
SAPPHIRES FROM THE ANDRANONDAMBO REGION, MADAGASCAR

By Dietmar Schwarz, Eckehard J. Petsch, and Jan Kanis

Since 1993, large amounts of gem-quality sapphires from the Andranondambo region of southern Madagascar have entered the international gem market. These sapphires, which are found in metamorphic skarn-type deposits, show a broad range of gemological and chemical properties, many of which are similar to those of sapphires from Sri Lanka, Myanmar (Burma), and even Kashmir. Most of the Andranondambo sapphires are heat treated in Bangkok; these can be separated from their non-heat-treated counterparts on the basis of inclusion features and absorption spectra. Key factors in the separation of Andranondambo sapphires from synthetic sapphires of different manufacturers are chemistry (especially the Ga content of the natural material) and internal features.

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Madagascar has been a major gem-producing country for many years. In the past, the most important gems have been various pegmatite minerals such as beryls and tourmalines (see, for example, Chikayama, 1989) and emeralds from schist-type deposits (Schwarz, 1994). Most recently, however, fine sapphires have emerged onto the international gem market (figure 1).

Corundum occurrences in Madagascar have been reported occasionally in the literature (for geographic locations, see figure 2). Schmetzer (1986) mentions rubies from Vatomandry and Gogogogo in the southern region. Chikayama (1989) cites Gogogogo and Ejeda on the southwestern part of the island (rubies); Amboasary in the southeast, near Tolanaro (sapphires); and Antanifotsy in the central region, about 100 km south of Antananarivo (rubies and sapphires). Koivula et al. (1992) describe an unusual type of multi-colored sapphire from a locality called Iankaroka, southwest of Betroka, in Toliara Province. Non-gem-quality rubies examined in the Gübelin Laboratory in 1994 reportedly originated from Ihosy, about 120 km north of Betroka (L. Gentile, pers. comm., 1994). Whereas none of these localities has had much commercial importance, however, the Andranondambo (also called Andranondamtso) deposit in southern Madagascar has turned out to be a significant new source for fine blue sapphires. This has been of special interest for the gem trade, because Bangkok dealers report that some of the classic sources for high-quality blue sapphires in Kashmir, Myanmar (Burma), and Sri Lanka are declining in production.

The much-talked-about Andranondambo sapphire deposit is not a recent discovery, although fine-quality sapphires from here first appeared on the world market only a few years ago (Eliezri and Kremkow, 1994; Kammerling et al., 1995a). As early as 1952/53, French geologist Paul

Figure 1. In only the last few years, Madagascar has produced numerous fine sapphires. Although most of the crystals are small, some excellent large stones have also been recovered. The fine sapphires in this suite are all reportedly from the Madagascar deposits. The 16 graduated pear-shaped sapphires in the yellow-gold necklace weigh a total of 149.87 ct, the sapphires in the earrings weigh a total of 45.68 ct, and the ring is set with a 54 ct pear-shaped sapphire. Courtesy of Mouawad Jewelers.



Hibon reported the occurrence of small (up to 10 mm) eluvial sapphire crystals that came from an area 1 km northeast and 2 km south of Andranondambo village; the sapphires were found together with a previously unknown mineral that was subsequently named hibonite (Noizet and Delbos, 1955; Curien et al., 1956).

About four years ago, in 1992, local miners and Malagasy traders first offered on the Antananarivo market parcels of sapphires in various tones of blue, including a milky blue type (geuda), of which 90% were very small crystals. When one of the authors (EJP) visited Andranondambo in March 1995 with one of the claim owners, Chabany, he learned that rumors first circulated in Fort Dauphin, now called Tolanaro, that a new sapphire deposit had been found near the city of Bekily, in the central portion of southern Madagascar. It was subsequently shown, though, that the stones were from farther southeast, near Andranondambo. Thai merchants soon discovered that the pale milky blue sapphires reacted very well to heat treatment, changing to an attractive blue that in some cases

was comparable to that of Kashmir sapphires. From then on, Thai, Indian, and other traders rushed to Madagascar to purchase rough material.

As news of the rich sapphire deposit spread quickly in Madagascar, thousands of gem miners traveled to the Andranondambo area, leaving behind their aquamarine and tourmaline mines in other regions of the island. As a result, production of these latter gem minerals dropped dramatically. Even in the Mananjary region, a decline in emerald production was noted. It is estimated that as many as 10,000 miners were aggressively working the new area at different times, leading to numerous fights and even some murders. According to various Bangkok dealers, since the end of 1994 approximately 100 kg of rough Andranondambo sapphires have been shipped to Bangkok monthly, with as much as 80% of the material ultimately usable for jewelry purposes (usually after heat treatment). Although most of the crystals are small, about 10%–15% are 2–7 ct and crystals as large as 50–60 grams—although not entirely gem quality—have appeared in the marketplace. The largest Madagascar sapphire



Figure 2. The Andranondambo sapphire deposit is located in southern Madagascar, east of the village of Andranondambo, approximately 150 km by gravel road from Amboasary.

reported to date is a 17.9 kg piece of rough that was recently described by Gary DuToit, of the Asian Institute of Gemological Sciences (AIGS) laboratory, as "definitely gem-grade sapphire, a fine gem blue color" ("The find of a lifetime," 1996).

During the March 1995 visit to the sapphire deposit, Mr. Petsch's reconnaissance flight in a small twin-engine plane over the Andranondambo mining area (figure 3) was followed by a Landcruiser safari to the sapphire deposit to collect first-hand information and samples. The present study is based on information gathered during this visit, and on the examination and analysis of samples obtained from the deposit at that time as well as from marketing channels in Bangkok and Switzerland.

LOCATION AND ACCESS

Situated in the Indian Ocean, Madagascar is the world's fourth largest island, 1,580 km long and 580 km at its widest point. The Andranondambo deposit is located at 24°26' E and 46°37' S. Travel from Tolanaro to Amboasary, about 70 km, is on a good paved road that follows the southern coastline (again, see figure 2). From Amboasary, however, the journey continues on a gravel road north through Behara and Tranomaro to the village of Andranondambo. The conditions of this latter road are so poor, however, that it takes five to six hours to cover the approximately 150 km from Amboasary to the mining area, through sparsely populated territory. This trip is possible only with a well-equipped four-wheel-drive vehicle. The road to Tranomaro crosses arid land covered by huge forests of cactus-like succulents that are so dense they are virtually impenetrable. There is very little rainfall in this

Figure 3. Seen from the air, looking north, the Andranondambo sapphire deposit looks like Swiss cheese, with hundreds of small shafts made by local miners over a distance of about 3 km. The buildings in the far north, near the river, belong to an overseas mining company. Photo by E. J. Petsch.



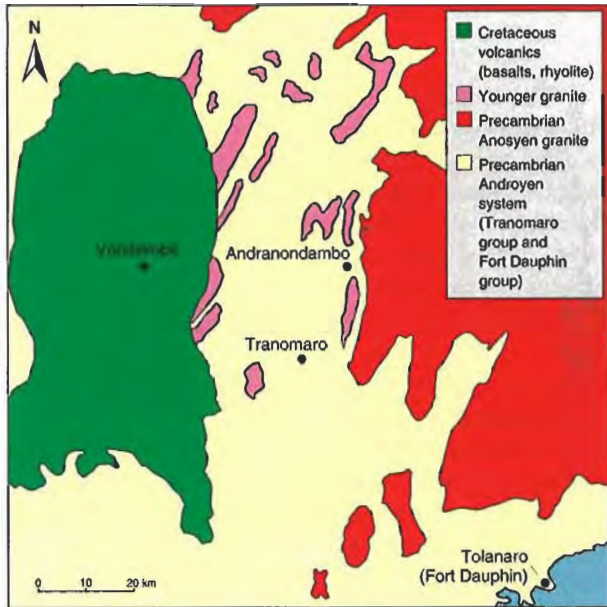


Figure 4. This geologic map of the Andranondambo region (adapted from Besairie, 1970) shows the location of the Fort Dauphin and Tranomaro groups of the Androyen system, in which the sapphires have been found. Also shown are the Cretaceous volcanics, younger granites, and Precambrian Anosyen granites.

region, and the climate is extremely hot. After Tranomaro, the succulent forests become less dense and the higher, semi-desert plateau presents a more pleasant, hilly landscape. There are no major rivers or lakes in this plateau region, which has an average altitude of 500 m above sea level, with several hills rising up to 1,200 m. The dry climate makes it possible to reach the mining area year round.

Andranondambo is a very small village, but the shanty town that has sprung up near the deposit is extensive; as noted earlier, at times it has housed as many as 10,000 people, under the most primitive hygiene conditions. By March 1995, only about 3,000 miners were still searching for sapphires in Andranondambo proper. One reason for this is that the local miners have only primitive equipment, which makes it impossible to sink extremely deep shafts. Therefore, only a limited number of miners can work effectively at any one shaft (see "Mining" below). Another, perhaps more important, reason is the discovery of sapphires nearby, about 10–12 km north of Andranondambo, at Antsiernene. According to Thomas Banker, of GemEssence Ltd. in Bangkok (pers. comm., June 1996), there is a new shanty town of 3,000–4,000 diggers in that area, which is also responsible for many of the fine southern Madagascar sapphires that are entering the market.

GEOLOGY AND OCCURRENCE

Serious geologic studies of Madagascar began only after its annexation by France in 1896. The first geologic map of the entire island was published in 1900, on the occasion of the International Geological Congress. The classic three-volume work on the mineralogy and petrology of Madagascar was published by Lacroix (1923).

The southern three-quarters of Madagascar is occupied by the Precambrian basement complex, of which the oldest system (> 3 billion years old) is the Androyen. The Androyen system is subdivided into three groups, two of which are found in the Andranondambo area (figure 4): the Fort Dauphin group, which is composed mainly of hornfels with cordierite; and the Tranomaro group, which consists mainly of a varied series of originally sedimentary rocks that were subsequently subjected to high-grade (granulite) metamorphism (Rakoton-drazafy et al., 1996).

The sapphire deposits in the Andranondambo region occur in the high-grade granulite facies, metamorphic rocks of the Tranomaro group; in this area, the granulite facies consist of crystalline limestone (marble, figure 5) containing some diopside, anorthite-rich plagioclase, and wollastonite, as well as gneisses and pyroxenites. The granulite belt in the Andranondambo region is approximately 30 km wide and is sandwiched between two younger

Figure 5. Miners dig through the crystalline limestones along the eastern contact of the Andranondambo deposit. In the background is the Precambrian Anosyen granite massif. Photo by E. J. Petsch.





Figure 6. At the Andranondambo mining area, it is dangerous to walk between the deep shafts, which are sometimes not more than 50 cm apart. Note in the shafts the profile of the cataclastic structure of the calcareous sapphire-bearing rock. Photo by E. J. Petsch.

formations: the extensive Cretaceous volcanic massif (mountainous mass) that outcrops in the vicinity of Vohitsimbe in the west (again, see figure 4), and the Precambrian Anosyen granite massif in the east (figure 5). The area also has experienced episodes of intrusion by younger granites and the formation of skarns (Rakotondrazafy et al., 1996). Clearly, the rocks of the Androyen system have been repeatedly subjected to various types of geologic processes (e.g., metamorphism, igneous activity) throughout their long history. The profile exposed in the various shafts (see, e.g., figure 6) shows a cataclastic structure (i.e., a rock texture resulting from tectonic forces), which indicates that intense mechanical forces have crushed the rocks.

The sapphires actually occur in thin veins in the metamorphic rock. These have been described as fine strings, meandering through the rock, that seem to start and stop without any real geologic definition. An American mining engineer working in the area describes the occurrence as a "pea soup" mixture of minerals (T. Banker, pers. comm., 1996). H. Hänni suggested that the sapphires formed locally in nests and pockets in the reaction zones between pegmatite dikes and pyroxenite (as reported in Kammerling et al., 1995b).

Numerous explanations for the origin of sapphires and other varieties of gem corundum in calcareous metamorphic rocks are found in the literature. The explanation applicable to each deposit depends on the extent of metamorphism in the region, the nature and abundance of mineral impurities (e.g., clay minerals) in the original rock, whether or not additional elements have been added during the metamorphic event (e.g., metasomatism), as well as other factors, the discussion of which is beyond the scope of this article.

MINING

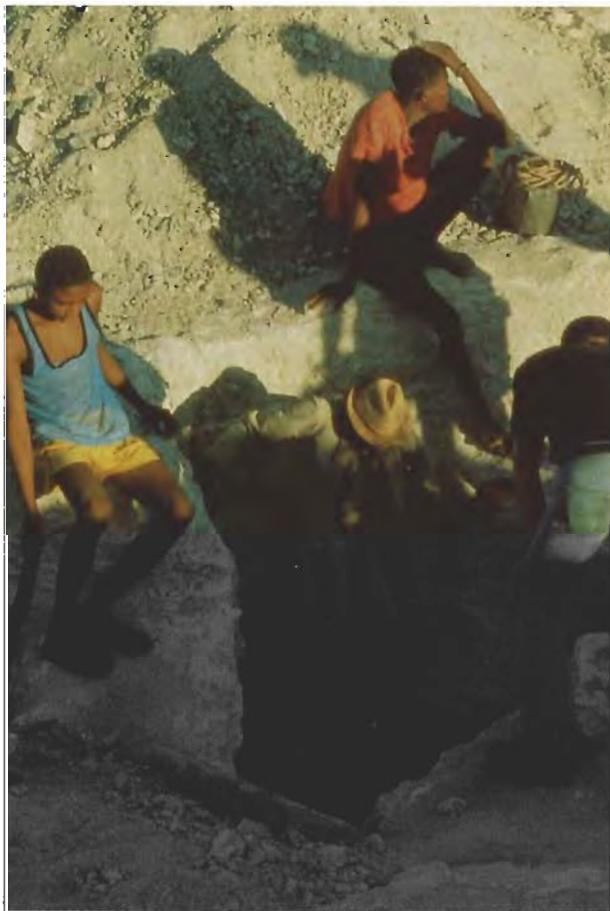
The irregularly shaped Andranondambo sapphire deposit covers an area that is at least 3 km long and varies in width between 500 and 1,000 m (again, see figure 3). From the air, one can easily observe the location and extent of the exposed mining area. The northern extremity, crossed by a small river and visible on figure 3, is the only section of the deposit where mechanical mining was being done, by an overseas company, in March of 1995. Today, there are a number of Thai groups, a Swiss group, a French group, and more than one Israeli concern working in the area, usually in partnership contracts with local residents. Mining concessions have been granted to some of these groups, with each concession 2.5 km × 2.5 km. However, local miners often do not observe the boundaries of the concessions. They regularly mine on the land illegally but with the approval of the local chiefs, who make their own often-powerful claims on the basis of ancestral rights (T. Banker, pers. comm., June 1996).

The local miners work independently in small groups by sinking narrow (2 to 2.5 m in diameter) shafts as much as 20 to 30 m deep (figures 6 and 7), which is as far as they can safely dig using manual mining methods. Fortunately, the area is very dry, so there is no rain or groundwater to cause the collapse of these shafts, which would further endanger the lives of the miners. The workers excavate the

calcareous rock with 2-m-long crowbars and shovels to open their shafts. The material is hoisted in buckets to the surface with a rope, and after dry sorting the waste is carried to huge dumps. Every group of miners has its own small claim area where shafts are sometimes no more than half a meter apart, making it very dangerous to walk over some parts of the deposit (again, see figure 6).

At the time of Mr. Petsch's visit, the deposit was being worked very inefficiently, with some of the waste material being dumped on unexploited sections of the mining area (again, see figure 5). To date, however, no serious effort has been made to bring in heavy machinery to mine the deposit by open pit and set up a sophisticated processing plant. This is largely due to the nature of the veins, which, as noted above, are relatively thin, discon-

Figure 7. Small groups of miners work at each shaft, descending by ropes, tree trunks, or crude wooden ladders as deep as 20–30 m to reach the gem-bearing veins. Photo by E. J. Petsch.



tinuous, and do not appear to follow any set pattern (T. Banker, pers. comm., 1996). Consequently, the occurrence of sapphire crystals is erratic.

PRODUCTION AND DISTRIBUTION

During his visit, Mr. Petsch saw no more than a few hundred grams of small gem-quality sapphires, most of which varied between 0.2 and 0.5 grams each. This left the impression that production at the time was very limited, considering the vast number of miners that had been working the area. Although larger crystals (2+ grams) have been reported, not a single crystal of more than 1 gram was seen during the visit (which consisted of two days at the mine and several days in the general area). There are always traders in the mining village, buying most of the miners' production at the end of each day. In fact, some Thai dealers were living permanently in the shanty town. Amornpongchai (1995, p. 6) reported that "around 100 Thai traders are in the country buying rough at the moment" (that is, at the beginning of 1995).

Most of the Andranondambo sapphire production is sent directly to Bangkok for heat treatment and cutting. K. Siu of Tai Hang Gems in Bangkok (pers. comm., 1996) estimates that about 90% of the gem-quality rough material is submitted to heat treatment before cutting. Part of the material is also cut in Israel. The finished goods are marketed mainly through channels in Thailand and Switzerland.

As noted earlier, dealers in Bangkok report that on average 100 kg of rough enters that city monthly from the Andranondambo region, 80 kg of which is gem quality. Most of the crystals are small, cutting stones less than 4 mm. Nevertheless, as much as 15% of the gem-quality crystals yield cut stones over 2 ct. Very large crystals—50–60 grams—have been recovered, but these usually must be cut before heat treatment to remove the potentially damaging negative crystals. However, a number of 15–20 ct cut stones have been reported in the trade and seen at the Gübelin Laboratory. The largest of the Madagascar sapphires shown in figure 1 is 54 ct, and (again as noted above) a 17.9 kg rough blue sapphire from Madagascar recently appeared in Bangkok.

MATERIALS AND METHODS

The test sample consisted of more than 800 non-heat-treated crystals of varying (including gem) quality that ranged from about 0.2 to 4 ct (see, e.g.,

figure 8). All were purchased by Mr. Petsch during his March 1995 visit to the mining site. From this collection, we selected a number of pieces for gemological research. One or two windows were polished on 200 non-heat-treated crystals to facilitate testing. Sixty additional crystals were subjected to heat treatment, half of these by T. Häger at

Figure 8. As these crystals from the test sample show, Andranondambo sapphires have a broad range of variability in their morphology. The most common type is the dipyrmaid, shown here at the top right and center right. Note also the dissolution features on the surface of the crystal on the bottom right in particular. The crystals range from 0.46 ct (bottom left) to 0.98 ct (center left). Photo © GIA and Tino Hammid.

the University of Mainz, Germany, and the other half by K. Siu of Tai Hang Gems Ltd., Bangkok. Windows were also polished on these heat-treated samples for examination. In addition, several parcels of faceted Andranondambo sapphires (about 60 total, ranging from 1 to 6 ct) were obtained through marketing channels in Bangkok and Switzerland for examination and chemical analysis. These stones had been heat treated in Bangkok (the treatment conditions are not known).

Refractive indices, birefringence, optic character, and pleochroism were recorded for each of 50 non-heat-treated and 50 heat-treated samples. Specific gravity was determined hydrostatically on 60 faceted stones and 40 crystals. The fluorescence behavior was checked for the entire test sample, more than 800 crystals and faceted stones. Color and fluorescence of 60 of these samples were checked before and after heat treatment.

One hundred non-heat-treated sapphires, out of the 200 polished (windowed) samples, and 100 heat-treated sapphires (40 windowed and 60 faceted stones) were subjected to spectroscopic examination. Polarized ultraviolet-visible-near infrared spectra (280 to 880 nm) were run on a Perkin Elmer Lambda 9 spectrophotometer. We recorded a total of 100 spectra (both *o* [ordinary ray] and *e* [extraordinary ray]; 50 from samples that had not been heat treated, and 50 from heat-treated stones). Twenty samples were measured before and after heat treatment. Infrared analyses were performed on about 20 of the stones with a Pye-Unicam FTIR 9624 spectrometer. A total of about 80 polished samples and faceted stones were analyzed by means of energy-dispersive X-ray fluorescence (EDXRF) spectroscopy. These analyses were performed on a Tracor Northern Spectrace 5000 system, using a program specially developed by Prof. W. B. Stern, of the Institute of Mineralogy and Petrography, University of Basel.

The internal features (growth characteristics) were studied in all 320 windowed or faceted samples. To identify the mineral inclusions, we had selected samples polished down until the inclusions to be analyzed were exposed at the surface. Analyses of about 40 mineral inclusions were carried out with a scanning electron microscope equipped with an energy-dispersive spectrometer (SEM-EDS) at the SUVA laboratory, Lucerne. The mineral inclusions of about 20 polished samples were examined by Raman spectroscopy at the AIGS laboratory, in Bangkok.



As mentioned above, some stones in our test sample were heat treated in Bangkok and some were treated at the University of Mainz. Mr. Siu explained that the details of his heat-treatment process for the Andranondambo sapphires depend on the color of the original material. Pale blue sapphires are heated in a charcoal oven in a reducing atmosphere. For darker crystals, the material is first heated in an oxidizing environment. The sapphires are then heated in a gas oven at high temperatures (1200°–1700°C), for varying lengths of time, depending on the nature of the starting material. The oxidation/reduction can be controlled by changing the O₂/H₂ gas ratio. Mr. Häger used a slightly oxidizing atmosphere and temperatures of about 1850°C for approximately five hours. He heat-treats the stones in alumina crucibles without adding Al₂O₃ powder.

CHARACTERIZATION OF THE ANDRANONDAMBO SAPPHIRES

Visual Appearance. A large number of the Andranondambo sapphires showed more or less well-developed crystal habits (again, see figure 8). These can be classified into four main types: (a) dipyrnidal (with or without a basal face), (b) prismatic (always with a basal face), (c) transition or combination type—prismatic + dipyrnidal, and (d) distorted plate-like or distorted dipyrnidal crystals. By far, the most common type is the dipyrnid. Most of the Andranondambo sapphires showed at least a few crystal faces; rarely were they entirely irregular or fragments. Some of the crystals displayed interesting dissolution features on their surfaces (again, see figure 8). Before any treatment, the samples were typically weak to saturated light blue to dark blue; almost all of the crystals showed distinct color zoning.

Once faceted, the heat-treated samples are typically blue with tones that range from medium dark to very dark (figure 9); rarely, they appear almost black in daylight. Eye-visible color zoning is often present, but eye-visible internal features such as minerals or fissures are relatively rare. Cut stones of less than 1 ct can be quite clean, even when examined with a gem microscope at moderate (20×–30×) magnification.

Gemological Properties. The standard gemological properties for the Andranondambo sapphires (see table 1) were found to be consistent with corundum in general.



Figure 9. Heat-treated sapphires from southern Madagascar (like these 0.28–0.57 ct stones) typically range from medium dark to dark blue. Courtesy of heat treaters Kenneth Kin Ming Siu and Joao Jose Ip Iau Tchun; Photo © GIA and Tino Hammid.

Pleochroism. All heat-treated samples exhibited distinct to strong dichroism. In paler non-heat-treated crystals, the pleochroism was sometimes less distinct. Normally, the colors seen in the dichroscope are blue (parallel to the c-axis) and greenish blue (perpendicular to the c-axis).

Fluorescence. Most of the Andranondambo sapphires (heat treated and non-heat-treated) were inert to both long- and short-wave UV radiation. Rarely, we observed a bluish white fluorescence in non-heat-treated crystals exposed to long-wave UV. Some heat-treated stones showed a chalky blue or

Table 1. Gemological characteristics of sapphires from Andranondambo, Madagascar.

Property	No. samples (natural/heat treated) ^a	Natural (non-heat-treated)	Heat treated
Color ^a	800/120	Weak to saturated colors ranging from light to dark blue. Almost all crystals show distinct color zoning.	Medium to highly saturated blue with medium to very dark tones. The color zoning, in general, is less distinct.
Clarity	800/60	Very clean to heavily included. Most faceted material slightly included to clean.	Same as non-heat-treated.
Refractive indices	50/50	$n_e = 1.760\text{--}1.762$ $n_o = 1.768\text{--}1.770$	Same as non-heat-treated.
Birefringence	50/50	0.008–0.009	Same as non-heat-treated.
Optic character	50/50	Uniaxial negative	Same as non-heat-treated.
Specific gravity ^b	60 faceted 40 crystals ^b	3.99–4.01 3.89–3.99	Same as non-heat-treated.
Pleochroism	50/50	Light greenish blue (perpendicular to c-axis). Saturated blue; rarely, violetish blue (parallel to c-axis). Sometimes less intense in paler crystals.	Light greenish blue (perpendicular to c-axis). Saturated blue; rarely, violetish blue (parallel to c-axis). Distinct to strong.
Fluorescence ^a (reaction to UV radiation)	800/120	Usually inert to long- and short-wave; sometimes faint bluish white to long-wave; very rarely, a faint red fluorescence to long-wave UV is seen.	By far, most samples are inert to long- and short-wave UV; rarely, chalky blue or green to long- and short-wave; a weak red fluorescence to long-wave UV is extremely rare.
Optical absorption spectrum (UV/Vis)	50/50	<ul style="list-style-type: none"> • Most pronounced absorption minimum, in general, around 490 nm (<i>e</i>-spectrum). • Absorption edge, in most cases, at relatively high values (compared to sapphires from Myanmar and Sri Lanka): <i>o</i> ~ 320–335 nm, <i>e</i> ~ 320–340 nm. • Very rarely, absorption shoulder around 320 nm. 	<ul style="list-style-type: none"> • Almost always, the absorption minimum shifts to 360 or 420 nm (<i>o</i>- and <i>e</i>-spectrum). • Absorption shoulder (around 320–330 nm) becomes more pronounced and more frequent than in non-heat-treated sapphire.
Chemistry (trace and minor elements)	60/20	$\text{Fe}_2\text{O}_3 = 0.12\text{--}0.61$ $\text{TiO}_2 = 0.01\text{--}0.10$ $\text{Ga}_2\text{O}_3 = 0.01\text{--}0.04$ $\text{Cr}_2\text{O}_3 < 0.01$ $\text{V}_2\text{O}_5 < 0.01$ $\text{MnO} < 0.01$	Same as non-heat-treated.
Internal features ^c (growth characteristics)	200/120	<ul style="list-style-type: none"> • Strong color zoning, mainly parallel to the basal face <i>c</i>; sometimes very dark blue or brownish bands. • Prominent growth structures (parallel to the basal pinacoid <i>c</i>, to various dipyrramids [normally <i>n,z</i>], to the 2nd order prism <i>a</i>, and to the rhombohedron <i>r</i>). • Healing fissures with varying textures; often "frosty" appearance. • Negative crystals showing a large variation in sizes and shapes. • Stringers of pinpoints. • Fine hollow tubes. • Mineral inclusions: calcite, apatite, feldspar (plagioclase, K-feldspar), phlogopite, Mg-hornblende, pyroxene ("hedenbergite"), rutile (grains and needles), Fe-mineral (exact nature not yet determined, probably hematite), Ca- and K-silicates (exact nature not yet determined). • Tentatively identified (based on visual appearance): "sulfide," "spinel," thorianite/uraninite. 	<p>Changes after heat treatment:</p> <ul style="list-style-type: none"> • Mineral inclusions become "turbid"-translucent or even opaque; superficially, they appear glass- or mirror-like, some porcelain-like. • Stress fissures are formed around crystal inclusions and negative crystals; these show a mirror effect (mostly, they have a frosted appearance). In other healing fissures, the original fluid inclusions become rounded and look like highly reflective spheres. Rarely, textures are similar to those observed in some synthetic flux corundums. • Most striking are fine-, medium- or, sometimes, coarse-grained bands that are grayish white; these bands may have a bluish gleam. • Color zoning (mostly weak to moderate with light to medium blue tones), parallel to the basal pinacoid <i>c</i>, to different dipyrramids, to the 2nd order prism <i>a</i>, and to the rhombohedron <i>r</i>.

^a For "color" and "fluorescence," 60 of the 800 non-heat-treated samples were also tested after heat treatment.

^b Some of the crystals contained many mineral inclusions.

^c Most of the minerals were identified by SEM-EDS; calcite, apatite, phlogopite, and rutile were also found by RAMAN spectroscopy.

green fluorescence in short- or long-wave UV; this was probably induced by heat treatment, as we did not observe it in any of the 800 non-heat-treated stones we examined (see also Themelis, 1992). Very rarely, we observed a faint red fluorescence to

long-wave UV in both heat-treated and non-heat-treated samples.

Internal Features/Growth Characteristics. *Growth Structures.* The dominant crystal forms are the

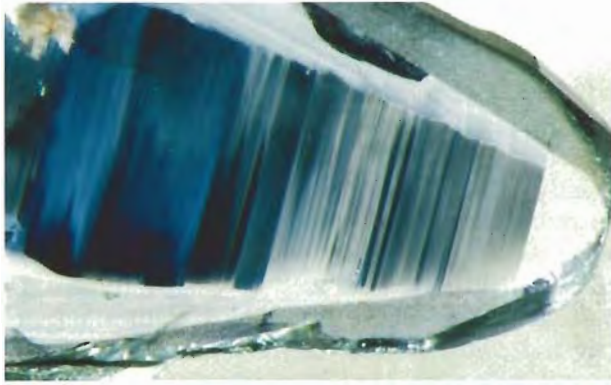


Figure 10. These growth structures and color zoning were common in the Andranondambo sapphires examined (view perpendicular to the *c*-axis): narrow growth planes parallel to the basal face *c* and repetitive sequences of the dipyramids *n* and *z*. Color bands that show different shades of blue are confined to these well-defined domains. Magnified 40 \times .

dipyramids *n* $\{2\bar{2}43\}$ and *z* $\{2\bar{2}41\}$ and the basal pinacoid *c* $\{0001\}$; the second order prism *a* $\{11\bar{2}0\}$ and the rhombohedron *r* $\{10\bar{1}1\}$ may also be of importance. Under the gem microscope, with an immersion liquid, most of the Andranondambo sapphires showed prominent growth characteristics that reflected most of the morphological properties that have been observed macroscopically. These consisted mainly of straight and angular sequences of growth planes/bands ("zones") parallel to the basal pinacoid *c*, the dipyramids *n* and *z* (often in repetitive sequences), the prism *a*, and the rhombohedron *r* (see figures 10 and 11).

Color Zoning. In most of the non-heat-treated crystals, color zoning was very pronounced, with dark, intense areas. After heat treatment, color zoning usually was less distinct, and for the most part the color bands were light to medium blue. The color bands were, in general, very narrow (figure 12) and tended to be concentrated in certain areas of the crystal. Even without magnification, the color zoning in the non-heat-treated crystals was often seen as strong, well-defined domains of a dark blue (almost black) or dark brownish blue that were typically delineated by faces parallel to the basal pinacoid *c*, the dipyramids *n* and *z* (normally, in repetitive sequences; again, see figure 10) and, rarely, the prism *a*. We commonly saw darker central zones (tube-, cone-, columnar-, or pipe-like in appearance; see, e.g., figure 13) with more-or-less well-defined outlines, similar to those observed in Mong Hsu rubies (Smith and Surdez, 1994; Peretti et al., 1995).



Figure 11. Also seen were growth structures and color zoning that consisted of sequences parallel to the dipyramid *n* and the rhombohedron *r*. Immersion; magnified 60 \times .

In some cases, the central zones were also accompanied and delineated by growth structures parallel to the basal *c* plane and to the dipyramidal faces.

A few crystals showed a dark blue border zone (rim) along the dipyramidal faces. These zones varied in thickness on the different faces but, in general, were less than 1 mm. The opposite case—that is, a large, intensely colored blue central zone (core) and a narrow near-colorless outer zone—also was observed. Here, the color zoning was parallel to the faces of the second-order prism *a* (figure 14). When looking parallel to the *c*-axis of the Andranondambo sapphires, we often saw different types of color zoning. Most frequent were very compact central zones of intense blue color and hexagonal

Figure 12. The color bands in Andranondambo sapphires, here shown parallel to the basal pinacoid, were typically very narrow. Magnified 80 \times .

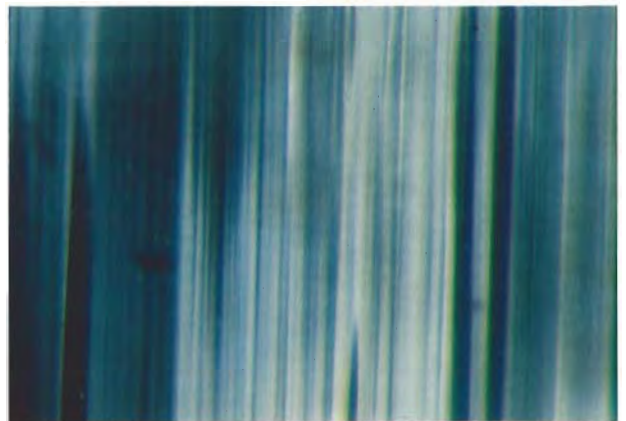




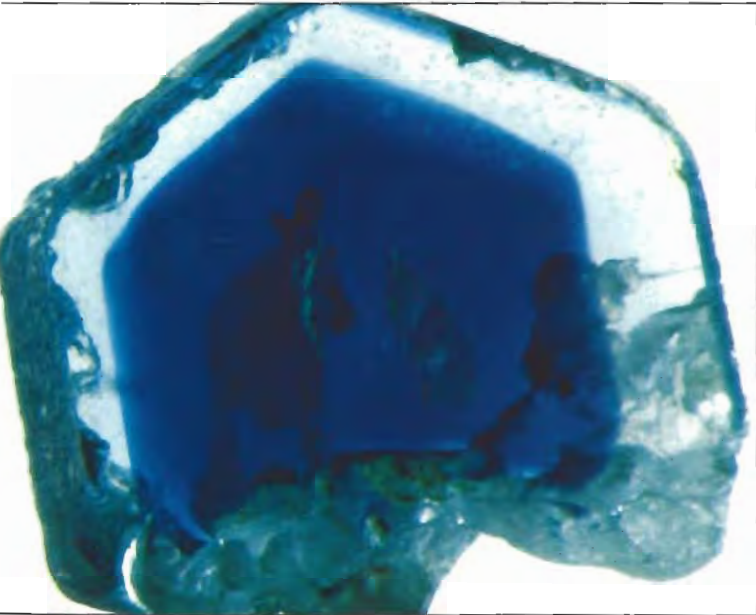
Figure 13. Commonly seen in the Andranondambo sapphire crystals was a central zone with a cone- (as here) or pipe-like appearance. Such central zones are delineated by planes parallel to the basal c face and by repetitive dipyramidal (n,z) faces. These central zones are similar in appearance to those observed in Mong Hsu (Myanmar) rubies. Magnified 60X.

outline, as well as hexagonal "growth rings" that varied in color intensity and thickness.

Twinning. Pronounced twinning is rare. In most cases, the presence of twin planes and intersection lines was only suggested.

Mineral Inclusions. The minerals we observed in Andranondambo sapphires were randomly dis-

Figure 14. In a few samples, a large, intensely colored blue core was surrounded by a narrow (< 1 mm) near-colorless "rim." Magnified 20X.



tributed. The most common mineral appeared to be calcite (chemical analyses showed an almost pure Ca-carbonate). The calcite crystals varied greatly in size (up to 1 mm) and shape. Some were rounded and some were elongated (figure 15), whereas still others were plate-like. Frequently, the calcite inclusions were well-developed, presenting various morphologies. Although usually transparent and colorless, the calcite crystals themselves sometimes contained numerous small (usually fluid) inclusions, which gave them a turbid white appearance.

Other colorless and transparent crystal inclusions were identified as apatite. They occurred most often as irregularly rounded prisms (figure 16), or as elongated hexagonal prismatic crystals. They also appeared as plate-like crystals with many faces. Two types of feldspar were identified. Plagioclase most commonly occurred as colorless, transparent grains of varying size (normally less than 0.5 mm) and irregular morphology, but it was sometimes seen as whitish crystals or as "filling material" in fissures. Typically, the plagioclase was of anorthite composition. The K-feldspar crystals appeared as transparent, often slightly yellow grains and as small, irregularly shaped crystals. Colorless, transparent, needle-like to long-prismatic or stalk-like crystals distributed without any orientation were identified as the amphibole Mg-hornblende.

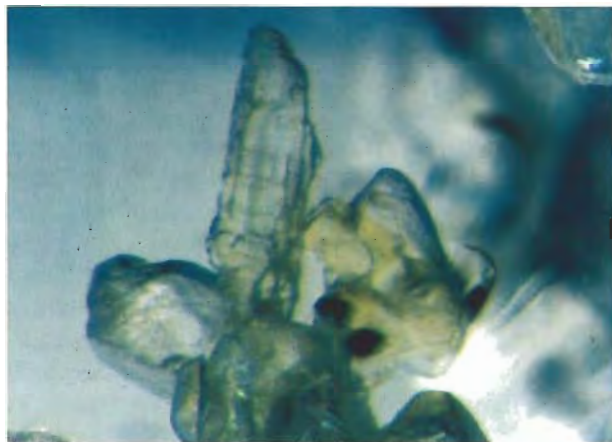
The second-most-common included mineral was biotite/phlogopite (figure 17). As a rule, it formed isolated orangy brown transparent platelets or mineral aggregates. The chemical analyses actually distinguished two types of mica: In addition to the "normal" biotite/phlogopite composition, some of the analyzed crystals showed distinct Ti concentrations (a few weight percent TiO_2). Sometimes, the mica crystals were intergrown with other mineral inclusions (most often, with calcite and pyroxene). A Ca/Al-silicate that normally occurs in the form of greenish brown grains or irregularly shaped crystals belongs to the pyroxene group (hedenbergite). The chemical analyses proved some crystals to be Ca- and K-silicates, but we have not yet determined their exact nature. Some grayish to black grains with metallic luster showed only the element titanium in the chemical analyses. With Raman spectroscopy, we identified these as rutile. We also saw rutile in the form of oriented needle-like crystals of varying length and as plate-like inclusions.



Figure 15. Colorless calcite crystals were the most common mineral inclusions identified in the Andranondambo sapphires. They occurred rounded or elongated (as shown here) or even plate-like. Magnified 80 \times .

A few mineral inclusions could not be analyzed chemically because they were too small or were in faceted gems that could not be polished to bring the minerals to the surface. These inclusions were identified on the basis of their visual appearance under the gem microscope: (a) opaque, brownish yellow grains with metallic luster (sulfide); (b) opaque, black, cube-like crystals with metallic luster, sometimes accompanied by stress-fissures,

Figure 16. Also identified in the sapphires from southern Madagascar were irregularly rounded prisms of apatite, like the sample shown here at the top center with some colorless to near-colorless calcite crystals and a few opaque black grains (probably rutile or spinel). Magnified 60 \times .

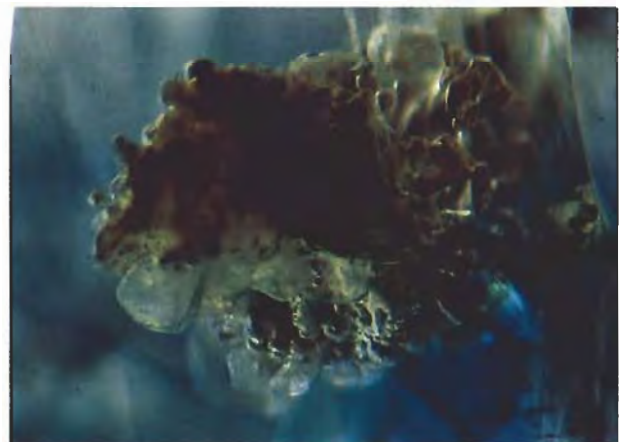


which are probably uraninite or uran-thorianite (see also "Discussion" section); and (c) other opaque grains with a grayish black metallic luster and more-or-less rounded outlines, which probably belong to the spinel group.

In one non-heat-treated sample, we observed fine yellowish brown needles and pinpoints that, in reflected light, had a strong metallic luster; these were concentrated in some well-delineated areas of the host crystal (figure 18). Although we could not conclusively identify these needles, chemical analyses in areas of the host crystal where the needles reached the surface revealed high Fe concentrations. This indicates that the needles are an Fe mineral (possibly hematite, which has been identified—e.g., by Barot et al., 1989—in sapphires from Kenya). We also observed, but could not identify, long, fine needles that ran parallel to the basal face of the host crystal.

Negative Crystals and Fluid Inclusions. Relatively common in the Andranondambo sapphires were so-called negative crystals and their fluid fillings. These inclusions varied greatly, from minute particles and flat, disk-like cavities to elongated, irregularly shaped cavities and large forms delineated by many faces or showing bizarre shapes. Some of the larger, elongated negative crystals were accompanied by tails or "seams" of smaller negative crystals (figure 19). Small negative crystals were often arranged in rows, giving the appearance of strings of

Figure 17. Biotite/phlogopite was the second most common mineral observed in the southern Madagascar sapphires, often appearing as mineral aggregates. Photomicrograph by E. J. Gübelin; magnified 66 \times .



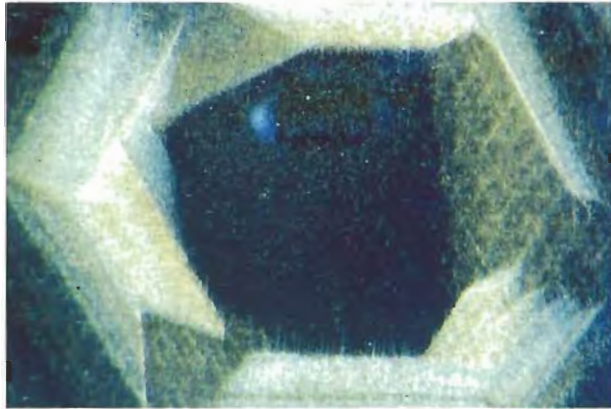


Figure 18. One crystal had concentrations (in well-defined areas) of fine needles and "pinpoints" of a yellowish brown color and a strong metallic luster in reflected light. Chemical analyses of the areas with high concentrations of these needles cutting the surface had distinctly higher Fe contents than the rest of the stone. Thus, the needles probably represent an Fe mineral (probably hematite). Magnified 60X.

pearls, or they were dispersed over former growth planes (figure 20). Sometimes, the negative crystals on the growth planes were accompanied by small crystals of different minerals. The faces of larger negative crystals (especially the flat ones) frequently showed a strong reflection (mirror effect) or striation of the cavity walls. All types of negative crystals may be accompanied by relatively flat healing fissures with random orientation.

Figure 19. Negative crystals were common in the Andranondambo sapphires. Here, large, elongated negative crystals are accompanied by a "seam" of smaller ones. Magnified 80X.



The nature of the material(s) filling the negative crystals is still not well known. Most of the negative crystals looked like single-phase fluid inclusions. However, they are probably two-phase inclusions in which one liquid phase occupies almost the entire cavity. One large three-phase negative crystal contained a colorless liquid, a brownish liquid, and a gas bubble. Rarely, we saw grayish black platelets with strong luster (graphite?) in the fluid inclusions; more common, however, were needle-like inclusions that we have not yet been able to identify.

The fact that the negative crystals in Andranondambo sapphires are often concentrated on growth planes can have significant consequences for heat treatment. As these inclusions commonly rupture at high temperatures, they may result in the breakage of the host crystal or cut stone.

Color Bands. The most striking internal feature in the heat-treated Andranondambo sapphires examined were the grayish white (rarely, grayish brown) fine-, medium-, or coarse-grained bands (figure 21). Because we did not see such bands in non-heat-treated Andranondambo stones, we believe that their formation is directly related to the heat-treatment process. In the Andranondambo sapphires, these HT-bands (the designation *HT* is given to emphasize that these structures formed during heat treatment) were observed in most of the samples examined; sometimes, especially in small stones, they were not easily seen. These bands were often accompanied by color zoning. Fine-grained HT-bands often appeared very compact, giving the impression of three-dimensional "block structures." Others were less compact and appeared fainter and more delicate. With the microscope, using oblique fiber-optic illumination, we frequently observed a bluish "gleam" to the HT-bands. Some very compact bands appeared brown in transmitted light.

Healing Fissures. Healing fissures were also quite common in the Andranondambo sapphires. They were typically flat, rarely wavy, with net-like, (rarely) grain-like, or tube-like "textures." They might consist of isolated rounded or elongated fluid inclusions, of larger negative crystals, or sometimes of "stringers" of small rounded or slightly elongated particles. Even in non-heat-treated stones, many healing fissures had a distinct frosty appearance. In the healing fissures of some heat-treated stones, the



Figure 20. In some of the southern Madagascar sapphires, negative crystals were dispersed over a former growth plane. Magnified 60 \times .

original fluid inclusions were rounded and looked like highly reflective spheres, or they had textures similar to those seen in some synthetic flux corundums (figure 22).

Other Internal Features. In the Andranondambo sapphires, we also observed: (a) stringers of pin-point-like inclusions in different arrangements (rarely, a sheaf-like appearance), some of which were very delicate (almost cobweb-like); and (b) fine hollow tubes (sometimes needle-like), which have been reported to contain polycrystalline material (by H. Hänni in Kammerling et al., 1995b). Any of the inclusion minerals described in the preceding sections may be accompanied by (c) wing-like healing fissures, unhealed stress fissures, or long, thin, tube- or canal-like inclusions (figure 23). Sometimes, we also observed swarms of delicate, divergent tubes and stringers, which were almost identical to the "comet tails" seen in many Kashmir sapphires.

After heat treatment, many of the originally transparent crystal inclusions turned turbid or even opaque. In addition, the surface of a mineral inclusion sometimes changed dramatically: Many crystal faces developed a porcelain- or glass-like appearance, whereas others became so reflective as to display a mirror effect. Sometimes, a surface acquired a frosted or even crust-like appearance. In some mineral inclusions, we observed the formation of small tension fissures at the contact with the host crystal. Several of the heat-treated Andranondambo

sapphires showed grayish white to white needle-like inclusions. Because the samples in which we observed these needles were seen only after heat treatment, we could not establish whether the needles were formed during treatment or were present before but changed their appearance during heating.

Absorption Spectra. Non-Heat-Treated Sapphires. A typical absorption spectrum for most of the non-heated Andranondambo sapphires is shown in figure 24a. The spectrum in figure 24b was seen in non-heat-treated material as well as in heat-treated samples. The broad absorption bands around 570 nm in the *o*-spectrum and around 700 nm in the *e*-spectrum are responsible for the blue color (see, e.g., Ferguson and Fielding, 1971 and 1972; Schmetzer and Bank, 1980; Fritsch and Rossman, 1987, 1988a and b; Moon and Phillips, 1994). The main difference between the two spectral types is the presence/absence of an absorption shoulder in the 320–330 nm range. The absorption minima for both spectral types lie around 360, 420, and 490 nm in both the *o*- and *e*-spectra. As a rule, in non-heat-treated Andranondambo sapphires the deepest absorption minimum for the *e*-spectrum was observed at 490 nm. In both heat-treated and non-heat-treated samples with the 320–330 nm absorption shoulder, the absorption minimum almost always shifted to 360 or 420 nm.

Figure 21. The most striking internal feature of the heat-treated Andranondambo sapphires examined were bands of fine-, medium-, or coarse-grained textures and grayish white (rarely grayish brown) color. The formation of these HT-bands is directly related to the heat-treatment process. Magnified 80 \times .



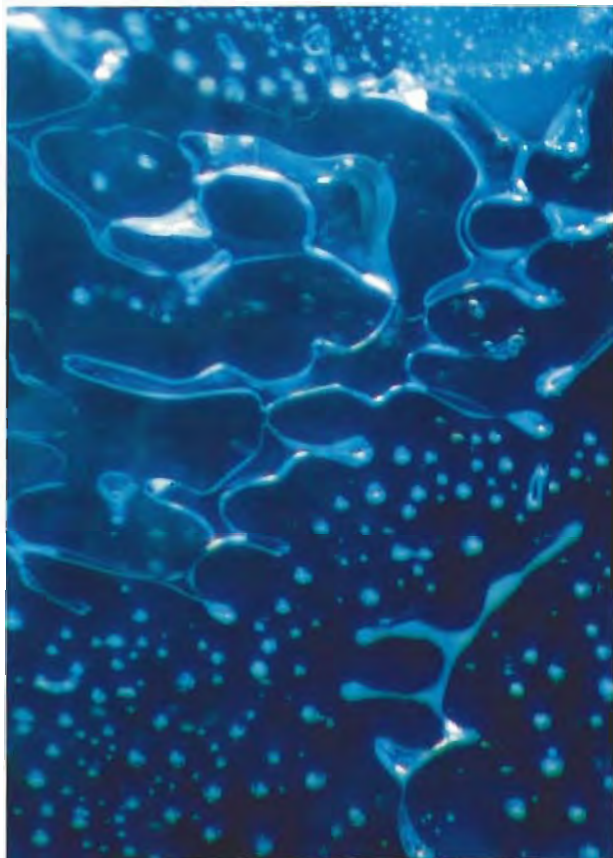


Figure 22. Healing fissures in some heat-treated Andranondambo sapphires were reminiscent of the textures observed in some flux-grown synthetic corundums. Magnified 60 \times .

Heat-Treated Sapphires. Most of the heat-treated samples had absorption spectra similar to that shown in figure 24b. The absorption shoulder around 320–330 nm is more or less pronounced, and in general the absorption edge lies between 290 and 300 nm. In non-heat-treated material, the absorption edge was usually located between 320 and 340 nm. It must be emphasized, however, that a strong 320–330 nm absorption shoulder was not always present in heat-treated Andranondambo sapphires. The shoulder may be very weak or even completely absent. As illustrated in figure 24 a and b, for the non-heat-treated and for most of the heat-treated Andranondambo sapphires, the absorption bands around 570 and 700 nm were dominant. These bands are ascribed to charge-transfer transitions between Fe^{2+} and Ti^{4+} (see, e.g., Krebs and Maisch, 1971; Ferguson and Fielding, 1971 and 1972; Schmetzer and Bank, 1980; Moon and Phillips, 1994). In rare cases, however, an additional

absorption trend, beginning at about 700 nm and extending into the near-infrared region as a result of $\text{Fe}^{2+} \leftrightarrow \text{Fe}^{3+}$ charge transfers (Krebs and Maisch, 1971; Ferguson and Fielding, 1971 and 1972; Schmetzer and Bank, 1980), may become more intense (figures 24 c and d). Very strong Fe^{3+} absorption features at 375 and 387 nm, which are considered typical for sapphires associated with basaltic rocks (see figure 24e, the spectrum of a sapphire from Antanifotsy, in central Madagascar), were not observed in the Andranondambo sapphires. For comparison, the absorption spectra considered typical for sapphires from Kashmir, Burma (Myanmar), and Sri Lanka are presented in figure 25.

Chemical Analysis. Table 2 gives the (semi-quantitative) EDXRF results for trace and minor elements in 80 sapphires from the Andranondambo deposit and in four sapphires of basaltic origin from Antanifotsy, central Madagascar.

Compared to the sapphires from Kashmir, which are associated with pegmatite intrusions (Levinson and Cook, 1994), and those from Myanmar and Sri Lanka, which are of metamorphic origin, the Andranondambo “skarn sapphires” have similar $\text{Fe}_2\text{O}_3 + \text{TiO}_2$ and $\text{V}_2\text{O}_5 + \text{Cr}_2\text{O}_3 + \text{MnO} + \text{Ga}_2\text{O}_3$ contents (although the latter may have a slightly broader range of variability; these figures are based on preliminary data from an ongoing Gübelin laboratory research project). The main difference between

Figure 23. It was not uncommon in the Madagascar sapphires to see minerals like this calcite crystal accompanied by a tube-like inclusion. Magnified 40 \times .



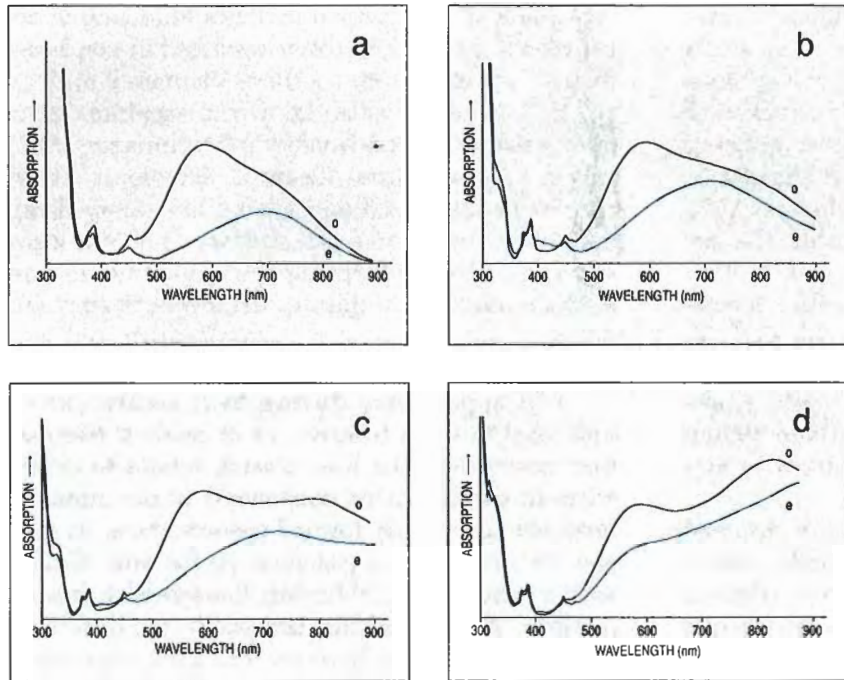


Figure 24. These are the most common absorption spectra recorded in the Andranondambo sapphires: (a) non-heat-treated; (b) heat treated and some non-heat-treated material; and (c) and (d) heat treated with dominant Fe^{2+} \leftrightarrow Fe^{3+} charge-transfer absorption in the near-infrared. Spectrum (e) was recorded from a "basaltic" sapphire from Antanifotsy, central Madagascar; it shows a typical strong Fe^{3+} absorption in the ultraviolet at 375 and 387 nm.

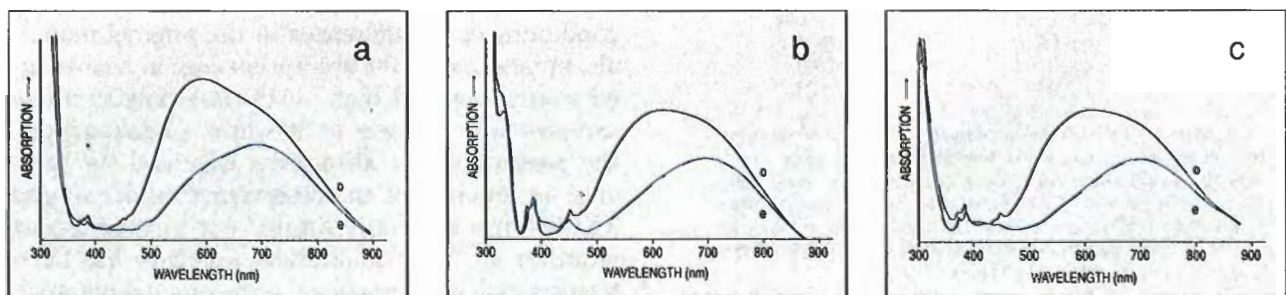
these and the basalt-associated Antanifotsy sapphires lies in the iron concentration, which is higher for the sapphires found in basaltic deposits. We did not see any definite correlations (for example, higher Ti contents where Fe concentrations are higher) in the Andranondambo sapphires. Also, there was no evidence of a simple correlation between iron content and color intensity.

DISCUSSION

Geology and Occurrence. The Andranondambo deposit—like the occurrences in Kashmir, Myanmar, and probably Sri Lanka—results from metamorphic conditions. The sapphires of the Andranondambo mining region in southeast Madagascar were

formed in U-Th skarns that belong to the Pan African granulitic formations. Rakotondrazafy et al. (1996) defined two main stages of crystallization in the skarns: The minerals aluminous diopside, CO_3 -scapolite, titanite or spinel, and thorianite/uraninite—as well as corundum—are characteristic of stage 1; one of the main mineral reactions of stage 2 is the crystallization of hibonite at the expense of corundum and spinel. Many of the Andranondambo sapphires are well-developed crystals (figure 8), which often show interesting dissolution features at their surfaces. The dissolution phenomena are the result of changes in the mineralogic environment during stage 2 of skarn metasomatism.

Figure 25. The three spectra shown here are typical for (a) Kashmir, (b) Burma (Myanmar), and (c) Sri Lankan blue sapphires.



The mineral inclusions in the Andranondambo sapphires—predominantly Ca minerals, especially calcite—reflect the nature of the surrounding metamorphic carbonate and calc-silicate host rocks and the paragenesis of these sapphires. Other minerals found in sapphires from this deposit include: apatite, feldspar (plagioclase and K-feldspar), phlogopite, Mg-hornblende, pyroxene (hedenbergite), rutile, Ca- and K-silicates, spinel, thorianite/uraninite, and sulfide. The following minerals related to sapphire genesis were identified in sapphire-bearing rock samples obtained at Andranondambo for this study: calcite, anorthite, wollastonite, phlogopite, hibonite, scapolite, pyroxene, K-feldspar, and amphibole. Behier (1960) also described spinel as occurring with sapphire in the Andranondambo area.

The lack of a continuous increase or decrease in the color intensity of the growth bands evident in most of the Andranondambo sapphires (figures 10–12) means that there was no continuous increase or decrease in the coloring agents present in the nutrient fluid during crystal growth. Rather, the sequences of alternating color zones indicate a multi-stage growth with the several growth phases characterized by changes in the genetic environment (e.g., variations in the composition of the nutrient).

Comparison to Sapphires from Other Localities.

Most of the Andranondambo sapphires that reach the gem market are heat treated. The fine-grained bands induced by heat treatment in the Andranondambo sapphires are not exclusive to this locali-

ty. Clouds of fine-grained particles following internal growth planes have been described in non-heat-treated sapphires from southern Vietnam (Smith et al., 1995). They are also known in sapphires from other basaltic sources (Kiefert and Schmetzer, 1987) and in sapphires from Kashmir (Schwieger, 1990) and Sri Lanka (based on Gübelin laboratory data). Because of their very small size, we could not identify the particles forming the HT-bands in the Andranondambo samples to determine if they are different from those seen in non-heat-treated sapphires from other deposits.

The appearance during heat treatment of unhealed tension fissures, or of healing fissures that extend into the host crystal, relates to differences in the expansion coefficients of the minerals involved. The newly formed fissures show, in general, two modes of appearance: (a) flat and circular with a "seam"; and (b) healing fissures with frosted textures. At the Gübelin laboratory, we have also seen both types in heat-treated sapphires from other sources. The absence of such fissures, as well as the presence of negative and/or mineral crystals that do not show evidence of rupture or other damage, provide good indication that a cut stone has not been subjected to heat treatment (figure 26).

Non-heat-treated samples, in general, show absorption spectra (figures 24 a and b, respectively) that are similar to those of Kashmir sapphires or, more rarely, to sapphires from Myanmar (figure 25). In the first case, the absorption edge is normally positioned at higher values ($\alpha \sim 320\text{--}335\text{ nm}$; $e \sim 320\text{--}340\text{ nm}$), compared to sapphires from Myanmar or Sri Lanka (again, see figure 25).

The heat-treatment process influences the absorption behavior of Andranondambo sapphires. However, the appearance of the absorption shoulder at about 320–330 nm cannot automatically be related to heat treatment, both because the absorption shoulder was not seen after treatment in many samples and because the shoulder was observed in some unheated stones (figure 24b). This variable absorption behavior may be due to different heating conditions or to differences in the original materials. In most cases, the absorption edge in heat-treated stones was still high (>315 nm); only in a few samples was it lower (< 305 nm). Consequently, the position of the absorption edge and the presence (or absence) of an absorption shoulder around 320–330 nm is of only limited use in establishing whether an Andranondambo sapphire has been heat treated. In comparison to the original material,

TABLE 2. EDXRF analyses of trace and minor elements in sapphires from the skarn-associated Andranondambo deposits and the basalt-associated Antanifotsy deposits.

Oxide	Content (wt.%)	
	Andranondambo ^a	Antanifotsy ^b
Fe ₂ O ₃	0.12–0.61	1.80–2.09
TiO ₂	0.01–0.10	0.04–0.08
Ga ₂ O ₃ ^c	0.01–0.04	0.01–0.02
V ₂ O ₅	< 0.01	< 0.01
Cr ₂ O ₃	< 0.01	< 0.01
MnO	< 0.01	< 0.01

^a Concentration ranges in 80 samples from the Andranondambo deposits.

^b Concentration ranges in 4 samples from the Antanifotsy region.

^c In 10 synthetic sapphires from Kyocera, examined by the senior author, the Ga concentration was < 0.01 wt. % (Ga₂O₃); in eight Seiko synthetic sapphires and in 36 Chatham flux-grown blue and orange synthetic sapphires, the Ga contents were below the detection limit of about 0.005 wt. % (Ga₂O₃) (see also Schrader and Henn, 1985).

the broad absorption bands in the 500–800 nm range do increase as a result of heat treatment. Empirical experience at the Gübelin Laboratory indicates that, in general, the absorption spectra of heat-treated Andranondambo sapphires are more similar to those of most Sri Lankan sapphires (when no absorption shoulder is present; see figure 25) or of Burmese sapphires (when a pronounced shoulder is developed; see figure 25). Whereas the absorption spectra of some Andranondambo sapphires (figures 24c–d) in the 500–800 nm range resemble those of sapphires originating from basalt-associated deposits, the Fe^{3+} absorption in the ultraviolet, at 375 and 387 nm, is never as intense as in typical basaltic sapphires (figure 24e).

The concentrations of Fe, Ti, and Ga in the Andranondambo sapphires sometimes reach values higher than those that are considered typical of sapphires from the metamorphic deposits in Myanmar and Sri Lanka (up to 0.61 wt.% Fe_2O_3 , 0.10 wt.% TiO_2 , and 0.04 wt.% Ga_2O_3). The iron contents of the Andranondambo sapphires, however, are lower than those measured in the four (basaltic) Antanifotsy sapphires, but they may overlap those of sapphires from other basaltic deposits (compare, e.g., Guo et al., 1992; Smith et al., 1995). The chemical behavior of the Andranondambo sapphires is probably related to the special genetic conditions that exist during skarn metasomatism.

The range of mineralogical and gemological properties shown by Andranondambo sapphires is relatively broad, but within this range are specimens with spectral and chemical characteristics as well as internal features similar to those of sapphires from Sri Lanka, Myanmar, and even Kashmir.

Internal features of non-heat-treated Andranondambo sapphires that resemble those of Sri Lankan or Kashmir sapphires include prismatic amphibole crystals; black, cube-like grains; colorless, irregularly rounded crystals; and short rutile needles. However, in our sample, we did not see the long, fine rutile needles that are typical for Sri Lankan sapphires (compare Gübelin, 1973; Webster, 1983; Anderson, 1990), or the nests/bands of short, dull rutile needles that are more common in Burmese sapphires (Gübelin, 1973). Nor did we see those internal features that are most typical of Kashmir sapphires (the velvety appearance that is caused mainly by clouds, lines, strings, and flake-like arrangements of dust-like inclusions; or the association of zircon, tourmaline, pargasite, plagioclase, allanite, uraninite [compare Schwieger, 1990]).



Figure 26. This 0.24 ct sapphire from southern Madagascar shows no evidence of rupture of the fluid inclusion or stress cracking around the small solid inclusions. This suggests that the stone was not subjected to high-temperature heat treatment. Stone courtesy of I. Z. Eliezri; photomicrograph by John I. Koivula, magnified 30 \times .

After heat treatment, many Andranondambo sapphires lack specific inclusion features. Small stones (< 1 ct) may be quite clean, even when examined with the microscope. For such stones, growth characteristics are of little or no diagnostic value, and identification should be based on absorption spectra and chemical data. It appears that the reaction to UV radiation is a useful additional test to separate the Andranondambo sapphires from their Sri Lankan counterparts. Sri Lankan sapphires very often show quite strong red or orange-red fluorescence to long-wave UV-radiation.

The properties for the few samples from Antanifotsy appear to be consistent with sapphires from other basaltic deposits (see, e.g., Kiefert and Schmetzer, 1987). The distinction between these basaltic sapphires and the Andranondambo sapphires is relatively easy based on the inclusion features, absorption spectra (figures 24a–e), and chemical properties (table 2).

Separation from Synthetic Sapphires. Andranondambo sapphires can be fairly easily separated from synthetic blue sapphires grown by different methods. The synthetics (Verneuil, Chatham, Kyocera, Seiko) normally have very little or no Ga (see the

footnote to table 2). In addition, most of the internal features seen thus far in Andranondambo sapphires are quite different from those observed in laboratory-grown sapphires (compare, e.g., Kane, 1982; Gübelin, 1983).

CONCLUSIONS

The appearance and properties of the sapphires from the Andranondambo deposit are related to the metamorphic geologic (skarn) environment in which these sapphires formed. Some Andranondambo sapphires, at least in some aspects, resemble sapphires from Sri Lanka, Myanmar, or Kashmir. On the one hand, non-heat-treated stones revealed some inclusions that are similar or almost identical to those seen in some Sri Lankan or Kashmir sapphires. On the other hand, many (heated and not-heated) Andranondambo sapphires showed "Burma-type" absorption spectra. In most cases, however, these Madagascar stones could be separated from sapphires of other localities by means of, in addition to inclusion features, absorption spectra in combination with chemical data.

The separation of heat-treated from non-heat-treated Andranondambo sapphires is easy when the so-called HT-bands are present. Additional features that indicate that the stone has been heat treated are changes observed in the appearance of many inclusions and, to some extent, the absorption spectra.

Although some internal features of Andranondambo sapphires may be similar to those observed in certain synthetic sapphires (especially the healing fissures in heat-treated Andranondambo stones and those seen in flux-grown synthetics), the overall inclusion scenes should make confusion unlikely. For sapphires that lack (typical) inclusions, a quite reliable separation is possible based on Ga content: The known synthetic sapphires have very little or no Ga, whereas the Madagascar stones can have quite high Ga values.

Precise production figures for the sapphire deposits of Andranondambo in southern

Madagascar are not available; nevertheless, we believe that thousands of kilograms of these sapphires have reached the gem market since 1992/93. For the trade, this has been important because these sapphires could, at least in part, compensate for the inconsistency of production from the traditional localities. In addition, a certain percentage of the Andranondambo material represents an alternative to "Burma-type" sapphires, and some stones have even been compared to Kashmir sapphires. As the relatively recent discovery of sapphires at the Antsiermene perimeter, less than 12 km north of Andranondambo, indicates, the regional geologic conditions in this part of the island favor the occurrence of other skarn-associated sapphire deposits.

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