
SAPPHIRES FROM ANTSIRANANA PROVINCE, NORTHERN MADAGASCAR

By Dietmar Schwarz, Jan Kanis, and Karl Schmetzter

Since 1996, large quantities of yellow to blue sapphires have been recovered from alluvial deposits derived from basaltic rocks in northern Madagascar. The crystal morphology, internal growth patterns, mineral inclusions, absorption spectra, and trace-element contents of these northern Madagascar sapphires are typical of "basaltic-magmatic" sapphires. Comparison of the properties of these sapphires to those of sapphires from different basaltic sources reveals no significant differences. The northern Madagascar sapphires are distinct from those from Andranondambo, a skarn-related deposit in southeastern Madagascar.

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Madagascar was first visited by Europeans in 1500, when the Portuguese navigator Diego Diaz landed at a beautiful and well-protected bay on the northern tip of the island. Another Portuguese seafarer, Hernán Suárez, was sent to Madagascar by the Viceroy of India and also landed at this bay, in 1506. Thereafter, the name *Diego Suárez* was adopted for both the bay and the nearby town. Although the town has recently reverted to its Malagasy name, Antsiranana, many in the gem trade continue to use the old name when referring to sapphires from northern Madagascar (figure 1), which have been mined there since the mid-1990s.

The principal deposits are actually situated about 70 km south of Antsiranana, in the Ambondromifely region in and near the Ankarana Special Reserve (figure 2), in Antsiranana Province. Elsewhere in northern Madagascar, sapphires have been found near Ambilobe and Milanoa (Superchi et al., 1997), which are located about 40 km and 100 km, respectively, south of Ambondromifely. The properties of all of the samples from these areas are consistent with those of "basaltic-magmatic" sapphires that are known from eastern Australia, Nigeria, Thailand, Laos, and Cambodia. These sapphires are generally blue-violet, blue, greenish blue, greenish yellow, or yellow, and thus were designated "BGY [blue-green-yellow] sapphires" by Sutherland et al. (1998a).

So far, only limited gemological data on the sapphires from northern Madagascar have been published (see, e.g., Superchi et al., 1997; Schwarz and Kanis, 1998). This article presents a more complete gemological and mineralogical description of this material.

HISTORY

Until fairly recently, sapphire occurrences in Madagascar were mentioned only occasionally in the literature. A few years ago, however, attractive blue sapphires were discovered at Andranondambo, in the southeastern part of the



Figure 1. Basalt-associated sapphire deposits were discovered in the Antsiranana Province of northern Madagascar in 1996. The blue-violet, blue, and greenish blue to greenish yellow colors shown here (1.04–2.98 ct) are typical of these sapphires; some exhibit distinct color zoning (see inset, 8.25 and 3.26 ct). Courtesy of Menavi International Ltd.; photo by Maha Tannous.

island, approximately 90 km northeast of Tolanaro/Fort Dauphin (Schwarz et al., 1996; Kiefer et al., 1996; Milisenda and Henn, 1996; Gübelin and Peretti, 1997; figure 2, inset). During the years following the Andranondambo "rush," other deposits were discovered in the same region.

In 1996, blue-violet, blue, greenish blue, greenish yellow, and yellow (BGY) sapphires were discovered near Ambondromifehy (Bank et al., 1996; Lurie, 1998). A parcel of sapphires from this new area was first examined by one of us (KS) in June of that year. Later, numerous parcels became available for testing, and several brief articles were published (Bank et al., 1997; Superchi et al., 1997; Gonthier, 1997; Schwarz and Kanis, 1998).

The Ambondromifehy deposit soon became one of the most productive sources of commercial-quality sapphire in the world ("Sapphire mining halted. . .," 1998). When the potential of the region became known, several thousand miners abandoned the Andranondambo area and migrated north to Ambondromifehy. During a brief visit there in July 1997, one of us (JK) saw thousands of miners digging sapphires west of the main road, No. 6, approximately 2.5 km southwest of Ambondromifehy village. By early 1998, about 10,000 diggers were active in the area (Lurie, 1998; "Sapphire mining halted. . .," 1998). Nigerian and Thai buyers purchased much of the daily sapphire production.

Unfortunately, much of the digging occurred within the borders of the 18,225 hectare Ankarana Special Reserve (figure 2), a nature reserve well known for its magnificent karst topography. The

World Wildlife Fund for Nature (WWF), which had been involved in managing the reserve since 1985, pressured the Malagasy government to stop the illegal mining. The government's solution was to prohibit all mining and commerce in sapphires from northern Madagascar, beginning in mid-April 1998. This comprehensive ban was applied to activities both within and outside the reserve (Lea, 1998; Lurie, 1998; "Sapphire mining halted. . .," 1998). However, because the government lacked the means to enforce this decision, the illegal mining and buying continued. Recognizing its failure to halt these activities, the government officially lifted the ban on August 17, 1998 (Holewa, 1998; Banker, 1998).

With the October 1998 discovery of attractive sapphire, ruby, and other gems west and south of the Isalo National Park (i.e., near Ilakaka, Sakaraha, and Ranohira; see, e.g., Johnson et al., 1999; Schmetzer, 1999a; figure 2, inset), many miners moved from the Ambondromifehy region to these extensive new alluvial deposits. By spring 1999, almost no mining activity was observed in Antsiranana Province (Schmetzer, 1999a), although some of the miners subsequently returned to the area when they could not obtain productive claims in the Ilakaka region (Laurs, 2000).

LOCATION AND ACCESS

The Ambondromifehy sapphire deposits are located at 12°54'S, 49°12'E (Carte topographique Ambilobe, 1:100,000, feuille U 32). The main road (RN6) from Antsiranana to Ambondromifehy is an all-weather

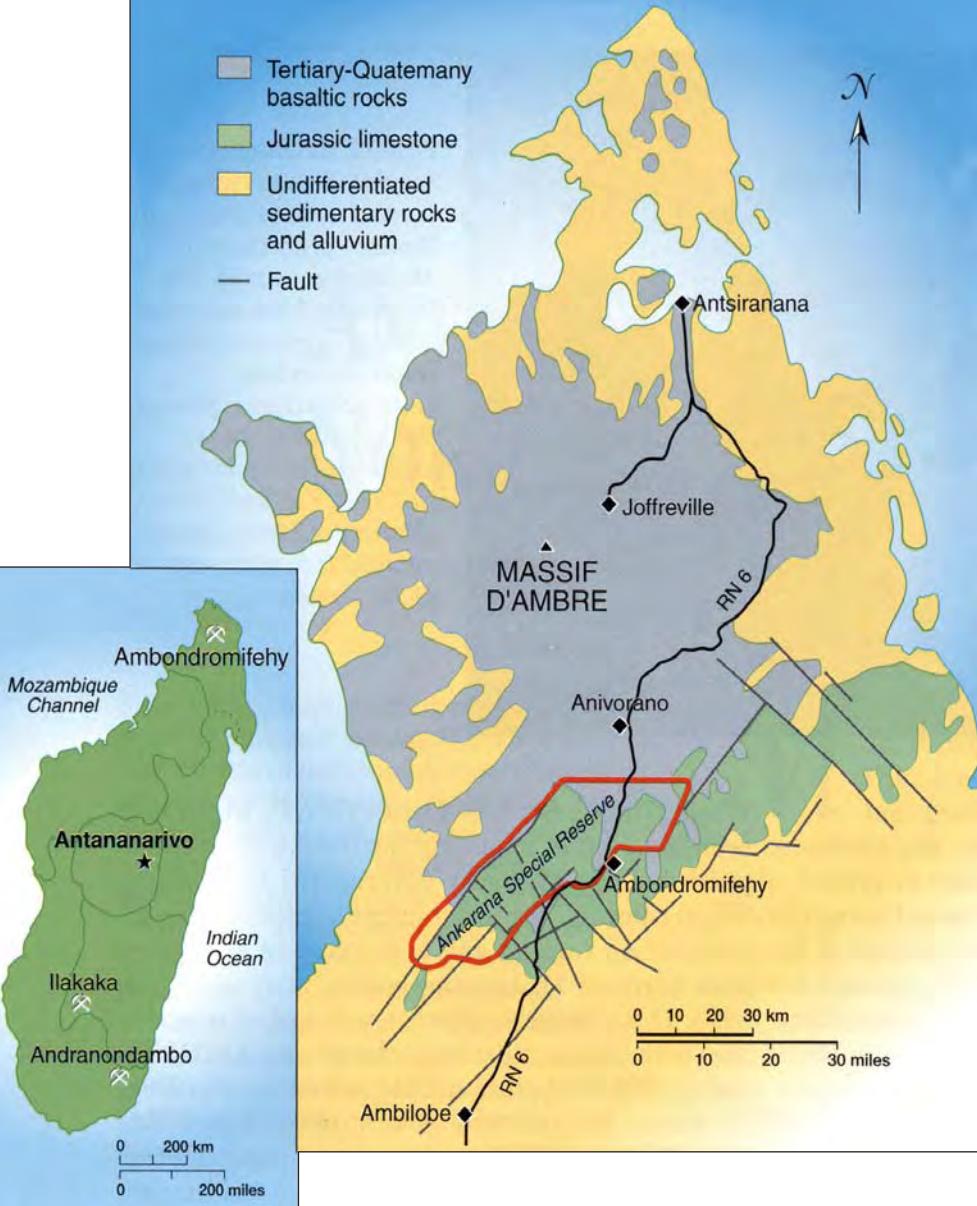


Figure 2. The most important sapphire deposits in Antsiranana Province, at the northern tip of Madagascar, are located in the Ambondromifehy region in and near the Ankarana Special Reserve. These deposits are associated with basalts of the Massif d'Ambre volcano. Erosion of the basalts deposited sapphire-bearing sediments on nearby limestones, particularly in the Ambondromifehy region. Other basalt-related sapphire deposits are located up to 100 km further south, near Ambilobe and Milaoa (not shown on the map). Geology after Saint-Ours and Rerat (1963), Saint-Ours et al. (1963), and Besairie (1969). The inset shows the location of the three major sapphire deposits in Madagascar: Ambondromifehy, Andranondambo, and Ilakaka.

paved road. It is not difficult to reach the various deposits from the main road on foot, although for safety reasons visitors should always be escorted by a reliable guide. One author (JK) noticed that the sapphire dealers are particularly unwelcoming to unescorted foreigners for fear of competition.

Diggers use local names to indicate the various sites where they work. For example, the occurrence visited by JK in 1997 is called Antokotaminbato, which is located approximately 2.5 km southwest of Ambondromifehy on the main road.

GEOLOGY AND OCCURRENCE

Corundum deposits related to alkali basalts are common in many regions—especially eastern Australia and Southeast Asia, but also Nigeria (Kanis and Harding, 1990). The origin of these rubies and sapphires has been widely debated among geologists and mineralogists (for a summary, see, e.g., Levinson and Cook, 1994; Sutherland et

al., 1998a). The alkali basalts are thought to carry the corundum crystals to the surface from the earth's interior, where they formed. Note, however, that different sources of gem corundum may be entrained by the basaltic magmas. New studies have shown that some basaltic fields (e.g., in Australia, Cambodia, Laos, and Thailand) yield two types of corundum: the “basaltic-magmatic” (hereafter, *magmatic*)—or BGY—sapphires are found together with “basaltic-metamorphic” (hereafter, *metamorphic*) pastel-colored sapphires and rubies. The latter gems are thought to be derived from metamorphic or metasomatic source rocks in the earth's interior. The two types of basalt-hosted sapphires can be identified by trace-element chemistry and/or absorption spectroscopy (Sutherland et al., 1998a and b).

Northern Madagascar is mostly covered by a 3,500 km² area of volcanic origin (again, see figure 2) that dates from the early Tertiary period to the

Quaternary. The 35-km-wide stratovolcano, the Massif d'Ambre, is constructed of alternating layers of lava and pyroclastic deposits along with abundant dikes and sills. Beneath the summit (which reaches 1,475 m above sea level), the mountain slopes gently from 800 m to 500 m into the surrounding flat plains. The sources of all major rivers in the region are found on the slopes of the Massif d'Ambre, and they have undoubtedly affected the formation of placer sapphire deposits.

Sapphire-bearing alluvial material derived from the eroded alkali basalts was deposited in voids and crevices of the weathered Jurassic Ankarana limestone that lies south of the Massif d'Ambre. Occasionally, these sediments are cemented by secondary carbonates (figure 3). Recent prospecting has failed to locate any sapphire-bearing basalt flows, perhaps because they lie buried beneath subsequent barren lava flows or were fully eroded in the area ("An initial appraisal . . .," 1997).

MINING AND PRODUCTION

The local miners dig pits up to 8 m deep to reach the sapphires, which are concentrated in the lower levels of the alluvium. The areas around the roots of the trees (mainly bamboo in this region) are also favorable sites, because the greater decomposition of the soil makes digging easier (figure 4). Mechanized mining has been conducted by only two companies, which set up operations outside the Ankarana reserve (see, e.g., figure 5). Significant quantities of commercial-grade sapphire were pro-

Figure 3. Sapphire crystals from northern Madagascar are occasionally found embedded in carbonate-cemented sediments. The dark blue sapphire shown here measures 14 mm long. Photo by M. Glas.

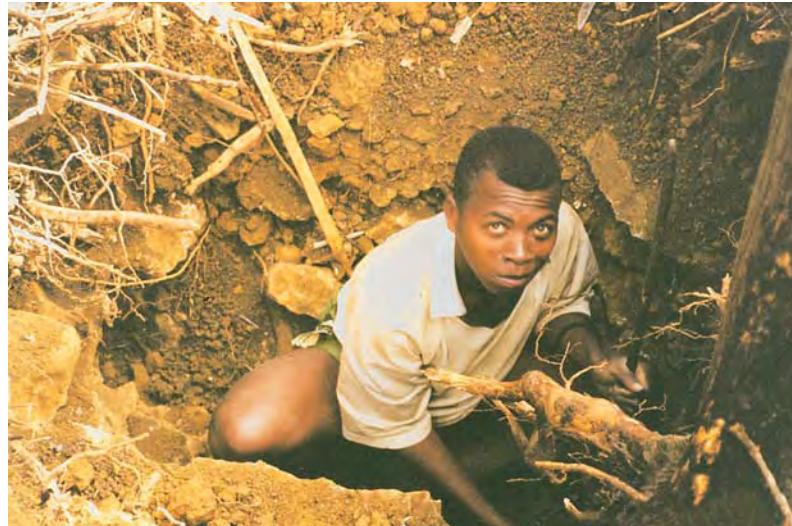


Figure 4. Miners at Ambondromifehy have found that digging around the roots of trees is the easiest way to recover sapphires. Photo by J. Kanis.

duced by these operations (see, e.g., figure 6). One of these, IMA Group/Suzannah, produced over 350 kilograms of corundum during the years 1996-1998, of which generally 12%-16% was facetable (Issac Mehditash, pers. comm., 2000).

An indication of the amount and quality of sapphires produced from one of these mines (ABFG) is given in box A. Heating is required for all but a very small percentage (usually <5%) of the rough gem sapphires from Ambondromifehy. Typically, heat treatment is applied to remove milky areas and to develop a blue to blue-violet color in unattractive white, yellowish green, or greenish yellow samples. The temperature, time, and gas atmosphere must be strictly controlled to prevent the sapphires from becoming too dark.

MATERIALS AND METHODS

The total sample set consisted of more than 1,000 BGY sapphire crystals, about 250 faceted sapphires, and 80 star (cabochon-cut) sapphires. From this large group, we selected the samples that were tested by the various methods described below.

All the sapphires were purchased in Madagascar by several gem dealers or by one of the authors (JK). No samples from trade centers outside Madagascar (e.g., Bangkok) were included in the study. The samples reportedly came from the Ambondromifehy region, which is the center of sapphire mining activity in northern Madagascar. However, the parcels also may have included magmatic sapphires from other sources within Antsiranana Province, as dealers



Figure 5. At this mechanized operation in the Anivorano area (the "M4" pit), a track-hoe dumps sapphire-bearing alluvium into a trommel (right). The gem-bearing gravel is then pumped from the small pit on the left to a nearby washing plant (see inset). Photos courtesy of Mega Gem s.a.r.l.

typically mix sapphires from different producers in a single parcel.

The fashioned samples were cut in Madagascar. The authors polished one or two windows on about 100 of the rough crystals to facilitate testing. The faceted stones reportedly had not been subjected to heat treatment before examination. However, one of us (KS) treated about 500 of the crystals to study

the effects of heating. These crystals were originally milky white, greenish yellow, and greenish blue. Details of the heat treatment process used are proprietary.

About 30 faceted samples and crystals with polished windows (which represented the full range of colors available) were tested by standard gemological methods for optical properties, fluorescence, and density (hydrostatically). Morphological and crystallographic features of about 100 crystals were determined with a standard goniometer. The inclusion features and internal growth structures (i.e., color zoning and growth planes) of about 70 faceted and 30 rough sapphires were examined with a horizontal microscope using an immersion cell. Solid inclusions were identified by laser Raman microspectrometry with a Renishaw Raman microprobe or a Philips XL 30 scanning electron microscope equipped with an energy-dispersive spectrometer (SEM-EDS).

Polarized ultraviolet-visible-near infrared (UV-Vis-NIR, 280 to 880 nm range) absorption spectra were recorded for 15 rough and 15 faceted natural-color sapphires (again, all colors; selected from the 100 examined microscopically above)—and approximately 30 heat-treated rough sapphires before and after treatment—with Leitz-Unicam SP 800 and Perkin Elmer Lambda 9 spectrophotometers. The orientation of the rough samples was determined in accordance with their external morphology. For the faceted sapphires, we selected only those samples with table facets that were oriented perpendicular to the c-axis, which produce the most accurate polarized spectra. For 10 samples selected on the

Figure 6. The rough sapphires are hand-sorted on light tables into separate quality and size categories. These parcels, totaling approximately 50 kg, were produced from the "M4" pit. Photo courtesy of Mega Gem s.a.r.l.



BOX A:

SAPPHIRE PRODUCTION FROM THE ABFG MINE, AMBONDROMIFEHY AREA

Compiled by M. Sevdermish, MENAVI International, Ramat Gan, Israel

At the time of this contributor's visit in mid-1999, the ABFG mine was a small mechanized operation located about 16 km south of Anivorano, close to the border of the Ankarana Special Reserve. An excavator and a water cannon were used to transport the gem-bearing soil into jigs, where the heavy components were separated and collected. Final sorting of the concentrate was done by hand.

The operation typically extracted 3-5 kg of sapphires in a 10-hour shift. Only about 17% of the rough produced was usable for heat treatment and cutting (table A-1). The color distribution of the original, untreated rough was reminiscent of Australian rough:

- 35% very milky bluish green (very few pieces are facetable after heating; most are low quality to cabochon, too dark)
- 30% very milky, almost opaque very dark blue (too dark after treatment)
- 23% transparent very dark blue, some with green or yellow zoning (nearly black after treatment)
- 5% pale gray or greenish blue and transparent (pale-colored crystals with small patches or zones of blue or green sometimes resulted in fine blue gems after treatment)
- 5% pale blue, milky (produced medium- to fine-quality gems after treatment, usually less than 1 ct after faceting)
- 2% other colors: yellow, "oily" green, and bicolored (most do not react to heating, but some "oily" green stones became almost black)

After the rough was sorted and cleaned, all samples of sufficient clarity and with a potentially suitable color were heat-treated. Virtually none of the rough produced from the ABFG mine was suitable for cutting before heat treatment. After each careful-

TABLE A-1. Characteristics of rough sapphires from the ABFG mine, before heat treatment.

Average weight (grams)	% of production	% cuttable	Cuttable as a % of total
>1	11	5-10	1
0.5-1.0	16	10-15	1.6
0.2-0.5	30	15-20	5
0.1-0.2	40	20-25	8
<0.1	3	25-30	1
Total	100		16.6

ly performed heating run (all treatment was conducted outside Madagascar), the sapphires were again sorted and some were removed for further heating. Up to 10 heat treatments at different atmospheric and temperature conditions may be necessary to achieve cuttable rough. The color distribution of the sapphires from the ABFG mine after heat treatment was as follows:

- 5% fine blue
- 30% medium blue
- 30% medium blue with greenish overtone
- 15% dark blue-violet, similar to dark Australian sapphires
- 5% greenish yellow
- 15% not usable (heavily included and/or uneven color distribution)

The weight and yield distribution of stones faceted from the treated rough are shown in table A-2.

In summary, about 5 kg of rough sapphire from this mine would be expected to yield 900 carats of faceted stones; this corresponds to a total yield from the rough of 3.6%. As of mid-2000, mechanized mining at ABFG had been halted.

TABLE A-2. Weight and yield distribution of heat-treated sapphires from the ABFG mine.

Weight category (grams)	Usable rough from total production (%)	Yield of faceted material from usable rough (%)	Average ct weight of faceted stones	Yield from 5 kg of rough (ct)
>0.5	2.6	16	1.0	100
0.2-0.5	5	18	0.3	350
<0.2	9	20	0.1	450

basis of their visible-range absorption spectrum, we also measured polarized spectra in the IR region up to 1800 nm using the Perkin Elmer Lambda 9 spectrophotometer.

The chemical composition of 137 rough (with at least one polished window) and fashioned samples, representing all color groups and the asteriated stones, was analyzed by energy-dispersive X-ray fluorescence (EDXRF) spectroscopy. These analyses were performed with a Tracor Northern Spectrace 5000 system, using a program specifically developed for trace-element geochemistry of corundum by Prof. W. B. Stern, Institute of Mineralogy and Petrography, University of Basel. These data were compared to EDXRF results of Schwarz et al. (1996) for sapphires from Andranondambo, Madagascar.

RESULTS

The results are summarized in table 1 and discussed below.

Visual Appearance. The natural-color Ambondromifehy sapphires (as they will be referred to in this section, although some may be from other deposits in Antsiranana Province) spanned a wide range of hues: blue-violet and various shades of blue, greenish blue, greenish yellow, and yellow (figures 7 and 8). One lot of 50 greenish yellow sapphires subjected to heat treatment showed almost no reaction, but the remaining 450 samples became a significantly more attractive blue-violet to blue. The greatest difficulty encountered during heat treatment was in making the crystals more trans-

TABLE 1. Gemological characteristics of sapphires from Antsiranana Province, Northern Madagascar.

Property ^a	No. samples	Description
Color	ca. 1,300	Homogeneous coloration (i.e., blue-violet, blue, greenish blue, greenish yellow, or yellow) is rare. More common is distinct color zoning with blue-violet, greenish blue to greenish yellow, and yellow low domains. Also bi- and tri-colored stones ^b .
Clarity	ca. 1,300	Very clean to fairly included. Many natural-color stones show translucent milky white or blue areas; some stones are completely translucent. Heating usually improves transparency.
Refractive indices	30	$n_e = 1.761\text{--}1.765$ $n_o = 1.769\text{--}1.773$
Birefringence	30	0.008
Optic character	30	Uniaxial negative
Specific gravity	30	3.99–4.02
Pleochroism	ca. 100	Yellow: Light yellow \parallel c-axis, slightly more intense yellow \perp c-axis (i.e., almost no pleochroism) Greenish blue: Yellow \parallel c-axis, blue to blue-violet \perp c-axis Intense blue to blue-violet: Blue \parallel c-axis, blue-violet \perp c-axis Greenish yellow to yellowish green: Greenish yellow to yellow-green \parallel c-axis, blue to blue-violet \perp c-axis
Fluorescence	30	Inert to long- and short-wave UV radiation
UV-Vis absorption spectra	60	Intense bands at 376, 388, and 450 nm in yellow sapphires. Blue and greenish blue sapphires also show intense bands with maxima at about 560 nm (\perp c > \parallel c), and at about 870–880 nm (\perp c > \parallel c). Greenish yellow to yellowish green sapphires have an additional weak absorption band at 542 nm (\parallel c > \perp c).
Internal features	100	<ul style="list-style-type: none"> • Often strong color zoning. • Growth patterns <ul style="list-style-type: none"> (1) Looking \perp c-axis: Either ω or z with n and c; combination of c with r; occasionally, oscillatory zoning between hexagonal dipyramids (e.g., ω and z) (2) At an inclination of 5°–10° to c: Characteristic pattern of ω or z faces (3) At about 30° to c-axis: Characteristic structure of two n faces and one r face. • Occasionally, lamellar twinning parallel to r.
Inclusions		<ul style="list-style-type: none"> • Mineral inclusions: Most common in unheated samples are mineral grains surrounded by a discord fissure with flattened two-phase (liquid-gas) inclusions in a rosette-like pattern oriented parallel to the basal pinacoid c. • Feldspar (as "rosette mineral" or in grains), zircon (some with unoriented tension cracks), columbite (needle-like crystals with Nb > Ta), spinel (hercynite), uraninite, and unidentified mineral grains (some with "comet tails"). • Unhealed or partially healed fissures; two-phase (liquid-gas) inclusions.

^a In general, the properties of the heat-treated sapphires duplicate those of the natural-color samples. Any differences are specifically noted in the text.

^b Heat treatment under strictly controlled conditions is necessary for most Antsiranana sapphires to remove milky areas and to develop a blue to blue-violet color in unattractive white, yellowish green, or greenish yellow samples.



parent without causing them to become too dark.

Most of the sapphires—both natural color and heat treated—showed distinct color zoning, with blue-violet, greenish blue to greenish yellow, and yellow domains within a single crystal. A small number revealed homogeneous coloration in these hues. Bicolored and tricolored stones also have been cut (figure 9).

A large number of the natural-color stones had translucent milky white or blue areas; some stones were completely translucent. This “milkiness” was typically removed with heat treatment. The remainder of the material was more transparent.

The milky white, grayish white, blue, or blue-violet cabochons we examined (figure 10) showed a sharp six-rayed star. In some of these star sapphires, and at least one faceted stone, we observed a colorless to gray core that was surrounded by a milky white to blue-violet rim (figure 10, inset). With the exception of a few stones cut as a novelty for collectors, the core is typically removed during cutting. Twelve-rayed star sapphires from northern Madagascar are extremely rare (see Schmetzer, 1999b).

Figure 8. These unheated samples show the appearance of yellow sapphires from Ambondromifehy. Note the sharp blue color zones in the 5 × 7 mm stone on the lower left. Photo by M. Glas.

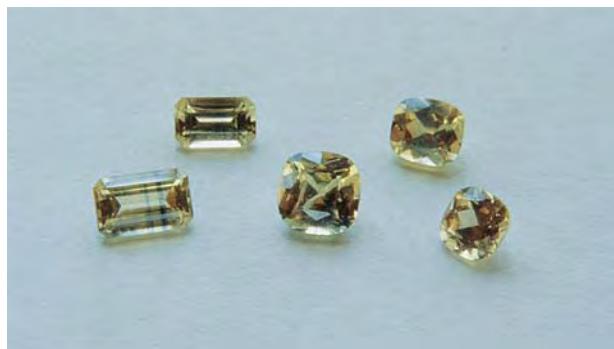


Figure 7. The Ambondromifehy area produces sapphires in a broad range of colors. These include the natural-color blue-violet and blue (left) and greenish blue (right) sapphires illustrated here. The blue-violet stone on the far left measures 8 × 10 mm; the largest greenish blue sapphire is 10 mm in longest dimension. Photos by M. Glas.



Figure 9. Prominent color zoning is shown by these particolored (yellow, greenish blue, and blue) Ambondromifehy sapphires. The stone on the far right measures about 4 × 8 mm. Photo by M. Glas.

Crystal Morphology. The sapphire crystals typically showed an elongated, barrel-shaped habit, although all were somewhat rounded and corroded. Most of the crystals were broken at both ends and revealed portions of only one hexagonal dipyramid as the dominant external form. A few samples were broken only at one end, and less than 5% of all the crystals examined were complete (i.e., with all faces intact).

In general, one of the hexagonal dipyramids ω {14 14 28 3}* or z {2241} was combined with the basal pinacoid c {0001}. Frequently, smaller faces of the rhombohedron r {1011} and of an additional hexagonal dipyramid n {2243} also were identified. Six combinations of these forms were observed (figure 11): ($c\omega$), ($c z$), ($c \omega r$), ($c z r$), ($c \omega r n$), and ($c z r n$).

Gemological Properties. For the most part, the properties of the heat-treated sapphires duplicated those of the natural-color samples. Any differences are specifically noted in the following discussion.

*Limitations in our measurement techniques did not allow us to distinguish between the two hexagonal dipyramids ω {14 14 28 3} and v {4481}.



Figure 10. Star sapphires from Ambondromifehy are commonly gray to blue. The largest cabochon here measures 9 × 10 mm. The sapphires in the inset have been cut to show the unusual cores seen in some of the samples; the faceted stone is 10 × 11 mm. Photos by M. Glas.

The densities and R.I.'s of the Andromifehy sapphires match those from other magmatic deposits. Measured densities vary between 3.99 and 4.02 g/cm³. R.I.'s range from 1.761 to 1.765 for n_e and from 1.769 to 1.773 for n_o , with a birefringence of 0.008.

Figure 11. The morphology of Ambondromifehy sapphires is dominated by hexagonal dipyramids ω or z combined with the basal pinacoid c . Additional hexagonal dipyramids n as well as rhombohedra r are also occasionally observed.



We observed four major types of pleochroic colors:

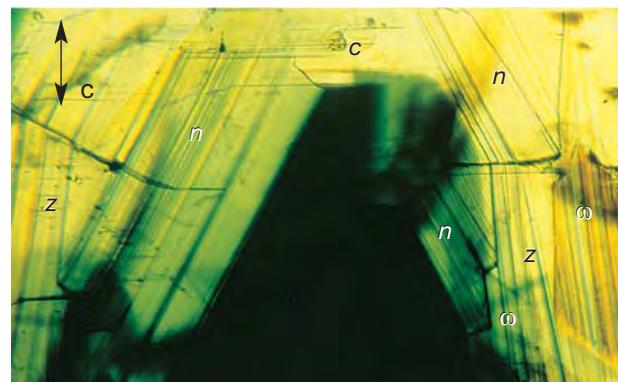
1. || c-axis light yellow, ⊥ c-axis somewhat more intense yellow, for yellow sapphires (i.e., samples with almost no pleochroism)
2. || c-axis yellow, ⊥ c-axis blue to blue-violet, for greenish blue sapphires
3. || c-axis blue, ⊥ c-axis blue-violet, for intense blue to blue-violet sapphires
4. || c-axis greenish yellow to yellow-green, ⊥ c-axis blue to blue-violet, for greenish yellow to yellowish green sapphires

The distinct color zoning shown by most of the sapphires (see, e.g., figure 9) usually consisted of a combination of two of the four pleochroic types mentioned above. In rare cases, we saw areas with three different types of pleochroism in a single color-zoned crystal.

The sapphires were inert to both long- and short-wave UV radiation.

Microscopic Characteristics. Most of the samples examined showed some fractures and two-phase (liquid-gas) inclusions, but these were not distinctive. Although many of the untreated stones showed some milkiness, no "silk" or other oriented mineral inclusions were visible in our samples at the magnification used for gemological microscopy (up to

Figure 12. This sample, viewed perpendicular to the c-axis, shows the typical growth patterns found in Ambondromifehy sapphires. Two hexagonal dipyramids ω and n are present in combination with the basal pinacoid c . Oscillatory zoning of ω with a third hexagonal dipyramid z is present in the lower right. Photomicrograph by K. Schmetzler; immersion, magnified 40×.



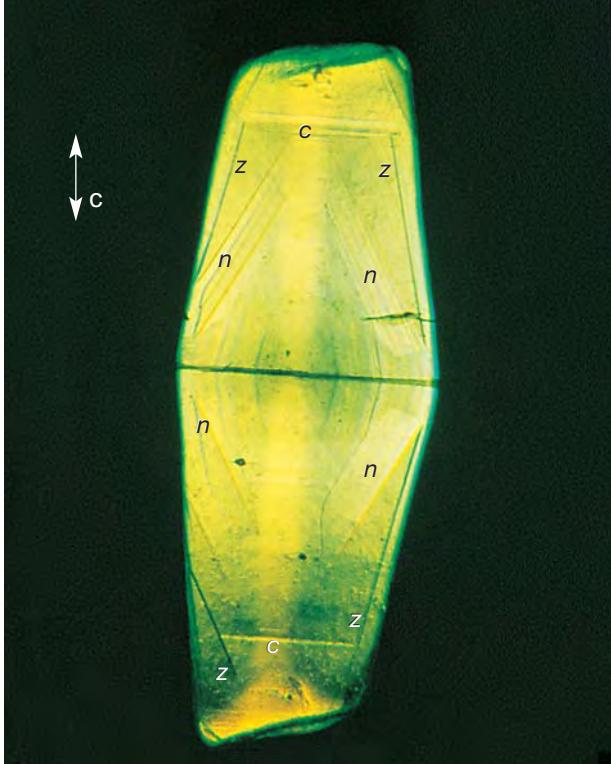


Figure 13. When viewed perpendicular to the *c*-axis, this Ambondromifehy sapphire crystal shows a first hexagonal dipyramid *n* that is overgrown by a second hexagonal dipyramid *z*; the basal pinacoid *c* is also developed. Photomicrograph by K. Schmetzer; immersion, crossed polarizers, magnified 20×.

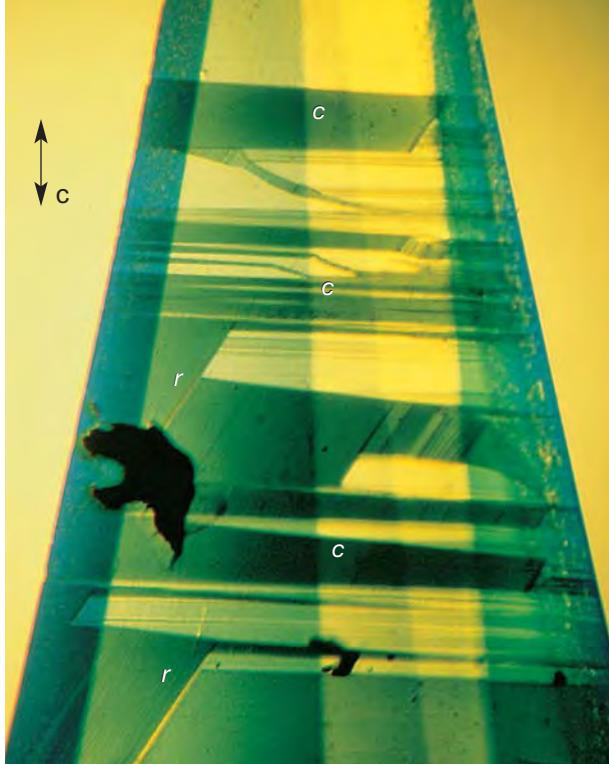


Figure 14. In this view perpendicular to the *c*-axis of a sapphire crystal from Ambondromifehy, intense color zoning is associated with the growth patterns. The positive rhombohedron *r* and basal pinacoid *c* are evident. Photomicrograph by K. Schmetzer; immersion, magnified 30×.

100×). We observed distinct mineral inclusions in only about 10%–20% of the samples examined. However, structural properties, notably specific growth features that can be used to indicate a natural origin, were found in most samples.

Growth Features. The internal growth patterns seen with immersion clearly reflect the external morphology of the samples. When the sample was observed perpendicular to the *c*-axis, two different types of morphology usually were evident (see also figure 11), that is, one of the two hexagonal dipyramids *ω* or *z* (which were dominant in the external

morphology) in combination with a third dipyramid *n* and the basal pinacoid *c* (figures 12 and 13). When viewed from another direction also perpendicular to the *c*-axis, a combination of the basal pinacoid *c* with the positive rhombohedron *r* was observed (figure 14). Occasionally, an oscillatory zoning between different hexagonal dipyramids (e.g., *ω* and *z*) is observed (again, see figure 12). Rotation of a sample through an angle of 30°, with *c* as the rotation axis, generally reveals a characteristic variation between these two frequently observed patterns (*c ω n* or *(c z n)* in one orientation, and *(c r)* in the other (figure 15). Color zoning associated with growth zoning is

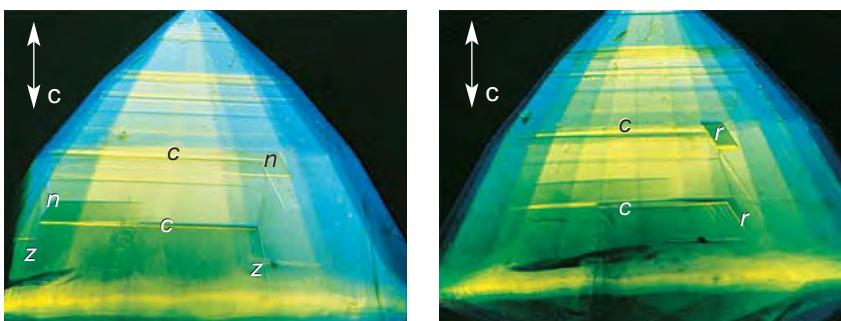


Figure 15. In these two views, a faceted Ambondromifehy sapphire has been rotated 30° around the *c*-axis. On the left, a combination of two hexagonal dipyramids *n* and *z* are present with the basal pinacoid *c*. On the right, a combination of the rhombohedron *r* with *c* is seen. Photomicrographs by K. Schmetzer; immersion, crossed polarizers, magnified 25× (left) and 30× (right).

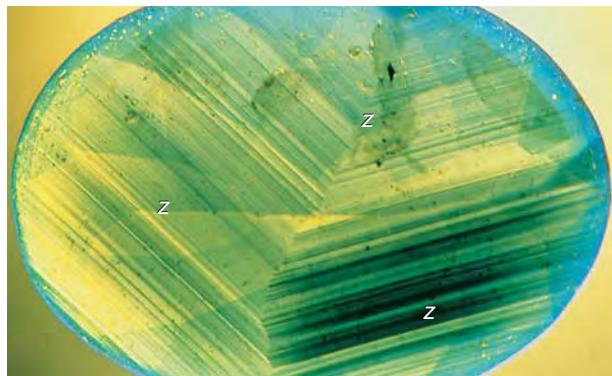


Figure 16. When inclined about 10° to the c-axis, a growth pattern consisting of several hexagonal dipyramids is normally seen in Ambondromifehy sapphires. In this case, two z faces are observed. Photomicrograph by K. Schmetzer; immersion, magnified 25x.

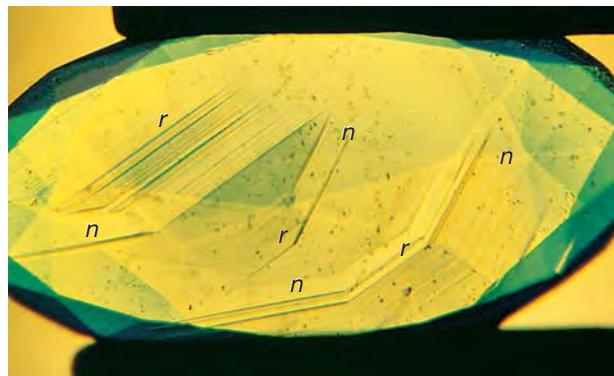


Figure 17. At an inclination of about 30° to the c-axis, the typical growth patterns seen in Ambondromifehy sapphires consist of n and/or r faces. In this orientation, a characteristic pattern (n r n) is seen. Photomicrograph by K. Schmetzer; immersion, magnified 30x.

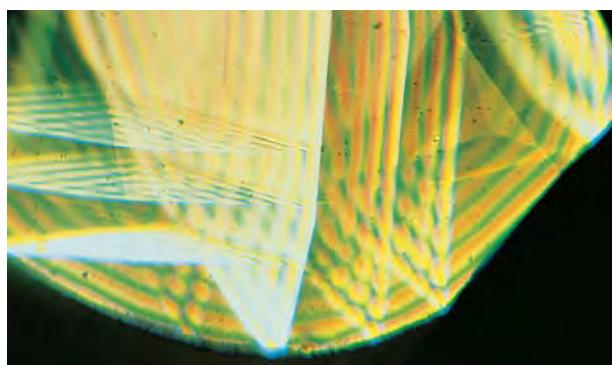
present frequently, but not in all samples.

At an inclination of 5° or 10° to the c-axis, a characteristic pattern consisting of the two hexagonal dipyramids ω or z was observed (figure 16). When the stone was inclined about 30° to the c-axis, a characteristic structure consisting of two n faces and one r face is seen (figure 17).

The hexagonal dipyramids ω or z were also dominant in the samples with asterism.

Twinning. Lamellar twinning parallel to the positive rhombohedron r occasionally was observed, usually as one or two isolated twin lamellae and less frequently as one or two sets of parallel twin lamellae (figure 18).

Figure 18. Two sets of intersecting twin lamellae are visible in this Ambondromifehy sapphire. Photomicrograph by K. Schmetzer; crossed polarizers, magnified 40x.



Mineral Inclusions. With Raman analysis and/or SEM-EDS, we confirmed inclusions of feldspar, zircon, columbite (with Nb>Ta), spinel (hercynite), and uraninite.

The most common inclusion in the unheated samples was a mineral grain surrounded by a discoid fissure with flattened two-phase (liquid-gas) inclusions in a rosette-like pattern. These rosettes show a consistent orientation parallel to the basal pinacoid c and, consequently, are seen best when viewed perpendicular to the c-axis (figures 19 and 20). We identified some of the mineral grains in the rosettes as feldspar.

Figure 19. The most frequently observed mineral inclusions in Ambondromifehy sapphires are feldspar crystals that are surrounded by rosettes of two-phase (liquid-gas) inclusions. The inset (view perpendicular to c) reveals the specific orientation of these flattened rosettes parallel to the basal pinacoid c . Photomicrographs by K. Schmetzer; immersion, magnified 50x and 60x (inset).

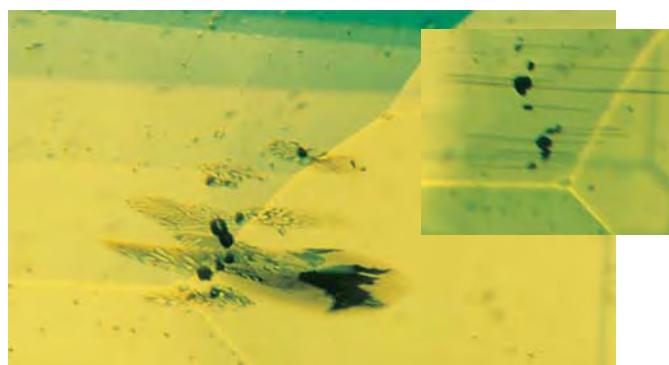




Figure 20. In a view almost parallel to the c-axis of this sapphire, the fine structure of a two-phase rosette surrounding a tiny feldspar crystal becomes visible. Photomicrograph by E. Gübelin; magnified 65×.

The rosettes are distinct from typical mineral inclusions with tension cracks (i.e., zircon in our samples), which are not oriented in a specific direction to the host sapphire crystal. Tension cracks surrounding mineral inclusions without a specific orientation were also observed occasionally in the heat-treated Ambondromifehy samples.

Another type of feldspar inclusion consisted of grains that lacked the rosette-like two-phase inclusions. Spinel and uraninite inclusions also occurred as grains, but they were seen only rarely in our samples. Columbite occurred as needles, which were found to contain only small amounts of tantalum (i.e., the analyses showed Nb>Ta).

In a few samples, we observed groups of uniden-



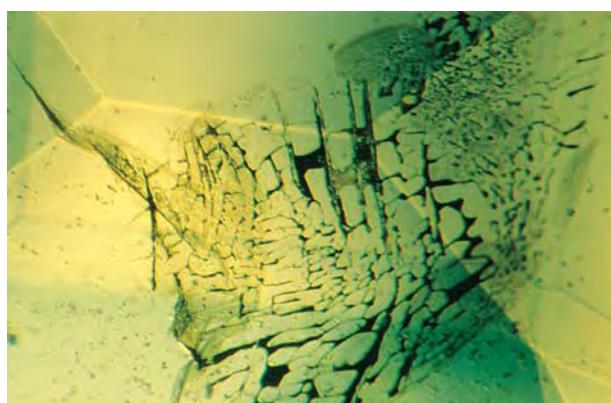
Figure 21. Groups of mineral inclusions, which have not yet been identified, were occasionally seen in the Ambondromifehy sapphires. Photomicrograph by E. Gübelin; magnified 65×.

tified mineral grains (figure 21) or other unidentified minerals accompanied by a "comet tail." Partially healed fissures also were present in some of the sapphires (figure 22).

Superchi et al. (1997) mentioned two additional minerals—pyrochlore and calcite—as inclusions in Ambondromifehy sapphires, but we did not identify these minerals in any of our samples.

Spectroscopic Properties and Color. The absorption spectra of the Ambondromifehy sapphires (see, e.g., figure 23) are typical of those recorded in BGY magmatic sapphires from other localities (see, e.g., Schmetzer and Bank, 1980, 1981; Schmetzer, 1987; Kiefert and Schmetzer, 1987; Smith et al., 1995). We recorded a continuous series of absorption spectra covering the entire range of colors, including yellow, greenish blue, and intense blue to blue-violet (figure 24A-C). All of these spectra had intense Fe^{3+} absorption bands at 376, 388, and 450 nm with weak polarization dependency, as generally is recorded for yellow sapphires (figure 24A). In the blue and greenish blue sapphires, the basic absorption spectrum found in yellow sapphires was superimposed by intense absorption bands assigned to $\text{Fe}^{2+}/\text{Ti}^{4+}$ charge transfer (maximum at about 560 nm with polarization $\perp c > \parallel c$), as well as to an $\text{Fe}^{2+}/\text{Fe}^{3+}$ pair absorption (maximum at about 870–880 nm with polarization $\perp c > \parallel c$; figure 24B and C)*. Due to the high intensity of

Figure 22. Partially healed fissures were present in some of the Ambondromifehy sapphires. Photomicrograph by K. Schmetzer; immersion, magnified 45×.



*Because of technical inconsistencies, the polarized absorption spectra of magmatic sapphires published by Schwarz et al. (1996) and Sutherland et al. (1998b) are partly incorrect in the range above 800 nm. In particular, an absorption maximum at about 800 nm in the spectra $\perp c$ is not realistic.

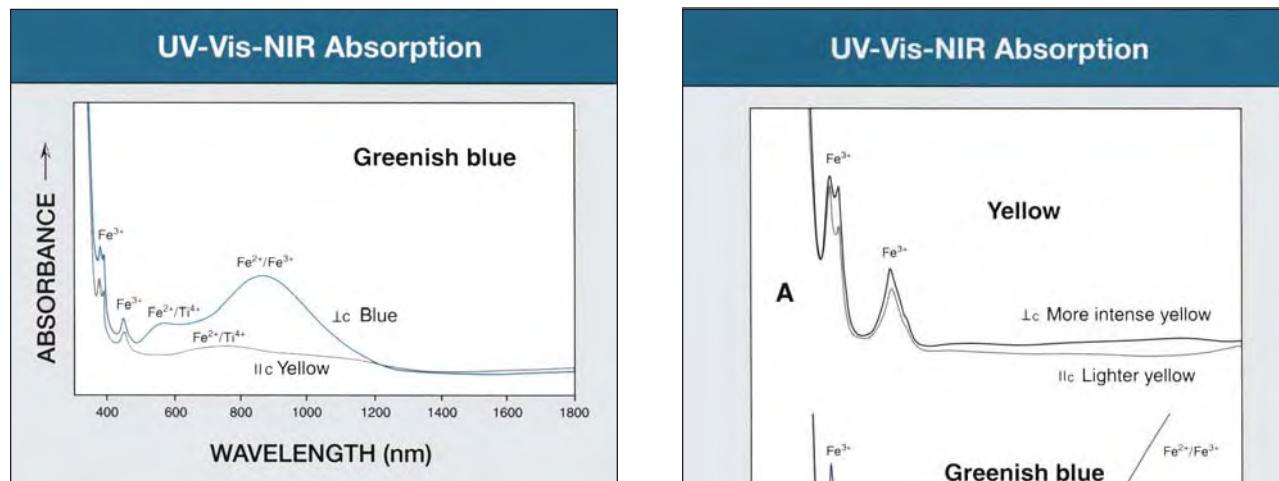


Figure 23. This absorption spectrum of a greenish blue Ambondromifehy sapphire (pleochroism $\parallel c$ yellow, $\perp c$ blue) in the 280 to 1800 nm range consists of a strong Fe^{2+}/Fe^{3+} band with a maximum in the infrared region, strong Fe^{2+}/Ti^{4+} pair absorption bands in the visible region, and Fe^{3+} bands in the blue-violet and UV regions.

the Fe^{2+}/Fe^{3+} pair absorption, a second Fe^{2+}/Ti^{4+} maximum at about 700 nm with polarization $\parallel c > \perp c$ (see figure 24E) is generally not resolvable. The spectra of the heat-treated intense blue-violet samples were identical to those of untreated sapphires of similar color.

In greenish yellow to yellowish green samples, the intermediate spectrum of greenish blue sapphire was superimposed by an additional weak absorption band in the 500–550 nm range (polarization $\parallel c > \perp c$; figure 24D). This absorption band causes a shift of the pleochroic color parallel to the c-axis from yellow to yellow-green or green; consequently, it shifts the overall color of the sapphire from greenish blue to greenish yellow or yellowish green. An absorption at 542 nm with identical polarization has also been documented in Verneuil titanium-doped synthetic sapphires, where it was assigned to Ti^{3+} (McClure, 1962). Although we do not know the exact mechanism by which Ti^{3+} stabilizes in iron-

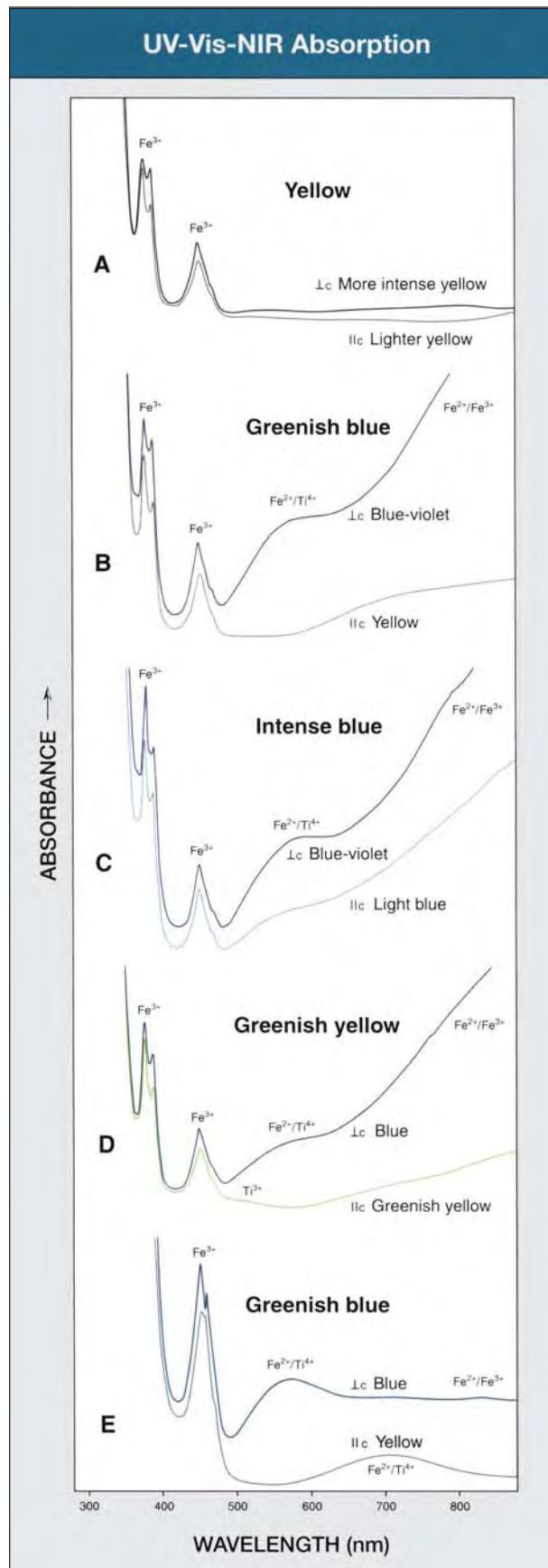


Figure 24. These absorption spectra in the 280–880 nm range cover the entire range of colors seen in Ambondromifehy sapphires. The spectra consist of superimposed Fe^{2+}/Fe^{3+} and Fe^{2+}/Ti^{4+} pair absorption bands, as well as intense Fe^{3+} and weak Ti^{3+} bands. Variations in the color/pleochroism of the sapphires is determined by the relative intensities of these absorption bands.

bearing natural sapphires, there has been no other assignment of this weak absorption maximum. It is worth mentioning that another example for the coexistence of Ti^{3+} and Fe^{2+} was found in Czochralski-pulled synthetic pink sapphire by spectroscopic examination (Johnson et al., 1995).

In magmatic sapphires, Fe^{2+}/Fe^{3+} pair absorption in the 870–880 nm range is, in general, much stronger than the Fe^{2+}/Ti^{4+} absorption bands at 560 and 700 nm (see, e.g., figures 23 and 24B–D). Only one of the Ambondromifehy samples, which had extremely pronounced and complex color zoning, revealed an absorption spectrum in which the Fe^{2+}/Ti^{4+} pair absorption bands were stronger than the Fe^{2+}/Fe^{3+} band in the infrared region (figure 24E).

Chemical Composition. Trace-element analysis has proved valuable in the identification of gem corundums formed in different geologic environments, as well as in the laboratory (see, e.g., Sutherland et al., 1998b; Muhlmeister et al., 1998;

Schwarz and Stern, 2000). The trace-element contents of 137 sapphires from northern Madagascar are presented in table 2.

Vanadium and chromium, in general, were below the detection limit of the analytical method used (about 0.005 wt.% V_2O_3 or Cr_2O_3). Only a few samples revealed traces of vanadium or chromium that were slightly above the detection limit. All samples revealed concentrations of iron and gallium that were typical of magmatic sapphires (see, e.g., Sutherland et al., 1998b).

The titanium content of the pure yellow samples was always below the detection limit (about 0.005 wt.% TiO_2). All of the samples with higher titanium values had blue color zones or a blue color component. Transparent, facet-quality samples (i.e., those that usually do not need heat treatment) other than yellow consistently revealed a low, but distinct, titanium content—averaging about 0.02 wt.% TiO_2 . Those samples with a milky white component, the typical material subjected to heat treatment, aver-

TABLE 2. EDXRF analyses of sapphires from Antsiranana Province, northern Madagascar, with comparison to Andranondambo.^a

Sample type	No. of samples	Concentration (wt.%)				
		TiO_2	V_2O_3	Cr_2O_3	Fe_2O_3 ^b	Ga_2O_3
Transparent yellow	14	bdl	bdl	bdl	0.73–1.56 (1.24)	0.02–0.06 (0.04)
Transparent yellow and blue (zoned), greenish yellow to yellowish green, greenish blue, blue, and blue-violet	94	0.005–0.11 (0.02)	bdl–0.01 bdl	bdl–0.01 bdl	0.46–1.73 (1.10)	0.02–0.07 (0.03)
Translucent greenish blue, blue, and blue-violet ^c (all milky, no cores)	19	0.02–0.15 (0.08)	bdl–0.01 bdl	bdl	0.66–1.40 (1.18)	0.02–0.08 (0.05)
Translucent gray and light blue star sapphires (all milky or with milky zones)	5	0.06–0.10 (0.08)	bdl–0.01 bdl	bdl	0.33–0.57 (0.44)	0.01–0.04 (0.02)
Zoned star sapphires	5					
Colorless to gray cores		0.02–0.04 (0.03)	bdl–0.01 bdl	bdl	1.24–2.31 (1.74)	0.05–0.11 (0.08)
Medium to intense blue rims ^d (all milky or with milky zones)		0.06–0.23 (0.15)	0.005–0.01 (0.01)	bdl	1.53–1.90 ^e (1.64)	0.06–0.90 ^e (0.09)
Overall Ambondromifehy ^f	137	bdl–0.23 (0.03)	bdl–0.01 bdl	bdl–0.01 bdl	0.33–1.90 ^e (1.00)	0.02–0.10 ^e (0.04)
Andranondambo ^g	80	0.01–0.10 (0.04)	bdl–0.01 bdl	bdl–0.01 bdl	0.12–0.61 (0.27)	0.01–0.04 (0.02)

^aMinimum and maximum values are given, along with the average (in parentheses below each range); bdl = below detection limit.

^bTotal iron as Fe_2O_3 .

^cThese sapphires turn intense blue to blue-violet after heat treatment.

^dSame samples as the ones with the colorless to gray cores.

^eOne sample showed distinctly higher contents of Fe_2O_3 (3.86 wt.%) and Ga_2O_3 (0.15 wt.%).

^fColorless to gray cores of zoned star sapphires not included.

^gFrom Schwarz et al. (1996); for additional microprobe analyses, see Kiefert et al. (1996).

aged about 0.08 wt.% TiO_2 , well above the mean value for the transparent sapphires.

In star sapphires and in milky stones, the measured elemental concentrations may be influenced by the presence of tiny inclusions such as rutile or ilmenite that reach the surface of the host corundum, rather than simply by the presence of transition metals within the corundum structure. In all the asteriated cabochons with a sharp six-rayed star, appreciable amounts of titanium were detected. In the milky white and gray to light blue star sapphires, the iron values were distinctly lower than those determined for more intense-blue star stones. Samples of the latter type were found to contain a colorless to gray transparent core (see, e.g., figure 10, inset), which lacks asterism and shows very low titanium contents (see table 2).

When we compared the data for all of the samples using correlation diagrams, we found no geochemical correlation between titanium and either iron or gallium; the concentrations of these elements varied independently. However, with greater iron contents, a trend toward increasing gallium values became evident.

As mentioned earlier, many sapphire fields from eastern Australia (particularly the Barrington basalt province in New South Wales) and Southeast Asia (e.g., West Pailin, Cambodia; Ban Huai Sa, Laos; and Chanthaburi, Thailand) are distinguished by the presence of two distinct corundum suites, which are thought to represent different sources in the earth's interior that were captured by basaltic magmas as they traveled to the surface (Sutherland et al., 1998b). These two corundum suites can be separated by trace-element contents, that is, by diagramming (1) $\text{Fe}_2\text{O}_3/\text{TiO}_2$ versus $\text{Cr}_2\text{O}_3/\text{Ga}_2\text{O}_3$, and (2) $\text{Fe}_2\text{O}_3/\text{Cr}_2\text{O}_3$ versus $\text{TiO}_2/\text{Ga}_2\text{O}_3$ (figure 25). In making these comparisons, we assigned a value of 0.005 for concentrations below the detection limit (i.e., for some TiO_2 and most Cr_2O_3 values). All of the sapphires from northern Madagascar that we analyzed by EDXRF belong to the magmatic suite.

DISCUSSION

Comparison to “Basalt-Hosted Magmatic” Sapphires from Other Localities. The sapphires from northern Madagascar showed the typical morphology of magmatic corundum, that is, faces of the basal pinacoid c , the positive rhombohedron r , as well as different hexagonal dipyramids. In particular, these sapphires formed as barrel-shaped crystals with dominant ω or z hexagonal dipyramids, and subordi-

nate c , r , and n faces; prismatic forms were not observed. The correlation between external crystal faces and internal growth structures has been shown for corundums from practically all basalt-hosted sources (Kiefert, 1987; Kiefert and Schmetzer, 1987 and 1991), including magmatic Vietnamese sapphires (Smith et al., 1995).

The following have been identified as typical mineral inclusions observed in magmatic sapphires: assemblages of feldspars (albite, calcic plagioclase, Na- and/or K-rich sanidine), zircon, columbite, rutile, hematite (sometimes in solid solution with ilmenite), spinel (hercynite, magnetite, gahnospinel, and/or cobalt-spinel), uranium-pyrochlore, pyrrhotite, thorite, and uraninite; low-Si and Fe-rich glassy inclusions have also been identified (see, e.g., Moon and Phillips, 1984, 1986; Coldham, 1985, 1986; Gübelin and Koivula, 1986; Irving, 1986; Kiefert, 1987; Kiefert and Schmetzer, 1987; Coenraads et al., 1990, 1995; Aspen et al., 1990; Guo et al., 1992, 1994, 1996a and b; Sutherland, 1996; Sutherland and Coenraads, 1996; Krzemnicki et al., 1996; Sutherland et al., 1998a and b; Maliková, 1999).

The mineral inclusions identified in Ambondromifehy sapphires (e.g., feldspar, zircon, columbite, hercynite, uraninite, pyrochlore) are typical of magmatic sapphires. The most common mineral inclusions in Ambondromifehy sapphires are feldspar crystals surrounded by “rosette-like” fissures. Similar-appearing inclusions have been described for corundums from elsewhere (see, e.g., Kiefert and Schmetzer, 1987; Guo et al., 1996a), with their consistent orientation—parallel to the basal pinacoid c —but not with the frequency observed in the northern Madagascar sapphires.

Some Ambondromifehy sapphires contain a colorless to gray central core, with a hexagonal outline, which is surrounded by milky white to blue-violet areas (figure 10, inset). This unusual feature is rarely found elsewhere. Similar colorless core zones, but with a triangular outline, occur in blue magmatic-type sapphires from Vietnam (Smith et al., 1995).

The UV-Vis-NIR absorption spectra of the Ambondromifehy BGY magmatic sapphires have features typical of those seen in basaltic sapphires from other localities (Schmetzer, 1987; Schmetzer and Kiefert, 1990; Kiefert and Schmetzer, 1991; Krzemnicki et al., 1996; Schwarz et al., 1996; Sutherland et al., 1998b). Therefore, absorption spectra cannot be used to distinguish Ambondromifehy sapphires from those of other basaltic fields.

As shown in the correlation diagrams (figure 25), the trace-element contents of Ambondromifehy sapphires overlap with those of magmatic samples from Barrington and Pailin (see Sutherland et al., 1998b). Further overlap has been observed in population fields of magmatic sapphires from Nigeria, Laos, and various other Australian basalt fields (D. Schwarz, unpublished data). Similar trace-element contents were also described for magmatic sapphires from Shandong Province, China (Guo et al., 1992). Consequently, the separation of magmatic sapphires from different basalt fields by their trace elements seems rather unlikely. Nor is there any significant difference in internal features or gemological properties that could be used to separate sapphires formed in this environment.

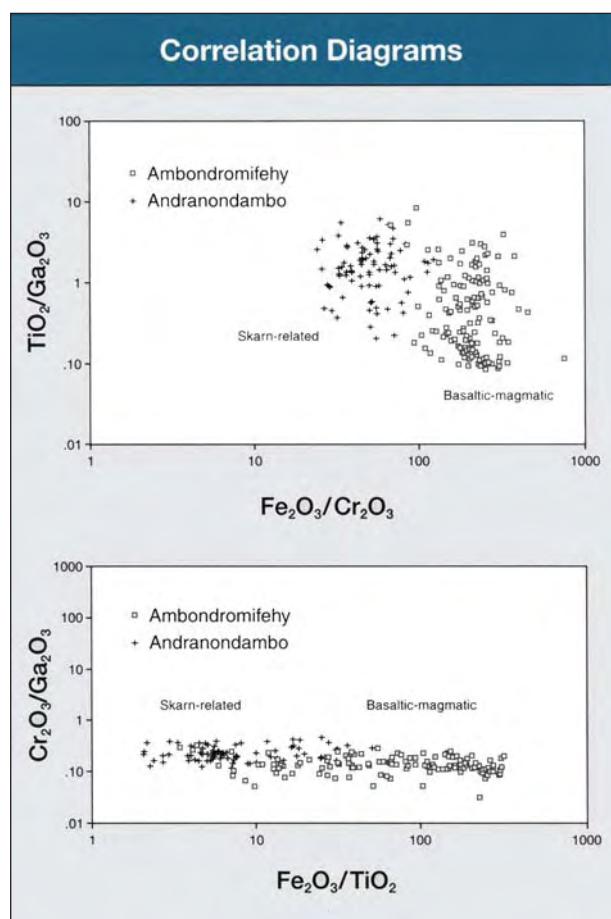
Comparison to Andranondambo Sapphires. The gemological characteristics of sapphires from Andranondambo, southeastern Madagascar, were detailed by Schwarz et al. (1996) and by Kiefer et al. (1996). Subsequent studies of the associated mineral assemblages attributed their formation to metamorphic skarn processes (Gübelin and Peretti, 1997). The magmatic sapphires from northern Madagascar can be separated from the skarn-related Andranondambo sapphires on the basis of diagnostic growth patterns, inclusions, and spectroscopic features (see references cited above). Here, we compare the chemical properties of gem corundum from these two important localities (table 2).

Ambondromifehy sapphires typically show higher iron and gallium concentrations than Andranondambo stones. Individual trace elements show considerable overlap, so are not diagnostic. However, using the previously described correlation diagrams of $\text{Fe}_2\text{O}_3/\text{TiO}_2$ versus $\text{Cr}_2\text{O}_3/\text{Ga}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3/\text{Cr}_2\text{O}_3$ versus $\text{TiO}_2/\text{Ga}_2\text{O}_3$, a clear separation between most samples from these two deposits is possible (figure 25). We found that it is also possible to separate similarly colored blue sapphires from the new metamorphic Ilakaka deposits by trace-element chemistry (D. Schwarz, unpublished data).

Distinction from Synthetic Sapphires. The separation of Ambondromifehy sapphires from synthetic blue or yellow sapphires, regardless of the growth method (e.g., flame-fusion, flux, floating zone, Czochralski-pulled, hydrothermal), is fairly simple. Most of the internal features (e.g., growth patterns and mineral inclusions, when present) seen in the natural stones differ quite markedly from those

observed in laboratory-grown sapphires. Absorption spectra of Ambondromifehy sapphires overlap with those of some synthetic sapphires (e.g., some flux-grown Chatham or hydrothermal Russian synthetic sapphires). However, the trace-element composition of the natural sapphires reveals significant differences from their man-made counterparts. In general, with careful microscopic examination, the experienced gemologist can determine conclusively the natural or synthetic origin of an unknown sapphire in the yellow to blue color range (see, e.g., Liddicoat, 1989; Thomas et al., 1997).

Figure 25. In these trace-element correlation diagrams, the population field of the skarn-related sapphires from Andranondambo shows minor overlap with that of the magmatic samples from Ambondromifehy. Chemical correlation diagrams are one of the techniques used to separate sapphires and rubies from different host rocks.



SUMMARY AND CONCLUSIONS

A large region in northern Madagascar, near the town of Ambondromifehy, has been the source of considerable quantities of sapphires in a variety of colors, but primarily blue, blue-violet, greenish blue, and yellow. Much of the digging for these alluvial deposits has occurred in or near the Ankarana Special Reserve, which has led to significant problems with ecologists. Most of the sapphires in virtually all hues are heat treated to remove milkiness in all or part of the stone and produce a better color. Ninety per cent of the crystals heat treated for this study changed to a more transparent and more attractive blue-violet to blue. Several asteriated stones were examined, a few with unusual colorless to gray cores.

The faceted Ambondromifehy sapphires showed distinctive internal growth patterns. In addition, many contained unusual rosette-like features: mineral grains (some identified as feldspar) surrounded by a discoid fissure with flattened two-phase inclusions. Spinel, uraninite, and columbite were also identified.

The absorption spectra and EDXRF analyses provided results that are typical for basaltic-magmatic sapphires from other localities. However, these same analyses (as well as internal growth patterns

and inclusions) can be used to separate magmatic sapphires from sapphires that formed in a different environment, such as the skarn-related sapphires from the Andranondambo deposit in southeastern Madagascar.

Although mining in Ambondromifehy dropped sharply with the discovery of sapphires in Ilakaka (and the movement of miners to that area), activity in northern Madagascar has increased in recent months. It appears that there is still considerable potential, but most of the mining continues to be small scale, with little or no mechanization.

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