THE YOGO SAPPHIRE DEPOSIT

By Keith A. Mychaluk

Yogo Gulch, discovered more than 100 years ago, is one of four major sapphire-producing areas in Montana, United States. Yogo sapphires are known for their uniform, well-saturated blue color; relative absence of inclusions and zonation; and high luster and brilliance in both artificial and natural light; they do not require heat treatment. Rough crystals, usually flat with low cutting retention, generally weigh less than one carat (but have been reported up to 19 ct). Unlike the other Montana deposits, which are secondary, Yogo sapphires are mined directly from a lamprophyre host rock. There are at least six known dikes, five sapphire-bearing, at Yogo. From 1895 to 1994, the Yogo deposit produced an estimated 18.2 million carats of rough that are believed to have yielded more than 500,000 carats of cut stones. Considerable reserves remain.

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The state of Montana, in the western United States, hosts several large and economically important sapphire deposits. The four major deposits—at Yogo Gulch, Missouri River, Rock Creek, and Dry Cottonwood Creek—were all discovered in the late 1800s by gold prospectors. Three of the deposits are large secondary (placer) occurrences for which the original source rocks have not been conclusively identified. At Yogo Gulch (henceforth referred to as Yogo), however, the sapphires are found *in situ* in a lamprophyre dike system, with only minor related placer deposits. Yogo is one of the few major sapphire mines worldwide where sapphires are extracted directly from their host rock.

Not only are Yogo sapphires unique among Montana sapphires in terms of deposit type, but they also exhibit distinctive gemological features. The vast majority of Yogo sapphires are naturally the same uniformly saturated blue (figure 1), whereas sapphires from the placer deposits of western Montana are predominantly pale green, blue, or yellow before heat treatment. The relative absence of inclusions, fractures, and color zoning also distinguishes Yogo sapphires from other Montana sapphires.

Unlike sapphire-producing areas elsewhere in the state, which have received little geologic investigation since the significant contribution made by Clabaugh (1952), Yogo Gulch has been studied since the late 1970s by various geologists (see, e.g., Meyer and Mitchell, 1988; Brownlow and Komorowski, 1988; Dahy, 1988, 1991; and Baker, 1994).

The author was the first geologist to study the Vortex mine, an extension of the Yogo sapphire deposit developed in 1987 (Mychaluk, 1992). Between 1990 and 1992, the author collected and studied 200 rock and 100 rough sapphire samples from the Vortex mine and tailings from the nearby English and American mines. Representative samples of various rock types, and the minerals separated from them, were examined by thin-section microscopy and X-ray diffraction analysis. The author also analyzed core-drilling logs and samples from drill holes made by Vortex Mining Company in 1993. Further, the author visited the Vortex mine many times between 1990 and 1995, and was the first

Figure 1. The sapphires from the historic deposit at Yogo Gulch, Montana, are noted for their deep, uniform color and their brilliance when cut. Unlike most sapphires on the market today, they are not heat treated. Typically, though, they are small (the rough averages less than 1 ct). The loose Yogo sapphires illustrated here weigh 0.93—1.34 ct; they and the pin set with Yogo sapphires are courtesy of Mac Mader and American Gem Corp. The Yogo sapphire in the ring weighs 1.04 ct; it is courtesy of Robert E. Kane. Photo © Harold & Erica Van Pelt.

geologist to view the lowest workings of the 61-m-deep mine in 1994 .

This article reviews the history of the sapphire deposit at Yogo Gulch and the distinctive gemological properties of the sapphires. The geology and occurrence of the sapphires is discussed, including examination of various theories as to how they were formed and emplaced. Attention is also given to historical production and ore-grade variability of the entire Yogo deposit.

LOCATION AND ACCESS

The Yogo Gulch sapphire deposit is located about 25 km (15 miles) southwest of Utica, Montana, in Judith Basin County (figure 2). The deposit lies within the legal land description of T.13.N, R.11.E, sections 20 through 24, on the northeastern flanks of the Little Belt Mountains; it is about 33 km (20 miles) from the historic lead-zinc-silver mining camps of Neihart and Hughesville. The mine is accessible all year by U.S. Forest Service gravel roads leading south from Utica. Utica itself is located on Montana Route 239, approximately 28 km (17 miles) southeast of Stanford, the county seat, and roughly 125 km (78 miles) southeast of Great Falls.

The eastern portion of the deposit is located in grass-covered rolling hills, whereas the western portion is situated in rugged and heavily forested terrain. Yogo Creek, in Yogo Gulch, flows across the deposit in the west and has carved a canyon through ancient limestone formations. Yogo Creek is a tributary of the Judith River, which in turn flows into the Missouri River.

Figure 2. This map of Montana shows the locations of the state's four major sapphire-producing localities: (1) Yogo Gulch, (2) Missouri River (Eldorado, Spokane, French, Gruell's, Cheyenne, Dana's, and American bars), (3) Rock Creek, (4) Dry Cottonwood Creek. Modified from Zeihen, 1987.

HISTORY OF MINING AT YOGO GULCH

Sapphires were first discovered in Montana—in the Missouri River near Helena—on May 5, 1865, by Ed Collins. Gold prospectors later found sapphires in Dry Cottonwood Creek north of Butte in 1889, and in Rock Creek near Philipsburg in 1892 (Clabaugh, 1952; again, see figure 2). In general, the sapphires from these three deposits proved to be of low-saturated colors; natural, deep blue stones were rare. However, the last significant sapphire discovery in Montana, at Yogo Gulch in 1895, yielded superb blue stones. The history and general geology of Yogo are discussed in detail by Clabaugh (1952) and Voynick (1987a). Except as noted, the author has drawn the following account from these two authors.

Placer gold was discovered by prospectors in the upper end of Yogo Creek in 1866, but the area was not given serious attention until 1878. Several more years passed before, in 1895 gold prospector Jake Hoover began to collect the translucent blue stones that were being trapped in his sluices in lower Yogo Creek. He sent samples to an assay office, which then forwarded them to Dr. George F. Kunz, at Tiffany & Co. in New York City (Clabaugh, 1952). The stones were identified as sapphires of unusual quality, and Kunz sent Hoover and his partners a check in the amount of $3,750 (about twice what his gold operation had paid). This figure was based on the current London prices paid for rough sapphires from Southeast Asia: $6 per carat for first-quality stones, $1.25 per carat for second quality, and $0.25 per carat for everything else (Voynick, 1987a). Tiffany & Co. eventually became an important buyer of Yogo sapphires and manufactured some important pieces of reportedly Yogo sapphire jewelry, including the famous Iris Brooch (figure 3).

In 1896, Jim Ettien, a local sheep herder, discovered several hundred carats of sapphires around badger and gopher burrows aligned along a linear depression that marked the surface exposure of an igneous dike (now called the "A" dike; see figure 4) on the flatlands above Yogo Creek (Weed, 1899). He staked the first claims to the dike that year. Soon others, notably John Burke and Pat Sweeney, staked more claims to the dike. By 1897, Hoover and his partners had bought out Ettien's claims and formed the New Mine Sapphire Syndicate.

In 1898, London gem merchants Johnson, Walker and Tolhurst Ltd., acquired the majority interest in the New Mine Sapphire Syndicate and began an intensive mining and marketing effort. They initially concentrated on removing sapphire-bearing ore from surface outcrops of the middle section of the A dike by means of hydraulic mining; this area is now referred to as the English Cut (figure 5). By 1902, the syndicate had two underground operations, the English (or British) mine and the Middle mine, working the dike.

The American Sapphire Company of New York began operations on the western third of the A dike by purchasing Burke and Sweeney's claims in 1904; it opened the American mine—also underground—in 1905 (Clabaugh, 1952). In 1909, its capital exhausted, the firm reorganized as the Yogo American Sapphire Company. The New Mine Sapphire Syndicate acquired Yogo American in 1914. Although the syndicate never reopened the American mine, they recovered the $80,000 purchase price under the supervision of the company's renowned mine manager, Englishman Charles Gadsden, by reworking the mine's tailings.

The New Mine Sapphire Syndicate continued underground mining at the English and Middle mines until 1923, when a severe storm destroyed equipment and infrastructure alike. The operation continued by processing stockpiled ore until 1929, when economic factors (including the loss of the market for industrial-quality corundum to synthetics, and taxation by both the U.S. and British governments) finally forced it to close. After more than 25 years of inactivity, the New Mine Sapphire Syndicate sold the property to American interests in 1955. Total production from 1895 to 1929 amounted to 16 million carats of sapphires, of which about 2.25 million carats were gem quality—with an estimated value between $20 million and $30 million (in 1952 dollars; Clabaugh, 1952).

Figure 3. One of the most famous pieces of Yogo sapphire jewelry is this "Iris Brooch," a corsage ornament containing 120 Yogo sapphires (as well as diamonds, demantoid garnets, and topaz) that was manufactured by Tiffany & Co. at the turn of the century. Photo courtesy of the Walters Art Gallery, Baltimore, Maryland.

Various groups attempted to reopen Yogo between 1955 and 1968, but met with little success; the geology of the deposit was not well understood, mining costs were high, and marketing was limited. In 1968, Sapphire Village Inc. purchased the property. The firm raised capital by subdividing agricultural land near the mine and selling the residential lots with the right to dig limited quantities of sapphire-bearing ore from the eastern portion of the A dike (Voynick, 1987a). In 1972, Chikara Kunisaki bought out the other shareholders of Sapphire Village and formed Sapphire International Corp. The Kunisaki Tunnel, which reportedly cost $5 million to construct, was driven eastward into the A dike at the old American mine site. The operation proved uneconomic and in 1978 was leased to a new venture, Sapphire-Yogo Mines. Full-scale mining never materialized, and the property was returned to Sapphire International the following year (Voynick, 1987a).

Colorado-based Intergem Inc. leased the property from Sapphire International from 1980 to 1986. Intergem's mining effort focused on the eastern portion of the A dike, now known as the Intergem Cut (figure 4; Dahy, 1988). Intergem also expanded into jewelry manufacturing and made a serious attempt to reestablish Yogo sapphires in the U.S. market. As a result of an aggressive promotional campaign, which guaranteed that their sapphires were not heat treated, Intergem sold 4,000 carats of cut sapphires and $3 million of finished jewelry in 1984 (Voynick, 1987a). However, higher taxes, greater regulation by the state government, and persistent financial problems forced Intergem into insolvency in 1986 (Voynick, 1987a). Ownership of the property again returned to Sapphire International, now called Roncor, in 1987.

Since 1987, Roncor has been reworking tailings and unprocessed ore left over from the Intergem era. Roncor, like Intergem, is vertically integrated: It not only mines Yogo sapphires, but it also manufactures jewelry. It, too, guarantees that the sapphires are not heat treated. In 1993, Roncor signed a two-year, $2 million agreement with AMAX Inc. (now Cyprus-AMAX Inc.) to help evaluate the potential of the Yogo deposit (Verbin, 1993). Cyprus-AMAX has since removed an 8,000-ton bulk sample from two inclines driven into the A dike—one at the Middle mine and the other along the Intergem Cut (L. Perry, pers. comm., 1995). The

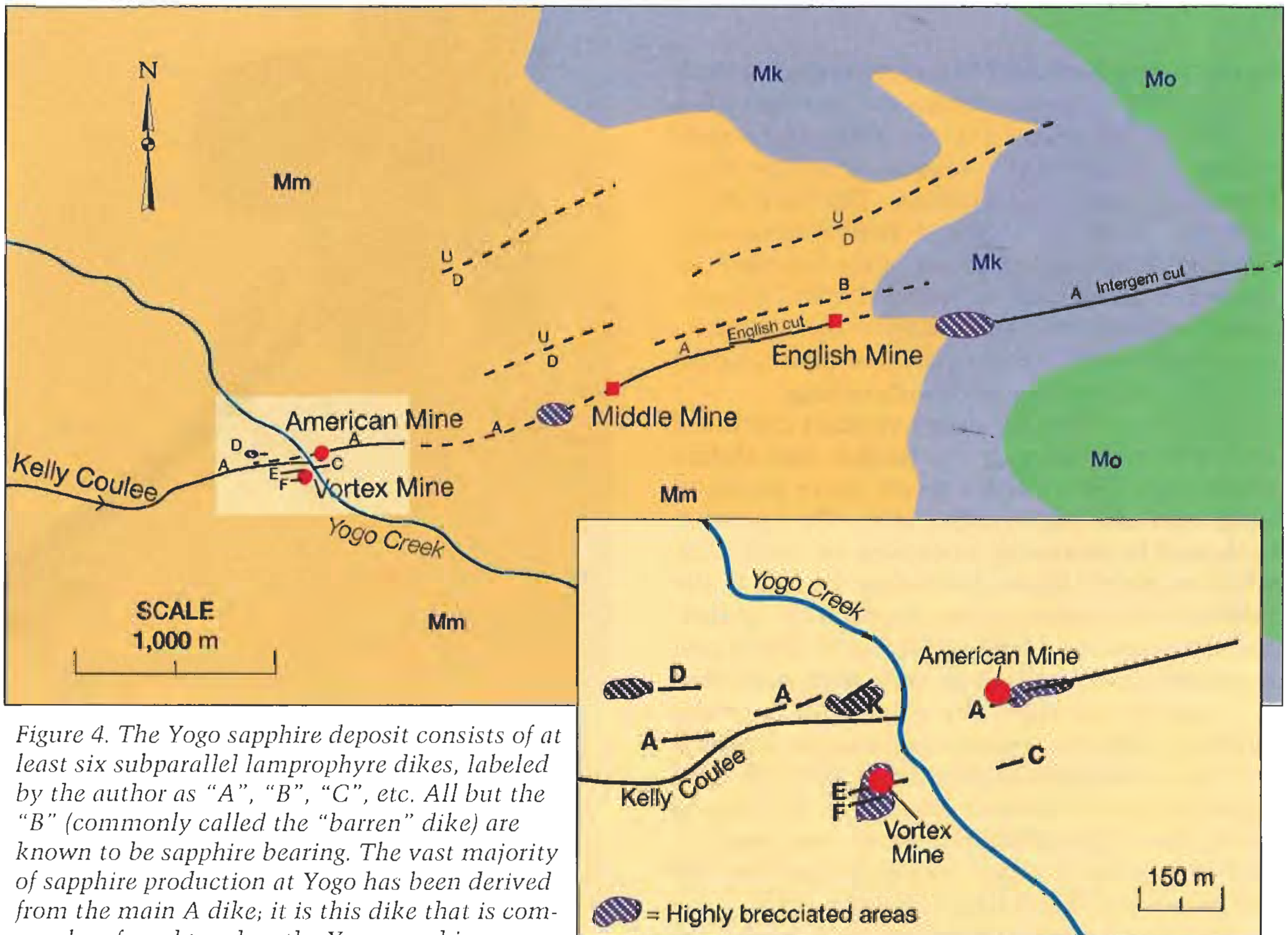


Figure 4. The Yogo sapphire deposit consists of at least six subparallel lamprophyre dikes, labeled by the author as "A", "B", "C", etc. All but the "B" (commonly called the "barren" dike) are known to be sapphire bearing. The vast majority of sapphire production at Yogo has been derived from the main A dike; it is this dike that is commonly referred to when the Yogo sapphire deposit is discussed. The inset provides detail on the area that is currently active. The dike system has intruded into limestone of the Mission Canyon formation (Mm) and shales of the younger Kibbey (Mk) and Otter (Mo) formations, probably along a pre-existing fault or fracture. Dahy (1988) mapped several faults paralleling the dike system to both the north and south (where upthrown side = U and downthrown side = D). Map modified from Dahy (1991).

sample was partially processed during the summer of 1994 at Roncor's on-site plant (P. Ecker, pers. comm., 1994), but the results are confidential. Cyprus-AMAX was unable to negotiate a new lease arrangement with Roncor; their lease expired on January 31, 1995. (P. Ecker, pers. comm., 1995).

Figure 5. The sapphire-bearing A dike, which has produced the bulk of Yogo sapphires, averages 2.4 m wide and has a known length of 5 km (not continuous). The upper portions have weathered to a soft clay-like material. The A-dike section shown here was hydraulically mined by the British New Mine Sapphire Syndicate at the turn of the century; it is now referred to as the English Cut. Photo by the author.

Figure 6. Yogo blue sapphires are known for their well-saturated color and brilliance when faceted. These three stones, which range from 0.50 to 1.69 ct, were cut from Vortex mine material. Courtesy of Vortex Mining Co.; photo © GIA and Tino Hammid.

Figure 7. A small portion of Yogo sapphires are violet to purple, like the 1.27-ct stone shown here with two blue Yogo counterparts (2.22 and 2.77 ct). Note that all three stones are rounded, without distinct crystal faces. This is typical of the Yogo rough. Courtesy of Vortex Mining Co.; photo © GIA and Tino Hammid.

The Vortex Mining Company was formed in 1984 by a group of local Utica, Montana, prospectors. Vortex's exploration effort resulted in significant discoveries on the west end of the deposit, including several new sapphire-bearing dikes and associated brecciation zones (Voynick, 1987a and b; Dahy, 1988, 1991; Mychaluk, 1992). The Vortex mine began operations in 1987, and it is currently the only active underground mine at Yogo. Vortex Mining is also involved in jewelry manufacturing as well as mining. Both Roncor and Vortex Mining continue to market Yogo sapphires as the world's only sapphire that is guaranteed not to be heat treated.

GEMOLOGICAL CHARACTERISTICS

Color. Yogo sapphires are famous for their uniform blue color, general absence of inclusions and zonation, as well as for their vivid luster and brilliance in both artificial and natural light (see, e.g., figures 1, 3, and 6). Approximately 97% of all Yogo sapphires are "cornflower blue" and 3% are various shades of violet or purple (D. Brown, pers. comm., 1995; figure 7). George F. Kunz used the term *cornflower blue* to describe the color of Yogo sapphires, referring to the common garden flower of that name (*Centaurea cyanus*). Stones with distinct red, pink, or green hues are extremely rare and are usually too small for faceting (M. Ridgeway, pers. comm., 1993). Hughes (1990) stated that Intergem recovered only two "true" rubies and 10 green sapphires from 300,000 carats of Yogo rough, none of which were suitable for faceting. New Mine Sapphire Syndicate mine manager Charles Gadsden found only three or four rubies between 1895 and 1929 (Clabaugh, 1952).

Because Yogo sapphires are typically a well-saturated, uniform blue—rather than pale or zoned—it has not been necessary to heat treat the stones for the commercial market (Voynick, 1987a; L. Perry, pers. comm., 1994). Hughes (1990, p. 305) stated, "More amazing than the color itself is the great consistency of color from one stone to the next. Virtually all are of the same even-blue hue." It is

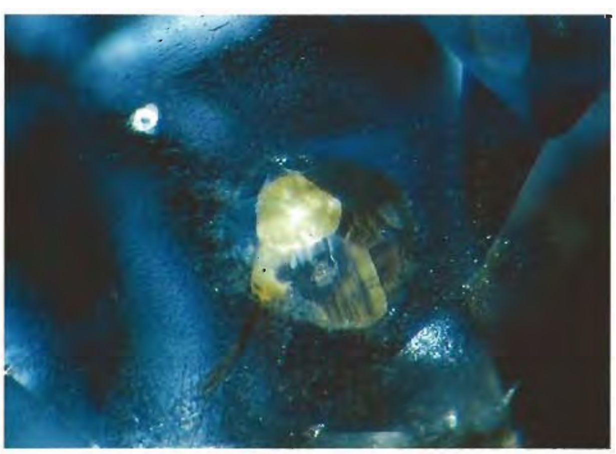
Figure 8. Some Yogo sapphires show a distinct alexandrite effect, like the approximately 1-ct stone in the center of this photo. It changes from purple (similar to the stone on the right) in incandescent light to blue (similar to that of the stone on the left) in day or fluorescent light. Photo by John I. Koivula.

this blue color that has been likened to that of sapphires from Kashmir (Sinkankas, 1976), although other gemologists find that the color appearance of Yogo sapphires is very distinctive (R. E. Kane, pers. comm., 1993).

Dichroism in Yogo sapphires can be quite pronounced (Clabaugh, 1952; Allen, 1991): light green perpendicular to the c-axis, blue parallel to the c-axis. Some chromium-bearing Yogo sapphires exhibit an alexandrite effect, appearing blue in day or fluorescent light and red (Baker, 1994) or purple (figure 8; J. I. Koivula, pers. comm., 1995) under incandescent light.

Inclusions. Yogo sapphires also have few detracting inclusions (Zeihen, 1987; Brownlow and Komorowski, 1988; Hughes, 1990). Gübelin and Koivula (1986) did note small inclusions of pyrite, dark mica, calcite, analcime (figure 9), and rutile (figure 10). Dunn (1976) also identified inclusions of spinel. Gübelin and Koivula (1986) reported that many Yogo inclusions appear similar to those found in Thai rubies, a conclusion later supported by Hughes (1990).

Figure 9. Although most Yogo sapphires are relatively clean, inclusions of analcime have been seen in many stones. Photomicrograph by John I. Koivula; magnified 40×



Crystal Shape and Size. Dominant crystal forms are short rhombohedral prisms terminated by the basal pinacoid (Clabaugh, 1952; Hughes, 1990; DelRe, 1994), although Yogo sapphires typically show little evidence of their original crystal shapes (again, see figures 7 and 8). Most of the stones recovered are rounded (figure 11), chipped, abraded, pitted, or broken into shards and wafers. The apparent modification of the original crystal shapes has been explained by partial dissolution (resorption) by the host magma (Clabaugh, 1952; Dahy, 1988), mechanical abrasion during dike emplacement and brecciation (Mychaluk, 1992), and to some extent by mining and recovery methods (e.g., blasting and crushing of the ore). It should be noted, though, that most Yogo sapphires also have "flat" shapes, as indicated by the crystal faces that can still be seen. Intergem consulting geologist Delmer Brown (pers. comm., 1995) has hypothesized that, because the specific gravity of the sapphires is greater than that of the host rock, only crystals of this shape (i.e., lower mass) wafted to the top; possibly, mining deeper in the dike will reveal more euhedral and fewer flat crystals. Chemical reactions between the sapphires and iron in the magma have also created dark green hercynite ($FeAl_2O_4$) reaction rims around some of the sapphires (Clabaugh, 1952).

Figure 10. Another inclusion seen in some Yogo sapphires is rutile. Photomicrograph by John I. Koivula; magnified 30×

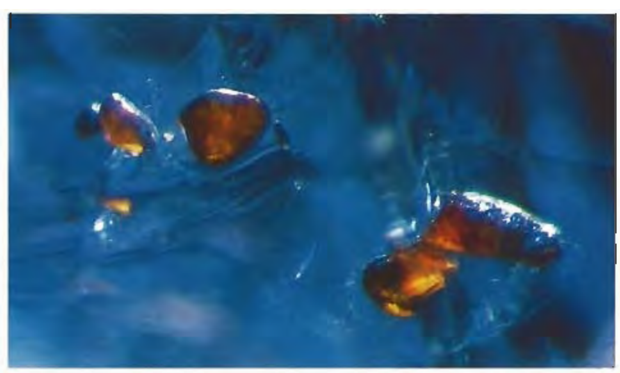


Figure 11. Rough Yogo sapphire crystals often appear rounded, broken, or flattened. The Vortex mine specimen shown here is a classic example of a Yogo sapphire that was chemically rounded (actually, partially resorbed) during transportation in the host magma. The faceting-quality sapphire measures 5 mm long × 2 mm deep. Photo by Maha DeMaggio.

Most rough Yogo sapphires weigh less than one carat, although stones up to 19 ct have been found. Clabaugh's list of some larger rough Yogo sapphires included individual stones weighing 10 and 12 ct. Nevertheless, Hughes (1990) stated that only 10% of the rough stones recovered from Yogo exceed one carat.

The flat shapes of most of the Yogo crystals recovered thus far is a major drawback for gem cutters. Cutting retention for a standard brilliant cut averages 20%. The largest rough Yogo sapphire, 19 ct (found in 1910), was reportedly cut into four stones, one of which weighed 8.5 carats (Clabaugh, 1952). According to Voynick (1987a), the largest known cut Yogo sapphire weighs 10.2 carats and is presently in the collection of the Smithsonian Institution. However, some gemologists feel—because of its inclusions—that the source of this stone has been wrongly identified. It has exsolution needles of rutile in a hexagonal zoned pattern, and large liquid-and-gas CO_2 fluid inclusions, both of which are not found in Yogo sapphires (J. I. Koivula, pers. comm., 1995).

GEOLOGY

Overview. The Yogo Gulch deposit has traditionally been described, for simplicity, as a single sapphire-bearing igneous dike (Clabaugh, 1952; Meyer and Mitchell, 1988; Dahy, 1988; Brownlow and Komorowski, 1988). However, the deposit actually consists of a complex set of subparallel lamprophyre dikes (a lamprophyre is a group of dark, porphyritic igneous rocks that usually contain phenocrysts of dark mica, pyroxene, or olivine in a fine-grained, crystalline groundmass and associated breccia zones. It appears that the emplacement of these dikes has been influenced by faulting and the development of karst in the host limestone (karst is a type of topography formed on or within limestone by dissolution; it is characterized by sinkholes, caves, and underground drainage). Six of the dikes, labeled "A" through "F" for the purpose of this article, are shown in figure 4 and discussed below.

Main (A) Dike. The A dike has produced the bulk of Yogo sapphires to date. Hence, before the author's research, it is the only dike that was studied in any detail. The A dike is about 5 km long and <1 to 6 m (average 2.4 m) wide (Clabaugh, 1952). The dike has intruded limestone (Mission Canyon formation) and shales (Kibbey and Otter formations), probably along a pre-existing fault or fracture. Only very limited contact-metamorphic effects are seen in the host rocks, indicating relatively quick emplacement and cooling. According to Dahy (1991), the dike may be separated into three *en echelon* (overlapping or step-like) segments in a zone oriented S75°W; each segment has been significantly mined, both on the surface and underground. The three original underground mines at Yogo—the English, Middle, and American—are all located on the A dike. They have provided the vast majority of geologic and mineralogic data available to date on the Yogo deposit.

"Barren" (B) Dike. The B dike lies approximately 183 m to the north of the A dike and runs parallel to it for about 1.6 km. The apparent absence of sapphires in this dike has been explained by the fact that it is a mafic lamprophyre (specifically, a minette), whereas thus far sapphires have been found only in ultramafic lamprophyre (Dahy, 1988). Given the limited sampling that has taken place to date, though, further research is needed to verify this theory.

C Dike. Approximately 46 m south of the A dike, near the American mine, is the sapphire-bearing C dike (Dahy, 1988). Discovered at the same time as the A dike, the C dike was not developed because it

Figure 12. The Vortex mine was first discovered around 1924, when a group of miners, related to the old Yogo American Sapphire Company, sank several prospect pits into this cliff. Vortex Mining Co. began development of the long-abandoned site in 1987. The main shaft, pictured here, has now reached a depth of 61 m. Sapphires are being recovered from at least one dike. Photo by the author.

is much thinner (15 cm) than the A dike (an average of 2.4 m wide). However, the American Sapphire Company recovered some sapphires from a small, 6-m-long, adit that was driven into it in 1902 (P. Ecker, pers. comm., 1994). There is no current production from this dike. Nor has any mineralogic or geologic description of the dike ever been published, although the author has observed that the dike material has been significantly altered by CO_2-rich ground water to yellow clay minerals.

D Dike. The D dike is located on the north rim of Kelly Coulee, at the west end of the Yogo deposit. Its orientation is slightly different—due east-west—from that of the other dikes described here (which are slightly inclined to the south; Voynick, 1987b). Vortex mined this dike in the mid-1980s. They found it to be approximately 0.6–1.2 m wide and proved a length of 152 m (P. Ecker, pers. comm., 1994). Like the C dike, all D-dike material has been altered to yellowish clay minerals; no original, unweathered dike rock has been found. As of 1987, the largest rough stone recovered from the D dike was 6 ct, whereas the largest cut stone weighed 2.4 ct (Zeihen, 1987). Currently, there is no mining activity at this dike.

E Dike. Across Yogo Creek from the American mine is the new Vortex mine (figure 12). This thin, highly weathered dike was initially discovered from a set of prospect pits made in 1924. Vortex Mining began development in 1987 (L. Perry, pers. comm., 1994). Subsequent work determined that the dike within the Vortex mine is not an extension of the main A dike, but rather is a separate dike, labeled "E" here (again, see figure 4). In the upper levels of the Vortex mine, the E dike is only a few centimeters wide; but along the 30-m section of dike currently exposed by mining at the 61-m level, the dike is about 0.5 m wide, strikes S45°W, and is highly weathered to a reddish brown color. According to core drilling, unaltered dike material exists at a depth below 100 m (total proven depth is 110 m). Currently, all Vortex mine production is derived from the E dike and associated breccia zones.

F Dike. In 1993, core drilling by Vortex Mining revealed this new dike. Although underground tunneling has not yet reached the F dike, drilling indicates that it is approximately 1 m wide and strikes S60°W, on an intersect angle with the E dike to the southwest. Like the E dike, F has been proved to exist as deep as 110 m.

Secondary Deposits. Erosion of the dike system has created minor secondary sapphire deposits. Colluvial deposits on hillsides below the English mine and English Cut were quickly mined out at the turn of the century by the New Mine Sapphire Syndicate (Voynick, 1987a). In addition, Yogo Creek cuts through the A dike at the American mine, and has scattered sapphires as far as 4 km downstream. However, the sapphire-bearing gravels within Yogo Creek have never been commercially mined (L. Perry, pers. comm., 1994). Because the secondary occurrences are so limited, Intergem believed that the primary deposit had only recently been exposed by erosion (Voynick, 1987a).

Figure 13. This photo clearly illustrates the effect weathering has had on Yogo sapphire-bearing rock. The greenish-gray sample of unweathered A-dike lamprophyre (from underground workings of the English mine) is composed of mica, pyroxene, analcime, and carbonates. The large circular feature is a carbonate-filled, pyroxene-rimmed vesicle; these vesicles were "bubbles" of an immiscible liquid within the Yogo magma. The reddish brown specimen is highly weathered material from the E dike within the Vortex mine; it consists of clays, carbonates, and some chlorite. After significant exposure to CO_2-rich ground water, the greenish-gray specimen would eventually look like the reddish sample. Because it is much easier to process weathered dike material, Yogo sapphire miners still (as they did 70 years ago) expose large piles of hard, unweathered Yogo dike ore to rain, snow, and frost to accelerate the decomposition process. Photo by Maha DeMaggio.

Mineralogy of the Dike Material. Mineralogic studies have shown that unweathered A-dike rock consists of phenocrysts of phlogopite and clinopyroxenes (augite) in a groundmass of analcime and various carbonates. Lesser amounts of titaniferous magnetite, ilmenite, apatite, zeolites, spinel, serpentine, and chlorite are also present, as are accessory sapphire, kyanite, garnet, and quartz (Clabaugh, 1952; Meyer and Mitchell, 1988; Brownlow and Komorowski, 1988; Dahy, 1988, 1991). For the most part, dike material from the Vortex mine has been altered to clay minerals by CO_2-rich surface and ground water. Analyses revealed that the weathered lamprophyre contained carbonates, clays (montmorillonite and kaolinite; both identified by X-ray diffraction analysis), biotite, chlorite, magnetite, goethite/hematite pseudomorphs after pyrite, and minor apatite, quartz, pyroxene, rutile, and feldspar, as well as accessory sapphire and kyanite (Mychaluk, 1992). Meyer and Mitchell (1988) classified the unweathered rock as an ultramafic lamprophyre, variety ouachitite (figure 13). Lamprophyres, like kimberlites and lamproites, are thought to have been generated at great depths. Accordingly, Dahy (1991) believed that the Yogo magma formed at 125 km depth (i.e., in the upper mantle), but the lamprophyre did not begin to crystallize until it approached the Earth's surface (Meyer and Mitchell, 1988).

Although field evidence only indicates an age younger than about 320 million years (My), the dike system itself is generally assumed to be approximately 50 My old and is a member of the central Montana alkaline igneous province (Meyer and Mitchell, 1988; Brownlow and Komorowski, 1988). The geologic province hosts a suite of alkaline (typically Si deficient and high in Mg and K), upper-mantle-derived rocks. These include kimberlites, lamprophyres, lamproites, shonkonites, and carbonatites, which comprise several major igneous centers and mountain ranges in central Montana (Baker and Berg, 1991).

Ore-Grade Variability. Although Clabaugh (1952) stated that the grade of the A dike is 20–50 carats per ton (ct/t), more recent mining activity has shown that the grade is even more variable and sporadic. In fact, within the Vortex mine alone the grade may range from zero to as high as 70 carats per ton (Mychaluk, 1992). Dahy (1988) believed that multiple episodes of magma intrusion occurred along the A dike, producing a dilution effect whereby sapphire-bearing dike rock is diluted with sapphire-barren dike rock. Evidence included brecciated (broken and re-formed) samples of A-dike rock that contain two mineralogically distinct lamprophyres, one having brecciated and incorporated fragments of the first. Textural and mineralogically distinct samples of lamprophyre are common in the A dike.

Furthermore, the development of karst may have influenced Yogo ore grade. Work by Dahy (1988) led to the conclusion that karst features were present prior to the emplacement of the dike system and that karst continued to develop after dike emplacement. Sinkholes and small natural caves are common in and around the current mine workings. Brecciated rock within these karst features may or may not contain sapphires, depending on a complex set of conditions, including whether the breccia was formed before or after dike emplacement.

There are at least six main brecciated zones within the Yogo sapphire deposit; four are located along the A dike, including the Kelly breccia (the letter "K" in figure 4). Although sapphires have been mined from the Kelly breccia, underground workings within breccias of the American mine produced little or no sapphire (Voynick, 1987a). Breccias are also quite common within the Vortex mine, mainly between the E and F dikes. These breccias are sapphire-bearing, with grades as high as 5 ct/t. The sixth breccia zone occurs on the west end of the D dike, on the ridge overlooking Kelly Coulee. These breccias have never been exploited, so it is not known whether they contain sapphires. Originally, the Kelly and Vortex mine breccias were interpreted to be volcanic breccias related to diatreme activity (Dahy, 1988, 1991; Mychaluk, 1992), although Baker (1994) suggests that they may simply be karst features such as collapsed sinkholes.

ORIGIN OF THE YOGO SAPPHIRES

The origin of sapphires in the Yogo dike system has generated much discussion and debate over the past century. Many of the first geologists to study the deposit concluded that the sapphires must have been formed directly from the Yogo magma as phenocrysts (Pirsson, 1900). These early workers envisioned the silica-deficient Yogo magma incorporating large amounts of Al-rich shales as it rose toward the surface. The magma consumed the aluminum and subsequently crystallized corundum directly from it. Later researchers, notably Clabaugh (1952), suggested that the Yogo magma incorporated fragments of a kyanite-bearing gneiss, instead of shales. The kyanite, a source of aluminum, was then consumed by the magma and later crystallized as corundum. Baker (1994) agrees with this latter phenocryst model and argues that inclusions he observed within Yogo sapphires, such as CO_2 gas and analcime, could only have been formed directly from the Yogo magma.

However, it is also possible that the sapphires were incorporated as inclusions in the Yogo magma (i.e., are xenocrysts). A detailed model describing this theory is presented by Dahy (1988). He envisioned that metamorphic rocks (e.g., gneiss) below the Yogo area already contained corundum, as they do in other parts of Montana (Clabaugh, 1952). The Yogo magma, as it rose toward the surface, captured fragments of the corundum-bearing gneiss and transported it upward as xenoliths. The corundum crystals were eventually released into the magma as foreign fragments (i.e., xenocrysts). Dahy further hypothesized that magmatic heat naturally "heat treated" the corundum into uniform blue, gem-quality sapphire. Much of the corundum was later resorbed into the magma as it rose to the surface, creating the spinel reaction rims seen around some sapphires and rounding, pitting, and etching others. Evidence to support this theory includes the discovery of a xenolith—containing corundum, feldspar, augite, and spinel—which Dahy (1988) interpreted as a metamorphosed clay or bauxite. Another possibility is that the sapphires crystallized in an earlier magma and were subsequently borne upward; they would still be called xenocrysts because they did not crystallize in the transporting magma. Meyer and Mitchell (1988) also presumed that Yogo sapphires were xenocrystic.

New evidence supporting the xenocrystic origin of the Yogo corundum crystals comes from thermodynamic modeling of the crystallization sequence of the Yogo magma, which is now represented by the rock ouachitite. Such models can be calculated today with computer programs that use thermodynamic data for multicomponent (SiO_2, Al_2O_3, FeO, and other chemical constituents) silicate liquids (magmas). Computer simulations of the crystallization of the Yogo magma by J. Nicholls, University of Calgary, using the program described by Ghiorso and Sack (1995) suggest that corundum could not have crystallized directly from the Yogo magma. There are, however, some caveats to the conclusions drawn to date; additional research is needed to resolve this question.

MINING AND PRODUCTION

Mining and Processing. Gem-quality Yogo sapphires are extracted directly from their host rock. CO_2-rich surface and ground water has weathered portions of the lamprophyric dike rock to a soft, friable material that disintegrates in water (owing to its content of montmorillonite and other clay minerals). Unweathered dike rock, on the other hand, is in a hard, competent state, so mining requires careful blasting. To extract the gems from the rock, early sapphire miners exposed both types of material to rain, snow, and frost on large wooden "weathering floors" (Clabaugh, 1952). Within six to 12 months, the dike rock would decompose, at which point the sapphires could be recovered by simple

Figure 14. At the Vortex mine processing plant, ore is loaded into the yellow hopper, which feeds into the large rotating trommel. Heavy chains in the trommel help break down sapphire-bearing ore, which is then fed into a jig behind the bulldozer. Final clean-up of the sluice tray in the jig is done by hand. Photo by the author.

gravity methods such as sluicing. Today, small processing plants with rotating trommels break down the sapphire-bearing ore and trap the sapphires in modified jigs and sluices that are usually used in placer gold recovery (figure 14). Both steam and dilute HCl acid have been used experimentally to decrease ore-processing time, although neither method has been fully implemented (P. Ecker, pers. comm., 1994). Large amounts of goethite/hematite (limonite) cubes are also recovered in the processing jigs. The cubes may be heated to change the limonite to a magnetic phase for easier removal from the jig concentrates, a technique used by the New Mine Sapphire Syndicate at the turn of the century (Voynick, 1987a). Final sorting of the concentrate for sapphires is done by hand.

Production. Most of the Yogo sapphires recovered to date have come from six locations in the deposit: English Cut, English mine, Middle mine, American mine, Intergem Cut, and Vortex mine. Initially, sapphires were extracted by the New Mine Sapphire Syndicate from surface exposures of the A dike—and the colluvial gravels weathered from them—by means of hydraulic mining. This initial mining (roughly 1895–1901) occurred mainly at the English Cut, where early miners had to construct a 15-km-long flume to bring in the water needed for processing. Clabaugh (1952) reported production figures ranging from 296,862 carats in 1898 to 777,550 carats in 1901.

The next phase of mining at Yogo, which was also by the New Mine Sapphire Syndicate, occurred underground at the English and Middle mines. Between 1902 and 1929, 200,000 tons of ore were extracted from the English mine, with a grade of 20–50 carats of rough per ton (Clabaugh, 1952). At 8–15 m below the surface, the Middle mine connects with the English mine (figure 7 in Clabaugh, 1952); the English mine was worked to a maximum depth of 76 m. Neither mine has been commercially operated since 1929, although the old Middle mine workings were the site of a 1993 Cyprus-AMAX bulk sample (the results of which have not been made public).

Between 1901 and 1914, first the American Sapphire Co. and then the Yogo American Sapphire Co. extracted a total of 3 million carats of sapphire rough from the American mine, which was worked to a depth of 91 m. The mine was not operated again until the early 1970s: Between 1970 and 1973, Sapphire International Corp. produced 300,000 carats of rough, of which 15%—or 45,000 carats—was gem quality (Dahy, 1988). In 1974, a further 250,000 carats of rough was produced (Sinkankas, 1976). Therefore, a total of at least 3.55 million carats of rough have been recovered from the American mine.

The three underground mines and hydraulic operations on the English Cut produced an estimated 16 million carats of rough sapphires between 1895 and 1929, according to Clabaugh (1952), who compiled detailed production statistics for this period. Fourteen percent, or about 2.25 million carats, of these stones were gem quality.

Intergem undertook a large-scale strip-mining operation along the east end of the A dike (now referred to as the Intergem Cut). Between 1980 and

1986, Intergem produced an estimated one million carats of rough sapphires from this cut (Dahy, 1988). Because, as discussed above, the sapphire content can vary greatly from one part of a dike to another, ore grades ranging from 5 to 50 carats of rough per ton have been reported (Voynick, 1987a). Cyprus-AMAX also took a bulk sample from the Intergem Cut in 1993, but little other development work has occurred there since 1986.

Currently, the Vortex mine is the only fully operating underground mine at Yogo, albeit relatively small compared to past operations. As of January 1995, the mine was 61m deep with one 50-m-long tunnel at the 61-m level, three 91-m-long tunnels at the 18-m level, and one 12-m-long adit at ground level (L. Perry, pers. comm., 1995). Although first opened in 1987, the Vortex mine only recently began full-time ore extraction. Allen (1991) stated that the Vortex mine is capable of producing 400 carats of rough sapphires a day, of which half are suitable for cutting. The mine produced 5,000 and 12,000 carats, respectively, of gem-quality sapphires in 1992 and 1994. There was no 1993 production because of a core-drilling and mine-development program (L. Perry, pers. comm., 1995). As noted earlier, the ore grade at the Vortex mine also varies greatly, from 0 to 70 carats of rough per ton.

Roncor, the current owner of the English, Middle, and American mines and the English and Intergem Cuts, has not undertaken any underground or hydraulic mining. Rather, most of Roncor's production is derived from reprocessing old mine tailings and left-over ore from the Intergem era. With this technique, Roncor has produced a reported 30,000 to 50,000 carats of rough sapphires annually (Verbin, 1993).

Total production for the deposit's 100-year operating period has been estimated by the author, by updating Clabaugh's figures, to be approximately 18.2 million carats of rough sapphires, of which 14%—or about 2.55 million carats—were of gem quality. Assuming an average cutting retention of 20%, the Yogo deposit has probably produced 510,000 carats of cut sapphires.

The geology of the deposit indicates that the depth of the A dike is considerably greater than the 91 m reached thus far. Given that the specific gravity of the sapphires is higher than that of the host rock, there may be even more sapphires at lower levels. One can conclude, therefore, that the reserves are significant, perhaps twice what has already been recovered, although the cost of recovery may be prohibitive.

SUMMARY AND CONCLUSION

Over 100 years of intermittent operation, the Yogo sapphire deposit has produced an estimated 18.2 million carats of rough sapphires, of which about 2.55 million were gem quality. More than a half million carats of cut sapphires have entered the marketplace from this locality. Approximately 97% of these gems are "cornflower" blue, whereas 3% are various shades of violet; there is no commercial heat treatment of this material. Yogo sapphires also contain fewer inclusions and fractures than sapphires from most other localities, although only about 10% of rough Yogo sapphires exceed one carat—their main drawback as a gemstone. Cutting retention of these typically flat-shaped crystals average 20%, producing many stones in the 0.10- to 0.50-ct range. Marketing high-quality sapphires of this size has been difficult for past and present producers. Profitability is further hampered by the extra costs associated with underground mining and subsequent ore processing, which are not incurred with alluvial sapphire deposits.

Geologic investigations have revealed that the deposit consists of at least six subparallel ultramafic lamprophyre dikes—not just one as is popularly recorded. Sapphires have been discovered in all the dikes except the B, or "barren," dike. The deposit has been influenced by the development of karst and by pre-existing faults and fractures in the host limestone, as well as by multiple magma intrusions. There is great variability in grade within the dike: Some areas produce little or nothing, and others produce as much as 70 carats of rough sapphire per ton of ore.

There is considerable disagreement in the literature as to whether the sapphires originated in the magma (as phenocrysts) or were part of "foreign" rocks transported to the surface by the magma (xenocrysts). Recent thermodynamic computer modeling lends some support to the theory that the Yogo sapphire crystals were xenocrysts. However, the original source of the Yogo sapphires, if truly xenocrysts, remains a mystery.

Sapphire reserves at Yogo appear to be considerable. On the basis of reports in the literature and his experience, the author estimates that they probably—if not practicably—exceed twice what has already been produced. Because of greater activity by groups such as Vortex, Roncor, and Cyprus-AMAX, the author suspects that production will gradually increase during the next decade, yielding many more of the now-legendary Yogo sapphires.

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