An Update on "Paraíba" Tourmaline from Brazil

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Vivid blue, green, and purple-to-violet cuprian elbaites, renowned in the gem trade as "Paraíba" tourmalines, continue to be recovered in small amounts from northeastern Brazil. Since the initial discovery of this copper-bearing tourmaline in 1982, production has been sporadic and has not kept up with the strong market demand. Mining currently takes place at the original discovery—the Mina da Batalha—and at adjacent workings near São José da Batalha in Paraíba State. At least two pegmatite localities (the Mulungu and Alto dos Quintos mines) in neighboring Rio Grande do Norte State have produced limited quantities of cuprian elbaites. All of these pegmatites occur within Late Proterozoic metamorphic rocks of the Equador Formation; the source of the copper is unknown. Six blue to blue-green elbaites from Mulungu had lower copper contents (up to 0.69 wt.% CuO) than the brightly colored Mina da Batalha material reported in the literature.

Unusually vivid "neon" blue, green-blue, green, and violet elbaite tourmalines first appeared in the jewelry trade in 1989 (Koivula and Kammerling, 1989a). Some of these colors were so striking (figure 1) that initially there was uncertainty over the identity of the material. Eventually it was learned that they were recovered from several small granitic pegmatite dikes at a single deposit near the Brazilian village of São José da Batalha in north-central Paraíba State.

Fritsch et al. (1990) described the gemological properties and visible absorption spectra of these new gem elbaites, and demonstrated the relationship between their colors and their unusual chemical compositions. They reported that the blue-to-green colors are primarily due to copper (Cu^{2+}), whereas increasing absorption due to manganese (Mn^{3+}) gives rise to reddish violet-to-violet colors (see also Henn and Bank, 1990, 1991; Rossman et al., 1991). The Paraíba tourmalines represented the first recorded instance of copper occurring as a coloring agent in this mineral. More recently, gem tourmalines colored by copper have been found elsewhere in northeastern Brazil, and in a locality near Ilorin in western Nigeria (Henricus, 2001; Milisenda 2001; Smith et al., 2001; Zang et al., 2001). The colors of some cuprian elbaites can be changed by heat treatment, and some are fracture-filled to improve their apparent clarity.

During the 1990 Tucson gem show, prices for this material skyrocketed from a few hundred dollars to over $2,000 per carat in just four days (Federman, 1990; Reilly, 1990). Restricted availability due to limited production over much of the past decade has only added to the value and mystique of these cuprian elbaites. In recent years, 3+ ct fine-quality blue to green-blue faceted tourmalines from the São José da Batalha area have sold for $20,000 per carat in Japan (R. Van Wagoner, pers. comm., 2001).

Until recently, difficulties involving legal ownership caused restricted access to the Mina da Batalha. In August 2000, however, the authors were able to visit the locality and gather first-hand information on the geology, current mining activities, and tourmaline production. During this same trip, we also

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Gems & Gemology, Vol. 37, No. 4, pp. 260–276

Figure 1. These tourmalines (2.45–9.60 ct), recovered from the Mina da Batalha in Brazil's Paraíba State in the early 1990s, are representative of some of the "turquoise" blue and blue-green tourmaline colors produced at this locality. Courtesy of K. Elawar; photo © Harold & Erica Van Pelt.

briefly visited the Mulungu mine near Parelhas (figure 2) in neighboring Rio Grande do Norte State (see Laurs and Shigley, 2000a,b), which has produced small amounts of cuprian tourmalines. A recent article by Austin (2001) describes the recovery of gem tourmalines from secondary alluvial and eluvial deposits adjacent to the Mina da Batalha.

The Mina da Batalha deposit is one of many gem pegmatite areas in the Borborema geologic province of northeastern Brazil. Some of these pegmatites have been mined for strategic minerals since the 1940s, and more recently for tourmaline, aquamarine, and other gems (Almeida et al., 1944; Silva et al., 1995; Pinto and Pedrosa-Soares, 2001). To date, only a few pegmatites have produced copper-bearing elbaite tourmalines, within a narrow region that extends approximately 90 km northeast from São José da Batalha into Rio Grande do Norte. In this article, we describe the geology of the Mina da Batalha and associated alluvial/eluvial deposits, and also update the gemology of "Paraíba" tourmaline. Brief descriptions of cuprian elbaites from two other pegmatite mines (Mulungu and Alto dos Quintos) in Rio Grande do Norte State also are included.

Members of the gem trade typically use the name *Paraíba* for vivid blue to blue-green tourmalines from northeastern Brazil. However, in this article, we consider *Paraíba tourmaline* to be a trade name for blue, green, and purple-to-violet elbaite tourmalines from the Mina da Batalha and associated deposits near São José da Batalha that contain at least 0.1 wt.% CuO (an amount of copper that is easily detected by energy-dispersive X-ray fluorescence [EDXRF] chemical analysis; see Fritsch et al., 1990, p. 204).

LOCATION AND ACCESS

Pegmatites containing gem tourmalines are found throughout the Serra das Queimadas mountain range (known locally as the Serra dos Quintos) in both Paraíba and Rio Grande do Norte. This general area lies about 230 km northwest of Recife and 210 km west-northwest of João Pessoa (again, see figure 2). It is about 7° south of the equator.

The Mina da Batalha can be reached by flying to Recife, João Pessoa, or Campina Grande (the closest commercial airport). From the last, a paved road leads 60 km west to the towns of Joazeirinho and Assunção, and a dirt road then proceeds 14 km to the village of São José da Batalha (located 4.5 km north of Salgadinho). The mine is situated on a small steep-sided hill known as Morro Alto, about 2 km west-southwest of the village (figure 3).

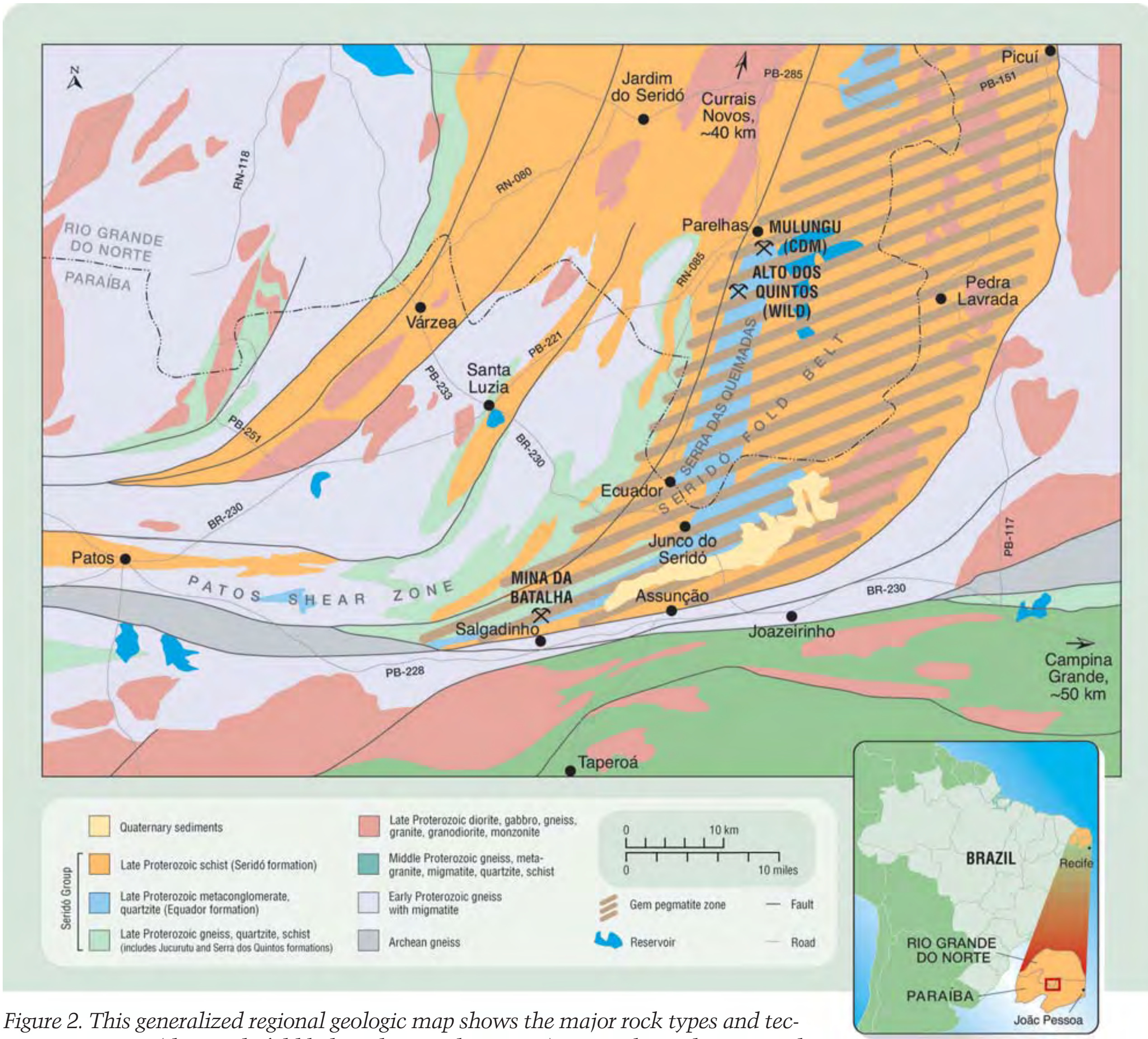

Figure 2. This generalized regional geologic map shows the major rock types and tectonic structures (the Seridó fold belt and Patos shear zone) in Paraíba and Rio Grande do Norte States in northeastern Brazil. Locations are indicated for the Mina da Batalha and the Mulungu (also known as the Capoeira, Boqueirãozinho, or CDM mine) and Alto dos Quintos mines (also known as the Wild mine), the area of gem pegmatite mineralization, as well as local towns and roads. The majority of the gem pegmatites are found in the quartzites of the Equador formation. Modified from Jaguaribe SE (2000).

The topography in this part of northeast Brazil has been eroded over geologic time to form a peneplain—a relatively flat or gently undulating land surface known locally as the *Planalto da Borborema*. Occasional prominent steep-sided granitic hills, called inselbergs, project upward above the surrounding terrain. Elevations typically range from about 200 to 1,000 m above sea level. Rainfall averages between 25 and 100 cm per year. A semiarid climate is created by high temperatures (24°–28°C or ~80°F average, occasionally exceeding 40°C/104°F), and by periods of drought that reoccur every eight to 10 years (each lasting one to five years). The local vegetation, called a *caatinga* forest, consists of low- to mid-sized trees, thorny bushes, and cacti.

This is one of the poorest and more sparsely populated regions of Brazil. Farming, ranching, manufacturing of tile and ceramics, and small-scale mining provide a difficult subsistence for the local people. Historically, production of industrial beryl, mica, quartz, feldspar, kaolin clay, and ores of uranium, tantalum, niobium, tungsten, tin, and some gold has been important for the local economy, although market demand for some of these commodities has varied considerably over the past decades (see Beurlen, 1995). Gemstones are a byproduct of these mining activities, but high extraction costs and a weak national economy have curtailed mining

Figure 3. This view, looking south in August 2000, shows Morro Alto on the right and the Serra do Frade ridge on the skyline. Extensive mine dumps from the Mina da Batalha are visible at the base of Morro Alto, and stockpiled dump material and eluvium/alluvium is present along the base of the ridge. Photo by Brendan M. Laurs.

for gems throughout this region and much of Brazil in recent years. Nonetheless, the very high values of these cuprian elbaites have stimulated local exploration for other potential sources of this gem material.

GEOLOGIC SETTING

Regional Geology. The geology of northeastern Brazil is quite complex (again, see figure 2). This region, known as the Borborema Province, consists mainly of Archean and Early Proterozoic gneisses and migmatites, as well as Late Proterozoic igneous and metamorphic rocks. Included in the latter are those of the Seridó Group (which consists of the Jucurutu, Equador, Seridó, and Serra dos Quintos formations). Radiometric age dating indicates that several major episodes of regional deformation (or orogenies) took place in this geologic province, producing widespread metamorphism, folding, and faulting, and accompanied by several periods of granitic magmatism (see Jardim de Sá, 1984; Jardim de Sá et al., 1987; Ferreira et al., 1998; Sial et al., 1999; Brito Neves et al., 2000; Nascimento et al., 2000).

The most recent of these tectonic cycles—between 650 and 480 million years (m.y.) ago—is referred to as the Brasiliano–Pan-African orogeny. This continental-scale tectonic system extended into western-central Africa (around Nigeria), as these geologic events occurred prior to the separation of South America from Africa (see Trompette, 1994). Within the Borborema Province, rocks of the Seridó Group were folded into a series of northeast-trending anticlines and synclines that comprise the Seridó fold belt (Ebert, 1970; Corsini et al., 1991; Vauchez et al., 1995). Numerous granitic bodies and associated pegmatites formed during the latter stages of this orogeny, between about 510 and 480 m.y. ago (van Schmus et al., 1995; Beurlen et al., 2000; Araújo et al., 2001). The pegmatites are confined mostly to the Seridó fold belt (Ebert, 1970; Corsini et al., 1991; again, see figure 2); more than 200 are known within an area measuring approximately 75 × 50 km that stretches southward from the town of Currais Novos (Silva et al., 1995). The majority of the mineralized pegmatites occur within the Seridó and Equador formations, which form much of the 30-km-long Serra das Queimadas range (Silva, 1993).

The Borborema pegmatites typically form tabular-, lens-, or dike-like bodies that vary from tens to hundreds of meters in length, and up to tens of meters in width. The larger pegmatites have a simple mineralogy—mainly feldspars, quartz, and mica (muscovite and some biotite). The smaller, but more numerous, "complex" pegmatites are internally zoned, and typically contain central quartz core zones (sometimes rose quartz). They have a varied mineralogy, often with gem and rare-element minerals (e.g., beryl, tantalite-columbite or manganotantalite, spodumene, cassiterite, garnet, and tourmaline), which have made them targets of mining activities.

In some areas, much of the feldspar (in both types of pegmatite) has been altered to white kaolin clay. Kaolinization appears particularly strong in the pegmatites lying south of the town of Ecuador (including those at the Mina da Batalha), whereas the feldspars are relatively unaltered in those to the north (e.g., at the Mulungu and Alto dos Quintos mines). The kaolinite formed after crystallization of the pegmatites and their gem minerals, and is not related to the presence of copper. The source of the copper in the tourmalines is unknown, but it is generally thought to have been derived from underlying copper-bearing rocks and incorporated into the pegmatitic magmas (Karfunkel and Wegner, 1996).

Local Geology. Gem-bearing pegmatites are present over a distance of several hundred meters on and adjacent to Morro Alto (figure 4). This hill forms part of a ridge called Serra do Frade, within the Serra das Queimadas mountain range. These pegmatite dikes are locally referred to as "lines" by the miners (numbered 1 through 6, with the last also called the "Jucurí" line [figure 5] after a prominent tree that grew near its outcrop). Individual pegmatites are tabular or vein-like in shape, and vary in thickness—from a few centimeters up to 2 m, although portions of line 4 are up to 4 m thick. The most productive dikes for gem tourmaline are typically less than 1 m thick.

As seen on Morro Alto, the pegmatites are oriented roughly parallel to one another; they strike southeast (60°–70°). They are typically separated from one another by 5–20 m of host rock (a foliated muscovite quartzite of the Equador formation). The steeply dipping (65°–75° northeast) dikes discordantly cross-cut the foliated quartzite (which dips 35°–40° south). Contacts between the pegmatite dikes and the quartzite are sharp and distinct, with very little or no hydrothermal alteration of the latter. The pegmatites are primarily composed of kaolinized feldspar, along with quartz and micas (muscovite and lepidolite). Besides schorl and elbaite tourmalines, other accessory minerals include tantalite, manganotantalite, amethyst, and citrine.

Typical of gem pegmatite deposits elsewhere, tourmaline mineralization at the Mina da Batalha is distributed irregularly within the pegmatites. Mr. Barbosa's experience has shown that the most promising areas for exploration are near the quartz core zones, where tourmaline occurs in association with lepidolite mica. Mineralized zones within a dike, which typically consist of a series of small ("fist"-sized) clay-filled "pockets" or thin "stringers," can extend for a distance of several meters. Less commonly, the gem tourmaline is found intergrown with massive quartz or embedded in kaolinized feldspar. Some of the larger tourmaline crystals embedded in quartz have been partially or totally replaced by lepidolite mica to form pseudomorphs.

Observations during mining revealed that different colors of tourmaline were encountered at various levels within the pegmatites. In addition, each dike tends to produce somewhat different colors, quantities, and qualities of tourmaline. According to Heitor Barbosa (pers. comm., 2001), line 1 produced the greatest quantity of crystals and the

Figure 4. This simplified sketch map shows the locations of the pegmatite dikes referred to as "lines" 1 through 4 (5 and 6 are not shown) on Morro Alto. Also shown are property boundaries for groups that are currently engaged in the recovery of gem tourmaline. Both primary (pegmatite) and secondary (alluvial/eluvial) deposits are being worked. Modified from mine map commissioned by Heitor Barbosa, January 2000.

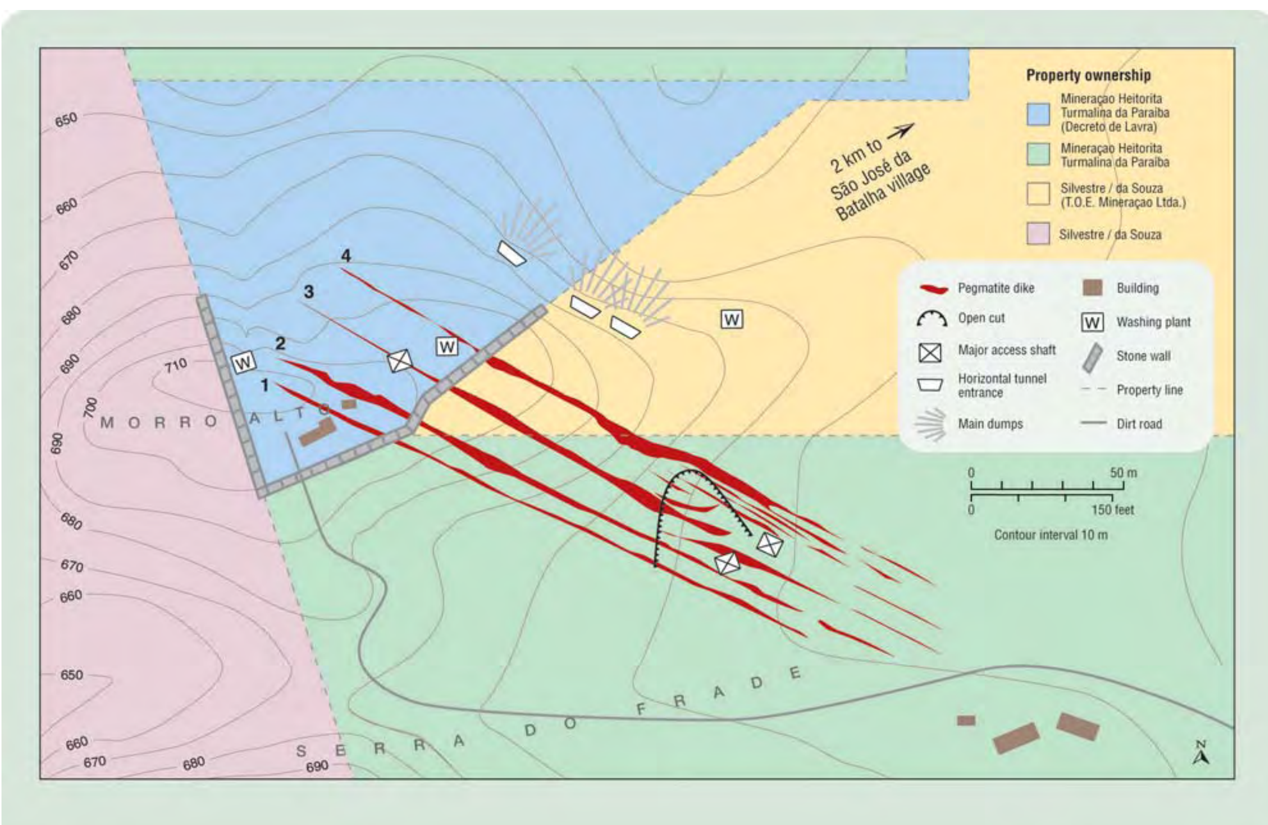

Figure 5. This view, looking northwest in August 2000, shows the excavation of line 6 (called the Jucurí line in this area) that was mined beneath shallow alluvium by T.O.E. Míneraçâo Ltda. The narrow width, steep dip, and elongate shape of the dike are typical of pegmatites in the São José da Batalha area. Photo by David Sherman.

Figure 6. Although most of the tourmaline crystals found in the Mina da Batalha area are broken and/or chemically etched fragments (right crystal, 10.5 grams), in rare instances they are euhedral with well-formed terminations, as shown by the crystal on the left (14.8 grams). Courtesy of Heitor Barbosa.

largest (mainly green, as well as grayish purple that would heat treat to bright greenish blue). Line 2 yielded smaller amounts with better color—particularly in green and the prized blue that did not need heat treatment. Lines 3 and 4 produced a variety of colors, but in lesser qualities and quantities. Line 6 produced small crystals with good blue-to-green colors, and line 5 was not productive.

Most of the tourmaline crystals from both the pegmatites and the adjacent alluvial/eluvial deposits are found as naturally broken and/or corroded fragments weighing less than one gram. In rare instances, the crystals are euhedral with well-formed terminations (see Wilson, 2002; figure 6). The crystals may be evenly colored, as in figure 6, or multicolored (blue, violet, green, purple, etc.) with various color-zoning patterns centered on the c-axis (figure 7; Cook, 1994). Occasionally, they are color zoned parallel to the c-axis.

HISTORY AND MINING OF THE MINA DA BATALHA AREA

Mining the Primary Pegmatites on Morro Alto. In 1982, a year following the discovery of tourmaline in a manganotantalite prospect on Morro Alto by the Brazilian Geologic Survey (CPRM), Heitor Barbosa organized initial mining by a group of about 13 garimpeiros (Koivula and Kammerling, 1990b; Barbosa and Cook, 1991). Three of the six dikes (lines 1, 2, and 3) were excavated downward from their outcrops at the top of the hill. In August 1987,

Figure 7. This 5.53 ct polished crystal fragment from the Mina da Batalha is color zoned perpendicular to the c-axis. As seen in the inset (magnified 5×), the zones are separated by either sharp or diffuse boundaries. Photos by John I. Koivula.

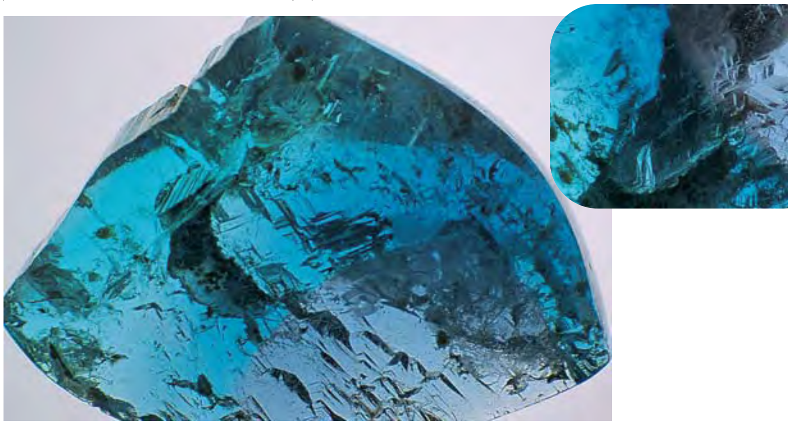

Figure 8. In the early 1990s, numerous near-vertical shafts were dug to explore the pegmatites on Morro Alto at the Mina da Batalha (left). Each shaft is marked by a white dump. A similar view, looking north, is shown in August 2000 (right). Most of the pegmatite dump material and underlying soil have been scraped from the hillside for stockpiling and processing to recover tourmaline fragments. The wall was constructed in the late 1990s to prevent entry into Heitor Barbosa's property. Also visible on the top of Morro Alto in the right photo are a small washing plant (to the left), a new building for the workers, and a water tank. Photos by Brian C. Cook.

small amounts of tourmaline fragments with bright blue sections were first encountered at depths of about 30 m within lines 1 and 2. Later that year, Mr. Barbosa filed a mining claim (*alvara de pesquisa**) on the Morro Alto pegmatites.

Subsequently, several kilograms of gemmy green crystals were recovered that yielded hundreds of carats of fine-quality cut stones. Mina da Batalha tourmaline was first sold in Brazil in late 1988. February and March 1989 witnessed the production of the first facet-quality bright blue tourmalines, with rough as large as 10.5 grams. Some of this material was provided to GIA for examination (Hargett and Kane, 1989; Koivula and Kammerling, 1989a,b); Fritsch et al. (1990) described the broad range of material from the mine, and attributed the unusual coloration to both copper and manganese.

Maximum production of gem tourmaline occurred in 1990–1991. By this time there were numerous shafts (figures 8 and 9), some of which reached depths of more than 60 m. Hundreds of meters of horizontal tunnels also were driven along the dikes at various levels from the shafts. Remarkably, most of the mining was accomplished by candlelight using only simple hand tools and occasional blasting. The pegmatite material was hoisted to the surface in buckets by hand-driven winches, and the contents were sieved or washed prior to removing the tourmaline by hand.

For most of the 1990s, the mine was embroiled in ownership disputes, and several opposing groups were active at the deposit. These competing mining activities (some illegal) were frequently disorganized, haphazard, and ineffective at sustaining gem tourmaline production. Between 1992 and 1996, mining came to a near standstill due to lengthy court cases involving mine owners, foreign investors, politicians, and local groups or individuals. As a result of the legal proceedings, the mine site was divided into several sections with different owners (Weldon, 1999). Mr. Barbosa retained the majority of the workings on Morro Alto under a mining deed (a *decreto de lavra***). Other groups or individuals divided the remaining portion (about 1,000 ha) among themselves under an *alvara de pesquisa*. From 1994 until recently, the only significant production came from processing of the former mine dumps, which yielded several kilograms of tourmaline fragments (most less than 0.5 ct).

In 1997, Mr. Barbosa began restoring the under-

**Alvara de pesquisa* ("exploration right"): Rights granted to an applicant by the Departamento Nacional de Produçaõ Mineral (DNPM) to stake a claim on an area to explore for minerals or gemstones. This authorization is valid for three years, but it does not constitute legal ownership of a mine.

***Decreto de lavra* ("mining decree"): Mining rights granted by the DNPM after the applicant has successfully passed through the exploration stage on a patented mining claim. The applicant must have submitted a full development plan for the mine as well as an environmental impact report. The decree is valid for the rest of the mining life of the deposit, as long as the grantee fulfills his legal obligations and provides an annual report on mining activities.

ground workings at the Mina da Batalha (Barbosa and Cook, 1999). He also began construction of a large stone wall on part of the mine site to prevent illegal entry. In 1998–1999, two horizontal tunnels were driven southwest from near the base of Morro Alto to intersect the pegmatites, providing better access to deeper, unmined areas. The ore and waste rock could then be removed by wheelbarrow through these tunnels rather than by haulage up the near-vertical shafts. In 1999, Mr. Barbosa initiated a core-drilling program and hired a geologist to help guide future mining.

The following year, Mr. Barbosa purchased an additional section of the property, so he now owns about 80% of the Morro Alto hill (the remaining 20% is owned by João and Edna Silvestre Henrique de Souza). He installed fluorescent lighting in the tunnels and an electric winch, and in August 2000 he resumed underground mining (figure 10) with two teams of miners using pneumatic hammers. A small washing plant has been in operation since March 2000. Its processing capacity is about 28 m^3 of material per day. A more sophisticated processing plant, with a capacity of 45 m^3 per day, should be fully operational by February 2002. Mr. Barbosa estimates that as much as 10,000 m^3 of pegmatite material has been processed since mining commenced at the Mina da Batalha (pers. comm., 2001).

Mining the Areas Surrounding Morro Alto. Beginning in 1998, efforts were initiated to recover gem tourmaline from alluvium below Morro Alto, and from eluvium on the top and sides of the hill. In 1999, T.O.E. Míneraçâo Ltda. entered into a leasing agreement with João and Edna Silvestre Henrique de Souza to explore (via an *alvara de pesquisa*) a portion of the pegmatites on the western side of the Morro Alto, as well as secondary deposits lying downslope (figure 11), on property owned by the de Souzas. This group is working an alluvial area of approximately 100 × 1,000 m, and an eluvial area of approximately 80 × 200 m (D. Sherman, pers. comm., 2001).

Equipment used to recover tourmaline from the area surrounding Morro Alto includes a hydraulic excavator, backhoe, and dump truck. A small washing facility—which can process up to 20 m^3 of material per day—began operation in early 2000. With a large volume of material awaiting processing, a larger processing plant—which can handle 200–320 m^3 of material a day—was built and became operational in October 2000 (figure 12). After large rock fragments (>5 cm) are removed, the finer material passes

Figure 9. This shaft at the Mina da Batalha follows one of the pegmatites to a depth of approximately 20 m, and provides access to an extensive part of the underground workings. When looking down the shaft, the narrow width (typically about 1 m) and steep dip are clearly evident (see inset). The shafts were dug using hand tools, and the pegmatite material was removed by winch. Photos by Brendan M. Laurs.

Figure 10. Heitor Barbosa is shown with a pegmatite in a tunnel at the Mina da Batalha. The white areas in the pegmatite are kaolinized feldspar, and the dark gray areas are quartz. The sides of the tunnel consist of the quartzite of the Equador formation that hosts the pegmatite. Photo by Brendan M. Laurs.

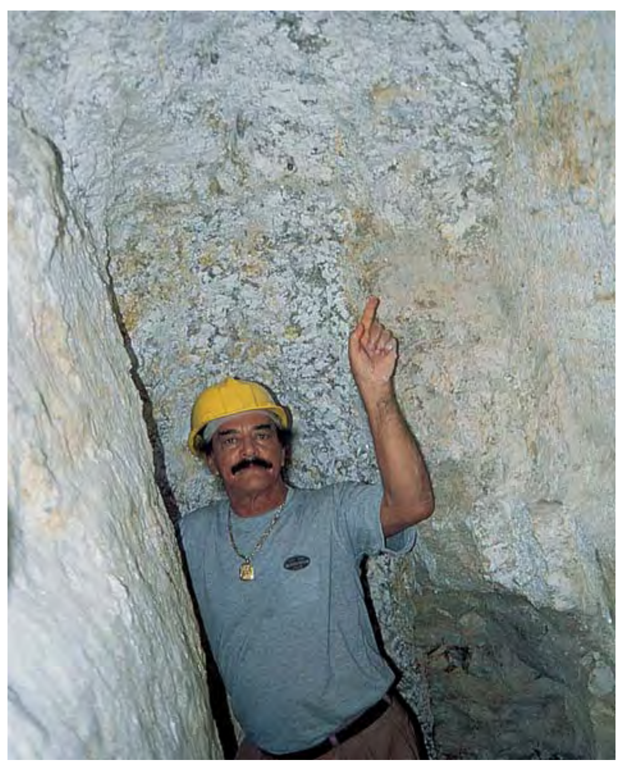

Figure 11. This view, looking southeast from Morro Alto in August 2000, shows the large area that is being worked to recover gem tourmaline from alluvium and eluvium. The stockpiled mine dumps will also be processed for gem tourmaline. Photo by Brendan M. Laurs.

through dry and wet vibrating sieves to form a concentrate (sized 6 mm to 5 cm). The tourmaline is then hand-picked from the concentrate.

Although some tourmaline has been recovered from alluvial sediments near the surface, the best production came from older alluvium (covered by 1–2 m of overburden) that may represent a former stream channel (Austin, 2001). In addition, T.O.E. is working an extension of one of the pegmatite dikes

Figure 12. T.O.E. Míneraçâo Ltda. has constructed a large processing plant to recover gem tourmaline from stockpiled mine dumps and alluvial/eluvial material surrounding Morro Alto. Photo by David Sherman.

(line 6, or Jucurí; again, see figure 5). T.O.E. also excavated an unmined portion of line 4 while mining eluvium on the flank of Morro Alto.

Exploratory work by T.O.E. has revealed additional pegmatite dikes beneath the alluvium at depths of about 2 m (Austin, 2001; Sherman, 2001). These dikes strike in a significantly different direction from those on the hill, and are likely to be separate pegmatites not recognized previously (D. Sherman, pers. comm., 2001). In September 2001, Mr. Barbosa located a new pegmatite near the western edge of his property; this dike also strikes nearly perpendicular to the others on Morro Alto. The de Souzas are exploring another pegmatite that lies west of line 1 just beyond the property boundary of Mr. Barbosa. This dike has yielded small quantities of yellow-green tourmalines (S. Barbosa, pers. comm., 2001). Ongoing work at the Mina da Batalha and in the surrounding area is revealing the structural complexity of the dike system.

PRODUCTION FROM THE MINA DA BATALHA AND SURROUNDING AREA

Production of the best blue-to-green cuprian tourmaline (see, e.g., figure 13) during the past decade has not kept up with market demand. Most production from the Mina da Batalha came during 1989–1991, when an estimated 10,000–15,000 grams of gem-quality (i.e., facetable plus some cabochon quality) crystals and fragments were recovered (H. Barbosa, pers. comm., 2001). Since 1992, tourmaline production from the Mina da Batalha has been sporadic and limited (Koivula et al., 1992a; Koivula et al., 1993c, 1994). However, in recent years the supply of "Paraíba" tourmaline has increased (see, e.g., "Strong demand in Japan…," 1999; "New find of Paraiba…," 2001).

Production by T.O.E. since mid-2000 has exceeded 100 grams of gem-quality blue to green-blue tourmaline per month; their total production of various colors to date is about 3 kg (D. Sherman, pers. comm., 2001). The largest gem-quality fragment recovered from the alluvium thus far weighed about 8 grams, although the typical size is less than 1 gram.

Most cut cuprian elbaites from the São José da Batalha region range from 0.15 to 0.75 ct. However, the area is the source of several large faceted stones, such as a 33.13 ct green rectangular cushion cut (see figure 6 in Koivula and Kammerling, 1991b, p. 184) and a >45 ct bluish green trilliant (W. Larson,

Figure 13. This crystal (5.0 cm high) and cut stone (4.0 ct) illustrate the intense color of fine-quality copper-bearing tourmaline from the Mina da Batalha. From the Mike Scott collection; photo © Harold & Erica Van Pelt.

pers. comm., 2001). Blue crystals exceeding 30 grams have been found, but gem-quality blue crystals over 3 grams are rare. The 15.0 ct blue cuprian tourmaline in figure 14 was faceted from the 14.8 gram crystal shown in figure 6. The largest good-quality blue tourmaline crystal found to date reportedly weighed 41 grams (H. Barbosa, pers. comm., 2001).

In the experience of co-authors BC and MB, the preference in the trade is for the bright, saturated greenish blue or violetish blue to blue, and to a lesser extent, "pure" green tourmalines from Paraiba. Members of the trade often describe the more vibrant colors with names such as "neon" or "electric." "Heitorita" is a trade name used by Heitor Barbosa and his associates for the small production of intense blue to blue-green tourmalines that do not need heat treatment (see, e.g., figure 6).

OTHER BRAZILIAN SOURCES OF CUPRIAN ELBAITE

The high demand for "Paraíba" tourmaline has stimulated a search for similar material from other pegmatite deposits throughout the region. Table 1 includes sources that are known by us, or have been reported by others, to have produced blue-to-green cuprian tourmalines. The Mulungu and Alto dos Quintos mines are described below. In the experience of BC and MB, none of these occurrences has yet produced material of saturated (vibrant) blue to blue-green colors similar to that from the Mina da Batalha and the surrounding area.

Reports of additional localities for copper-bearing gem tourmalines in this region of Brazil include: (1) Paraíba State—Alto Quixaba pegmatite north of Frei Martinho (Ferreira et al., 2000); and (2) Rio Grande do Norte State—Bolandeiro pegmatite, 36 km south-southeast of Parelhas (Bhaskara Rao et al., 1995), and Gregorio pegmatite, 20 km south-southwest of Parelhas (Adusumilli et al., 1994); see also Karfunkel and Wegner (1996).

Figure 14. The center stone in this pendant is a 15.0 ct tourmaline from the Mina da Batalha, which was cut from the 14.8 gram crystal in figure 6. The stone is surrounded by 16 carats of diamonds. Photo by Luna Wong; courtesy of Fine Gems Ltd., Hong Kong.

Mulungu Mine. In 1991, cuprian elbaites were discovered in colluvium at what is known as the Mulungu mine, located 5 km north-northeast of Parelhas and 60 km northeast of the Mina da Batalha. This mine has also been called the Capoeira, Boqueirãozinho, or CDM (see, e.g., Adusumilli et al., 1993; Karfunkel and Wegner, 1996; Johnson et al., 2000).

Only recently (1999) have elbaite crystals been found in the primary pegmatite, which forms an elongate, lenticular body that intrudes at a steep angle into a metasedimentary host rock. It strikes in an east-west direction, and is exposed over a distance of about 200 m. The maximum width is at least 10 m. The pegmatite is mineralogically zoned, and consists of feldspar, muscovite, and quartz, with accessory tourmaline, fluorapatite, and phosphate minerals. It also contains chalcocite and digenite, two copper sulfides that are rare in pegmatites, but occur here in pods up to 20 cm in diameter in the footwall portion (Robinson and Wegner, 1998; Falster et al., 2000). Mining takes place from an open pit dug into the colluvium, as well as from some underground tunnels that follow the zone of tourmaline mineralization within the pegmatite dike (figure 15).

In the early years of production, some cuprian tourmaline from this mine was mixed with Mina da Batalha material, and sold as tourmaline from the "new Paraíba mine" (figure 16). It reportedly also has been marketed as tourmaline from the Mina da Batalha ("The nomenclature controversy," 2001).

Alto dos Quintos Mine. This pegmatite body occurs on a hillside about 9 km south of Parelhas (and 45 km northeast of the Mina da Batalha). Also known as the Wild mine (Soares, 1998; Soares et al., 2000a; figure 17), it is exposed over an area of 150 by 20 m. The principal minerals include feldspar, quartz, and muscovite; accessory minerals include apatite, beryl, columbite, spodumene, lepidolite, and gahnite. In 1995–1996, this pegmatite deposit produced some large (up to 25 cm long), multicolored-tourmaline mineral specimens. Most of the copper-bearing tourmalines are not gem quality, although facetable crystals have been recovered from pegmatite pockets on at least two occasions in 2000 and 2001. Small

TABLE 1. Summary of gemological data on copper-bearing tourmalines.[a]

Locality	Mina da Batalha, Paraíba[b]	Mina da Batalha, Paraíba[b]	Alto dos Quintos mine, Rio Grande do Norte	Mulungu mine, Rio Grande do Norte	Edeko mine, western Nigeria[c]
Source	Fritsch et al. (1990)	Henn and Bank (1990)	Soares (1998, 2000a,b)	This study	Smith et al. (2001)
Number of samples	13	6	12	6	1
Colors	B, bG, bPr, BG, G, gGr, prPk, Pr, vB, yG	B, G	B	B, BG, bG, gB	prPk to B, bG, V
Refractive indices					
n_ε	1.619–1.621	nr	1.624	1.618–1.619	1.620
n_ω	1.638–1.646		1.646	1.638–1.639	1.638
Birefringence	0.018–0.025	nr	0.022	0.019–0.021	0.018
Specific gravity	3.03–3.12	nr	3.03	3.08–3.10	nr
Copper content (wt.% CuO)	0.37–2.38	0.75–2.47	0.60–0.78	0.41–0.69	nr
Other chemical elements reported	Bi, Pb, Zn	nr	Bi, Zn	Bi, Pb, Zn	nr
UV fluorescence	Inert (LW, SW)	nr	nr	Inert (LW, SW)	Inert (LW, SW)
Inclusions	Three-phase, fingerprints, growth tubes, metallic flakes	nr	Two-phase, fingerprints	Fingerprints, feathers, growth tubes, two-phase, filled fractures[d]	Fluid inclusions

[a] *Abbreviations: B = blue, BG = blue-green, bG = bluish green, bPr = bluish purple, G = green, gB = greenish blue, gGr = greenish gray, Pr = purple, prPk = purplish pink, V = violet, vB = violetish blue, yG = yellowish green; nr = not reported.*

[b] *Additional data for tourmaline from the Mina da Batalha are provided by Bank et al. (1990), Bank and Henn (1990), Ferreira et al. (1990), Brandstätter and Niedermayr (1993, 1994), and Cassedanne (1996).*

[c] *See also Milisenda (2001) and Zang et al. (2001); the latter reported 0.51–2.18 wt.% CuO, as well as traces of Bi, Pb, and Zn.*

[d] *Falster et al. (2000) reported plate-like copper inclusions and up to 1.4 wt.% CuO in tourmaline from Bocheiron Zinho, another name for the Mulungu mine.*

Figure 15. Cuprian elbaite tourmaline is occasionally recovered from the Mulungu mine near Parelhas, Rio Grande do Norte. This August 2000 photo shows one of three main shafts, along with a building being constructed for mine staff and support materials. Photo by Brendan M. Laurs.

gemmy areas in some of these crystals were fashioned into "sky-blue" melee-sized gems, and have also been sold as "Paraíba" tourmaline.

GEMOLOGICAL CHARACTERISTICS AND CHEMICAL COMPOSITION

Over the past decade, a small number of faceted blue-to-green tourmalines have been submitted to the GIA Gem Trade Laboratory to determine if they contained copper and met the gemological description of Paraíba tourmaline (see, e.g., Reinitz, 2000). In all those cases where sufficient copper was detected by EDXRF chemical analysis, the gemological properties were found to be consistent with the data reported by Fritsch et al. (1990) in the original material. However, to expand the data on copper-bearing tourmalines from this region, we characterized six blue to bluish green faceted tourmalines from the

Figure 16. The faceted blue tourmaline on the left (4.65 ct) is representative of fine copper-bearing tourmaline from the Mulungu mine near Parelhas, while the other two stones (5.73 and 2.87 ct) are from the Mina da Batalha. Photo by Maha Tannous.

Mulungu mine; samples known to be from the Alto dos Quintos mine were unavailable for examination.

Materials and Methods. The six Mulungu tourmalines (0.47–1.35 ct, reportedly heated) were supplied by one of the authors (MB). Refractive indices were measured with a Duplex II refractometer. Specific gravity was calculated by the hydrostatic method from three sets of weight measurements recorded with a Mettler AM100 electronic balance. Fluorescence to UV radiation was documented in darkroom conditions using a standard long-wave (365 nm) and short-wave (254 nm) GIA GEM Instruments UV lamp. Observations of internal features were made with a binocular gemological

Figure 17. Located 9 km south of Parelhas, the Alto dos Quintos mine has been explored for cuprian elbaite for several years. Photo by Brendan M. Laurs.

microscope. Quantitative chemical analyses for 17 elements were obtained on all six Mulungu tourmalines (see table 2).

Results and Discussion. The gemological properties of Mulungu tourmalines examined for this study, and information taken from the published literature on material from this and other localities, are summarized in table 1. The R.I. and S.G. values of all the copper-bearing tourmalines fall within the ranges reported for elbaites in general (compare to Dietrich, 1985; Deer et al., 1997). As reported by Fritsch et al. (1990), Koivula et al. (1992b), Brandstätter and Niedermayr (1993, 1994), and Cassedanne (1996), the most interesting inclusions in "Paraíba" tourmaline are copper, but we did not observe copper inclusions in our Mulungu samples. However, Falster et al. (2000) reported plate-like copper inclusions in tourmaline from Bocheiron Zinho, another name for the Mulungu mine. Internal features in our Mulungu samples consisted of "fingerprints" comprised of liquid and liquid-and-gas inclusions, low-relief feathers, occasional growth tubes, and flash-effect colors from what appear to be oil-filled fractures (this oil could be forced out of the fractures with a thermal reaction tester).

The chemical analyses of our Mulungu samples revealed a generally lower copper content than has been reported for elbaites of similar color from the Mina da Batalha (up to 0.69 wt.% CuO versus up to 2.38 wt.% CuO, respectively; see tables 1 and 2). Tourmalines of similar color from Alto dos Quintos are reported to have a similar copper content (up to 0.78 wt.% CuO) as our Mulungu samples (Soares, 1998). However, the Cu content of the Nigerian cuprian tourmalines analyzed thus far is similar to that of the Mina da Batalha material, with up to 2.18 wt.% CuO (Zang et al., 2001). Similar amounts of other chromophoric elements (i.e., Mn, Fe, Ti, Cr, and V) were present in gem tourmalines from both

TABLE 2. Microprobe analyses of blue to blue-green cuprian elbaite from the Mina da Batalha (Paraíba) and Mulungu (Rio Grande do Norte) mines.[a]

Property/ chemical component	Mina da Batalha (Fritsch et al., 1990)[b]				Mulungu mine (this study[c])					
Color	Blue	Bluish green	Bluish green	Blue-green	Blue	Blue-green	Green-blue	Green-blue	Green-blue	Bluish green
Refractive index										
n_ε	1.619	1.620	1.620	1.621	1.619	1.618	1.618	1.619	1.618	1.618
n_ω	1.639	1.640	1.640	1.646	1.639	1.638	1.638	1.638	1.638	1.639
Birefringence	0.020	0.020	0.020	0.025	0.020	0.020	0.020	0.019	0.020	0.021
Specific gravity	3.11	3.09	3.12	3.12	3.09	3.09	3.09	3.08	3.08	3.10
Oxides (wt.%)										
SiO_2	36.97	36.75	36.83	36.53	37.00	37.07	35.99	37.21	37.79	36.97
TiO_2	bdl	0.07	0.11	0.06	bdl	bdl	bdl	0.03	0.02	0.06
Al_2O_3	38.95	38.99	39.35	38.58	40.81	37.62	37.64	41.35	40.43	37.63
Bi_2O_3	0.11	0.83	0.03	bdl	0.47	0.27	0.46	0.48	0.81	0.47
V_2O_3	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
FeO[d]	bdl	0.15	0.34	0.07	bdl	0.26	0.03	0.23	0.08	0.30
MnO	2.30	1.32	0.85	1.48	0.42	3.15	2.05	0.81	0.79	2.49
CuO	**0.72**	**1.08**	**2.37**	**1.76**	**0.44**	**0.54**	**0.69**	**0.51**	**0.40**	**0.41**
MgO	bdl	0.18	0.95	bdl	bdl	bdl	bdl	bdl	bdl	bdl
CaO	0.55	0.19	0.24	0.05	0.47	0.46	0.59	0.08	0.13	0.56
Na_2O	2.26	2.32	2.47	2.49	1.91	2.23	2.05	1.99	1.99	2.14
K_2O	0.02	0.02	0.02	0.02	0.04	0.04	0.03	0.03	0.03	0.04
PbO	bdl	bdl	0.02	bdl	0.08	0.08	0.23	0.04	0.02	0.06
ZnO	bdl	0.11	0.08	0.25	0.03	bdl	bdl	0.08	0.24	0.50
F	na	na	na	na	0.77	1.21	1.11	0.42	0.56	1.18
Partial total[e]	81.88	82.01	83.66	81.29	82.44	82.93	80.87	83.26	83.29	82.81

[a] *Abbreviations: bdl = below detection limit, na = not analyzed.*

[b] *See also Bank et al. (1990), Ferreira et al. (1990), Henn and Bank (1990), Henn et al. (1990), Rossman et al. (1991), Brandstätter and Niedermayr (1993, 1994), and Simmons et al. (2001).*

[c] *Data obtained with a JEOL JXA-733 electron microprobe at the California Institute of Technology, Pasadena, California. Operating conditions: 15 kV beam voltage, 25 nA beam current, 10 micron spot size, with mineral or synthetic compounds as standards and the CITZAF data correction procedure. Analyses represent the average of three data points on the table facet.*

[d] *All iron reported as FeO.*

[e] *Partial totals do not include Li_2O, B_2O_3, and H_2O, which could not be analyzed by the electron microprobe. Chromium and chlorine were below the detection limit in all of the samples we analyzed.*

deposits. Trace elements that are unusual in elbaite tourmalines (such as Bi, Pb, and Zn) but present in the Mina da Batalha material are also present in Mulungu tourmaline and in cuprian tourmalines from other localities (Brazil and Nigeria). Thus, it is not possible to conclude that a blue-to-green cuprian tourmaline is from the original Batalha deposit solely on the basis of chemical composition.

CUTTING AND DISTRIBUTION

Most rough from the São José da Batalha area is sold to select cutting firms in Brazil and Germany. In turn, they sell the faceted material directly to a small number of dealers and jewelry manufacturers in the U.S., Japan, and Europe. Very special crystals or cut stones are marketed to private collectors.

Cutting of "Paraíba" tourmaline is similar to that for other gem tourmalines. Although some of this material is distinctly pleochroic, the bright blue tourmaline exhibits minimal pleochroism so faceting can be done in any orientation. Because of the high value of the rough, polished stones may display a variety of shapes and sizes to maximize yield. Some cutters feel that these tourmalines appear to be more resistant to chipping during manufacturing than other tourmalines.

The larger and higher-quality blue cuprian tourmalines from the São José da Batalha area have been sold mainly in Japan and the U.S. Additional markets include Europe, Hong Kong, Singapore, and Taiwan ("Paraiba tourmaline output…," 1999). The brightly colored stones are commonly set in high-karat gold jewelry (see, e.g., figure 18).

TREATMENTS

As mentioned above, the six Mulungu cuprian tourmalines were "oiled" to minimize the visibility of surface-reaching fractures, as is commonly done with emeralds. Reportedly, some "Paraíba" tourmaline is also fracture-filled (see "Paraíba's Tucson connection," 2001). However, in the experience of BC and MB, this treatment is done only to lower-quality material. This practice is used in Brazil for a variety of colored gemstones to improve their apparent clarity.

Heating is also widespread with the cuprian elbaites. It is the understanding of BC that almost all of the material from the Mulungu mine is heat treated as a standard practice. According to R. Van Wagoner (pers. comm., 2002), at least 80% of the transparent blue to greenish blue material from the São José da Batalha area is heated. However, depending on the pegmatite being worked, there is a variable percentage of rough produced that is "common" green and cannot be improved with heat treatment. Heating is usually carried out after faceting so that few fluid inclusions are present. It requires careful control of temperatures as well as heating and cooling times, in addition to the proper selection of the starting material (which only comes through experience).

Figure 18. Tourmaline from the Batalha mine is set in these rings of high-karat gold. Manufactured by Brian C. Cook and Paula Bailey; photo by Maha Tannous.

The treatment is carried out in simple electric furnaces without any atmosphere controls, typically at temperatures ranging from 480° to 620°C. These temperatures are significantly higher than some of those reported initially (e.g., 225°–250°C in Koivula and Kammerling, 1991a) and are slightly higher than those reported by Koivula and Kammerling (1990c): 350° to 550°C. According to R. Van Wagoner (pers. comm., 2002), in general purplish red stones turn "emerald" green at 480°–500°C but will lighten if heated too far. The "neon" blue and "turquoise" colors can be produced at 550°–620°C, depending on the starting color. Darker stones typically are more saturated after heating, but in some cases the color will fade if the stone is heated at too high a temperature.

Currently, we know of no reliable means to distinguish most of the heated and non-heated cuprian tourmalines except, perhaps, by the presence of visual indications such as undamaged or heat-damaged fluid inclusions. Heating is complicated by the complex chemical composition of tourmaline, and any of a variety of color-causing elements (some in different valence states) that may be present in an individual stone. Note, too, that not all colors of "Paraíba" tourmaline can be improved by heating. In very general terms, the following color changes can be achieved with heat treatment (Bernardes, 1999; R. Van Wagoner, pers. comm., 2002; see also figure 17 in Fritsch et al., 1990, p. 202).

- Purplish red → "emerald" green
- Purple → light purple
- Greenish blue → "neon turquoise"
- Violet to violetish blue → light blue to "neon" blue
- Dark blue → "neon" blue

IMITATIONS

Various substitute gem materials have occasionally been offered as "Paraíba" tourmaline, including tourmalines that lack copper. Some other imitations are:

- Bluish green apatite from Brazil and Madagascar (Koivula and Kammerling, 1990a; Koivula et al., 1993a), and blue cat's-eye apatite (Koivula and Kammerling, 1991c)
- Doublets of tourmaline and colorless glass (Koivula and Kammerling, 1991c)
- Triplets of colorless beryl and blue or blue-green cement (Koivula et al., 1993b; Johnson and Koivula, 1996)
- Triplets of topaz and greenish blue cement (DelRe, 1995)
- Irradiated blue topaz (Koivula and Kammerling, 1991c)
- Greenish blue Tairus hydrothermal synthetic beryl (W. Barshai, pers. comm., 2001)

Standard gemological properties can be used to separate each of these imitations from cuprian elbaite.

CONCLUSION

Over the past decade, blue-to-green cuprian elbaites from the São José da Batalha area in Paraíba State have enjoyed strong demand due to their bright, saturated colors. Following the first important finds in the late 1980s, gem tourmaline production from the Mina da Batalha slowed until recently because of legal disputes over mine ownership, as well as disorganized and often ineffective mining. Recovery during the past two years from the surrounding area has provided additional gem tourmaline. The settlement of legal disputes at the Mina da Batalha and its environs has initiated a new stage of mining activity, resulting in further production of cuprian tourmaline.

Copper-bearing tourmalines have been found in at least two other pegmatites in the neighboring state of Rio Grande do Norte, which has led to expanded exploration for gem pegmatites in this region. A recent discovery of cuprian tourmaline, possibly geologically related to the Brazilian occurrences, has also been made in Nigeria. These finds have complicated the nomenclature of "Paraíba" tourmaline. Although some gem dealers believe they can identify the bright blue Mina da Batalha cuprian tourmalines on the basis of color, saturation, and brilliance, studies to date indicate that the gemological properties and chemical compositions of the cuprian tourmalines from these various sources overlap to such an extent that they cannot be distinguished by standard gem-testing methods.

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ACKNOWLEDGMENTS: The authors thank Heitor and Sergio Barbosa of Heitorita Turmalina da Paraíba in São José da Batalha for the opportunity to visit the Mina da Batalha in August 2000, and for information on their mining operations. They thank the following for providing information on the mining operations surrounding the Mina da Batalha: David Sherman, president of Treasures of the Earth (T.O.E.) Inc., Los Gatos, California; Horst Munch, a mining geologist with T.O.E. Míneração Ltda., Parelhas, Brazil; and Gordon Austin, a geological engineer and consultant with Goryll-AZ, Oro Valley, Arizona. Ronaldo Miranda (Governador Valadares, Brazil) is thanked for hosting the authors at the Mulungu mine near Parelhas. Dino DeGhionno of the GIA Gem Trade Laboratory in Carlsbad, assisted with the gemological documentation of six cuprian elbaite tourmalines from this mine. Dr. Chi Ma of the Division of Geological and Planetary Sciences, California Institute of Technology, in Pasadena, performed microprobe analyses of these Mulungu samples. Robert Van Wagoner of Beija-Flor Gems, Aspen, Colorado, kindly supplied information on heat treatment and pricing, as well as tourmaline samples for examination and photography. Dr. A. Bhaskara Rao, of Rao's Resources, Brasilia, Brazil, provided literature on tourmaline from northeastern Brazil. Walter Barshai, of J/V Tairus and Pinky Trading Co. Ltd., Bangkok, Thailand, provided samples of the greenish blue Tairus hydrothermal synthetic beryl that they are selling as a Paraíba tourmaline imitation.

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