Granitic Pegmatites as Sources of Colored Gemstones

Article *in* Elements · August 2013

DOI: 10.2113/gselements.8.4.281

William B Simmons
University of New Orleans

Federico Pezzotta
Museo di Storia Naturale, Milano

Hartmut Beurlen
Federal University of Pernambuco

Granitic Pegmatites as Sources of Colored Gemstones

Simmonsite, Zapot pegmatite, Gillis Range, Mineral Co., Nevada, USA. Named in honor of W.B. Simmons. The sample is 1.5 cm long. Photo: A. Falster

William B. Simmons[1], Federico Pezzotta[2], James E. Shigley[3], and Hartmut Beurlen[4]

1811-5209/12/0008-0281$2.50 DOI: 10.2113/gselements.8.4.281

Pegmatites are sources of gem-quality crystals of beryl, tourmaline, topaz, spodumene, and spessartine. Historic localities are found in Brazil, Madagascar, Russia, and the United States, but important deposits have recently been discovered in Africa and Asia. Most high-quality gem minerals occur in miarolitic cavities found near the centers of pegmatite bodies or in reaction zones between pegmatites and ultramafic host rocks. The most important gem-bearing granitic pegmatites formed at shallow levels in the continental crust during the latest stages of collisional plate tectonic events. Single, spectacular miarolitic cavities in some pegmatites have produced tons of gem crystals valued in excess of $50 million.

Keywords: gems, granitic pegmatites, miarolitic cavities

INTRODUCTION

Pegmatites are the source of fine and valuable colored gemstones, including varieties of beryl, tourmaline (see Pezzotta and Laurs 2011), topaz, spodumene, and spessartine (Figs. 1, 2; Table 1). More than 50 less familiar gemstones also occur in pegmatites (Simmons 2007). Historically, pegmatite deposits in Brazil, Madagascar, Russia, and the United States have been the principal sources of gem minerals. More recently, these classic sources have been joined by important gem deposits in Africa (Congo, Mozambique, Namibia, Nigeria, Tanzania, Zambia) and Asia (Afghanistan, Pakistan) (Table 2).

All significant gem-bearing pegmatites are granitic in composition. Only rarely do pegmatite bodies of mafic or alkaline compositions (e.g. gabbro, nepheline syenite) contain gem minerals, such as microcline (amazonite), sodalite, and zircon.

GEM MINERALS IN GRANITIC PEGMATITES

Gem-quality crystals principally occur in the interiors of zoned pegmatites or in reaction zones adjacent to pegmatites. The three main settings are:

Crystals "frozen" in massive quartz or feldspar in the core or core margin of a pegmatite

Aquamarine (green-blue to blue beryl variety) and **tourmaline** commonly occur in massive quartz or feldspar of the centrally located pegmatite core zone or in the core margin, the region around the core. Typically, only parts of these crystals are of gem quality, and gemstock is recovered by breaking out clear portions from the crystals.

Crystals in reaction zones surrounding pegmatites that intrude mafic rocks

Emerald (the grass green, Cr- or Cr–V-rich variety of beryl) and **alexandrite** (the Cr- or Cr–V-rich variety of chrysoberyl) in "Urals-type" deposits, such as those in the Ural Mountains of Russia, the Kafubu area of Zambia, and the Mananjary area of Madagascar, are produced from the interaction of Be-rich pegmatitic fluids with chromium-bearing mafic country rocks (Schwarz et al. 2002; Zwaan et al. 2005; Groat et al. 2007).

Figure 1 Granitic pegmatites have produced a spectacular variety of colored gemstones. Examples are, left to right from the upper left, pink morganite beryl (Brazil, 100.99 ct, 35.96 × 25.69 mm), blue topaz (Zimbabwe, 25.67 ct), green elbaite tourmaline (Afghanistan, 12.33 ct), red-violet elbaite tourmaline (Brazil, 16.87 ct), blue aquamarine beryl (Brazil, 17.96 ct), orange spessartine garnet (Sri Lanka, 5.13 ct), bicolored pink and blue elbaite tourmaline (Namibia, 9.88 ct), and lilac-pink kunzite spodumene (Madagascar, 21.40 ct). These gemstones are part of the Edward J. Gübelin gem collection, which was acquired by the Gemological Institute of America (GIA) in 2005. Courtesy of the GIA Gem Collection; photography by Robert Weldon, copyright GIA

1 Department of Earth and Environmental Science
University of New Orleans, 2000 Lakeshore Drive
New Orleans, LA 70148, USA
E-mail: wsimmons@uno.edu

2 Museo di Storia Naturale
Corso Venezia 35, Milano, I-20121, Italy
E-mail: fpezzotta@yahoo.com

3 Gemological Institute of America
5345 Armada Drive, Carlsbad, CA 92008-4602, USA
E-mail: jshigley@gia.edu

4 Department of Geology, Federal University of Pernambuco
Rua Acadêmico Hélio Ramos, 54740-530, Recife, Pernambuco, Brazil
E-mail: beurlen@ufpe.br

Figure 2 Group of gem crystals from granitic pegmatites. Left to right: spodumene (kunzite, California, USA, 284 g), spodumene (triphane, Afghanistan, 196 g), beryl (Heliodor, Ukraine, 303 g, 14 cm tall), tourmaline (Brazil, 25 g), beryl (aquamarine, Vietnam, 37 g), topaz (China, 375 g), and quartz (smoky quartz, Namibia, 219 g). Specimens courtesy of Bill Larson, Pala International, Fallbrook, California; photography by Robert Weldon, copyright GIA

Crystals in miarolitic cavities (also known as pockets)

The gem varieties of **beryl** (*aquamarine, heliodor, morganite*), **spessartine**, **spodumene** (*kunzite, hiddenite*), **topaz,** and **tourmaline (***indicolite, rubellite, verdelite, liddicoatite,* etc**.**) occur almost exclusively in miarolitic cavities (open or clay-filled voids) in the cores of pegmatites; they may also occur in cavities in the coarse interior units surrounding quartz-rich cores (the core-margin zone). See Figure 3 for an idealized representation of a miarolitic cavity.

Gem-bearing pockets represent the ultimate concentrations of exotic elements, volatiles, and other fluxes present in pegmatites. They contain the most evolved assemblage of gem-quality minerals and associated rare Nb–Ta–Sn oxides, phosphates, fluorides, borates, and borosilicates. The high value of gem material makes these pegmatites highly sought. Examples of miarolitic cavities in well-known gem-producing pegmatites are shown in Figure 4. However, cavities containing gem-quality crystals are very rare. Most pegmatite mines only produce high-quality gem minerals sporadically and thus cannot be operated economically. Nevertheless, some pegmatites are exceptionally rich in miarolitic cavities and have produced large quantities of gem materials regularly and over long periods.

LARGE AND FAMOUS MIAROLITIC CAVITIES

Single miarolitic cavities in some pegmatites have produced millions of dollars worth of gemstock, sufficient in some cases to temporarily lower worldwide gem values. In 1973,

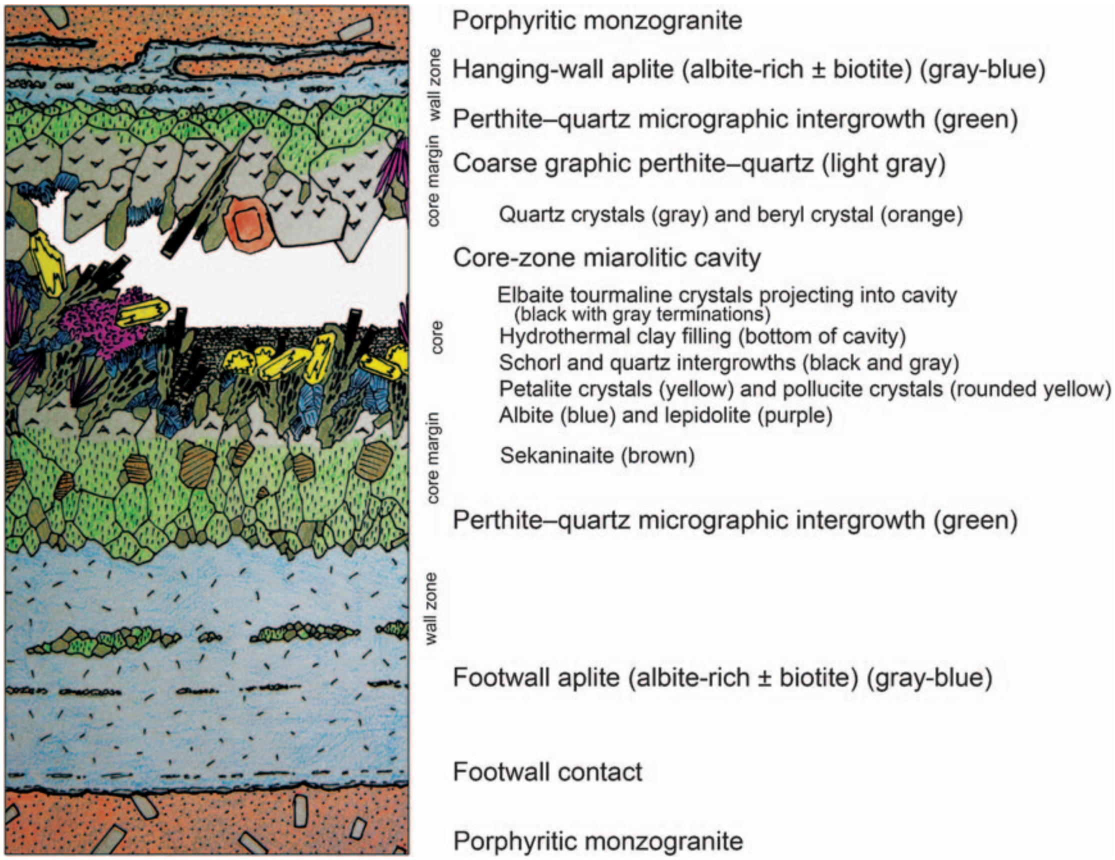

Figure 3 Idealized Elba pegmatite. Drawing by Federico Pezzotta

TABLE 1 GEMSTONES OCCURRING IN PEGMATITES

Mineral group and/or species	Gemological variety[1]	Colors of gem varieties	Pegmatite family
Major Economic Importance			
Beryl	Aquamarine	b, g	NYF & LCT
	Emerald[2]	g	NYF & LCT
	Goshenite[3]	c	LCT > NYF
	Heliodor	y	NYF > LCT
	Morganite	p-o	LCT
Topaz		c, b, br, y	NYF > LCT
Tourmaline group (elbaite, liddicoatite, rossmanite)[4]	Achroite[3]	c	LCT
	Canary	y	LCT
	Indicolite	b	LCT
	Paraiba	b, g-pr	LCT
	Rubellite	r-p	LCT
	Verdelite	g	LCT
Spessartine		o	LCT
Spodumene[5]	Hiddenite	g	LCT
	Kunzite	p, pr	LCT
Minor Economic Importance and/or Collector Stones (selected)			
Brazilianite		y-g	LCT
Chrysoberyl		g-y	LCT
Danburite		y, br	LCT
Euclase		b, g	LCT
Fluorapatite		b, g, p, pr	LCT
Hambergite		c	LCT > NYF
Jeremejevite		b, c	NYF
Microcline	Amazonite	g, b-g	NYF > LCT
Alkali feldspar	Moonstone	w, b-w	NYF & LCT
Petalite		c	LCT
Pezzottaite		r	LCT
Phenakite		c, y	NYF > LCT
Quartz	Amethyst	pr	NYF & LCT
	Citrine	y	NYF & LCT
	Rock-quartz	c	NYF & LCT
	Rose	p	NYF & LCT
	Smoky	br	NYF & LCT
Sodalite		b	Alkalic
Zircon		y, br, g	NYF

The list consists of two categories based on the abundance and commercial value of these minerals in the jewelry marketplace: the most important pegmatite gem minerals, such as beryl and tourmaline; less important gems, such as spodumene, and unusual gems, such as euclase, that are rare but of interest to gem and mineral collectors. For the definitions of pegmatite families, see Černý et al. (2012 this issue).

LCT = lithium–cesium–tantalum-enriched granitic pegmatites; NYF = niobium–yttrium–fluorine-enriched granitic pegmatites. Explanation of color codes: c = colorless, b = blue, br = brown, p = pink, r = red, g = green, y = yellow, o = orange, w = white, pr = purple, hyphenation indicates combined colors e.g. b-w = bluish white

1 – the most significant; 2 – occurring mostly confined to the reaction zone with mafic host rock; 3 – important only if treated (irradiation and heating) to produce pink or red color; 4 – see Pezzotta and Laurs (2011) for complete description and updated nomenclature; 5 – also includes yellow varieties important only if treated (irradiation and heating) to produce pink color

a famous 2 × 3 × 7 m pocket in the **Dunton pegmatite** on Newry Mountain, Maine, USA, yielded about two tons of gemmy, bicolored, green and red elbaite tourmaline crystals (F. Perham 2010, pers. comm.). The gem value of that pocket in today's market would be about 40 million dollars! The **Jonas pegmatite**, in the Conselheiro Pena district of Brazil, contained a single 2 × 2.5 × 3 m cavity that yielded 3.6 tons of top-quality, red elbaite (rubellite) crystals. This discovery produced over 200 kg of cutting-quality gem rough, and two of the world's best rubellite crystals, known as the "Rocket" (illustrated in *Elements,* volume 7, page 309) and the "Jonina" (Cornejo and Bartorelli 2010). These meter-sized crystals reportedly sold for about one million dollars each in 1978. Giant, polychromatic, prismatic liddicoatite crystals, up to 1 m long and 35 cm across, were found at localities in the Fianarantsoa region and at **Anjanabonoina** (Betafo, Antananarivo region) in Madagascar (Pezzotta 2001). These crystals were the source of the world's most beautiful color-zoned tourmaline slices (Dirlam et al. 2002). The chambered pegmatites near **Volodarsk-Volynsky**, Ukraine, contained pockets as large as 12 × 4 × 5 m that produced tree-trunk-sized (0.5 × 1 m) gem topaz and heliodor (yellow beryl), one weighing 22 kg (Kievlenko 2003; Lyckberg et al. 2009). Pegmatites in Afghanistan and Pakistan produce exceptionally fine gem crystals of beryl, topaz, spodumene, and tourmaline (FIGS. 2, 5). The **Himalaya Mine** in Mesa Grande, California, USA (Fisher 2002) has produced tons of gem- and specimen-grade tourmaline over the last 100 years (FIG. 4), and the **Mount Mica pegmatite** in Maine is producing large, zoned tourmaline crystals from pockets as large as 1.5 × 2 × 7 m (Simmons et al. 2005) (FIG. 4). Miarolitic pockets such as these are the Holy Grail for pegmatite miners.

ORIGIN OF GEM-FORMING MELTS

Pegmatite-forming melts with the potential for crystallizing gem minerals originate mostly during the crystallization of a parental granitic melt. Because the granitic melt initially crystallizes mainly feldspars and quartz, the residual melt is progressively enriched in elements excluded from the structure of these early crystallizing phases. Water and fluxing components such as B, P, Li, and F also increase in the late-stage granitic melt. The volatile components and other fluxes lower the viscosity and the solidification temperature, inhibit crystal nucleation, and greatly enhance chemical diffusion within the melt. If the concentration of volatiles, mainly H_2O, of the remaining residual melt exceeds its solubility limit, an aqueous fluid exsolves from the melt and promotes the formation of a miarole, or primary pocket. Nearly pure, gem-quality crystals of Be-, Li-, B-, and F-silicate minerals (along with other non-gem minerals) form in these pockets as the final products of crystallization (Simmons et al. 2003; London 2008).

FORMATION OF MIAROLITIC CAVITIES AND GEM-QUALITY CRYSTALS

Miarolitic cavities form in residual melts that have accumulated via fractional crystallization (Cameron et al. 1949; Jahns and Burnham 1969), with or without constitutional zone refining (London and Morgan 2012 this issue). Miarolitic cavities develop as a result of oversaturation of the residual pegmatite melt in volatile components (primarily water). Černý (2000) discussed three principal mechanisms that promote the separation of supercritical aqueous fluid from the pegmatitic melt: (1) decompression in the ascending magma (pressure quench), (2) fractional crystallization during isobaric solidification, and

Figure 4 Examples of miarolitic cavities. Top row, left to right: miarolitic cavity (25 cm across) containing red elbaite (rubellite) crystals (up to 5 cm in length) in the Himalaya dike, San Diego County, California; PHOTO BY GENE FOORD; cavity in the Pederneira pegmatite, Minas Gerais, Brazil, about 80 cm wide, insert shows single indicolite tourmaline from this pocket, PHOTOS BY MARCO LORENZONI. Bottom row, left to right: miarolitic cavity with 20 cm spodumene crystal, Ocean View mine, San Diego County, PHOTO BRENDAN LAURS; miarolitic cavity, Mount Mica pegmatite, Maine (50 cm wide), inset shows green elbaite (12 cm long) just recovered from pocket, PHOTOS BY SKIP SIMMONS

(3) depletion of fluxing components (B, F, P, Li) by crystallization of minerals containing these elements (chemical quench).

Decompression If a volatile-rich melt decompresses as a result of ascent or uplift due to tectonic forces, the pressure on the melt decreases and volatiles may exsolve as bubbles. If the exsolved bubbles are trapped in the viscous, solidifying granitic melt, miaroles may form. Miaroles are commonly lined by coarse-grained quartz and feldspars, and they may contain gem-quality beryl and topaz. These pegmatites are classified as beryl–topaz type in the NYF family (Černý et al. 2012 this issue). A close spatial association between miarolitic granites and related, overlying tuff deposits (e.g. Moat Mountain, New Hampshire, USA, and Erongo Mountains, Namibia) attests to the shallow emplacement depth of this type of pegmatite deposit.

Fractional Crystallization Exsolution of volatiles can also occur as a result of isobaric fractional crystallization of a volatile-rich melt. In the final stages of pegmatite solidification, this process leads to volatile saturation and exsolution of an H_2O-rich supercritical fluid (Jahns and Burnham 1969). Exsolution of aqueous fluid occurs typically very late in the solidification process, and if the fluids don't escape to the host rock, they form pockets along the core margin of the pegmatites (Fig. 3). At this stage, the concentrations of incompatible elements in the residual pegmatitic melt are high enough to allow the crystallization of rare and unusual minerals, and, most importantly, large euhedral crystals can grow unimpeded into the fluid-filled portion of the pocket (Simmons 2007; London 2008).

Depletion of B, Li, F, and P The presence of B, Li, F, and P in the pegmatite melt enhances the solubility of water in the melt and depresses the melt's solidus (London 2008). Abundant crystallization of B-, Li-, F-, and P-bearing minerals (e.g. tourmaline, lepidolite, amblygonite, spodumene, etc.) during the late stages of pegmatite solidification extracts these elements. Removal of these solubility-enhancing components results in the release of supercritical aqueous fluid, which contributes to the formation of miarolitic cavities due to a quenching of the melt.

A Model for Pocket Formation

Pegmatites crystallize inward from their contacts or wall zones. As crystallization proceeds, the residual melt accumulates toward the center of the dike and becomes progressively enriched in volatiles, which can exsolve to form centrally located primary pockets (Simmons 2007; London 2008). Two factors are critical in this process. First, the primary melt must initially contain sufficient volatiles so that late-stage exsolution can occur. Second, the pressure regime must not be too high (<3 kb), as exsolution is inversely proportional to pressure. Pockets are most abundant in shallow-level pegmatites and are virtually absent in pegmatites formed under high-pressure conditions (Simmons et al. 2003). Mining experience and geologic observations indicate that some structural features are of key importance for promoting the accumulation of residual fluids and the development of large cavities or sequences of cavities. These structural features include the intersection of cogenetic dikes, changes of strike or dip directions of dikes, a sudden increase in the width of a dike, and the occurrence of large enclaves of host rock within pegmatite bodies (Simmons et al. 2003). In tabular dikes, the occurrence of miarolitic cavities is generally associated with a sudden increase in the width of the pegmatite core zone at the expense of the surrounding zones and with a corresponding increase in crystal size.

According to the most widely accepted theory of pocket formation (Jahns and Burnham 1969), once the supercritical aqueous fluid starts to exsolve, diffusion of ions from the coexisting silicate melt into the fluid supplies nutrients to the crystals growing in the miaroles. Continued rapid diffusion of ions from the silicate melt to the growing crystal surfaces in the fluid of the protopocket explains why pockets appear to contain more crystals than could

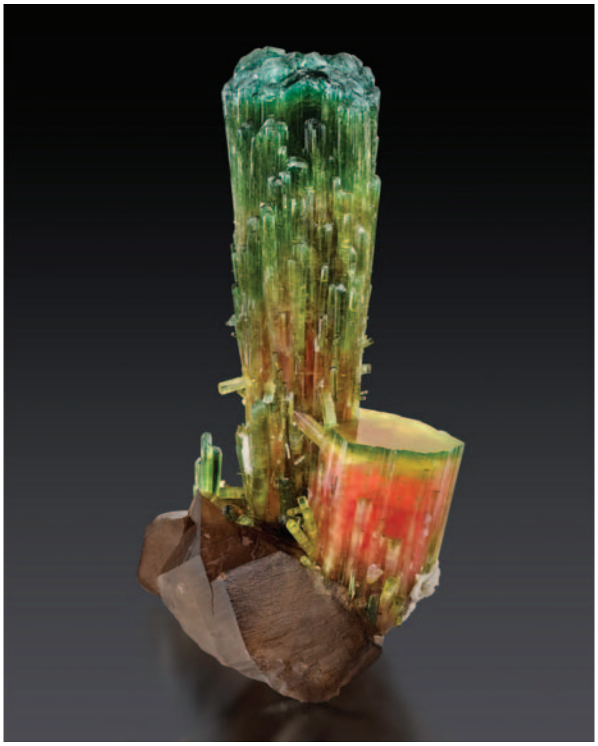

FIGURE 5 Group of polychrome elbaite crystals, 31 cm tall, associated with smoky quartz; Paprok, Kunar, Afghanistan. Specimen: DANIEL TRINCHILLO; PHOTO: JAMES ELLIOTT

have grown from a less dense, volatile-rich pocket-forming fluid alone. Thomas and Davidson (2012) studied the nature, composition, distribution, and water content of melt inclusions in pegmatite minerals; they concluded that, as temperature decreases, pegmatite-forming melt exsolves a low-density melt fraction characterized by a high content of fluxing elements, and that this melt fraction separates and accumulates, promoting the formation of cavities. This low-density melt, also known as *high-density fluid*, can further separate, at its lowest temperature, a *low-density fluid*, which is responsible for latest-stage crystal growth and mineral alteration. Whatever the mechanism, minerals growing in volatile-rich pocket environments can develop pristine, nearly pure, gem-quality crystals. Crystals growing from the margins of the pocket develop gemmy terminations, and those that grow almost entirely inside the pocket may develop into nearly flawless gem crystals (FIG. 2).

POCKET RUPTURE AND LATE-STAGE HYDROTHERMAL ALTERATION

When pegmatites approach the final stages of solidification, the fluid pressure inside a pocket may eventually cause it to rupture. Rupture is controlled by a combination of lithostatic load and the tensile strength of the rock. In other instances, pressure may be released as a result of fractures intersecting the pocket. Such fractures may result from contraction of the surrounding rock due to cooling and pegmatite crystallization, or they may be tectonically induced. Whatever the cause, pocket rupture can have a destructive effect on the contents of the pocket. Crystals may fracture from sudden decompression or be abruptly thrust into a field of chemical instability, leading to corrosion or alteration, and generally resulting in crystals with little or no commercial value. Even in cases where pocket rupture does not occur, corrosion and alteration typically affect crystals in the largest cavities because the hydrothermal fluid reacts with previously formed minerals as temperature and pressure decrease. In some exceptional cases, late-stage corrosion dissolves the less-gemmy portions of crystals and only high-quality, gemmy remnants of crystals, also known as "gem nodules," are preserved. Many of the heliodor crystals from Volodarsk-Volynsky, Ukraine, resulted from this process. From a mining point of view, the ideal scenario is to have just the right chemical composition for gem crystals to form with no late-stage alteration. In unaltered gem-bearing pockets, the pressurized fluid may have gradually escaped by diffusion into the wall rock or by slowly leaking via small fractures during the terminal stages of cooling.

As rare as pockets are, those containing gem minerals are much rarer, and pockets with gem crystals that have not been mechanically disrupted or suffered various degrees of corrosion and alteration are extraordinarily scarce. It is indeed remarkable that so many famous pockets actually survived with their gem contents intact.

AGES OF GEM-PRODUCING PEGMATITES

Most of the large gem-producing pegmatite districts, including those in Brazil, Namibia, Tanzania, Mozambique, and Madagascar, are Neoproterozoic in age; they formed

SPOTLIGHT ON BRAZIL

BRAZIL is by far the most important country for pegmatitic gemstones, with production dating to the late 17th century. Two regions, the eastern-northeastern part of Minas Gerais and the northeastern area of the country (parts of the states of Paraíba, Rio Grande do Norte, and Ceará), are the most important producers of colored gemstones; these regions are called the Eastern Brazilian Pegmatite Province (EBPP) and Borborema (or Northern) Pegmatite Province (BPP), respectively (Scorza 1944).

In the EBPP, pegmatites located in the Conselheiro Pena district (Pedrosa-Soares et al. 2011) include the Jonas pegmatite, described in the text, and the Urucum pegmatite, which produced more than 3 tons of gem-quality kunzite in 1968. Several albite-rich pegmatites in the northern part of this district are the source of rare, bright yellow brazilianite crystals. The two mines that produced most of the spectacular tourmaline specimens found in museums and private mineral collections worldwide exploit the Morro do Cruzeiro and Pederneira pegmatite groups, located in the São José da Safira district, south of Araçuaí and northwest of Governador Valadares. Homogeneous or color-zoned crystals weighing up to 14 kg, with pink to red bases and green to blue rims and terminations, were found in these pegmatites. Another outstanding deposit is the Limoeiro pegmatite in the Araçuai district. This pegmatite produced mainly gem-quality blue topaz crystals (up to 24 kg) associated with polychrome elbaite crystals (Cassedanne 1991). At Ponto Marambaia in the Paraíso pegmatite district, a group of small, Li-poor and F-rich pegmatites are famous for spectacular finds of gem-quality topaz and two exceptionally large aquamarine crystals. In 1910, the 110 kg "Papamel" aquamarine crystal was discovered, and in 1954, the 33.6 kg "Martha Rocha" crystal, which contained nearly 100,000 carats of gem rough with a value of over 20 million dollars at \$200/carat, was found (Cornejo and Bartorelli 2010).

In the BPP, the only prominent gem production is from the four "Paraíba tourmaline" deposits: Batalha, Quintos, Glorious, and Capoeira 2 (the latter being the site of the only still-active mine). "Paraíba tourmaline"—copper bearing, "electric blue" elbaite—is one of the most highly prized gemstones and is worth up to \$25,000 per carat (FIG. 7). "Paraíba tourmaline" occurs exclusively in highly evolved spodumene- or lepidolite-bearing pegmatites intruding iron-poor quartzites (Beurlen et al. 2011).

during the latest stages of the tectono-metamorphic Pan-African event (870–550 Ma), which involved the Gondwana paleocontinent (Fig. 6). Gem pegmatites in Finland and Ukraine are Paleoproterozoic (2500–1650 Ma) in age. Major gem-producing pegmatites in the United States, Italy, Russia, China, Myanmar, Vietnam, Afghanistan, and Pakistan are related to younger, Phanerozoic (<542 Ma) orogenic or anorogenic events. It is noteworthy that the presence of shallowly emplaced, gem-bearing pegmatites of Neoproterozoic age implies that the host terrains have been tectonically stable and not deeply eroded since pegmatite formation and have not undergone subsequent metamorphism.

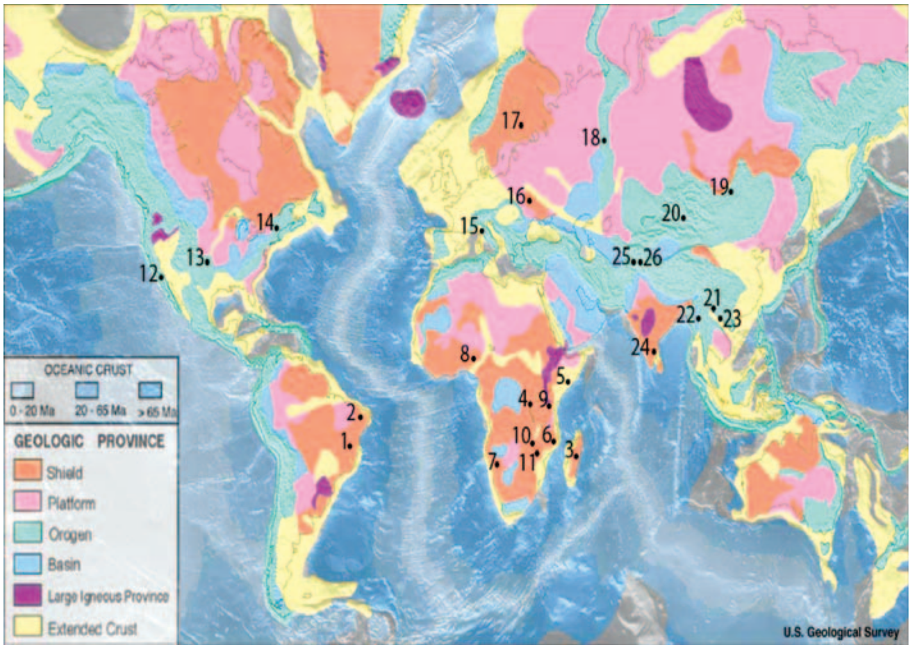

Figure 6 Major gem-pegmatite districts of the world; the numbers correspond to the districts in Table 2. Geologic Province Map of the World, U. S. Geological Survey (http://earthquake.usgs.gov/research/structure/crust/maps.php)

Table 2 MAJOR GEM-PEGMATITE DISTRICTS AND NOTABLE GEM MINERALS

1.* **Brazil**: Minas Gerais
Beryl (aquamarine, morganite, heliodor), topaz, tourmaline, spodumene (kunzite, hiddenite), brazilianite, euclase, quartz (rose, smoky, citrine), amblygonite–montebrasite

2. **Brazil**: Paraíba, Rio Grande do Norte
Tourmaline (Paraíba variety), beryl (aquamarine, morganite, heliodor), euclase, quartz (rose, smoky, citrine), spessartine

3. **Madagascar**: Antananarivo, Fianarantsoa, Toamasina
Tourmaline, beryl (aquamarine), spodumene (kunzite), londonite, pezzottaite, hambergite, orthoclase/sanidine, quartz (rose), spessartine, danburite, phenakite

4. **D. R. Congo**: Katanga, Nord Kivu
Tourmaline

5. **Kenya**: Coast
Tourmaline

6. **Mozambique**: Nampula, Tete, Zambezia
Tourmaline, spessartine, beryl (aquamarine), topaz, spodumene (kunzite), quartz (rose)

7. **Namibia**: Erongo
Tourmaline, beryl (aquamarine), topaz, jeremejevite

8. **Nigeria**: Edo, Kaduna, Kwara, Nassarawa, Oyo, Plateau
Tourmaline, chrysoberyl, topaz, beryl, phenakite, spodumene, spessartine

9. **Tanzania**: Arusha, Morogoro, Tanga
Tourmaline, spessartine

10. **Zambia**: Central, Eastern
Tourmaline, beryl (emerald), spessartine

11. **Zimbabwe**: Mashonaland West
Beryl (aquamarine), topaz, tourmaline

12. **United States**: California, Mesa Grande, Pala, Ramona
Tourmaline, beryl (aquamarine, morganite), spessartine, spodumene (kunzite)

13. **United States**: Colorado Collegiate Range
Beryl (aquamarine), phenakite

14. **United States**: New England, Maine, New Hampshire, Connecticut
Tourmaline, beryl (aquamarine), pollucite

15. **Italy**: Elba
Tourmaline, pollucite

16. **Ukraine**: Zhytomyr
Beryl (heliodor, aquamarine), topaz

17. **Finland**: Luumäki (South Karelia)
Beryl (aquamarine), tourmaline

18. **Russia**: Ural Mountains
Beryl (aquamarine, emerald), topaz, chrysoberyl (alexandrite)

19. **Russia**: Zabaykalsky (Transbaikalia)
Tourmaline, danburite, pollucite, spessartine, beryl (aquamarine), topaz

20. **China**: Xinjiang Uygur
Beryl (aquamarine), tourmaline

21. **China**: Yunan
Tourmaline, beryl (aquamarine), spessartine

22. **Myanmar**: Mogok, Momeik
Tourmaline, phenakite, petalite, pollucite

23. **Vietnam**: Yen Bai
Tourmaline, microcline (amazonite)

24. **India**, Tamil Nadu
Beryl (aquamarine)

25. **Afghanistan**, Kunar, Nuristan
Tourmaline, spessartine, topaz, beryl (emerald, aquamarine), spodumene (kunzite)

26. **Pakistan**, Gilgit-Baltistan
Tourmaline, spessartine, beryl (aquamarine), topaz

* Numbers correspond to map locations in Figure 6.

Sources: Clifford et al. 2011; Cornejo and Bartorelli 2010; Groat et al. 2007; Falster et al. 2002, 2005; Pezzotta 2001; Shigley et al. 2010; Simmons 2007

CONCLUSIONS

Gem minerals originating from pegmatites are of tremendous importance in the jewelry trade. Beryl, garnet, spodumene, topaz, and tourmaline are among the most spectacular and colorful examples of crystals from the mineral kingdom. Large, colored crystals that can be cut and carved to yield transparent gems are actively sought by the worldwide gem industry. The demand for natural gems has elevated miarolitic granitic pegmatites to a level of economic significance that far exceeds their geological abundance. Although we now know much about the formation of these aesthetic and highly prized gem minerals in pegmatites, the specific details of their origin still intrigue and challenge gemologists and pegmatologists.

ACKNOWLEDGMENTS

We thank David London for inviting us to participate in this issue of *Elements*. Special thanks to Alexander Falster and Karen Webber, who helped with the preparation and editing of early versions of the manuscript. Thanks also to Robert Weldon for expert photography (Figs. 1, 2, and 7). William Larsen kindly loaned us the gem-quality samples shown in Figure 2. We also thank Daniel Trinchillo and James Elliott for the photograph in Fig. 5. The manuscript benefited from reviews by David London, John Valley, Dan Kontak, Pierrette Tremblay, and three anonymous reviewers. Their suggestions significantly improved the manuscript and are gratefully acknowledged.

Figure 7 This 8.80 ct crystal (7 mm tall) and 10.91 ct gemstone represent some of the best and most valuable copper-bearing elbaite tourmaline found in the late 1980s and early 1990s in the Batalha pegmatite dike, located near the village of São José da Batalha in the state of Paraíba, northeastern Brazil. Photograph by Robert Weldon, copyright GIA

REFERENCES

Beurlen H, de Moura OJM, Soares DR, Da Silva MRR, Rhede E (2011) Geochemical and geological controls on the genesis of gem-quality "Paraíba Tourmaline" in granitic pegmatites from northeastern Brazil. Canadian Mineralogist 49: 277-300

Cameron EN, Jahns RH, McNair AH, Page LR (1949) Internal Structure of Granitic Pegmatites. Economic Geology Monograph 2, 115 pp

Cassedanne JP (1991) Tipologia das jazidas brasileiras de gemas (Typology of the Brazilian gem deposits). In: Schobbenhaus C, Queiroz ET, Coelho CES (eds) Principais Depósitos Minerais do Brasil, Vol IV(A). Departamento Nacional da Produção Mineral-DNPM (Brazilian Geological Survey), Brasília, Brazil, pp 17-52

Černý P (2000) Constitution, petrology, affiliations and categories of miarolitic pegmatites. In: Pezzotta F (ed) Mineralogy and Petrology of Shallow Depth Pegmatites. Memorie della Società Italiana di Scienze Naturali e del Museo Civico di Storia Naturale di Milano 30, pp 5-12

Černý P, London D, Novak M (2012) Granitic pegmatites as reflections of their sources. Elements 8: 289-294

Clifford J, Falster A, Hanson S, Liebetrau S, Neumeier G, Staebler G (eds) (2011) Topaz Perfect Cleavage. extraLapis (English edition), Lithographie LLC, Denver, 100 pp

Cornejo C, Bartorelli A (2010) Minerals and Precious Stones of Brazil. Solaris Cultural Publications, São Paulo, 704 pp

Dirlam DM, Laurs BM, Pezzotta F, Simmons WB (2002) Liddicoatite tourmaline from Anjanabonoina, Madagascar. Gems & Gemology 38: 28-53

Falster AU, Jarnot MD, Neumeier GA, Simmons W, Staebler GA (eds) (2002) Tourmaline. extraLapis (English edition), Lapis International, Denver, 106 pp

Falster AU, Jarnot M, Neumeier G, Simmons W, Staebler G, Wilson T, Wise M (eds) (2005) Beryl and Its Color Varieties. extraLapis (English edition), Lapis International, Denver, 112 pp

Fisher J (2002) Gem and rare-element pegmatites of southern California. Mineralogical Record 33: 390-396

Groat LA, Giuliani G, Marshall DD, Turner D (2007) Emerald. In: Groat LA (ed) Geology of Gem Deposits. Mineralogical Association Canada Short Course 37, pp 79-109

Jahns RH, Burnham CW (1969) Experimental studies of pegmatite genesis: I. A model for the derivation and crystallization of granitic pegmatites. Economic Geology 64: 843-864

Kievlenko E (2003) Geology of Gems. Ocean Pictures Ltd. Moscow, Russia, 468 pp

London D (2008) Pegmatites. Canadian Mineralogist Special Publication 10, 347 pp

London D, Morgan GB (2012) The pegmatite puzzle. Elements 8: 263-268

Lyckberg P, Chornousenko V, Wilson WE (2009) Famous mineral localities: Volodarsk-Volynski, Zhitomir Oblast, Ukraine. Mineralogical Record 40: 473-506

Pedrosa-Soares AC and 11 coauthors (2011) Late Neoproterozoic-Cambrian granitic magmatism in the Araçuaí orogen (Brazil), the Eastern Brazilian Pegmatite Province and related mineral resources. Geological Society Special Publication 350: 25-51

Pezzotta F (2001) Madagascar – A Mineral and Gemstone Paradise. extraLapis English 1, 97 pp

Pezzotta F, Laurs BM (2011) Tourmaline: The kaleidoscopic gemstone. Elements 7: 333-338

Schwarz D, Giuliani G, Grundmann G, Glas M (2002) The origin of emerald. In: Emeralds of the World. extraLapis English 2, pp 10-15

Scorza EP (1944) Província Pegmatítica da Borborema. Departamento Nacional da Produção Mineral-DNPM, Brazilian Geological Survey, Rio de Janeiro, Divisão de Geologia e Mineralogia Boletim 112: 1-57

Shigley JE, Laurs BM, Janse AJA, Elen S, Dirlam D (2010) Gem localities of the 2000s. Gems & Gemology 46: 188-216

Simmons WB (2007): Gem-bearing pegmatites. In: Groat LA (ed) Geology of Gem Deposits. Mineralogical Association Canada Short Course 37, pp 169-206

Simmons WB, Laurs BM, Falster AU, Koivula JI, Webber KL (2005) Mt. Mica: a renaissance in Maine's gem tourmaline production. Gems & Gemology 41: 150-163

Simmons WB, Webber KL, Falster AU, Nizamoff JW (2003) Pegmatology: Pegmatite Mineralogy, Petrology and Petrogenesis. Rubellite Press, New Orleans, LA, 176 pp

Thomas R, Davidson P (2012) Water in granite and pegmatite-forming melts. Ore Geology Reviews 46: 32-46

Zwaan JC and 10 coauthors (2005) Emeralds of the Kafubu area, Zambia. Gems & Gemology 41: 2-34