SAPPHIRES FROM SOUTHERN VIETNAM

By Christopher P. Smith, Robert C. Kammerling, Alice S. Keller, Adolf Peretti, Kenneth V. Scarratt, Nguyen Dang Khoa, and Saverio Repetto

Gem-quality blue to bluish green sapphires from basaltic terrains in southern provinces of Vietnam have been entering the gemstone market since the late 1980s. Visits to two of the sapphire-producing areas—Phan Thiet and Di Linh—confirmed that the sapphires occur in association with alkali basalts. Mining was done by hand at the Phan Thiet localities and with relatively sophisticated equipment at Di Linh. Investigation of 250 faceted samples revealed gemological, spectroscopic, and chemical properties similar to those of other basaltic sapphires. Notable internal features are prominent growth structures, distinctive color zoning, various cross-hatch to lath-like "cloud" patterns, and several mineral inclusions.

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In recent years, considerable attention has been focused on the deposits of ruby and fancy-colored sapphires in northern Vietnam (see, e.g., Kane et al., 1991; Kammerling et al., 1994). Yet, significant corundum deposits have also been found in southern Vietnam. Since the late 1980s, blue to bluish green gem-quality sapphires (figure 1) have been recovered from secondary deposits in basaltic terrains in the provinces of Binh Thuan (formerly Thuanh Hai), Lam Dong, Dong Nai, and Dac Lac (figure 2). With the start of both organized and wide-scale independent mining in approximately 1990, thousands of carats of these sapphires began to enter the gem market through Thailand and elsewhere. To date, mining activity has been erratic, although periods of intense activity marked the first half of the 1990s. In fact, a spring 1995 report stated that more than 10,000 people had gone to central "Darlac" [Dac Lac] Province in search of sapphires ("Sapphire Fever Strikes . . .," 1995). Because the blue sapphire deposits of southern Vietnam appear to cover a fairly wide area, and they are easily mined from secondary gravels, future prospects appear promising.

In late 1992 and early 1993, several of the authors (RCK, SR, AP, KVS, ASK) visited the deposits at Phan Thiet (Binh Thuan Province) and Di Linh (Lam Dong Province) and collected firsthand information and samples. Additional samples were obtained through various marketing channels within Vietnam. At the time of our visits, there was no formal mining in Dong Nai Province, although we were told that sapphire had been found in the area of Gia Kiem, in central Dong Nai. Nor was there organized activity at Dac Lac. This report focuses on the geologic occurrence of these blue to bluish green sapphires, the mining methods used to extract them, and their gemological properties (especially their distinctive internal structure and other internal features).

Figure 1. Commercial quantities of blue sapphire have been mined from various regions in southern Vietnam. These Vietnamese sapphires range from 0.50 to 1.58 ct. Jewelry courtesy of The Gold Rush, Northridge, California; photo by Shane F. McClure.

GEOLOGY AND OCCURRENCE

In northern Vietnam, the gem corundums (primarily rubies and fancy sapphires, although some blue sapphires have been reported) occur in metamorphic rocks, specifically marbles (see, e.g., Kane et al., 1991). In contrast, the blue to bluish green gem corundums in southern Vietnam are found in alkali basalts (volcanic igneous rocks). Like the first gem corundums discovered in northern Vietnam, however, those in the south are recovered from secondary deposits, mainly alluvials (placers).

The geologic setting of these southern Vietnam sapphires is similar to that of alkali basalts elsewhere in Southeast Asia and China, such as Mingxi in Fujian Province (Keller and Keller, 1986), Penglai on Hainan Island (Wang, 1988), and Changle in Shandong Province, China (Guo et al., 1992b); Chanthaburi-Trat and Kanchanaburi, Thailand (Vichit et al., 1978); Pailin, Cambodia (Jobbins and Berrangé, 1981); and Monghkak, Myanmar (Hlaing, 1993). At these localities, the alluvial and eluvial deposits result from concentration of the gem corundums by weathering and mechanical processes; zircon, spinel, and garnet may also be recovered.

The volcanic activity in Southeast Asia that brought the corundum-bearing alkali basalts to the surface began at least 13 million years (My) ago and has continued to the present (see, e.g., Barr and Macdonald, 1981). During Middle and Late Cenozoic time (since about 37 My ago), Southeast Asia experienced block faulting as a result of regional tension, with the subsequent formation of grabens (long, narrow troughs, such as those in East Africa and the Rhine Valley, bounded by normal faults). Thus, topographically, this part of southern Vietnam may be viewed as consisting of numerous partly eroded plateaus separated by trough-like valleys. Volcanic activity along the rifts resulted in a broad basalt cover over much of the area. The depressions were filled not only with basalts but also with sediments, including corundum, derived from the weathering of rock formations at higher elevations (i.e., the upraised fault blocks; Barr and Macdonald, 1981).

Basalt is a general term for fine-grained, dark-colored, mafic (high Fe and Mg) igneous rocks composed chiefly of calcium-rich plagioclase and calcium-rich clinopyroxene (mainly augite). There are two major types of basalt: tholeiite and alkali. In

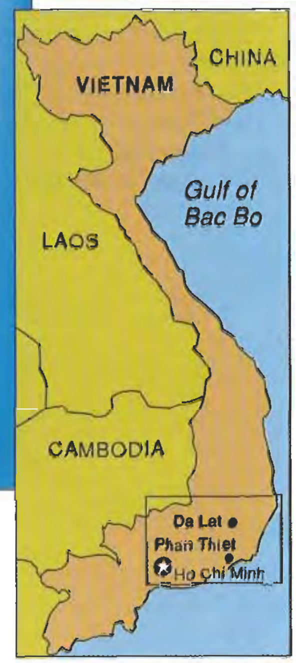


Figure 2. To date, the most important sapphire-producing areas of southern Vietnam have been associated with the alkali basalts of Binh Thuan, Lam Dong, Dong Nai, and Dac Lac provinces. The deposits at Da Ban and Ma Lam in Binh Thuan Province and Di Linh in Lam Dong Province were visited by the authors.

areas where more than one type of basalt occurs, as in southern Vietnam and elsewhere in Southeast Asia, usually the older flows are tholeiites and the younger flows alkali basalts. Corundum is found only in association with alkali basalts, which constitute a small percentage of all basalts; they are characterized by higher alkali (>3–5 wt.% Na_2O + K_2O) and lower silica (40–50 wt.% SiO_2) contents compared to the more common tholeiitic basalts (see, e.g., Levinson and Cook, 1994).

Figure 3. At Da Ban, most of the mining is done with simple hand tools, like the pick used by these miners to remove the potentially gem-bearing gravels. Photo by R. C. Kammerling.

Basaltic magmas form within the upper mantle (that part of the Earth below the crust) by a process known as partial melting (i.e., melting of selective components—about 5–10%—of mantle peridotite). Of the two major types of basalts, alkali basalts typically form at greater depths (about 60–120 km) than tholeiites (about 20–80 km). In addition, alkali basalts frequently contain abundant xenoliths and xenocrysts (rocks and crystals, respectively, included in a magma but not formed from the magma itself), which were picked up from the mantle as the magmas rose to the surface. Among these xenocrysts are sapphire and other varieties of corundum (see, e.g., Levinson and Cook, 1994).

To date, sapphires have been found in basaltic alluvials in four provinces in southern Vietnam: Binh Thuan, Lam Dong, Dong Nai, and Dac Lac. The authors gained access to mining operations in Binh Thuan (the Phan Thiet District) and Lam Dong (the Di Linh District).

THE PHAN THIET DISTRICT

The Phan Thiet sapphire-mining district in Binh Thuan Province lies near the coastal city of Phan Thiet, about 200 km (124 miles) due east of Ho Chi Minh City (again, see figure 2). At the time of our visits, travel into the mining areas by non-Vietnamese nationals required special permits, which were checked at police posts throughout the region. The authors were accompanied by local government officials when they went into the Phan Thiet mining district, which included two large areas: Da Ban and Ma Lam.

Da Ban Mining Area. *Access.* Da Ban is located near Hong Son Village, about 28 km (17 miles) northeast of Phan Thiet City. We reached the mining area by driving a combination of paved and winding dirt roads and then walking the last 1 km northwest through a shallow valley. Unlike the lush tropical vegetation we had encountered in the ruby-mining areas in northern Vietnam, the vegetation in this hot, dry region was mostly scrub.

Mining. The mining area was a field of small, irregularly shaped pits typically about 1–2 m deep; local miners told us that the sapphires were found relatively close to the surface. We could not discern a distinct gravel layer in any of the pits. Although most were very small and shallow, barely holes in the ground, some of the pits were as large as 3 × 4 m (as shown in Koivula et al., 1992).

In November 1992, the area was being worked by several small groups of local villagers. They used agricultural hand tools—hoes and shovels—first to remove the vegetation and topsoil, and then to dig down to and through the gem-bearing zone (figure 3). They shoveled the gravels into wood-framed sieves and then washed them using water that had accumulated in their or another pit. The miners examined the gravels and removed any gem material by hand on site.

Local villagers told the authors that at the very height of activity only a few weeks earlier, 2,000–3,000 people had worked about a 7-km^2 of this mining district. They said that mining activity had decreased recently because (1) local government officials had made concerted efforts to curb illegal digging, and (2) much of the material was relatively low quality and so brought low prices.

At one house in the area, miners showed us a small lot (about 100 ct) of rough stones that ranged from light to very dark blue to greenish blue. They said that this material, much of which did not appear to be cuttable, was recovered over four days by seven people. This seemed to confirm the assessment that generally only poor-quality material was being found at that time.

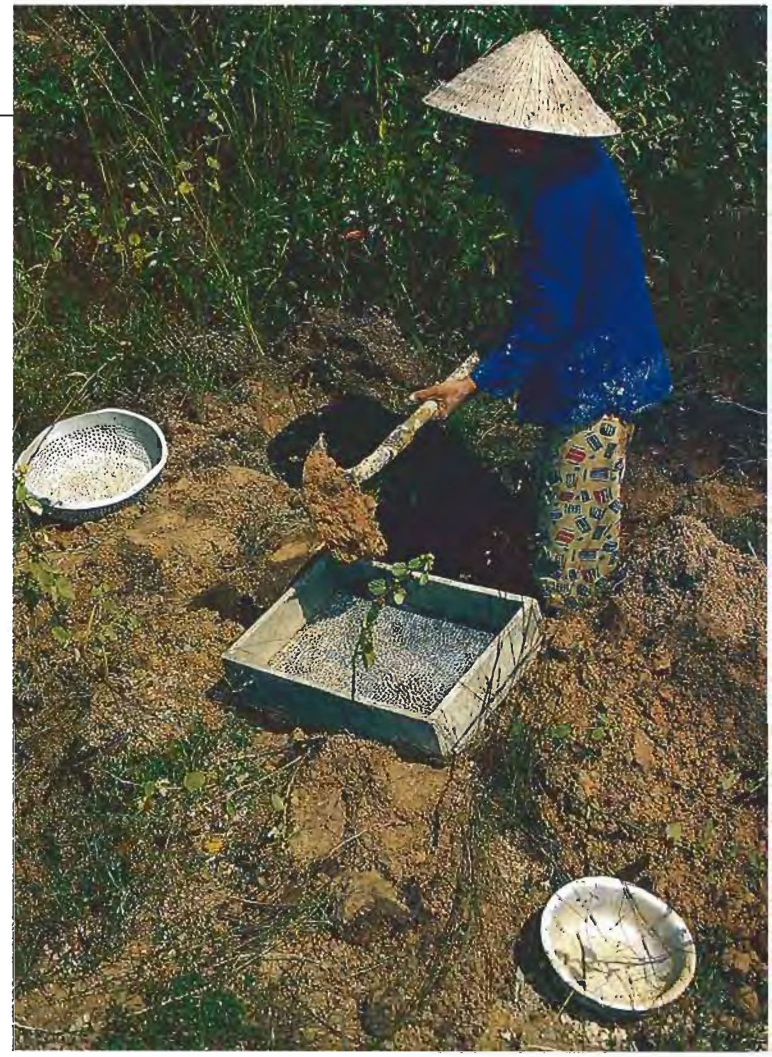


Figure 4. This miner throws gravel into a simple metal sieve for washing at Ma Lam. As at Da Ban, many miners work in the hot sun, shoveling dirt and gravels, and then carrying the heavy sieves to nearby ponds. Photo by R. C. Kammerling.

Ma Lam Mining Area. *Access.* We reached Ma Lam from Phan Thiet City by driving a circuitous route north-northwest about 20 km (12 miles), through Sara and Ham Chinh villages. The final kilometer or so was on a poorly delineated dirt road.

Mining. This field of mining pits extended over a larger area—several square kilometers—than that at Da Ban. Here, the pits ranged from about 0.5 to 2 m deep. Miners used shovels to excavate the sandy soil until they reached the gravel-bearing zone. They threw the gravels (figure 4) into crude metal

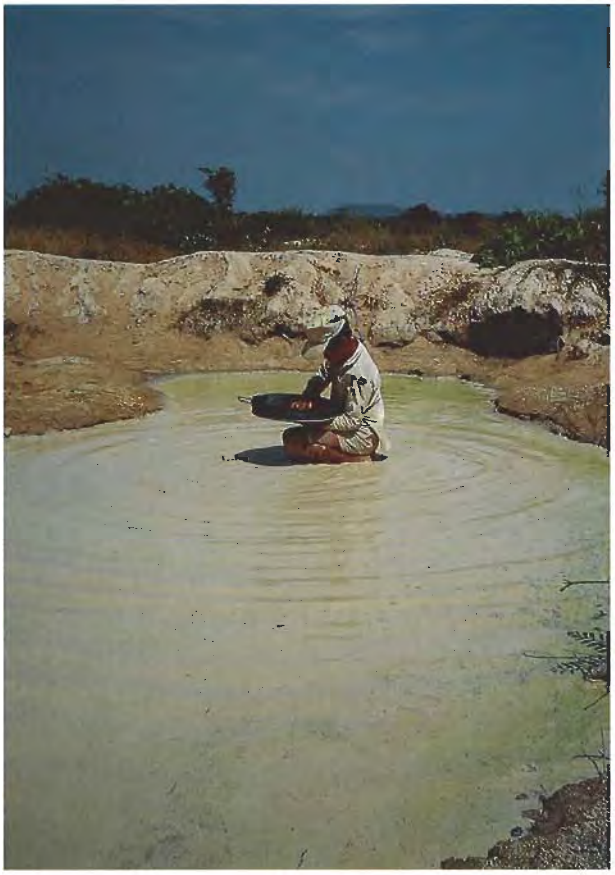


Figure 5. Most of the ponds used for washing the gravels at Ma Lam appeared to be old pits that had been filled with groundwater. Here a young boy searches for pieces of gem rough. Photo by A. S. Keller.

sieves that they took to nearby flooded, previously excavated pits for washing (figure 5). As at Da Ban, there were no distinct boundaries to the gravel layer.

We encountered several dozen men, women, and children mining in the area, singly and in groups of up to about 10. We were told that, in November 1992, about 400 people were mining in the region, compared to about 1,000 only a few months previously. The miners reported an average total yield for Ma Lam of about 100 stones a day.

Marketing. Some of the sapphires recovered by local miners in Binh Thuan Province were marketed in Phan Thiet City through a government selling office, actually a branch of the Vietnam National Gold, Silver, and Precious Stones Corporation (figure 6). Here, we saw several lots (about 2,000 carats total) of rough sapphires. The best of these were nearly euhedral to slightly rounded subhedral crystals displaying strong green and blue dichroism. Most of the stones were small—less than 3 ct—although a few were over 10 ct. The larger pieces were nearly opaque. In many of the stones, we noted distinct color banding as well as what appeared to be epigenetic iron-based staining.

Only about 5% of the material we saw was of cutting quality. However, Donato Cremaschi, an experienced gem cutter working in Ho Chi Minh City at the time, told us that about 10% of the sapphires brought into his offices were cuttable. Because of the fees charged by the government selling office, and the desire to control distribution themselves, miners and dealers typically sold as much as 95% of their production through channels other than the official government market.

DI LINH DISTRICT

Location and Access. The Di Linh District, encompassing the Di Linh and Binh Dien mining areas, is located in Lam Dong Province, adjacent to and north of Binh Thuan Province. Although the mining areas can be reached by driving from Ho Chi Minh City to Phan Thiet and then traveling almost due north, a more direct route is to drive northeast from Ho Chi Minh City to Da Lat City, which can be used as a base from which to visit Di Linh City. From Ho Chi Minh City, which is near sea level, to

Figure 6. Lots of rough sapphire were brought to the Phan Thiet branch of the Vietnam National Gold, Silver, and Precious Stones Corporation by local miners and dealers at the time of the authors' visit. Photo by R. C. Kammerling.

Da Lat, the road climbs to an elevation of about 1,500 m; it passes through rubber tree and eucalyptus plantations, and then tea and coffee plantations closer to Da Lat. The Summer Palace of the former imperial families is located in the resort city of Da Lat. Locals regularly pan for gold in the river that runs through the city.

Two of the authors (AP, KS) visited the mining operation of the Vietnam National Gems Company (Vinagemco) at Di Linh in October 1992. (Vinagemco had a joint venture with the Thai firm BH Mining to mine rubies and sapphires in Luc Yen.) They reached the mining area by traveling about 40 km (24 miles) southwest from Da Lat, then leaving the main road and traveling southeast about 2 km through hilly country on a rough, winding trail. During the rainy season (approximately May through August), only a large four-wheel-drive vehicle can negotiate the road. The topography of the mine area is typical of that at many other basaltic regions: undulating, with numerous flat-topped hills.

Figure 7. At Di Linh, in Lam Dong Province, the joint venture Vinagemco uses a backhoe to remove the overburden and reach the gem gravels. A dump truck then carries the gravels to a nearby washing plant. Photo by K. V. Scarratt.

Mining. Unlike the rudimentary independent mining seen in the Phan Thiet district, Vinagemco had mechanized much of their sapphire-recovery operation at Di Linh (figure 7). A backhoe removed the overburden and then the sapphire-bearing gravels. A dump truck took the gravels to a processing plant about 100 m from the mining site for washing. The gravels were sent through a wooden hopper, into a rotating trommel, and then onto a wooden jig. At the time of our visit, however, this process had produced a potentially deadly environment in and around the washing plant: Large areas of quicksand, some 3 m deep, had formed from the run-off water.

There was also considerable independent mining in the Di Linh area. Miners worked the hills surrounding the Vinagemco plant, and then brought the excavated gravels to nearby streams for washing.

GEMOLOGICAL CHARACTERISTICS OF SOUTHERN VIETNAM SAPPHIRES

Materials and Methods. The test sample for this study consisted of more than 250 faceted, non-heat-treated gem-quality sapphires ranging from 0.14 to 3.44 ct, and six rough crystals ranging from 3.54 to 7.32 ct. All were obtained from various marketing channels in Vietnam and represented to be from southern Vietnam. This entire collection was examined to document the range of color, diaphaneity, reaction to ultraviolet luminescence, and microscopic features.

For more detailed analyses, a subset of roughly 100 of the faceted stones was selected to represent the full range of colors, including tone and saturation as well as hue variations, of the complete test sample. The gemstones in this group were examined by the senior author (CPS) to produce the broader scope of data presented in this article. Of this subset, 50 samples were also examined to record their refractive indices, birefringence, optic character, pleochroism, and optical absorption spectra (desk-model spectroscope), all with standard gemological instrumentation. Specific gravity was determined on 25 faceted stones and five of the rough crystals by the hydrostatic weighing method.

Approximately 50 stones were selected from the above 100 samples for spectroscopic and chemical analysis, as well as for examination of growth structure. A Perkin Elmer Lambda 9 spectrometer was used to perform polarized ultraviolet-visible through near-infrared spectroscopy (slit opening 0.5 nm, interval 0.2, response 1.0, and scanning speed 120 nm/min.) on two groups of stones: 49 in the region 200–900 nm, with a beam condenser and polarizing filters; and six in the region 300–2000 nm, with a calcite polarizer and beam condenser. We performed infared analyses on 39 samples with a Pye-Unicam FTIR 9624 spectrometer, using a diffused reflectance unit for sample measurement. Semi-quantitative chemical analyses were conducted on 53 specimens by means of energy-dispersive X-ray fluorescence (EDXRF) analysis. This was performed on a Tracor Northern Spectrace 5000 system, using a program specially developed by Prof. W. B. Stern, Institute of Mineralogy and Petrography, University of Basel.

The internal growth structures of 80 faceted stones were analyzed with the use of a horizontal microscope, a specially designed stoneholder, and a mini-goniometer attached to one of the oculars on the microscope, employing the methods described by Schmetzer (1986a and b) and Kiefert and Schmetzer (1991a). Inclusion analysis was performed on almost 40 mineral inclusions in 32 stones. Some were analyzed with a scanning electron microscope–energy dispersive spectrometer (SEM-EDS), others with X-ray diffraction analysis, and some with both techniques. Some of the stones were polished to expose specific inclusions.

Visual Appearance. Most of the *crystals* studied appeared rounded or tumbled, with no indication of the original crystal form. Some, however, showed less evidence of weathering and revealed overall forms (i.e., crystal habits) that were either oblong or blocky. Clearly displayed on the surfaces of these crystals were severely etched or dissolved features typical of rough sapphires from basaltic deposits (figure 8); these result from contact with the highly corrosive alkaline basalt magmas (Tombs, 1991; Coenraads, 1992a and b). Consequently, at best there was only an approximate indication of the original crystal habit. We also noted chipped or broken areas, and parting along basal planes. See the "Growth Characteristics" section for specific details about crystal habit.

Figure 8. The rough crystal surfaces of the southern Vietnam sapphires displayed the heavy dissolution effects typical of corundums that have been brought to the surface by alkali basalts. Overhead illumination.

Face up, the *faceted samples* were predominantly blue to greenish blue to bluish green, with tones from medium-light to very dark (figure 9). Many were so dark that they appeared black in standard daylight. A common trait was strong, eye-visible color zoning (again, see "Growth Characteristics" below).

In diaphaneity, the faceted samples ranged from transparent to translucent, depending on the nature and number of inclusions as well as on color saturation and tone. Much of the sample material was essentially devoid of eye-visible inclusions, although most displayed an overall "sleepy" appearance.

Gemological Properties. The standard gemological properties for the sample stones are listed in table 1. They were found to be consistent with corundum in general (see, e.g., Webster, 1983; Liddicoat, 1989) and, in particular, with blue to bluish green sapphires from various other basaltic sources (see, e.g., Keller, 1982; Coldham, 1985; Wang, 1988; Hughes, 1990; Hurlbut and Kammerling, 1991).

Pleochroism. All samples exhibited a distinct to strong dichroism when viewed with a calcite dichroscope. Hues ranged from blue to violetish blue parallel to the c-axis, and blue-green to yellow-green perpendicular to the c-axis. It is important to note that all of the blue to bluish green sapphires examined for this study displayed pleochroic colors in these hue ranges. The variations in face-up appearance, with the exception of color zoning, were related to differences in the orientation of the faceted stones with respect to their optic axis.

Growth Characteristics. As mentioned previously, the external condition of the rough crystals prevented identification of their growth morphology by standard techniques. We were able to accomplish this only by documenting the internal growth structures and color zoning, which represent a history of the original sapphire crystal as it grew below the earth's surface. Classification of the crystal habits and growth characteristics can help separate natural corundum from its synthetic counter-

Figure 9. The sapphires from southern Vietnam typically range in color from medium-light to very dark blue to bluish green. Less frequently seen are green to yellowish green sapphires, or stones with a violet color. These Vietnamese sapphires range from 0.42 to 3.44 ct. Photo by Shane F. McClure.

parts, as well as help distinguish between corundums from various sources (see, e.g., Peretti et al., 1995).

Growth Structures. Prominent growth structures were observed in essentially all of the faceted sapphires examined. These structures consisted of straight and angular sequences of growth planes composed of the basal pinacoid *c* {0001}, positive rhombohedral *r* {$10\bar{1}1$} faces, and different dipyramidal faces, such as *n* {$22\bar{4}3$}, *z* {$22\bar{4}1$}, *v* {$44\bar{8}3$}, and ω {14 14 $\overline{28}$ 3} or ν {$44\bar{8}1$}. Limitations of the interpretation method do not allow for a separation of these last two dipyramidal faces, which hereafter are called ω/ν. Most of the faceted stones examined contained enough internal crystallographic information for us to extrapolate their original crystal habit (figure 10). By far, two dipyramidal crystal habits, some of which have been modified to barrel shapes, dominated in the southern Vietnam sapphires. These were composed of *c, r, z* and *c, r, n,* and *z* faces (as shown in figure 11). In both cases, the basal pinacoid *c* was small and subordinate, while the dipyramid *z* was the largest and most dominant crystal face. In rare instances, we observed a change between these two crystallographic habits during the growth of a single sapphire crystal.

To a much lesser degree, we were able to reconstruct other crystal habits, including thick tabular habits with *c, r,* and *z* faces, or *c, r,* and ω/ν, both of which possessed dominant *c* and *r* crystal faces. In addition, in rare instances, we also observed these tabular crystal habits with very small and subordinate *n* crystal faces present sporadically. A barrel-shaped dipyramidal habit of *c, r, n,* and *v* faces was also observed (again, see figure 11). Some faceted stones only displayed growth structures of *c, r,* and *n* faces; however, such a habit has not been documented in sapphires from basaltic sources, and these stones may have been cut from fragments of a larger crystal.

Color Zoning. Obvious color zoning was present in most of the stones examined (figure 12). This consisted of straight and angular color banding that was parallel to the previously described crystal planes and growth structures. Alternation in color banding between consecutive growth layers was common. This occurred most frequently in two basic forms: (1) strong, sharply bordered blue bands alternating with narrow, colorless bands (figure 13); and (2) strong blue bands alternating with yellowish to brownish bands (figure 14). These two forms of color banding typically occurred parallel to *r* and/or *z*. Parallel to the basal pinacoid *c* crystal planes, zones with very little or no color were observed, or in some instances color banding alternated between light blue and colorless.

TABLE 1. Gemological characteristics of basaltic sapphires from southern Vietnam.

Properties	No. of samples	Observations
Color	250	Weak to highly saturated colors ranging from blue to bluish green, with tones from light to extremely dark
Clarity	250	Very clean to heavily included, most in the range of slightly to moderately included
Refractive index	50	n_ε = 1.760–1.764 n_o = 1.769–1.772
Birefringence	50	0.008–0.009
Optic character	50	Uniaxial negative
Specific gravity	25 faceted 5 crystals	3.99–4.02
Pleochroism	45	Strong dichroism: blue to violetish blue parallel to the c-axis and mostly green-blue to yellow-green perpependicular to the c-axis
Fluorescence to UV radiation	250	Inert to long- and short-wave
Optical absorption spectrum (nm)	45	450 (strong, broad) 460 (moderate to strong, broad) 469 (weak to moderate, broad)
Internal features[a]	250	Strong color zoning, prominent growth structures, laminated twinning, very fine grained clouds, several types of cloud patterns, various needle-like inclusions, "fingerprints," and negative crystals and crystalline inclusions of : Plagioclase feldspar (Na, Al, Si / K, Ca) Uranpyrochlore (Nb, U, Ca, Ti, Ta, Na / Fe) Columbite (Nb, Fe, Mn / Ta, Ti)[b] Zircon (Zr, Si / Hf) Ilmenite (Fe, Ti / Mn[?]) Pyrrhotite (Fe, S) Magnetite-hercynite (spinel), (Fe, Al / Si, Ti, Mn Zn) Chromite-hercynite (spinel) (Fe, Cr, Al) Goethite (XRD) Kaolinite (IR spectroscopy)

[a] *Major/minor elements determined for those crystalline inclusions identified by SEM-EDS are given in parentheses after the inclusions.*
[b] *Also identified by X-ray diffraction analysis (XRD).*

Figure 10. The internal growth structures seen in many of the sapphires provided enough information to enable the senior author to extrapolate the original crystal habit. This 0.44-ct Vietnamese sapphire shows a combination of crystal planes, composed of: basal pinacoid c *(0001), the roughly horizontal growth planes; connected to a more subordinate series of dipyramid* n *(22$\bar{4}$3) crystal planes, creating an angle of 118.8° with the basal growth planes; and dominant dipyramid* z *(22$\bar{4}$1) crystal planes, the nearly vertical growth planes, creating an angle of 100.4° with the basal growth planes. Rotating this stone about the vertical axis through 30°, a combination of* c *(0001) and* r *(10$\bar{1}$1) crystal planes were visible, creating an angle of 122.4°. This information permits a crystal habit of* c, r, n, *and* z *to be assumed for the original crystal (also refer to figure 11b). Immersion, view perpendicular to the c-axis, transmitted illumination, magnified 15×.*

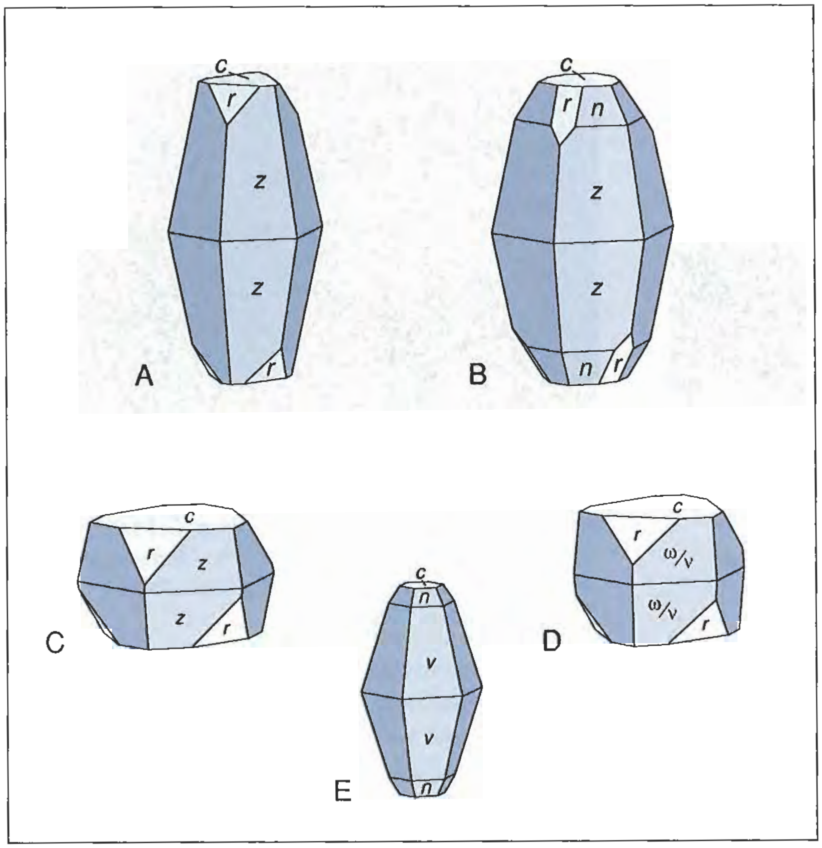


Figure 11. The sapphires from southern Vietnam revealed several different crystal habits. Of these, two oblong to barrel-shaped forms were statistically abundant, composed of: (A) dominant dipyramid z *$(22\bar{4}1)$ faces, with subordinate basal pinacoid* c *(0001) and positive rhombohedron* r *$(10\bar{1}1)$ faces; (B) dominant* z *faces, in addition to more subordinate dipyramid* n *$(22\bar{4}3)$,* c, *and* r *faces. Additionally, tabular crystal habits were also indicated, composed of: (C) dominant* c *and* r *faces, with intermediate to subordinate* z *faces; (D) dominant* c *and* r *faces, with intermediate dipyramid* ω *$(14\ 14\ \overline{28}\ 3)$ or* v *$(44\bar{8}1)$ faces. To a lesser extent, another barrel-shaped crystal form was identified, composed of: (E) dominant dipyramid* v *$(44\bar{8}3)$ faces, in addition to subordinate n,* c, *and* r *faces.*

One of the more intriguing types of color zoning consisted of a colorless "core" through the center of the original crystal. These "cores" represent crystal growth by one of two distinct methods: (1) a colorless sapphire crystal (core) formed during initial crystal growth and was subsequently overgrown by a sapphire with a strong blue color; or (2) the sapphire grew with a crystallographically preferred color orientation, where the basal planes are colorless while the positive rhombohedra and dipyramid faces are strong blue. Often these colorless "cores" had interesting geometric forms (figure 15), with blue outlines created by a combination of positive rhombohedra and dipyramid forms. In faceted stones, these "cores" commonly looked like colorless "holes" in otherwise blue stones, or they were merely colorless zones of various shapes and sizes (again, see figure 12).

Twinning. Twinning parallel to the *r* faces was seen in several of the stones examined (figure 16). They usually had only one direction of laminated twinning, parallel to a single positive rhombohedron *r* crystal face; occasionally, however, there were two or three twinning systems, parallel to additional positive rhombohedral planes.

Inclusions. The most prominent inclusion feature consisted of whitish, very fine-grained "clouds" of minute inclusions confined to growth planes; at

Figure 12. Distinct color zoning is readily seen in the southern Vietnam sapphires when they are immersed in methylene iodide. Also note the remainders of the colorless "cores." Immersion, photo by Shane F. McClure.

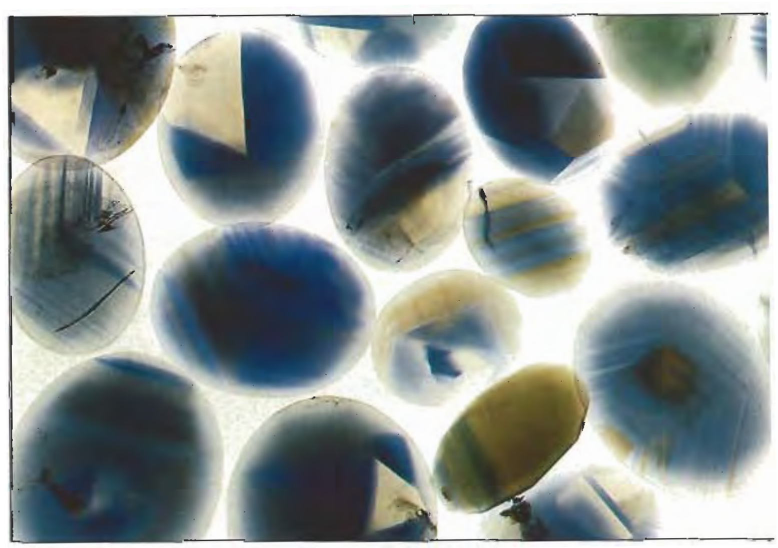


Figure 13. Strong, sharply bordered blue color bands alternating with narrow colorless bands was one type of distinctive color zoning noted in the sapphires from southern Vietnam. Photomicrograph by Dr. Eduard J. Gübelin; magnified 50×.

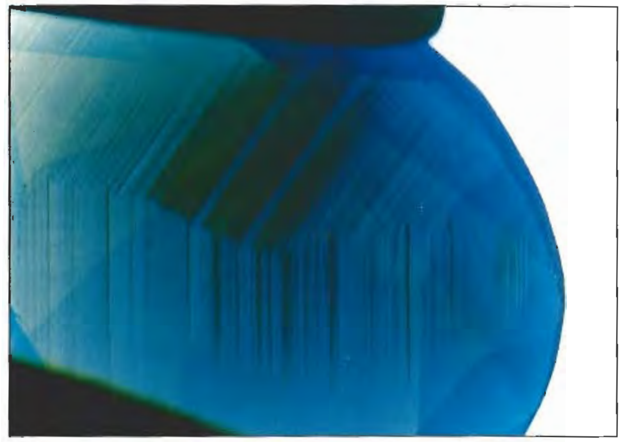


Figure 14. Additional distinctive color zoning, alternating between strong blue and light brown to yellow, tended to concentrate parallel to r *(vertical) and/or* z *(diagonal) planes. Immersion, transmitted illumination, magnified 16×.*

lower magnification, they look like whitish zonal bands (figure 17). EDXRF analysis indicated that generally the particles in these clouds were not related to TiO_2 (i.e., rutile) content. In a couple of instances, however, we recorded a higher level of TiO_2 in areas where these clouds were present (up to 0.24 wt.%; also refer to table 2) as compared to other, more transparent areas in the stone.

Less commonly, concentrations of white particles were seen to occur in other forms, such as fine, narrow, planar clusters grouped together to create cross-hatch or lath-like patterns (figure 18). The individual particles resembled thin blades or very fine, acicular crystals that are crystallographically oriented. Also noteworthy were dust-like clusters reminiscent of snowflakes (figure 19). Stringers of pinpoint inclusions were often seen in curved wisps following no particular crystallographic orientation, or extending in a straight line perpendicular to growth planes.

Needle-like inclusions were also noted in a small number of samples, along the intersection of two or three laminated twin planes. Typically

Figure 15. Colorless cores were frequently seen in the southern Vietnam sapphires, oriented parallel to the c-axis of the original rough sapphire crystal. This triangular image results from strongly colored r *planes surrounding colorless* c *planes. Immersion, transmitted illumination, magnified 15×.*

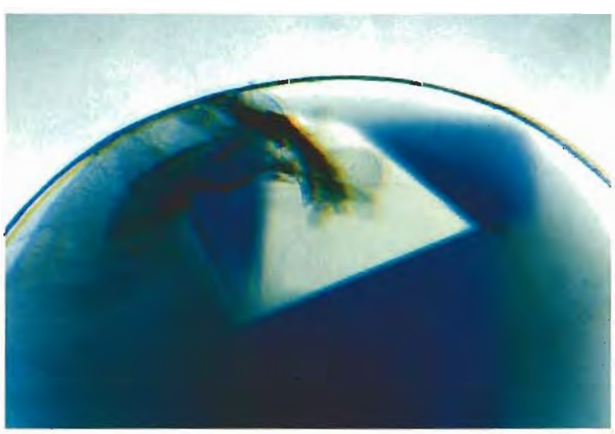
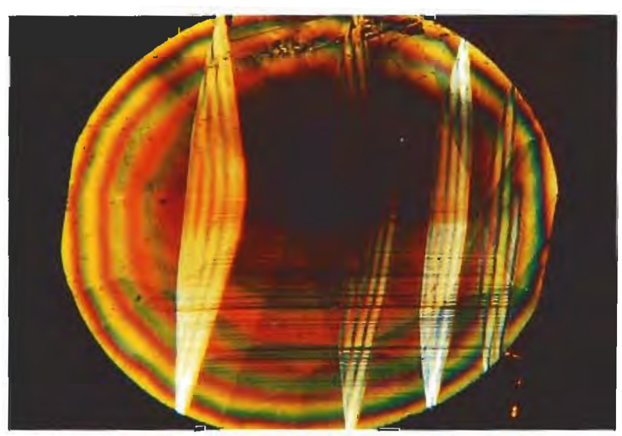


Figure 16. Laminated twinning (shown here as bright vertical planes) was relatively common in the sample sapphires, generally following only one direction, parallel to a single r *$(10\bar{1}1)$ face. However, occasionally two or three systems were observed, parallel to additional rhombohedral faces. Immersion, transmitted illumination between crossed Polaroids; photomicrograph by Karl Schmetzer.*



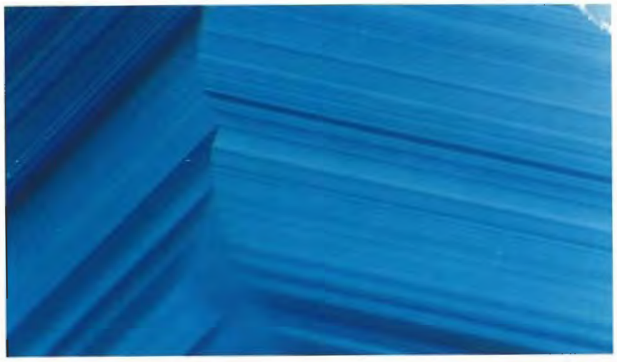


Figure 17. The most commonly observed inclusion feature in the sapphires from southern Vietnam consisted of clouds of fine-grained particles following internal growth planes, and thus appearing as straight and angular whitish bands. Shown here parallel to two dipyramidal z planes. Oblique fiber-optic illumination, magnified 25×.

TABLE 2. Semi-quantitative chemical analyses of trace elements in the blue to bluish green basaltic sapphires from southern Vietnam.[a]

Oxide	Content (wt. %)	Measured in >80% of samples
Fe_2O_3	0.43 –1.82	0.55–1.60
TiO_2	0.003–0.240	0.01–0.09
Ga_2O_3	0.021–0.052	0.02–0.04
V_2O_5	0.001–0.017	0.00–0.01
MnO	0.000–0.017	0.00–0.01
Cr_2O_3	0.000–0.009	0.00–0.01

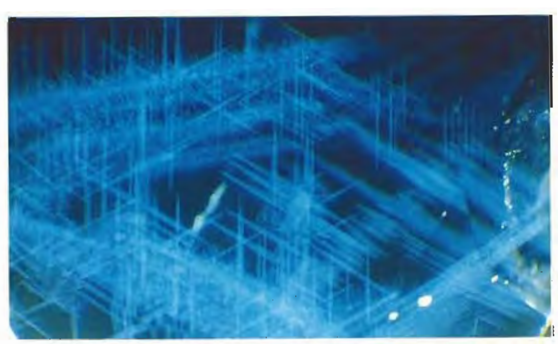
[a]*Analyses conducted on 53 specimens by EDXRF. See "Materials and Methods" section for details.*

these needles extended in only one direction (figure 20), but they extended in two or three directions in a small number of stones. Occasionally, these inclusions were orange-brown when penetrated by late-forming minerals that have resulted from weathering, such as kaolinite (refer to the "Infrared Spectrometer" section below).

While not generally found in basaltic sapphires, very fine needles (presumably of rutile or ilmenite) have been documented in corundum from other basaltic sources, such as Thailand (Schlüssel, 1991). We observed similar-appearing inclusions in a small number of the sapphires from southern Vietnam, but we were not able to analyze them to determine their true identity.

Relatively few crystalline inclusions were observed in the sapphires examined. To date, we have identified a total of nine different mineral inclusions by SEM-EDS and/or X-ray diffraction analysis (again, see table 1). Most common were transparent colorless crystals of plagioclase feldspar (figure 21), which appeared in a variety of forms, including flat and tabular, oblong and prismatic, as well as more equidimensional shapes. Curiously, some of these transparent, colorless crystals had their own inclusions (again, refer to figure 21). Prismatic crystals of zircon were accompanied by small stress fractures, and "comet tail" inclusions—caused by growth disturbances within the host sapphire—trailed some crystals. In several sapphires, we identified octahedral crystals of uranpyrochlore, many of which were surrounded by radiation-damage "halos" oriented parallel to the basal crystal planes (fig-

Figure 18. Some of the more distinctive inclusion features consisted of unique cross-hatch (left) to lath-like (right) cloud patterns, composed of individual whitish particles which resemble thin "blades" or very fine acicular crystals. Left: Darkfield illumination, magnified 15×; photomicrograph by Dr. Eduard J. Gübelin. Right: Oblique fiber-optic illumination, magnified 25×.



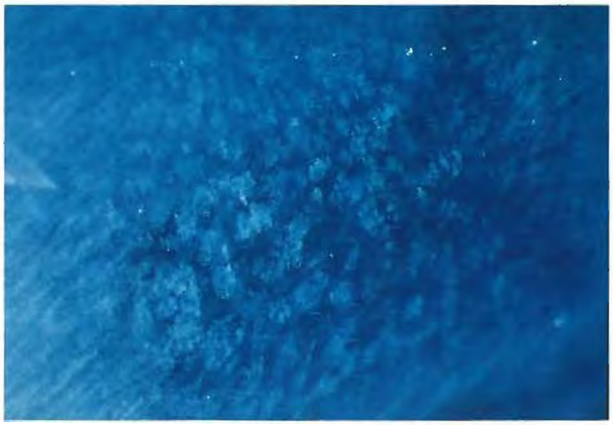


Figure 19. Snowflake-like inclusions were observed in a few of the sapphires from southern Vietnam. Oblique fiber-optic illumination, magnified 30×.

ure 22). Some of these crystals appeared bright orange to orange-red, whereas others were essentially black; some were well-formed octahedra, whereas others were slightly rounded or even broken fragments.

Opaque, black-appearing, euhedral-to-subhedral (massive, nondistinct) crystals were commonly observed. These were most frequently identified as columbite (figure 23) and ilmenite (figure 24), but some were pyrrhotite. Severely corroded crystals of magnetite-hercynite (spinel) had a "brassy" color and strong iridescence when illuminated with an intense fiber-optic light source. Smaller opaque, black, octahedral crystals were identified as chromite-hercynite (spinel). Table 1 gives the major and minor elements found in some of the mineral inclusions identified by SEM-EDS.

A wide variety of negative crystals were also observed. Some looked like translucent yellowish orange to orange-brown solid inclusions, having been completely filled—via associated fractures reaching the surface—by late-forming minerals such as goethite (figure 25). Healed fractures were particularly abundant (figure 26); often they, too, were yellowish orange to orange-brown as a result of epigenetic staining by iron-hydroxides.

Absorption Spectra. *Desk-model Spectroscope.* Within the visible range, a general absorption to approximately 425 nm was apparent, together with a series of strong absorption bands centered at about 450, 460, and 469 nm. The first two bands commonly overlapped and merged to form a single broad band. Such strong absorption characteristics

Figure 20. Needle-like inclusions extend in a single direction along the intersection of two systems of twin lamellae. Occasionally these fine tubules appeared yellow to brown when penetrated by kaolinite. Oblique fiber-optic illumination, magnified 25×.

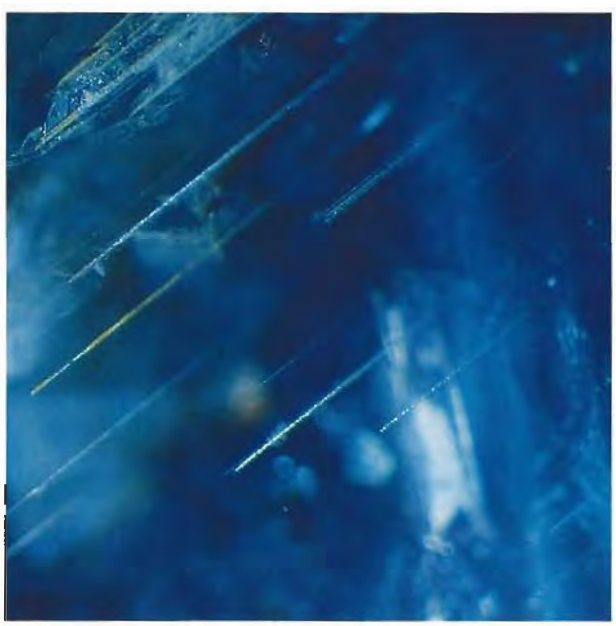


Figure 21. Transparent colorless crystals of plagioclase feldspar were the most frequently observed sizable mineral inclusion. These crystals were present in several shapes, including flat and tabular to more equidimensional forms. Some even had their own inclusions. Oblique fiber-optic illumination, magnified 50×.

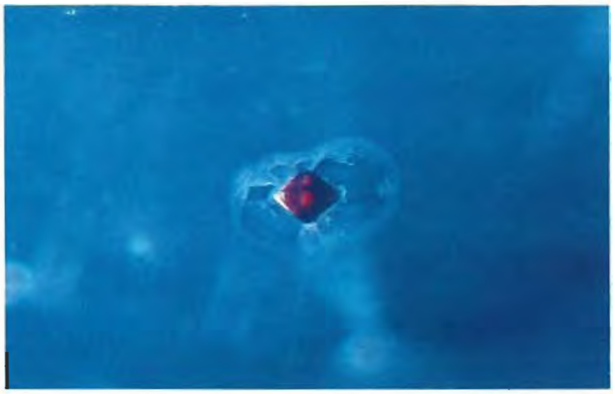


Figure 22. Uranpyrochlore crystals, common in sapphires from other basaltic occurrences, were identified in several of the sapphires from southern Vietnam. Typically, they appeared bright orange to orange-red and black. They were often associated with radiation-damage halos, which extended parallel to the basal growth planes. Oblique fiber-optic illumination, magnified 35×.

are typical of blue to bluish green sapphires with high iron contents.

UV-Vis-NIR Spectrometer. Because corundum is dichroic, the face-up color appearance of these faceted sapphires is essentially a consequence of the crystallographic orientation during cutting. Therefore, we will address all of the samples measured (blue to bluish green) as a single group when comparing their polarized spectra.

The spectra recorded had features typical of those seen in blue sapphire, with variations in the relative intensities of the absorption bands associated with the color-causing mechanisms (Fe^{3+}, $Fe^{2+} \leftrightarrow Ti^{4+}$, $Fe^{2+} \leftrightarrow Fe^{3+}$) observed (figure 27 a–c); however, the spectrum illustrated in figure 27c was by far the most common (seen in almost 80% of the stones examined). All spectra displayed prominent peaks in the ultraviolet region at 375 nm and 387 nm, as well as in the visible region at 450, 460, and 469 nm, which are all related to pairs of trivalent iron (Fe^{3+}; see, e.g., Emmett and Douthit, 1993). Typically, no distinct variation was observed in these bands in the spectra parallel and perpendicular to *c*, although a weak "shoulder" was occasionally seen at the base of the 375-nm peak (at about 380 nm) perpendicular to *c*.

Blue coloration in sapphire is essentially caused by intervalence charge-transfer processes (IVCT) of the ion pairs $Fe^{2+} \leftrightarrow Ti^{4+}$ and $Fe^{2+} \leftrightarrow Fe^{3+}$ (see, e.g., Fritsch and Rossman, 1987, 1988a and b; Fritsch and Mercer, 1993). Because these absorption bands are highly pleochroic, they cause a shift in the position of the absorption maxima perpendicular and parallel to the c-axis (see, e.g., Schmetzer and Bank, 1980; Kiefert, 1987; Schmetzer, 1987).

Infrared Spectrometer. In addition to showing the dominant absorption characteristics of corundum

Figure 23. The southern Vietnam sapphires also contained groups of black-appearing acicular columbite crystals. The thinner "rods" displayed a rich red color along the edges when viewed with a pinpoint fiber-optic light source. Magnified 42×.

Figure 24. Opaque, black crystals of ilmenite—observed in different euhedral to subhedral forms—were another addition to the diverse mineral inclusions found in the southern Vietnam sapphires. Oblique fiber-optic illumination, magnified 35×.

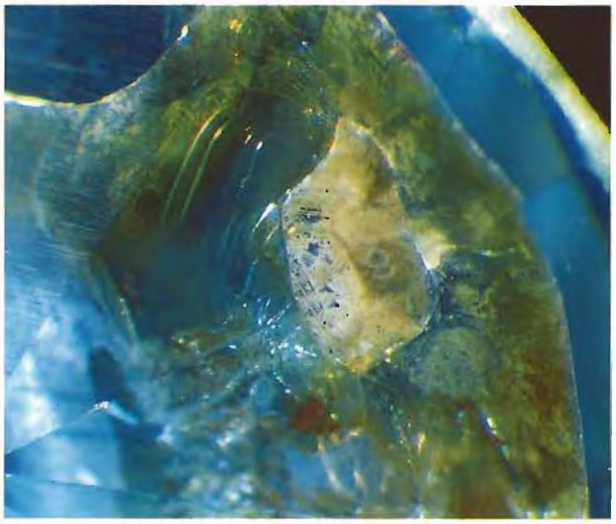


Figure 25. Staining was commonly observed in the fracture systems, as was the filling of negative crystals—a result of the epigenetic penetration by late-forming minerals such as goethite. Oblique fiber-optic illumination, magnified 30×.

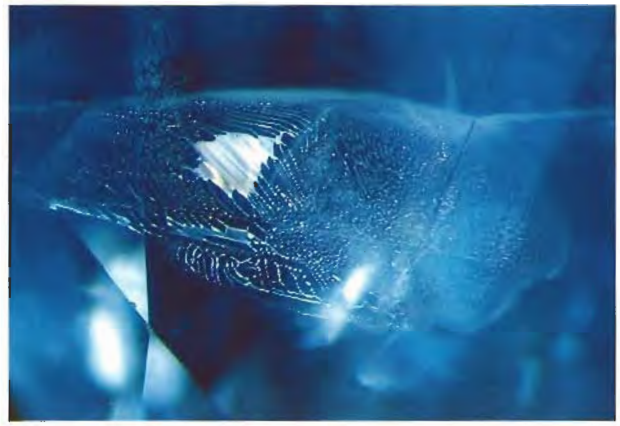


Figure 26. Healed fractures were common in the sapphires from southern Vietnam. Oblique fiber-optic illumination, magnified 35×.

between approximately 300 and 1000 cm^{-1} (peak positions at about 760, 642, 602, and 450 cm^{-1}; Wefers and Bell, 1972), these (non-heat-treated) sapphires revealed a series of absorption peaks in the 2500–4000 cm^{-1} region. The strongest was centered at about 3309 cm^{-1}, typically with a shoulder at about 3293 cm^{-1}. Additional peaks were seen at about 3232 and 3189 cm^{-1}, with very minor peaks at about 3367 and 3269 cm^{-1} (figure 28). Generally, only the 3309 and 3232 cm^{-1} peaks were present. This region of the spectrum identifies structural OH groups bound to various trace elements (i.e., vanadium, titanium, iron, or magnesium) in the corundum structure (Volynets et al., 1972; Berán, 1991). Additionally, the mineral kaolinite was indicated in fracture systems (again, see figure 20) by the presence of four OH absorption peaks at approximately 3697, 3669, 3652, and 3620 cm^{-1} (Häger and Greiff, in preparation).

Chemical Analysis. EDXRF analysis revealed aluminum (Al) as the sole major element, which is consistent with the chemical formula of corundum (Al_2O_3). Oxygen (O), with an atomic number of 8 (too low to be detected by this method), is assumed to be stoichiometric. Typical of basaltic sapphires, iron (Fe) was the most significant minor element, present as an impurity. Necessary to the color-causing mechanism in blue sapphires ($Fe^{2+} \leftrightarrow Ti^{4+}$), titanium was the next most important trace element recorded, followed by measurable concentrations of gallium (Ga). Other trace elements were sometimes present in negligible amounts, including V, Cr, and Mn. The complete chemical data are given in table 2.

DISCUSSION

In general, the blue to bluish green sapphires from southern Vietnam have properties and characteristics similar to those of sapphires from other alkali basalt environments, including Australia (Coldham, 1985), Cambodia (Jobbins and Berrangé, 1981), China (Keller and Keller, 1986; Wang, 1988; Guo et al., 1992b), Nigeria (Kiefert and Schmetzer, 1987), and Thailand (Vichit et al., 1978; Schlüssel, 1991).

Prominent growth structures and color zoning—in parallel, straight, or angular to geometric patterns—established the crystal morphology. The internal growth structures of the southern Vietnam sapphires are similar to those of sapphires from other basaltic deposits around the world (Kiefert and Schmetzer, 1987; Kiefert, 1987; Kiefert and Schmetzer, 1991b). Although a "stepped" occurrence of *c* and *r* faces, as described by Kiefert and Schmetzer (1987) for basaltic sapphires from Nigeria, was also occasionally present in the sapphire from Vietnam, it was not as dominant as that illustrated for Nigerian material. Color zoning in the southern Vietnam sapphires was even more distinctive than the growth structures: strong, sharply bordered blue color banding that alternated with narrow, colorless bands or yellowish to brownish bands parallel to the crystal planes *r* and *z*. In addition, many of the sapphires revealed a colorless "core."

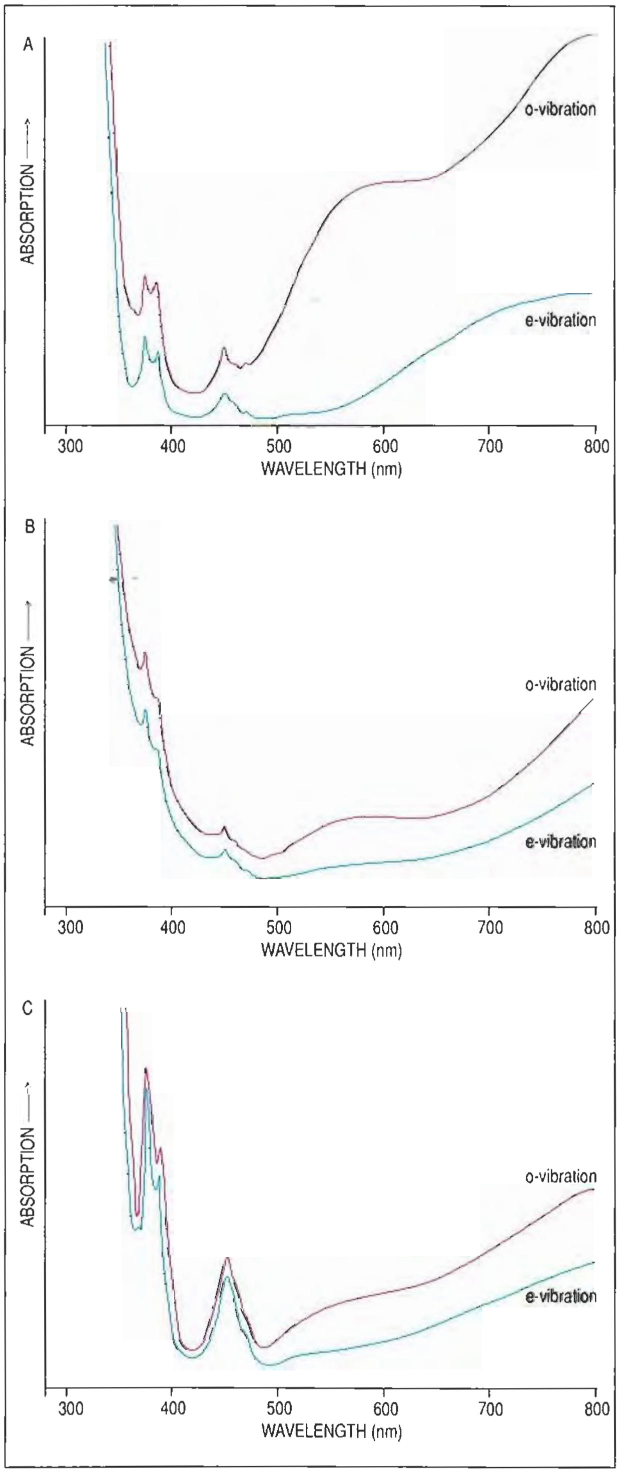


Figure 27. These three sets of UV-visible spectra are representative for the blue to bluish green sapphires from southern Vietnam. Typical of sapphires from basaltic sources, they are dominated by three essential absorption mechanisms (Fe^{3+}, $Fe^{2+}\leftrightarrow Ti^{4+}$, and $Fe^{2+}\leftrightarrow Fe^{3+}$). Sharp bands in the ultraviolet at 375 and 387 nm, as well as in the visible region at 450 nm, with bands at 460 and 469 nm, are the result of trivalent iron (Fe^{3+}) absorption. Charge-transfer absorption by $Fe^{2+}\leftrightarrow Ti^{4+}$ is responsible for the absorption maximum between 550 and 600 nm in the ordinary spectrum (vibrational direction perpendicular to the c-axis) and approximately 680 to 750 nm in the extraordinary spectrum (parallel to the c-axis). ($Fe^{2+}\leftrightarrow Fe^{3+}$ charge transfers account for maxima in the region between approximately 870 and 890 nm, seen in these spectra as a general trend of increasing absorption toward the near-infrared.)

Various types of "clouds" were the most common inclusions observed. Although the very fine-grained whitish clouds may be seen in sapphires from other sources (e.g. Kashmir, Australia, Cambodia, or Sri Lanka), the cross-hatch or lath-like patterns have not been seen in other sapphires. The dust-like "snowflake" inclusions encountered occasionally appeared similar to those documented for sapphires from Kashmir (Schwieger, 1990).

The very fine, whitish needles (presumably rutile or ilmenite) seen in our samples lacked the well-formed, strongly iridescent appearance of the rutile needles and platelets observed in sapphires from metamorphic environments such as Sri Lanka and Burma (see, e.g., Gübelin and Koivula, 1986).

All of the mineral inclusions identified—plagioclase feldspar, zircon, uranpyrochlore, columbite, ilmenite, pyrrhotite, chromite-hercynite and magnetite-hercynite (solid-solution-series spinels), as well as goethite—have been observed and identified in sapphires from other basaltic sources (see, e.g., Gübelin and Koivula, 1986; Kiefert, 1987; Kiefert and Schmetzer, 1987; Guo et al., 1992a; Guo, 1993).

The UV-Vis-NIR absorption spectra obtained for our samples are typical of sapphires in general and, more specifically, of basaltic sapphires, particularly in relation to the absorption bands toward the near-infrared region resulting from $Fe^{2+}\leftrightarrow Fe^{3+}$ IVCT. This particular color-causing mechanism is absent in sapphires of metamorphic origin (such as

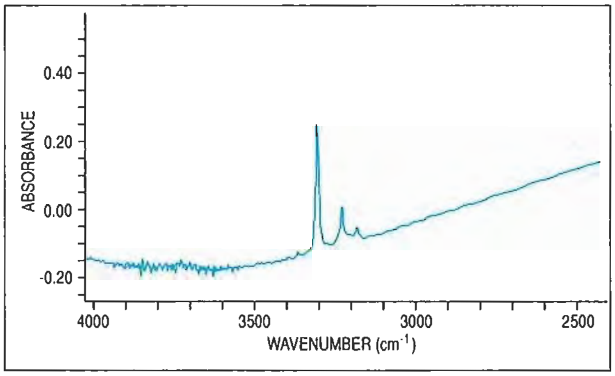


Figure 28. The infrared spectra of the (non-heat-treated) basaltic Vietnamese sapphires typically revealed a series of distinct absorption peaks. These absorption features are related to structural OH groups within the sapphire. Spectra recorded on a Pye-Unicam 9624 FTIR spectrophotometer.

those from Sri Lanka, Myanmar, or Kashmir), although it can be produced to a minor degree in metamorphic sapphires through heat treatment (Schmetzer, 1987). It has been suggested that the trends of certain spectral curves in the region 280–880 nm might aid in identifying sapphires from specific basaltic deposits around the world (see, e.g., Poirot, 1992). The great variability in spectra recorded in this sample, however, is in agreement with Schmetzer (1987,) and strongly suggests the need for care when attempting to use these properties to identify a basaltic sapphire's possible country of origin.

The structural OH groups recorded in the mid-infrared region of the spectrum of the southern Vietnam sapphires are the same as those commonly recorded in sapphires of basaltic origin (e.g., Moon and Philips, 1994). However, these absorption peaks have also been documented in non-basaltic corundums as well as in Verneuil and hydrothermally grown synthetic corundum (for further reference, see Smith, 1995, pp. 326–328).

The EDXRF results are consistent with those chemical analyses reported for sapphires from other basaltic sources (Pearson, 1982; Tombs, 1991; Guo et al., 1992b; Guo, 1993).

At present, many researchers believe that sapphires found in association with alkali basalts did not form from the basalts themselves (e.g., Coenraads et al., 1990; Coenraads, 1992b; Guo et al., 1992a, 1994; Levinson and Cook, 1994). A comparison of the internal growth structures and the condition of the external surface features in our sample supports this thesis: that is, that the sapphires did not form in those (highly aggressive) magmas; rather, the basalts merely acted as the transport mechanism by which the sapphires were brought to the surface.

Some blue sapphires are also known to come from the predominantly ruby-producing areas of Luc Yen and Quy Chau in northern and central Vietnam (respectively). However, both of these sources are metamorphic, so the properties of these sapphires are undoubtedly more similar to those from metamorphic sources.

CONCLUSION

Since their initial discovery in the late 1980s, thousands of carats of blue to bluish green sapphires from southern Vietnam have entered the world gem market. The secondary deposits from alkali basalts in Binh Thuan and Lam Dong provinces were at the height of their production in 1991 and 1992, when virtually thousands of Vietnamese flocked to these areas to mine for the corundums. Largely because miners were not able to realize the same financial returns as in the ruby-producing sources in central and northern Vietnam (Quy Chau and Luc Yen), but also because of government efforts to control the gem-producing regions, most current efforts are by groups of independent miners, usually small scale. The mixing of synthetic gem materials with natural ones has plagued the sapphire-producing regions in Vietnam just as it has the ruby-producing localities: Three of the authors were offered flame-fusion synthetic blue sapphires as natural while at the mining sites.

The combination of absorption spectrum and internal characteristics determined for the southern Vietnam sapphires should provide a clear and ready means of separating them from their synthetic counterparts. This collection includes the various "cloud" patterns and mineral inclusions observed, as well as the internal growth structures and color zoning. In most cases, these sapphires can be readily separated from sapphires of metamorphic (marble-type) sources such as Sri Lanka, Kashmir, and Burma, because of the comparatively higher iron contents present in basaltic sapphires and the properties that high Fe influences (i.e., mineral inclusions, spectra, and chemistry). Separating these sapphires from those of other basaltic sources is more difficult. Nevertheless, there were certain inclusion features found in our samples—cross-hatch or lath-like "cloud" patterns, the distinctive color zoning, and the colorless "core"—that we have not seen in sapphires from other basaltic sources. These may prove useful for such separations in the future.

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