Update on Emeralds from the Sandawana Mines, Zimbabwe

By J. C. (Hanco) Zwaan, Jan Kanis, and Eckehard J. Petsch

Zimbabwe's Sandawana mines have been an important producer of emeralds for 40 years. Since the mines came under new ownership in 1993, consistent production has been established and, in addition to the small sizes for which Sandawana is known, greater numbers of polished stones as large as 1.50 ct have been produced. Currently, mining at the most active area, the Zeus mine, is done underground, with the ore processed in a standard washing/screening trommel plant. Sandawana emeralds can be readily separated from emeralds from other localities. They have high refractive indices and specific gravities. Two amphiboles, actinolite and cummingtonite, are abundant inclusions; albite and apatite are common. Also found are remnants of fluid inclusions. Chemically, Sandawana emeralds typically have a very high chromium content.

ABOUT THE AUTHORS

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Please see acknowledgments at end of article.

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It is believed by some that the area now known as Zimbabwe was the fabled land of Ophir, which produced gold for King Solomon's temple. By the middle of the 10th century, the discovery of ancient gold workings in different parts of the country had led Arab geographers to speculate on Ophir in their writings (Summers, 1969). Although gold, and even diamonds, stimulated exploration in the 20th century, for gemologists the most important discovery was the large emerald deposit found in the mid-1950s at the area called Sandawana. For four decades, Sandawana has provided the jewelry industry with large quantities of fine, if typically small, emeralds (figure 1). Production was sporadic for much of this period, but new ownership in the mid-1990s has brought renewed attention to exploration and mining, with excellent results in terms of both the quantity and quality of the stones produced.

Although the Sandawana mines have been known for some time now, only short articles on the characteristics of Sandawana emeralds have been published to date. There has been little information about the mining area and the techniques used for exploration, mining, and processing. This article attempts to fill that gap. Not only does it provide some results of a detailed study on the geologic factors that contributed to emerald formation in this part of Zimbabwe, but it also offers new data on the distinctive properties of these emeralds.

HISTORICAL BACKGROUND

In 1868, German geologist Carl Mauch uncovered some of the ancient gold workings to which Arab geographers had referred—in the interior of what is now Zimbabwe, near Hartley (now Chegutu). Subsequently, after Cecil Rhodes's British South Africa Company obtained a charter to promote commerce and colonization in Zimbabwe in 1889, prospecting for gold became a major industry. The simplest surface indicator was an ancient working. In the nine years between 1890 and the outbreak of the South African Boer

Figure 1. The Sandawana mines are known for the small but fine emeralds that have been produced there for more than 40 years. This 16-strand necklace is composed entirely of Sandawana emeralds, more than 1,000 beads, which range from 4 to 7 mm in diameter. Courtesy of Fine Emerald, Inc., New York City; photo © Harold & Erica Van Pelt.

War in 1899, over 100,000 gold claims were pegged (Summers, 1969).

The search for gems in Zimbabwe appears to be more recent and can be dated only from H. R. Moir's 1903 diamond find in the Somabula Forest (Mennell, 1906). Some prospecting and minor mining for diamonds took place between 1905 and 1908, but these efforts faded as the results did not meet the expenses. Subsequently, several workers tried to make their fortunes in small mining operations, but interest waned and activity all but ceased (Wagner, 1914).

In 1923, Zimbabwe became a British colony under the name Southern Rhodesia. A sudden change in the fortunes of the nation's gemstone industry arrived in the mid-1950s, as a result of increased demand for beryllium and lithium minerals. On October 7, 1956, the first emerald was found in the Belingwe district (now Mberengwa) by Laurence Contat and Cornelius Oosthuizen, two former civil servants who had relinquished their posts to take up full-time prospecting. This first stone was recovered in the Mweza Hills about 5 km west-southwest of the confluence of the Nuanetsi (now Mwenezi) and Mutsime Rivers. They called their first claim "Vulcan" (Martin, 1962).

On May 17, 1957, after a rainstorm, a Vulcan worker named Chivaro found a deep green crystal protruding from a muddy footpath, some 2.5 km northeast of what eventually became the Vulcan mine. He reported the find to his employers, who rewarded him handsomely. Follow-up at the spot, which would later become known as the Zeus mine, revealed the presence of more such crystals in the "black cotton" soil, the popular name for a dark calcareous soil, relatively high in montmorillonitic

Figure 2. The Sandawana emerald mines are located in southern Zimbabwe, 65 km by gravel road from Mberengwa, the nearest village.

clay, that formed from rocks with a low silica content. Recognizing the superior quality of these crystals, Contat and Oosthuizen cautiously checked out the potential value through various renowned gemologists, including Dr. Edward Gübelin, before revealing the discovery to government officials and seeking security protection. Late in 1957, Contat and Oosthuizen sent the first parcel of rough emeralds to the United States. By February 1958, suitable regulations to control the mining and marketing had been promulgated; shortly afterwards, production formally began. The earliest processing consisted of simply washing wheelbarrow loads of soil (Böhmke, 1982).

When these rich-green stones came on the world market, Zimbabwe quickly established itself as a source of fine emeralds. By late 1959, after washing a mere 70 m^3 of soil, Contat and Oosthuizen made their fortune by selling out to a subsidiary of the large mining company RTZ (Rio Tinto Zinc) that was owned jointly by RTZ (53%) and the Zimbabwean public (47%).

The name *Sandawana*, which refers to the mining area and the emeralds mined there, was derived from that of a mythical "red-haired animal." According to local African folklore, possession of one of this animal's red hairs would result in lifelong good fortune (Böhmke, 1982). Similarly, it was believed that possession of a Sandawana emerald should bring the owner good luck!

The discovery of large quantities of fine emeralds at Sandawana sparked further interest in emerald prospecting. Within a few years, determined prospectors were rewarded with new finds in the Filabusi and Fort Victoria (now Masvingo) districts (see figure 2).

Some of these occurrences have been described by Anderson (1976, 1978), Martin (1962), and Metson and Taylor (1977). A more recent (1984) discovery was at Machingwe (Kanis et al., 1991), about 12 km northeast of the Zeus mine (figure 3), also in the Mweza Hills. Because RTZ insisted on strict secrecy, Dr. Gübelin's initial article, published in 1958, was not followed by another paper until 24 years later: In 1982, resident geologist F. C. Böhmke published his lecture on "Emeralds at Sandawana."

In May 1993, RTZ sold the Sandawana company to a newly formed company, Sandawana Mines (Pvt.) Ltd., of which the Zimbabwean government is a minor shareholder. Co-author E. J. Petsch (Idar-Oberstein) was appointed chairman of the new board. He worked with a new technical team—consisting of Mr. P. J. Kitchen (Camborne School of Mines), co-author J. Kanis (consulting geologist), Dr. A. N. Ncube (mineralogist and director of the company), and Mr. A. H. F. Braunswick (who continued as general manager of the mine)—to revitalize all activities at Sandawana. Additional investment provided new mining equipment, transportation, housing, and important improvements to underground mining and ore processing.

In 1996, Mr. D. B. Siroya of Dubai became the chairman. The company, which is headquartered in Harare, currently employs about 400 workers at the mine, of which 60 are security officers. As is the case with most gem mines, security is a major concern.

LOCATION AND ACCESS

Zimbabwe is a landlocked country in south-central Africa, covering an area of 390,624 km^2. It is surrounded by Zambia, Botswana, South Africa, and Mozambique (again, see figure 2). Zimbabwe lies astride the high plateaus between the Zambezi and

Limpopo rivers. In the south and southeast of the country are the extensive Limpopo and Save basins, which form part of the Low Veld land below 3,000 feet (915 m).

The Sandawana mines are located in the Low Veld (coordinates roughly 20°55′S and 29°56′E, confirmed by global positioning satellite [GPS] readings), approximately 830 m above sea level. The temperature ranges from a high of 41°C in the summer (November) and a low of 6°C in the winter (May). The area has an average summer rainfall of 700 mm, with occasional light drizzle in winter. The natural vegetation is open savanna (Böhmke 1982).

Zimbabwe has a well-maintained road system, and the nearest villages to the Sandawana mines—Mberengwa and West Nicholson—can be reached from Masvingo, Gweru, or Bulawayo on good tarred roads (again, see figure 2). The exception is the last 65 km traveling via Mberengwa (or 68 km coming via West Nicholson), which are on gravel roads that, during the winter rainy season, are best traversed using a four-wheel-drive vehicle. When the weather conditions are good, however, the easiest way to reach the Sandawana area is by a small plane, as there is a good landing strip at the Zeus mine. The mine can be visited by invitation only.

The Sandawana mines have their own medical clinic, which is essential in this remote area, and a primary school. There is also a sports-clubhouse, a soccer club, a community hall, a general store, as well as regular bus service to the capital, Harare.

The mining lease and claim holdings cover a 21-km-long strip along the southern slope of the Mweza Hills. They are bordered on the north by the densely populated Communal Lands. On their southern flank, the Sandawana claims share a 16km-long electrified game fence with "The Bubiana Conservancy." This syndicate of seven different ranches, which covers an area of 350,000 acres, represents one of the largest private game reserves in the world and is supported by the World Wildlife Fund.

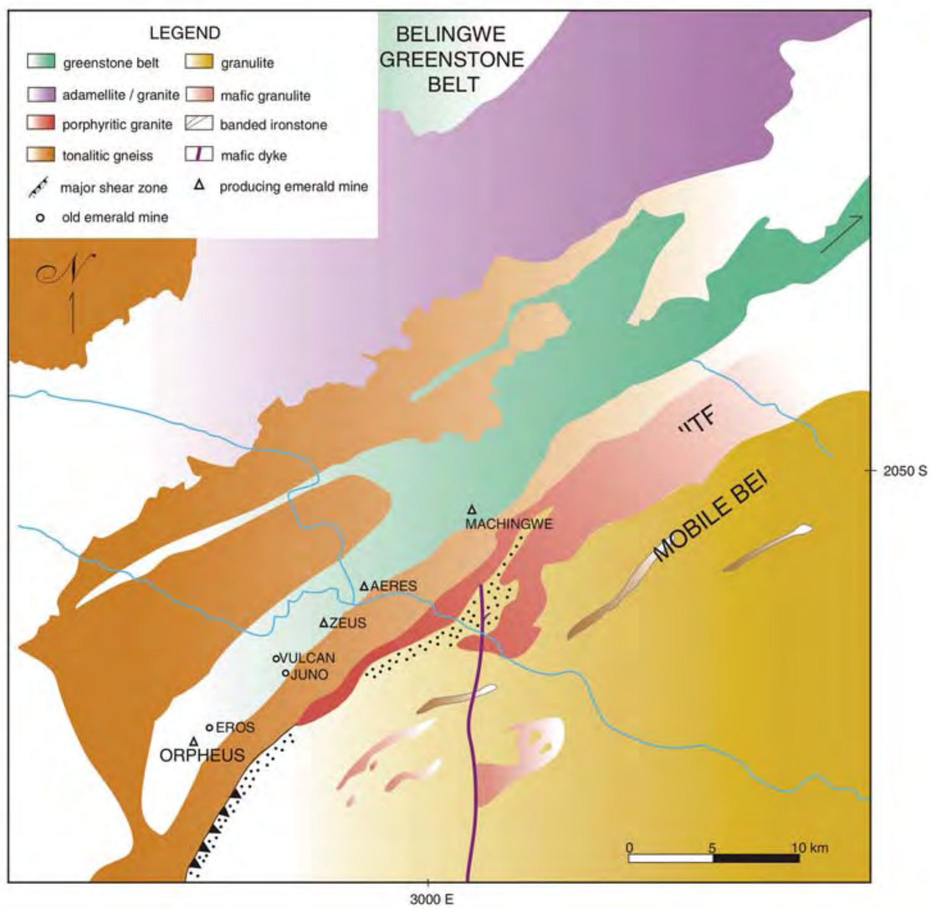


Figure 3. This simplified geologic map shows the location of both the currently producing emerald mines and the old emerald mines in the Mweza greenstone belt, near the major shear zone between the Zimbabwe craton and the Limpopo mobile belt. This map is mainly based on data from Robertson (1973) and Mkweli et al. (1995), and from satellite images.

GEOLOGY AND OCCURRENCE

The Zimbabwe craton (a relatively stable part of the Earth's continental crust) covers a large part of Zimbabwe and consists of Archean greenstone belts and granite terrains. The greenstone belts are important producers of gold, but they also contain significant amounts of chromium and nickel. The Great Dike, 530 km long and up to 4 km wide, crosses the Zimbabwe craton from north to south and is a major source of chromium.

There are few early papers on the geology of the Sandawana region (Worst, 1956; Gübelin, 1958; Böhmke, 1966), but geologic research in this area has intensified recently, as evidenced by the detailed studies on nearby greenstone belts (e.g., Fedo et al., 1995; Fedo and Eriksson, 1996) and the adjacent Limpopo mobile belt (e.g., Rollinson and Blenkinsop, 1995; Mkweli et al., 1995).

These studies underline the important magmatic and tectonic processes in the area, which resulted in the emplacement of emeralds there, and include new data on the timing of these events. In addition, the petrologic and mineralogic aspects of the complex Sandawana occurrence will be published in the near future (J. C. Zwaan, in prep.). Such publications ultimately are possible because of the open attitude of Sandawana Mines (Pvt.) Ltd.

The Sandawana emerald deposits lie along the southern limb of the Mweza greenstone belt, which is located at the southern margin of the Archean Zimbabwe craton, close to the northern margin of the Limpopo mobile belt (again, see figure 3). The Mweza greenstone belt consists of a series of intensely deformed and moderately metamorphosed ultramafic-to-mafic volcanic rocks and metasediments. It also contains numerous relatively small pegmatite bodies that tend to be concentrated at the southern end of the belt. Emeralds occur near the pegmatites at the contact with (ultra)mafic lavas; they are concentrated in pockets at sites where the pegmatite is tightly folded and/or the rocks are sheared. These "ideal" locations are characterized by actinolite schist streaks in the pegmatite and pegmatitic stringers in the adjacent actinolite schist (figure 4).

An order of geologic events in the Sandawana region has been reconstructed from field evidence and geochronological data (Robertson, 1973; Rollinson and Blenkinsop, 1995; Mkweli et al., 1995; Fedo and Eriksson, 1996). About 2.6 billion years ago, the Northern marginal zone was uplifted over the Zimbabwe craton, accompanied by thrusting in a north-northwest direction. Associated with this at the southern border of the Mweza greenstone belt was a series of shear zones (planar zones of relatively intense deformation, resulting in crushing and brecciation or ductile deformation of the rock; such areas are often mineralized by ore-forming solutions). In response to the uplift and thrusting, crustal shortening occurred, which caused folding and metamorphism of the greenstone belt. The old greenstones consist of ultramafic lavas, which are

Figure 4. At Sandawana, emeralds are typically found in the zone (outlined in red here) at the contact of small pegmatite bodies and greenstone (left, in the Zeus mine, 25/28 stope, 200 foot [61 m] level). Schlieren (streaks) of actinolite and phlogopite in pegmatite are commonly seen in the "ideal" emerald-bearing pegmatite bodies (right, in the Zeus mine, 17/16 stope, 250 foot [76 m] level). Photos by J. C. Zwaan.

Figure 5. The open pit of the original Zeus mine was called the "Bank of England" because it was extremely rich in emeralds. Buildings in the foreground are the offices, workshop, and processing plant. The employees' village is visible in the background. Note also the granitic hills of the Northern marginal zone of the Limpopo belt at the horizon. Photo by E. J. Petsch.

"komatiitic" in composition (highly magnesium- and chromium-rich).

Widespread magmatic and hydrothermal activity occurred at the same time as the shearing, in the course of which beryllium-bearing granitic pegmatites intruded into the chromium-bearing ultramafic (komatiitic) rocks of the Mweza greenstone belt. Fluids present in the pegmatite/greenstone contact zone incorporated beryllium and chromium and migrated along local shear zones, in which the emerald crystals subsequently crystallized. The deformation in the area, the uplift of the Northern marginal zone, the intrusion of the pegmatites, and the metamorphism in the greenstone belt occurred so close in time that they cannot be resolved geochronologically. This would imply that the Sandawana emeralds formed during the main deformation event, around 2.6 billion years ago.

MINING

Since the discovery of the Sandawana deposits in 1956, an almost continuous exploration program has been carried out within the 21-km-long claim holding. Over the years, systematic trenching and surface drilling of profiles for structural studies has led to the discovery of many emerald-bearing sites, including: Eros, Juno, Aeres, and, more recently, Orpheus. Nevertheless, since the earliest days, emerald exploitation has been concentrated mainly in the Zeus area (again, see figure 3).

The Zeus mine was an open-cast operation until the pit reached 15 m. It was so rich in emeralds that the location was nicknamed the "Bank of England" (figure 5). Subsequently, the Zeus mine was developed into a modern underground mine. Over a strike of 700 m, four vertical shafts have been sunk. The No. 3 shaft (figure 6) currently serves as the main production shaft, reaching levels as far down as 400 feet (122 m). Another almost vertical shaft serves the mine from 400 feet (122 m) to the 500 feet (152 m) level. Levels and sublevels are 25 feet (7.6 m) apart vertically and are connected by raises. Drifts (horizontal tunnels) are mined along the hanging and footwall contacts of the pegmatites, and mining of the emerald-bearing shoots is done by stoping methods. Ore is removed via small tunnels called ore passes. It is then transported in cocopans (ore carts) on rails to the haulage shaft.

More than 40 km of tunnels and shafts have been dug at the Zeus mine. All underground survey data are plotted on a composite mine plan, scale 1:1000. Since its inception, the survey department has maintained a three-dimensional model of the underground mine workings.

Figure 6. The main production shaft at the Zeus mine, the No. 3 shaft, serves as a haulage shaft down to 400 feet (122 m). Photo by E. J. Petsch.

After extensive trenching (figure 7, left), surface drilling (figure 7, right), sampling, and some open-pit mining, exploration shafts recently were sunk at the Aeres-3 and Orpheus sections. These prospects are 3 km northeast and 10 km southwest of the Zeus mine, respectively (again, see figure 3).

PROCESSING

Waste rock loosened by the blasting is dumped near the haulage shaft, and rock with any "green" in it taken from the (narrow) ore-zone is transported to the processing plant and batch processed. Exceptionally rich matrix with fine-quality emeralds visible is hand cobbed underground and treated separately from the normal run-of-mine material. Some of these pieces are selected for sale as collectors' specimens.

The processing plant is a standard washing/screening trommel plant with a capacity of approximately 300 tons of ore per month. About 42 people work there, eight hours a day, five days a week.

After the ore passes through a grizzly-grid (24 cm), it is broken by a jaw crusher. (Although some emeralds might be slightly damaged by the jaw crusher, there is no alternative for large tonnages.) The ore is then washed and sized, with the largest (over 20 mm) and smallest (under 3 mm) pieces separated out in a rotating trommel. Additional vibrating screens further separate the material into specific size ranges, so that larger and smaller pieces are not mixed (and the latter hidden by the former) during the next stage of sorting, on slow-moving conveyor belts. Under strict security, 30 hand-pickers scan this material for emeralds (figure 8). For emerald recovery from the 1.6–6 mm fraction, Sandawana has introduced innovative processing technology based on gravity separation. The DMS (dense media separation) module, which has a capacity of one ton of ore per hour, was originally designed for diamond processing. This technology enables the mine to recover those smaller emeralds that might be overlooked in the course of hand sorting (figure 9).

Next, "cobbers" use tungsten-tipped pliers and chipping hammers to liberate the emeralds from their matrix with a minimum of damage (figure 10). Some material needs additional tumbling for further cleaning. Last, all the rough emeralds are sorted according to size, color, and clarity to prepare parcels for the international market. The entire processing plant area is surrounded by a security fence, patrolled by security staff, and monitored by security officers using closed-circuit television.

THE SANDAWANA ROUGH

The majority of the rough emeralds are recovered as crystal fragments, most of which show a few crystal faces. Also seen are well-formed short-prismatic hexagonal crystals with pinacoidal terminations. In fact, most of the emeralds seen *in situ* to date have been either euhedral or subhedral, with prominent prismatic faces (figure 11). Many of the crystals contain fractures filled with fine-grained albite, which represent very weak zones. Consequently, these emeralds break easily when they are removed from the host rock or processed.

Most of the emeralds are medium to dark green. Although pale-green stones (perhaps more appropriately called green beryls) have occasionally been found, to date these have been seen only in the pegmatite, away from the contact with the schist.

Sandawana emerald crystals are typically small

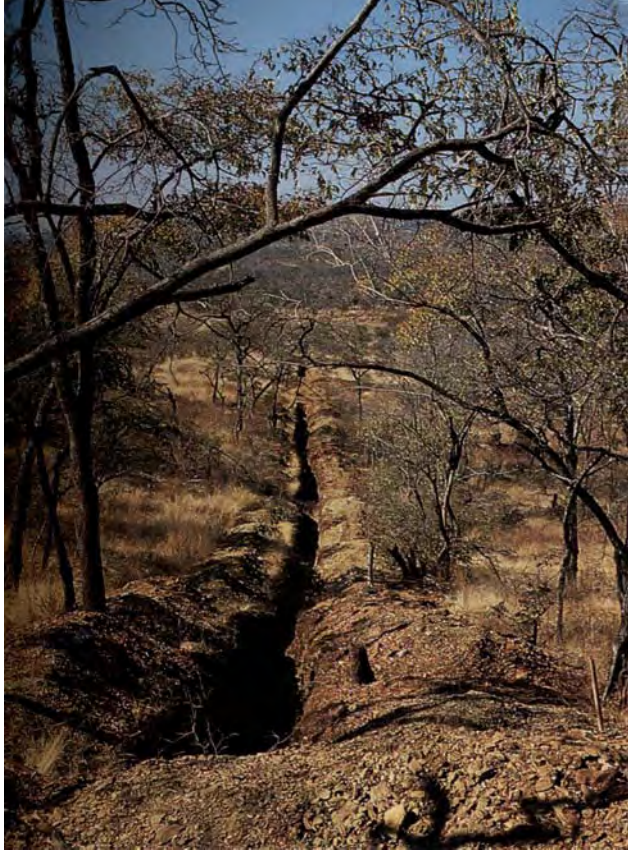


Figure 7. Exploration activities at Sandawana include (left) cross-trenching at the Aeres-3 section to find new pegmatite bodies, and (top) surface drilling at Orpheus to locate new ore zones. Photos by J. C. Zwaan (left) and E. J. Petsch (top).

(most gem-quality material is between 2 and 8 mm, although opaque crystals as large as 12 mm are frequently seen), but some larger crystals were found recently. The largest crystal that one of the authors (JCZ) has seen was 1,021.5 ct, found at the Orpheus mine in 1995. It showed complex interpenetrant twinning and, in addition to the first-order prismatic faces, a small second-order bipyramidal face. Some of the larger crystals from Orpheus (figure 12) were found in "khaki"-colored altered schist near a pegmatite at the surface. These crystals represent the more common crystal habit for this size, showing prismatic faces and rounded-to-somewhat irregular terminations, with pinacoidal faces only partly developed. Most of these large crystals contain a substantial portion that is suitable for cutting, usually as cabochons. The average retention after cutting is 10%–20% of the original weight. The general manager of the mines recently reported that larger crystals, about 25 to 100 ct each, are now regularly extracted from the Zeus mine as well.

PRODUCTION AND DISTRIBUTION

Since 1993, when the mine changed management, monthly emerald production has improved considerably and become more consistent. As noted earlier, crystals in the 25–100 ct range are now produced fairly regularly (precise quantities are not available); a few exceptional crystal clusters, weighing around 500 ct, have also been found. Nevertheless, many polished stones weigh less than 0.25 ct, as previously described by Gübelin (1958), although a substantial number of polished stones weighing between 0.25 and 0.80 ct have entered the market. Additionally, stones weighing above 1 ct and even close to 2 ct are sometimes produced. Cut Sandawana emeralds of 1.50 ct or more are still rare (figure 13).

Although the quantity of emeralds produced varies somewhat from month to month, figures over the last three years show a production of at

Figure 8. Ore fractions on the slow-moving conveyor belts are carefully checked for emeralds by hand-pickers. Gem-quality pieces are deposited in safety boxes by each sorter. Photo by E. J. Petsch.

Figure 9. The high-efficiency DMS (dense media separation) module is used at Sandawana to separate emeralds in the 1.6–6 mm fraction of run-of-mine material from the other minerals that are present in the ore zone. This computer-controlled module can process about one ton of ore per hour. Photo by J. C. Zwaan.

least 60 kg of mixed grades of rough emeralds per month, of which 10% is usually transparent enough and of a sufficiently attractive color to be faceted or cut *en cabochon*.

As regulated by the government, part of the production is cut locally for export from Zimbabwe. However, the greater part of the rough material is sold to traditional clients and, in recent years, also

Figure 10. Tungsten-tipped pliers are used to free the emeralds from their matrix. Photo by E. J. Petsch.

at regular invitation-only auctions. Sales of all gem materials (rough and cut) in Zimbabwe are monitored by the Mineral Marketing Corporation of Zimbabwe (MMCZ). For those emeralds cut officially in Harare, the fractures are not filled with an oil or an artificial resin. When fractures in these stones are filled, this happens at a later stage "along the pipeline."

Although it is difficult to give a precise estimate of reserves, ongoing exploration in the Sandawana area indicates that current production can be maintained for many years to come.

GEMOLOGICAL CHARACTERISTICS

Materials and Methods. For this study, we examined a total of 68 emerald samples, of which 36 (ranging from 0.07 to 1.87 ct) were polished. Almost all of the rough samples were transparent to translucent, suitable for cutting. Some of the material was collected *in situ* during fieldwork. The rest was obtained from the mine run, but from material that was kept separate for each stope, so that we could identify from which mine or part of the mine it came. Most of the rough emeralds were found near the contact between pegmatite and schist, but we also studied one 2.5 cm pale-green gem-quality crystal that was recovered from the pegmatite 1.25 m from the contact.

A Rayner refractometer with an yttrium aluminum garnet (YAG) prism was used to measure the refractive indices and birefringence of all polished samples. We measured specific gravities on all samples—except the 11 from which thin sections were made (see below)—using the hydrostatic method. Inclusions were identified using a standard gemological (Super 60 Zoom Gemolite Mark VII) microscope, a polarizing (Leica DMRP Research) microscope, and a laser Raman microspectrometer (Dilor S.A. model Microdil-28). For the detailed study of fluid inclusions, we had polished thin sections made from 11 samples. Polarized absorption spectra of 10 representative medium- to dark-green samples were taken with a Pye Unicam PU 8730 UV/VIS spectrometer under room-temperature conditions.

Quantitative chemical analyses were carried out on some emeralds and some inclusions with an electron microprobe (JEOL model JXA-8800M). In total, 40 spot analyses were performed on four gem-quality medium- to dark-green rough emeralds and the one light-green emerald extracted from a peg-

Figure 11. Most of the emeralds seen in situ *(here, in fine-grained, sugary albite) have been either euhedral or subhedral, with prominent prismatic faces. Photo © NNM, The Netherlands.*

Figure 12. Note the crystal habits of these large emerald crystals found at the Orpheus mine, 103.58 ct (left) and 64.95 ct (right). Both have translucent areas from which cabochons or beads could be cut. Photo © NNM, The Netherlands.

matite, all from the Zeus mine, and one medium-green emerald from the Orpheus mine; 23 were performed on amphibole inclusions; and 20 analyses were done on other inclusions.

Both the Raman and microprobe analyses were performed at the Institute of Earth Sciences, Free University of Amsterdam.

Visual Appearance. Fashioned Sandawana emeralds are known for their attractive color. Most of the samples we examined were a vivid green with medium to dark tones (figure 14). It is striking that the darker tones are not restricted to the larger stones; for instance, one stone weighing only 0.10 ct had a medium dark tone. Sandawana emeralds typically show even color distribution and are slightly to heavily included. Eye-visible internal features such as minerals or (partially healed) fractures are quite common.

Physical Properties. The standard gemological properties of the Sandawana emeralds tested are given in table 1 and discussed below.

Refractive Indices. The measured values fell within a somewhat narrower range than was indicated by Gübelin (1958; n_ε =1.581–1.588 and n_ω =1.588–1.595), which only confirms that small variations exist. More than 70% of the stones tested showed n_ε = 1.585–1.586 and n_ω = 1.592–1.593, and 90% showed a birefringence of 0.007.

Specific Gravity. The measured values varied between 2.73 and 2.80. However, stones weighing 0.15 ct or more gave results between 2.74 and 2.77, and most stones (66%) showed values around

Figure 13. Although the row of calibrated emeralds (0.09–0.18 ct) is more typical of the emeralds routinely produced from the Sandawana mines, more larger stones, such as the approximately 0.80 ct pear shape, have been produced recently. Stones like the 3.67 ct Sandawana emerald in the ring are still extremely rare. The row of calibrated emeralds is courtesy of Edward Boehm, Joeb Enterprises, Atlanta, Georgia; the ring and pear-shaped emerald are courtesy of The Collector Fine Jewelry, Fallbrook and La Jolla, California. Photo © Harold & Erica Van Pelt.

Figure 14. These stones, which range from 0.28 to 1.87 ct, are part of the group of 36 cut Sandawana emeralds examined for this study. ***.*** *Like most of the polished samples studied, they are medium to dark in tone. Photo © NNM, The Netherlands.*

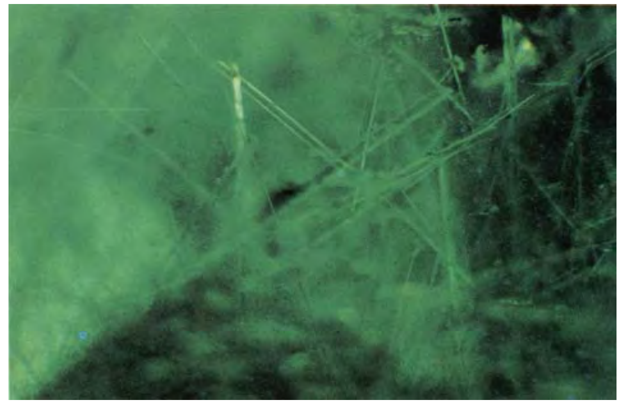


Figure 15. The "tremolite" needles and laths that are a well-known hallmark of emeralds from Sandawana were conclusively identified as actinolite and cummingtonite. Darkfield illumination, magnified 50×; photomicrograph by J. C. Zwaan.

2.75–2.76. These numbers are consistent with earlier reports by Gübelin (1958) and Böhmke (1966). Note that the smaller stones with higher specific gravities contained many (predominantly amphibole) inclusions. Thus, the scattering of values between 2.73 and 2.80 can be attributed in part to inaccuracy due to the small size of the stones and the greater influence of the inclusions at these sizes.

TABLE 1. Physical properties of 36 cut emeralds from Sandawana, Zimbabwe.

Color	Saturated colors ranging from medium to dark green. Color is evenly distributed; only weak color zoning is seen in some crystals and polished stones.
Clarity	Slightly to heavily included
Refractive indices	n_ε = 1.584–1.587, n_ω = 1.590–1.594
Birefringence	0.006–0.007
Optic character	Uniaxial negative
Specific gravity (samples 0.15 ct)	2.74–2.77
Pleochroism	Dichroism: yellowish green (ω) and bluish green (ε)
Fluorescence	Usually inert to long- and short-wave ultraviolet radiation. Sometimes faint green to long-wave UV.
Reaction to Chelsea filter	Light pink to pinkish red; the majority of the material shows pink
Internal features	• Mineral inclusions: actinolite and cummingtonite needles and long-prismatic laths, randomly oriented; albite and apatite, both showing various morphologies; phlogopite, calcite, dolomite, quartz, ilmenorutile • Partially healed fissures • Decrepitated primary fluid inclusions, typically rectangular in shape • Weak, if any, color zoning; complex zoning roughly parallel to the prismatic crystal faces seen in some clean crystals

Internal Features. *Mineral Inclusions.* The most abundant inclusions in the Sandawana emeralds examined are fibrous amphibole crystals (figure 15), which were previously described by various authors (e.g., Gübelin, 1958; Böhmke, 1982) as tremolite needles or fibers. In this study, we identified two amphiboles. Actinolite (a series with tremolite and ferro-actinolite) was identified by optical microscopy with transmitted light and by electron microprobe analyses. Tremolite and actinolite have the same basic chemical formula, $Ca^2(Mg,Fe^{2+})_5$-$Si_8O_{22}(OH)_2$, but they have different $Mg/(Mg + Fe^{2+})$ ratios. Tremolite contains very little iron and is extremely rich in magnesium ($Mg/(Mg + Fe^{2+})$ = 1.0–0.9). Actinolite, however, contains significantly more iron ($Mg/[Mg + Fe^{2+}]$ = 0.50–0.89; e.g., Leake, 1978; Fleischer and Mandarino, 1995). The analyses gave a $Mg/(Mg + Fe^{2+})$ ratio of 0.69–0.74, which is well within the actinolite field.

The other amphibole, identified with these same techniques, is cummingtonite, which occurs both as fibers and as somewhat thicker prismatic crystals. It is as abundant as actinolite and sometimes (where the fibers are large and thick) can be distinguished from it by its slightly higher relief in transmitted light and the presence of lamellar twinning in polarized light (figure 16).

Using the electron microprobe, we observed that the thicker actinolite crystals are zoned and often show a rim of cummingtonite; in contrast, the cummingtonite crystals are not zoned. In many thinner amphibole needles, actinolite is intergrown

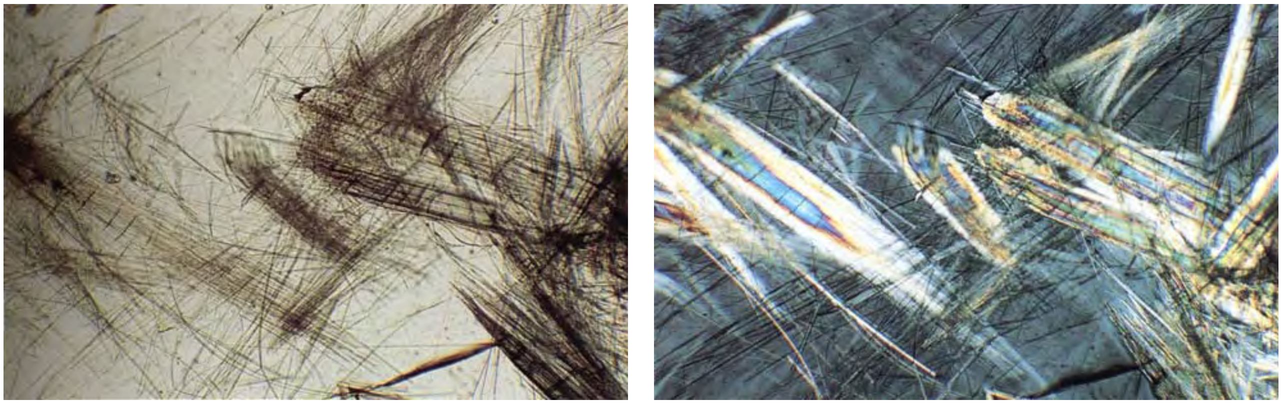


Figure 16. Long-prismatic crystals of the amphiboles actinolite and cummingtonite were identified in the Sandawana emeralds studied. In transmitted light (left), the cummingtonite laths (here, on the right of the photomicrograph) show a slightly higher relief. Between crossed polarizing filters (right), these same cummingtonite laths show lamellar twinning. Photomicrographs by J. C. Zwaan; magnified 35×.

with cummingtonite. Therefore, it will not come as a surprise that it is virtually impossible to distinguish between actinolite and cummingtonite with a normal gemological microscope, using either transmitted or darkfield illumination.

Another fairly common mineral inclusion is albite. It most frequently occurs as large tabular fragments (figure 17) or as small, slightly rounded, colorless crystals (figure 18). It also occurs in the form of a whitish, rectangular crystal surrounded by minute grains of (probably) albite, which give it the appearance of a snowball (figure 19).

Apatite is a common inclusion, too, but the apatite crystals are often very small and show various morphologies. Apatite may occur in clusters of small colorless-to-light green crystals, or as isolated, idiomorphic crystals, sometimes brownish green but also colorless (figure 20). In addition, apatite frequently occurs as rounded crystals with an irregular surface (figure 21). This illustrates that, in some gem materials, the same mineral can have a variety of appearances, which makes these inclusions difficult to identify by using only the microscope. In many cases, Raman spectroscopy helped reveal the true nature of an inclusion (see, e.g., Pinet et al., 1992; Hänni et al., 1997); in some, it easily distinguished between albite and apatite, which may look very similar.

Phlogopite is abundant in the ore zone where the emeralds are found, but it was only occasionally present in the samples we studied. The distinctive orangy brown plate-like crystals are easy to identify

Figure 17. Large colorless to milky white tabular albite crystals, such as the one shown here near the surface of the stone, frequently occur in Sandawana emeralds. Oblique illumination, magnified 60×; photomicrograph by J. C. Zwaan.

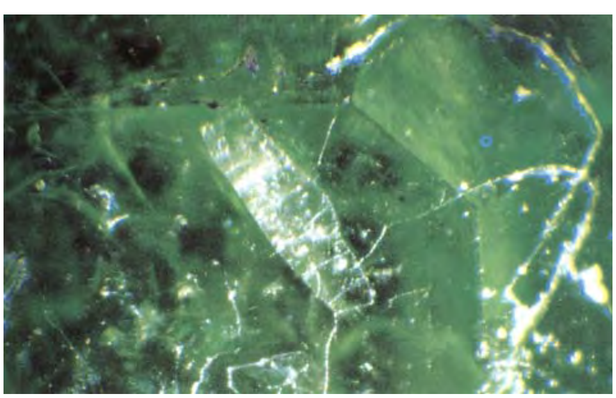
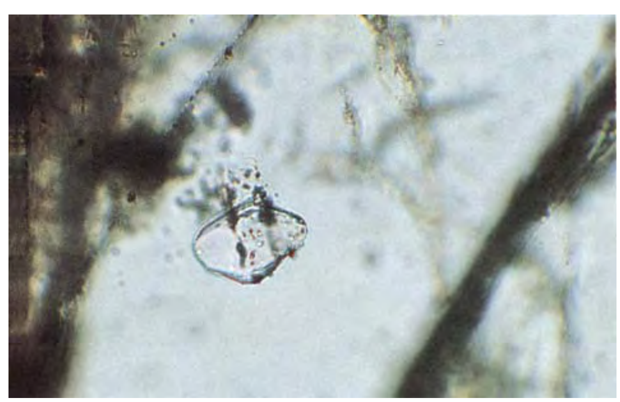


Figure 18. Many Sandawana emeralds of various qualities were also seen to contain small, rounded, colorless albite crystals. Transmitted light, magnified 125×; photomicrograph by J. C. Zwaan.



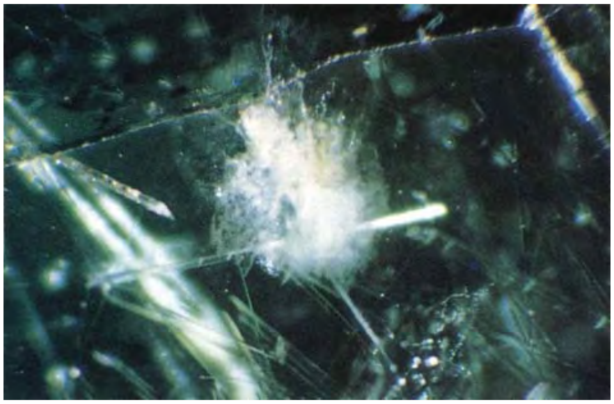


Figure 19. This albite crystal, which is surrounded by minute inclusions (probably also albite), looks like a snowball. Oblique illumination, magnified 60×; photomicrograph by J. C. Zwaan.

Figure 20. A cluster of small apatite crystals lies near a larger brownish green apatite in this Sandawana emerald. Transmitted light, magnified 100×; photomicrograph by J. C. Zwaan.

visually (figure 22; identification confirmed by microprobe). Inclusions also identified visually (and confirmed by microprobe) were calcite and a dolomite-group carbonate, emerald, quartz (very small, elongated, and rounded crystals), and zircon (minute crystals). Large black crystals of chromium-bearing ilmenorutile were found in one cut emerald, but they cannot be considered common inclusions. Gersdorffite, another opaque mineral, also was identified by microprobe analysis, but it is only present as extremely small grains. In the reaction rim of a medium-green emerald that was found in the pegmatite near a streak of amphibole schist (only 10 cm away from the contact with the greenschist), the lithium amphibole holmquistite was tentatively identified (from electron microprobe analysis and calculation of the chemical formula) but no cummingtonite or actinolite. This was confirmed by optical microscopy: The amphiboles analyzed showed straight extinction under crossed polarizing filters, which is characteristic for holmquistite. We did not encounter any of the resorbed garnet inclusions that had been previously described (Gübelin, 1958; Gübelin and Koivula, 1992); similar-appearing inclusions (figure 23) were investigated with Raman spectroscopy but could not be identified as garnet

Figure 21. In a classic "Sandawana scene" of long actinolite and cummingtonite crystals, lie three small, rounded apatite inclusions with slightly corroded surfaces—very different in appearance from those apatites shown in figure 20. Transmitted light, magnified 160×; photomicrograph by J.C. Zwaan.

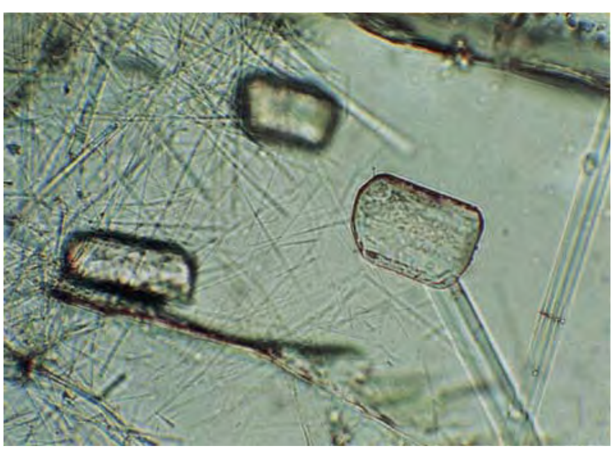
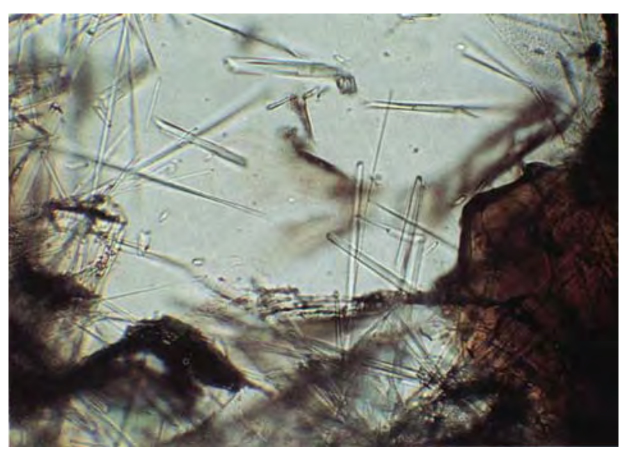


Figure 22. Seen here at the edge of a piece of gem-quality rough, this orangy brown plate-like crystal is phlogopite, which is somewhat rare in Sandawana emeralds. The black inclusion at the lower left was tentatively identified as a metamict zircon. Transmitted light, magnified 100×; photomicrograph by J. C. Zwaan.



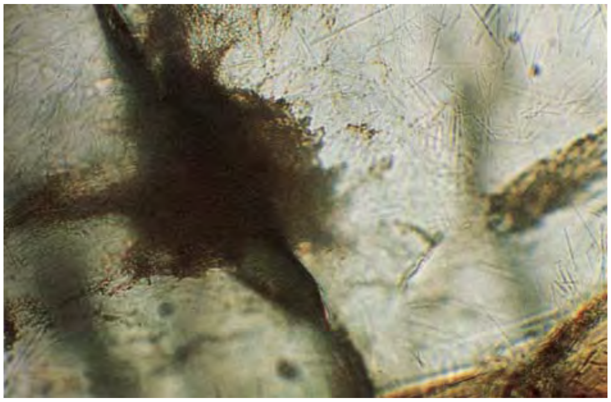


Figure 23. Although similar in appearance to previously described garnet inclusions with brownish haloes, the inclusion shown here is probably a mixture of limonite (on the basis of visual appearance) and amphiboles (as identified by Raman spectroscopy). Garnets were not identified in any of the Sandawana emeralds studied for this report. Transmitted light, magnified 160×; photomicrograph by J. C. Zwaan.

(which should be easily identified by that method; see Pinet et al., 1992).

Fluid Inclusions. Much more difficult to investigate than the solid inclusions, the fluid inclusions seen in the samples we investigated are very different from the well-known brine inclusions present in, for example, Colombian emeralds. In our search for fluid inclusions, we did find partially healed fractures with minute inclusions to be quite common (figure 24). However, most of these inclusions were so small (less than 6 μm in diameter) that they could not be analyzed by Raman spectroscopy. Some of the slightly larger inclusions in a partially healed fracture were found to be empty, and quite a few contained minerals that were identified as carbonates (figure 25).

Slightly larger isolated inclusions (approximately 35 μm long) were seen to occur as small, dark, comma-like features oriented parallel to the c-axis (figure 26). These inclusions, too, were empty and carbonate has been identified near them. Carbonate is often found near decrepitated inclusions that may have contained CO_2 (J. Touret, pers. comm., 1996). These isolated inclusions thus can be interpreted as the remnants of primary CO_2 inclusions.

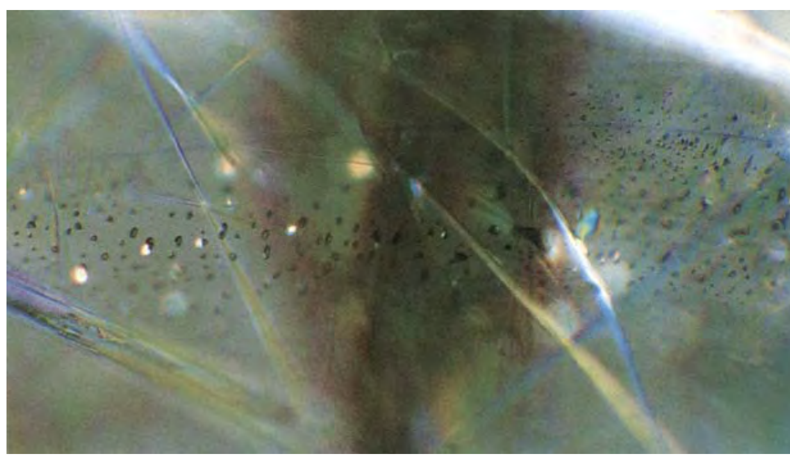
In addition to these partially healed fissures and isolated decrepitated inclusions, straight trails with decrepitated inclusions were also a common feature in the emeralds from Sandawana (figure 27).

Tube-like two-phase, liquid and gas, inclusions were seen in one sample, but they were difficult to identify with a standard gemological microscope because there were so few of them and they were extremely small.

Figure 24. Partially healed fractures containing minute inclusions were often present in the Sandawana emeralds examined. Darkfield illumination, magnified 60×; photomicrograph by J. C. Zwaan.

Growth Zoning. In most of the samples, the color was evenly distributed. Occasionally, we saw a very weak and broad medium to medium-dark green color zoning , which was straight and parallel to the prismatic crystal faces. Some clean idiomorphic crystals with an even color distribution actually showed complex deformation twinning when viewed with crossed polarizers (figure 28). This pattern, together with anomalous birefringence, indicates considerable directional stress during crystal growth.

Figure 25. A closer look at the minute inclusions in a partially healed fracture reveals that the doubly refractive minerals are carbonates. Transmitted light, crossed polarizers, magnified 175×; photomicrograph by J. C. Zwaan.



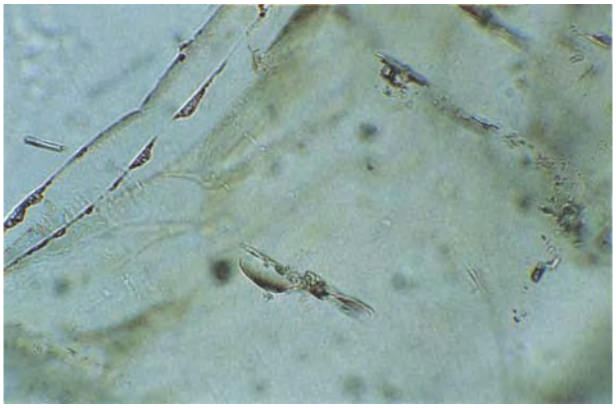


Figure 26. These comma-like, decrepitated, isolated inclusions with whitish carbonate represent the remnants of primary CO_2 inclusions. Transmitted light, magnified 200×; photomicrograph by J. C. Zwaan.

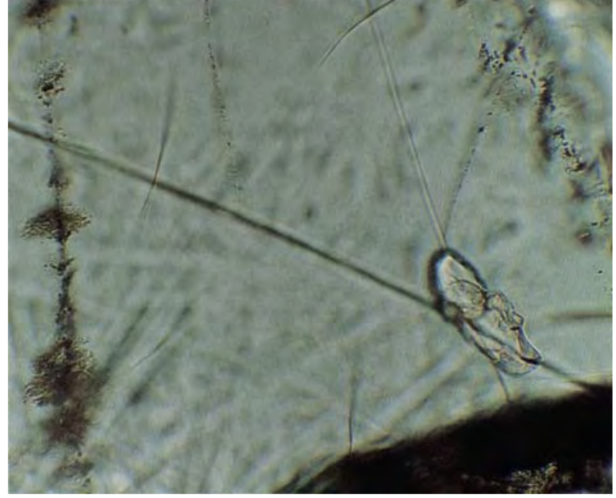
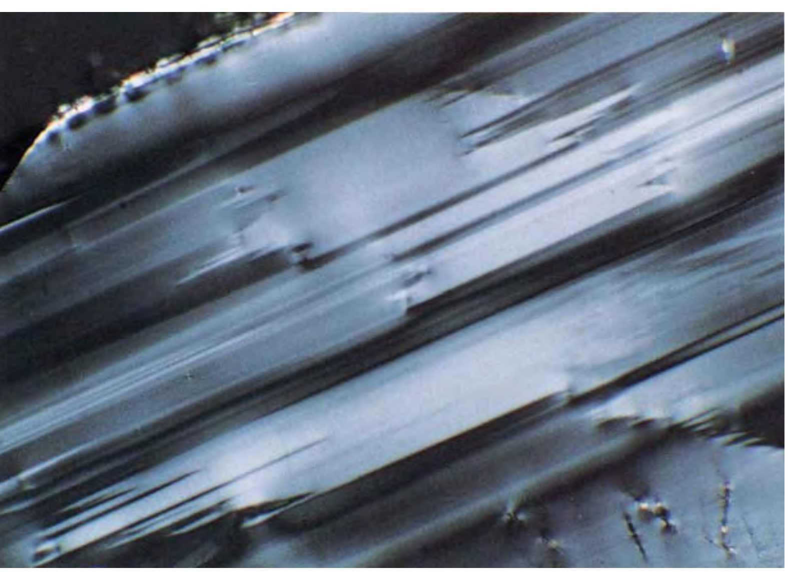


Figure 27. The trail with decrepitated inclusions on the left is a common feature in Sandawana emeralds; it indicates the earlier presence of fluids. Albite crystals are visible on the right. Transmitted light, magnified 125×; photomicrograph by J. C. Zwaan.

Absorption Spectrum. A typical absorption spectrum for Sandawana emeralds is shown in figure 29A. Broad absorption bands around 430 nm and 610 nm (for the ordinary ray), and the sharp peak at 683 nm, are reportedly caused by Cr^{3+}, whereas the broad band around 810 nm is attributed to Fe^{2+} (Wood and Nassau, 1968; Schmetzer et al., 1974). The spectrum is characteristic for a so-called "Cr^{3+}-emerald" (Schmetzer et al., 1974), in which the color is solely due to Cr^{3+} ions. The low absorption minimum in the green and the steep slopes of the Cr^{3+} absorption bands produce the vivid green color. Possible chromophores such as V^{3+} and Fe^{3+} are not present in sufficient quantities to contribute to the color (see Chemical Analysis, below). Although present, small amounts of Fe^{2+} do not influence the color, because the peak lies outside the visible-light region, in the near-infrared.

Figure 28. Observation of this Sandawana emerald between crossed polarizers revealed complex zoning caused by tapered deformation twins. The anomalous birefringence also indicates crystal growth under considerable directional stress. Transmitted light, magnified 40×; photomicrograph by J. C. Zwaan.



The spectra of emeralds from Sandawana can be distinguished from the spectra of "Cr^{3+}-emeralds" from Colombia by the intensity of the Fe^{2+} absorption band in the former. Only the e-spectrum of Colombian emeralds may show a very weak, broad absorption band around 800 nm, but in most cases an iron spectrum can barely be detected (e.g., Bosshart, 1991; Henn and Bank, 1991). Emeralds from many other localities in which Fe^{3+} contributes to the color show an additional (often low intensity) peak around 370 nm (e.g., Schmetzer et al., 1974; Henn and Bank, 1991). Figure 29 provides examples of spectra caused by various chromophores.

CHEMICAL ANALYSIS

Table 2 gives the average quantitative results that we obtained with the electron microprobe. The Sandawana emeralds are characterized by an extremely high chromium content. Average concentrations varied between 0.6 and 1.3 wt.%, but spot analyses revealed chemical zoning on a small scale within the samples, with concentrations varying from 0.38 to 1.48 wt.%. In one sample from the Zeus mine, the range was even greater, 0.13 to 3.05 wt.%. In those stones where weak color zoning was observed, the slightly darker green zones revealed more chromium, but often no straightforward correlation between color intensity and chromium content could be found.

From these analyses, it can be seen that the chromium content is partly consistent with the values given by Gübelin (1958), Martin (1962), and Hänni (1982), but it can also be substantially higher.

The Sandawana emeralds also show low Al_2O_3 content but very high MgO and Na_2O contents.

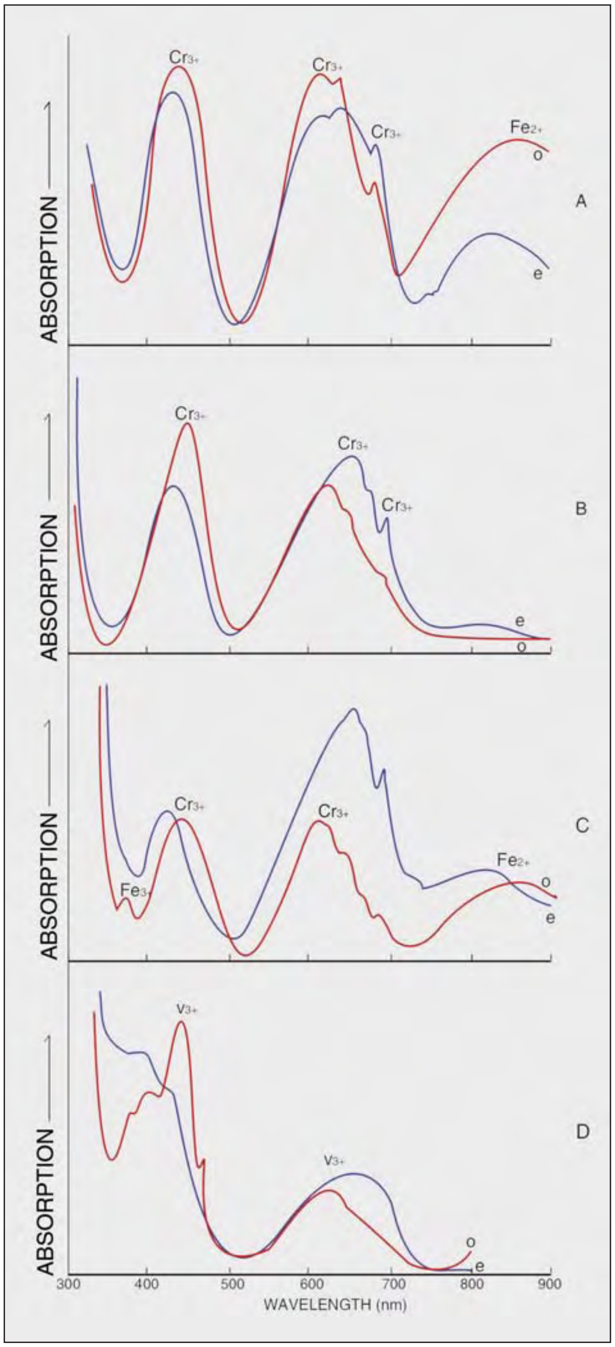


Figure 29. The absorption spectrum recorded in Sandawana emeralds (A) is comparable to that of Colombian emeralds (B), but the former has a strong absorption band in the near-infrared due to Fe^{2+}. The spectrum of one Brazilian emerald (C) shows an additional peak in the violet due to Fe^{3+}. The spectrum of a chrome-free emerald from Salininha, Brazil, which is colored by V^{3+}, is shown in (D). Spectra B and C are from Henn and Bank (1991); spectrum D is from Wood and Nassau (1968). Red line = ordinary ray, blue line = extraordinary ray.

TABLE 2. Microprobe results of analyzed elements in four medium- to dark-green emeralds (range of average results) and one pale green beryl (the average for each element) from Sandawana.[a]

Oxide	Medium- to dark-green emeralds from the Zeus and Orpheus mines (wt.%)	Pale green beryl from the Zeus mine (wt.%)
SiO_2	62.6 –63.2	62.8
Al_2O_3	13.0 –13.7	14.3
Cr_2O_3	0.61– 1.33	0.16
V_2O_3	0.04– 0.07	0.04
FeO	0.45– 0.82	0.71
MgO	2.52– 2.75	2.38
Na_2O	2.07– 2.41	2.30
K_2O	0.03– 0.06	0.06
Cs_2O	0.06– 0.10	0.09
Rb_2O[b]	≤ 0.04	bdl
CaO[b]	≤ 0.03	bdl
TiO_2[b]	≤ 0.05	bdl

[a] *Comments: BeO, Li_2O, and H_2O cannot be analyzed with a microprobe. MnO, Sc_2O_3, F, and Cl were below the detection limits. Total iron is reported as FeO.*
[b] *Most of the analyses gave values equal to or below the detection limit (bdl).*

Using Schwarz's empirical subdivision of low, medium, and high concentrations of elements in emerald (see, e.g., Schwarz, 1990), we would also conclude that the iron content is medium whereas the vanadium content is very low. Notable is the presence of cesium. As observed by Bakakin and Belov (1962), Cs is present typically in Li-rich beryl. Lithium cannot be analyzed by microprobe, but its presence is indicated by Gübelin (1958), Martin (1962), and Böhmke (1982), who reported Li_2O values ranging from 0.10 to 0.15%, respectively.

On the basis of structural refinements, Aurisicchio et al. (1988) proposed three types of beryls: "octahedral," in which substitutions in the Al octahedral site by Fe^{2+} and Mg^{2+} plus Fe^{3+}, Cr^{3+},

V^{3+}, Mn^{2+}, and Ti^{4+} represent the main isomorphous replacement; "tetrahedral," in which the main substitution is Li in the Be tetrahedral site; and "normal," in which the two substitutions occur together, but to a limited extent. In this model, a compositional gap exists between beryls with octahedral and tetrahedral substitutions. According to this model, the analyzed emeralds from Sandawana would fall in the category of "octahedral" beryls.

DISCUSSION

Geology and Occurrence. The magnesium and chromium in Sandawana emeralds come from the greenstones into which the small pegmatites intruded. This is confirmed by the analysis of the pale-green beryl that was found in the pegmatite 1.25 m from the contact with the greenstones (table 2). It contains less Mg and Cr than the emeralds, which were found closer to the contact. Most of the komatiites that comprise the greenstones are Archean in age, and resemble in composition the Archean mantle. In this respect, one could suggest that emeralds from Sandawana owe their magnificent color (caused by chromium accompanied by a relatively low concentration of iron) to the composition of the very old greenstones in which they crystallized. The exact conditions under which the emeralds formed are still under investigation. The fact that most of the fluid inclusions have decrepitated suggests a long crystallization history, but shearing does not seem to be the most important factor. If it were, inclusions would be transposed in a series of secondary healed fractures, which is not commonly the case. Decrepitation of single inclusions is more likely related to episodes of sudden regional decompression (block uplift) after initial formation. However, more evidence is needed before any definite statements can be made on this subject.

Like Sandawana, many other emerald occurrences are located near the margin of cratonic areas, close to mobile belts (a long, relatively narrow crustal region of tectonic activity) or suture zones. For example, the Afghanistan emeralds are located in the Panjsher suture zone, which marks the closure of the Paleotethys Ocean; the Pakistan emeralds occur in the Indus suture zone, which is the collision margin between the Indo-Pakistan subcontinent and Asia; and the occurrence of emeralds in Russia is related to the collision of the European and Asian plates to form the Ural Mountains (Kazmi and Snee, 1989). However, the Sandawana emerald occurrence is much older than the Asian or Russian deposits. This ancient suture zone may represent a collision between microcontinents, but the extent to which modern concepts of plate tectonics may be applied to this region is still under debate.

Identification. The higher R.I. values of Sandawana emeralds make them very easy to distinguish from their synthetic counterparts. The latter typically have lower refractive indices, roughly between 1.56 and 1.58 (see, e.g., Webster, 1983; Schrader, 1983; Liddicoat, 1989), although some Russian hydrothermal synthetic emeralds have shown R.I.'s up to 1.584 (see, e.g., Koivula et al., 1996).

On the basis of refractive index, birefringence, and specific gravity values (see, e.g., Gübelin, 1989; Schwarz, 1990, 1991; Schwarz and Henn, 1992), emeralds from Sandawana resemble emeralds from the Ural Mountains of Russia, the Habachtal region of Austria, the Santa Terezinha de Goiás deposits of Brazil, certain mines in Pakistan, and the Mananjary region in Madagascar. From table 3, it can be seen that emeralds from most of these other localities show greater variation in properties than the Sandawana stones. Also, most emeralds from the Ural Mountains and from the Mananjary region have lower values than those recorded for the Sandawana stones.

A comparison of inclusions reveals that emeralds from the Swat and Makhad mines in Pakistan do not contain any amphibole fibers and needles but frequently show black chromite and many two-phase (liquid-gas) and three-phase (liquid-gas-solid) inclusions (Gübelin, 1989); thus, they look quite different from Sandawana emeralds. Emeralds from the Charbagh and Khaltaro mines in Pakistan (not mentioned in table 3 because most of the stones examined came from the Swat mines [the largest mines] and Makhad, and can be considered most representative of Pakistan emeralds) may contain brownish green to black actinolite rods, but certainly not thin fibers of amphibole; they also show slightly lower specific gravities and refractive indices (Gübelin, 1989).

Emeralds from the Ural Mountains may contain actinolite rods that closely resemble the long-prismatic actinolite and cummingtonite crystals observed in Sandawana emeralds. However, the thin and often curved fibers seen in Sandawana emeralds have not been reported in Uralian emeralds; in the latter, phlogopite is frequently present

TABLE 3. Physical properties of emeralds from various localities.[a]

Locality	Refractive indices n_ε	Refractive indices n_ω	Birefringence	Specific gravity
Sandawana, Zimbabwe	1.584–1.587	1.590–1.594	0.006–0.007	2.74–2.77
Swat Mines, Pakistan	1.578–1.591	1.584–1.600	0.006–0.009	2.70–2.78
Makhad, Pakistan	1.579–1.587	1.586–1.595	0.007–0.008	2.74–2.76
Ural Mountains, Russia	1.575–1.584	1.581–1.591	0.007	2.72–2.75
Habachtal, Austria	1.574–1.590	1.582–1.597	0.005–0.007	2.70–2.77
Santa Terezinha de Goiás, Brazil	1.584–1.593	1.592–1.600	0.006–0.010	2.75–2.77
Mananjary Region, Madagascar	1.580–1.585	1.588–1.591	0.006–0.009	2.68–2.73

[a] *Pakistan data from Gübelin, 1989; Russia data from Schmetzer et al., 1991, and Mumme, 1982; Austria data from Gübelin, 1958, and Schwarz, 1991; Brazil data from Schwarz, 1990, and Lind et al., 1986; Madagascar data from Hänni and Klein, 1982, and Schwarz and Henn, 1992.*

as rounded platelets or as large, elongated tabular crystals (Schmetzer et al., 1991; Gübelin and Koivula, 1992). Although phlogopite has been found in emeralds from Sandawana, it is uncommon. Like the Uralian emeralds, the emeralds from Habachtal contain actinolite rods and phlogopite platelets, but —like the Sandawana emeralds—the Austrian stones also have apatite crystals (Gübelin and Koivula, 1992). However, these emeralds normally show an inhomogeneous—"patchy"—color distribution (Morteani and Grundmann, 1977) that has not been seen in Sandawana emeralds.

Although amphibole has been identified in emeralds from Santa Terezinha, Brazil, these emeralds are characterized by abundant opaque inclusions such as black spinel (as small octahedra and larger irregular grains), hematite, rutile, and pyrite. They also contain various pale-brown to colorless carbonates, which are present as irregular grains, aggregates, and fillings of fractures, but also as rhombohedra (Schwarz, 1990). By contrast, opaque inclusions of distinguishable size are rare in Sandawana emeralds, so separation from these Brazilian emeralds should be relatively easy.

Inclusions in emeralds from Madagascar may look very similar to those found in Sandawana emeralds, because long-prismatic amphibole rods are frequently found (Schwarz and Henn, 1992; Schwarz, 1994) as well as fibrous aggregates of talc (Schwarz, 1994), which may resemble the amphibole fibers present in Sandawana emeralds. Feldspar crystals and carbonates have also been identified, although feldspar is less common in Madagascar stones (Schwarz, 1994). Hänni and Klein (1982) identified apatite, too. However, in many Mananjary emeralds, transparent, somewhat rounded or "pseudo-hexagonal" mica (usually biotite/phlogopite) is the most common inclusion (Hänni and Klein, 1982; Schwarz and Henn, 1992; Schwarz, 1994). Fluid inclusions were observed in most Mananjary emeralds; the larger inclusions are often somewhat rectangular-shaped negative crystals filled with gas and liquid (Hänni and Klein, 1982; Schwarz, 1994), but three-phase (solid-liquid-gas) inclusions may also occur (Schwarz and Henn, 1992). As mentioned above, neither mica nor fluid inclusions are frequently found in Sandawana emeralds.

The chemistry of emeralds from the mentioned localities provides additional evidence (table 4). The chromium content is distinctly lower for emeralds from the Ural Mountains, Habachtal, and the Mananjary region. For the Uralian emeralds, this was confirmed by Laskovenkov and Zhernakov (1995), who gave typical chromium contents of 0.15–0.25 wt.%, with the content in some stones as high as 0.38 wt.%. In emeralds from Santa Terezinha, the chromium content can be very low, but also very high. However, the sodium content is lower—and, in most cases, the iron content is higher—than in emeralds from Sandawana.

All of the Sandawana emeralds we tested showed high magnesium and sodium contents, with little variation from stone to stone as well as within a stone. The average compositions can thus be compared with compositions of emeralds from other localities with the help of, for instance, Na_2O/MgO and Na_2O/Al_2O_3 variation diagrams (figure 30). In both diagrams, the representative points for Sandawana emeralds show distinctly high contents of both sodium and magnesium. Only some emeralds from Habachtal and the Mananjary region, and emeralds from the Swat and Makhad mines, Pakistan, show comparable contents and ratios. As stated above, this similarity poses no problem for Habachtal and Mananjary emeralds, because these contain less chromium. Emeralds

TABLE 4. Chemistry of emeralds with overlapping physical properties (wt.%).[a]

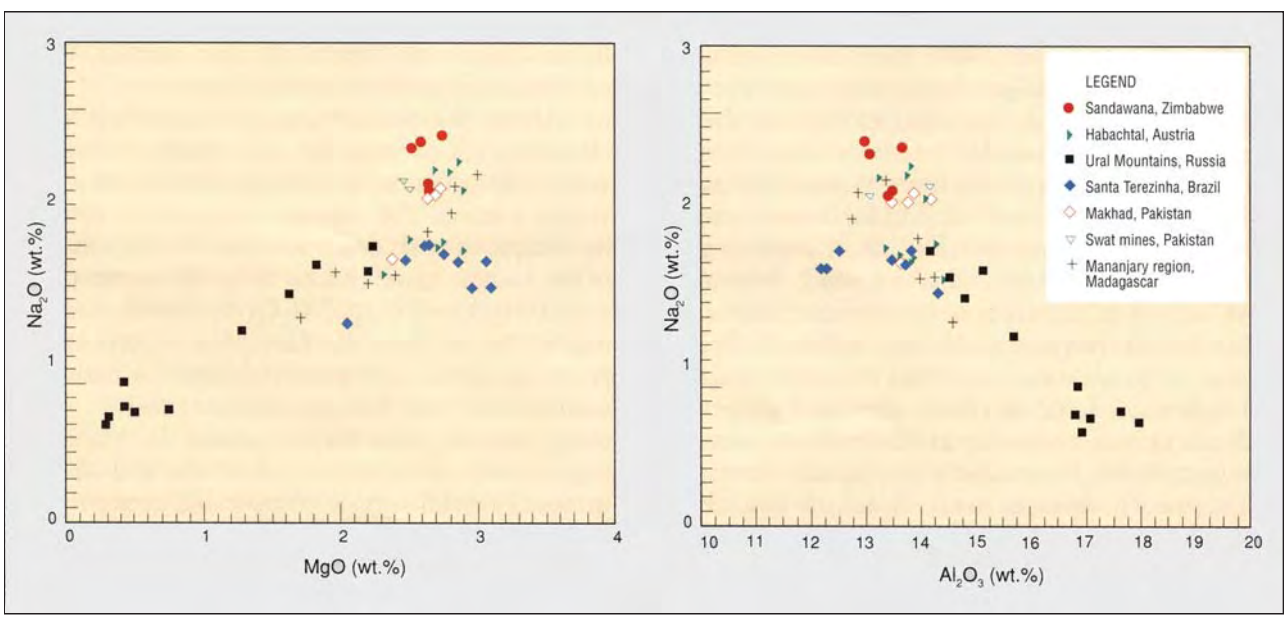
Oxide	Sandawana, Zimbabwe	Swat mines, Pakistan	Makhad, Pakistan	Ural Mountains, Russia	Habachtal, Austria	Santa Terezinha, Brazil	Mananjary Region, Madagascar
SiO_2	62.6 –63.2	62.7 –62.8	62.2 –62.9	64.6 –66.9	64.6 –66.1	63.8 –66.5	63.3 –65.0
Al_2O_3	13.0 –13.7	13.1 –14.2	13.5 –14.2	14.2 –18.3	13.3 –14.5	12.2 –14.3	12.8 –14.6
Cr_2O_3	0.61– 1.33	0.39– 1.17	0.23– 1.26	0.01– 0.50	0.01– 0.44	0.06– 1.54	0.08 – 0.34
V_2O_3	0.04– 0.07	0.01– 0.06	0.04– 0.06	≤ 0.04	≤ 0.04	≤ 0.08	≤ 0.03
FeO	0.45– 0.82	0.52– 0.91	0.44– 0.67	0.10– 1.16	0.61– 1.87	0.77– 1.82	0.91– 1.46
MnO	n.d.[b]	n.d.	n.d.	≤ 0.03	≤ 0.05	≤ 0.02	—
MgO	2.52– 2.75	2.46– 2.50	2.37– 2.68	0.29– 2.23	2.33– 2.92	2.48– 3.09	1.71– 3.00
Na_2O	2.07– 2.41	2.06– 2.11	1.64– 2.05	0.61– 1.72	1.54– 2.24	1.46– 1.73	1.28– 2.16
K_2O	0.03– 0.06	—	≤ 0.02	≤ 0.07	0.01– 0.10	≤ 0.03	0.05– 0.21
Cs_2O	0.06– 0.10	—	—	—	—	—	—
Rb_2O	≤ 0.04	—	—	—	—	—	—
CaO	≤ 0.03	n.d.	n.d.	≤ 0.03	0.02– 0.04	—	—
TiO_2	≤ 0.05	n.d.	0.01– 0.02	≤ 0.05	≤ 0.03	—	n.d.
Sc_2O_3	n.d.	—	0.17– 0.19	—	—	—	—
Mo_2O_3	n.d.	—	—	—	≤ 0.04	—	—

[a] *Pakistan data from Hammarstrom, 1989; Russia data from Schwarz, 1991, and Schmetzer, 1991; Austria data from Schwarz, 1991; Brazil data from Schwarz, 1990; Madagascar data from Schwarz and Henn, 1992, and Hänni and Klein, 1982.*
[b] *n.d. = not detected; — = no data.*

from Pakistan may be readily distinguished by their different inclusion scenery. Note that emeralds from the Makhad mine were found to have appreciable scandium (table 4), which was not detected in the Sandawana emeralds.

Because of the relatively constant properties of Sandawana emeralds, these stones can be readily separated from emeralds from other localities on the basis of a combination of physical properties, inclusions, and chemistry.

Figure 30. These variation diagrams of Na_2O versus MgO (left) and Na_2O versus Al_2O_3 (right) in emeralds with comparable physical properties illustrate that the Sandawana emeralds can be distinguished by their high sodium content, with overlapping values for emeralds from Austria and Pakistan. Urals and Habachtal data from Schwarz (1991); Santa Terezinha data from Schwarz (1990); Pakistan data from Hammarstrom (1989); Madagascar data from Hänni and Klein (1982) and Schwarz and Henn (1992).



CONCLUSION

First discovered in 1956, Sandawana emeralds have become well known for their splendid vivid green color and the typically small size (0.05–0.25 ct) of the polished stones (figure 31). Since Sandawana Mines Pvt. (Ltd.) assumed management of the mines in 1993, more stones up to 1.50 ct have been produced. Stones above 1.50 ct are still rare.

The emeralds probably formed during a major deformation event around 2.6 billion years ago, when small beryllium- and lithium-bearing pegmatites intruded into chromium- and magnesium-rich greenstones, which incorporated the elements necessary for emerald to crystallize.

Sandawana emeralds show relatively constant physical properties, with high refractive indices and specific gravities compared to emeralds from other localities. Also unlike emeralds from many other localities, they are not characterized by fluid inclusions but rather by laths and fibers of amphibole, both actinolite and cummingtonite (previously reported to have been tremolite). Other common inclusions are albite and apatite. The relative absence of fluid inclusions is due to decrepitation of these inclusions during geologic history. Nevertheless, remnants of fluid-inclusion trails are common features.

The chemistry is characterized by very high contents of chromium, sodium, and magnesium. Chromium contents in some samples were substantially higher than in specimens reported from other deposits.

Although most emeralds from other localities with physical properties that overlap those for Sandawana emeralds also show solid inclusions, including actinolite rods (Russia, Brazil, Austria, Madagascar), it is relatively easy to distinguish emeralds from Sandawana by their internal characteristics. Amphibole fibers, in particular, are seldom seen in stones from other localities, whereas they are abundant in Sandawana stones. Phlogopite and some opaque inclusions, though identified in Sandawana emeralds, are much less common than in emeralds from the other localities. The chemistry of emeralds from Pakistan is closest to that recorded for Sandawana stones, but emeralds from the two localities can easily be distinguished by their completely different internal characteristics.

Figure 31. Sandawana emeralds are popular in rings because of their saturated color in small sizes. The four emeralds in this anniversary ring weigh a total of 0.32 ct. Courtesy of Suwa & Son, Tokyo, Japan.

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REFERENCES

Anderson S.M. (1976) A note on the occurrence of emerald at Mayfield Farm, Fort Victoria, Rhodesia. *Journal of Gemmology*, Vol. 15, No. 2, pp. 80–82.

Anderson S.M. (1978) Notes on the occurrence and mineralogy of emeralds in Rhodesia. *Journal of Gemmology*, Vol. 16, No. 3, pp. 177–185.

Aurisicchio C., Fioravanti G., Grubessi O., Zanazzi P.F. (1988) Reappraisal of the crystal chemistry of beryl. *American Mineralogist*, Vol. 73, pp. 826–837.

Bakakin V.V., Belov N.V. (1962) Crystal chemistry of beryl. *Geokhimiya*, Vol. 5, pp. 420–433.

Böhmke F.C. (1966) The geology of the Sandawana Mines.

Internal report, Sandawana Mines, Harare, Zimbabwe.
Böhmke F.C. (1982) Emeralds at Sandawana. In *Gemstones, Report of the Sixth Annual Commodity Meeting*, Institution of Mining and Metallurgy (IMM), London, United Kingdom, pp. A110–A122.
Bosshart G. (1991) Emeralds from Colombia (Part 2). *Journal of Gemmology*, Vol. 22, No. 7, pp. 409–425.
Fedo C.M., Eriksson A., Blenkinsop T.G. (1995) Geologic history of the Archean Buhwa greenstone belt and surrounding granite-gneiss terrane, Zimbabwe, with implications for the evolution of the Limpopo belt. *Canadian Journal of Earth Sciences*, Vol. 32, pp. 1977–1990.
Fedo C.M., Eriksson K.A. (1996) Stratigraphic framework of the -3.0 Ga Buhwa Greenstone Belt: A unique stable-shelf succession in the Zimbabwe Archean craton. *Precambrian Research*, Vol. 77, pp. 161–178.
Fleischer J.A., Mandarino J.A. (1995) *Glossary of Mineral Species 1995*. The Mineralogical Record Inc., Tucson, Arizona.
Gübelin E.J. (1958) Emeralds from Sandawana. *Journal of Gemmology*, Vol. 6, No. 8, pp. 340–354.
Gübelin E.J. (1989) Gemological characteristics of Pakistani emeralds. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 75–92.
Gübelin E.J., Koivula J.I. (1992) *Photoatlas of Inclusions in Gemstones*, 2nd rev. ed. ABC Edition, Zurich, Switzerland.
Hammerstrom J.M. (1989) Mineral chemistry of emeralds and some associated minerals from Pakistan and Afghanistan: An electron microprobe study. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 125–150.
Hänni H.A. (1982) A contribution to the separability of natural and synthetic emeralds. *Journal of Gemmology*, Vol. 18, No. 2, pp. 138–144.
Hänni H.A., Kiefert L., Chalain J.P. (1997) A Raman microscope in the gemmological laboratory: First experiences of application. *Journal of Gemmology*, Vol. 25, No. 6, pp. 394–406.
Hänni H.A., Klein H.H. (1982) Ein Smaragdvorkommen in Madagaskar. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 31, No.1/2, pp. 71–77.
Henn U., Bank H. (1991) Außergewöhnliche Smaragde aus Nigeria. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 40, No. 4, pp. 181–187.
Kanis J., Arps C.E.S., Zwaan P.C. (1991) 'Machingwe': A new emerald deposit in Zimbabwe. *Journal of Gemmology*, Vol. 22, No. 5, pp. 264–272.
Kazmi A.H., Snee L.W. (1989) Geology of the world emerald deposits: A brief review. In H. Kazmi and L. W. Snee, Eds., *Emeralds of Pakistan: Geology, Gemology and Genesis*, Van Nostrand Reinhold, New York, pp. 165–228.
Koivula J.I., Kammerling R.C., DeGhionno D., Reinitz I., Fritsch E., Johnson M.L. (1996) Gemological investigation of a new type of Russian hydrothermal synthetic emerald. *Gems & Gemology*, Vol. 32, No. 1, pp. 32–39.
Laskovenkov A.F., Zhernakov V.I. (1995) An update on the Ural emerald mines. *Gems & Gemology*, Vol. 31, No. 2, pp. 106–113.
Leake B.E. (1978) Nomenclature of amphiboles. *American Mineralogist*, Vol. 63, pp. 1023–1052.
Liddicoat R.T. (1989) *Handbook of Gem Identification*, 12th ed., 2nd rev. printing. Gemological Institute of America, Santa Monica, CA.
Lind Th., Henn U., Bank H. (1986) Smaragde von Sta. Terezinha de Goias, Brasilien, mit relativ hoher Lichtbrechung. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 35, No. 4, pp. 186–187.
Martin H.J. (1962) Some observations on Southern Rhodesian emeralds and chrysoberyl. *Chamber of Mines Journal*, Vol. 4, No. 10, pp. 34–38.
Mennell F.P. (1906) Somabula diamond field of Rhodesia. *Geological Magazine*, Vol. 3, No. 508, pp. 459–462.
Metson N.A., Taylor A.M. (1977) Observations on some Rhodesian emerald occurrences. *Journal of Gemmology*, Vol. 15, No. 8, pp. 422–434.
Mkweli S., Kamber B., Berger M. (1995) Westward continuation of the craton-Limpopo belt tectonic break in Zimbabwe and new age constraints on the timing of the thrusting. *Journal of the Geological Society*, *London*, Vol. 152, pp. 77–83.
Morteani G., Grundmann G. (1977) The emerald porphyroblasts in the penninic rocks of the central Tauern Window. *Neues Jahrbuch für Mineralogie Mitteilungen*, Vol. 11, pp. 509–516.
Mumme I. (1982) *The Emerald*. Mumme Publications, Port Hacking, N.S.W., Australia.
Pinet M., Smith D., Lasnier B. (1992). Utilité de la microsonde Raman pour l'identification non destructive des gemmes. In *La Microsonde Raman en Gemmologie—Revue de Gemmologie a.f.g.*, No. outside of series, pp. 11–61.
Robertson I.D.M. (1973) Potash granites of the southern edge of the Rhodesian craton and the northern granulite zone of the Limpopo mobile belt. In Lister L.A., *Symposium on Granites, Gneisses and Related Rocks*, Geological Society of South Africa Special Publication 3, Salisbury, pp. 265–276.
Rollinson H., Blenkinsop T. (1995) The magmatic, metamorphic and tectonic evolution of the Northern Marginal Zone of the Limpopo belt in Zimbabwe. *Journal of the Geological Society*, London,Vol. 152, pp. 65–75.
Schmetzer K., Berdesinski W., Bank H. (1974) Über die Mineralart Beryll, ihre Farben und Absorptionsspektren. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 23, No. 1, pp. 5–39.
Schmetzer K., Bernhardt H., Biehler R. (1991) Emeralds from the Ural Mountains, USSR. *Gems & Gemology*, Vol. 27, No. 2, pp. 86–99.
Schrader H.W. (1983) Contributions to the study of the distinction of natural and synthetic emeralds. *Journal of Gemmology*, Vol. 18, No. 6, pp. 530–543.
Schwarz D. (1990) Die brasilianischen Smaragde und ihre Vorkommen: Santa Terezinha de Goiás/Go. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 39, No. 1, pp. 13–44.
Schwarz D. (1991) Die chemischen Eigenschaften der Smaragde III. Habachtal/Österreich und Uralgebirge/UdSSR. *Zeitschrift der Deutschen Gemmologischen Gesellschaft*, Vol. 40, No. 2/3, pp. 103–143.
Schwarz D. (1994) Emeralds from the Mananjary Region, Madagascar: Internal features. *Gems & Gemology*, Vol. 30, No. 2, pp. 88–101.
Schwarz D., Henn U. (1992) Emeralds from Madagascar. *Journal of Gemmology*, Vol. 23, No. 3, pp. 140–149.
Summers R. (1969) *Ancient Mining in Rhodesia*. Trustees of the National Museum of Rhodesia, Mardon Printers, Salisbury.
Wagner P.A. (1914) *The Diamond Fields of Southern Africa*. Reprinted 1971, Struik (Pty) Ltd., Cape Town, South Africa.
Webster R. (1983) *Gems: Their Sources, Descriptions and Identification*, 4th ed. Rev. by B. W. Anderson, Butterworth-Heinemann, London.
Wood D.L., Nassau K. (1968). The characterization of beryl and emerald by visible and infrared absorption spectroscopy. *American Mineralogist*, Vol. 53, pp. 777–799.
Worst B.G. (1956) *The Geology of the Country between Belingwe and West Nicholson*. Southern Rhodesia Geological Survey, Bulletin No. 43.