madagascar	Henn and Milisenda (2001), Glas (2002), F. Danet (pers. comm., 2009), Scovil (2010)
Antananarivo—Anjanabonoina, Antandrokomby, Antsikoza, Antisirabe, Betafo, Manjaka, Mount Bity, Vohitrakanga	Laurs (2000), Pezzotta (2001b), Dirlam et al. (2002), De Vito et al. (2006), Danet (2007), Praszkier (2010)
Fianarantsoa—Alakamisy Itenina, Ambatofinandrahana, Ambatovita, Bevaondrano, Ilakaka, Isahara, Valozoro	Milisenda et al. (2001b), Danet (2006), Pezzotta (2001f,g,h,2006)
Toamasina—Ambatondrazaka	
Toliara—Taolagnaro	Pezzotta and Jobin (2004)
Mozambique	Glas (2002), Rondeau and Delaunay (2007), J. Marques (pers. comm., 2009)
Cabo Delgado	Fritz et al. (2007a)
Manica—Nhampassa, Pataguenha	
Nampula—Nametil: *Mogovolas*; Moma: *Mavuco*; Nacala-a-Velha: *Nacala*	
Tete—Marávia: *Marironguè*	
Zambézia—Alto Molócuè: *Namacotche*; Gilé: *Muhano, Naípa*; Mocuba, Muiane, Naquissupa	Bettencourt-Dias and Wilson (2000) Schäfer and Arlt (2000), Abduriyim and Kitawake (2005), Schappmann (2005), Abduriyim et al. (2006), Michelou (2006), Milisenda et al. (2006), Laurs and Zwaan (2007), Laurs et al. (2008a,b), Neves (2009), Pardieu et al. (2009d)
Namibia	Jahn et al. (2001), Glas (2002)
Erongo—Eausiro, Kubas, Neu Schwaben, Omapyo, Otjua, Uis, Usakos	Keller et al. (1999), Laurs (2002a), Mossman (2002), Rustemeyer and Deyer (2003), Trumbull et al. (2008), G. Schneider (pers comm., 2009)
Nigeria	Glas (2002), Laurs et al. (2002a,b), Michelou (2006,2007), Breeding et al. (2007), Rondeau and Delaunay (2007), Laurs (2009a), J. Michelou (pers. comm., 2009)
Ekiti—Ijero Ekiti	
Jigawa	
Kaduna—Kagarko	
Kwara—Babana, Lemo, Ndeji, Ora, Oro	
Nassarawa—Akwandoka, Garantu, Keffi	Michelou (2008-2009). Befi et al. (2009)
Niger—Kontagora, Pandogari, Sarkin Pawa	
Oyo—Are, Budo, Ilorin: *Edeko*; Iseyin, Itasa, Komu, Ogbomosho	Henn (2001), Laurs (2001c, 2009c), Milisenda and Henn (2001), Smith et al. (2001), Laurs et al. (2002a,b), Abduriyim et al. (2006)
Zamfara	
Tanzania	Glas (2002), W. Balmer, D. Mantheakis, and M. Saul (pers. comm., 2009)
Arusha—Landanai	Pardieu (2007b)
Manyara—Lengasti	Simonet (2006), S. Merisheki (pers. comm., 2009)
Morogoro—Mkuyuni, Uluguru Mountains	Quinn and Laurs (2006b)
Tanga—Daluni, Mnazi	
Zaire	
Katanga—Manono	Glas (2002)
Zambia	Glas (2002)
Central—Kabwe: *Jagoda, Kumanga*; Mkushi	Milisenda et al. (2000), Laurs (2004c)
Eastern—**Lundazi:** *Aries, Canary, Kalungabeba*; Nyimba: *Hofmeyer*	Milisenda et al. (2000), Laurs (2004c), Laurs et al. (2007,2009)
Zimbabwe	L. F. Marsh and F. Mutugumbate (pers. comm., 2009)
Mashonaland West—Mwami: *Gwati, Saint Ann's*	Glas (2002)
Matabeleland South—Gwanda	
♦ Asia	
Afghanistan	D. Blauwet (pers. comm., 2009)

Gem material/locality	Reference
Nuristan—Chatrus, Diwaneh Baba, Gamitha, Golmata, Kalaigal, Kanalook, Kantiwa, Kurgal, Konquwa, Masey, Mawi, Nilaw-Kolum, Nishai, Papra, Paprowk, Rhodisht, Wama	Glas (2002), Natkaniec-Nowak et al. (2009)
Kunar—Gur-Salak, Kala, Khana-Khana, Paroon Valley	
China	Liu (2004), Ou Yang (2005), Smith et al. (2005), Michelou (2006), X. Yuan (pers. comm., 2009)
Guangxi—Huangbao	Glas (2002)
Inner Mongolia—Jiaoligetai	Glas (2002)
Shanxi—Wutaishan Mountains, Yunzhongshan Mountains	Glas (2002)
Sichuan—Kangding, Wenchuan, Xiaojin	
Yunnan—Gaoligongshan Mountains: *Fugong, Gongshan, Lushui*	Wu (2004)
Xinjiang Uygur—Altai Mountains: *Koktokay*	Tang et al. (2004), Wang et al. (2007), Zhang et al. (2008), Li (2009)
India	G. Choudhary and J. Panjikar (pers. comm., 2009)
Andhra Pradesh—Araku Valley, Borra, Vishakhapatnam	Sarkar and Guru (2010)
Orissa—Boudh, Jharsuguda, Sambalpur	
Myanmar	Kane (2002), T. Hlaing (pers. comm., 2009)
Karen	
Kayah—Pawn Chaung	Hlaing (2008)
Mandalay—Singu: *Letpanthla*	Hlaing (2007)
Shan—Makmai, Molo, Mong Hsu, Mong Long, Mong Pan, Momeik	Glas (2002), Kyi et al. (2005)
Pakistan	Obodda (2003), Hammer and Muhammad (2004), Blauwet (2004), Blauwet and Muhammad (2004), D. Blauwet (pers. comm., 2009)
Azad Kashmir—Neelum Valley: *Dongar Nar*	Beesley (2004)
Gilgit-Baltistan—Astore Valley: *Harchoo Nirai, Mir Malik, Nanga Parbat*; Braldu Valley: *Dassu, Hoh Nala, Tosho*; Hunza Valley: *Nagar*; Indus Valley: *Baluchi, Baralooma, Gochalay, Kaotoonery, Khargulook, Shengus, Stak Nala*	Laurs (2001d), Glas (2002)
Russia	
Transbaikalia—Chita: *Adun-Chilon, Borschevochniye Mountains, Sherlova Gora;* Krasnyy Chikoy: *Malkan Mountains*	Simmons et al. (2001), Glas (2002), Smirnov et al. (2003), Peretyazhko et al. (2004), Hochleitner (2005b), Lyckberg (2005b), Zagorsky et al. (2005), Zagorsky and Peretyazhko (2006), Badanina et al. (2008), Zagorsky (2010)
Sri Lanka	G. Zoysa (pers. comm., 2009)
Central—Badulla, Elahera, Passara, Polonnaruwa	
Sabaragamuwa—Balangoda, Embilipitiya, Kolonne, Ratnapura	
Uva—Okkampitiya	
Western—Avissawella	
Vietnam	
Yen Bai—An Phu, Khai Trung, Luc Yen, Minh Tien, Tan Lap	Pham et al. (2004a), D. Blauwet (pers. comm., 2009)
♦ North America	
Canada	
Northwest Territories—O'Grady Lake	Ercit et al. (2003), Wilson (2007, 2010)
United States	White (2010)
California—San Diego–Pala: *Pala Chief, Stewart*, Ramona: *Little Three*; Warner Springs: *Cryo-Genie*	Morgan and London (1999), Laurs (2001f, 2001i, 2002j, 2004b), Simmons et al. (2001), Fisher (2002,2008), Swoboda and Larson (2006), Symons et al. (2009), Ertl et al. (2010)
Maine—Oxford: Mount Apatite, *Mount Mica, Newry, Paris*	Simmons et al. (2001,2005a,b), Freeman (2005), Laurs and Freeman (2005)
♦ South America	
Brazil	César-Mendes et al. (2001), Pinto and Pedrosa-Soares (2001), Neves (2009)
Ceará—Solonópole-Quixeramobim	
Minas Gerais—Araçuaí-Itinga-Santa Clara: *Baixão, Jenipapo, Piauí, Pirineus, Teixeirinha, Urubú*; Coronel Murta: *Aqua Branca, Barra de Salinas, Baixa Grande, Lavrinha, Lorena, Morro Redondo, Ouro Fino, Paineira, Pau Alto*; Salinas: *Salinas*; Virgem da Lapa: *Campinho, Manoel Mutuca*; Conselheiro Pena-Divino das Laranjeiras-Governador Valadares-Galiléia: *Jairo, Pamaro, Sapo*; Malacacheta–Franciscópolis-Resplendor-Santa Rosa: *Mutuca, Nova Santa Rosa*; São José da Safira-Agua Boa; *Aricanga, Chiá, Cruzeiro, Pederneira, Santa Rosa*	Bilal et al. (2000), Mossman (2001), Bastos (2002), Karfunkel et al. (2002), Steger (2006), Viana et al. (2007), Menezes (2009)
Paraíba—Frei Martinho: *Alto Quixaba*; Pedra Lavrada: *Serra Branca*; Salgadinho: *Mina da Batalha, Mineração Batalha*	Shigley et al. (2001b), Cook (2002), Wilson (2002), Ferreira et al. (2005), Abduriyim et al. (2006), Michelou (2006), Furuya (2007a), Beurlen et al. (2009a,b)
Rio Grande do Norte—Parelhas: *Alto da Cabeça, Bulandeira, Mulungu (Boqueirãozinho/Capoeira), Quintos do Baixo*	Johnson et al. (2000b), Laurs and Shigley (2000), Shigley et al. (2001b), Milisenda (2005), Abduriyim et al. (2006), Baumgartner et al. (2006), Michelou (2006), Furuya (2007a), Soares et al. (2008), Beurlen et al. (2009a,b)

ZOISITE (Includes tanzanite)

♦ Africa	
Tanzania	
Arusha—**Merelani Hills**	Malisa (2003), Scheepers and Scheepers (2003), Pardieu and Senoble (2005e), Zancanella (2004,2006,2007), Smuts (2005), Michelou (2006), Pardieu (2007b), Giuliani et al. (2008), Pardieu et al. (2009a), Wilson et al. (2009), Schroeder (2010)
♦ Asia	
Afghanistan	
Nuristan—Shinwari	Beaton and Lu (2009)
Pakistan	D. Blauwet (pers. comm., 2009)
Gilgit-Baltistan—Shigar Valley: Alchuri	Blauwet (2006b)

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ACKNOWLEDGMENTS

The authors greatly appreciate the numerous individuals who supplied information for the gem locality tables regarding particular gem materials found in their respective countries. Please see the G&G Data Depository for a complete listing. Also see the Depository for a complete list of references.

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Key to abbreviations: *Gems & Gemology* = *G&G*; *Jewelers' Circular-Keystone* = *JCK*; *Revue de Gemmologie a.f.g.* = *Rev. de Gem.*

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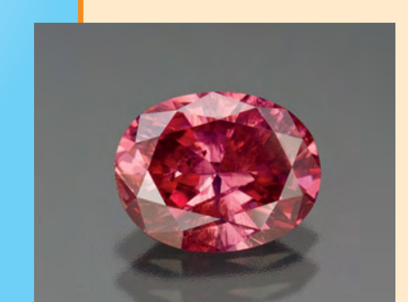
MAJOR WORLD GEM PRODUCING REGIONS

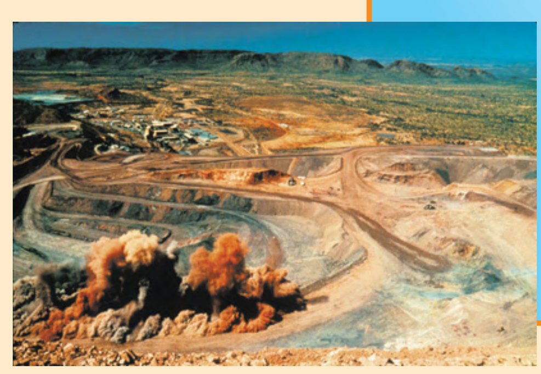
GIA

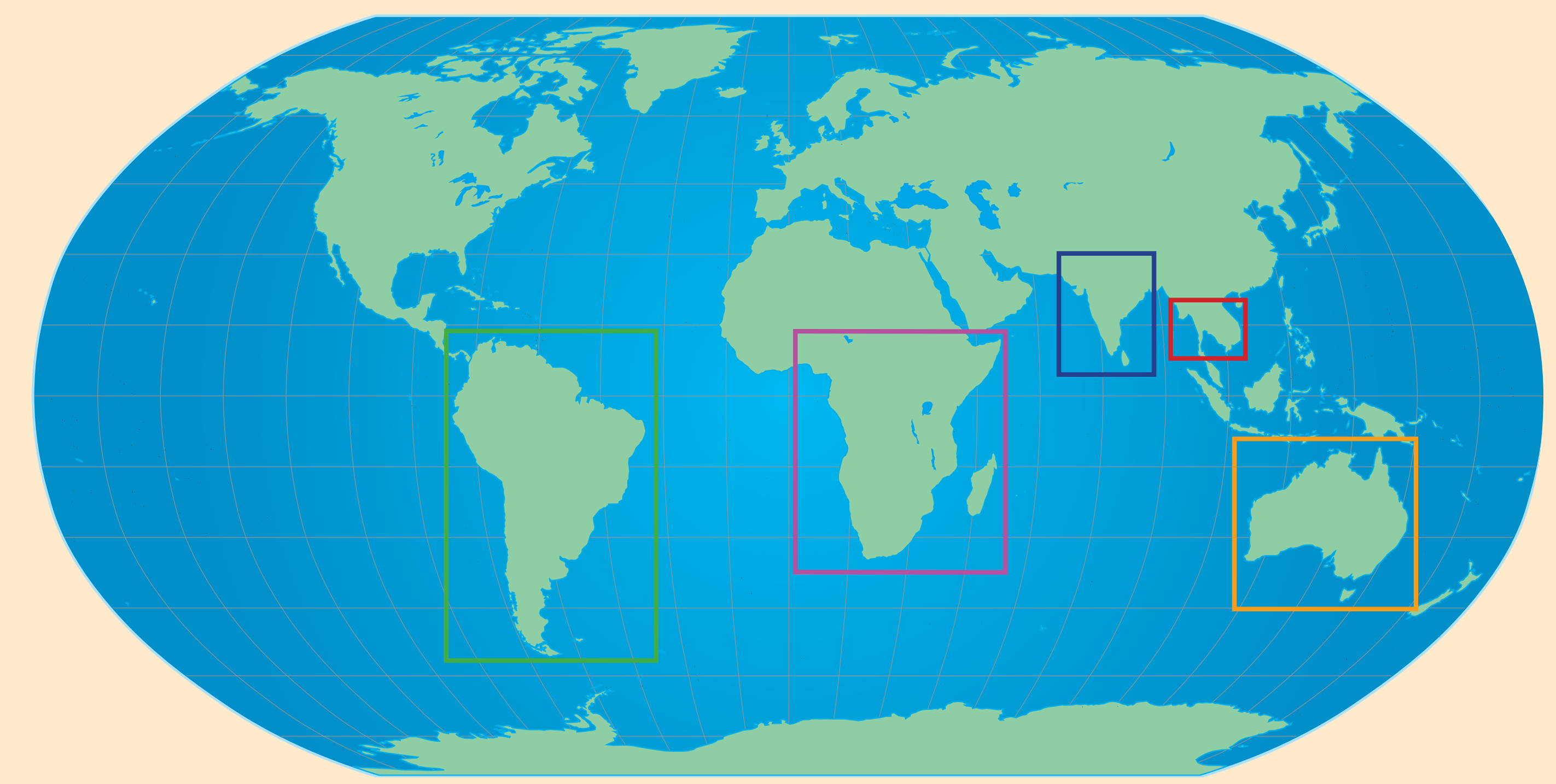
AUSTRALIA

1 Kununurra: Dia
2 Derby: Dia
3 Pilbara, Wodgina: Em
4 Poona: Em
5 Yerilla Station: Chp
6 Menzies: Em
7 Dowerin: Alx, Chb
8 Borroloola: Dia
9 Lambina: Opl
10 Mintabie: Opl
11 Coober Pedy: Opl
12 Stuart Creek: Opl
13 Andamooka: Opl
14 Cowell: Nph
15 Mount Surprise: Em
16 Hughenden: Fsp
17 Kynuna: Opl
18 Opalton: Opl
19 Anakie, Rubyvale: Sa, Zrn
20 Davenport: Opl
21 Palpara: Opl
22 Jundah: Opl
23 Yaraka: Opl
24 Bulgroo: Opl
25 Eromanga: Opl
26 Quilpie: Opl
27 Toompine: Opl
28 Koroit: Opl
29 Yowah: Opl
30 Marlborough: Chp
31 Emmaville, Torrington: Em
32 Glen Innes: Sa
33 Inverell, Swanbrook: Ru, Sa
34 Bingara: Ru, Sa
35 Lightning Ridge: Opl
36 Macquarie River: Ru, Sa
37 White Cliffs: Opl
38 Broken Hill: Rdn
39 Yarrowitch: Sa
40 Barrington, Gloucester: Ru, Sa
41 Cudgegong River: Ru, Sa
42 Oberon, Vulcan Forest: Sa
43 Tumbarumba: Ru, Sa
44 Weldborough: Sa


South Sea cultured pearls (~14 mm) from Australia
Robert Weldon

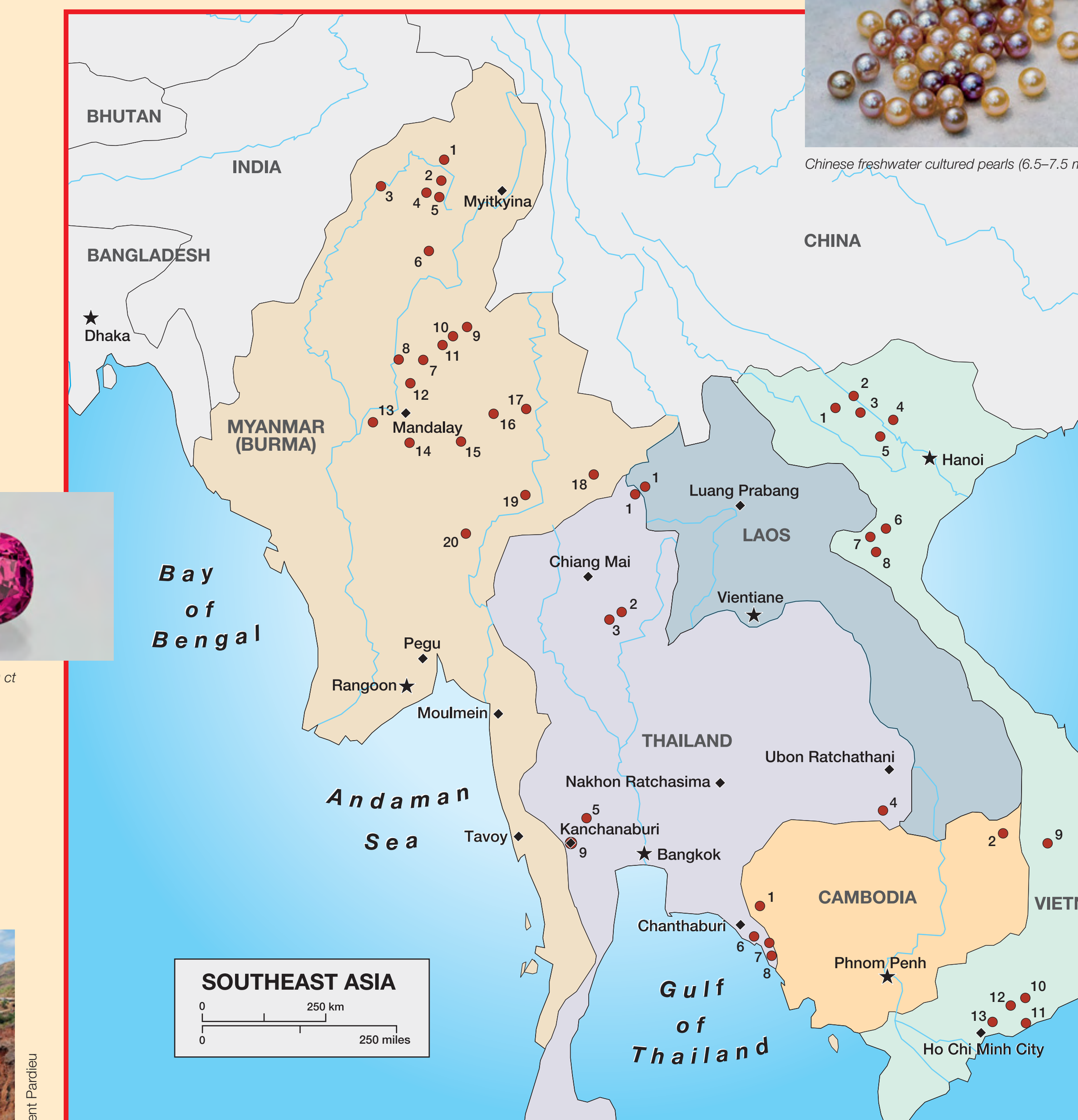

Fancy purplish red Argyle diamond, 1.74 ct
Rio Tinto Diamonds/Robert Weldon


Blasting at Australia's Argyle diamond mine, near Kununurra



This chart accompanies the article published in the Fall 2010 issue of ***Gems & Gemology*** (Vol. 46, No. 3) titled "Gem Localities of the 2000s," by J. E. Shigley, B. M. Laurs, A. J. A. Janse, S. Elen, and D. M. Dirlam. These regional maps show the approximate locations of gem localities that were significant or showed future potential in the first decade of the 2000s. Some regions (e.g., Russia and North America) are not shown due to space limitations. In general, the locality names listed here refer to the district where each gem deposit occurs. For some localities (i.e., in Sri Lanka and elsewhere), the mine/deposit/occurrence name is shown. In a few instances, localities plotted here are for overlapping mining areas at the scale of these maps. In such cases, not all the gem minerals indicated are found at each of these localities.

SOUTHEAST ASIA




Chinese freshwater cultured pearls (6.5–7.5 mm)
Valerie Power


Spinel from Vietnam, 4.69 ct
Robert Weldon

Cambodia
1 Pailin: Ru, Sa
2 Bong Long: Zrn

Laos
1 Ban Houayxay: Ru, Sa, Spl

Myanmar
1 Hukawng Valley: AC
2 Nam Phyu: Ru
3 Hkamti: AC, Jd
4 Hpakant, Kansi, Tawmaw: Jd, MSS
5 Nanyaseik: Ru, Sa, Spl
6 Mohnyin: Ky
7 Bernardmyo, Kabaing, Kyatpyin, Kyauksin, Mogok: Abg, And, Ap, Brl, Dnb, Krn, LL, Ol, Ru, Sa, Scp, Sdl, Spl, Sps, Tpz, Zrn
8 Thabeikkyin: Ru, Zrn
9 Mong Hkak: Sa
10 Molo: Brl, Phk, Tpz, Tur
11 Momeik (Mong Mit): Ap, Brl, Dnb, Phk, Tur
12 Singu: Ap, Tur
13 Natogyi: Opl
14 Kume: Brl, Grs, Tpz
15 Mong Long: Tur
16 Makmai: Tur
17 Mong Hsu: Dsp, Ru, Sa, Tur
18 Mong Hsat: Alm
19 Mong Pan: Tur
20 Pawn Chaung: Spl, Tur

Thailand
1 Chiang Khong: Sa
2 Den Chai: Sa
3 Wang Chin: Sa
4 Nam Yuen, Nong Khon: Ru, Sa
5 Bo Phloi: Sa
6 Khao Ploi Waen: Sa
7 Bo Rai, Bo Waen, Nong Bon, Tok Phrom, Welu Klang: Ru
8 Khao Saming: Ru
9 Kanchanaburi: Sa

Vietnam
1 Tu Le: Tpz
2 An Phu, Bai Da Lan, Khai Trung, Luc Yen, Minh Tien, Minh Xuan, Tan Lap, Truc Lau: Brl, Fsp, Ru, Sa, Spl, Tur, Zrn
3 Tan Huong, Thac Ba, Yen Bai: Ru, Sa, Spl
4 Thach Khoan: Brl
5 Phu Tho: Brl
6 Xuan Le: Tpz
7 Qui Chau, Qui Phong: Brl, Ru, Sa, Spl, Zrn
8 Qui Hoop: Ru, Sa
9 Bien Ho: Ol
10 Di Linh: Sa
11 Ma Lam, Phan Thiet: Ru, Sa
12 Bao Lac: Sa, Tpz
13 Xa Gia Kiem, Xuan Loc: Sa

SOUTH ASIA/SRI LANKA

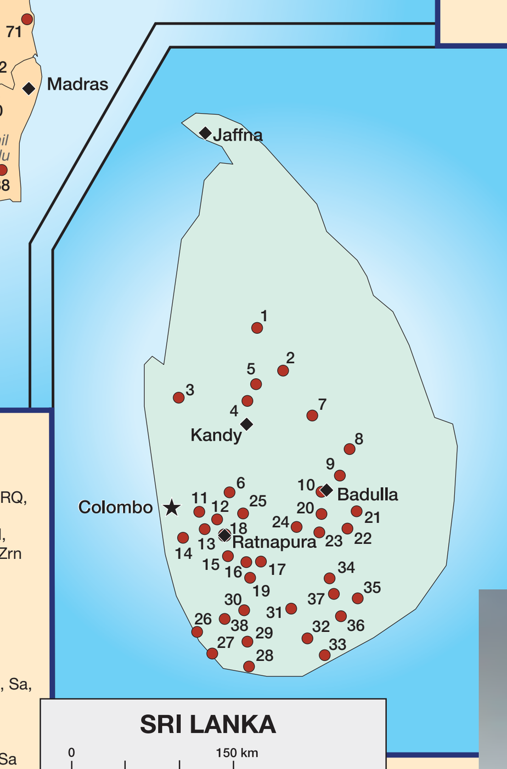
Afghanistan
1 Khash: Em, Ru
2 Fargon Meeru: Ttn
3 Sar-e-Sang: LL
4 Diwaneh Baba: Tur
5 Papra, Paprowk: Brl, Tpz, Tur
6 Kalaigal, Kantiwa, Munjagal, Nishai, Waigal, Warma: Brl, Grs, Tur
7 Darra-i-Pech, Gur-Salak, Kala, Khana Khana, Paroon Valley: Adr, Brl, Sps, Tur
8 Mawi, Nilaw-Kolum: Brl, Spd, Tur
9 Kurgal, Shamya, Titin: Em, Tur
10 Jegdalek, Shinwari: Ru, Sa, Zo
11 Panjshir Valley: Em
12 Maidan Shahr: Sa
13 Moqor: Qz

India
1 Baramula: Fsp
2 Doda: Sa
3 Sunjam: Brl, Sa
4 Zanskar: Brl
5 Wangtu: Fsp
6 Sarwad (Sarwar): Alm, Brl, Prp
7 Rajgarh: Ap, Em
8 Sangwa (Taranau): Alm, Prp
9 Ajmer: Alm, Ap, Brl, Em, Fsp, Grs
10 Kakaoria, Tonk: Alm, Brl, Prp
11 Panwar: Brl
12 Shahpura: Brl, Grs
13 Bendria, Bhilwara: Alm, Ap, Fsp, Prp
14 Kaliguman: Em
15 Udaipur: Alm, Em, Prp
16 Panna: Dia
17 Indarwa: Fsp
18 Hazaribag: Brl, Fsp, Grs
19 Kodarma: Fsp
20 Baraganda: Ap
21 Manbhum: Fsp
22 Singhbhum: Tpz
23 Raipur: Alx, Dia, RQ, Ru
24 Deobhog: Alx
25 Bastar: Ru
26 Aurangabad: RO
27 Jharsuguda: Tur
28 Sambalpur: Alx, Alm, Brl, Chb, Crd, Em, Prp, Sa, Tur, Zrn
29 Deogarh: Alm, Grs, Prp
30 Jharposi: Grs
31 Angul: Alm, Grs, Prp, Ru
32 Ghatpara: Grs
33 Nawapara: Alx, Sa
34 Balangir: Alm, Brl, Chb, Em, Grs, Ky, Prp, Ru, Sa, Tpz, Zrn
35 Subarnapur: Alm, Brl, Tpz
36 Boudh: Tpz , Tur
37 Kantabanji: Brl, Chb
38 Phulabani: Alm, Brl, Em, Grs, Prp
39 Hinjlibahal, Kalahandi: Alm, Ap, Chb, Crd, Grs, Ky, Prp, Ru, Zrn
40 Koraput: Alm, Chb, Grs, Prp
41 Rayagada: Chb, Sil
42 Shimoga: Grs
43 Chikmagalur: Ru
44 Hassan: Grs, Ru
45 Pavagada: Ru
46 Durgahahalli, Ramanahalli, Tumkur: Ru
47 Bangalore: Fsp
48 Nagamangala: Ky
49 Subrahmanya: Ru
50 Somvarpet: Ru
51 Coorg, Madikeri: Ru
52 Mysore: Fsp, Grs, Ky, Ru
53 Maddur: Ru
54 Channapatna: Ru
55 Bobbili: Sil
56 Srikakulam: Alx, Chb
57 Araku Valley, Borra: Ap, Chb, Sil, Tur
58 Paderu: Chb, Sil
59 Vizianagaram: Alx, Chb
60 Chintapalli: Chb, Sil
61 Addatigala: Alx, Chb
62 Vishakhapatnam: Alx, Ap, Chb, Ru, Tur
63 Godavari (Kakinada): Alx, Chb
64 Ratnagiri Hills: Sa
65 Bhadrachalam: Alm, Prp
66 Warangal: Ru
67 Nalgonda: Ru
68 Khammam: Alx, Chb, Ru
69 Guntur: Ru
70 Anantapur: Ru, Sa
71 Nellore: Fsp, Grs
72 Chittoor: Alm, Prp, Ru
73 Hindupur: Sa
74 Thiruvalla: Crd
75 Kolattupuzha: Alx, Ru
76 Quilon: Chb, Sa
77 Aruvikkara, Uzhamalakkal: Alx, Brl
78 Trivandrum: Crd, Fsp, Sa
79 Nayyar, Ooruttambalam: Alx, Fsp
80 Vellore, Venkatpuram: Ru, Sa
81 Salem: Alm, Ap, Brl, Em, Fsp, Prp, RQ, Ru
82 Nilgiri: Alm, Grs, Prp
83 Coimbatore: Brl
84 Tarapuram: Brl
85 Namakkal: Ap, Ru, Sil
85 Paramatti: Ru
86 Kangayam, Padiyur, Tiruppur: Alx, Brl, Chb, Crd, Fsp, RQ, Ru, Sa, Scp, Spl, Tpz, Zrn
87 Karur, Kunjampalayam: Alm, Alx, Brl, Chb, Crd, Fsp, Prp, RQ, Ru, Sa, Scp, Spl, Tpz, Ttn, Zrn
88 Sivapuram: Brl
89 Tiruchchirappalli: Alm, Brl, Crd, Fsp, Prp, Spl, Zrn
90 Kiranur: Crd, Fsp
91 Kadavur: Brl
92 Dindigul: Alx, Brl, Chb, Fsp
93 Kurumbapatti: Brl
94 Palni: Alx
95 Ramanathapuram: Zrn
96 Madurai: Alm, Alx, Brl, Chb, Crd, Fsp, Prp
97 Varusha Nadu: Brl
98 Tirunelveli: Alx, Chb, Tpz, Zrn
99 Kanniyakumari: Alx, Brl, Chb, Sa, Tpz, Zrn

Nepal
1 Dhading: Ru, Sa

Pakistan
1 Neelum Valley: Ru, Sps, Tur
2 Basha Valley, Braldu Valley, Shigar Valley: Ap, Brl, Em, Ru, Sa, Spl, Tpz, Tur
3 Hunza Valley: Ap, Brl, Ru, Sa, Spl, Tpz, Tur
4 Raikot: Brl
5 Astore Valley: Tur
6 Batwash Gah, Mir Malik, Nanga Parbat: Adr, Sa, Tur
7 Indus Valley: Brl, Fsp, LL, Sps, Tpz, Tur
8 Battakundi, Kaghan Valley, Sapat: Adr, Ol, Ru, Sa
9 Swat Valley: Em
10 Mardan: Tpz

Sri Lanka
1 Eppawala: Ap
2 Polonnaruwa: Alm, Sa, Tpz, Tur
3 Akurana: Sa
4 Kaikawala, Matale, Rattota: Brl, RQ, Tpz
5 Elahera, Kongahawela: Alm, Crd, Fsp, Krn, Sa, Spl, Tpz, Ttn, Tur, Zrn
6 Nawalapitiya: Brl, Tpz
7 Mahiyanganaya: Ap
8 Bibile: Sa
9 Lunugala: Sa
10 Badulla: Tur
11 Avissawella, Pugoda: Sa, Tur
12 Eheliyagoda, Kuruwita: Crd, Grs, Sa, Scp, Spl
13 Inginiya, Kiriella: Sa, Spl
14 Horana, Pelpola: Sa, Spl
15 Kalawana, Niwitigala: Alx, Chb, Sa
16 Opanayaka, Pelmadulla: Alx, Brl, Chb, Sa
17 Balangoda: Chb, Fsp, Sa, Spl, Tpz, Tur, Zrn
18 Ratnapura: Alm, Alx, Ap, Brl, Chb, Crd, Fsp, Grs, Krn, Sa, Scp, Spl, Tpz, Tur
19 Kolonne, Rakwana: Alx, Chb, Krn, Ol, Ru, Sa
20 Passara: Sa, Tur
21 Moneragala: Sa
22 Okkampitiya: Ap, Crd, Grs, Krn, Sa, Spl, Tur
23 Wellawaya: Opl, Sa
24 Haputale: Sa
25 Hatton, Maskeliya: Alm, Brl
26 Ambalangoda, Mitiyagoda: Brl, Fsp
27 Galle: RQ, Ttn
28 Matara: Grs, Sa
29 Akuressa, Kamburupitiya: Alx, Chb, Grs, Ttn
30 Deniyaya, Morawaka: Alx, Ap, Chb, Zrn
31 Embilipitiya: Sa, Spl, Tur, Zrn
32 Ridiyagama: Sa
33 Hambantota: Brl
34 Tanamalwila: Grs
35 Kataragama: Grs, Sa, Spl, Spd, Ttn, Zrn
36 Lunugamwehera, Tissamaharama: Brl, Grs
37 Telulla: Grs
38 Pattara: Alx, Chb




Ruby mine at Jegdalek, Afghanistan
Vincent Pardieu


Blue sapphire from Sri Lanka, 10.21 ct
Kris Gem Int'l/Robert Weldon

AFRICA/MADAGASCAR

Angola
1 Dundo: Dia
2 Nzaji (Andrada): Dia
3 Cafunfo: Dia
4 Cuango-Luzamba: Dia
5 Lucapa: Dia
6 Saurimo: Dia

Botswana
1 Letlhakane: Dia
2 Palapye: Dia
3 Jwaneng: Dia

Central African Republic
1 Kotto River: Dia
2 Mambéré River: Dia

Democratic Republic of the Congo
1 Virunga: Tur
2 Walikale: Tur
3 Manono: Tur
4 Bushimaie River: Dia
5 Kasai River: Dia

Ethiopia
1 Chumba: Alm
2 Agere Maryam: Alm
3 Mezezo: Opl
4 Wegel Tena: Opl

Kenya
1 Narok: Tur
2 Eldoret: Ru
3 West Pokot: Ru
4 Turkana: Sa
5 Garba Tula (Dusi): Sa
6 Embu: Brl
7 Kitui: Crd, Qz, Sa
8 Kajiado: Alm, Grs
9 Chawia, Manoa, Mgama, Taita Hills: Alm, Grs, Ru, Spl, Sps, Tur
10 Mangare, Mukongonyi, Mwachango, Rukanga: Alm, Grs, Ru, Spl, Tur
11 Kisoli, Kuranze, Lasamba Hill, Mwakinsunzuru: Alm, Grs, Ru, Sa, Tur

Lesotho
1 Kao, Letšeng-la-Terae, Liqhobong: Dia

Madagascar
1 Befotaka: Sa
2 Antetezambato: Adr
3 Ambakirano, Manambato: Ap, Qz
4 Amboahangimamy, Ambondromifehy, Antserasera, Anivorano: Ru, Sa
5 Ankarafa, Daraina: Ap, Ttn
6 Milanoa: Ap
7 Ambilobe: Ap
8 Andapa: Brl, Qz, Tpz
9 Boriziny: Brl, Qz
10 Mahajamba: Brl
11 Tsaratanana: Qz
12 Andriamena: Brl
13 Ambohimaranitra: Sps
14 Andriba: Ru
15 Kandreho: Fsp
16 Analangoaika, Andilamena, Antanimenabaka, Antanimbohibe: Qz, RQ, Ru
17 Moramanga: RQ, Ru
18 Ambatomafana: RQ
19 Andreba: Alm
20 Ambatondrazaka: Alm, Brl, Chb, Fsp, RQ, Ru, Tur
21 Didy: Qz, RQ, Ru
22 Sahaviavy Fito: RQ
23 Lakato: RQ
24 Beforona (Ambohitranefitra): Ru
25 Ranomafana: RQ
26 Ambodilazana, Amboditavolo, Ambodivandrika, Vatomandry: Qz, Ru, Sa
27 Tetezampaho: Ru
28 Marolambo: Alm, Prp
29 Ankazobe: Brl, Chb
30 Tsiroanomandidy: RQ
31 Ambohidrano, Mahasolo, Soavinandriana: Brl, Euc, Qz
32 Faratsiho: Ru, RQ, Tpz
33 Antanifotsy, Antsahanandriana, Mandrosohasina: Ru, Sa, Zrn
34 Bevitsika Mountain: Qz
35 Ambohimanambola: Fsp
36 Antsirabe, Betafo, Soamiakatra: Alm, Brl, RQ, Ru, Spd, Tur
37 Andongologo, Anjanabonoina, Antsikoza, Mahaiza, Vohitrakanga: Brl, Dnb, Phk, Qz, RQ, Spd, Tur
38 Mangataboahangy: Qz
39 Anjomakely: Sa
40 Ambohimanitra, Antandrokomby, Manjaka, Mount Bity: Brl, Dnb, RQ, Spd, Tur
41 Sakaraha: Sa
42 Anavoha, Fotodrevo: Alm, Prp, Ru
43 Gogogogo, Vohitany: Grs, Ru
44 Ejeda: Grs, Ru
45 Behara, Betioky, Maniry: Alm, Fsp, Grs, Ru
46 Tranoroa: Alm, Prp
47 Berenty: Grs
48 Ambatomanaho: Crd
49 Ambovombe: Alm
50 Amboasary: Brl, Sa, Zrn
51 Taolagnaro: Alm, Tur
52 Ambinda: Sa
53 Betroka: Alm, Krn, Sa, Zrn
54 Mahasoa: Fsp
55 Mahabo: Fsp
56 Ianapera: Em
57 Sakoandroa: Prp, Sps
58 Ampanihy, Antaratra, Bekily: Alm, Grs, Prp, Sa, Sps
59 Iankaroka, Voronkafatra: Sa
60 Ambatomena: Ru
61 Beraketa: Opl
62 Mitsinjo, Tsivory: Ap, Opl
63 Isahara: Brl, Qz, Tpz, Tur
64 Andranondambo: Sa
65 Ifotaka: Qz
66 Vorondolo: Qz
67 Ifanadiana: Em
68 Ambodibakoly, Irondro, Kianjavato, Morafeno: Em
69 Ambatovita: Brl, Dnb, Spd, Tur
70 Bevaondrano: Tur
71 Ambatofinandrahana: Qz, Tur
72 Andranolava: Sa
73 Voandambo: Brl, Spd
74 Ambositra: Alm, Chb, Fsp, Qz, RQ, Tpz
75 Valozoro: Tur
76 Sakeny: Ru
77 Ranohira: Alm
78 Ilakaka: Alm, Alx, Chb, Ru, Sa, Spd, Sps, Tpz,Tur, Zrn
79 Alakamisy Itenina: Tur
80 Miarinarivo: Ru
81 Ankaditany, Sakalalina, Zazafotsy: Alm, Sa
82 Ambinda, Sahambano: Fsp, Sa
83 Vondrozo: Qz
84 Marosely: Ru, Sa

Malawi
1 Mzimba: Brl
2 Ntcheu: Ru, Sa

Mozambique
1 M'Sawize: Ru
2 Marrupa: Ru
3 Montepuez: Ru
4 Namapa: Qz
5 Muiane: Brl, Tpz, Tur
6 Malema: Brl, Scp
7 Cuamba: Alm
8 Nacala-a-Velha: Tur
9 Lalaua: Brl
10 Zumbo: Brl, Qz
11 Changara: Ru
12 Mutarara: Brl, Sa
13 Chimoio: Sa
14 Nametil: Tur
15 Chalaua, Moma: Brl, Tur
16 Gilé, Ile, Murrua, Uape: Brl, Em, Qz, Scp, Spd, Tur
17 Alto Molócuè: Brl, Qz, RQ, Tur
18 Mocuba: Brl
19 Milange: Brl, Qz
20 Marávia: Brl, Fsp, Tpz, Tur
21 Naquilite, Naquissupa: RQ, Tur
22 Nhampassa: Tur
23 Pataguenha: Tur

Namibia
1 Hartmann Mountains: Sps
2 Namib Desert (Sarusas): Qz
3 Outjo: Tur
4 Otjiwarongo: Qz
5 Uis: Tur
6 Goboboseb: Qz
7 Erongo Mountains, Klein Spitzkoppe, Tubussis: Adr, Brl, Tpz, Tur
8 Rössing: Brl
9 Neu Schwaben: Tur
10 Oranjemund: Dia
11 Eausiro: Tur
12 Omapyo: Tur
13 Kubas: Tur

Nigeria
1 Babana: Grs, Tur
2 Budo, Iseyin: Sps, Tur
3 Komu: Spd, Sps, Tur
4 Itasa: Tur
5 Are: Tur
6 Igbo Ora: Brl
7 Olonde: Brl
8 Ijebu Igbo: Brl
9 Ogbomosho: Sps, Tur
10 Lemo, Ndeji: Tur
11 Ilorin: Tur
12 Oro: Tur
13 Ijero Ekiti: Tur
14 Ora: Tur
15 Egbe: Brl
16 Okene: Brl
17 Okuta: Phk
18 Kontagora: Tur
19 Makutu: Grs
20 Paikolo: Brl
21 Pandogari: Spd, Tur
22 Sarkin Pawa: Tur
23 Keffi: Tur
24 Garatu: Tur
25 Akwandoka, Akwanga: Brl, Tur
26 Nassarawan Eggon, Shabu: Em, Tpz
27 Kagarko: Tur
28 Kwoi: Brl
29 Godogodo, Kafachan: Sa
30 Gwantu, Nandu: Em
31 Bomo: Brl, Tpz
32 Jos: Phk
33 Magama: Tpz
34 Tafawa Balewa: Sa
35 Gunda: Sa
36 Jalingo: Qz
37 Ganye: Sa
38 Gembu: Sa

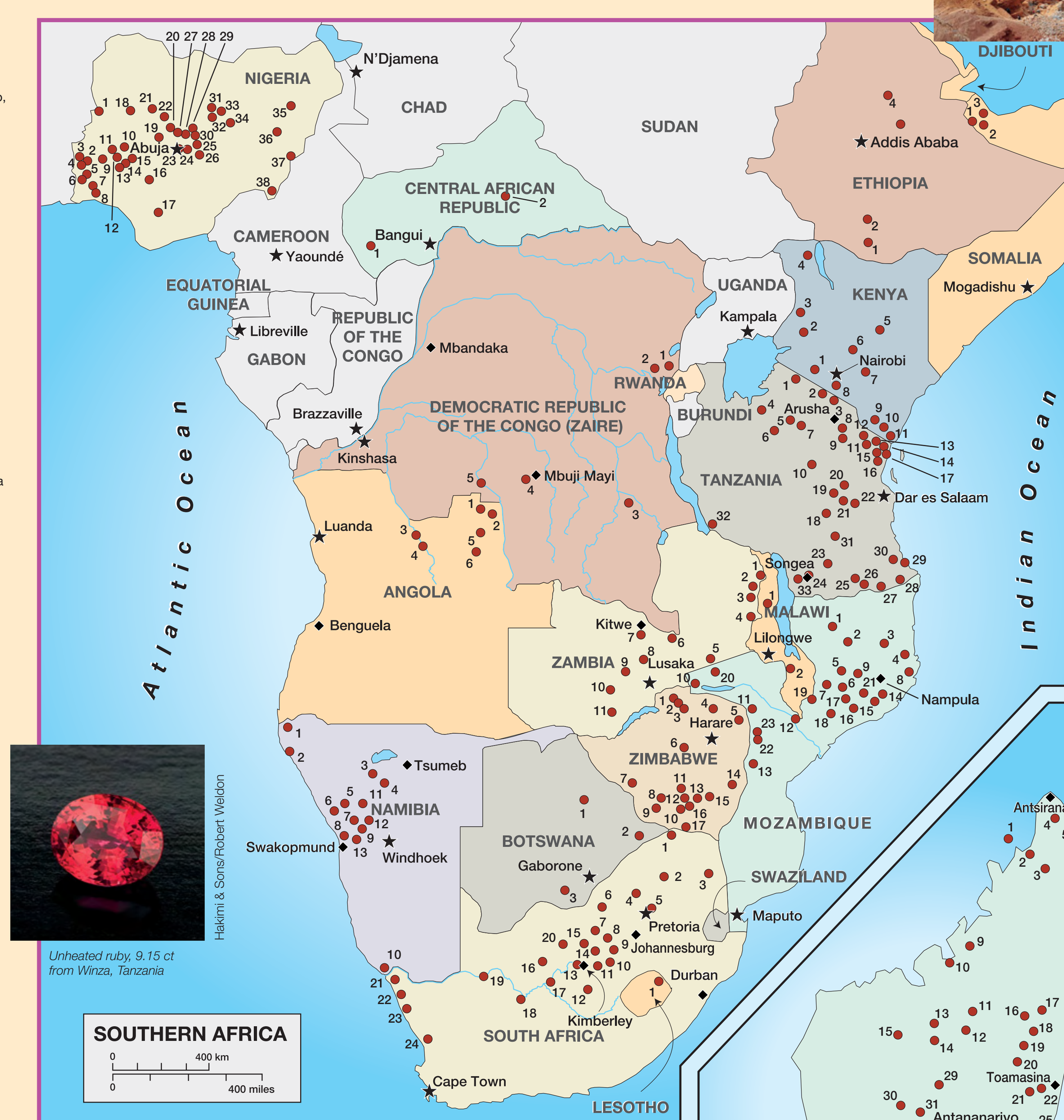
Somalia
1 Booroma (Alihiley): Em
2 Booroma (Simodi): Em
3 Qabri Baxar: Opl

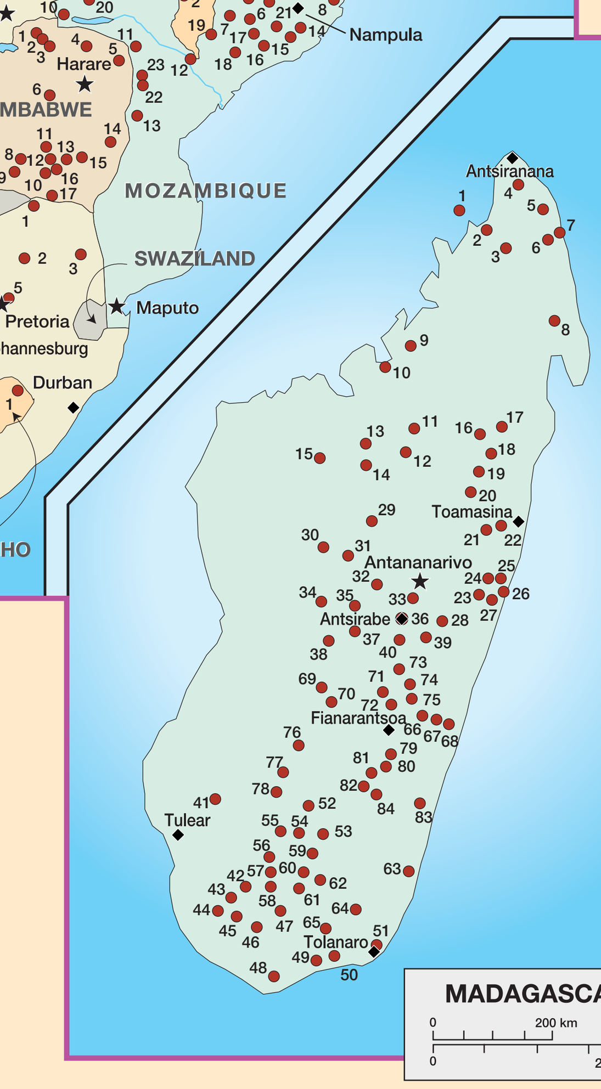
South Africa
1 Messina: Dia
2 Potgietersrus: Dia
3 Gravelotte: Em
4 Pretoria: Dia
5 Pretoria (Cullinan): Dia
6 Swartruggens: Dia
7 Lichtenburg: Dia
8 Ventersdorp: Dia
9 Kroonstad: Dia
10 Theunissen: Dia
11 Dealesville: Dia
12 Koffiefontein: Dia
13 Barkly West, Boshof, Kimberley: Dia
14 Bloemhof: Dia
15 Schweizer-Reineke: Dia
16 Lime Acres: Dia
17 Douglas: Dia
18 Prieska: Dia
19 Keimoes: Brl
20 Reivilo: Dia
21 Alexander Bay: Dia
22 Port Nolloth: Dia
23 Springbok: Dia
24 Vredendal: Dia

Tanzania
1 Loliondo: Brl, Grs, Ky, Sps
2 Engare Naibor: Fsp
3 Longido: Fsp, Ru
4 Mwadui: Dia
5 Mangola: Em
6 Kisiriri: Zrn
7 Mayoka: Alx, Chb, Em
8 Komolo, Merelani Hills, Lelatema Mountains: Alm, Ax, Grs, Spl, Zo
9 Landanai, Lossongonoi, Naberera, Narujuruju: Fsp, Grs, Ru, Tur
10 Haneti: Chp
11 Hedaru: Alm
12 Mwembe, Pare Mountains, Same: Alm, Crd, Zrn
13 Mnazi: Tur
14 Kalalani, Kigwase, Mwakijembe, Umba Valley: Alm, Grs, Prp, Ru, Sa, Sps, Tur, Zrn
15 Usambara Mountains: Krn
16 Korogwe: Zrn
17 Daluni: Tur
18 Winza: Ru, Sa
19 Mpwapwa: Crd, Scp
20 Geiro, Lukande: Fsp
21 Kilosa: Fsp
22 Matombo, Mkuyuni, Mvuha, Uluguru Mountains: Alm, Dnb, Ru, Sa, Spl, Tur
23 Nyamtumbo: Brl
24 Songea: Brl, Ru, Sa
25 Mtetesi River, Tunduru: Alm, Brl, Chb, Grs, Ru, Sa, Spl, Taf
26 Lumesule River, Muhuwesi River: Alm, Chb, Grs, Ru, Sa, Spl
27 Masuguru: Ru, Sa
28 Namaputa: Alm
29 Ngapa: Ru, Sa
30 Mpekenyera, Namungu Hill: Grs
31 Chipa, Lukande, Mahenge, Epanko: Alm, Ru, Sa, Spl
32 Chala, Sumbawanga: Brl, Em, Ru
33 Mbinga: Ru, Sa

Zambia
1 Muyombe: Chb
2 Chama: Brl
3 Sangu: Prp
4 Lundazi: Brl, Sps, Tur
5 Nyimba: Tur
6 Mkushi: Brl, Tur
7 Luanshya (Kufubu River): Em, Phk
8 Kabwe: Tur
9 Mumbwa: Qz
10 Itezhi-Tezhi: Brl
11 Kalomo: Qz

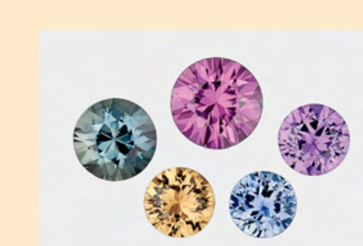
Zimbabwe
1 Makuti: Crd
2 Karoi: Em
3 Mwami: Brl, Chb, Em, Euc, Tpz, Tur
4 Guruwe: Tpz
5 Mutoko, Rushinga: Brl
6 Kadoma: Chb, Euc
7 Nyamandlovu: Qz
8 Filabusi: Brl
9 Gwanda: Tur
10 Mberengwe: Em
11 Somabhula: Alx, Chb, Em, Ru, Sa, Tpz
12 Zvishavane: Crd
13 Masvingo: Alx, Em, Chb
14 Marange: Dia
15 Chikwanda: Em
16 Zvishavane: Dia
17 Beitbridge: Crd






Spinel mining at Mahenge, Tanzania
Vincent Pardieu

Unheated ruby, 9.15 ct from Winza, Tanzania
Hakimi & Sons/Robert Weldon


Unheated Madagascar sapphires (~0.6–2 ct)
Fine Gems Int'l/Robert Weldon

Colombian emerald, 2.59 ct
RareSource/Robert Weldon

SOUTH AMERICA

Paraiba tourmaline deposit, Mina da Batalha, Brazil
Brendan Laurs

Paraiba tourmaline, 13.14 ct
Robert Weldon

Argentina
1 Capillitas: Rds

Bolivia
1 Sandoval: Qz
2 Independencia: Sdl

Brazil
1 Boa Vista: Dia
2 São Geraldo do Araguaia: Opl
3 Itacupim Island: Trq
4 Marabá, Tocantins River: Dia, Qz
5 Pau d'Arco: Qz
6 Gilbués: Dia
7 Pedro II: Opl
8 Quixeramobim: Tur
9 Solonópole: Tur
10 Caiçara, Tenente Ananias: Brl, Em
11 São João do Sabuji: Brl
12 Equador, Pedra Lavrada: Euc, Tur
13 Acari, Carnaúba dos Dantas, Parelhas: Brl, Crd, RQ, Sps, Tur
14 Lajes Pintadas: Brl
15 Frei Martinho: Tur
16 Santa Luzia: Grs
17 Salgadinho: Tur
18 Pimenta Bueno: Dia
19 Juina: Dia
20 Cuiabá: Dia
21 Monte Santo: Em
22 Peixe: Alm, Sps
23 Pilão Acado: Em
24 Campo Formoso, Pindobaçu: Alx, Em
25 Lençóis: Dia
26 Caetité: Qz
27 Brumado: Em
28 Anajé: Em
29 Vitória da Conquista: Brl, Ky
30 Itambé: Brl
31 Macarani, Maiquinique: Brl
32 Alcobaça: Brl
33 Itanhém: Brl
34 Minaçu: Alx
35 Santa Teresinha de Goiás: Em
36 Pirenópolis: Em
37 Pedra Azul: Brl, Tpz
38 Medina: Brl, Tpz
39 Itinga, Jequitinhonha: And, Qz, RQ, Tpz
40 Araçuaí, Coronel Murta, Virgem da Lapa: Brl, Qz, Tpz, Tur
41 Caraí, Padre Paraíso: Brl, Chb, Tpz
42 Catuji: Brl, Tpz
43 Teófilo Otoni, Topázio: Brl
44 Agua Boa, Malacacheta: Alx, Ru, Sa, Tur
45 São José da Safira, Virgolândia: Crd, Sps, Tur
46 Diamantina: Dia
47 Coromandel: Dia
48 Ferros, Hematita, Itabira, Santa Maria de Itabira: Alx, Brl, Em, Tpz
49 Ouro Preto: Euc, Tpz
50 Conselheiro Lafaiete: Rdn
51 Indaiá: Ru, Sa
52 Sapucaia: RQ, Ru, Sa
53 Manhuaçu: Alx, Sa
54 Aracruz: Scp
55 Divino das Laranjeíras: Abg, Brz, Tur
56 Galiléia, São Geraldo do Baixio: Brl, Qz, Spd, Sps, Tur
57 Conselheiro Pena: Em, Euc, Qz, Sps, Tur
58 Resplendor: Brl
59 Pancas: Brl
60 Baixo Guandu: Brl
61 Colatina: Chb
62 Itaguaçu: Brl
63 Castelo: Brl
64 Mimoso do Sul, Muqui: Brl
65 Paraíso do Tocantins: Em
66 Salinas: Tur
67 Capelinha: Ttn

Chile
1 El Polvo: LL

Colombia
1 Muzo, Maripí (La Pita), San Pablo de Borbur, Yacopí: Em
2 Chivor, Gachalá, Macanal: Em, Euc
3 Mercaderes: Sa

Guyana
1 Bartica: Dia
2 Issano: Dia
3 Lethem: Dia

Peru
1 Nazca: Opl
2 Ica: Opl
3 Yauli: Rds
4 Oyón: Rds
5 Huachocolpa: Rds

Uruguay
1 Artigas: Qz

Venezuela
1 Santa Elena de Uairén: Dia
2 El Dorado: Dia
3 Paviche: Dia
4 Caicara: Dia

KEY/ABBREVIATIONS

● Gem Locality ★ National Capital ◆ City

Abg	Amblygonite	Dnb	Danburite	MSS	Maw-sit-sit	Scp	Scapolite		
AC	Amber/copal	Dia	Diamond	Nph	Nephrite	Spd	Spodumene		
And	Andalusite	Dsp	Diaspore	Opl	Opal	Sil	Sillimanite		
Alx	Alexandrite (chrysoberyl)	Em	Emerald (beryl)	Ol	Peridot (olivine)	Sdl	Sodalite		
Alm	Almandine/rhodolite	Euc	Euclase	Phk	Phenakite	Spl	Spinel		
Adr	Andradite/demantoid	Fsp	Feldspar	Prp	Pyrope	Sps	Spessartine		
Ap	Apatite	Grs	Grossular/hessonite/tsavorite	Qz	Amethyst/citrine/ametrine	Taf	Taaffeite		
Ax	Axinite	Crd	Iolite (cordierite)	Rds	Rhodochrosite	Tur	Tourmaline		
Brl	Beryl	Jd	Jadeite	Rdn	Rhodonite	Tpz	Topaz		
Brz	Brazilianite	Krn	Kornerupine	RQ	Rose quartz	Trq	Turquoise		
Chb	Chrysoberyl	Ky	Kyanite	Ru	Ruby (corundum)	Ttn	Sphene (titanite)		
Chp	Chrysoprase	LL	Lapis lazuli	Sa	Sapphire (corundum)	Zo	Zoisite/tanzanite		
						Zrn	Zircon		

GEMS & GEMOLOGY

'10 CHALLENGE WINNERS

This year, hundreds of readers participated in the 2010 GEMS & GEMOLOGY Challenge. Entries arrived from around the world, as readers tested their gemological knowledge by answering questions listed in the Spring 2010 issue. Those who earned a score of 75% or better received a GIA Letter of Completion recognizing their achievement. The participants who scored a perfect 100% are listed here.

Congratulations

AUSTRALIA **Queensland,** *Palm Beach:* Bert Last. **Tasmania,** *Huonville:* Joseph Bini. **Victoria,** *Ringwood:* Paulina Holmer. **South Australia,** *Grange:* Barbara Wodecki • **BELGIUM** *Brussels:* Sheila Sylvester. *Diegem:* Guy Lalous. *Diksmuide:* Honore Loeters. *Ruiselede:* Lucette Nols. • **CANADA** **British Columbia,** *Victoria:* Anthony De Goutiere. **Ontario**, *Kingston:* Brian Randolph Smith. *St. Catharines:* Alice Christianson. **Quebec**, *Montreal:* Marie-France Gilmert • **FRANCE** *Les Breviaires:* Thierry Cathelineau • **GREECE** *Thessaloniki:* Panagiotis Efthimiadis • **INDONESIA** *Jakarta:* Warli Latumena • **IRAN** *Tehran:* Sabrina Amiri Garousi • **IRELAND** *Galway:* Simon Zaletel • **ITALY** *Latina Scalo:* Guidi Giuseppe. *Malnete:* Gabriele Tralli. *Tarvisio:* Chiara Piussi • **JAPAN** *Tokyo:* Naoko Tokikuni • **KENYA** *Nairobi:* Marvin M. Wambua• **LITHUANIA** *Vilnius:* Saulius Fokas • **NETHERLANDS** *Voorburg:* Wilma van der Giessen • **RUSSIA** *Moscow:* Vadim Prygov • **SWITZERLAND** *Geneva:* Julie Falquet, Kanchan Nair. *Muri bei Bern:* Michael Huegi. *Zurich:* Doris Christine Gerber, Eva Mettler • **UNITED KINGDOM** *Buckinghamshire:* Claire Mitchell. *Edinburgh:* A. Ewen Taylor. *London:* Karin Sixl-Daniell • **USA** **Arkansas,** *Greenbrier: Beverly A. Brannan.* **California,** *Carlsbad:* Michael Evans, Brenda A. Harwick. *Marina Del Rey:* Veronika Riedel. *Palo Alto:* Grace Pahed. *Rancho Cucamonga:* Sandy MacLeane. *Santa Barbara:* Joanne Moy. **Colorado,** *Denver:* Alan Winterscheidt. **District of Columbia,** *Washington:* Eloise Gaillou. **Florida,** *Clearwater:* Tim Schuler. *Deland:* Sue Angevine Guess. *Satellite Beach:* Consuelo Schnaderbeck. *Venice:* Robert G. Campbell, Geraldine M. Vest. **Georgia,** *Roswell:* Gary Braun. **Indiana,** *Indianapolis:* Wendy Wright Feng. **Iowa,** *West Des Moines:* Frank Herman. **Louisiana,** *Baton Rouge:* Cynthia Gestring-Blumberg. **Maryland,** *Chevy Chase:* Andrea Blake. *Park Hall:* Pamela D. Stair. **Massachusetts,** *Millbury:* Bernard Stachura. **Minnesota,** *Minneapolis:* Andy Stevens. **Missouri,** *Saint Ann:* Bruce S. Hoffmann. **Nevada,** *Las Vegas:* Colleen Walsh. **New Jersey,** *West Orange:* Jessica M. Craig. **New York,** *City Island:* Marjorie Kos. *Huntington Station:* Elizabeth DiMaulo. *Tarrytown:* Ronnie Xu. **North Carolina,** *Advance:* Blair Tredwell. *Kernersville:* Jean A. Bonebreak. **Oregon,** *Medford:* Barbara Johnson. *Newport:* Richard Petrovic. **Rhode Island,** *Rumford:* Sarah Horst. **South Carolina,** *Sumter:* James S. Markides. **Texas,** *Amarillo:* Daniel Novak. *Amherst:* Joane Hayworth. *Cypress:* Christine Schnaderbeck. *Dallas:* Shawn Shannon. *Houston:* Kathy Ann Parks. **Virginia,** *Hampton:* Edward A. Goodman. **Washington,** *Lake Tapps:* Lois A Henning. *Seattle:* Lorrie Heavey. **Wisconsin,** *Beaver Dam:* Thomas Wendt.

ANSWERS

See pages 74–75 of the Spring 2010 issue for the questions.

1 (d), 2 (a), 3 (a), 4 (b), 5 (c), 6 (a), 7 (c), 8 (d), 9 (c), 10 (b), 11 (b), 12 (d), 13 (c), 14 (b), 15 (a), 16 (c), 17 (d), 18 (a), 19 (d), 20 (d), 21 (b), 22 (d), 23 (d), 24 (a), 25 (d)

’10

GEMSTONE ENHANCEMENT AND ITS DETECTION IN THE 2000S

Shane F. McClure, Robert E. Kane, and Nicholas Sturman

Advances in technology and increased demand for lower-priced gem materials contributed to the proliferation of new treatments throughout the first decade of the 2000s. The developments that made the most difference were the diffusion treatment of corundum with beryllium, diffusion of copper into feldspar, clarity enhancement of ruby and diamond, and heat treatment of diamond, ruby, and sapphire. Gemological laboratories and researchers have done their best to keep up with these treatments, and the jewelry trade has struggled with how to disclose them. This article summarizes these developments and the methods used to identify the various enhancements.

Another decade has passed since we reviewed the events of the 1990s as they pertained to gemstone enhancements and their detection (McClure and Smith, 2000). At that time, we observed that the issue of disclosure (and, especially, the failure to disclose) had caused major upheaval in all areas of the jewelry industry. We ended that retrospective article by stating there would be no end to fresh challenges in treatment identification and disclosure as we entered the new millennium.

The 2000s certainly lived up to our expectations. There were treatments discovered that no one suspected were possible. There were crises of disclosure that resulted in televised exposés and unfavorable publicity for the industry. There were improvements in treatments developed in the ’90s that made them more efficient and often harder to detect.

Detection methods have also become more and more complex. Gemological laboratories have had to invest in more sophisticated instrumentation, sometimes at great expense. For the frontline laboratories, being a good gemologist is no longer good enough. You must also have training in the earth sciences and analytical instrumentation to function effectively in such an environment. Now more than ever, the gemologist in the trade must be able to recognize when a stone requires more advanced testing.

It is important to emphasize that many of these treatments can still be detected with standard gemological equipment, but staying current on the latest developments is absolutely essential. The knowledge base concerning treatments is constantly changing.

Nearly every gem material (e.g., figure 1) is subject to treatments of one form or another. Building on previous reviews (Kammerling et al., 1990a; McClure and Smith, 2000; Smith and McClure, 2002), the aim of this article is to provide an overview of the treatments and identification challenges associated with them that were common during the first decade of the 2000s. The authors strongly recommend that readers familiarize themselves with the original references, as all the pertinent information cannot be presented in a review article.

See end of article for About the Authors and Acknowledgments.
GEMS & GEMOLOGY, Vol. 46, No. 3, pp. 218–240.

Figure 1. The 2000s continued to see the widespread use of treatments on a wide variety of gemstones. The gems shown here were enhanced during the 2000s by heat (unless otherwise noted) or other methods known prior to the decade: (1) 8.43 ct aquamarine; (2) 16.86 ct tanzanite; (3) 10.08 ct tourmaline; (4) 4.65 ct Paraíba tourmaline; (5) 3.36 ct red beryl (clarity enhanced); (6) 3.07 ct ruby; (7) 53.54 ct Cu-bearing tourmaline, Mozambique; (8) 13.97 ct zircon; (9) 2.60 ct emerald (clarity enhanced); (10) 6.43 ct zircon; (11) 8.04 ct blue sapphire; (12) 12.15 ct pink sapphire; (13) 13.67 ct yellow sapphire; and (14) 9.07 ct blue topaz (irradiated and heated). Nos. 1, 3, 6, 8, 9, 11, 12, and 13 are courtesy of Evan Caplan (Omi Gems, Los Angeles); 2, 4, 5, 7, and 10 are from Fine Gems International; and 14 is from Tino Hammid. Photo by Tino Hammid, © Robert E. Kane.

NOMENCLATURE AND DISCLOSURE

Although there is no global standard regarding specifically how a seller should disclose gem treatments or enhancements, there is general agreement that they *should* be disclosed. This disclosure should be to all purchasers, at all levels of commerce (from miner to cutter, wholesaler, jewelry manufacturer, retailer, and—ultimately—the consumer). To find the proper protocol in your country or area, contact one of your national or regional colored stone and diamond organizations, such as AGTA (www.agta.org), ICA (www.gemstone.org), CIBJO (download.cibjo.org), or the World Federation of Diamond Bourses (WFDB, www.wfdb.com).

In the early 2000s, a group that came to be known as the Laboratory Manual Harmonisation Committee (LMHC) was formed at the request of leaders of the colored stone industry. Its purpose was to bring together representatives of many of the major gem laboratories and attempt to standardize wording on their reports ("International labs. . . ," 2000). The LMHC is autonomous and has representatives from the U.S., Switzerland, Thailand, Italy, and Japan. If agreement is reached on a given subject, they issue an information sheet with the wording expected to be seen on reports from those labs. To

Figure 2. This group of diamonds (0.30–0.74 ct) illustrates the wide array of colors that can be produced by artificial irradiation with subsequent annealing. Courtesy of Lotus Color; photo by Robert and Orasa Weldon.

date, 10 such information sheets have been issued, and the group continues to meet twice a year (to download these standardized nomenclature sheets, go to www.lmhc-gemology.org/index.html).

THERMAL ENHANCEMENT

For a wide variety of gem materials, heat treatment is still the most common enhancement. In some cases, heat treatment can still be identified by routine methods. In others, conclusive identification is possible only with advanced instrumentation and techniques. In still other gems (e.g., aquamarine, citrine, amethyst, and tourmaline), heat treatment remains virtually unidentifiable by any currently known methods. For this last group of stones, which are heated to induce permanent changes to their color, this enhancement may be the rule rather than the exception. One should assume that most of those gem materials have been heated.

High-pressure, high-temperature (HPHT) treatment of diamonds was only introduced commercially in 1999, and much of the first decade of the 2000s was devoted to expanding this high-tech treatment to colored diamonds on the one hand—and detecting it on the other. Research efforts thus far have provided methods to identify not only the lightening of off-color diamonds, but also the production of a wide variety of fancy colors.

Diamond. The last decade bore witness to the greater presence of color-treated diamonds, with the global trade reportedly approaching 25,000 carats per month in the latter half of the decade (3–5% of the total diamond trade; Krawitz, 2007). Although not specifically noted, this figure probably refers mostly to irradiated and annealed diamonds of many different colors. Irradiation, heating, HPHT, or a combination of these treatments can create virtually every hue (figure 2), including black and colorless.

HPHT Treatment to Remove Color. HPHT treatment of diamonds to remove or induce color was a central topic of the diamond community throughout the 2000s. In 1999, General Electric Co. and Lazare Kaplan International announced the commercial application of an HPHT process for faceted diamonds (Pegasus Overseas Limited, 1999) that removed color from brown type IIa stones (by annealing out vacancy clusters associated with the brown color in plastically deformed diamonds; Fisher, 2009). Even though scientists had recognized these and other possibilities 30 years earlier (see, e.g., Overton and Shigley, 2008), the results came as a surprise to many in the diamond world—a type IIa brown diamond of any size could be transformed into a colorless stone (see, e.g., Smith et al., 2000). After HPHT treatment, the majority of these diamonds received D through G color grades, and the results were permanent (Moses et al., 1999). Gemological researchers globally mobilized to understand and identify the process (e.g., Chalain et al., 1999, 2000; Schmetzer, 1999; Collins et al., 2000; Fisher and Spits, 2000; Smith et al., 2000).

By late 2000, more than 2,000 decolorized type IIa HPHT-treated diamonds had been seen at the GIA Laboratory (McClure and Smith, 2000). Today, with several treaters in various countries removing color from diamonds with HPHT annealing, this treatment has become almost commonplace.

Determining diamond type is central to the detection of colorless to near-colorless HPHT-treat-

ed diamonds. For a thorough review of how diamond type is determined, see Breeding and Shigley (2009). Nearly 99% of all natural gem diamonds are type Ia. Thus far, all colorless to near-colorless HPHT-treated diamonds reported in the literature have been type IIa. Fortunately, it is easy to determine if a diamond is *not* a type IIa by using the DiamondSure (Welbourn et al., 1996), SSEF Type II Diamond Spotter (Boehm, 2002; Hänni, 2002), or other simple gemological methods (Breeding and Shigley, 2009). At the present time, if a colorless to near-colorless diamond is not type IIa, then it is not HPHT treated.

Visual features related to damage caused by the extreme conditions of the treatment may be seen in some colorless to near-colorless HPHT-treated diamonds. These include a frosted appearance caused by etching or pitting, as well as gray or black graphitization, on naturals or fractures where they come to the surface. Such features are not *commonly* observed in untreated colorless type IIa diamonds, although lightly pitted surfaces and graphitized or graphite inclusions have been seen on rare occasions. Therefore, such features are a good indication of treatment, but they are not proof by themselves (Moses et al., 1999; McClure and Smith, 2000; Gelb and Hall, 2002). Because these heat damage–related features are not always present in a faceted diamond or may be difficult to discern, detection of HPHT treatment in a type IIa diamond generally requires measurement of the absorption and/or photoluminescence (PL) spectra taken with the diamond cooled to a low temperature (see Chalain et al., 1999, 2000; Collins et al., 2000; De Weerdt and Van Royen, 2000; Fisher and Spits, 2000; Hänni et al., 2000; Smith et al., 2000; Collins, 2001, 2003; Novikov et al., 2003; and Newton, 2006).

HPHT Treatment to Produce Color. Refinements to HPHT processing have yielded commercial production of a variety of colors in both type I (orangy yellow, yellow, to yellow green) and type II (pink or blue) diamonds (Shigley, 2008; see, e.g., figure 3).

Identifying HPHT-treated type Ia diamonds requires both IR and low-temperature visible-range spectroscopy, but several gemological properties offer evidence (see Reinitz et al., 2000). The pink and blue HPHT-treated diamonds initially examined by Hall and Moses (2000, 2001b) ranged from Faint and Very Light to Fancy Intense and Fancy Deep. Low-temperature PL spectra identified these products. As discussed below, combining treatments (e.g., HPHT annealing, irradiation, then low-temperature heating) can produce interesting results, such as intense pink-to-red diamonds (Wang et al., 2005b). Smith et al. (2008a,b) contributed useful charts for identifying the natural or treated origin of color in pink and blue diamonds.

Figure 3. This 0.34 ct Fancy Light gray-blue diamond was successfully turned Fancy blue by HPHT treatment. Photos by Elizabeth Schrader.

Heat-Treated Black Diamond. In the late 1990s, it became popular to pavé-set small natural-color black diamonds alongside colorless diamonds in jewelry (Federman, 1999; Gruosi, 1999; Misiorowski, 2000). This design trend continued into the 2000s. As is often the case with successful jewelry lines, less-expensive approaches soon followed. Harris and Vance (1972) had experimented with the production of artificial graphitization in diamond, which Hall and Moses (2001a) confirmed by heating a sample under vacuum for a few minutes to several hours and turning it black; Raman spectra showed a pattern that matched graphite. Notari (2002) discussed several different commercially practiced methods of heating to produce graphitization and black coloration in diamonds.

In many cases, microscopic examination with fiber-optic illumination can provide proof of heat treatment in black diamonds—the black (graphitized) areas are largely confined to surface-reaching cleavages and fractures (Hall and Moses, 2001a). In natural-color black diamonds, the graphitization is randomly dispersed throughout, referred to as a "salt and pepper" effect (Kammerling et al., 1990b). This random orientation is also seen in other color-causing inclusions in natural-color black diamonds, such as magnetite, hematite, and native iron (Titkov et al., 2003). This determination, however, requires a gemologist experienced in examining known samples of both natural-color and heat-treated black diamonds (see, e.g., Smith et al., 2008c).

Ruby and Sapphire. As in the preceding two decades, the heat treatment of corundum to substantially

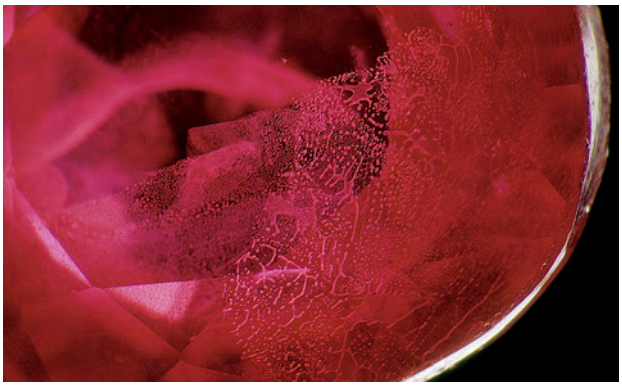


Figure 4. Heat treatment with the stone placed in a flux has largely healed this fracture in a Mong Hsu ruby. However, it has left behind a "fingerprint" that looks similar to those found in synthetic rubies, another challenge for the gemologist. Photomicrograph by S. F. McClure; magnified 40×.

change its color remained a troublesome issue. Heating was applied to the vast majority of rubies and all colors of sapphires during the 2000s.

In some cases, clarity was also affected, as with the flux-assisted healing of fractures (in combination with high-temperature heat treatment) that began in the early 1990s with the discovery of huge quantities of ruby at Mong Hsu, Myanmar (see Peretti et al., 1995; figure 4). The 2000s ushered in a greater understanding of this material—which dominated the ruby market—and cooperation between gemological laboratories to adopt standardized wording to describe heat treatment in corundum and, most importantly, the degree to which fracture "healing" has occurred and the amount of solidified flux "residue" (see e.g., www.lmhc-gemology.org/index.html). Today, there is less production of ruby at Mong Hsu, but this technique is now being used on rubies from Africa (Shor and Weldon, 2009).

There were also new areas of concern, such as beryllium diffusion with high heat (see "Diffusion Treatment" below) and the "Punsiri" high-temperature treatment for blue sapphires. With regard to the latter, concerns arose in late 2003 when some laboratories first observed unusual color concentrations in larger heat-treated blue sapphires (figure 5) immersed in methylene iodide (Scarratt, 2004; Smith et al., 2004). All had one consistent characteristic: a colorless or near-colorless outer rim and a deep blue (or, if color change, purple) interior (figure 6).

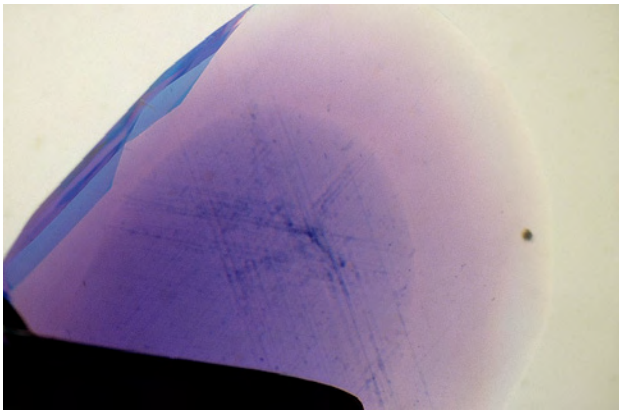
After comprehensive analytical research (and GIA and AGTA observation of the technique as performed by treater Tennakoon Punsiri in Sri Lanka), the SSEF, AGTA, and GIA laboratories all came to the same conclusion: These stones were not diffused with beryllium or any other element (McClure, 2003b; Hänni et al., 2004; "ICA issues its first lab report. . . ," 2004). The major gem labs continue to identify sapphires treated by the "Punsiri" method as natural sapphires that show evidence of heat treatment.

Beginning mid-decade, demand and scarcity significantly drove up prices for colorless or "white" sapphire. As a result, dealers in Sri Lanka reported that lightly colored sapphires had been heated to render them colorless (Robertson, 2008). Ironically, the scarcity of natural white sapphire was caused in part by the large quantities that were being used for Ti blue diffusion and, to a lesser extent, Cr red diffusion.

Since the two previous *G&G* retrospective articles on treatments (Kammerling et al., 1990a;

Figure 5. This matched pair of blue sapphires (3.07 and 3.10 ct) were heat treated by the Punsiri method. Photo by Maha Tannous.

Figure 6. The unusual color zoning in this color-change sapphire is typical of stones treated by the Punsiri method. Photomicrograph by S. F. McClure; magnified 10×.



McClure and Smith, 2000), heat-treatment technology—in the form of electric furnaces with precise temperature and atmospheric controls—has become more sophisticated and accessible. During the 1980s and 1990s, nearly all commercial corundum heat treatment was being conducted in Thailand. While Thailand remains important, Sri Lanka is now a major force, and smaller yet very effective corundum-heating capabilities exist in other producing regions such as Africa, Myanmar, China, and the U.S. (Montana). Nevertheless, some pink sapphires and rubies continue to be heated using simple blowpipe methods at mine sites and trading centers in Vietnam, Sri Lanka, and elsewhere (R. Hughes, pers. comm., 2010).

Heat treatment, particularly at high temperatures, can dramatically alter the internal characteristics and properties of sapphires and rubies. During the past decade, a number of articles addressed heat-treatment techniques and their effects on gem corundum from localities such as Madagascar (Wang et al., 2006a), Montana (Schmetzer and Schwarz, 2007; Kane, 2008), Australia (Maxwell, 2002), Vietnam (Winotai et al., 2004), Myanmar (Kyi et al., 1999), and Malawi (Rankin, 2002; Rankin and Edwards, 2003). Schmetzer and Schwarz (2005) discussed the identification of natural, heated, and Be-diffused yellow to reddish orange sapphires from Sri Lanka, Montana, Madagascar, and Tanzania. David and Fritsch (2001) contributed a valuable study on the use of infrared spectra to distinguish heated rubies and sapphires from 20 different geographic origins.

Proof that a ruby or sapphire has been heat treated is sometimes readily apparent, but in many cases it requires considerable knowledge and observational skills. The criteria for identifying heat treatment in rubies and sapphires using a microscope were set forth during the 1980s and '90s (for a summary, see Kammerling et al., 1990a). Most still apply. They include stress fractures surrounding melted or heat-altered inclusions; spotty coloration in blue stones, best seen with diffused illumination; colored halos surrounding altered solid mineral inclusions; stubby, partially absorbed (dot-like) silk; and pockmarked, resorbed facets.

Relatively low-temperature heating (i.e., 800–1200°C), particularly of purplish pink sapphires (and some purplish red rubies) to remove the blue color component, is still very difficult to detect with standard microscopic testing. The lower the temperature used, the more difficult the detection will be (Krzemnicki, 2010).

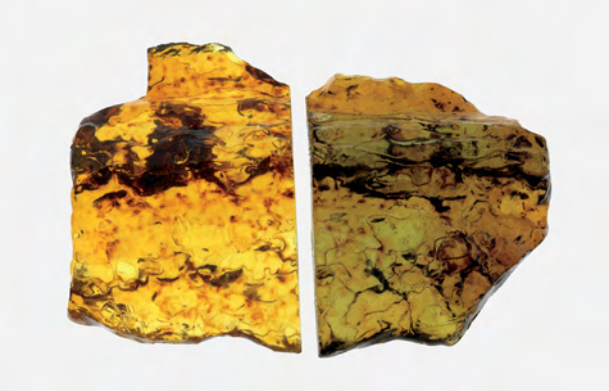


Figure 7. This ~7.5-cm-wide piece of amber was cut in half and the segment on the left treated by the first step of the "greening" process and the half on the right treated by both steps to turn it green. Photo by C. D. Mengason.

Equally important is being able to prove that a ruby or sapphire has *not* been heat treated. The decade yielded rich contributions in this area; see Shor and Weldon (2009) and Shigley et al. (2010) for important literature references. Smith et al. (2008d) and Smith (2010) provided useful charts for identifying the natural or treated state in rubies and sapphires from around the world.

Amber. Amber and copal are still heated to improve clarity, color, and hardness, and to induce "sun spangles" (Kammerling et al., 1990a; O'Donoghue, 2006). In 2009, Abduriyim et al. described a new method to produce a green color in amber and copal (figure 7), some as bright and green as peridot, using a two-stage process of controlled heat and pressure in an autoclave for long durations. Multiple treatments may increase the color saturation, producing an intense, pure green hue that has not been seen in untreated amber. The treatment also reportedly hardens the amber, making it more stable (Abduriyim et al., 2009). While infrared spectroscopy can distinguish amber from copal (Guiliano et al., 2007), this new treatment process "ages" the copal, rendering its properties similar to those of amber and making its identification as copal extremely difficult, even with advanced analytical methods.

The presence of a small absorption around 820 cm^{-1} in the FTIR spectra confirmed the use of multiple treatments on all the commercial "green amber" samples tested by Abduriyim et al. (2009). Although the use of heat treatment on a specific piece can be ascertained, whether or not the original starting material was copal or amber still cannot be routinely identified.

Garnet. Around 2003, members of the trade began reporting that Russian demantoid is routinely subjected to low-temperature heat treatment to remove or reduce the brown color component ("The reds. . . ," 2003; N. Kuznetsov, pers. comm., 2003). Other than the presence of altered inclusions in some stones, no measurable gemological means of detection has yet been reported. The result is that some international laboratories make no determination of whether a demantoid has been heated, whereas others will state if indications of heating are present (Pala International, 2010).

Spinel. As was the case with garnet, it was long believed that spinel was never treated. Beginning in 2005, however, researchers determined that certain pink-to-red spinels from Tanzania were heat treated (Saeseaw et al., 2009a). In 2007, four large (6–54 kg) spinel crystals were faceted into many thousands of fine gems from melee sizes up to 10–50 ct (Pardieu et al., 2008). Again, rumors of heated spinel began to circulate. This prompted researchers to conduct before-and-after heat treatment studies of spinel from various localities. It was concluded that heated and unheated natural spinel could easily be distinguished by the width of the 405 cm^{-1} Raman line, or by examining the width of the Cr^{3+} PL spectrum line in stones containing sufficient chromium (Saeseaw et al., 2009b,c; Kondo et al., 2010).

Tourmaline. The heat treatment of Cu-bearing tourmalines from Paraíba, Brazil, and the enormous demand for both the natural-color and heat-treated material, continued through the decade. An interesting twist occurred when Cu-bearing tourmalines were discovered in Nigeria (Smith et al., 2001; Breeding et al., 2007) and Mozambique (Abduriyim and Kitawaki, 2005; Abduriyim et al., 2006; Laurs et al., 2008).

These tourmalines were commonly heated (e.g., figure 8) to create a wide range of attractive colors similar to many of those found in Paraíba. With the exception of obviously heat-altered inclusions, standard testing cannot identify heat treatment in these tourmalines.

For several decades, heat has been known to reduce saturation in overdark red tourmalines. However, many cutters resist heating these stones because tiny fluid inclusions tend to burst during heating and cause breakage (B. Barker, pers. comm., 2008).

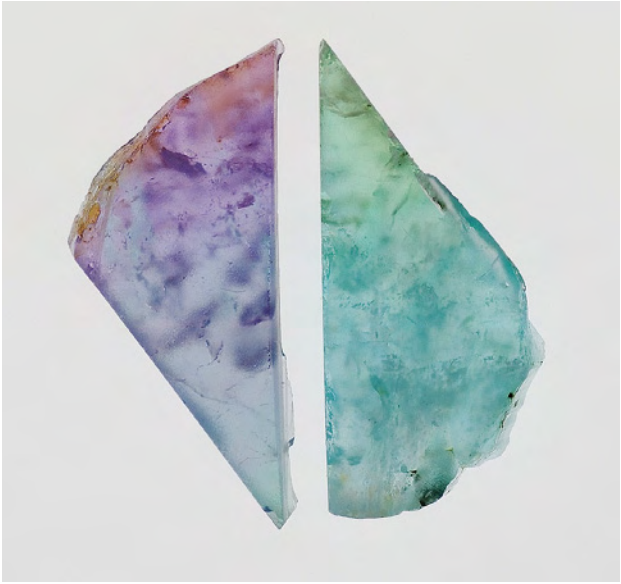


Figure 8. This copper-bearing tourmaline from Mozambique was cut in half, and the piece on the right (8 × 20 mm) was then heat treated. Photo by C. D. Mengason.

Zircon. Faceted orangy, pinkish, and yellowish brown zircons from Tanzania, known by trade names such as "cinnamon" zircon, were plentiful in the market (see figure 1, no. 10). To lighten overdark tones, nearly all such stones in the market have been heated—often in a test tube with low heat (R. Shah, pers. comm., 2010). Since there is no means of identifying whether these gems—like blue zircon—have been heated, we recommend that all zircon of this color range be considered as heated.

Cultured Pearls. Although not widely recognized, heat is sometimes used to alter the appearance of cultured pearls. Heat alone usually produces more saturated yellow colors, and other effects can result when heat is used in combination with other methods ("Better techniques improve brown pearls," 2006) such as bleaching. In all cases, detecting heat treatment can be challenging. There are no obvious thermally enhanced inclusions as in some gems, and the only useful methods determined to date usually involve UV fluorescence reactions and UV-Vis-NIR spectroscopy (Elen, 2001; Wade, 2002).

DIFFUSION TREATMENT

Diffusion treatment was more problematic for colored stones than any other enhancement in the 2000s. Beryllium diffusion, in particular, "upped the bar" on the sophistication of equipment and level of knowledge needed by gem laboratories.

Corundum. Titanium diffusion of sapphire continued throughout the decade, with one instance reported of these stones sold in Australia as heat-treated Ceylon sapphire ("Fusion treated sapphire alert," 2001). Little changed with this method, and its identification remains the same—color concentration along facet junctions, facet-related color, high relief in immersion, and the like (Kane et al., 1990).

Chromium diffusion of corundum has been debated as being more of a chemical reaction at the surface of the stone than true diffusion. It was actually shown on some stones to be a synthetic ruby overgrowth (Smith, 2002). This treatment is very difficult to perform, and to the authors' knowledge is not currently being used.

The diffusion of corundum using cobalt was also reported in the last decade (Kennedy, 2001; McClure, 2002b), but this material was easily identified with magnification and diffused light by a very shallow color layer that showed spotty coloration, as well as observation of a cobalt spectrum with a desk-model spectroscope.

The first serious diffusion challenge started in 2001, when large numbers of pinkish orange ("padparadscha") sapphires showed up in certain markets (Genis, 2003). The color was attributed to a new form of heat treatment done in Thailand. Some labs in Japan are said to have issued over 25,000 reports stating just that (Genis, 2003; Weldon, 2003). In early 2002, however, examination with the stones immersed in methylene iodide revealed that they had a surface conformal layer of orange color surrounding a pink core (Weldon, 2002; figure 9). With this discovery, the illusion that the color was caused by "standard" heat treatment began to crumble ("Orange crush," 2002).

The story is well documented by Emmett et al. (2003). At first, the reason for the orange surface-related color zone could not be determined. The standard equipment available in gemological laboratories detected nothing unusual (McClure et al., 2002). At the February 2002 Tucson shows, however, it was announced that the culprit was beryllium ("GIA-GTL suspects beryllium causes orange colour in treated pink sapphires," 2002; Hughes, 2002; Genis, 2003). Unfortunately, beryllium was almost unknown in corundum, with very little information available in the literature.

There were two major differences between Ti and Be diffusion. First, beryllium, being a very small atom, was capable of diffusing all the way through even large sapphires. Titanium could not do this, even with heating times lasting several weeks. Second, titanium is only capable of creating blue color in sapphire. Beryllium, however, can affect virtually every color of corundum in some way when combined with Fe (figure 10). Colorless, light yellow, or light blue can be turned to intense yellow (see, e.g., figure 11); pink can be altered to orange or padparadscha color; dark brownish red to bright red; and dark inky blue to lighter blue—just to name some of the possibilities (Coldham, 2002; Henricus, 2002; Moses et al., 2002).

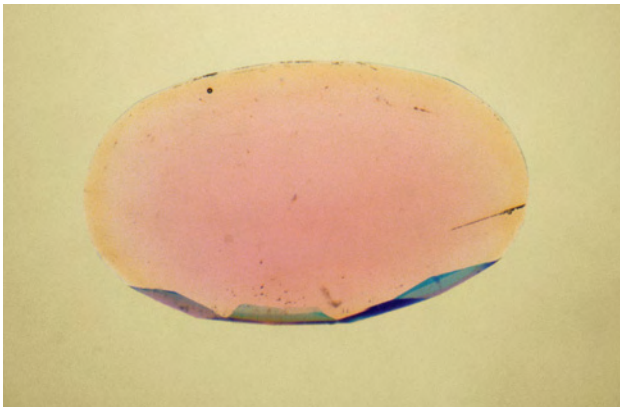


Figure 9. A shallow surface-related orange rim around a pink core is diagnostic of some Be-diffused sapphires. Photomicrograph by S. F. McClure; magnified 10×.

Identifying this treatment turned out to be complicated. Severely heat-damaged inclusions were found in many of these treated stones (Roskin, 2003a; Schmetzer and Schwarz, 2005), but they only indicate that the stone was treated at extreme temperatures—they do not prove the presence of Be (Emmett et al., 2003). After a time, we started to see Be-diffused blue sapphires treated by an even newer method that showed no surface-related characteristics and created unusual inclusions (figure 12; Choudhary, 2006; Kitawaki and Abduriyim, 2006; Roskin, 2006; DuToit et al., 2009). These inclusions also did not prove Be treatment, but they strongly indicated that further testing was needed.

Areas of synthetic corundum overgrowth were commonly seen on Be-diffused faceted stones, but Be was not necessary for this to happen (McClure, 2002a). UV fluorescence was helpful in some situations, but not all (Fritsch et al., 2003). Even chemical analysis was a problem, as the standard instruments used at gemological laboratories and most universities (EDXRF and electron microprobe) cannot detect light elements such as beryllium. Detecting Be meant using instrumentation such as mass spectrometers. At that time, no gemological laboratory

Figure 10. Almost every color of corundum can be affected in some way by beryllium diffusion, as illustrated by this large group of Be-diffused rough and faceted stones (1.03–8.53 ct). Photo by Robert Weldon.

possessed this capability, so testing had to be done at commercial laboratories, which is very expensive. Today, several gem labs have this equipment in-house and offer Be testing as a service.

Feldspar. In 2002, a transparent red feldspar colored by copper debuted on the market, reportedly originating from the Congo. This did not raise suspicion initially, as natural red feldspar colored by copper was already well known (from Oregon). Over time, however, the supposed location of this feldspar mine kept changing—to "China," "Inner Mongolia," and then "Tibet." Although most of the feldspar was red, some green material also entered the market (e.g., figure 13).

The first question raised about this material had nothing to do with treatment, but focused on nomenclature (Krzemnicki, 2004a): Was it labradorite or could it be called andesine? Andesine was rare in gem quality, so this could be very valuable to marketing efforts. Although much of the material was indeed andesine, in time this became a secondary issue. Large amounts of this feldspar were being sold as all-natural, untreated material. In July 2008, however, Masashi Furuya of the Japan Germany Gemmological Laboratory reported that he had direct evidence (from experiments done in Thailand) that this feldspar was being diffusion treated by a three-step process that took months to complete (Furuya, 2008). He also mentioned the same type of material being diffused in China by an unknown process.

Other reports suggested that the unusual color zoning found in this material indicated diffusion treatment (Fritsch et al., 2008). Subsequent studies conflicted with this idea, showing natural Oregon material with very similar zoning (McClure, 2009).

To address the controversy, systematic experiments were undertaken to diffusion treat plagioclase. They showed it was surprisingly easy to duplicate the Cu-diffusion process in only a few days (Roskin, 2008; Emmett and Douthit, 2009). Also, gemologists visited a mine in China's Inner Mongolia that produced andesine-labradorite, but

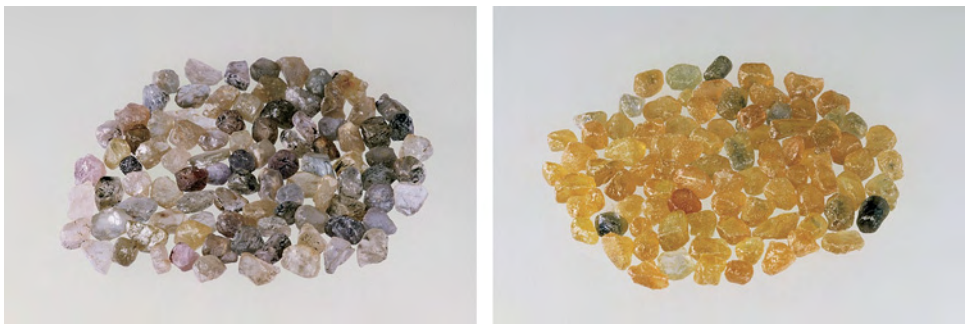


Figure 11. As these before-and-after images illustrate, beryllium diffusion can produce profound color alterations in corundum, here turning 1–2 ct light blue sapphires to intense yellow. Photos by Maha Tannous.

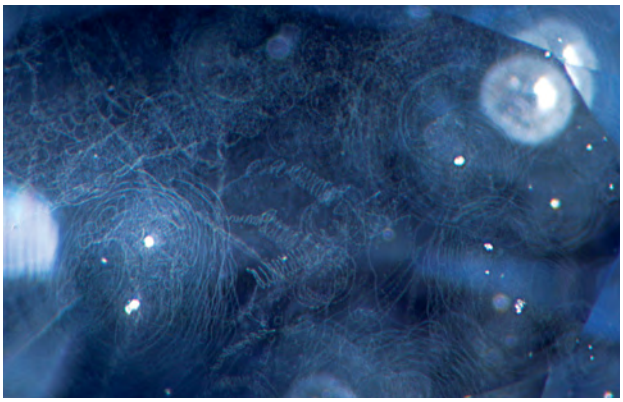


Figure 12. Later developments in Be diffusion of blue sapphires created some very unusual inclusions. Photomicrograph by S. F. McClure; field of view 2.0 mm.

only with a pale yellow color (Abduriyim, 2008). The material could not be simply heated to red or green because it contained virtually no copper (Thirangoon, 2009). This fact left diffusion as the only possible treatment method for these stones.

Claims of a mine in Tibet began in 2005, but their credibility was questionable. In 2008, a team visited a mine in Tibet, collected samples, witnessed mining, and documented red andesine that appeared to be *in situ* (Abduriyim, 2008). However, the samples collected proved to be virtually identical to the diffused Inner Mongolian red andesine, calling the mine into question again. Its authenticity is still not resolved.

With the controversy surrounding this material, identification of this feldspar as treated is still problematic using standard gemological techniques, primarily because the issue of the Tibet mine is not resolved. Color zoning may be useful. A complete "bull's-eye" color zoning with red-inside-green usually means the stone is natural, while green-inside-red may indicate treatment (McClure, 2009). However, if you have a partial "bull's-eye" or merely zoned areas, this criterion is unreliable. To date, larger platelets of copper have been found only in the natural Oregon material (McClure, 2009; Rossman, 2009, 2010). However, separation of Oregon and Chinese feldspar in a gemological laboratory is not difficult as they are all distinct chemically.

Topaz. Blue-to-green topaz surface-treated with cobalt was marketed in the 2000s as an alternative to irradiated blue topaz (Federman, 2007a), a tactic that took advantage of the public's fear of radiation. This material has long been marked as "diffusion treated," even though this claim was never truly substantiated. Gabasch et al. (2008) determined that the layer of coloration was "diffusion induced," creating new phases at the surface. This is not so different from the opinions put forth in the late '90s that the treatment was more of a chemical reaction than diffusion.

Several companies announced lines of "diffusion treated topaz" in new colors of red and pink to "champagne" and bicolors (Roskin, 2003b; "Diffused topaz from India," 2003), but questions still exist as to whether they are from a diffusion or coating process.

Identification of this material is fairly easy. With magnification, the color has a spotty appearance and, due to the extremely thin nature of the color layer, any small chips or abrasions will show the colorless nature of the base topaz.

Other Materials. The discovery that diffusion treatment of feldspar was possible generated claims that many other gems—such as Cu-bearing tourmaline from Mozambique, Imperial topaz, and tsavorite (Federman, 2009)—were also being diffusion treated. To date, no significant scientific data have been presented to support these claims, though experiments have begun to explore some of these possibilities (Saeseaw et al., 2009a).

There was one report of tanzanite possibly being diffused, but examination of the suspect stones showed no evidence of diffusion (Wang, 2003).

CLARITY ENHANCEMENT

During the 1990s, clarity enhancement was one of the jewelry trade's most formidable challenges. Its use

Figure 13. Represented as untreated plagioclase from Tibet, these feldspars weigh 0.45–15.51 ct. Photo by Robert Weldon.

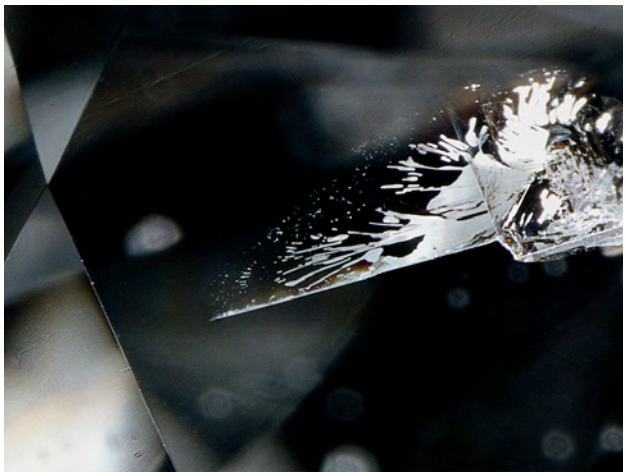


Figure 14. The filler in most clarity-enhanced diamonds is easily damaged by heat, which created the voids seen in this stone. Photomicrograph by S. F. McClure; field of view 2.1 mm.

with emeralds—in what had basically amounted to a trade secret—was touted publicly and almost caused the crash of the emerald market. In addition, the clarity enhancement of diamonds spread rapidly, with improper disclosure causing the ruin of some businesses. Clarity enhancement has remained a serious issue in the 2000s. However, the methods changed and the focus has been on different gem materials.

Diamonds. The biggest concern about the clarity enhancement of diamonds via fracture filling revolved around the durability of the glass filler. Damage due to heat (figure 14) from standard jewelry repair procedures, such as retipping, inevitably caused problems at the retail level. One of the major treaters (Oved) announced in 2000 that they had developed a filler that could withstand such heat (Bates, 2000;"Oved announces. . . ," 2000). However, testing showed that although the new Oved filler material seemed to withstand higher temperatures, it still could be damaged by some jewelry repair procedures, even when performed by a master jeweler (Shigley et al., 2000). Oved instituted a policy of laser inscribing their company name on a bezel facet of all the diamonds they treated so the filled stones could not be misrepresented (Gallagher, 2000).

The practice of laser drilling diamonds to create an opening through which acid could be introduced to remove a dark inclusion had remained unchanged for many years, until a new version was introduced that took advantage of advances in laser technology. Developed in Israel and referred to as the "KM treatment" (short for *kiduah meyuhad*, or "special drill" in Hebrew; Horikawa, 2001), this method did not actually drill a hole into the stones. Instead, it used lasers to create a small fracture from the inclusion to the surface so that the inclusion could be bleached without leaving a tell-tale hole at the surface (figure 15; McClure et al., 2000a). Unfortunately, this treatment entered the market undisclosed, and its fraudulent nature caused the Israel Diamond Bourse to outlaw its use. It continues to be encountered, and is often referred to as "internal laser drilling."

Identification is done with magnification. The laser leaves behind lines or dots of irregular squiggles, with feathers leading from an inclusion to the surface (figure 16). These marks tend to look black in transmitted light, and are usually confined to a feather (McClure et al., 2000a; Cracco and Kaban, 2002; McClure, 2003a). They may be tiny and difficult to find even with a microscope—or large and numerous, easily seen with a loupe.

Other observations were posted in the literature periodically. Among them were changes in flash-effect colors (Cracco and Johnson, 2008), filled fractures in treated-color diamonds (Song et al., 2009; Gelb, 2005), difficult-to-identify damaged fillers (Gelb and Hall, 2005), and fracture filling associated with a pink dye (Yeung and Gelb, 2004).

Ruby. The first report of faceted rubies showing a flash effect similar to that seen in clarity-enhanced diamonds was in 2004 ("Lead-glass impregnated ruby. . . ," 2004). Chemical analysis revealed that these rubies were filled with a high-lead-content glass. Soon other labs reported this treatment ("New treatment on unheated rubies. . . ," 2004; Rockwell and Breeding, 2004; Milisenda et al., 2005).

It became apparent that this treatment was going to be very significant to the industry (Roskin, 2004). The starting material was very low quality, translucent-to-opaque, non-gem rough from Madagascar (Pardieu, 2005). By a process that involved low-temperature heating, cleaning in an acid bath, and then filling with a high-lead-content glass, this non-gem corundum was transformed into transparent, facetable material (figure 17). This made available huge amounts of treated rubies that were usually sold at very low prices.

Identification of these filled rubies was not difficult. Most had so many filled fractures that the flash effect was easy to see with magnification, although the red color of the ruby sometimes partially masked the orange flash (McClure et al., 2006; figure 18). Flattened gas bubbles and high-relief unfilled areas within the fractures were also readily visible with

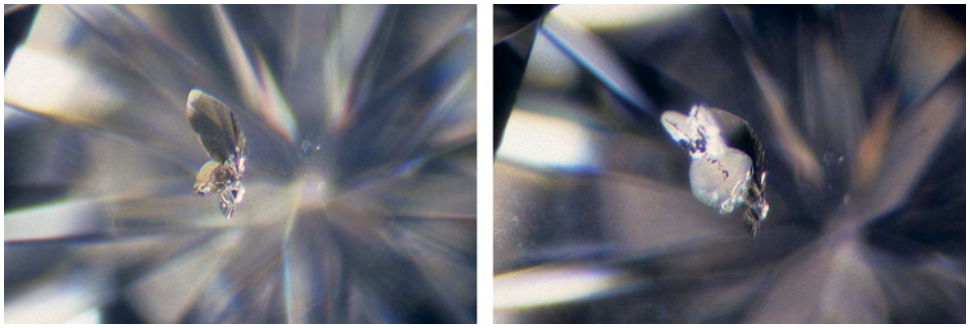


Figure 15. Internal laser drilling can create a feather from a black inclusion to the surface of the diamond, providing a conduit for the acid that will then bleach the inclusion, as shown in these before (left) and after photos. Photomicrograph by S. F. McClure; magnified 40×.

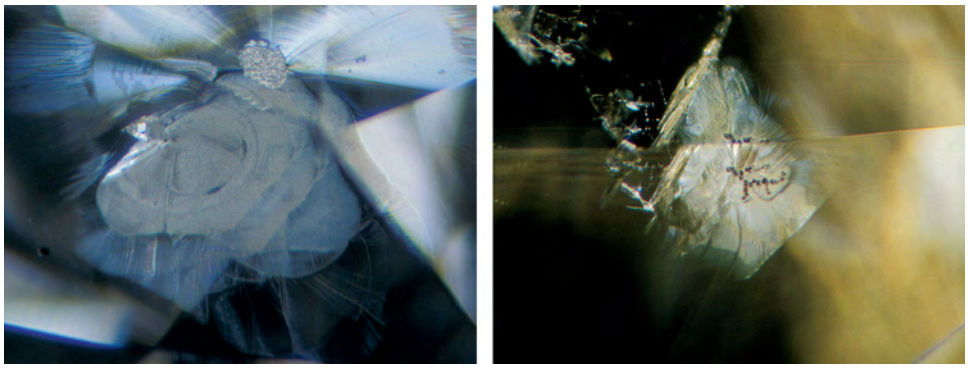


Figure 16. Internal laser drilling can be identified by the characteristic inclusions—such as dots, squiggles, and disk-like marks—it leaves behind. Photomicrographs by S. F. McClure; magnified 25× (left) and 40×.

magnification. However, the use of reflected light to look for differences in surface luster was not very helpful in this case. The luster of this glass was very similar to that of ruby, sometimes even higher (Smith et al., 2005), so it was much more difficult to see than the more typical silica glass fillers.

The filler proved relatively durable to heat (up to ~600ºC), but it was easily etched by even mild acids such as pickling solution (McClure et al, 2006). This etching turned the filler white near the surface, rendering it quite visible.

Also of concern was the decreasing quality of the starting material. We began to see stones where the flash was everywhere, and internal filled cavities containing large spherical gas bubbles were common (Scarratt, 2009).

The nomenclature for this treatment soon became an issue. The early material was referred to as *clarity enhanced* because even though the treatment was fairly extensive, the rubies were mostly solid material that would be expected to stay together even without the treatment. However, some of the later material contained so much glass that it appeared the glass was actually holding the pieces of ruby together. Soaking such stones in hydrofluoric acid to remove the glass resulted in their falling apart along fractures or being reduced to tiny pieces (Scarratt, 2009). Accordingly, GIA developed a three-tiered system, keeping *clarity enhanced* for more solid material, specifying *ruby with glass* for stones that needed the glass to stay together, and using *ruby/glass composite* for those composed of unrelated pieces of ruby floating in glass (Scarratt, 2009; figure 19). The other labs of the LMHC adopted these criteria. American Gemological Laboratories (AGL) and the International Colored Gemstone Association (ICA) have chosen to call all these stones *composite ruby*.

The real problem, however, is the large amount of this material that is being sold without any disclosure. So far, this treatment has even appeared in ruby

Figure 17. Filling ruby with a lead-based glass can change non-gem corundum (on left) to transparent, facetable rubies such as those on the right. The samples (2.13–39.17 ct) are courtesy of Hussain Rezayee and GIA; photo by Robert Weldon.

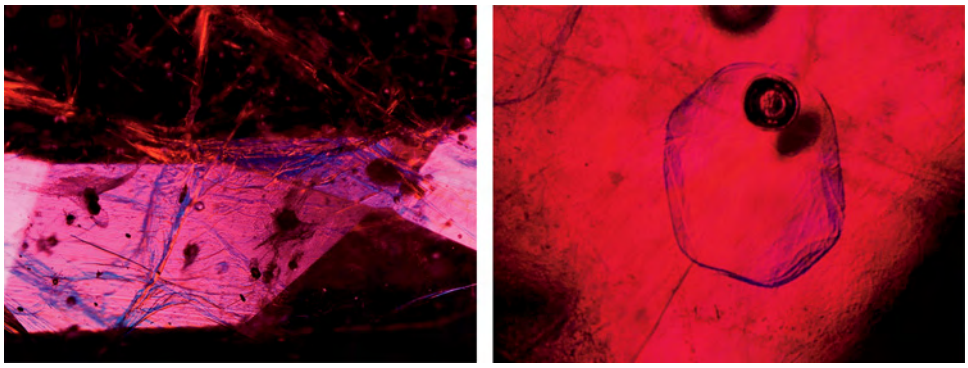


Figure 18. Blue and orange flash colors are the best indication of lead-glass filling, whether they are seen in fractures (left) or in internal cavities that often also have spherical gas bubbles (right, with only the blue flash color visible). Photomicrographs by S. F. McClure; fields of view 2.4 and 1.4 mm respectively.

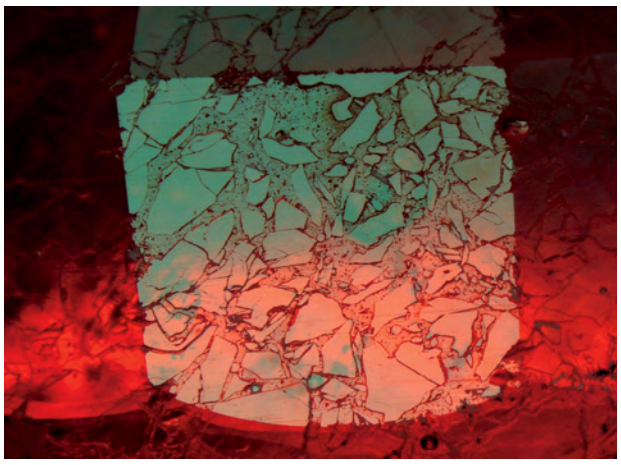
beads (Hänni, 2006a), color-change sapphires (Choudhary, 2008), hollowed-out rubies set in closed-back mountings (Krzemnicki, 2007), and estate jewelry (Quinn Darenius, 2010).

Emerald. The damage caused to the emerald market in the 1990s from lack of disclosure of clarity enhancement slowly began to fade in the 2000s (Gomelsky, 2003). However, the debate over the use of oil versus polymers as filler material continues, and a significant study was done on the durability of fillers (Johnson, 2007).

To address the possibility that a highly fractured stone was masquerading as a much finer one simply because of the treatment, labs started to state the degree of enhancement on their reports (e.g., McClure et al., 2000b). Different systems were developed with anywhere from three to nine categories (Gomelsky, 2001a,b); the most common were three- or four-tiered. Today, degree-of-enhancement calls have become standard procedure for emerald reports from all the major laboratories.

Near the end of the decade, it was reported that some emerald rough was being "stabilized" with hardened polymers, so larger stones could be cut (Roskin, 2007; Federman, 2008). In effect, though, the polymer glues the pieces of emerald together at the fractures (e.g., figure 20), so its removal would result in the stone falling apart (Federman, 2007b). This situation is very similar to that of the lead glass–filled rubies, making disclosure even more important.

Figure 19. Some lead glass–filled rubies have so much glass that they are actually pieces of ruby floating in glass. Such material is more properly called a ruby/glass composite. Photomicrograph by S. F. McClure; field of view 4.1 mm.



Other Materials. Laboratories have reported on many other filled gems. Some of those mentioned in the 2000s include: aquamarine and tourmaline (Wang and Yang, 2008; Deng et al., 2009), andalusite (Fernandes and Choudhary, 2009), fuchsite quartzite (Juchem et al., 2006), hackmanite (Wehr et al., 2009), and iolite (McClure, 2001).

IRRADIATION AND COMBINED TREATMENTS

Intense colors can be induced in many gems by exposing them to various forms of radiation, such as electrons, gamma rays, or neutrons. To remove unwanted color overtones, some irradiated stones are subsequently heated. While the 1980s saw significant experimentation and development in the area of gemstone irradiation, very few new types of irradiated gems appeared on the market during the 1990s and 2000s. Likewise, little progress was made in detection methods.

For many gems, there is no definitive test or series of tests to establish whether they have been irradiated. Even though irradiation has been used for many years to produce intense colors in yellow beryl, pink-to-red tourmaline, and kunzite, these enhancements remain undetectable. The same is true for blue topaz and many other routinely irradiated gem materials.

Blue irradiated (and annealed) topaz generates

more than $1 billion annually in retail sales (Robertson, 2007). The low cost of irradiated blue topaz (typically a few dollars per carat at wholesale) leaves the trade little economic incentive to determine whether or not the gem has been treated. As a result, all blue topaz is assumed to have been irradiated. The same is true for smoky quartz and dark yellow beryl.

Diamond. With the staggering prices realized at auction for some fancy-color diamonds during the last decade (e.g., more than $1 million per carat for some natural-color blue and green diamonds), there is huge incentive to determine whether a diamond's color is natural or irradiated. Large quantities of diamonds continued to be irradiated (often followed by low-temperature annealing at atmospheric pressures) to produce a wide variety of colors—red, orange, yellow, green, blue, violet, and purple—in saturations from light to very dark (see Overton and Shigley, 2008; Shigley, 2008). Many treaters produced small faceted irradiated (and annealed) colored diamonds for use in jewelry.

The most significant developments in diamond irradiation since 2000 were in combination treatments. Both natural and synthetic diamonds are now color enhanced by a process that involves first HPHT annealing, then irradiation, followed by low-temperature heating (likely in that order), to produce several colors, including red, pink, orange, and green (Schmetzer, 2004; Shigley et al., 2004; Wang et al., 2005a; Wang and Johnson, 2010b; Wang et al., 2010). Identification generally requires measurement in a laboratory of the absorption and/or photoluminescence spectral features present with the diamond cooled to a low temperature, although in some cases standard gemological testing can also offer clues (see e.g., Shigley, 2008). Other combinations also exist, such as irradiated and glass-filled diamonds (Gelb, 2005; Gelb and Hall, 2005).

Topaz. The potential enforcement of Nuclear Regulatory Commission (NRC) guidelines on irradiated gems (American Gem Trade Association, 2007) caused great concern in the first decade of the 2000s. Since 1986, NRC regulations have stated that any neutron-irradiated gemstone produced in or imported into the U.S. must be tested for residual radiation by an NRC-licensed testing facility (Nuclear Regulatory Commission, 1986; Ashbaugh, 1988). Whereas considerable amounts of blue topaz were once treated in the U.S.—and then properly tested for radioactivity and held until the radioactivity subsided—nearly all treated blue topaz entering the market since the latter half of the decade has been irradiated and annealed in other countries, some of which may not restrict the export of "hot" material.

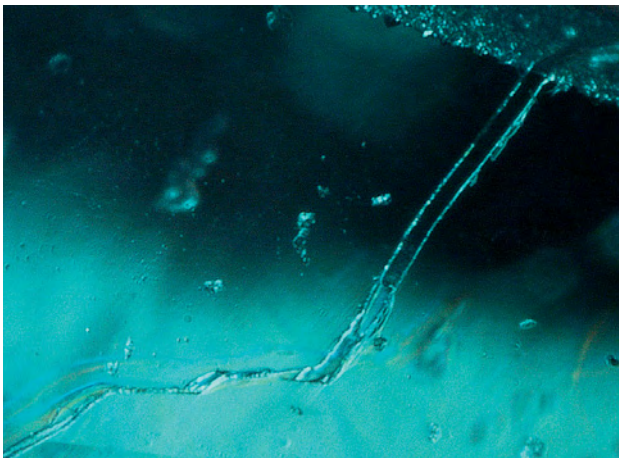


Figure 20. In some emeralds, as with some rubies, the filler material may actually be holding the stone together. Note in this emerald that the resin is binding material that otherwise would be broken by the large, wide fractures.

Amid the confusion generated by this issue, several major retail chains and department stores stopped selling blue topaz. After receiving numerous trade and public inquiries regarding blue topaz, the NRC issued a fact sheet on irradiated gemstones (United States Nuclear Regulatory Commission, 2008). To further address the issue, the Jewelers Vigilance Committee (JVC) and American Gem Trade Association (AGTA) published a 2008 brochure titled "The Essential Guide to the U.S. Trade in Irradiated Gemstones."

To our knowledge, the NRC has still not enforced its regulations, and neutron-irradiated blue topaz continues to be imported and sold in the U.S. However, no blue topaz containing residual radioactivity has been reported recently in the trade.

Earlier—around 2000—Europe faced similar concerns that irradiated blue topaz exhibiting residual radioactivity had made its way into several different countries (Kennedy et al., 2000).

U.S. Postal Service Irradiation. During the anthrax scare of late 2001, the USPS irradiated envelopes and packages to kill potential biological agents. The company that the postal service contracted with to perform the test, SureBeam, used a linear accelerator to create a beam of high-energy electrons. The potential impact of this exposure was immediately recognized, since the same ionizing radiation is routinely used to change the color in several types of

gems. McClure et al. (2001) showed alarming evidence of several gems that had their color changed dramatically after being exposed in SureBeam's facility to the same dosage as was used for the mail. The USPS subsequently abandoned these procedures, after determining that the time and money needed to sanitize all mail would be prohibitive.

Green Quartz. In the latter part of the decade, an unusual amount of faceted green quartz suddenly appeared on the world market. Nearly all these gems—which originated from Rio Grande do Sul, Brazil—began as colorless to light yellow quartz that was subsequently irradiated to produce the green color (Kitawaki, 2006; Schultz-Güttler et al., 2008). Natural green quartz does exist but is extremely rare, and "greened quartz" (also known as prasiolite) is produced by heating certain types of amethyst. Irradiated green quartz shows a broad spectral absorption at 592–620 nm, while prasiolite exhibits a broad band centered at 720 nm. When examined under a Chelsea filter with incandescent light, irradiated green quartz appears red and prasiolite appears green (Schultz-Güttler et al., 2008; Henn and Schultz-Güttler, 2009).

Beryl. In addition to the huge quantities of irradiated yellow beryl, which remains undetectable, irradiated yellowish green beryls were seen. Milisenda (2007a) reported absorption lines between 500 and 750 nm for the ordinary ray, which are also typically seen in artificially irradiated "Maxixe-type" beryls. Milisenda (2007b) reported a beryl with "Maxixe-type" spectra that was offered for sale as a cat's-eye scapolite but proved to be a blue irradiated cat's-eye beryl.

Hiddenite. Milisenda (2005a) reported on a parcel of intense green faceted spodumenes from Pakistan, offered for sale in Idar-Oberstein as hiddenite, that were artificially irradiated. The stones revealed a broad absorption band centered at 635 nm. As expected for this material, the color faded to the original pale pink within a few days.

Pearls. The irradiation of pearls has been known for decades, and little has changed since 2000. The treatment is almost always associated with freshwater pearls or nuclei, since the radiation appears to alter the state of the trace element manganese found in these materials. Gray, silvery gray, and black colors have all been produced. In fact, pearls were one of the gems significantly altered by the U.S. postal service irradiation mentioned above. Detection remains a challenge in some cases, and research has continued on its identification (Liping and Zhonghui, 2002).

SURFACE COATING

As it has been for centuries, applying surface coatings to change the color of gems continues to be a common practice. Not only do gemologists need to be aware of high-tech coatings, we must also remember to look for older, simpler alterations.

Diamonds. Just as Miles (1964) described decades ago, in 2003 Sheby reported seeing two slightly yellow diamonds that were coated with a blue material to improve the apparent color. Also as a recent reminder, Eaton-Magaña (2010) described a 1.5 ct diamond with a color equivalent to Fancy pink that revealed a nearly imperceptible trace of reddish material on a natural when viewed with the microscope. After cleaning, the diamond was graded Faint pink.

Sputter-coated optical thin films were originally developed in the 1940s to improve the optical performance of lenses. We continued to see similar coating technology used on diamonds in the 2000s. Evans et al. (2005) and Wang et al. (2006b) reported on faceted diamonds that were colored pink by sputter-coated thin films. A potentially new kind of diamond coating was described by Epelboym et al. (2006)—rather than using the fluoride coatings previously known, pink and orange-treated diamonds were suspected of being coated with a silica film doped with gold.

Shen et al. (2007) reported that the trade was submitting greater numbers of pink diamonds coated by calcium fluoride (CaF_2) to the GIA Laboratory for grading and origin reports. They also described Serenity Technologies' use of multiple micro-thin coatings of various compositions to produce a variety of colors on diamonds, including intense blue, green, yellow, and orange to pink to purple-pink (figure 21).

We continue to see crude yet effective colored coatings applied to the girdle facets of diamonds with permanent markers and solutions made from colored art pencils.

Diamond-Like Carbon Thin Films. Super-hard coatings, such as diamond-like carbon (DLC) films, are becoming increasingly popular for a variety of mechanical, scientific, and technological applications, such as cutting tools, razor blades, and the like. This technology is also making its way into the gem industry. Several companies, including Serenity Technologies and Zirconmania, market DLC-coated cubic zirconia. Eaton-Magaña and Chadwick (2009) reported that these products were easily separated from diamond.

Serenity Technologies also offers a "patent pending nanocrystalline diamond coating process" named "Diamond Rx" which they apply to a variety of gems, including emerald, apatite, chrome diopside, zircon, peridot, tourmaline, kunzite, tanzanite and aquamarine (Serenity Technologies, 2010). They maintain that such coatings are extremely durable. However, it is very difficult (and sometimes impossible) to identify whether these DLC coatings are in fact even present on a gemstone.

Tanzanite. In April 2008, a Los Angeles gem dealer encountered two parcels comprising a few hundred color-coated tanzanites (E. Caplan, pers. comm., 2010; figure 22). Research concluded that the smaller stones (4.5 mm) could be identified on the basis of unusually intense color for their size, by areas of wear seen with microscopic examination, and by unusual surface iridescence ("American Gemological Laboratories identifies. . . ," 2008; McClure and Shen, 2008). Larger stones (e.g., 3+ ct) were much more difficult to identify with magnification, but EDXRF and LA-ICP-MS analyses revealed Co, Zn, Sn, and Pb in the coating (McClure and Shen, 2008). Since their initial sighting, coated tanzanites have all but disappeared from the market.

Topaz. In the late 1990s, we began to see different colors of topaz (blue-to-green, orange, pink, and red) that were being represented as "diffused" (Fenelle, 1999; McClure and Smith, 2000). Schmetzer (2006, 2008) reviewed the patent literature and concluded that the various mechanisms and treatment methods were not diffusion and should all be described as "surface coated." However, Gabasch et al. (2008) showed that certain colors were due to coatings, whereas others were diffusion-induced. For more details, see the section on topaz under "Diffusion Treatment" above.

Coral. Typically, gem coatings are ultra-thin. However, Hänni (2004) described black coral (also known as horn coral) that was coated with several relatively thick layers of artificial resin.

Pearls. Any gem can be coated to alter its color, provide a degree of protection, improve the luster, or mask some imperfection. Pearls usually fall into the latter three categories. Porous by nature, pearls may be coated for protection from harmful chemicals. Or they may have luster and/or surface imperfections that a coating can hide. In this decade, a number of coatings were applied to natural and cultured pearls (Moses and Reinitz, 2000; Hurwit, 2002; Krzemnicki, 2005a; Shor, 2007). One development in particular that should be carefully monitored by the pearl industry in the future is the application of DLC coatings (Drucker, 2008) to improve durability.

Figure 21. New coatings can turn diamonds virtually any color, as illustrated by these ~0.40 ct coated diamonds. Courtesy of Serenity Technologies; photo by C. D. Mengason.

DYEING

Although it dates back to the time of Pliny (23–79 AD), dyeing continues to be seen in nearly every gem material that is porous or has surface-reaching fractures. Careful microscopic examination will frequently reveal the presence of dye in cracks and around grain boundaries. In a number of porous materials, rubbing the surface with a cotton swab soaked in acetone or a 10% hydrochloric acid solution can identify the presence of dye. In others, absorption spectra can provide proof of dyeing.

Pearls. Dye continues to be used to improve the appearance of lower-quality natural and cultured

Figure 22. Tanzanite coated with a cobalt-colored material was of great concern for a brief time. All of these tanzanites (0.50–3.01 ct) were coated, but the one on the lower left was repolished to give an idea of the original (paler) color. Courtesy of Fine Gems International; photo by Roger Mathis, ©Robert E. Kane.

Figure 23. Dyed "golden" pearls, such as the 11.4–14.0 mm cultured pearls shown here, were only one of the identification challenges related to pearls in the last decade. Photo by Robert Weldon.

pearls (Hurwit, 2001; Overton and Elen, 2004; Wentzell, 2005). While the majority of dyed pearls are nacreous, dye may also be used to make non-nacreous pearl imitations more convincing, such as those mimicking Melo pearls (Wentzell, 2006). Of ongoing concern since the late 1990s is the detection of dyed "golden" cultured pearls (figure 23; "Concerns raised. . . ," 2003; Liu and Liping, 2007). Some samples present identification challenges, requiring the use of chemical analysis to detect trace elements such as iodine. Other developments involve the use of additional whitening compounds in freshwater non-beaded cultured pearls (Shouguo and Lingyun, 2001) and the use of metallic dyes injected into pearl sacs ("Pre-harvest colour-treated Akoya unveiled," 2008; Coeroli, 2010). A form of dyeing marketed as "lasering" has also been reported. This is said to produce dark "peacock" green or dark purple colors (Liping, 2002).

Other Gem Materials. Several other dyed gem materials were encountered during the decade. Blue and green diamond crystals were found to owe their color to dyeing (Van der Bogert, 2005). Quartzite was dyed red to imitate ruby (Mayerson, 2003a), whereas green dye was found in quartzite to resemble emerald (Milisenda, 2003). Mayerson (2003b) described an effective simulant for high-quality jadeite: a tricolored (lavender, green, and orange) dyed and polymer-impregnated quartzite bangle bracelet. Tan et al. (2006) used light-induced autofluorescence spectroscopy to identify dyed polymer-impregnated jadeite. Of particular interest was dyed jadeite found to resemble nephrite jade (Mayerson, 2004).

Low-quality red and blue corundum were found to have been dyed (Milisenda, 2004). A parcel of faceted "rubies" purchased in Afghanistan was identified by Milisenda (2005b) as dyed sillimanite. Dyed blue carbonate minerals, such as magnesite and dolomite, were sold as turquoise ("Some dyed minerals. . . ," 2000). To imitate common opal from the Peruvian Andes, marble was dyed pink and fashioned into beads (Milisenda, 2006). Raman and IR spectra identified dyed black chalcedony in an attractive pendant set with diamonds and pearls (DeGhionno and Owens, 2003). A copper-based dye was detected with UV-Vis-NIR spectroscopy in a natural-appearing chalcedony bead (Inns, 2007a).

BLEACHING

Bleaching is a process that uses agents such as acids or hydrogen peroxide to remove unwanted color from a gem. Only a limited number of materials will respond to such treatment.

Jadeite. Jadeite with brown staining caused by natural iron compounds is often bleached with acid. This treatment started in the 1990s and was categorized in the impregnation section of McClure and Smith (2000). This is because jadeite treated in this manner must be impregnated with polymers, as the acid damages the structure, making it very susceptible to breakage.

This treatment has become commonplace in the jadeite market. However, the bleaching itself typically cannot be detected, only the polymers used for impregnation (Sun, 2001; Fan et al., 2007). The treatment is now being used on nephrite jade as well (Jianjun, 2005).

Pearls. Bleaching is considered an "acceptable" pearl treatment due to the difficulty of proving a pearl's exposure to chemicals such as hydrogen peroxide. All types of pearls are routinely bleached: natural, bead cultured, and non-bead cultured. Akoya cultured pearls continue to be routinely bleached and "pinked" (Roskin, 2002b). Bleaching is also known to be a major component of the proprietary process used to produce the "chocolate" cultured pearls (figure 24) that entered the market during the decade (Zachovay, 2005; Hänni, 2006b; Wang et al., 2006c; Federman, 2007c).

Other Materials. While there are undoubtedly addi-

Figure 24. It is believed that most of the "chocolate" cultured pearls on the marketplace in the last decade were originally black cultured pearls that were treated by a process that involved bleaching to achieve this color. This strand (12.0–13.7 mm) is courtesy of Emiko Pearls International; photo by Robert Weldon.

tional porous materials that could be bleached, the only other one we could find reference to is coral. Black coral is bleached to "golden" coral, which is easily identified by its distinctive structure (Weldon, 2003).

IMPREGNATION

Impregnation of aggregate stones and other porous materials was seen more often in the first decade of the 2000s. This is largely due to increased demand for inexpensive stones, a phenomenon primarily driven by television shopping networks. The practice now extends to some unusual materials as well. A number of the gems were only usable in jewelry when they were treated by impregnation (often referred to as "stabilization").

Jadeite. The polymer impregnation of jadeite following the bleaching process described above was common during the last decade and will likely remain so in the future. At least one new analytical method was reported to detect this treatment (Liu et al., 2009), but its identification is still usually done with IR spectroscopy.

Nephrite. Nephrite was reported to have been polymer impregnated after bleaching with the intent of imitating "Hetian white" nephrite (Jianjun, 2005). It, too, can be positively identified by IR spectroscopy.

Turquoise. The greater demand for turquoise (a favorite of TV shopping networks) led to the use of more lower-quality impregnated material. Sometimes the treatment is so extensive that the material is actually a composite (figure 25), and gemological properties such as SG and RI no longer match turquoise (Choudhary, 2010; McClure and Owens, 2010). Materials used for impregnating turquoise include wax and hardened polymers. A UV-hardened polymer was identified as a filler for the first time using Raman spectroscopy (Moe et al., 2007).

Identification of this treatment is still mostly accomplished via IR spectroscopy (Henn and Milisenda, 2005; Chen et al., 2006), although many examples show veins and cavities filled with polymers that are visible with magnification.

Late in the decade, a product marketed as "Eljen" turquoise was claimed to be treated by a new proprietary process that improved the hardness and polish of soft porous turquoise. Testing showed it to be impregnated with a polymer, but it did seem harder than most impregnated turquoise, which would account for the improved polish (Owens and Magaña, 2009).

Opal. Natural opal—a hydrous, porous material—has a tendency to dry out and crack spontaneously. This tendency is so strong in opal from some deposits that most of the material is not usable in jewelry (e.g., Virgin Valley, Nevada). To address this problem, two new treatments were reported in the 2000s: (1) oil or wax impregnation of Mexican fire opal (Gambhir, 2001); and (2) a drying-out process followed by impregnation with a silica compound, used on Ethiopian opals (Filin and Puzynin, 2009).

Other Materials. As mentioned at the beginning of this section, impregnation was used on a number of more unusual materials during the decade. These include quartzite (Kitawaki, 2002; Juchem et al., 2006), seraphinite (Henn, 2008), and sillimanite (Singbamroong, 2005). It even extended to some manufactured materials, most notably a much-

Figure 25. The demand for turquoise is so strong that low-quality material is being treated by polymer impregnation and pressed into a composite material to make it salable. The treatment is sometimes so extensive that the gemological properties are altered. These carvings, 3.0–6.0 cm wide, are courtesy of Silver Express; photo by Robert Weldon.

debated material from Mexico called "Rainbow Calsilica" (Kiefert et al., 2002). This material required impregnation with polymers to be useful in jewelry, as it was very porous and would not take a polish in its original state (Kiefert et al., 2002; Frazier and Frazier, 2004).

LUSTER ENHANCEMENT

This term is sometimes used to describe a treatment common to jade and some other gem materials in which a substance such as wax is rubbed on the surface of the stone to improve its appearance. The wax is only present on the surface and in depressions such as grooves in carvings, so it is not considered an impregnation. Although such substances are sometimes applied to pearls (Petersen, 2000), *luster enhancement* of pearls typically has a somewhat different meaning.

In the cultured pearl industry, the name *Maeshori* is associated with this kind of treatment (Akamatsu, 2007; Shor, 2007). Developed in the 2000s to improve the prepolishing process, it involves the use of solvents to "clean" nacreous pearls and hence produce a more lustrous surface. Various other forms of this treatment also exist (Lingyun et al., 2007). Polishing continues to be used on all types of nacreous and non-nacreous pearls to improve their salability. It takes place at all steps of the supply chain (Pousse, 2001), starting with the farmers, who often tumble their cultured pearls with walnut chips (N. Paspaley, pers. comm., 2008) and/or other materials and then polish them.

CONCLUSIONS

The first decade of the 2000s brought many new, unanticipated enhancements. Some of these—such as HPHT treatment and beryllium diffusion of corundum—usually cannot be identified by gemologists with standard equipment. In most cases, stones that might be treated by these methods must be sent to a well-equipped gemological laboratory to get a conclusive identification. Still, today's gemologist can benefit by developing their ability to recognize when a stone shows evidence it has *not* been treated (particularly for rubies and sapphires) and also recognizing when they cannot tell and the stone must be sent for further testing.

It is interesting that in their retrospective of the 1990s article, McClure and Smith (2000) predicted that new filling processes would bring clarity enhancement to ruby, sapphire, and alexandrite. Three years later, at least part of this prediction came true with the development of a lead-glass filler for ruby. There is every reason to believe that this treatment, or a similar one, will soon extend to other relatively high RI materials.

Already in 2010 we have seen several new developments, including lead-glass filling of star rubies (Pardieu et al., 2010a) and a combination treatment of rubies from Mozambique that includes partial healing of fractures and partial filling with a glass that does not contain lead (Pardieu et al., 2010b).

With these developments, disclosure has become a significant topic at every trade show and gemological conference. As the trade discovered with emerald fillers (and the impact of nondisclosure on emerald sales) in the '90s, they neglect this subject at their peril. Consensus is critical. Discovering a treatment exists and developing identification criteria are an important start, but the trade and gemological community must work together to address the issues of what to call a treated material, how to disclose it, and how to make sure it gets disclosed. Important steps in this direction have been made, but more are needed.

McClure and Smith (2000) also predicted—correctly—that technology would advance at an even faster rate during the next decade. This will undoubtedly be the case from now on, making the unforeseen the norm in the gemological world as it is in the world at large.

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ACKNOWLEDGMENTS

The authors thank Allison DeLong, Sheryl Elen, Caroline Nelms, and other staff members of the Richard T. Liddicoat Library and Information Center for their help with the references for this article. They also thank the following for information regarding specific treatments: Nickolai Kuznetsov of Stoneflower Co.; Richard W. Hughes, Bangkok; Raja Shah, Color First, Tampa, Florida; Bill Barker, Barker & Co., Scottsdale, Arizona; and Evan Caplan, Omi Gems, Los Angeles.

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Key to abbreviations: *Australian Gemmologist* = *AusG*; *Canadian Gemmologist* = *CanG*; *Colored Stone* = *CS*; *Diamond and Related Materials* = *DRM*; *Gemmology* = *Gem.*; *Gems & Gemology* = *G&G* (Gem News = GN, GNI = Gem News International, Lab Notes = LN); *Jewelers' Circular-Keystone* = *JCK*; *Jewellery News Asia* = *JNA*; *Journal of Gemmology* = *JofG*; *Journal of the Gemmological Association of Hong Kong* = *JofGemHK*; *Journal of Gems & Gemmology* = *JofG&G*; *Lapidary Journal* = *LJ*; *Modern Jeweler* = *MJ*; *National Jeweler* = *NJ*; *Professional Jeweler* = *PJ*; *Rapaport Diamond Report* = *RDR*; *Revue de Gemmologie a.f.g.* = *Rev. de Gem.*; *(Gemmologie:) Zeitschrift der Deutschen Gemmologischen Gesellschaft* = *(Gem:) Z. Dt. Gemmol. Ges.*

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DEVELOPMENTS IN GEMSTONE ANALYSIS TECHNIQUES AND INSTRUMENTATION DURING THE 2000S

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The first decade of the 2000s continued the trend of using more powerful analytical instruments to solve gem identification problems. Advances in gem treatment and synthesis technology, and the discovery of new gem sources, led to urgent needs in gem identification. These, in turn, led to the adaptation of newer scientific instruments to gemology. The past decade witnessed the widespread use of chemical microanalysis techniques such as LA-ICP-MS and LIBS, luminescence spectroscopy (particularly photoluminescence), real-time fluorescence and X-ray imaging, and portable spectrometers, as well as the introduction of nanoscale analysis. Innovations in laser mapping and computer modeling of diamond rough and faceted stone appearance changed the way gemstones are cut and the manner in which they are graded by gem laboratories.

The science of gemology has its roots in two main functions: observation and interpretation of those observations. With this approach, gemologists have developed quite effective ways of identifying gem materials, separating natural from laboratory-grown samples, and detecting various treatments. For decades, interpretation of clues seen with the refractometer, polariscope, microscope, and hand spectroscope seemed all that was necessary for the identification of most gem materials. However, the late 1970s and '80s witnessed major advances in gem synthesis methods and the application of treatments to a wider array of materials, creating a need to apply the same observational and interpretational skills to data collected with more sophisticated analytical instruments. Subsequently, infrared and UV-visible spectrometers, as well as energy-dispersive X-ray fluorescence (EDXRF) and Raman instruments, met many of the analytical needs of gemological laboratories (Devouard and Notari, 2009; Hänni, 2009; Hainschwang, 2010). These technologies were further refined and new ones were adapted (see, e.g., figure 1) as more advances were made in gem synthesis and treatment, and as computer technology for instrument control and data collection enabled more applications.

Looking back at the two previous *G&G* retrospective technology articles (Fritsch and Rossman, 1990; Johnson, 2000), it is apparent that gemological laboratories have embraced modern analytical instruments more and more in recent years. In the gemological literature, it is common to see these instruments referred to as "advanced" or "high tech." The reality is that most of these technologies have existed for some time in research universities and other industries. In most cases, the instrumentation required modification for the nondestructive analysis of faceted gemstones. Additional challenges were involved in the collection of high-quality data from gems using these instruments. The adaptation

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GEMS & GEMOLOGY, Vol. 46, No. 3, pp. 241–257.

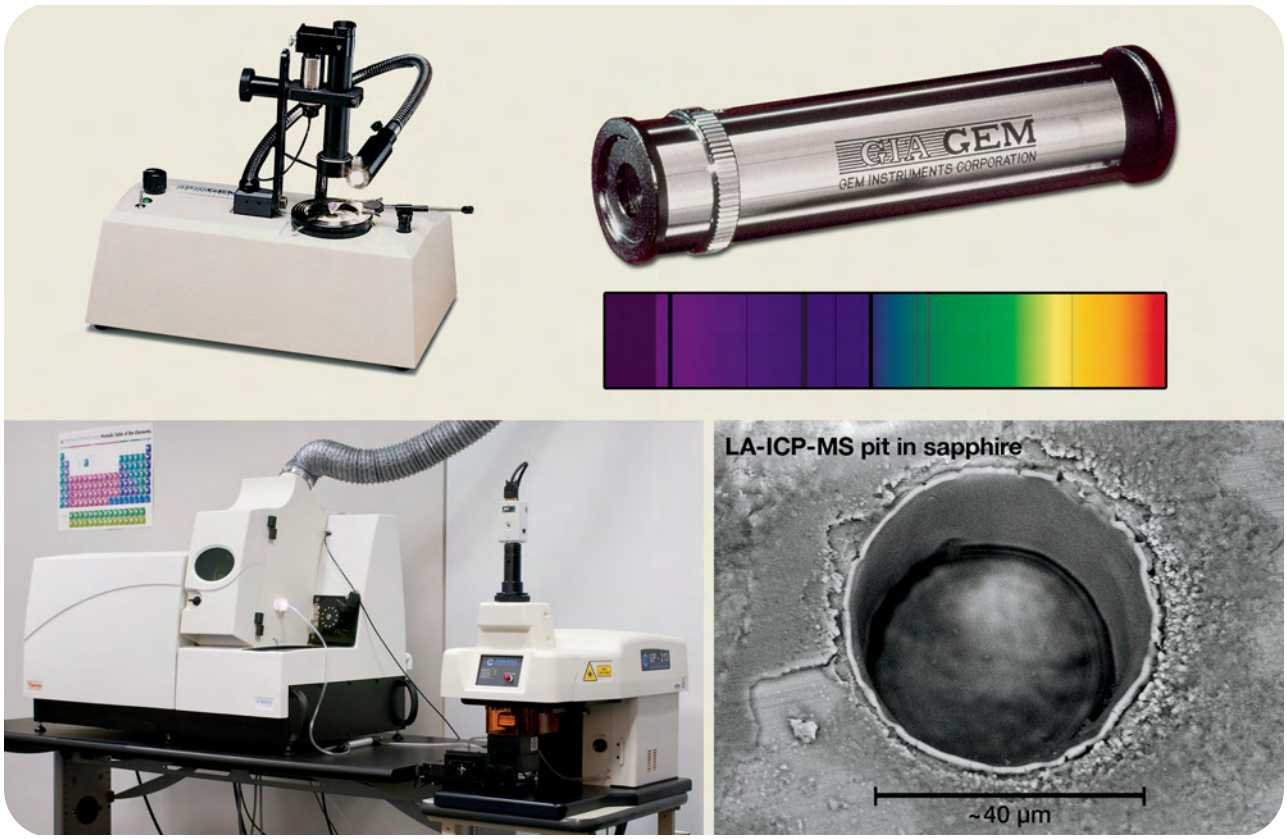


Figure 1. During the first decade of the 2000s, gemologists benefited from expanded spectroscopic capability. While they continued to use desktop and handheld spectroscopes (top) for daily identification, they also had access to information provided by high-resolution analytical instruments such as LA-ICP-MS (bottom) in the well-equipped gemological laboratory. LA-ICP-MS requires the removal of a minute amount of material for analysis, but the resulting pit is visible only with magnification (as in the SEM image seen here). Photos by Kevin Schumacher (lower left) and A. Shen (lower right).

of existing technology to gemological applications is the true innovation for gemologists.

This article surveys advances in analytical instrumentation during the first decade of the 21st century (2001–2010). The reader will see that the application of new technologies for gem analysis is an evolving process, driven by industry demands but also heavily influenced by the availability and affordability of the instrumentation.

HOW FAR WE'VE COME SINCE 2000

General Electric's introduction of HPHT treatment of diamonds at the end of the 1990s had a huge impact on the diamond industry and gemological laboratories alike. Almost overnight, we learned that colorless as well as fancy-colored diamonds could, within hours, be produced from off-color (typically brown) starting material in the same types of high-pressure, high-temperature presses used to grow synthetic diamonds (figure 2; see, e.g., Fisher and Spits, 2000; Smith et al., 2000). In many cases, there were no reliable ways for gemologists to visually distinguish these HPHT-treated diamonds from naturally colored stones (Moses et al., 1999). The effects of this treatment almost single-handedly thrust photoluminescence (PL) analysis into the gemological limelight (Chalain et al., 1999).

The early 2000s also saw huge improvements in the growth of synthetic diamonds by the chemical vapor deposition (CVD) method. Prior to this decade, the vast majority of single-crystal CVD synthetic diamonds consisted of very thin (≤1 mm) plates or coatings on seed crystals (Wang et al., 2007). By 2010, faceted colorless, brown, yellow, and pink samples up to ~1 ct were being produced by at least one U.S. company (Apollo Diamond Inc.) and were being submitted to the GIA Laboratory for grading reports. Crystals as large as 10 ct have reportedly been grown in university and research laboratories (Hemley and Yan, 2005; Wang et al., 2007, 2010). PL

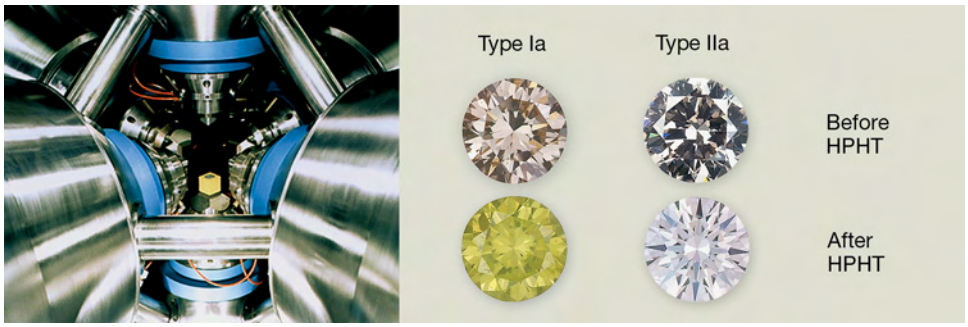


Figure 2. At the end of the 1990s, HPHT treatment of diamond using large presses (left) changed the industry forever and drove innovation in the use of analytical techniques such as photoluminescence to identify the origin of color in diamonds. Photos by Robison McMurtry.

analysis and luminescence imaging proved essential for the identification of many of these new synthetic diamonds. The DiamondView instrument, developed by De Beers in the mid-1990s (Welbourn et al., 1996), provided a practical means of imaging growth-related fluorescence patterns.

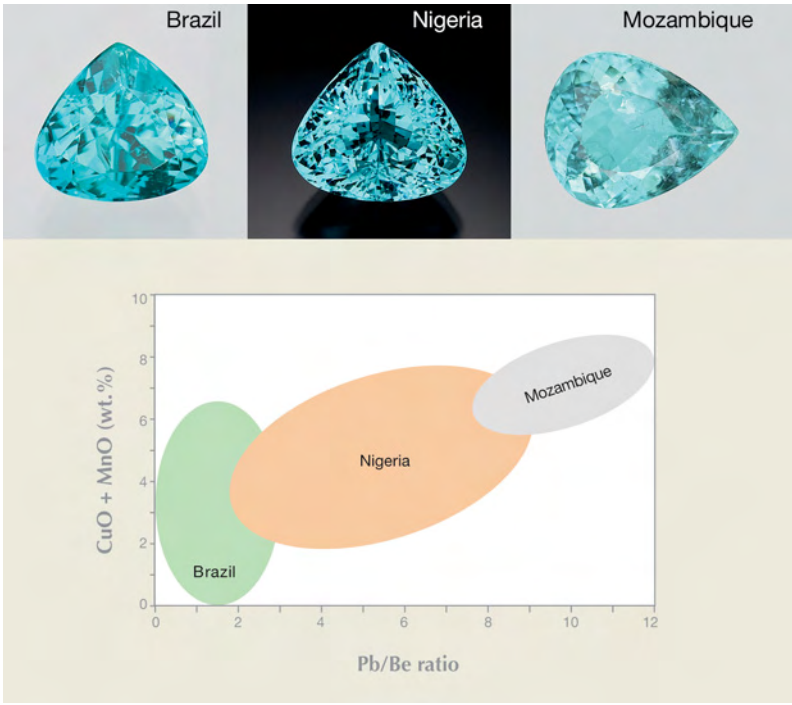
The colored stone industry was not without several critical events as well. In 2002, the undisclosed diffusion of trace amounts of beryllium into corundum nearly destabilized the sapphire trade due to the influx of large amounts of treated orange, red, and pinkish orange ("padparadscha") material (see, e.g., Emmett et al., 2003; Notari et al., 2003). Because the light element Be cannot be detected by EDXRF analysis, which was routinely used to determine chemical composition in many gemological laboratories, researchers and lab gemologists turned to laser-induced breakdown spectroscopy (LIBS) and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS).

The first decade of the 2000s also saw increased demand for country-of-origin information on lab reports for rubies, sapphires, and emeralds. Discoveries of new sources for copper-bearing tourmaline in Nigeria (2001) and Mozambique (2005) generated interest in separating these gems from those of Brazil (figure 3; see Abduriyim et al., 2006; Laurs et al., 2008). The value of trace-element analysis to country-of-origin determination further spurred the use of LA-ICP-MS in the gemological community. The demand for gem lab report services to be offered on-site at trade shows prompted the development and proliferation of portable infrared and visible-range absorption spectrometers.

This past decade also witnessed new developments in the pearl industry, including treated yellow and "chocolate" cultured pearls, the introduction of cultured conch pearls, and the proliferation of beadless cultured pearls (Elen, 2002; Wang et al., 2006; Krzemnicki et al., 2009a; Wang et al., 2009; Karampelas et al., 2010; Krzemnicki et al., 2010). The need to identify these products led to broader use of X-ray and luminescence imaging.

Late in the decade, a new generation of very thin colored or colorless surface coatings began to be applied to diamond, topaz, cubic zirconia, and tanzanite (e.g., Shen et al., 2007, Gabasch et al., 2008; McClure and Shen, 2008). The semiconductor industry and academic communities developed sophisti-

Figure 3. New sources of copper-bearing tourmaline were discovered in Nigeria (19.90 ct) and Mozambique (4.29 ct) in the early 2000s, driving a demand for country-of-origin certification to separate them from Brazilian Paraíba stones (2.59 ct). LA-ICP-MS analysis of trace elements in tourmaline proved to be very effective in separating these tourmalines (graph simplified from Abduriyim et al., 2006). Photos by Robert Weldon.



cated tools for nano-scale fabrication, coating, and analysis. This technology was then applied to a variety of gem materials as coatings and chemically modified surface layers of just a few tens of nanometers thick. While such treatments can often be identified using standard gemological observation, some are difficult for gemologists to detect.

Nano-fabrication methods to improve gemstone appearance have also been introduced recently (Gilbertson et al., 2009). In addition, the 2000s were marked by increased demand by consumers for more cut-quality information on diamond grading reports. Evaluation of cut quality became much more feasible over the last 10 years thanks to advances in gemstone facet mapping tools and automated facet and proportion measuring techniques (Moses et al., 2004).

Of course, not all the instrument technologies that were used to address gemological problems became mainstays in gem labs. Techniques such as EPR/ESR, XRD, NMR, NAA, PIXE, SEM, TEM, and others were occasionally applied for specific research needs, but due to cost, sample destruction, or limits on applications, these powerful tools have not yet seen routine use in solving gemological challenges. See the *G&G* Data Depository (gia.edu/gandg) for a list of references to studies in which these other techniques were applied to gemological problems.

CHEMICAL ANALYSIS

One of the most important advances in gemology since 2000 is the emergence of new techniques for microchemical analysis. This technology has been extensively used by the materials science and geology communities since well before 2000. Commonly the term *microchemical analysis* refers to techniques using micrometer-to-submicrometer beams of charged particles or electromagnetic radiation for localized chemical analysis, such as an electron microprobe or secondary ion mass spectrometry (SIMS). Microprobe analysis has been used in gemology for decades, while SIMS was introduced to the gem trade in the early 2000s. However, these two types of instruments have not become widely available in gemological laboratories due to their high acquisition and operating costs, and sample preparation requirements (mounting, carbon coating, etc.). The widespread use of another technique, LA-ICP-MS, greatly changed the gemological identification landscape in the first decade of the 2000s.

LA-ICP-MS. A typical quadrupole ICP-MS attached to a laser ablation unit (213 nm or 193 nm wavelength) can be acquired for a quarter the price of an electron microprobe or SIMS instrument (the latter generally costs in excess of US$1 million). LA-ICP-MS can detect almost all chemical elements with detection limits in the range of parts per million (ppm) to even parts per billion (ppb) levels (Abduriyim and Kitawaki, 2006; Sylvestor, 2008).

An LA-ICP-MS instrument consists of three components: (1) a laser ablation unit, (2) an inductively coupled plasma torch, and (3) a mass spectrometer (figure 4). Three commonly used laser wavelengths are 266, 213, and 193 nm, the choice of which is typically determined by the primary use of the instrument. The laser physically ablates (removes) small amounts of material from a gem sample using short pulses. The typical spot size for analysis is ~40 μm in diameter (again, see figure 1), approximately half that of a human hair. The ablation depth is ~20–30 μm. The required sample amount is in the picograms (10^{-12} g) to nanograms (10^{-9} g) range, which is an extremely small amount of material

Figure 4. LA-ICP-MS consists of a laser-ablation sample introduction chamber, an inductively coupled plasma (ICP) unit, and a mass spectrometer (MS); the diagram is adapted from Masaaki (2006). Typical laser ablation spots are very small (40 μm across, see also figure 1), as seen compared to a standard laser inscription on the girdle of a sapphire (right). Photomicrograph by J. Shigley; magnified 10×.

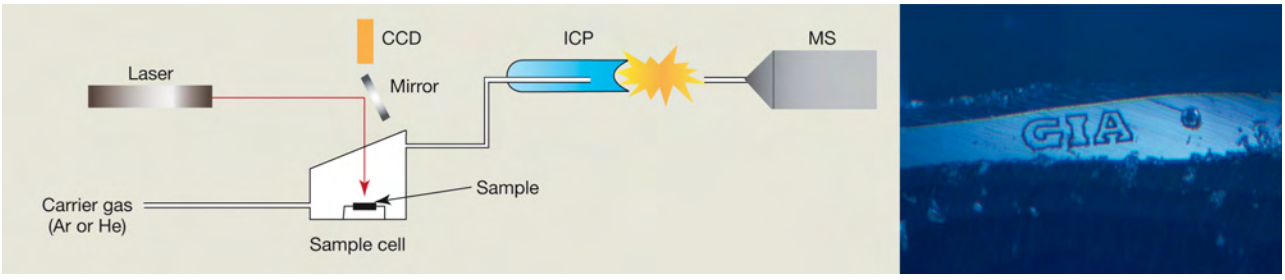


Figure 5. Beryllium-diffusion treatment of sapphire to produce padparadscha-like and other colors led to the widespread use of LA-ICP-MS in gem labs. The untreated stone is 88.11 ct and the Be-diffused sample is 2.16 ct. Photos by Kevin Schumacher (left) and Robert Weldon (center).

(i.e., <0.00000001 ct). Therefore, this method is generally considered minimally destructive.

After ablation, the vaporized material is transported by a carrier gas (usually He or Ar) to the ICP-MS where a plasma torch, typically operating at 8,000–10,000°C, ionizes the sample aerosol, causing all atomic elements present to have positive or negative charges. Once the sample is ionized, the ions are sent to the last part of the instrument, the mass analyzer (most commonly, a quadrupole mass spectrometer). The mass spectrometer separates the different ions in the plasma before they enter the detector, which measures the quantity of each ion.

One big advantage of LA-ICP-MS analysis is that it requires minimal sample preparation. In addition, it can analyze samples of almost any shape and size. Since laser pulses ablate the sample continuously, any possible surface contamination will be ablated away after a few laser pulses and does not affect the analysis. In reality, the LA-ICP-MS is analyzing a "depth profile" of a sample, beginning at the surface and extending into its interior. This feature can be advantageous for some applications, such as study of inclusions. LA-ICP-MS can be fully quantitative if a set of standards with known concentrations for the elements of interest in the same matrix is available. Also useful are some commonly available multi-element doped glass standards (see, e.g., Abduriyim and Kitawaki, 2006; Sylvestor, 2008). Without the use of such standards, the analytical results obtained by this technique must be considered semiquantitative.

As noted earlier, the introduction of LA-ICP-MS was a matter of necessity for the identification of Be-diffused sapphires (figure 5; see also Emmett et al, 2003), since traditional techniques, such as EDXRF and electron microprobe analysis, could not detect elements as light as beryllium. With its excellent detection ability (<0.2 ppm) for Be, LA-ICP-MS rapidly found its way into gemological laboratories in the 2000s.

The superior sensitivity of LA-ICP-MS to almost all elements in the periodic table has given gemologists new insights and perspectives on various gem materials. For example, data produced by this technique are now being used for country-of-origin studies on rubies, sapphires, copper-bearing (Paraíba-type) tourmalines, and emeralds (e.g., Abduriyim and Kitawaki, 2006; Abduriyim et al., 2006). In addition, many attempts were made to study trace elements in diamonds to determine their geographic origin in support of the Kimberley Process (Weiss et al., 2008; McNeill et al., 2009). However, little progress was made on this front because trace-element impurities in diamonds could not be consistently linked to geographic origin. This is probably because diamonds most often crystallize deep in the Earth's mantle. Unlike the source-specific trace elements in other gems that are often unique to particular regions (i.e., "countries") of the earth's crust, the mantle is a constantly evolving and mixing reservoir of partially molten rock beneath the crust, rendering diamond country-of-origin determination on the basis of trace elements all but impossible.

LA-ICP-MS has been used for a number of other applications, including the separation of natural and synthetic gems and the identification of pearl nuclei (e.g., Abduriyim et al., 2004; Sinclair, 2005; Wang et al., 2005; Jacob et al., 2006; Krzemnicki et al., 2007; Peucat et al., 2007; Breeding and Shen, 2010).

LIBS. This analytical method uses energy pulses from a high-energy laser to ablate small quantities of a sample. With focused laser beams, the area of abla-

tion can be just tens of micrometers wide. The ablated material is heated to such a high temperature that the atoms and ions are in an energetically excited state and emit light at characteristic wavelengths. The chemical elements present in the sample are measured by sensitive optical spectrometers positioned at the plume of ablated material.

LIBS instruments require no vacuum and typically have a microscope coupled to a video camera for precise positioning of the sample. LIBS costs less than many other instruments capable of trace-element analysis, provides rapid results, and is comparatively easy for an operator to use. Its application in gemology was motivated by the fact that LIBS is sensitive to beryllium, with detection limits of a few parts per million, so the technology was initially used to test for Be-diffused corundum (Krzemnicki et al., 2004, Abduriyim and Kitawaki, 2006). However, LIBS analyses have proved more difficult to rigorously quantify than analyses from LA-ICP-MS or SIMS, and LIBS instruments are less sensitive than the other two methods. LIBS has also been used to determine the minor and trace elements in beryl (McMillan et al., 2006a,b).

SIMS. This powerful method can analyze most elements of the periodic table with high sensitivity (parts per billion to parts per trillion). It can provide detailed compositional depth profiles near the surface of samples, even resolving chemical changes with depth at the nanometer scale, as seen in the chemical profile of a diamond surface coating shown in figure 6. While the sensitivity is excellent for most elements, the sample preparation needed is significant (see below) and the cost of analysis is high. Considerable time and effort is also necessary to produce the standards necessary for quantitative analyses. Nevertheless, SIMS is rapidly gaining importance in materials science, geoscience, and gemology (e.g., Emmett et al., 2003; Koch-Muller et al., 2006; Reiche et al., 2006; Fayek, 2009).

The analysis requires a flat surface, and the samples usually must be electrically conductive or coated with a thin layer of gold to maintain charge neutrality in the focused ion beam (typically oxygen or cesium ions). More-involved methods do exist, however, to flood nonconductive samples with electrons (negative ions) when positively charged ion beams are used. Samples are evacuated at ultra-high vacuum (10^{-10} torr) for several hours before entering the ion-beam compartment. The instrument pictured in figure 6 can accommodate samples up to 1 inch (2.5 cm) in diameter.

SIMS can measure the isotopic compositions of most elements, which opens the possibility of applying the data to country-of-origin determinations. Although seldom used in gemology today, the precise determination of isotopic ratios can be of great value in the origin determination of a wide variety of gem materials. Early studies (Giuliani et al., 2000, 2005) correlated emerald samples from a few localities with their measured oxygen isotope ratios. More recently, Giuliani et al. (2007) applied the technique to corundum, reporting that the ratio of ^{18}O to ^{16}O (expressed in units of $\delta^{18}O$) ranges between 1.3 and 15.6 parts per thousand (‰) as compared to an ocean water standard for samples of various geologic origins. For example, corundum samples from cordierite-grade metamorphic rocks had $\delta^{18}O$ of 1.7–2.9‰, whereas those from marble skarn deposits ranged from 10.7 to 15.6‰, indicating that isotopic signatures can be powerful tools for origin determination when combined with other gemological observations. It was also determined that heat treatment did not affect the oxygen isotopic values of these samples.

RAMAN AND LUMINESCENCE SPECTROSCOPY

Today, photoluminescence or UV-Vis-NIR absorption spectroscopy may be required to determine if a diamond is naturally colored or treated, and Raman spectroscopy often proves useful in colored stone identification. In most cases, a combination of spectral features and gemological properties can provide a reliable identification. In addition, the challenges presented by gem-quality CVD synthetic diamonds have made gemological laboratories more dependent on high-quality PL spectroscopy (e.g., Wang et al., 2007).

Both Raman and PL spectroscopy typically involve exciting a sample with a laser and analyzing the light given off in response. Raman scattering occurs when laser light is absorbed by the sample and, depending on the vibrational structure of the material, re-emitted (i.e., scattered) with frequencies that are shifted relative to the excitation source. Photoluminescence involves absorption of laser light, a photo-excitation process, and the dissipation of excess energy by emission of light of different wavelengths that depend on the electronic structure of defects present in the material. Most Raman spectrometers can measure photoluminescence as well as Raman scattering.

In the 2000 retrospective issue (Johnson, 2000), Raman spectroscopy and Raman libraries were dis-

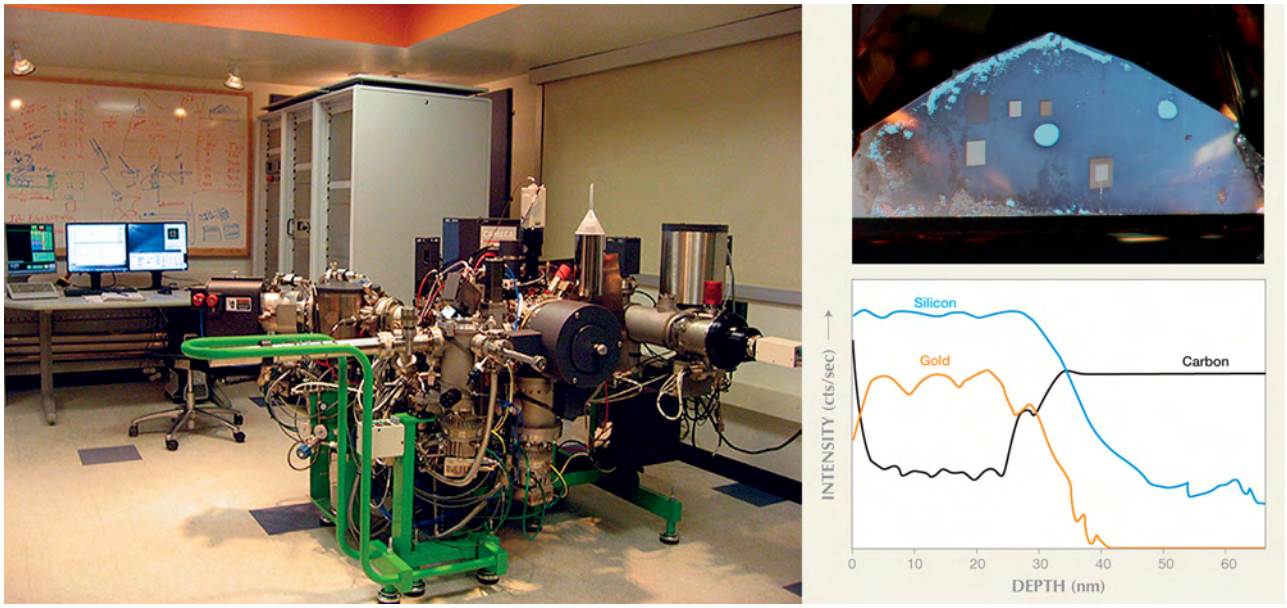


Figure 6. This Cameca IMS 7f-GEO magnetic sector SIMS instrument (left) is used at the California Institute of Technology. The ultra-high vacuum airlock through which samples are introduced is in the front left of the instrument. The mass spectrometer is to the right side, and the ion guns are at the rear-center and right side. SIMS was used to analyze the chemical composition of the coating on this facet of a pink diamond (leaving the rectangular spots on the oxidized coating seen in reflected light on the image at upper right; magnified 20×). Analysis revealed that the coating was composed primarily of Au and Si (lower right; modified from Shen et al., 2007). Photos by G. Rossman (left) and A. Shen (top right).

cussed and photoluminescence (PL) spectroscopy was mentioned briefly. At the time, the PL method did not have significant gemological applications or widespread use.

Raman. Raman spectrometers are useful for rapidly identifying gemstones, since most materials produce characteristic Raman spectra. Advances in NIR and visible lasers, charge-coupled device (CCD) detectors, and Rayleigh rejection filters have increased the detection sensitivity and decreased background fluorescence. With these advances, Raman spectra can be collected from most stones, even those with strong fluorescence reactions.

The use of Raman spectra to identify gem and other minerals requires a spectral reference library against which an unknown sample can be compared. One of the most reliable ones is the RRUFF project (Downs, 2006). See box A for a list of databases of interest to those involved with gem characterization.

Photoluminescence. Whereas Raman spectroscopy can prove that a sample is diamond, PL spectroscopy is needed to study the subtle distinctions in diamond lattice defects that are useful for distinguishing between natural, synthetic, and treated diamonds, and for determining the origin of a diamond's color. The configuration of the components within the diamond lattice—such as nitrogen, vacancies (missing carbon atoms), and out-of-position carbon—varies with a diamond's growth or temperature history. The high sensitivity of PL (typically at the parts-per-billion level) allows the detection of very subtle peaks that cannot be observed using other forms of spectroscopy (e.g., the H3 peak is rarely seen in the UV-Vis absorption spectra of colorless type IIa diamonds, but it is commonly observed in their PL spectra). Many such diamond peaks are included in Zaitsev (2003), an extensive compendium of spectral features obtained from much of the scientific diamond literature.

As an example, Fisher and Spits (along with Smith et al.) reported in 2000 on the HPHT decolorization of type IIa brown diamonds, and showed that laser-excited PL spectroscopy with the stones at liquid-nitrogen temperature (77 K) was a reliable method to identify them (see Johnson, 2000). Suddenly, PL spectroscopy was catapulted into widespread use in major gem testing laboratories, and it has since proved very helpful for detecting several types of color treatment in diamonds, including irradiation and combination treatments (e.g., Wang et al., 2005), as well as for identifying CVD synthetics (e.g., Martineau et al., 2004; Wang et al., 2007, 2010).

BOX A. ONLINE DATABASES WITH REFERENCE SPECTRA OR GEMOLOGICAL INFORMATION

A quality database of reference spectra is vital for proper interpretation of the data collected from most of the analytical instruments discussed in this article. However, compiling such a database is a very difficult task. A comprehensive set of representative gems is rarely available at any given time, so reference data must be collected over a long period of time in a manner that is consistent, reproducible, and universally accessible. Such a task is often very expensive and includes proprietary information, resulting in few publically available resources. Below we have provided some publically available (free or for purchase) online databases of interest to gemologists.

Bio-Rad Spectral Database
www.knowitall.com/academic/welcome.asp
Infrared and Raman spectra database of organic and inorganic chemical compounds

GIA Gem Project – Edward J. Gübelin Collection
www.gia.edu/research-resources/gia-gem-database/index.html
Infrared, visible, Raman, photoluminescence, and EDXRF spectra of gem minerals

National Institute of Standards and Technology (NIST), Washington DC: NIST Chemical WebBook
webbook.nist.gov/chemistry/
Infrared, visible, and mass spectra of standard reference materials

National Institute for Advanced Industrial Science and Technology (AIST), Japan: AIST Spectral Database for Organic Compounds (SDBS)
http://riodb01.ibase.aist.go.jp/sdbs/cgi-bin/cre_index.cgi
Infrared, nuclear magnetic resonance, and electron spin resonance spectra of organic chemical compounds

Sigma-Aldrich Chemical Catalogue
www.sigmaaldrich.com, search for "spectrum library"
Infrared, Raman, and nuclear magnetic resonance spectra of organic and inorganic chemical compounds

Mineral Spectroscopy Server, California Institute of Technology
http://minerals.gps.caltech.edu/FILES/Index.html
Visible, infrared, and Raman spectra of some minerals

RRUFF Mineral Database, University of Arizona
http://rruff.info/index.php
Chemical composition (electron microprobe), Raman spectra, and X-ray diffraction data of a large number of minerals (also infrared ATR)

PL spectroscopy has also proved useful for some colored stone applications. For example, separating natural from synthetic spinel can be difficult in high-clarity gems. However, PL analysis of samples with trace or higher concentrations of chromium can easily distinguish laboratory-grown material from natural spinel (figure 7; Notari and Grobon, 2003; Shen et al., 2004; Kitawaki and Okano, 2006). Similar features provide evidence for the heat treatment of natural spinel to enhance color (Saeseaw et al., 2009). Additionally, PL analysis can be combined with Raman spectroscopy to separate natural red coral from its dyed counterpart (Smith et al., 2007).

Cathodoluminescence (CL). Cathodoluminescence is the emission of light from a material that is excited by an electron beam. The resulting luminescence can be imaged to show spatial variations in color or intensity, or it can be collected as spectra in the UV-Vis-NIR range. Depending on the type of CL instrument, the sample needs to be under vacuum (typically ~10^{-6} torr), which can significantly add to data collection time.

In many cases, photoluminescence (in the case of spectra) and the DiamondView (in the case of imaging) can provide comparable data, and these instruments are used far more frequently in gemology because the samples do not need to be under vacuum. CL has similar applications to PL since it can excite peaks that can be used to determine diamond type, examine melee (Kanda, 2006; Kanda and Watanabe, 2006), and distinguish natural from synthetic diamonds on the basis of differences in growth morphology (e.g., Shigley et al., 2004).

The major advantages of CL analysis are its ability to resolve features down to 10–20 nm and the fact it allows simultaneous collection of imaging and spectroscopic data (e.g., Yang et al., 2003). Therefore, any features observed in CL imaging may be analyzed spectroscopically.

For materials of gemological interest, CL has been used mostly on diamonds, but also on quartz (Müller et al., 2003), jade (Kane and Harlow, 2006; Ouyang et al., 2006), and sapphire (Lee et al., 2006).

Figure 7. Photoluminescence analysis of red spinel (here, 10.42 ct) can separate natural from synthetic and heat-treated samples. Spectra are offset vertically for clarity. Photo by Robert Weldon.

ADVANCES IN SPECTROMETERS AND LIGHT SOURCES

Recent developments in spectrometers and light sources have produced instruments that are highly portable and available as modular components, allowing users to customize the instrumentation to fit their needs or to reduce expenses by purchasing only the necessary equipment and spectrometer resolution. This new generation is also quite affordable, as high-quality spectra can be obtained from instruments costing as little as a few thousand dollars, depending on the application.

Spectrometers. In the last several years, the availability of spectrometers with charge-coupled device (CCD) detectors has greatly increased the speed of collecting UV-Vis-NIR absorption and fluorescence spectra (down typically from a few minutes to a few seconds), and made it possible to easily measure very short-lived phosphorescence spectra (see, e.g., Fritsch et al., 2003; Eaton-Magaña et al., 2008).

Earlier technology (such as wavelength-scanning spectrometers and spectrofluorometers) cannot record time-dependent spectra (e.g., phosphorescence), because those instruments sequentially proceed across the wavelength range by moving a prism or diffraction grating to collect spectral data. In contrast, the CCD spectrometers developed during this decade can simultaneously collect data over the entire wavelength range (although with reduced resolution for large wavelength ranges). Depending on the light source and the material being evaluated, these spectra can be collected over extremely short integration (i.e., data collection) periods.

Light Sources. In 2005, researchers studied the phosphorescence spectra of the Hope diamond (Eaton-Magana et al., 2008) using a CCD spectrometer and a broadband UV source that provided radiation in the 215–400 nm range. This broad range made it impossible at the time to distinguish the various phosphorescence reactions at short- and long-UV wavelengths unless a filter that limited the wavelength range was used. This considerably reduced the luminescence signal intensity and required a high-sensitivity, low-resolution spectrometer.

Since then, several alternative light sources have been introduced that are considerably advanced in their technology, light output, and size. UV-range LEDs have improved significantly in the last few years, and have a high energy output that enables the use of a high-resolution spectrometer and shorter integration times (figure 8). They also surpass standard gemological lamps in that they provide only a very narrow band of UV radiation. These UV sources have resulted in significant improvements in the quality of fluorescence and phosphorescence spectra.

REAL-TIME IMAGING

Imaging techniques have always been important in the analysis and identification of gems. From the face-up color to the nature of inclusions and other internal features, gems have a variety of properties that require visual representation. Thanks to advances in digital photography, the first decade of the 2000s saw the development of real-time imaging of properties such as fluorescence and X-ray transparency. Prior to this decade, these techniques were limited by long exposure requirements. Real-time imaging allows for instant visual analysis of bulk fluorescence, internal structures, and differences in luminescence between host gem and fracture-filling materials (Notari et al., 2002). Compared to conventional film-based analysis, in which only a few areas or viewing angles of a stone are typically recorded, real-time imaging allows for a more complete evaluation of the gem. In most instruments, samples can

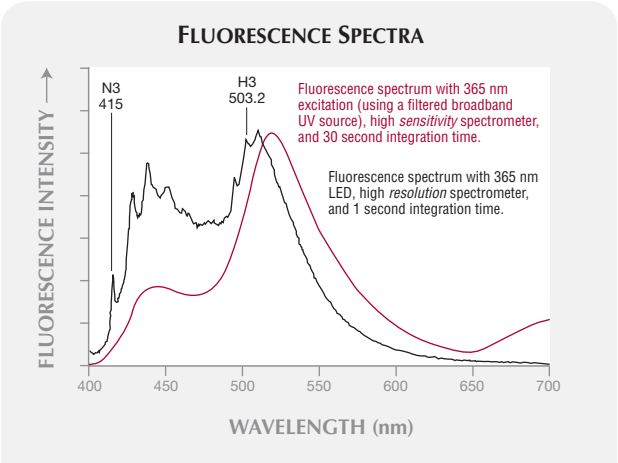


Figure 8. The fluorescence collected from analogous greenish yellow diamonds, but illuminated by different light sources, show different spectra (red spectrum, from Eaton-Magaña et al., 2007, collected June 2005; blue spectrum collected November 2009). The later-generation LED allows the use of a higher-resolution spectrometer, which reveals much finer detail, including the N3 (415 nm) and H3 (503.2 nm) zero-phonon lines and their sidebands. These narrow-band LEDs provide gemologists with a better understanding of the causes of fluorescence in gems.

be moved and rotated while images are continuously acquired and viewed. In an ever-evolving world of complex gem treatments and synthetics, subtle details seen in several orientations are often the key to identification.

DiamondView. The DTC DiamondView instrument was introduced in the 1990s for separating natural from HPHT-grown synthetic diamonds (Welbourn et al., 1996). While the instrument remains valuable for that purpose, the 2000s saw the development of several new applications. In addition to growth sectors, a number of defects can be identified that provide useful information about the thermal history of a diamond, including some indications of HPHT treatment (Breeding et al., 2006). Also, CVD synthetic diamonds can often be identified by a characteristic pattern (figure 9).

Features seen with the DiamondView in colored stones were shown to be valuable as well. Heat treatment of ruby and sapphire can sometimes be identified from blotchy colored patterns of fluorescence, and growth lines in high-clarity flame-fusion synthetic gems can often be identified in the DiamondView because they tend to fluoresce enough to show their curved pattern even when they are not easily visible with a microscope (again, see figure 9; Breeding et al., 2006). Fracture-filling materials in many treated gems have a distinctive fluorescence when viewed with the DiamondView. For example, the type of glass filler used in ruby and sapphire can be identified from the fluorescence color: Lead-glass fillers fluoresce blue, whereas typical heating-related glass-filled fractures and cavities usually show a white fluorescence. The DiamondView can also be used to separate oil and epoxy fillers in emeralds (Breeding et al., 2006).

X-ray Radiography and Tomography. We also saw real-time X-ray imaging applied to gem analysis during the first decade of the 2000s. X-ray techniques are particularly useful for evaluating whether pearls are natural or cultured and grown in saltwater or freshwater, by revealing details of their internal characteristics. X-radiography has long been used to reveal the growth structure and presence or absence of a bead nucleus in natural and cultured pearls. The instrumentation now allows the analyst to move the pearls and other samples laterally while viewing radiography images in real time. In addition, the X-ray detector and/or source can be moved to image different depth sections within the pearl, all while the changes are seen on a monitor (and can be captured digitally at any time). Whereas older, film-based radiography was used to collect only 1–2 image positions due to the time required to develop

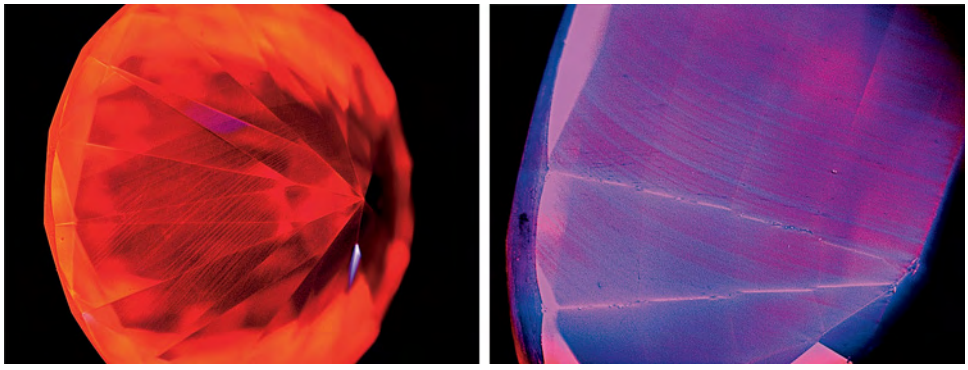


Figure 9. The DTC DiamondView instrument allows for real-time imaging of fluorescence features in diamonds and other gems, such as the characteristic curved growth lines seen in CVD synthetic diamond (left) and synthetic sapphire (right). Photos by Karen Chadwick (left) and C. M. Breeding (right).

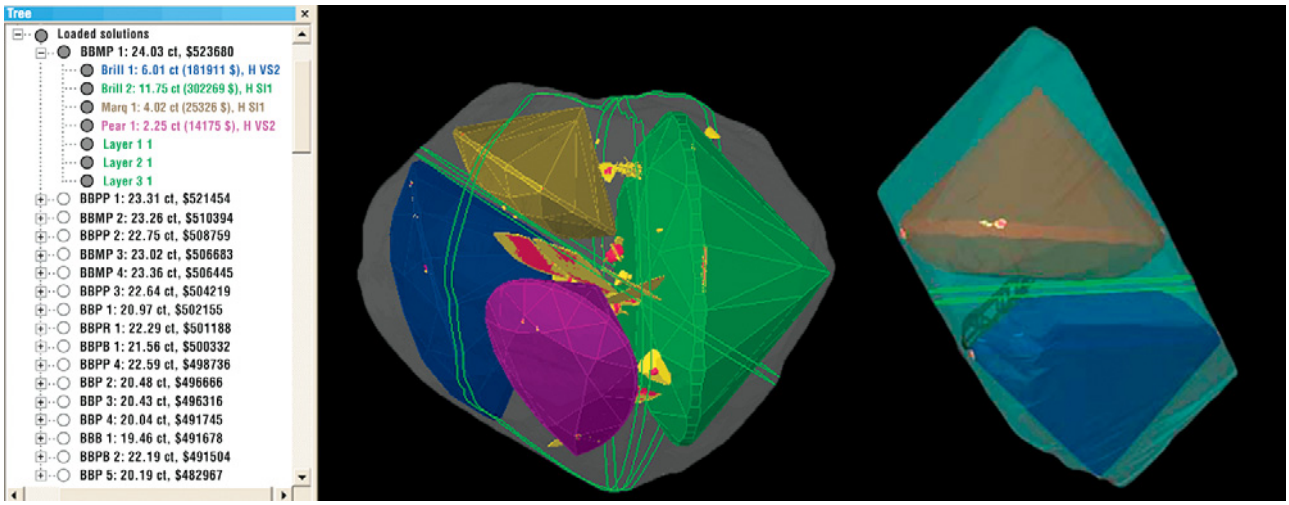


Figure 10. Software such as the Lexus M-Box has provided unprecedented opportunities for gem cutters to map their rough stones to maximize cutting efficiency. Composite image courtesy of Lexus.

the film, the newer, digital imaging systems allow for virtually unlimited images that can be adjusted as they are seen by the analyst.

Another advancement in imaging that the gemological community first used in the 2000s involves X-ray computed microtomography. This technique enables high-resolution X-ray "slices" through a rotating pearl (Krzemnicki et al., 2009a, 2010; Karampelas et al., 2010) that are then combined using specialized computer software to generate a three-dimensional (3D) representation of its internal structure. Despite long acquisition times, this type of imaging is potentially valuable for pearl identification because a single radiograph is limited by the angle at which it is collected relative to the orientation of internal features. X-ray computed microtomography overcomes that limitation by creating a full 3D rendering of the sample.

A related technique, X-ray topography, has been used to study the internal structure and growth history of diamonds (Diehl and Herres, 2004).

DIAMOND CUTTING AND EVALUATION

For centuries, it was understood that the face-up appearance of polished diamonds is related to facet arrangement and their relative angles (e.g., Moses et al., 2004). As profit margins for gem cutting have decreased, tools for planning the optimized cutting of rough diamonds have improved. Diacom, Lexus, OGI, and Sarin have introduced methods of scanning the shape and dimensions of rough diamonds, and some map inclusions as well (e.g., Sarin's new Galaxy 1000 and the Lexus M-Box; see figure 10). The Galaxy 1000 system can map inclusions in frosted rough diamonds. Software packages help operators determine the highest value for recovery by offering various cuts and clarities, along with estimated finished carat weights. These software packages consider the grading standards of different labs, and can be adjusted to meet manufacturer-specific parameters for cutting. Various types of equipment also assist the operator in monitoring the multiple phases of the cutting process. Automatic marking, laser cutting, bruting, and polishing machines have reduced the work force needed, now that one person can monitor many machines at once.

With the advent of noncontact optical measurement tools in the 1990s, advances in computer ray-tracing, various handheld viewers, equipment to assess light performance, and computer simulations of these tools, cut grading analysis for round brilliant diamonds has gone far beyond the basic angles that were long understood by cutters. The result is the development of various cut grading systems since 2000, including:

- American Gem Society's Angular Spectrum Evaluation Tool (ASET) and cut grading system
- GIA's cut grading system
- Holloway Cut Adviser (HCA)
- HRD's cut grading system
- Imagem's VeriGem
- isee2 cut grading system
- William Bray's diamond cut scoring system

NANO-SCALE CONSIDERATIONS

For decades, gemological observations were focused on macroscopic features and microscopic details at

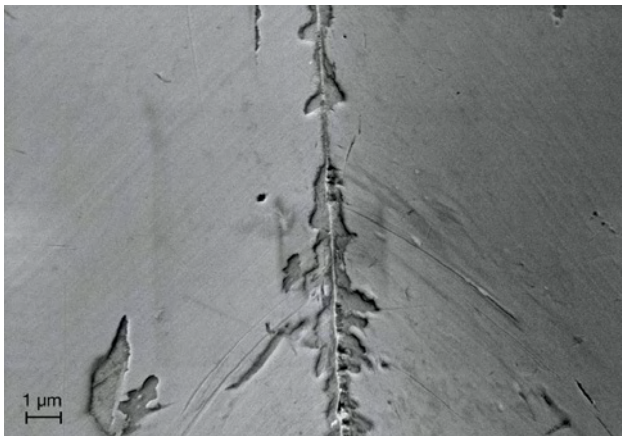


Figure 11. The early 2000s saw diamond coatings as thin as 60 nm being applied to gemstone surfaces to produce color. This SEM image shows slight wear of the coating near a facet junction on a coated pink diamond. Gemologists sometimes use this type of imaging to better understand the nature of these ultra-thin gem coatings. Micrograph by W. Wang.

the scale of millimeters or even as small as micrometers. The first decade of the 2000s, however, introduced nano-scale etching features and surface coatings to the gem industry (Rossman, 2006).

In 2009, researchers presented a method of plasma etching to create microscopic diffraction gratings on the pavilion facets of round brilliant cut diamonds (Gilbertson et al., 2009). The result was a noticeable increase in the fire seen when the diamonds were viewed face-up. The diffraction gratings were etched at the nano- to micrometer scale to separate incident white light into its spectral colors and thereby produce the new visual effect.

Also during the decade, extremely thin surface coatings were applied to a variety of gem materials (including diamond, topaz, quartz, tanzanite, and cubic zirconia) to significantly change a stone's color (figure 11) and resistance to wear. Individual coating layers, composed of elements such as Si, Ca, F, O, C, Au, Ag, Ti, Co, Fe, and Cr (Shen et al., 2007, Gabasch et al., 2008; McClure and Shen, 2008), have been measured using SIMS depth profiling analysis to be only a few tens of nanometers thick (again, see figure 6).

While most of these new nano-scale gem treatments and coatings can be detected by careful microscopic examination, some remain difficult to identify. For a better understanding of the nature of the coatings and treatments, gem laboratories have reached out to the broader research community for new techniques capable of analyzing at that scale. Many commercial companies have expressed intentions to continue refining the quality of their nano-scale treatments, so it is critical that laboratories be proactive and evaluate alternative techniques and instruments such as nanoSIMS and focused ion beam (FIB) technologies that are designed for sample preparation and analysis at the nano scale.

NanoSIMS. SIMS instruments (described above) produce an analysis spot of several tens of micrometers in diameter. In situations where smaller resolution is required, trace-element and isotopic analysis can be done on spots of a few tens of nanometers using a nanoSIMS instrument. It can analyze up to seven different masses at a time, allowing precise isotopic ratios to be determined from the same small volume. While this technology is not regularly used for gemological investigation, it has great potential for

Figure 12. Ultra-shallow diamond engravings such as GemEx's ion images (left) and the DTC Forevermark (right) were reportedly created using focused ion beams. These marks are so shallow that they require special viewers (distributed by the engravers) to be easily seen. Photo courtesy of GemEx (left) and Forevermark (right.

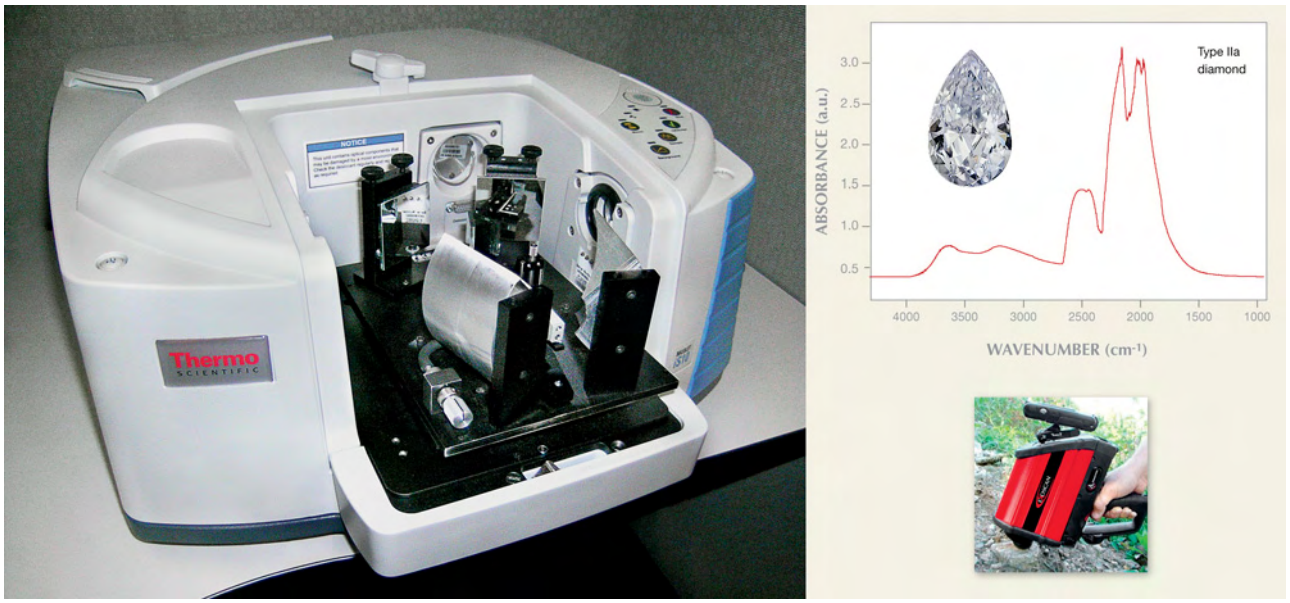


Figure 13. This Thermo iS10 FTIR (left) is one of the fast and portable desktop spectrometers often used by gemologists both in labs and at trade shows. Handheld FTIR units such as the Exoscan (lower right, designed by A2 Technologies) can be taken directly into the field to analyze gems and surrounding rocks. Both types of instruments are capable of providing valuable information about gems such as this 5.66 ct type IIa colorless diamond (upper right). Photos by C. M. Breeding (left), Robison McMurtry (upper right), and courtesy of A2 Technologies (lower right).

the identification of coatings and other nanometer-scale features of gems.

FIB. Another technology used by the semiconductor industry, FIB instruments focus a beam of ions of a chosen chemical element (usually gallium) on a target with a spot size of a few nanometers. The ion beams sputter away precise amounts of material, allowing precision milling of the target. Small, carefully controlled slices of a sample can be removed, typically for examination in a transmission electron microscope. Such slices are very useful for examining nano-scale inclusions in gems that are too small to be sampled by conventional microscopic means. The 2000s also saw the use of ion beams to create inscriptions or branding symbols on—or just under—a diamond's surface (e.g., Sheby and Cracco, 2002; figure 12).

HANDHELD AND PORTABLE SPECTROMETERS

The greater need for spectroscopic analysis in gem identification was accompanied by a desire to take the instruments "on the road." This has become particularly important for gemological labs that issue reports on-site at trade shows. In some cases, large gems or gem-encrusted artifacts at museums cannot be transported off-site for analysis, making it imperative that data be collected at the museum.

The first decade of the 2000s saw tremendous advances in the development of this portable technology. Portable (and some handheld) FTIR, UV-Vis-NIR, Raman, and EDXRF instruments all became readily available by the end of the decade. While handheld devices are not currently in widespread use in gemology, the advances in technology allow them to collect data comparable to many lab spectrometers.

Handheld FTIR instruments designed to be used in the field were equipped with diamond ATR (attenuated total reflectance) tips allowing for reflection analysis when the tip can be placed in contact with a sample. For transmission FTIR analysis, small, portable benchtop spectrometers became available. In most cases, these instruments are engineered for particular acquisition needs (i.e., the mid-infrared range) and have fixed beam splitters, higher resolution, and detectors that are electrically cooled, removing the need for a supply of liquid nitrogen for cooling (see, e.g., figure 13).

Handheld Raman instruments involved the localization of laser and optical components into a probe head that could be positioned very close to a sample, whereas tabletop Raman systems were engineered small enough to fit on a microscope (figure 14). Most handheld units have spectral resolution in the range of 7–10 cm^{-1}, which is lower than the resolutions typically used in a laboratory setting (<4 cm^{-1}), but

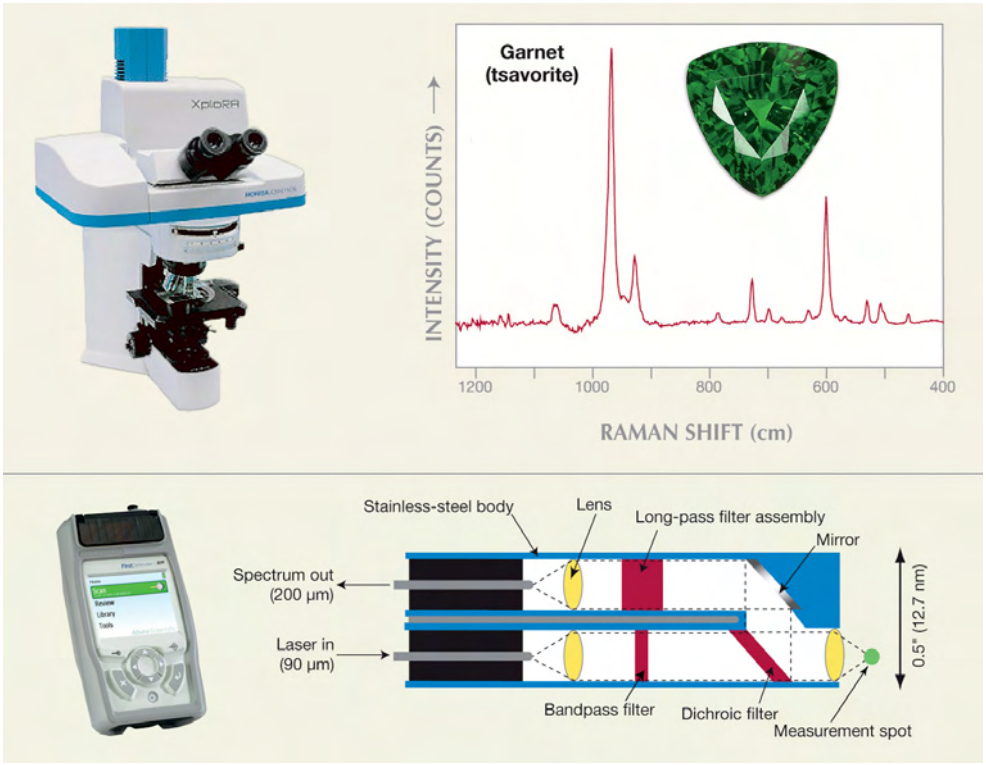
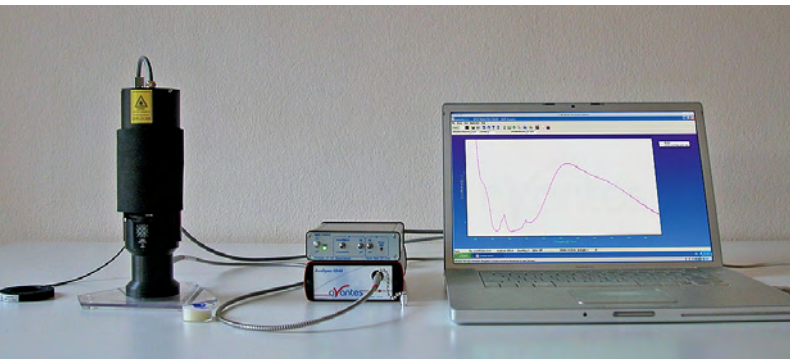


Figure 14. Portable desktop microRaman systems such as the Horiba XploRA (upper left) maintain most of the resolution of research-grade units, allowing for easy identification of gems such as this 2.05 ct grossular (upper right; photo by Robison McMurtry). The ability to localize Raman filters into a fiber probe (lower right; reproduced from Eckenrode et al., 2001) allows handheld units such as the FirstDefender RM (lower left; courtesy of Thermo Fisher Scientific) to be used almost anywhere.

still useful for identification of materials in the field.

UV-Vis absorption spectroscopy saw the development of numerous portable units based on small, fast CCD spectrometers, which were coupled by fiber-optic cables to various light sources and fiber probes or integrating spheres to provide a relatively easy means of collecting data from gemstones (figure 15; Krzemnicki et al., 2009b). This capability is particularly important for colored stones, because the visible absorption spectrum is a direct representation of the constituents (including defects, impurities, etc.) that cause color. An additional advantage of fiber-optic cables is their use in focusing incident light directly at, and collecting transmitted light directly from, the surface of a gem. With a traditional visible-range spectrometer, a faceted gemstone scatters the transmitted light so widely in the sample compartment that only a limited percentage of it falls on the detector.

Figure 15. Compact CCD spectrometers and light sources can be constructed into highly portable UV-Vis-NIR absorption spectroscopy units such as this one designed by SSEF (Krzemnicki et al., 2009b). Photo by M. S. Krzemnicki, © SSEF Swiss Gemmological Institute.



The early 2000s also saw the introduction of several handheld EDXRF analyzers (Voynick, 2010). While the elemental detection limits of these instruments are higher than their larger, laboratory counterparts, the handheld devices can be used in the field for immediate identification of the chemical composition of many gems.

While the desktop portable spectrometers generate data very similar to the data generated by their larger research-grade counterparts—which is then interpreted by a trained scientist—handheld spectrometers are typically used for field investigations and require instant data analysis and interpretation within the device itself. Thus, the quality of an analysis is often dictated by the quality of the library of reference spectra against which the data are internally compared to generate a match (particularly with Raman and FTIR spectroscopy; again, see box A). For

relevance to gemology, this means that an extensive collection of known gem materials (including rare and exotic gems, as well as synthetic and treated gem materials that are absent from most commercially available spectral libraries) must be available for analysis in order to create a comprehensive reference library. Analysis of an unknown sample in the field is of little value without such a database, so handheld instruments are often only as good as their reference libraries.

WHAT'S NEXT?

The coming decade will inevitably see improvements in the standard spectroscopic techniques (FTIR, UV-Vis-NIR, Raman) that are commonly used for gem applications (Fritsch 2006; 2007). As higher-resolution, faster, less-expensive detectors and more powerful light sources are introduced, many of these techniques will become even more important tools in everyday gem analysis. In fact, the next decade may well see small, portable spectrometers sitting alongside refractometers and microscopes on the desks of bench gemologists.

The next several years will likely include continued development and improvement of the coating techniques that were introduced in the first decade of this century. Detection of coatings on the order of a few tens of nanometers thick will require greater emphasis on surface profiling and nano-scale imaging.

A treatment that may become important in the industry is ion implantation of trace elements in gems to introduce color (e.g., Intarasiri et al., 2009). While this technique has been proved possible (e.g., figure 16), the current costs and damage to the stones have made it only a research curiosity for now. We speculate that the next decade will see refinement of this technique by treaters and the implantation of new impurities in gem surfaces. Gemological laboratories have seen very few ion-implanted samples for study, so a concerted effort is needed to characterize the results of this type of treatment before it becomes commonplace in the trade.

CONCLUSIONS

From the introduction of HPHT-treated diamonds at the end of the 1990s to the Be-diffusion of corundum in 2003 and the Cu-diffusion in feldspar over the last few years, the first decade of the 2000s was particularly challenging for the gemological community. These and other treatments, as well as advances in synthetic growth techniques (CVD, etc.), forced the development or adaptation of analytical instrumentation just to keep pace. The most significant changes came in the micro-scale chemical analysis of gems. LA-ICP-MS (and to some extent, LIBS) became mainstays in gem analysis for identifying treatments and providing reliable information about country of origin. New types of surface coatings led to the application of nano-scale analysis to gemological problems. Luminescence spectroscopy continued the breakneck pace of innovation initiated by HPHT treatment of diamonds. Raman and photoluminescence spectroscopy are now standard procedures in any gem laboratory that examines diamonds. Real-time imaging introduced a new level of viewing intricate details in pearls and fluorescence features in gems, while improvements in the portability of many instruments allowed them to be taken to museums and trade shows.

Gemology is a constantly evolving field, from the identification of treatments and synthetics to the grading of the cut quality of a faceted stone. As treatment and synthesis technology evolves to create gems or gem colors that more closely resemble their natural counterparts, the technology needed to identify them must keep pace. Gem treatment and synthesis facilities rarely provide information about their activities, so all must be inferred through careful, detailed interpretation of clues and comparison with known natu-

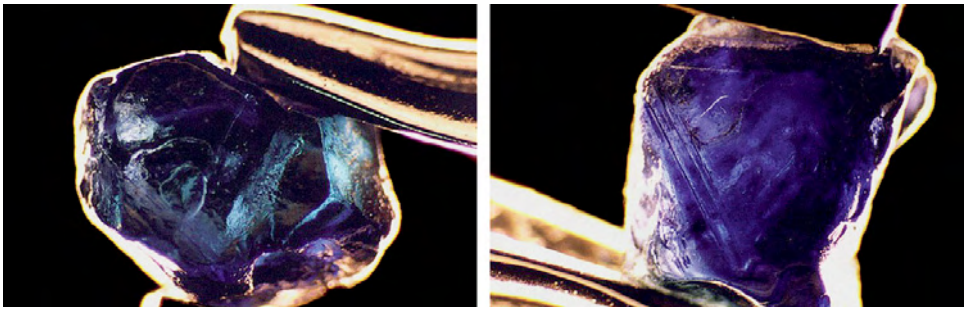


Figure 16. This sapphire from Southeast Asia is shown before (left) and after (right) treatment with ion implantation (photos from Intarasiri et al., 2009). This technique may play a role in color treatment in the coming decade.

ral, synthetic, and treated samples. In addition, most natural gems show tremendous variability, often rendering large spreads in analytical results and some uncertainty in interpretation. Nevertheless, the global gemological community has long managed to meet these challenges through a continued commitment to research. This commitment is the driving force behind the significant advances in the application of new technology to gem identification witnessed during the first decade of the 2000s.

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ACKNOWLEDGMENTS

The authors thank Dr. Wuyi Wang, Shane McClure, and Tim Thomas of GIA for helpful discussions.

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LETTERS

MORE ON THE RELATIONSHIP OF THE WITTELSBACH-GRAFF AND HOPE DIAMONDS

I must confess to serious reservations concerning the claim by the authors in the article "The Wittelsbach-Graff and Hope Diamonds: Not Cut from the Same Rough" (Summer 2010 *G&G*, pp. 80–88). They state that, based on "small but significant" differences in their red phosphorescence and major differences in observed strain patterns, their study "clearly shows that the [two diamonds] did not originate from the same crystal." How can they be so sure? They appear to believe that inhomogeneity within a single diamond crystal is impossible.

My study of different small gems cut from pieces produced when a very large diamond crystal was cut into the 407.43 ct Incomparable Diamond (*Lapidary Journal*, November 1994, pp. 35–37, 77–78) revealed not only that the original diamond was color zoned, but also that the different zones reacted differently to long-wave UV radiation. The darker brownish yellow gems fluoresced a strong yellow, while the colorless gems had no fluorescence—all cut from the same crystal. Could not, then, the Wittelsbach and the Hope have come from the same rough, each from a slightly different zone? By the same token, is it not possible that the strain patterns of different zones within a large crystal could also differ significantly? As far as I know, a study of strain patterns from different segments of a large zoned diamond crystal has never been conducted. For this reason I feel it is premature to make the claim that these two famous diamonds could not have been parts of a once very large crystal.

John S. White
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Reply. We are pleased to respond to Mr. White's thoughtful comments. He correctly notes that some natural diamonds can be very inhomogeneous in their luminescent and optical properties. However, there is an important distinction between the Incomparable and the Wittelsbach-Graff and Hope diamonds: The Incomparable is type IIa with very low impurity levels. The Wittelsbach-Graff and Hope are boron-containing type IIb diamonds, and therefore their luminescence properties cannot be directly compared to type IIa diamonds like the Incomparable (see C. M. Breeding and J. E. Shigley, "The 'type' classification system of diamonds and its importance in gemology," Summer 2009 *G&G*, pp. 96–111). Mr. White observed that the intensity of the yellow fluorescence in the Incomparable and sister stones correlated positively with the intensity of the brown-to-yellow bodycolor, and colorless regions were inert. In the Incomparable diamond, the "citron" yellow fluorescence was observed to be "more or less parallel to the table face" (J. S. White, "The tell-tale glow?," *Lapidary Journal*, November 1994, p. 37). In type IIa brown diamonds, yellow-green luminescence is known to be related to plastic deformation, mostly in lamellae along {111} that are related to the H3 center (two nitrogens associated with a vacancy; see, e.g., A. T. Collins et al., "Colour changes produced in natural brown diamonds by high-pressure, high-temperature treatment" *Diamond and Related Materials*, Vol. 9, 2000, pp. 113–122), which might be consistent with Mr. White's observations.

Some type IIb diamonds also show zoning (e.g., Summer 2005 Lab Notes, pp. 167–168), such as localized areas of type IIa (colorless with no boron) or of a gray component related to plastic deformation (see, e.g., D. Fisher et al., "Brown colour in natural diamond and interaction between the brown related and other colour-inducing defects," *Journal of Physics: Condensed Matter*, Vol. 21, 2009, Art. 364213, 10 pp.). But we observed no such zoning in the Wittelsbach-Graff and Hope diamonds either with visible light or in their phosphorescence behaviors.

In our study, we based our conclusion on results from three different observations: phosphorescence spectroscopy, strain patterns as observed under crossed polarizers, and dislocation networks revealed by the DiamondView instrument. The phosphorescence spectra from the two diamonds were remarkably similar, but showed small but reproducible differences, even when we looked at spectra collected from numerous places on each. The strain patterns revealed a more dramatic, and compelling, difference. Strain in natural diamonds is caused by stress applied when the crystals were at high pressure and high temperature, that is, before they reached the earth's surface (A. R. Lang, "Causes of birefringence in diamond," *Nature*, Vol. 213, 1967, pp. 248–251). The tatami strain pattern is attributed to plastic deformation that occurs in lamellae parallel to one, two, or three of the {111} octahedral planes, depending on the direction(s) of the external

(cont. on p. S4)

Cartier and America

By Martin Chapman, 177 pp., illus., publ. by Prestel USA [prestel.txt9.de], New York, 2009. US$35.00

High Jewelry by Cartier: Contemporary Creations

Ed. by Suzanne Tise-Isoré, 265 pp., illus., publ. by Flammarion [editions.flammarion.com], Paris, 2009. US$125.00

After establishing itself as a luxury goods retailer on the Boulevard des Italiens in Paris in the late 1890s, Cartier quickly became an internationally acclaimed fine jeweler. One of the forces behind the firm's meteoric rise was its presence in New York, setting it apart from Parisian contemporaries. Cartier's genuine interest in exceptional gems (diamonds, natural pearls, and faceted sapphires, as well as gem carvings) and dedication to excellence in design, materials, and fabrication catapulted it to the iconic status it still enjoys today. Originally a family company patronized by European and Indian courts, and then by American elites, the firm is now part of an international luxury group and remains on the cutting edge of fashion and jewelry creation.

In 2009, Cartier commemorated its first century in grand style with this pair of books. Both allow the reader to view Cartier's ascendance through an exceptional assembly of jewels, but their perspectives are radically different. *High Jewelry by Cartier* is a lavishly illustrated thematic catalogue of the brand's most recent work. *Cartier and America* was conceived more as a history book, showing the evolution of the brand and its following in America, particularly among famous collectors such as Marjorie Merriweather Post, Grace Kelly, and Elizabeth Taylor.

High Jewelry's strength lies in its beautiful photos of Cartier's latest creations. The red fabric cover and lettering are reminiscent of the famous Cartier signature box, and the overall presentation continues this luxurious motif with sketches and photos of wax and semi-finished jewelry presented in an artistic chiaroscuro, where the black background highlights their splendor and allows their full appreciation by the reader. Renderings of colored stones accurately represent their hues. Most of the pictures are magnified to display nuances of asymmetrical and uncalibrated gemstones, including briolettes, drops, and pearls.

Yet the book remains a beautiful enigma. It features magnificent representations of the pieces but provides minimal background, with no mention of provenance or date of origin. The reader might rightfully ask, for instance, if the pieces are privately owned or part of a museum collection. Were they a special order or a limited series? Were the gemstones recently cut, or are they older stones that have been incorporated into a contemporary setting? While the captions generally include the carat weight of center stones, it is difficult to determine the size of the pieces from the information provided.

Cartier and America takes a different approach. It was created to accompany the exhibition that took place at the Legion of Honor in San Francisco December 2009–May 2010. It contains many interesting photos of Cartier's New York flagship store on Fifth Avenue (renamed Place de Cartier in 2001) and noted American collectors adorned with their favorite Cartier jewelry. The result is a fascinating historical journey that showcases the distinct style of each period. The book portrays some of the jewels designed to cater to the tastes of America's fashionable elite. Some truly iconic pieces are featured, including Marjorie Merriweather Post's diamond and carved emerald pendant/brooch (which also appears on the cover of the book), the Daisy Fellowes so-called Hindu necklace, and the diamond tiaras and realistic snake and crocodile necklaces designed exclusively for Mexican actress María Félix. The three most outstanding chapters are those devoted to the Art Deco period, the Mystery Clocks (only 12 were ever created), and the final section featuring all 277 pieces from the exhibition, with thumbnail photos, detailed descriptions, and measurements.

Both books masterfully display Cartier's specificity of design; use of exceptional gemstones set in a vast array of materials; revival of exotic, whimsical animal and floral motifs; and finely articulated structures. Both provide a valuable resource for jewelry lovers who want to refer to Cartier's style from the early Belle Époque to contemporary creations.

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Gems and Gemstones: Timeless Natural Beauty of the Mineral World

By Lance Grande and Allison Augustyn, 369 pp., illus., publ. by The University of Chicago Press [www.press.uchicago.edu], Chicago and London, 2009. US$45.00

This fine book was written to coincide with the opening of the newly renovated Grainger Hall of Gems at the Field Museum in Chicago. The foreword captures the tenor: "As befitting a natural history museum, the Grainger Hall of Gems showcases not only scintillating cut gems and intriguing jewelry designs, it also features uncut crystals in all their amazing natural beauty. The juxtaposition of the natural form and the jeweler's art is the main thrust of the exhibition, and the inspiration for this companion volume."

The book flows logically from chapter to chapter. The first is a simple but sound introduction to gems. This is followed by "Formation of Gems" and "Classification of Gems," leading into the heart of the book. Here the Grainger collection is documented over more than 200 pages. Each gem species is discussed and illustrated with stunning photographs of loose gemstones, crystals, or mounted jewels from the collection. There are modern jewelry pieces and combinations of rough and cut stones, many in full-page presentation. Lead photographer John Weinstein did a fine job of preparing most of the images.

The Grainger gallery features many pieces from the Hope collection (the same collection that once contained the Hope diamond), and several are shown here. Some of the more famous Hope pieces are the Aztec "Sun-God" opal and "Blaze," a 97.45 ct red topaz set in a modern Lester Lampert design. This chapter continues with additional gem materials such as tanzanite, jadeite, spinel, and garnet, including tsavorite and a 7.13 ct Russian demantoid. One of the most stunning pieces is an Edwardian platinum necklace, exquisitely set with 300 small diamonds and a 60.2 ct blue sapphire carved into the form of a lovely face. The blue just glows.

The chapters continue with "Inorganic Gems Not Described Here" (included for the sake of completeness), "Organically Derived Gem - stones," and "Organic Gem Types," which deals with pearls, coral, amber, ivory, and the like. Also covered are precious metals (primarily gold); synthetics, simulants, and treatments ("Augmentation"); mining; ethics; folklore and magic; birthstones; and the history of the Field Museum's gem halls.

I highly recommend this book as a resource for anyone interested in fabulous examples of gems and jewels.

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Between Eternity and History: Bulgari. From 1884 to 2009, 125 Years of Italian Jewels

Edited by Amanda Triossi, 375 pp., illus., publ. by Skira Editore [www.skira.net], Milan, 2009. US$80.00

Greek jeweler Sotirio Bulgari established his first shop in Rome in 1884, thus launching the brand's rise to international prominence. To commemorate the 125th anniversary of this event, an exhibition of Bulgari creations was held from May to September 2009 at the Palazzo Delle Esposizioni, only a few blocks from the original location at 85 Via Sistina.

Ably curated by Amanda Triossi (who co-authored a previous book on Bulgari, reviewed in the Winter 2008 *G&G*), this exhibition amassed a huge—and heretofore unrivaled—collection of famous Bulgari pieces created throughout the years. There is perhaps no better way to view the arc of Bulgari's ascendance than through this assembly of jewels. And for those of us who were unable to travel to Rome to see this exhibition, Triossi has produced an artful coffee table book that comprehensively mirrors it.

The 900-plus illustrations include archival photos of 19th-century Rome, original jewelry sketches, and snapshots of movie stars wearing Bulgari jewelry. The catalogue is an interesting and comprehensive selection of the finest pieces, including jewelry from the Bulgari Vintage Collection and from private collectors such as Elizabeth Taylor.

The book traces the history of the brand from Sotirio Bulgari's early silver ornaments in the neo-Hellenistic tradition to the most contemporary fine jewelry pieces. It explores Bulgari's iconic styles, such as coin jewelry, the Melone bag, Tubogas jewelry, snake watches, and the Parentesi motif, to name a few. Finally, the book relates the house's transition from traditional silversmith to a high-end jeweler using platinum after 1905. As it became more established, Bulgari explored the many jewelry styles of the 20th century while affirming its own signature aesthetic, characterized by the use of very strong metal structures, cabochon-cut gemstones, and bold color contrasts. The firm's attention to design and craftsmanship, and its taste for fine gems, are particularly well illustrated here. The pictures, artfully color enhanced, even show the gemstones' inclusions.

Of the book's 19 chapters, the ones on the 1950s and 1960s "color revolution," the 1970s "eclectic creativity," and the 1980s and 1990s "opulence and colour" best illustrate Bulgari's uniqueness and innovation. During these decades, Italian design in general became more and more appreciated.

One of the most interesting sections features all 493 pieces gathered for the exhibition, with thumbnail photos and detailed descriptions and measurements. However, the book might have benefited from a paginated table of the illustrations and a glossary of jewelry terms, common Bulgari styles, and important members of the family. Last, more insight into both

the creative process of the early founders and today's corporate organization would have been interesting.

Nevertheless, the book is a must-have for gem enthusiasts, jewelry designers, appraisers, and even auctioneers who want to know Bulgari jewelry better. It allies the aesthetic quality of an art book with the precise, detailed documentation of a gemologist and art historian.

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OTHER BOOKS RECEIVED

Jewelry & Gems: The Buying Guide, 7th Ed. *By Antoinette Matlins and A. C. Bonanno, 306 pp., illus., publ. by GemStone Press [www.gemstonepress.com], Woodstock, VT, 2009, US$19.99.* This latest edition of Matlins's definitive consumer buying guide includes updates on the most recent diamond and colored stone treatments as well as changes in the market since the sixth edition appeared in 2005. Also expanded is the section on diamond color grading, with special attention to the problems inherent in grading fluorescent stones.

TWO

Contributions of the 4th International Symposium on Granitic Pegmatites. *Estudos Geológicos [www.ufpe.br/estudosgeologicos], Vol. 19, No. 2, 367 pp., 2009, US$25*. This proceedings volume presents papers from the PEG2009BRAZIL conference, held Aug. 30–Sept. 3, 2009, in Recife, Brazil.

TWO

Exotic Gems, Volume 1. *By Renee Newman, 153 pp., illus., publ. by International Jewelry Publications [www.reneenewman.com], Los Angeles, 2010, US$19.95.* The latest in Newman's series of consumer guides, this book reviews the characteristics, treatments, sources, history, and market factors for tanzanite, Zultanite, Ammolite, rhodochrosite, sunstone, moonstone, and other feldspars.

TWO

Agates II. *By Johann Zenz, 656 pp, illus., publ. by Bode Verlag [www.bodeverlag.de], Salzhemmendorf, Germany, 2010, €89.* This oversized, visually stunning work is a follow-up to the author's 2005 *Agates*. Over 2,000 photographs illustrate an array of agate and jasper specimens, accompanying a review of agate localities, mines, and prominent collectors.

TWO

Amber: The Natural Time Capsule. *By Andrew Ross, 112 pp., illus., publ. by Firefly Books [www.fireflybooks.com], Buffalo, NY, 2010, US$29.95.* This well-photographed volume captures the inclusions that occur in amber. A review of amber formation, chemistry, and localities is included, along with a guide to help identify included insects.

TWO

Pearl Buying Guide, 5th Ed. *By Renee Newman, 153 pp., illus., publ. by International Jewelry Publications [www.reneenewman.com], Los Angeles, 2010, US$19.95.* Updated from the fourth edition (see Spring 2004 *G&G*, p. 91), this latest version of Newman's guide for consumers adds a new chapter on antique pearl jewelry, more information on freshwater cultured and natural pearls, and hundreds of new photos and illustrations.

TWO

Gem and Ornamental Materials of Organic Origin. *By Maggie Campbell Pedersen, 268 pp., illus., publ. by NAG Press, London, 2010, £39.95*. This new version of Campbell Pedersen's essential reference for organic gems (see Summer 2004 *G&G*, p. 184) has been revised and updated to reflect developments since its first publication. New treatments—most notably to amber and copal—are covered, as are new gem materials that have come on the market since 2004.

TWO

LETTERS (cont. from p. S1)

forces applied to the stone. It is, therefore, unlikely for a single crystal to contain several regions with distinctly different strain features, and, in fact, such a situation has never been reported for natural diamonds.

The Hope diamond shows predominantly one direction of strain (again, see figures 8D-F in our article), which appears to be uniform throughout the diamond. The Wittelsbach-Graff diamond, on the other hand, exhibits a significantly finer-scale strain pattern, with distinct laminations oriented almost equally in three directions (figures 8A-C), and also uniform throughout the stone. The nature of the stress experienced by the two diamonds when they were still deep inside the earth was therefore significantly different: predominantly isotropic for the Wittelsbach-Graff diamond, and more unidirectional for the Hope diamond.

Finally, DiamondView images of the two stones revealed defect patterns that are typical of type II diamonds and are also the result of plastic deformation and annealing experienced deep in the earth (see Lang, 1967, and the references given in our article). Again, the mosaic defect patterns of the two diamonds, although uniform within each individual stone, are significantly different in scale from each other, indicating that they did not experience the same deformation and annealing history.

In the end, based on these observations and our collective experience, we could only conclude that the Wittelsbach-Graff and Hope diamonds did not come from the same original crystal.

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2010 GEMOLOGICAL ABSTRACTS

COLORED STONES AND ORGANIC MATERIALS

Inside emeralds. C. P. Smith and E. Quinn Darenius, *Rapaport Diamond Report*, Vol. 32, No. 9, 2009, pp. 139–148.

Originally found in ancient Egyptian mines in the 1st century BC, commercial sources of emerald now include Zambia, Brazil (the largest producer by volume), and most notably Colombia. Smaller but still important mines are located in Russia, Afghanistan, and Zimbabwe. Instability in Pakistan, Afghanistan, and Madagascar has caused output to drop significantly.

Most emeralds are heavily included, especially with feathers (open fissures). The high contrast between air-filled feathers and the emerald's bodycolor makes the inclusions readily visible. To reduce their visibility, treaters fill the fissures with oils, waxes, resins, and polymers, using a substance with a refractive index approximating that of the host emerald. This process is usually done after polishing, but some emeralds are treated in the rough to give them greater stability prior to cutting. Key internal features of emeralds from various geographic origins are reviewed. *JS*

DIAMONDS

The Argyle diamond mine in transition from open pit to underground extraction. G. Bosshart [george.bosshart@hispeed.ch] and J. G. Chapman, *Australian Gemmologist*, Vol. 24, No. 1, 2010, pp. 4–8.

At the Argyle diamond mine in Western Australia, an underground project is using block caving techniques to reach deeper portions of the diamondiferous lamproite. This program could

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

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extend the life of the mine to 2018. It entails a high level of automation, as well as measures to combat monsoonal downpours. *RAH*

Brown colour in natural diamond and interaction between the brown related and other colour-inducing defects. D. Fisher, S. J. Sibley, and C. J. Kelly, *Journal of Physics: Condensed Matter*, Vol. 21, No. 36, 2009, Art. 364213 (10 pp.).

Optical absorption spectroscopy was used to investigate current models for lattice defects in low-nitrogen (type IIa) diamonds. These defects give rise to the optical absorptions that produce brown and pink colors. The energy necessary to remove the brown color was consistent with expectations of the energy needed to remove so-called vacancy clusters. These neighboring groups of 40–60 missing carbon atoms represent the currently accepted model of the defect responsible for the optical absorption that produces the brown coloration. The theoretically determined electronic states for these vacancy clusters agree with observations of brown and pink diamonds. A model presented for these electronic states provides an explanation for the diamonds' colors, their photochromic effect, and their decolorization during HPHT annealing. *JES*

Dislocations, vacancies and the brown colour of CVD and natural diamond. R. Jones [jones@ex.ac.uk], *Diamond and Related Materials*, Vol. 18, No. 5/8, 2009, pp. 820–826.

Natural brown diamonds exhibit a broad featureless absorption that stretches from the infrared through the visible to the ultraviolet regions of the electromagnetic spectrum. HPHT annealing can remove this broad absorption, rendering the diamonds colorless and much more valuable. Scientists have proposed several ideas on the nature of the lattice defects that produce this absorption. Earlier investigators suggested that the brown color was due to broken carbon-carbon bonds, located along parallel planar structures (i.e., "graining") and thought to be sites of plastic deformation. Heating would be expected to heal these broken bonds or dislocations, accompanied by a decrease in the broad absorption. This model has several problems in correlating the dislocation density with the magnitude of the absorption. A newer model attributes brown color in low-nitrogen (type IIa) natural diamonds to absorption caused by globular multivacancy defects (i.e., vacancy clusters), and evidence seems to support this model. There is some uncertainty that this defect produces brown color in CVD-grown synthetic diamonds, since the coloration disappears at lower heating temperatures, suggesting a less stable type of lattice defect. *JES*

Properties of optically active vacancy clusters in type IIa diamonds. J.-M. Mäki [jmmaik@cc.hut.fi], F. Tuomisto, C. J. Kelly, D. Fisher, and P. M. Martineau, *Journal of Physics: Condensed Matter*, Vol. 21, No. 36, 2009, Art. 364216 (10 pp.).

Both colorless and brown type IIa diamonds were investigated to better understand the origin of the brown coloration. The brown diamonds were found to contain optically active vacancy clusters that strongly correlated with the optical absorption spectra. Such vacancy clusters were missing in the colorless diamonds. During HPHT annealing, these clusters gradually disappeared, and brown diamonds heated to 2500°C resembled the colorless samples visually and optically. The authors conclude that the brown coloration originates from the vacancy clusters, and their removal during HPHT annealing causes a loss of this coloration. *JES*

Formation of diamond in the earth's mantle. T. Stachel [tstachel@ualberta.ca] and J. W. Harris, *Journal of Physics: Condensed Matter*, Vol. 21, No. 36, 2009, Art. 364206 (10 pp.).

The principal sources of diamond are peridotitic and eclogitic domains located at depths of 140–200 km in portions of the lithosphere that underlie continental cratons. In these domains, diamonds probably formed in the presence of upwardly percolating carbonate- or methane-bearing melts, or under subsolidus conditions, in the presence of similar C-H-O fluids. Based on diamond composition and age dating, their precipitation from methane-bearing melts/fluids appears to have predominated in the Archean Epoch (prior to 2500 million years ago). Increased production and subduction of oceanic carbonate minerals during the Paleoproterozoic (2500–1600 Ma) gave rise to more oxidized fluids given off by subducted continental crust and, consequently, a shift toward diamond precipitation from more carbonate-bearing fluids in the lithosphere. Diamonds from some deposits with unusual chemical or carbon isotopic compositions reflect unique sets of formation conditions or modifications caused by post-growth geologic events. *JES*

Morphology and defects of diamond grains in carbonado: Clues to carbonado genesis. V. A . Petrovsky, A. A. Shiryaev [shiryaev@ns.crys.ras.ru], V. P. Lyutoev, A. L. Sukharev, and M. Martins, *European Journal of Mineralogy*, Vol. 22, No. 1, 2010, pp. 35–47.

Paramagnetic and non-paramagnetic defects in grains of diamond within Brazilian carbonado indicate that many of the studied specimens were annealed under mantle conditions, though for a relatively short time. The diamond grains showed various morphological forms with low degrees of dissolution; these included reentrant apexes and incomplete growth layers on faces. It is suggested that micron-sized single crystals of diamond of predominantly octahedral and cuboctahedral shape grew under conditions of lower carbon supersaturation. Decreasing temperature is a plausible driving force for crystallization. Mass crystallization of diamond occurred during the second stage of carbonado formation. The necessary carbon supersatura-

tion was probably caused by crystallization of other minerals, leading to a decrease in the volume and/or constitution of the parent solution. *RAH*

Nature and genesis of Kalimantan diamonds. C. B. Smith [chris_b_smith@btopenworld.com], G. P. Bulanova, S. C. Kohn, H. J. Milledge, A. E. Hall, B. J. Griffin, and D. G. Pearson, *Lithos*, Vol. 112S, 2009, pp. 822–832.

Diamonds have been recovered from alluvial sediments in the Indonesian province of Kalimantan on the island of Borneo since ancient times (~600 AD). Four main deposits are known. The diamonds are often of gem quality but tend to be small, though a few crystals over 100 ct have been found. No primary diamond-bearing igneous host rocks have ever been identified.

In this study, 872 diamonds from the four deposits were characterized by a range of techniques. On the basis of their crystal morphology and growth structures, as well as the nitrogen aggregation characteristics determined by IR spectroscopy, the diamonds resembled those transported to the surface by kimberlite or lamproite volcanism from sources in the subcontinental lithospheric mantle. The diamonds were divided into five genetic groups, which are found mixed together in each of the four deposits, presumably due to a long history of sedimentary recycling and alluvial transport. Thermobarometry calculations based on inclusion chemistry suggest the diamonds originated from depths of 120–160 km, similar to the mantle conditions of diamond formation in both Africa and Russia's Yakutia region. *JES*

Quantitative analysis of trace element concentrations in some gem-quality diamonds. J. McNeill, D. G. Pearson, O. Klein-BenDavid, G. M. Nowell, C. J. Ottley, and I. Chinn, *Journal of Physics: Condensed Matter*, Vol. 21, No. 36, 2009, Art. 364207 (13 pp.).

Scientists believe that diamonds crystallize from a fluid phase deep in the mantle, but the nature of this fluid is not fully understood. Tiny quantities of the fluid become trapped as inclusions, and even high-purity gem diamonds are thought to contain submicroscopic fluid or melt inclusions. When these diamonds are ablated for chemical analysis, the removed material will contain the contents of these inclusions as well as impurities in the diamond lattice. This article describes a new technique involving sector-field inductively coupled plasma–mass spectrometry (ICP-MS) for trace-element analysis of diamonds. Laser ablation occurs in a closed-system cell, and the products are preconcentrated in solutions for analysis. Using this method, the authors found that the detection limits for a wide range of elements lie between sub-picogram and low-picogram levels (1 pg = 1×10^{-12} g).

In this study, 10 colorless gem diamonds from the Cullinan (formerly Premier) mine in South Africa, one from Venezuela, and one each from the Udachnaya and Mir mines in Russia were investigated by ICP-MS chemical analysis, cathodoluminescence imaging, and infrared spectroscopy. All the diamond samples were in the form of polished flat plates. A wide range of elements were detected in the part-per-trillion (ppt) to part-per-million (ppm) range. Despite the small sample size, the authors found evidence for two types of diamond-forming fluids: one that displays enrichments in large-ion lithophile elements (LILE) such as Ba, U, and La versus Nb, and another that does not. This distinction seems to be consistent with similar studies of fluid-inclusion-rich fibrous (coated) diamonds.

Although more diamonds from additional sources need to be analyzed, this type of study provides a potential basis for determining the geographic origin of gem diamonds, allowing the industry to distinguish legitimate and illicit sources on the basis of trace-element chemistry. *JES*

GEM LOCALITIES

Colour-change garnets from Madagascar: Variation of chemical, spectroscopic and colorimetric properties. K. Schmetzer [schmetzerkarl@hotmail.com], H.-J. Bernhardt, G. Bosshart, and T. Hainschwang, *Journal of Gemmology*, Vol. 31, No. 5/8, 2009, pp. 235–282.

This study presents a detailed investigation of the color-change behavior of 52 gem garnets from Bekily, Madagascar. They were separated into two groups according to their color seen in daylight: those that were green to greenish blue, and those that were yellow-green to orange. In extreme cases, garnets from the first group may appear blue-green in daylight and purple in incandescent light. Electron microprobe data identified all the stones as pyrope-spessartine with minor amounts of Cr and V. The samples were divided into seven categories to correlate their chemical composition and their color-change behavior. Their visible spectra exhibited a dominant absorption band between 569 and 584 nm.

The origin of color in garnets is complex, with several transition metal cations (in varying concentrations and valence states) playing a potential role in causing or modifying the perceived colors. The authors found no simple parameters that explained the color or color-change behavior in the suite of garnets.

The authors recommend that the terms *alexandrite effect* and *alexandrite-like effect* only be used for stones that display a color change in the range historically described for natural alexandrite. Descriptive terms such as *faint*, *moderate*, *strong*, or *very strong*, which can represent a combination of both hue angle and color difference changes and can be correlated to these calculated values, provide some indication of color-change strength. In addition, they suggest that stones exhibiting a faint

color change be described as displaying a *color variation*, and that the term *color shift* be abandoned. *JES*

Gemmologische Kurzinformationen: Das neue Rubinvorkommen von Montepeuz, Mosambik [Gemological short notes: The new ruby deposit of Montepuez, Mozambique]. H. A. Hänni [h.a.haenni@sunrise.ch] and M. S. Krzemnicki, *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 58, No. 3–4, 2009, pp. 127–130 [in German with English abstract].

This study presents preliminary results on rubies from a new deposit in the Montepuez area of northeastern Mozambique. These iron-bearing rubies often show twin lamellae and contain minor rutile silk, corroded amphibole grains (identified by Raman analysis), negative crystals, zircons, fluids, and secondary minerals in fissures. The iron content affects the rubies' fluorescence and absorption spectrum. Energy-dispersive X-ray fluorescence (EDXRF) spectroscopy detected traces of Ti, Cr, Fe, and Ga. Rubies from Montepuez often have surface-reaching fissures, which makes them amenable to flux heating and glass filling. *GL*

The gemstone deposits of Brazil: Occurrences, production and economic impact. S. de Brito Barreto [bsandra@ufpe.br] and S. M. B. Bittar, *Boletín de la Sociedad Geológica Mexicana*, Vol. 62, No. 1, 2010, pp. 123–140.

The authors report that in 2005, Brazil ranked first in the world in variety and quantity of gems produced, with tourmaline, topaz, and quartz (agate, amethyst, and citrine) worthy of note. The country was also the second-largest exporter of emeralds, and one of the few sources of Imperial topaz and Paraíba-type tourmaline. It also provides diamonds, rubies, and sapphires on a smaller scale. Gem production occurs across the country but is especially concentrated in the states of Minas Gerais, Mato Grosso, Goiás, Rio Grande do Sul, and Bahia. These account for 97% of Brazil's official gem production. Gem production in Brazil is carried out by a few mining companies and thousands of independent miners, and the heavy tax burden on the mining sector allows the informal sector to thrive. This is reflected in the volume of gems smuggled abroad and the lower-than-expected official figures for production and sales. *DAZ*

Geographic typing of gem corundum: A test case from Australia. F. L. Sutherland and A. Abduriyim, *Journal of Gemmology*, Vol. 31, No. 5–8, 2009, pp. 203–210.

The authors compared previously published results from laser ablation ICP-MS analysis of sapphires from unknown mines in New South Wales, Australia, to the results from known mines. For indicating magmatic/metamorphic origin, Ga and Mg were the most important trace elements. The unsourced NSW sapphires were most similar to the Invernell and Barrington magmatic groups, and likely corresponded to the Invernell Blue Group. Such studies show promise in identifying the exact mine of origin for sapphires. *AB*

Les gisements de saphirs et rubis associés aux basaltes alcalins de Madagascar: caractéristiques géologiques et minéralogiques 2ème partie: Caractéristiques minéralogiques [Sapphire and ruby deposits associated to alkali basalts in Madagascar: Geological and mineralogical characteristics, Part 2: Mineralogical characteristics]. S. Rakotosamizanany, G. Giuliani, D. Ohnenstetter, A. F. M. Rakotondrazafy, and A. E. Fallick, *Revue de l'Association Française de Gemmologie*, No. 170, 2009, pp. 9–18 [in French].

In this study of basalt-associated corundum from Madagascar, sapphires from Ambondromifehy and Nosy Be typically displayed a barrel-shaped habit, though most were somewhat rounded and corroded. In general, one of the hexagonal dipyramids ω {14 14 $\overline{28}$ 3} or *z* {2$\overline{2}$41} was combined with the pinacoid c {0001}. Rubies from Soamikatra and corundum from Toamasina were generally rounded, but also short-prismatic or pseudohexagonal following their basal pinacoid *c*.

Iron is the main chromophore of sapphire; the Fe^{2+}/Fe^{3+} ratio and the quantity of titanium and chromium also present during formation determine the color. Chromium is the second most important chromophore for pink, violet-blue, and some blue-green to light blue sapphires. For ruby, chromium is the primary chromophore. Iron and vanadium produce red-brown to purplish blue crystals. The entire color range of the sapphire samples—including yellow, greenish blue, and blue to blue-violet—showed absorption bands at 376, 388, and 450 nm. Deeply colored, high-quality rubies were characterized by the ratio $Fe_2O_3/Cr_2O_3 \leq 1$.

The most common inclusions in sapphires from Ambondromifehy and Nosy Be were iron-bearing spinel (hercynite), Nb-Ta oxides, samarskite, and zircon. Ruby from Soamikatra contained rutile, zircon, apatite, phlogopite, albite, spinel, and garnet. The Vatomandry rubies contained rutile, zircon, pentlandite, talc, phlogopite, sillimanite, and titanite. The most common inclusions in Vatomandry sapphires were zircon and pyrochlore.

Before they were brought to the surface by alkali basalts, the origin of the sapphires can be linked to either a dominant magmatic process (linked to syenites) or a metamorphic process. Those with inclusions such as pyrochlore, samarskite, uraninite, and anorthoclase have a syenitic origin. The inclusion suite in the rubies provides proof of a metamorphic paragenesis. *GL*

Jadeite jade occurrence from the Sierra del Convento mélange (eastern Cuba). J. Cárdenas-Párraga [cpjuan@correo.ugr.es], A. García-Casco, K. Núñez-Cambra, A. Rodríguez-Vega, I. F. Blanco-Quintero, G. E.

Harlow, C. Lázaro, *Boletín de la Sociedad Geológica Mexicana*, Vol. 62, No. 1, 2010, pp. 199–205.

A large source of jadeite was recently discovered in eastern Cuba, in the Macambo region of the Sierra del Convento serpentinite-matrix subduction mélange. The jadeite has been found as centimeter-sized pebbles in local rivers and beaches, as centimeter- and meter-sized detrital pebbles in conglomerates containing other rocks from the mélange, and as *in situ* tectonic blocks within the mélange that range up to 6 m in dimension. Gem-quality jadeite samples from all three sources exhibited a homogenous light green color with granoblastic texture and fine-to-medium grain size. Considering the quantity and variety of jadeite, the Macambo deposits could become an important source of this gem material. Other areas of the Sierra del Convento mélange with similar geologic characteristics may also bear gem-quality jadeite. *AB*

The Merelani tanzanite mines. W. E. Wilson [minrecord@comcast.net], J. M. Saul, V. Pardieu, and R. W. Hughes, *Mineralogical Record*, Vol. 40, No. 5, 2009, pp. 346–408.

The authors give an in-depth account of the Merelani tanzanite mines in the Arusha region of Tanzania. After a brief description of the locale, the article details the often conflicting accounts of the discovery of the vanadium-rich blue zoisite now known as tanzanite (generally credited to Manuel de Souza, in 1967). Decades of claim stakes and changing ownership are discussed, concluding with the present-day mining areas demarcated by the Tanzanian government: Blocks A, B, C, and D. As of 2007, Block A was still producing but had never achieved high yield. Like Block A, Block B is difficult to access and riddled with primitive mine shafts and pits. This was the site of the 1998 and 2008 floods that killed hundreds of miners trapped underground. Block D, a similarly primitive mining area, was visited by two of the authors to document the mining conditions. Block C, owned by TanzaniteOne, the leading marketer of tanzanite, is the most modern and productive concession.

The second half of the article describes the geology of the Merelani area (part of the gemologically fascinating Mozambique Orogenic Belt), the formation of vanadium-bearing zoisite, and the many other minerals recovered from the deposit. Since 2005, intensive geological investigation of the reserves in Block C has revealed much larger tanzanite-bearing layers than anticipated, increasing the mine's life expectancy by more than 20 years. In addition to tanzanite, various colors of gem zoisite have been found, including yellow, pink, red, green, and bicolored varieties. While tanzanite made the mine famous, other gem-quality minerals found there include apatite, axinite-(Mg)—once mistaken for tanzanite—"chrome" tourmaline (dravite), green diopside, tsavorite, and green tremolite. The spectacular, often euhedral crystals are prized by mineral collectors who pay high prices for intact specimens. World record holders include a 185 g tsavorite (cut to 325 ct) mined from 160 m depth at Block D, the 3 kg "Mawenzi" gem-grade tanzanite crystal found at 270 m in Block C, and a heavily included 6.5 kg tanzanite crystal recovered from the TanzaniteOne Main Shaft in 2008.

The article concludes with tanzanite's morphological and gemological properties, including heat treatment and coloration mechanisms. *ES*

Microstructures observed in Andamooka matrix opal. G. Pearson [grantpearson@optusnet.com.au], *Australian Gemmologist*, Vol. 24, No. 2, 2010, pp. 32–37.

Stereomicroscopy and photomicrography of opals from Andamooka, South Australia, revealed a range of microstructures that differed from the usually assumed constitution of a simple quartz-rich sandstone cemented by opal. The porosity of the matrix opal enables it to be stained by black pigments to create a gem material that resembles the well-known black opal of Lightning Ridge, New South Wales. *RAH*

Moganite and quartz inclusions in the nano-structured Anatolian fire opals from Turkey. M. Hatipoğlu, *Journal of African Earth Sciences*, Vol. 54, No. 1/2, 2009, pp. 1–21.

Red, orange, yellow, and colorless opals are found near the town of Simav in west-central Turkey. They occur as small nodules within shrinkage and dehydration cracks in rhyolitic lavas and tuffs. This study characterized the opals using several analytical techniques. Microscopic examination revealed that they generally consist of a nano-sized matrix material (opal-CT and opal-C) and centrally located, micron-sized translucent inclusions consisting of particles of moganite, quartz, and an orthorhombic silica phase. The identification of these phases was confirmed by X-ray diffraction data. The opal nodules are believed to have formed by precipitation of colloidal silica, first producing the opal phases near the outer edges of the open vesicles, followed by formation of coarser moganite, quartz, and the third silica phase as the translucent inclusions near the central part of the vesicles. *JES*

The structure and chemical composition of trapiche blue sapphire from southern Vietnam and Cambodia. K. Khotchanin [kh_kanyarat@yahoo.com], P. Thanasuthipitak, and T. Thanasuthipitak, *Journal of the Gemmological Association of Hong Kong*, Vol. 30, 2009, pp. 25–35.

While trapiche emerald is well known, trapiche corundum (especially blue sapphire) is considerably rarer. The authors examined 33 blue sapphires from Vietnam and 27 from Cambodia. The majority showed trapiche structure, but non-trapiche specimens were included for comparison. The trapiche sapphires typically featured a brown core and brown to yellowish brown arms separating the sections of blue crystal; dotted and needle-like inclusions were also

seen. Iron and titanium were both present in the samples, but the iron was concentrated in the trapiche core while the titanium was evenly distributed for the most part. The authors also compared the visual characteristics of trapiche rubies and sapphires, as well as trapiche vs. star phenomena. The trapiche structure could point to a multistage growth process that starts at the core, with the arms and blue crystal segments growing concurrently but at different rates. *AB*

Tectonic implications of new single zircon Pb-Pb evaporation data in the Lossogonoi and Longido ruby-districts, Mozambican metamorphic belt of northeastern Tanzania. E. Le Goff [e.legoff@brgm.fr], Y. Deschamps, and C. Guerrot, *Comptes Rendus Geoscience*, Vol. 342, No. 1, 2010, pp. 36–45.

Ruby deposits at Lossogonoi and Longido in northeastern Tanzania are two of the numerous gem occurrences along the regional orogenic belt on the eastern margin of Africa, from Ethiopia down through Mozambique. Dating of zircons found in metamorphic rocks from the two ruby deposits demonstrates the existence of Archean and Paleoproterozoic igneous rocks with emplacement ages between 2636 and 2448 Ma. These ancient rocks were reworked much later (~640–600 million years ago) during the Pan-African orogeny. In both deposits, ruby is thought to have formed by a metamorphic-metasomatic process, which accompanied regional deformation of the host rocks roughly 610 million years ago. *JES*

U.S. gemstones: An overview. J. S. White, *Rocks & Minerals*, Vol. 85, No. 1, 2010, pp. 14–23.

While not as important a gem producer as nations such as Brazil or Madagascar, the United States enjoys an extraordinary diversity of gem deposits. Tourmaline occurs in pegmatite formations in both California and Maine. American tourmaline mining activity began in 1820, after glassy green fragments were found among the roots of a fallen tree at Mount Mica, Maine. Pegmatite discoveries in California were also serendipitous. During the 1860s, a salesman in Mesa Grande supposedly noticed children playing with brightly colored marbles that turned out to be tourmaline. This led to the discovery of several closely related deposits in the mountains of southern California. Between 1910 and 1920, 120 tons of tourmaline were extracted from the Mesa Grande area, mostly from the Himalaya mine.

Emerald and diamond deposits lie in North Carolina and Arkansas, respectively, but these are modest compared to other worldwide sources. Montana has been producing large quantities of sapphires since 1860. Dredged with gold along the Missouri River northeast of Helena, sapphire deposits were eventually found throughout the southwestern portion of the state. By 1959, the total production of industrial and gem sapphires from Montana was estimated at $3–$5 million. The easternmost deposit, located at Yogo Gulch, produces "cornflower" blue sapphire, and is the only Montana deposit that is mined from rock rather than dredged from gravel bars in the Missouri River. The largest fine faceted Montana sapphire is an 18.10 ct unheated blue from El Dorado Bar in Lewis and Clark County.

In Arizona, peridot of basaltic origin has been known for quite some time. But it was not until the 1990s that large-scale mining was attempted at the San Carlos Indian Reservation in Gila County. It was readily available at the Tucson shows for several years but seems to have disappeared from the market, reportedly because of rivalries within the tribal community. Turquoise was first mined at least 2,600 years ago in what is now New Mexico. More recently, production has taken place in Arizona (Globe-Miami district of Gila County) as a byproduct of copper mining. Nevada was the leading U.S. producer of turquoise until the 1980s.

Although the term *sunstone* refers to several different materials, the labradorite variety with copper inclusions comes from several active mines in Oregon, one in Harney County and the other five in Lake County. One of the Lake County mines produces an estimated 50,000 carats of facetable material annually, most of it fashioned into beads.

Opal occurs in several places in the U.S., most notably within beds of volcanic ash in Virgin Valley, Nevada, and in other deposits in Oregon and Idaho.

Two lesser-known gems occur only in the United States: benitoite from California and red beryl from Utah. Also cited as a possible uniquely American gem is hiddenite from North Carolina. Another "hiddenite" deposit has been found in Brazil, but the material lacks color stability under sunlight. (*Editors' note*: Hiddenite is also known from elsewhere; see K. M. Chadwick et al., "Gem News International: Cr/V-bearing green spodumene from Afghanistan," Fall 2007 *G&G*, pp. 265–267.)

JEC

INSTRUMENTS AND TECHNIQUES

Applications of Raman spectroscopy to gemology. D. Bersani [danilo.bersani@fis.unipr.it] and P. P. Lottici, *Analytical and Bioanalytical Chemistry*, Vol. 397, 2010, pp. 2631–2646.

Raman spectroscopy offers a nondestructive means of identifying gem inclusions and treatments, requiring only a small amount of material and no sample preparation. Raman analysis is not limited to inorganic crystals—it can also be used to gather data on organic and amorphous materials. Both laboratory and portable systems exist; laboratory setups offer better performance in terms of spectral and spatial resolution and acquisition time. Raman spectroscopy can be used to identify mineral species and composition, investigate the origin of a gem, and detect various treatments. *DAZ*

SYNTHETICS AND SIMULANTS

Kinetics of diamond single crystal growth in Fe-Co solvents doped with titanium and zirconium. V. V. Lysakovskii and S. A. Ivakhnenko, *Journal of Superhard Materials*, Vol. 31, No. 1, 2009, pp. 7–11.

This study examined the impact on diamond crystallization of varying the amounts of titanium and zirconium (known nitrogen-getters), coupled with varying temperature and pressure. Specifically, the authors researched the diamond types, growth rates, crystal habits, and nitrogen concentrations in high–pressure, high-temperature (HPHT) synthetic diamonds grown from an Fe-Co-C solution.

The authors employed pressures of 5.5–6.1 GPa and temperatures of 1380–1680ºC over a period of 22–150 hours. The dopant concentrations were 1.81–5.35 wt.% Ti and 0.64–6.30 wt.% Zr. These dopants were introduced as 50 μm thick foils. IR spectroscopy was used to determine nitrogen concentrations and impurity center types by applying known absorption coefficients.

The synthetic diamonds were types Ib, Ib+IIb, or IIa. They had nitrogen concentrations of <5–35 ppm, and average growth rates of 2.5–6.1 mg/h were recorded. The observed habits were cuboctahedral, tetragontrioctahedral-octahedral, and octrahedral. Below 3.6 wt.% Ti (or 2.54 wt.% Zr), type Ib or Ib+IIb synthetic diamonds were formed containing 15–35 ppm N. Increasing Ti to 5.35 wt.% (or Zr to 3.8 wt.%) produced type IIa diamonds with N concentrations below 5 ppm. However, with these higher dopant concentrations, light yellow-green type Ib crystals resulted at elevated pressure (6.1 GPa) and temperature. This is explained by the release of bound nitrogen; the chemical reaction favors the formation of Ti(Zr)-carbon inclusions over nitrogen compounds at lower pressure and temperature. Increasing the temperature resulted in crystal habits from cuboctahedral to tetragontrioctahedral-octahedral to octrahedral. *JS-S*

TREATMENTS

Brown diamonds and high pressure high temperature treatment. D. Fisher [david.fisher@dtc.com], *Lithos*, Vol. 112S, 2009, pp. 619–624.

With the rise in the HPHT-treatment of brown diamonds, there is considerable interest in determining the precise origin of their color. Brown diamonds can be either type I (nitrogen-bearing) or type II (largely nitrogen-free). Shear stresses late in their formation, possibly during kimberlite emplacement, induced plastic deformation in their crystal structure. This deformed crystal structure may contain vacancy clusters, or aggregates of small voids within the crystal. While vacancy clusters are difficult to analyze with existing technology, empirical observations (the clusters are removed by HPHT treatment) and theoretical calculations support the theory that a defect consisting of ~60 vacancies causes brown coloration. The article also addresses color removal and color alteration via HPHT treatment, as well as the methodology of detecting HPHT-treated stones, which is critical to maintaining consumer confidence in the diamond industry. *AB*

Coated and fracture-filled coloured diamond. Z. Song, T. Lu, M. Shen, J. Su, J. Dong, and X. Zhang, *Australian Gemmologist*, Vol. 24, No. 1, 2010, pp. 41–43.

Color and clarity enhancement were detected in a 2.05 ct brownish orange-yellow round brilliant that displayed features indicating coating and glass filling. Typical damage to the coating layer was seen, as well as a flash-effect from filled cracks. EDXRF analyses indicated the presence of Ag, Fe, Ti Al, Pb, and Br in the diamond. The authors concluded that this stone was treated by Pb and Br glass filling, followed by a coating that involved Ag and Fe nanoparticles. *RAH*

A comparison of diamonds irradiated by high fluence neutrons or electrons, before and after annealing. T. Hainschwang [thomas.hainschwang@gemlab.net], A. Respinger, F. Notari, H. J. Hartmann, and C. Günthard, *Diamond & Related Materials*, Vol. 18, No. 10, 2009, pp. 1223–1234.

The authors compared the visible and IR spectra for several type Ia diamonds before and after irradiation with high doses of neutrons or electrons, and then after annealing in 50°C increments up to 1100°C. The samples turned from near colorless to very dark green to opaque black upon irradiation, and then deep greenish yellow to deep orangy brown upon annealing. The amount of brown color produced during the annealing was found to be related to the type of radiation used, and likely to the total radiation dose. All the diamonds turned yellowish or orangy brown after annealing above 700°C. After annealing to ~900°C, most exhibited unusually strong H1b (~4932 cm^{-1}) and/or H1c (~5165 cm^{-1}) infrared absorptions. Because of their much greater mass, neutrons induced more extensive defects in the diamond lattice than electrons. Neutron bombardment also produced more spectral features. Certain features were found in type Ia diamonds irradiated in one way but not the other, suggesting that diamonds treated by either irradiation or annealing can be distinguished. *JES*

Effects of heating on fire opal and diaspore from Turkey. M. Hatipo lu, N. Can, and T. Karali, *Physica B*, Vol. 405, No. 7, 2010, pp. 1729–1736.

Important deposits of orange-red fire opal and yellow-green diaspore occur in Turkey. The opal is found in the Saphane region of Kütahya Province, and the diaspore in the Milas region of Muğla Province. Samples of both materials were characterized by X-ray diffraction, X-ray fluorescence spectroscopy, and IR spectroscopy. Gradual heating to 1400°C resulted in measurable weight losses, attributed to the removal of water (molecular H_2O and/or

OH groups) over particular temperature ranges—342–722°C in the fire opal, and 592–718°C in the diaspore. When faceting these materials, the lower temperatures of these ranges should be considered the point of decomposition, and not be exceeded. Complete decomposition occurred in both minerals between 1230 and 1350°C. These heating behaviors are slightly different from similar opal and diaspore samples found in other world localities.

JES

MISCELLANEOUS

Diamonds and clubs: The militarized control of diamonds and power in Zimbabwe. Partnership Africa Canada, June 2010, www.pacweb.org/Documents/diamonds_KP/Zimbabwe-Diamonds_and_clubs-eng-June2010.pdf.

Diamond production in Zimbabwe was mostly limited to accidental finds in alluvial gold diggings until 2004, when Rio Tinto began mining the Murowa kimberlite cluster. The Marange strike in June 2006, in Chiadzwa Province near the border with Mozambique, changed the picture after depressed economic conditions caused a massive diamond rush and tens of thousands of illegal miners descended on the area. The ensuing government crackdown led to allegations of widespread human rights abuses.

The paper, based on a field visit to Zimbabwe in April 2010, details how a handful of Zimbabwean politicians and military leaders have brutally seized control of the country's diamond resources, which they are using to jockey for power in a post-Mugabe era. This threatens the viability of the coalition government created in February 2009. The state of affairs in Zimbabwe clearly defies the Kimberly Process Certification System (KPCS) and highlights its shortcomings. The paper ends with a list of recommendations and calls for a restructuring of the KPCS to include a mandate to protect human rights.

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