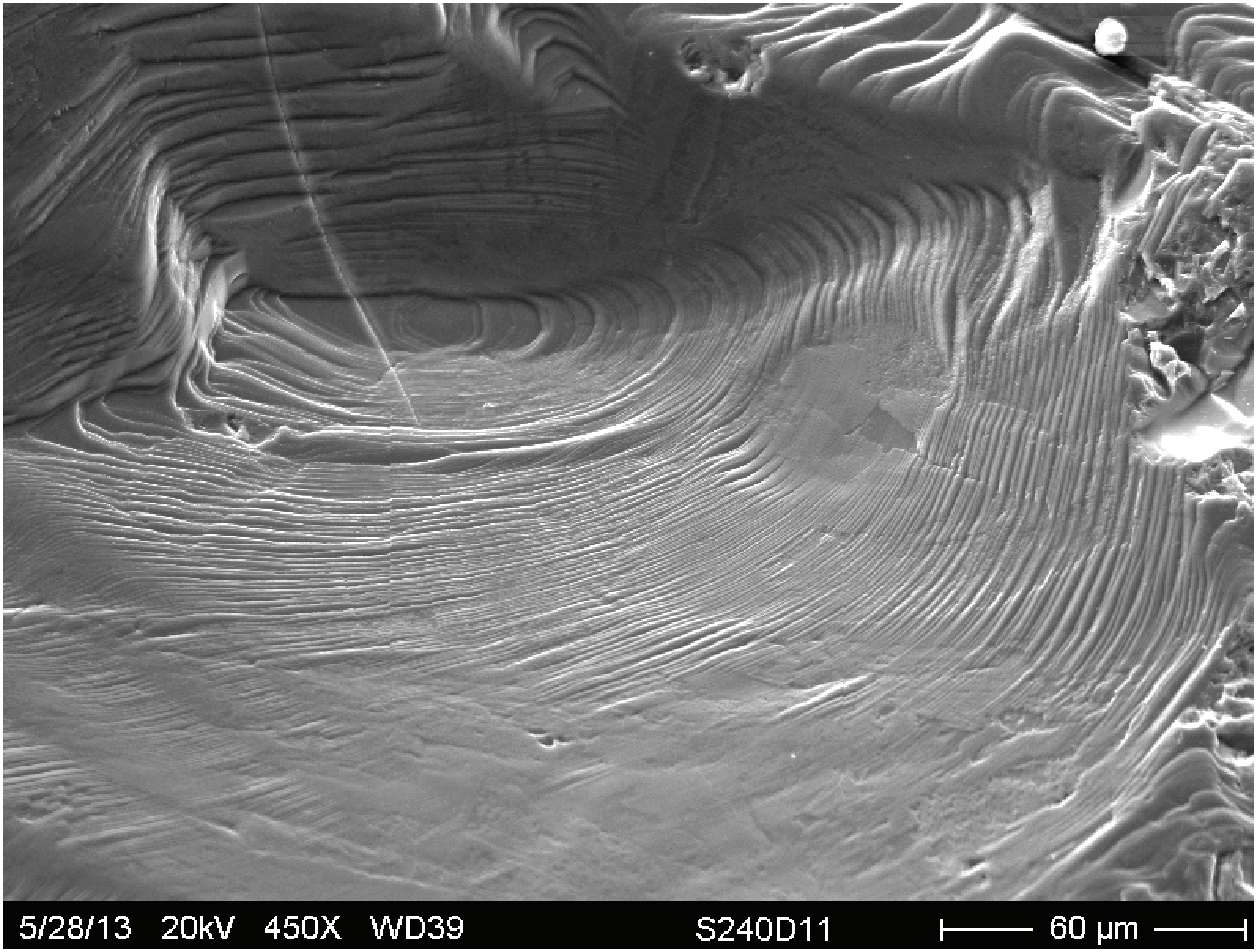
MORPHOLOGY OF SAPPHIRES FROM SECONDARY DEPOSITS, SOUTHWESTERN MONTANA



Richard B. Berg

Montana Bureau of Mines and Geology

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Front photo: Highly magnified scanning electron micrograph of sapphire mined by Neal Hurni from unmined gravel uphill from the dredge tailings on Eldorado Bar. Image by Nancy Equall, Image and Chemical Analysis Laboratory, Montana State University.

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ABSTRACT

Although there are many detailed published studies on the morphology of diamonds, such studies of sapphires are rare. The large collection of sapphires from the secondary deposits of southwestern Montana (Rock Creek, South Fork of Dry Cottonwood Creek, and the Missouri River near Helena) provides an opportunity for a detailed study using scanning electron microscopy. Although most of the sapphires described here are from alluvial deposits, the general term secondary deposit is used to include sapphires recovered from debris flows and eluvial deposits. Sapphires with relict crystal forms are rare. With the exception of minor evidence of abrasion caused by fluvial transport, observed features formed by resorption in the magma that transported the sapphire from the lower crust or mantle. The basal surface that consists of mesas surrounded by stepped surfaces is characteristic of many Rock Creek sapphires and was controlled by an unrecognized mechanism. Evidence of resorption along rhombohedral parting is rare on Rock Creek sapphires, but relatively common and distinctive for sapphires from the South Fork of Dry Cottonwood Creek. Many Missouri River sapphires have remnants of spinel on the surface that is an indication of reaction between a basic transporting magma and the sapphires. In contrast, sapphires from the Rock Creek area and the South Fork of Dry Cottonwood Creek lack adhering spinel, which indicates a more felsic transporting magma. The transporting magma for the Missouri River sapphires has not been identified.

INTRODUCTION AND OBJECTIVE

During research on the major secondary sapphire deposits in southwestern Montana (Rock Creek, South Fork of Dry Cottonwood Creek, and the Missouri River near Helena), it became obvious that there are differences in the morphology of sapphires from these three major deposits (fig. 1). Sapphires from the famous Yogo deposit are not included in this study, which is confined to sapphires from alluvium and related surficial deposits, including debris flows and eluvial deposits. The gemological characteristics of the Yogo sapphires are described by Renfro and others (2018). From more than 600 scanning electron micrographs, I selected those images that illustrate the characteristic features for each deposit. Initially I hoped to be able to explain the origin of all of these features, but this was pure wishful thinking for some of them. Perhaps future researchers using modern techniques and possessing greater knowledge of defects in crystal lattices will be able to explain more of these features.

Sources of the Sapphires

Almost all of the sapphires were obtained at the mines directly from the individuals who were or had actively mined specific deposits. The generosity of those individuals mining these sapphires is greatly appreciated. The name of the donor and the specific locality are given in the description for each figure, followed by the number of the parcel from which the illustrated sapphire was separated. For instance, specimen S155 is from a parcel with the same number that consisted of sapphires, with a total weight of 137.8 ct, collected from Upper Coal Gulch and given to me by Chris Cooney.

Sapphires from these deposits have been accessioned into the research specimen archives of the Montana Bureau of Mines and Geology, where they are available for further sapphire research.

Laboratory Procedures

After initial rinsing in water, individual sapphires were examined using a Leica binocular microscope with incident illumination from a fiber-optic light source. During this examination, sapphires were selected for studies of mineral inclusions that usually required preparation of petrographic thin sections and identification of inclusions by petrographic methods and energy dispersive x-ray analysis (EDX). The results of these determinations are reported by Berg (2007, 2014) and Berg and Landry (2018).

After examination using the binocular microscope, sapphires were selected for scanning electron microscopy (SEM). Individual sapphires were selected based on typical surface features, and in some instances, peculiar or what appeared to be photogenic features. Most sapphires were then cleaned by soaking them in

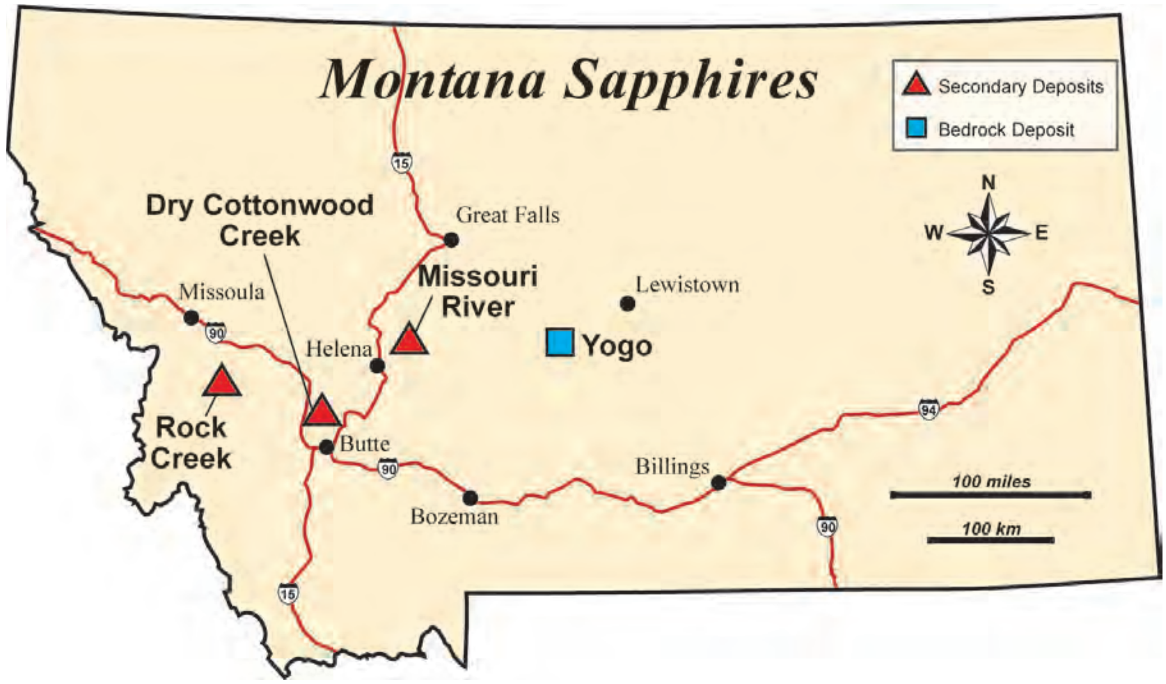


Figure 1. Major Montana sapphire deposits.

hydrofluoric acid (HF) overnight, which was very effective in removing adhering material deposited in the weathering environment.

Images with the date shown in the lower left-hand corner were recorded using a JEOL 6100 scanning electron microscope in the Image and Chemical Analysis Laboratory in the Department of Physics at Montana State University. Most specimens were coated with an Au-Pd coating and a few with an Ir coating. These images were recorded between October 2001 and July 2017 with the very capable assistance of Nancy Equall of the Department of Physics. More recent images were recorded using a MIRA3 Tescan in the Center for Advanced Mineral, Metallurgical, and Materials Processing (CAMP) at Montana Tech, where the specimens were Au coated. Gary Weiss ably assisted with this imaging. The number below the scale on these images indicates the length of the scale divided into tenths. BSE below the image indicates a back-scattered-electron image and SE indicates a scanning electron micrograph.

Several photomicrographs are included that were taken using a Leica M 165C binocular microscope with a planopo objective lens and fiber-optic lighting.

The procedure for recovering very small sapphires was as follows. The gravel was wet-sieved in sieves with progressively smaller openings, finally using a sieve with 125-µm openings. The fine fraction was put on a watch glass and "panned" in water under the petrographic microscope. Carful "panning" concentrated the heavy minerals (zircon and corundum) at the margin of the watch glass. After drying, the zircon and corundum grains were mounted in a permanent mounting medium for microscopic observation. This technique was also effective in the recovery of very small gold grains.

Corundum Crystallography

Corundum belongs to the trigonal crystal system, one of the seven crystal systems. The trigonal system is very similar to the hexagonal crystal system (fig. 2). Crystals in both systems have three "a" axes that in the hexagonal system are perpendicular to the C axis, but in the trigonal system the plane formed by the "a" axis is slightly inclined to the C axis. Rhombohedral twinning with Miller indices of $(10\bar{1}1)$ is common in corundum, and basal twinning with Miller indices of (0001) is reportedly less common. Polysynthetic twinning of rhombohedral orientation is common. Typically, many sapphires from the secondary deposits described here are tabular, with a flat surface perpendicular to the C axis and often a crude hexagonal outline when viewed perpendicular to the C axis. Hexagonal prisms are rarely found. Corundum has no cleavage, but according to some authors has both rhombohedral and basal parting that is attributed to rhombohedral and basal twinning.

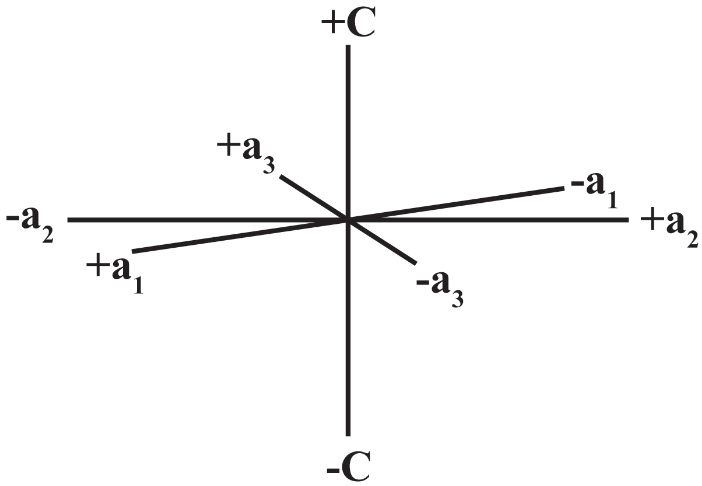


Figure 2. Diagram of the crystallographic axes of a mineral in the hexagonal crystal system, where the “a” axes are perpendicular to the C axis. The plane of the “a” axes is slightly inclined to the C axis in the trigonal crystal system. Figure used with permission from the Earth Science Museum, University of Waterloo, Waterloo, Ontario, Canada.

Some sapphires described here exhibit depressions with flat surfaces of basal orientation. These features are particularly common in the sapphires dredged from Hauser Lake, a short distance north of Canyon Ferry Dam. Although I examined eight petrographic thin sections of sapphires with basal depressions, and it is clear that these depressions are crystallographically controlled, I could not determine the cause. These thin sections were prepared parallel to the C crystallographic axis, thus perpendicular to the basal surfaces of the sapphires. Rhombohedral twinning was identified in all eight thin sections, five of which showed polysynthetic rhombohedral twinning. Careful examination of these thin sections failed to show evidence of planar features of basal orientation that could explain these flat depressions. All that can be concluded is that these surfaces are crystallographically controlled by an unrecognized mechanism.

ROCK CREEK SAPPHIRES

Sapphires from the Southwestern Part of the Rock Creek District

Introduction

The Rock Creek sapphire district, situated 100 km northwest of Butte, is the largest secondary sapphire deposit in Montana, with an estimated historic production of 70 tonnes (fig. 3). The geology of the southwestern part of this district is described in Montana Bureau of Mines and Geology Bulletin 135 (Berg, 2014) and also by Garland (2002).

Most of the sapphires described here were provided by Chris Cooney, owner of the Gem Mountain tourist operation, with a few collected by the author. From 1,056 sapphires examined using the binocular microscope, selected sapphires were examined by scanning electron microscopy. Figures 4–15 are images that show the morphology of selected sapphires.

Most Distinctive Features

1. Irregular hillocks on the basal surface are common, some of which have flat surfaces resembling miniature mesas (figs. 4A–4E). Some of these slope down to the prominent basal surface and consist of very small steps or grooves (figs. 4B–4D).
2. Surfaces of some equidimensional, frosted sapphires exhibit irregular ridges and projections as well as small depressions (figs. 5A–5D). Small chips on the surfaces of the projections are attributed to abrasion. Some depressions have slightly raised rims (fig. 6).
3. Some sapphires from Anaconda Bench and the North Fork of Coal Gulch are almost completely covered with kaolinite, which leaves a surface covered with conchoidal fractures when dissolved in HF (figs. 7A–7D). This feature is not seen on sapphires from the other two districts. A petrographic thin section of one of these sapphires shows that kaolinite fills fractures in the sapphire, essentially holding the fractured sapphire together (Berg, 2014).
4. Sapphires from Anaconda Bench and the North Fork of Coal Gulch are covered with irregular depressions coated with fine-grained material that may be severely etched corundum (figs. 8A, 8B, 8C). Both these surfaces and the kaolinite coating are equally perplexing and were observed only on sapphires from this part of the Rock Creek district.
5. Small remnants of spinel were not recognized on the surfaces of Rock Creek sapphires, unlike those found on many of the Missouri River sapphires. Black specks on the surfaces of Rock Creek sapphires were determined by EDX to contain Mn, attributed to mineral deposition in the weathering environment.

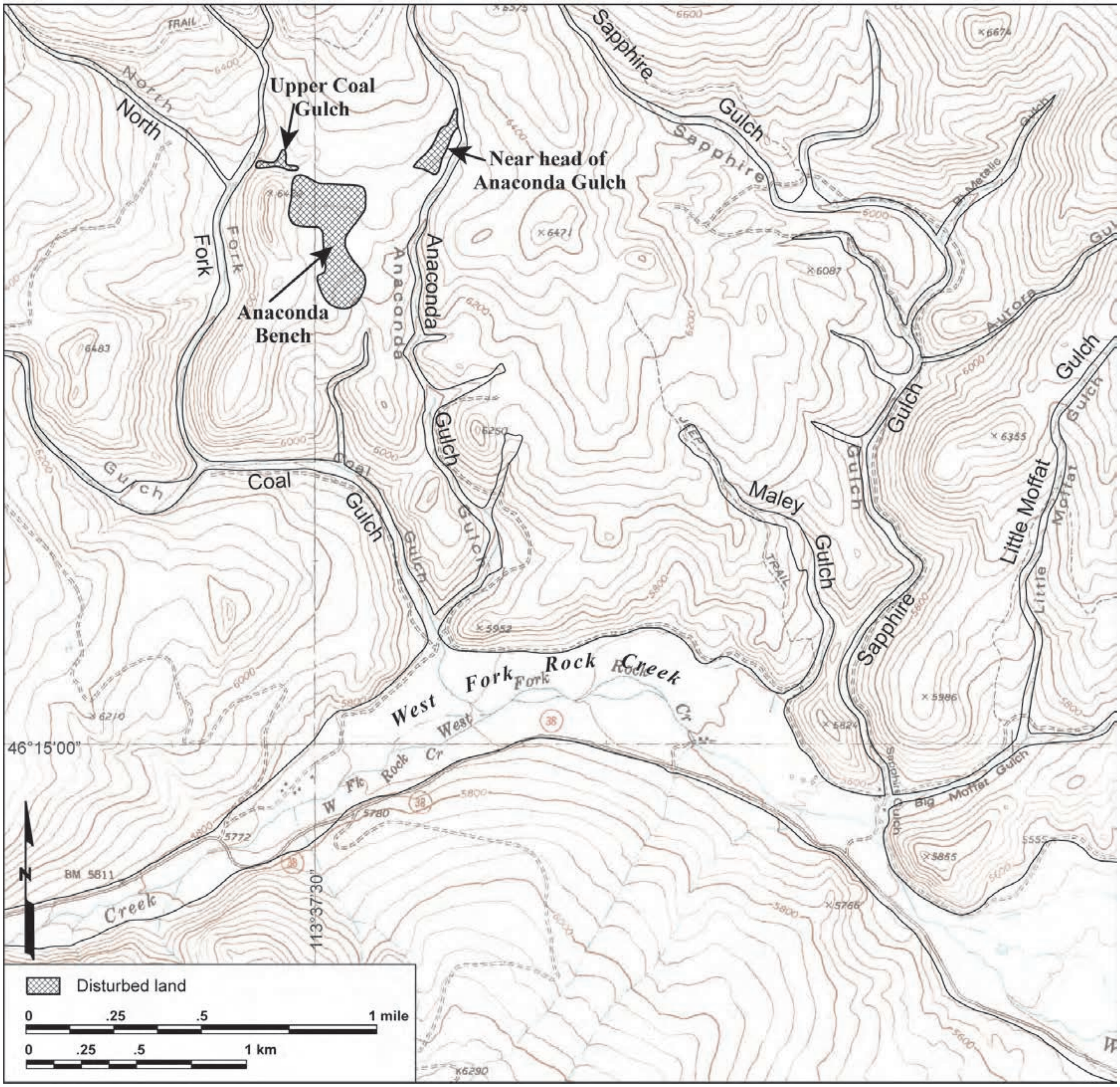


Figure 3. Localities of sapphires from the southwestern part of the Rock Creek District. See Berg (2014) for a detailed map.

A
B
C

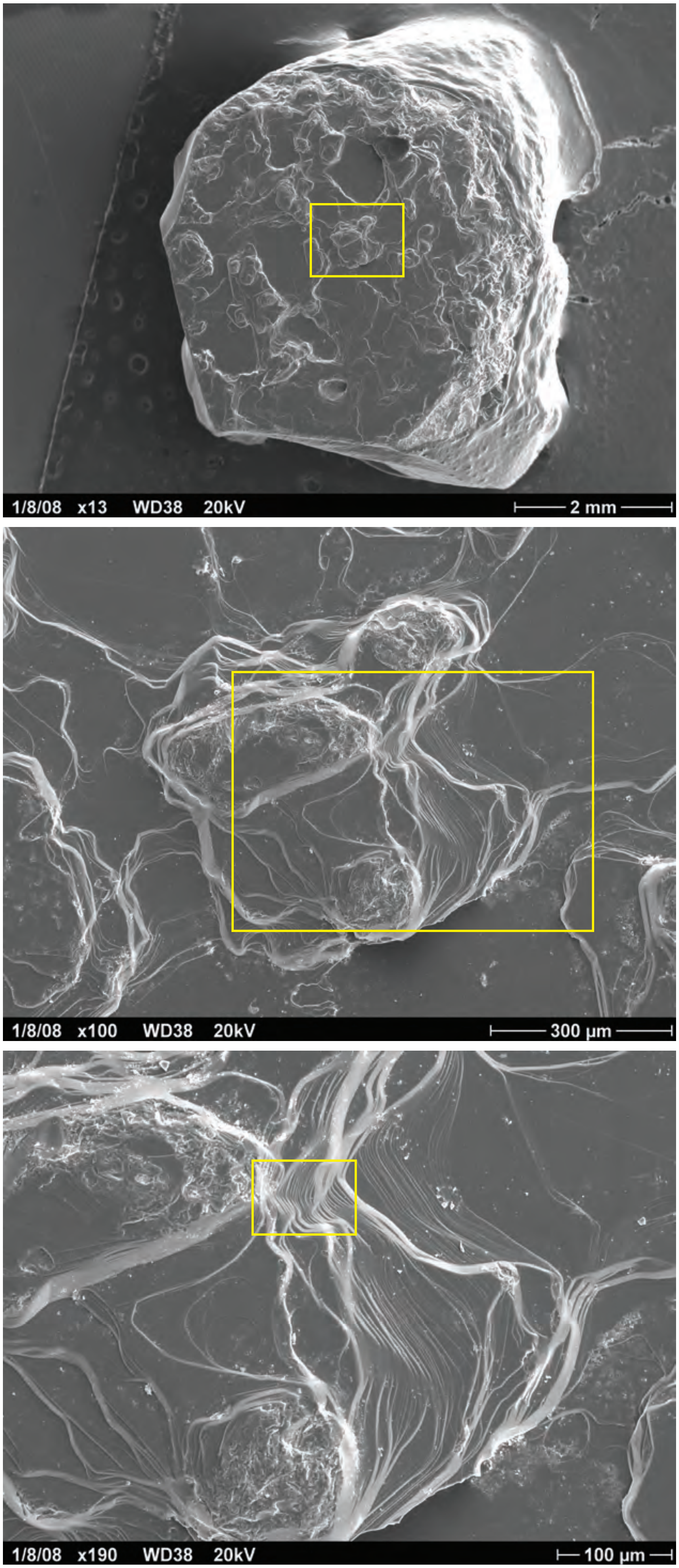


Figure 4 (A, B, C, D, E). **Observation**—This sequence of images at increasing magnification illustrates relatively common features on Rock Creek sapphires from the raised mesas on the basal surfaces to the very delicate adjacent grooved surfaces. **Interpretation**—Features produced by resorption in the magma largely of basal orientation. The very fine grooves are difficult to explain. It is interesting that some of the grooves branch. I have no explanation for this feature. **Source**—Anaconda Bench from Chris Cooney, from parcel S162.

D

E

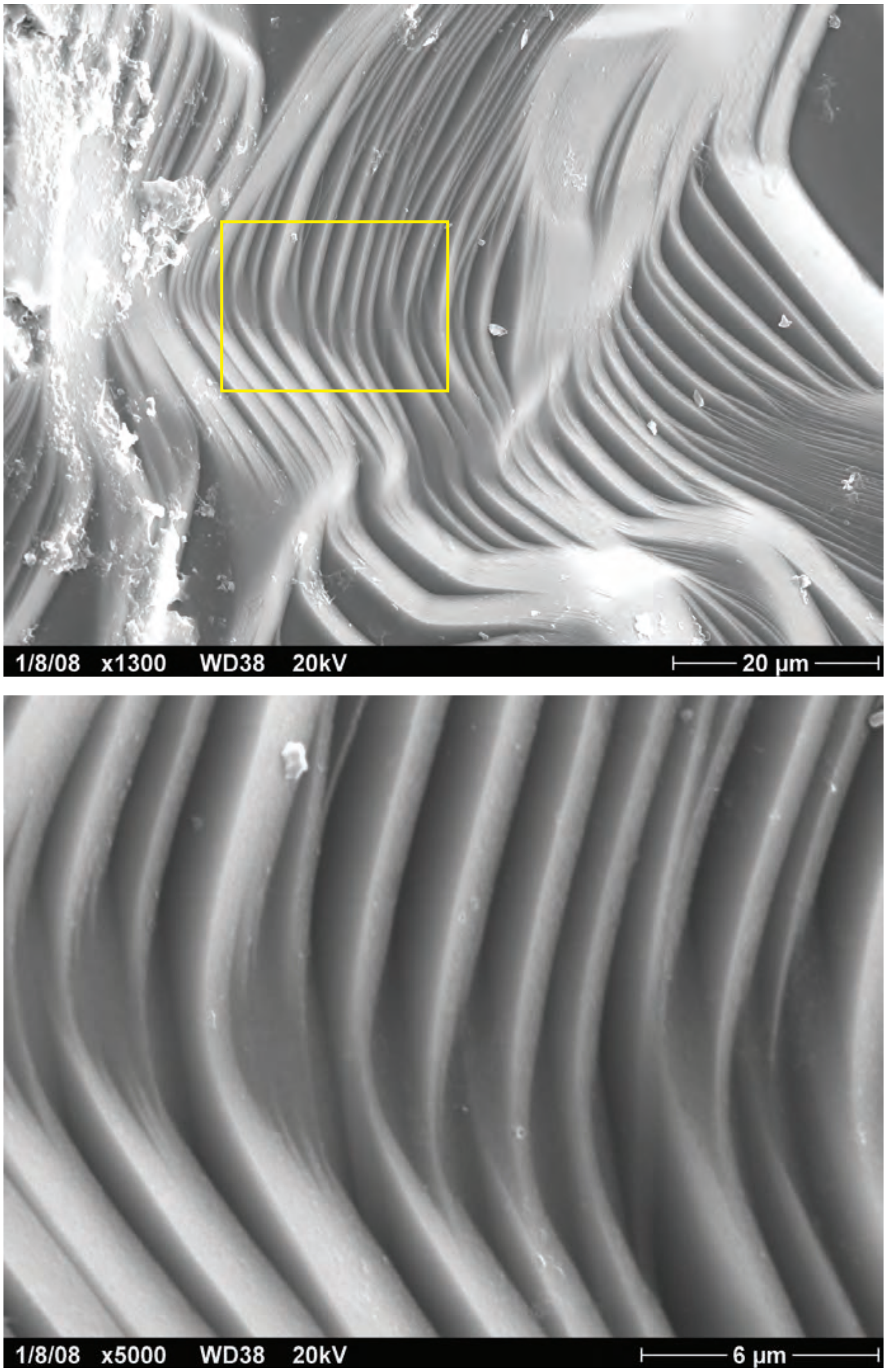


Figure 4, Continued (D and E).

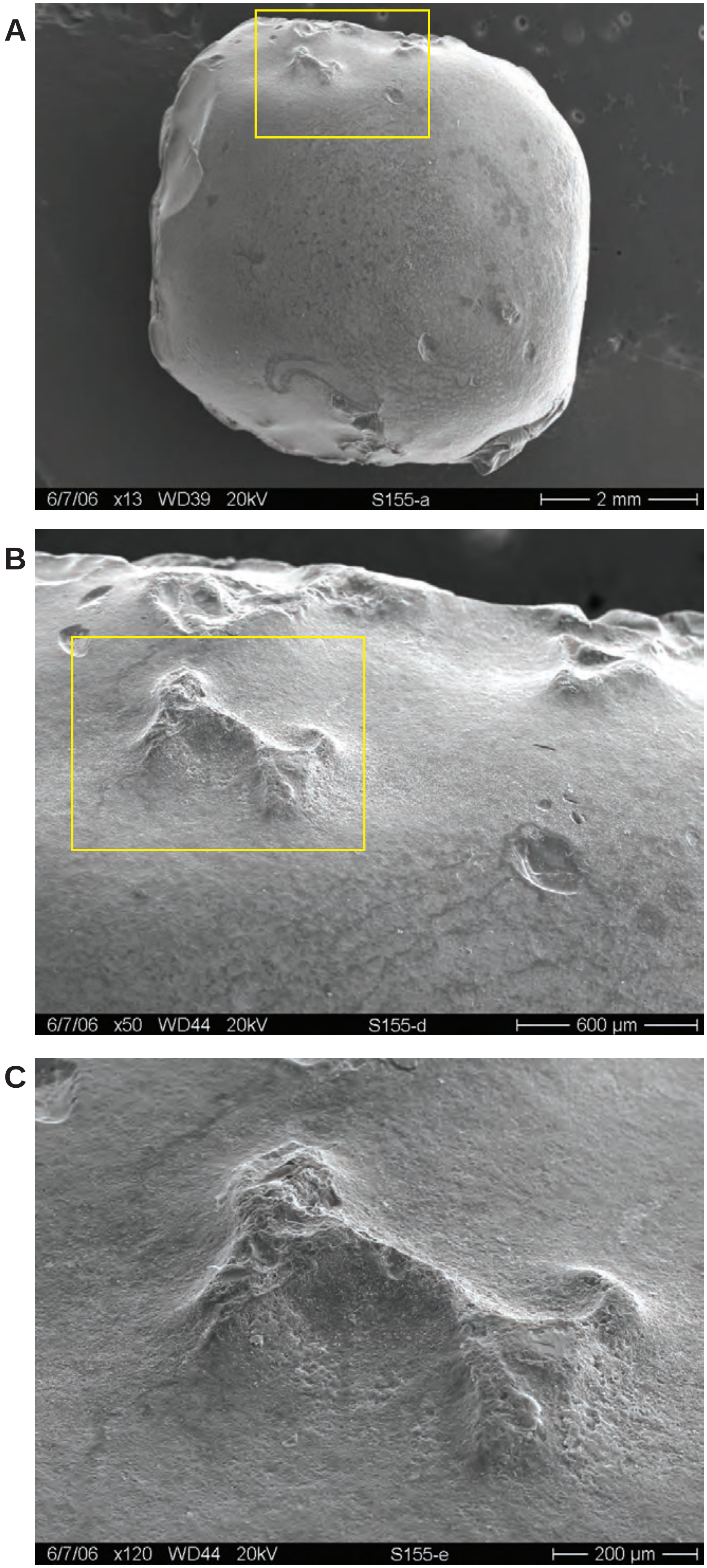


Figure 5 (A, B, C, D). **Observation**—This sequence of images shows irregular projections on the surface of an equidimensional sapphire and also small depressions (B) that do not appear to be etched as much as the surrounding sapphire. A fresh fracture is evident on the left side of the sapphire (A). The small chips on the high point of the ridge in C are caused by abrasion either during fluvial transport or, less likely, in the washing plant. Note the fine frosting of the surrounding sapphire surface (D). **Interpretation**—The features shown in A, B, and C do not seem to be crystallographically controlled, but evidently were caused by slower resorption compared to the surrounding sapphire. A possible explanation is that a difference in trace element chemistry may have resulted in slower resorption as compared to the surrounding sapphire. The scattered small depressions, 10 to 100 µm across (shown in D), were caused by resorption during magmatic transport, perhaps initiated by a defect or a mineral inclusion in the sapphire. **Source**—Upper Coal Gulch from Chris Cooney, from parcel S155.

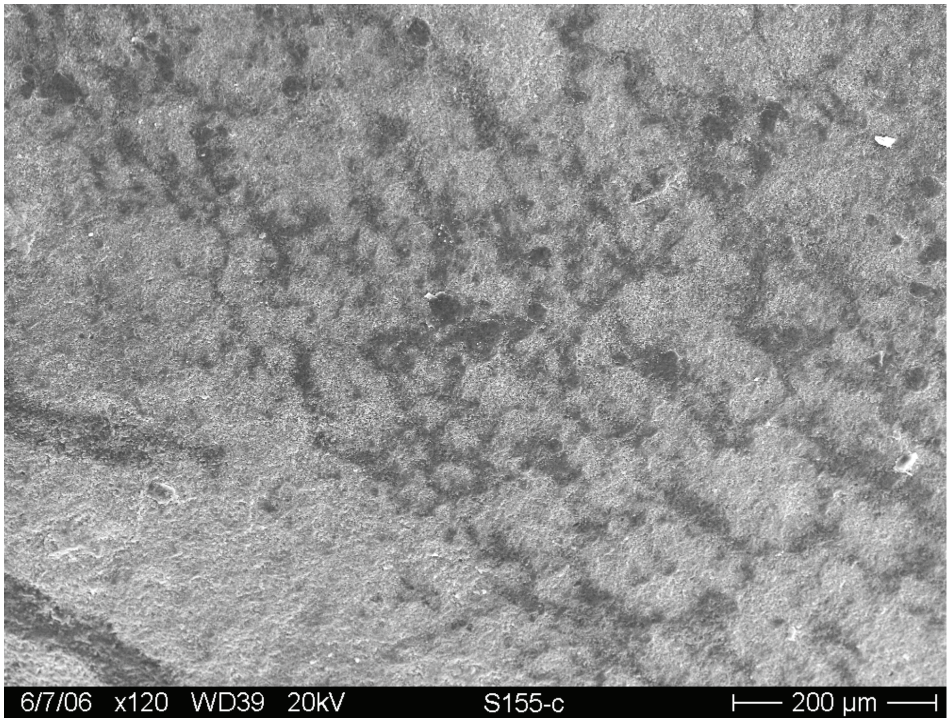
D


Figure 5, Continued (D).

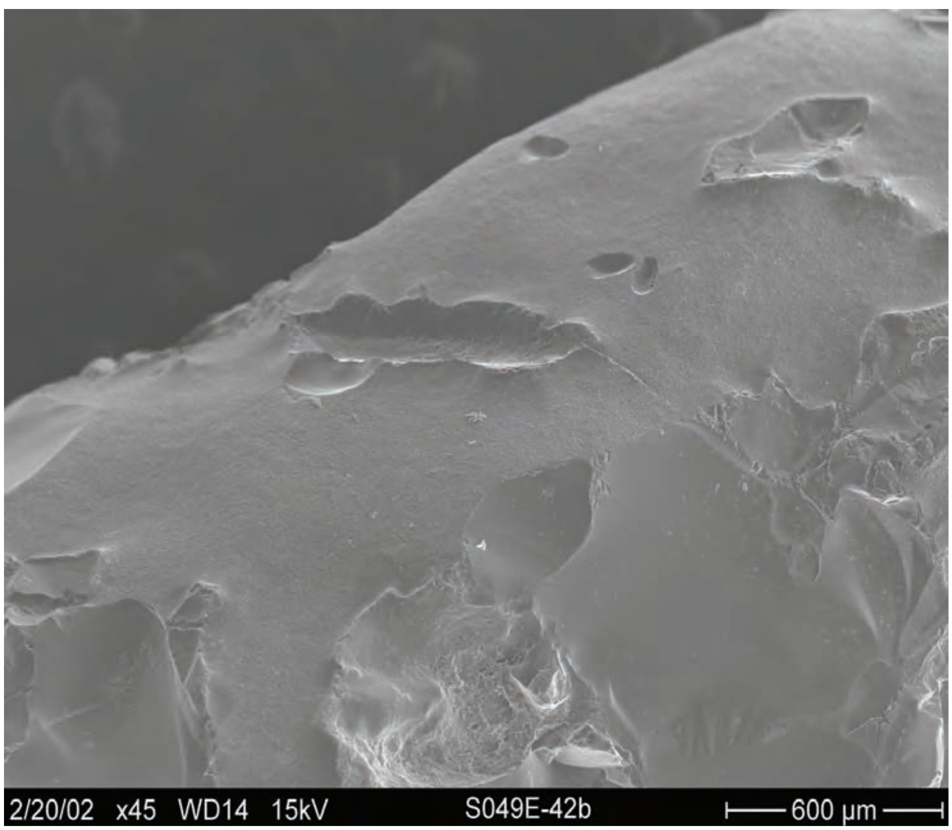
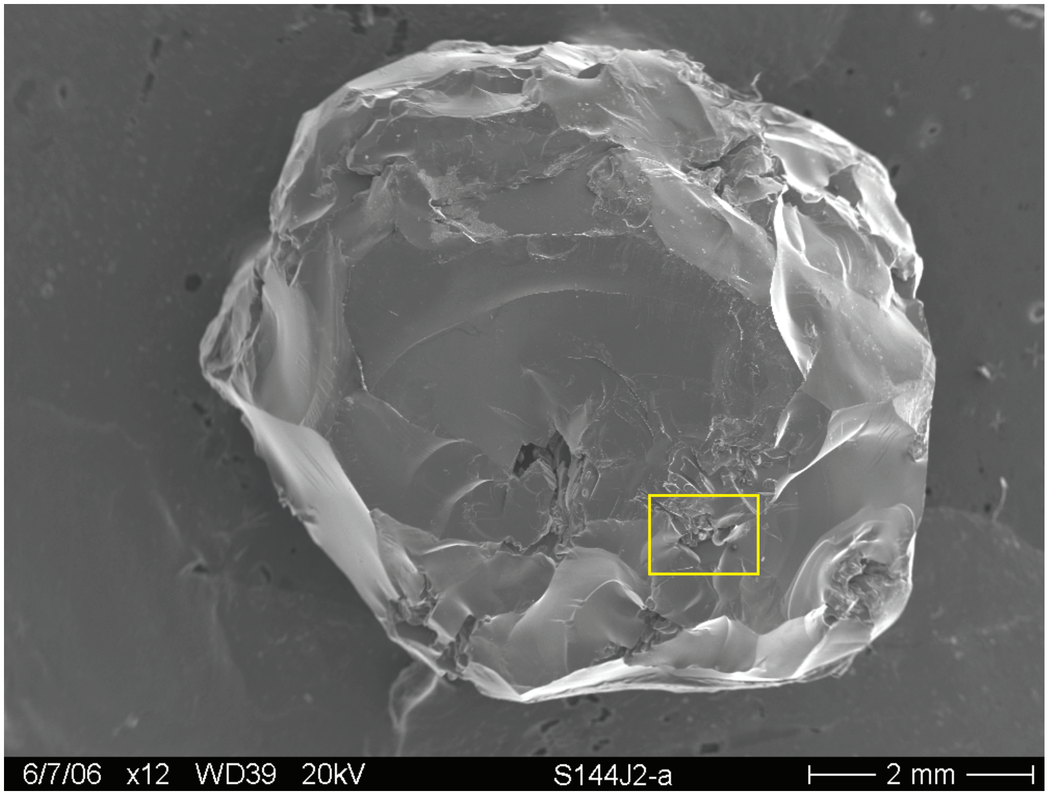


Figure 6. **Observation**—Rare sapphires with a frosted surface have these irregular depressions surrounded by raised rims. The depressions are not finely frosted like the surrounding sapphire. **Interpretation**—I have no reasonable interpretation for these interesting features. **Source**—Southwestern part of the Rock Creek district from Chris Cooney, from parcel S049.

A



B

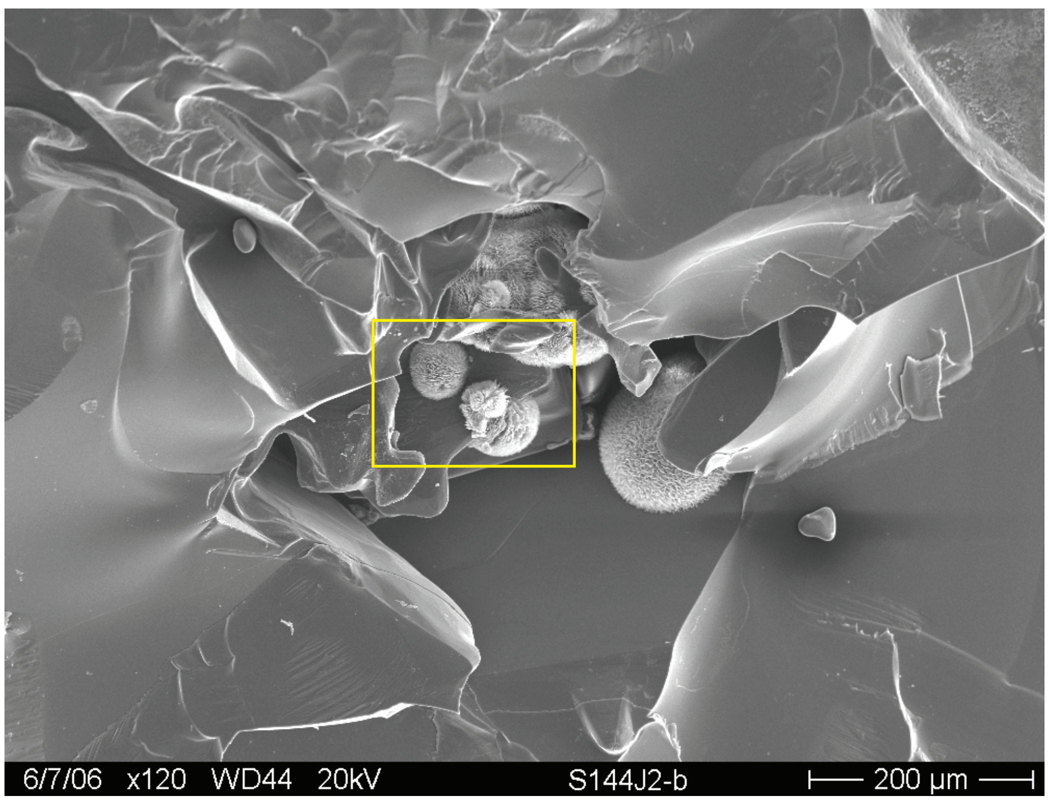
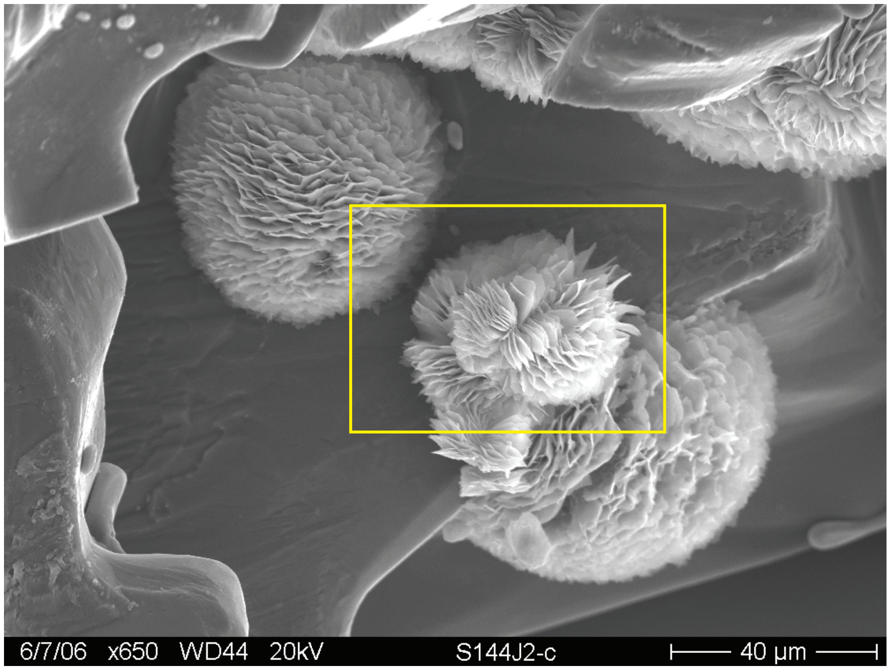


Figure 7A. **Observation**—Some of the sapphires from Anaconda Bench and the North Fork of Coal Gulch are almost completely coated with kaolinite. Following kaolinite dissolution by soaking overnight in HF, the sapphires are found to be covered with conchoidal fractures, and small sapphire shards were found in the bottom of the beaker.

Figure 7B. **Observation**—Enlarged image of a cavity in the lower right-hand area of the previous image showing small delicate crystals.

C



D

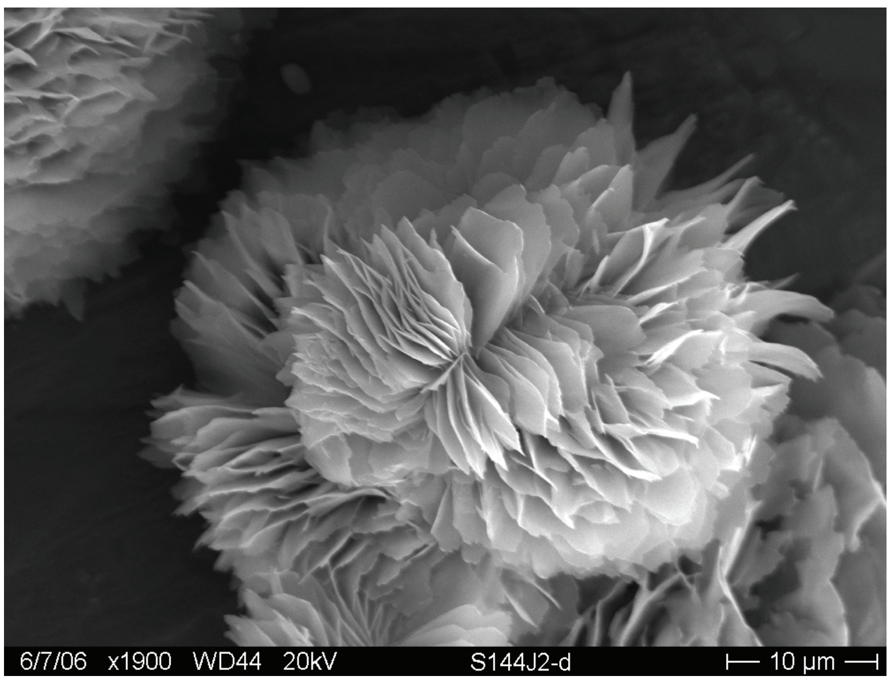


Figure 7C. **Observation**—These small delicate crystals were found only in this cavity and not in any other of the hundreds of sapphires examined by SEM.
Figure 7D. **Observation**—These crystals consist of only Ca and F as determined by EDX and are probably fluorite. The F is most likely from the HF and presumably the Ca is from a surface inclusion that provided the Ca. Because apatite has been identified in other alluvial sapphires from southwestern Montana, it is a reasonable Ca source. **Interpretation**—A petrographic thin section shows that these sapphires are veined with kaolinite. I speculate that kaolinite formed along fractures in the sapphire while the sapphire was in the lava by reaction of Si and H_2O from the lava with the fractured sapphire. Some feldspar in this volcanic rock was partly replaced by kaolinite (Berg, 2014, figs. 2, 10). The Si and H_2O may have been concentrated in the waning stages of crystallization of the lava. The development of fractures in the sapphire are difficult to explain. Expansion during replacement of sapphire by kaolinite may have caused fragmentation of the sapphire and formation of conchoidal fractures. **Source**—North Fork of Coal Gulch from Chris Cooney, from parcel S144.

A

B

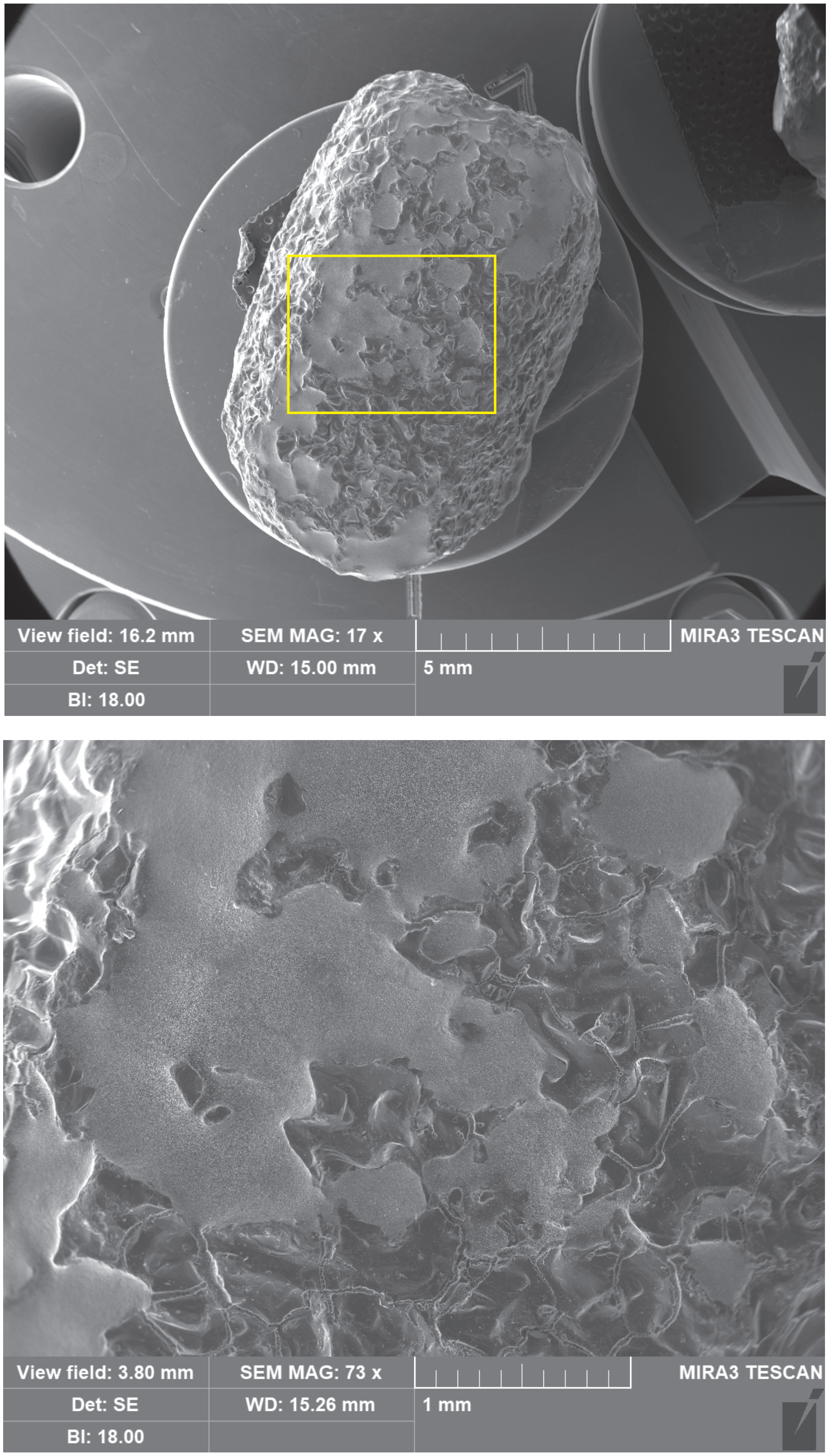


Figure 8A. **Observation**—This sapphire has been cleaned in HF before imaging. The sapphire is oriented with the C-axis parallel to the mount and the surface is covered with irregular depressions without apparent crystallographic control.

Figure 8B. **Observation**—Enlargement of area outlined in figure 8A. Many of the depressions are connected by irregular channels with surface texture similar to that of the large depressions.

C

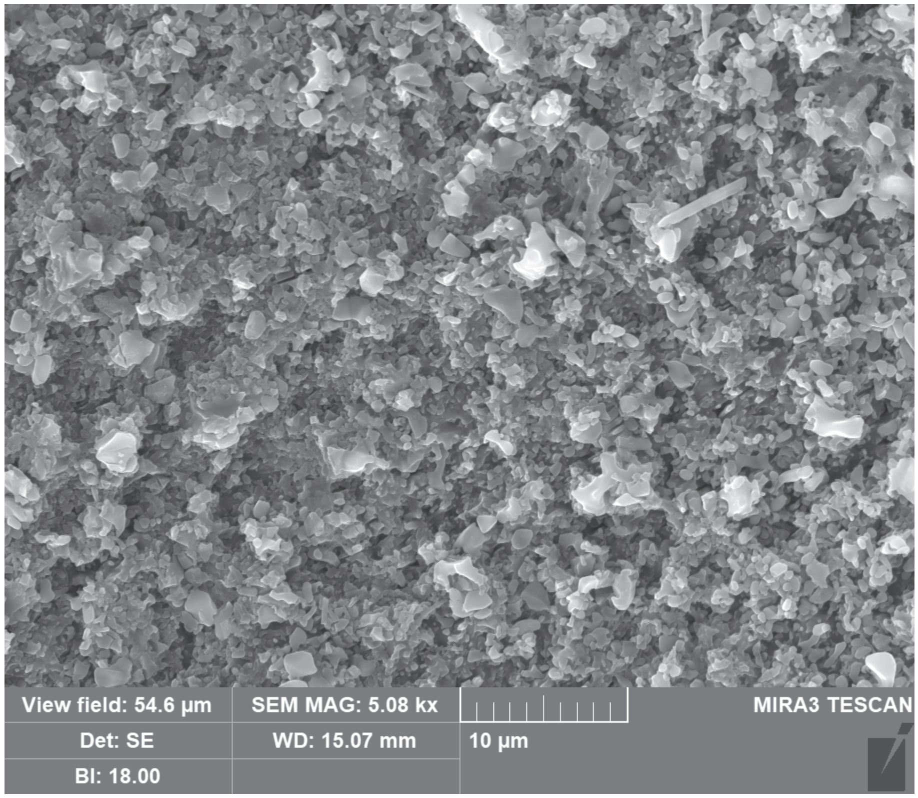


Figure 8C. **Observation**—Enlargement of the material in the large central depression in figure 8B. The minor division on the bar scale is 1 μm. **Interpretation** (speculation)—This fine-grained material in the connecting channels and depressions might be diaspore that formed by reaction of water in the magma with the sapphire. However, if this were correct then all of the sapphire should be coated with diaspore and it is not. An alternative explanation is that the depressions were formed by resorption of the sapphire and the fine-grained material is partly dissolved sapphire. These depressions and coating were only recognized on sapphires from the Anaconda Bench and the North Fork of Coal Gulch. **Source**—Anaconda Bench from Chris Cooney, from parcel S162.

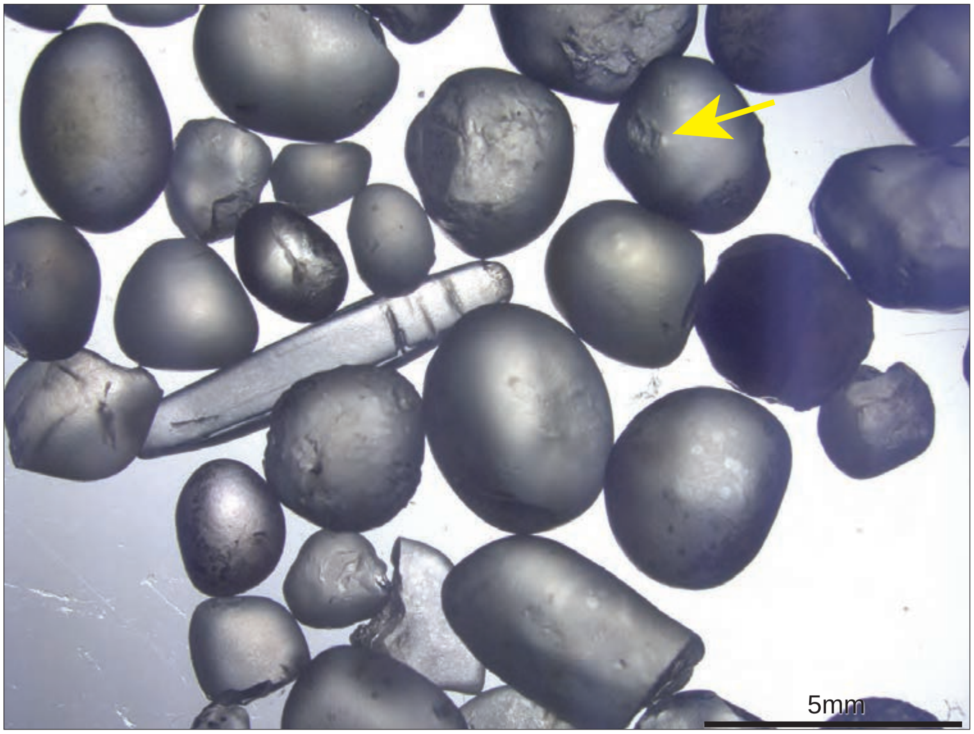


Figure 9. **Observation**—This back-illuminated photomicrograph shows small, rounded, frosted sapphires that were picked out of a parcel of Rock Creek culls. **Interpretation**—The high degree of rounding and frosting is unusual with no crystallographic control. The irregular projections on several sapphires and uniformly frosted surfaces indicate that the rounding is caused by resorption in the magma and not fluvial transport. **Source**—Probably between Anaconda Bench and Anaconda Gulch from Ben Duffey, from parcel S060.

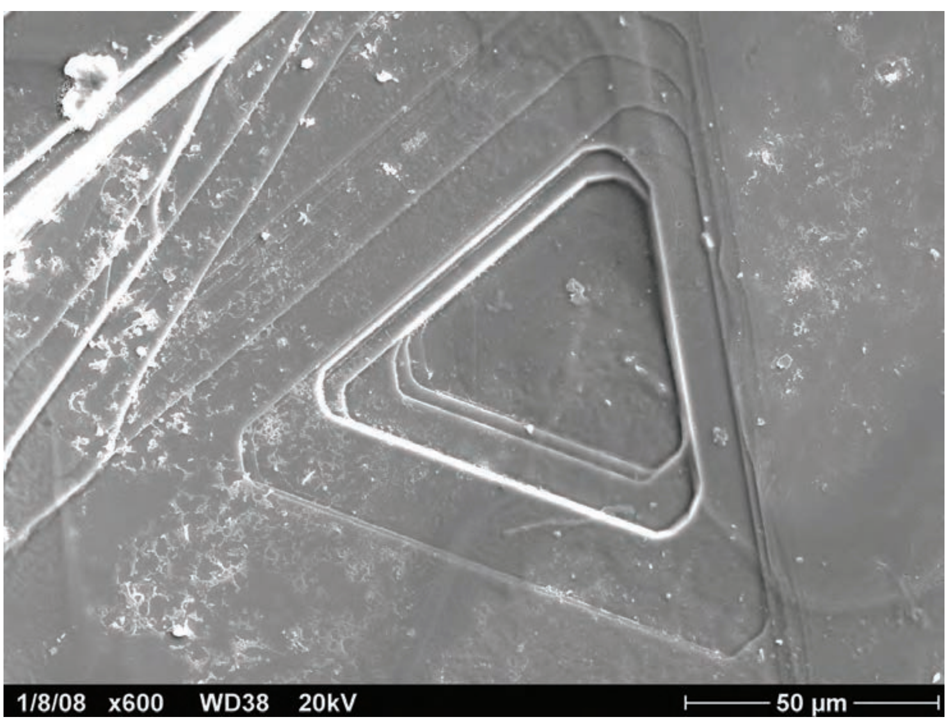


Figure 10. **Observation**—Although very rare, a few negative trigons occur on the basal surfaces of Rock Creek sapphires. **Interpretation**—Resorption in the transporting magma. **Source**—Anaconda Bench from Chris Cooney, from parcel S162.

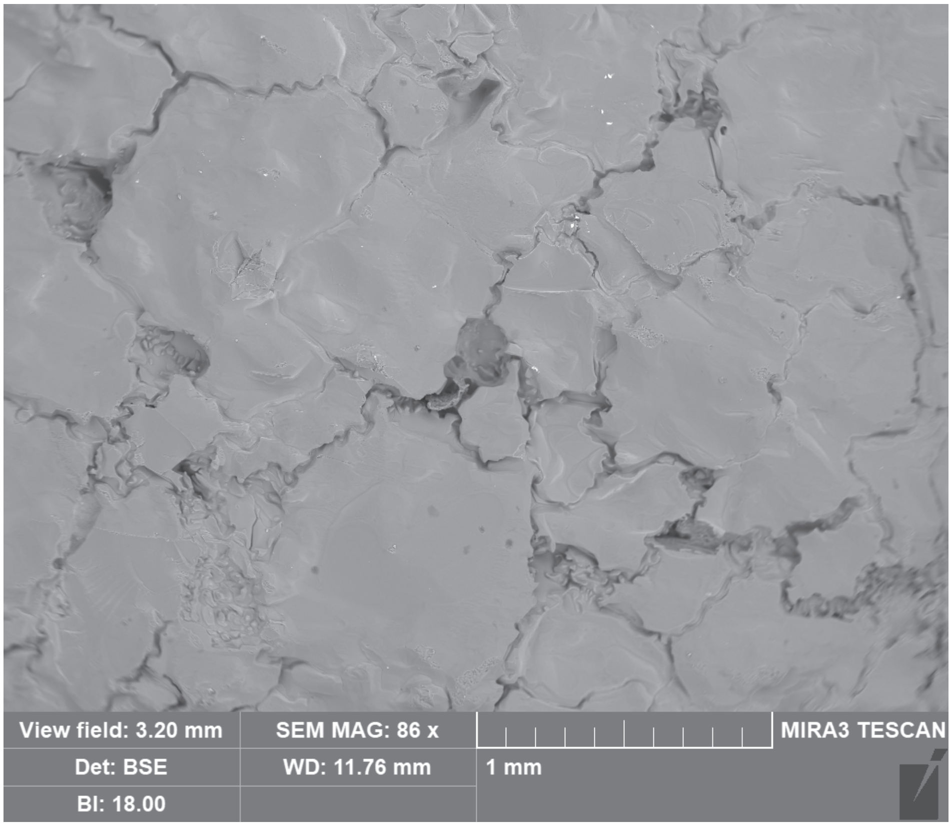


Figure 11. **Observation**—Possibly these irregular channels on the sapphire surface may have been filled with some material that was dissolved when the sapphire was cleaned in HF. **Interpretation**—Not explained. **Source**—Anaconda Bench from Chris Cooney, from parcel S081.

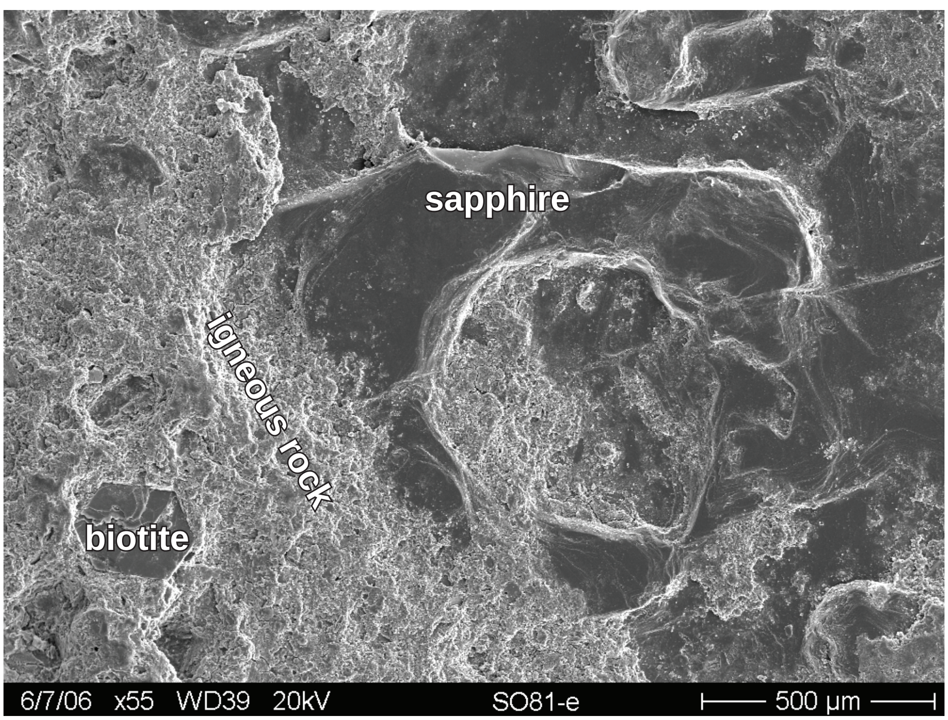


Figure 12. **Observation**—Some sapphires have remnants of fine-grained igneous rock on their surfaces. This image of the basal surface of a sapphire shows a euhedral biotite phenocryst within the igneous rock. **Interpretation**—Remnant of the igneous rock that carried this sapphire to the surface. **Source**—Anaconda Bench from Chris Cooney, from parcel S081.

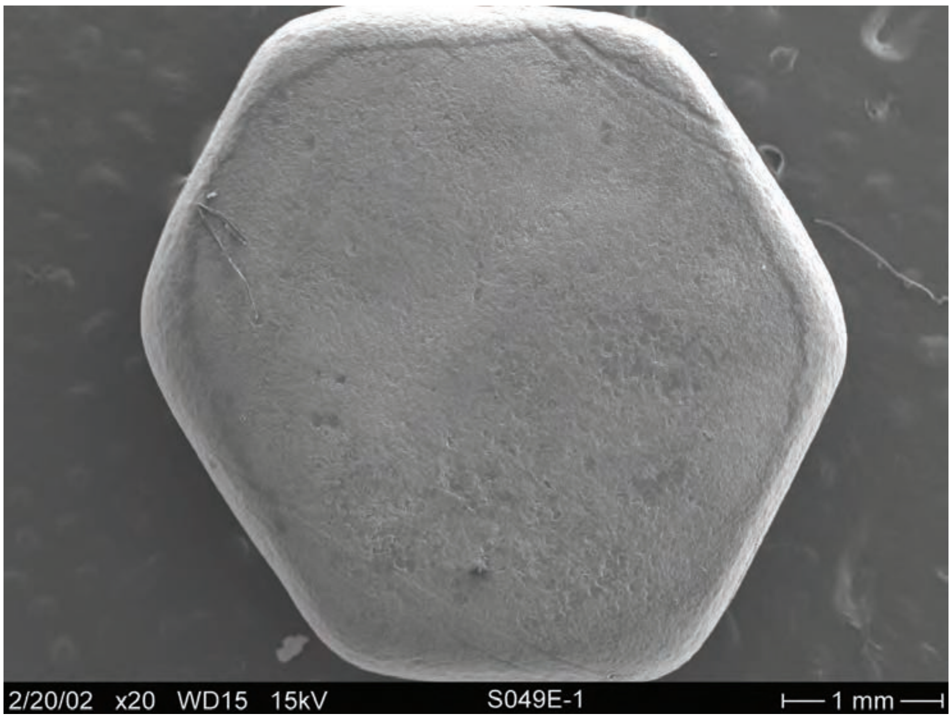


Figure 13. **Observation**—A few sapphires retain their original prismatic crystallographic form, as does this tablet with a prominent basal surface. The grooves in the upper right corner of the tablet were formed by resorption, probably along the rhombohedral twinning. **Interpretation**—Minor etching occurred during transport in magma.
Source—Southwestern part of Rock Creek district from Chris Cooney, from parcel S49.

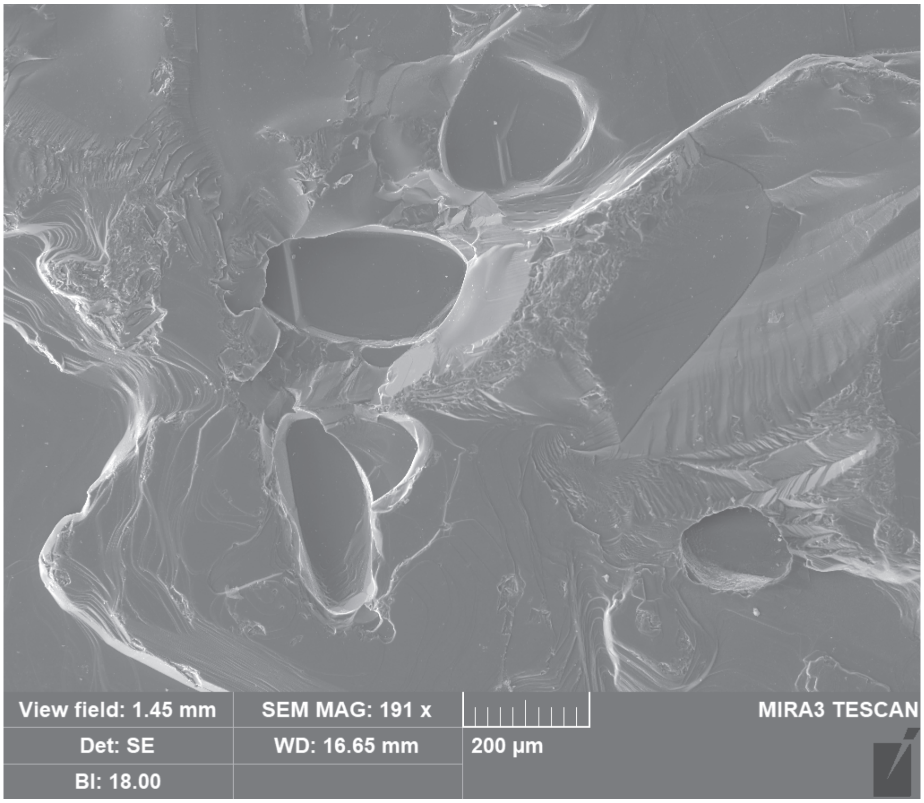


Figure 14. **Observation**—Deep circular to elliptical pits with flat bottoms that are approximately 200–300 μm across. This sapphire contains spherical inclusions visible within the sapphire about the same size as some of the pits on the surface. Average EDX analyses of three of these inclusions are SiO_2, 43 wt. percent; TiO_2, 0.3 wt. percent; Al_2O_3, 21 wt. percent; FeO, 9 wt. percent; MgO, 13 wt. percent; CaO, 11 wt. percent; Na_2O, 2 wt. percent; and K_2O, 0.3 wt. percent. Total is 99 wt. percent. The inclusions are possibly gedrite, but this interpretation is not supported by the elevated weight percent of oxides. Petrographic observations of one of these inclusions were not diagnostic. **Interpretation**—The abundant inclusions may have promoted resorption that formed these pits. The flat bottoms of these holes appear to be crystallographically controlled, just like similar features on some of the Missouri River sapphires. **Source**—Near head of Anaconda Gulch from Chris Cooney, from parcel S188.

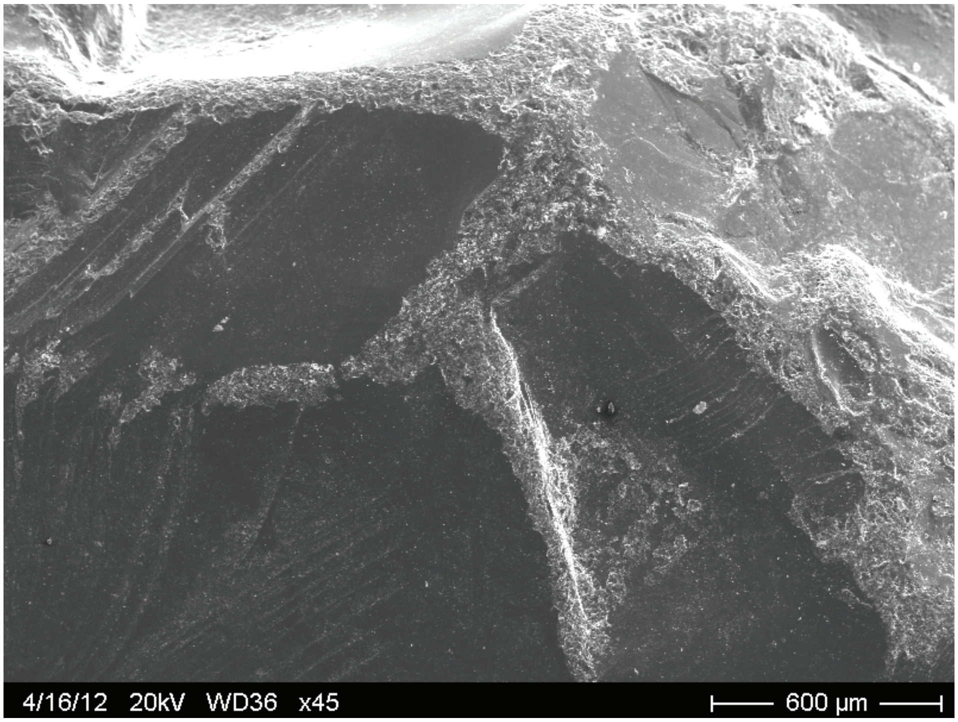


Figure 15. **Observation**—A few sapphires from the Rock Creek district show evidence of abrasion by the abundance of small chips on ridges on the surface of the sapphire. **Interpretation**—Most of the abrasion was caused by either fluvial transport or, less likely, during recovery in the washing plant. **Source**—Upper Coal Gulch from Chris Cooney, from parcel S161.

DRY COTTONWOOD CREEK SAPPHIRES

Sapphires from the South Fork of Dry Cottonwood Creek

Introduction

The South Fork of Dry Cottonwood Creek, situated northwest of Butte (fig. 1), is the smallest in both area and historical production of the three major secondary deposits in southwestern Montana (fig. 16). There is no current production from this district as of 2020. The felsic volcanic rocks of the Eocene Lowland Creek Volcanics are the probable bedrock source of these sapphires. See Berg (2007) and Garland (2002) for the detailed geology of this area. Sapphires described here were provided by Marc Bielenberg, Dale Siegford, and John Rex (fig. 16). In addition, I collected sapphires from the Upper Meadow, one of which is included here. Eight hundred and eighty-nine sapphires from this secondary deposit were examined using the binocular microscope. From these, sapphires were selected for scanning electron microscopy to best illustrate typical morphology or unusual features. These images are shown in figures 17–27.

Most Distinctive Features

1. Grooves of rhombohedral orientation are the most distinctive features of these sapphires and are generally more prominent than grooves of basal orientation.
2. Surfaces vary from finely etched (fig. 20) to more coarsely etched (figs. 18A–18C).
3. Rare approximately spherical sapphires have unusual projections (fig. 19).

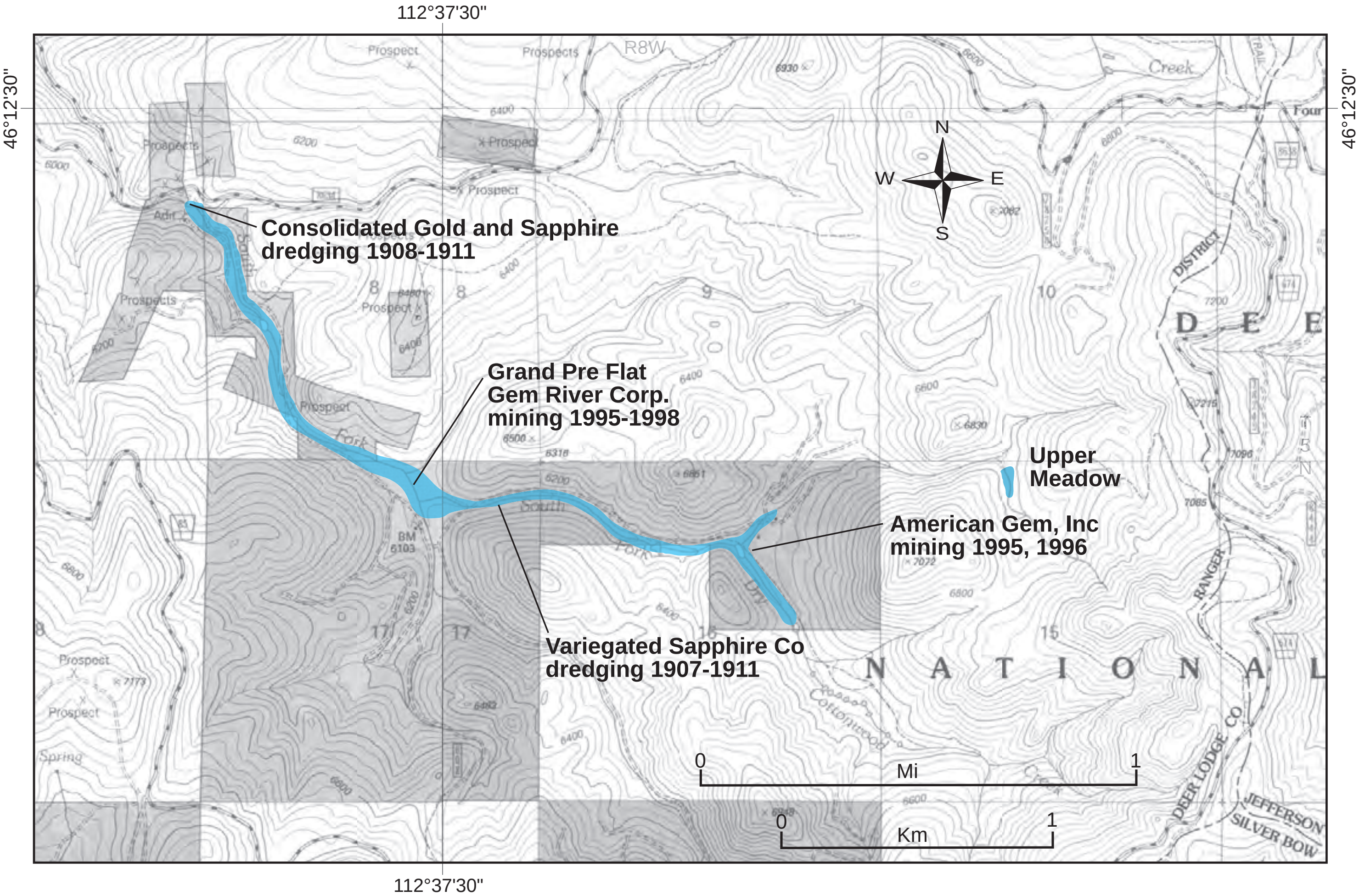


Figure 16. Sapphire deposits along the South Fork of Dry Cottonwood Creek shown in blue. Private land is indicated by gray shading. Sapphires from John Rex are from the area mined by American Gem, Inc., in 1995 and 1996. Map from Berg (2007).

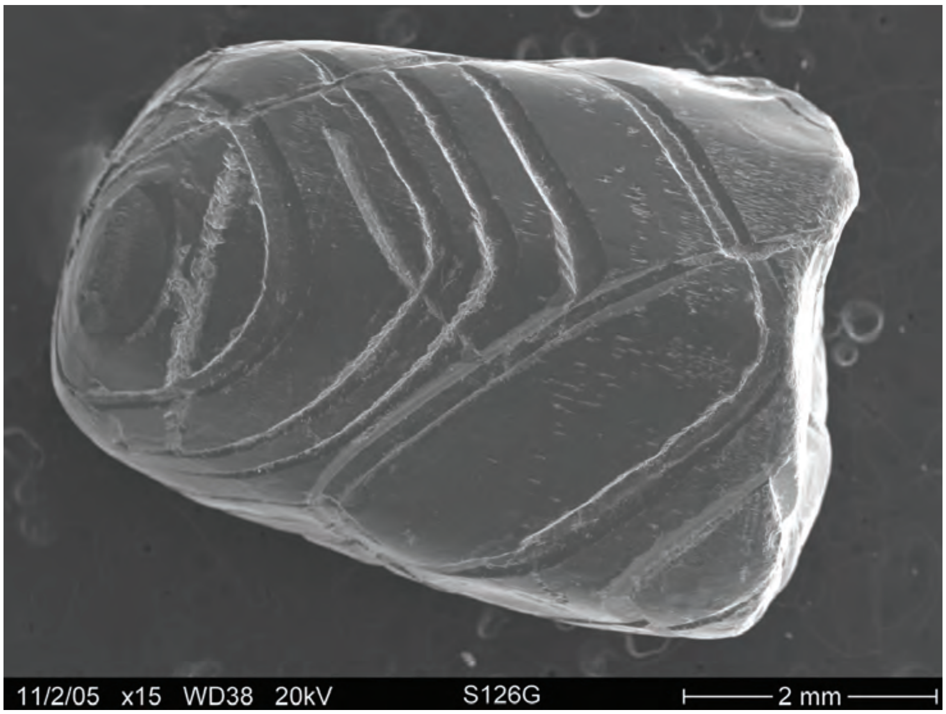
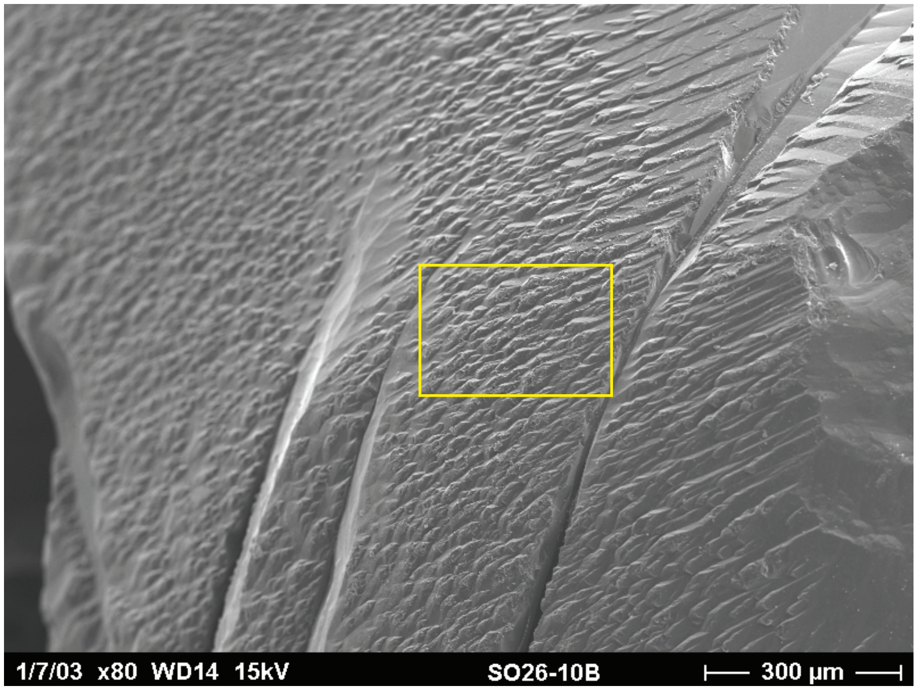


Figure 17. **Observation**—Highly resorbed prismatic sapphire showing well-developed grooves formed along rhombohedral twinning and less well-developed groove (to the left) of basal orientation. Rhombohedral grooves are typically better developed than basal grooves on sapphires from the South Fork of Dry Cottonwood Creek. **Interpretation**—The rhombohedral and basal grooves were all formed by resorption in the magma carrying the sapphire to the surface. **Source**—Marc Bielenberg, from parcel S126.

A



B

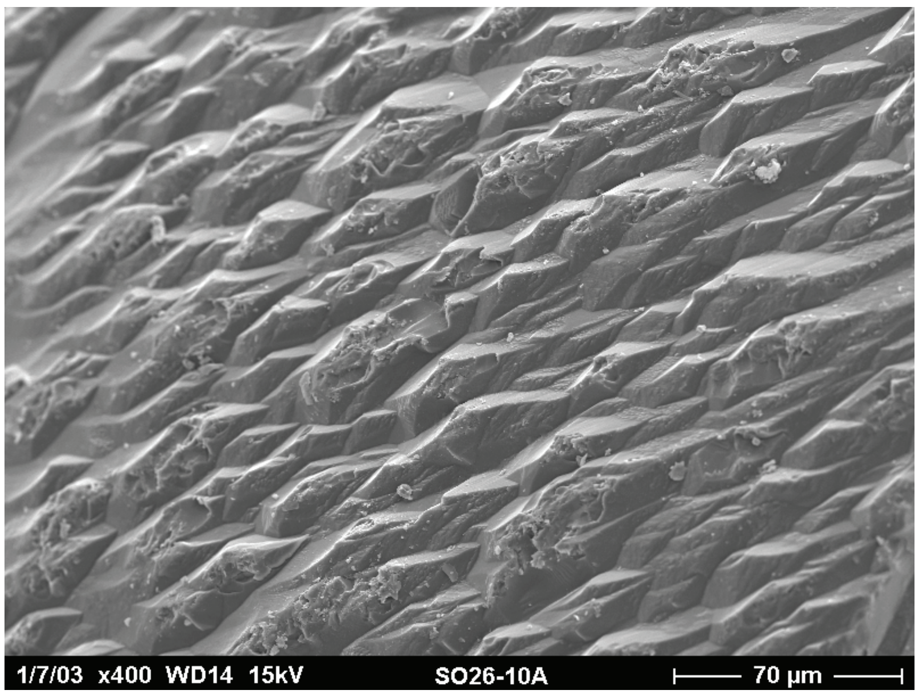


Figure 18A. **Observation**—This sapphire illustrates two features common to sapphires from the South Fork of Dry Cottonwood Creek. The relatively deep grooves parallel the rhombohedral parting that are surrounded by the coarsely etched surface. Note smooth sides of groove in the upper right-hand corner of image. **Interpretation**—Both features formed by resorption of the sapphire while carried in magma from an unrecognized source. Because the grooves are smooth and cut the rough surface, I speculate that they formed after the surrounding surface was etched.

Figure 18B. **Observation**—Enlargement of etched surface shown in figure 18A. **Interpretation**—Small chips on etched surface caused either by abrasion during fluvial transport or, less likely, during processing in the washing plant. Such abrasion on sapphires from the South Fork of Dry Cottonwood Creek is very rare. **Source**—John Rex from area mined by American Gem, Inc., 1995 and 1996 shown in figure 16, from parcel S026.

C

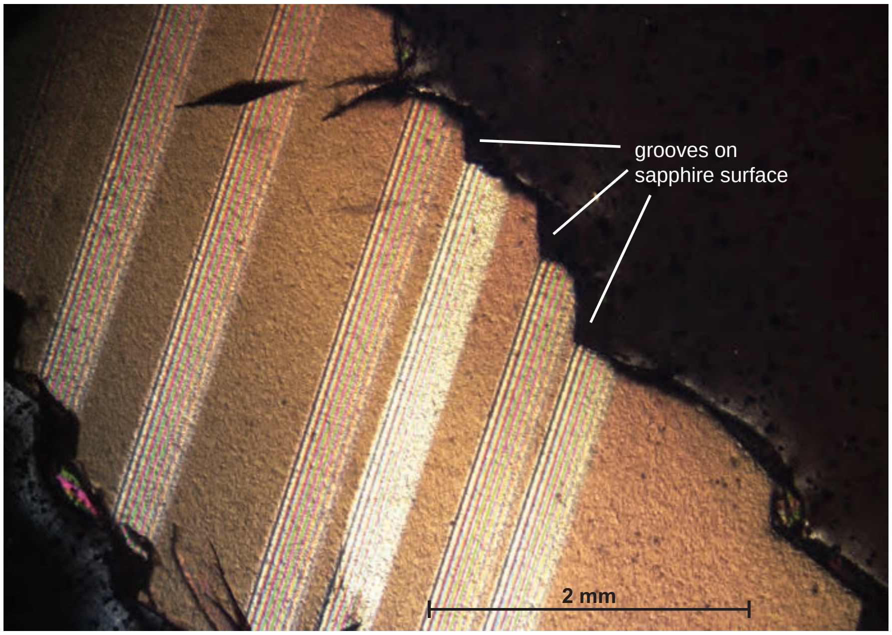


Figure 18C. **Observation**—Photomicrograph of a petrographic thin section cut almost parallel to the C axis, photographed with crossed polars showing polysynthetic twinning parallel to the rhombohedral parting. The embayed surface of the sapphire corresponds to the grooves, which are controlled by rhombohedral twinning. **Interpretation**—The polysynthetic twinning of rhombohedral orientation appears to control the resorption that formed the grooves on the surface of this sapphire. **Source**—John Rex from same locality as shown in figure 16, from parcel S026.

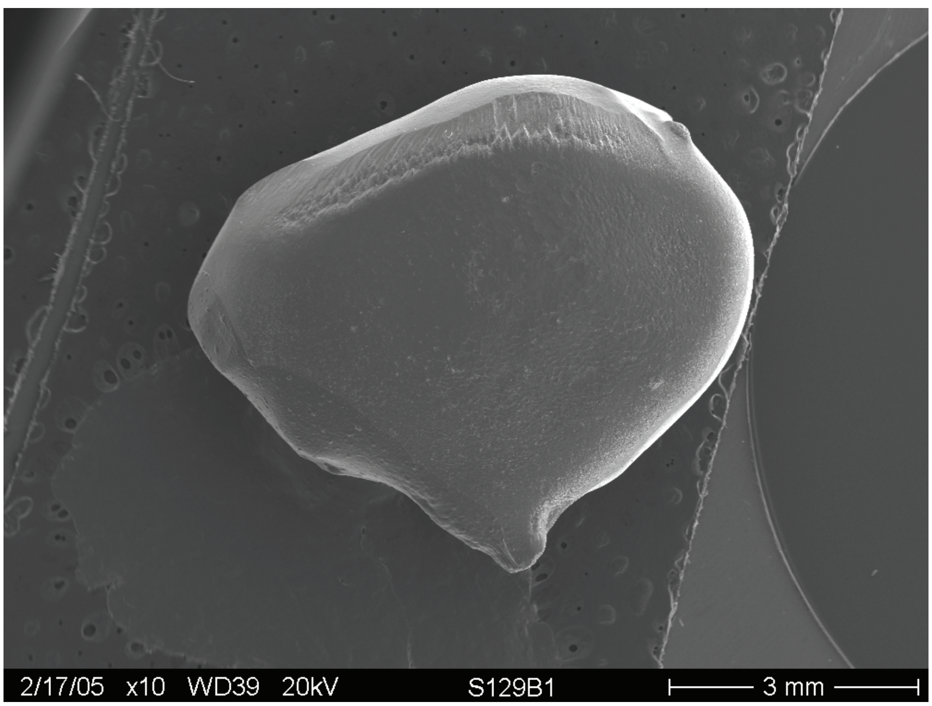


Figure 19. **Observation**—Partly spherical sapphire with projections and some sculpting shown near the top of the image. Microscopic examination of a petrographic thin section of one of these projections showed no discernible difference between the projection and the adjacent sapphire. **Interpretation**—The rounding of the sapphire was caused by resorption in the magma. The projections are attributed to resorption at a slower rate than the rest of the sapphire, possibly because of a difference in trace element chemistry or they were protected from resorption by a mineral inclusion at the surface that has been since resorbed. **Source**—Probably from Grand Pre-Flat from Marc Bielenberg, from parcel S129.

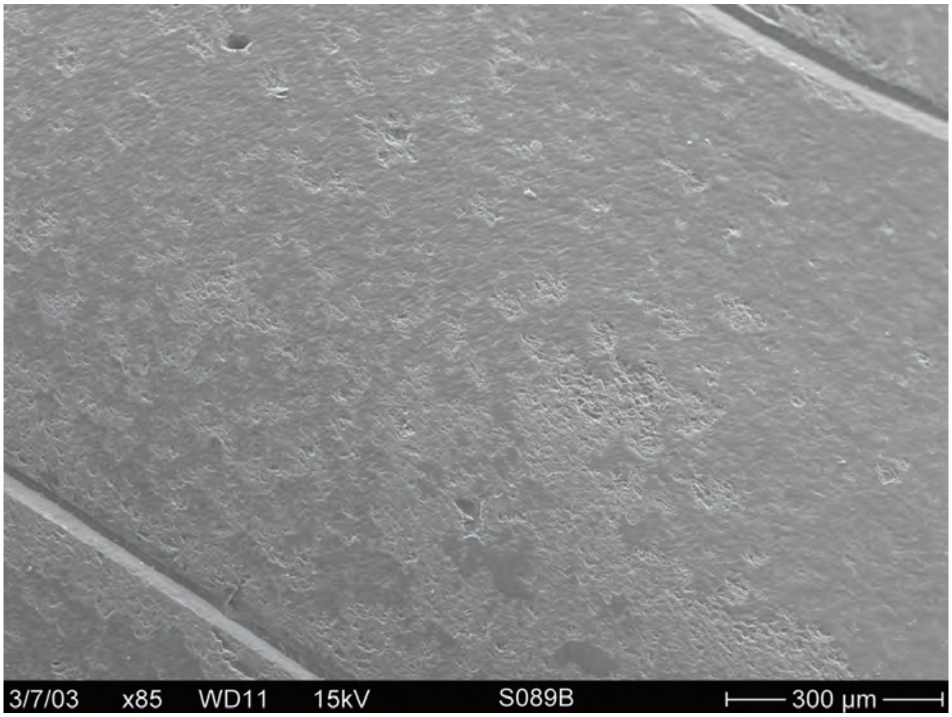


Figure 20. **Observation**—Example of finely etched surface found on most sapphires from the secondary deposits in southwestern Montana. At this magnification, the sapphire is characterized by an almost smooth surface with many small irregular pits. The two large grooves of rhombohedral orientation are smooth by contrast.
Interpretation—My speculation is that the grooves formed at the intersection of rhombohedral twinning with the surface where resorption proceeded more rapidly than the finely etched surface between the grooves. My speculation is that the smooth grooves formed after the finely frosted surface was etched.
Source—Dale Siegford, from parcel S089.

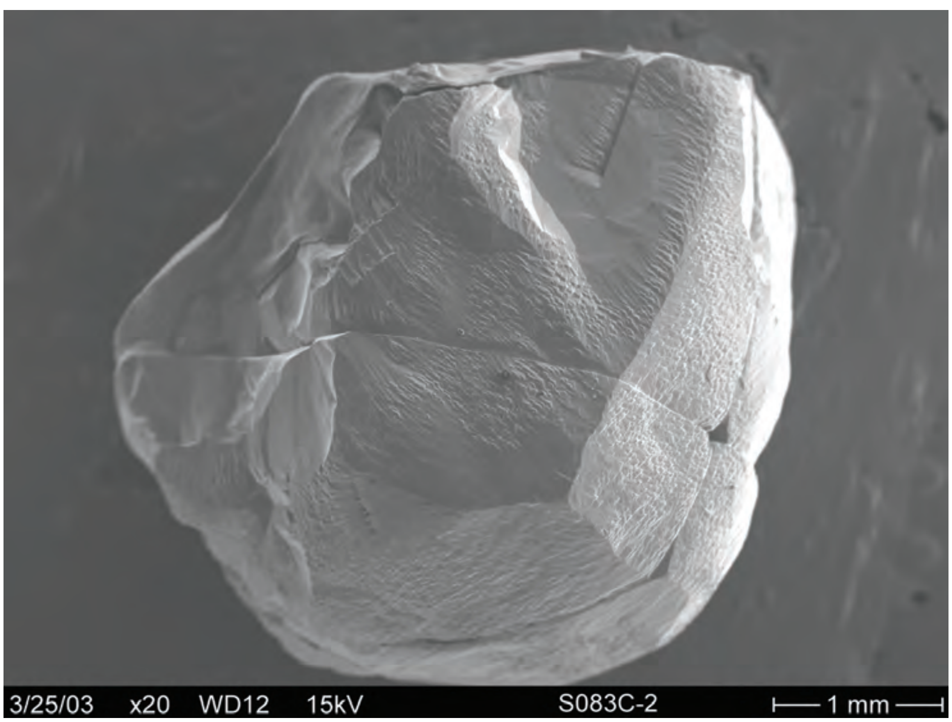


Figure 21. **Observation**—This image illustrates the intersection of grooves of basal and rhombohedral orientation. The smooth surface in the upper left is the mounting medium that held the sapphire during scanning electron microscopy.
Interpretation—Etching caused by resorption during magmatic transport.
Source—Collected by R.B. Berg from the Upper Meadow, from parcel S083.

A

B

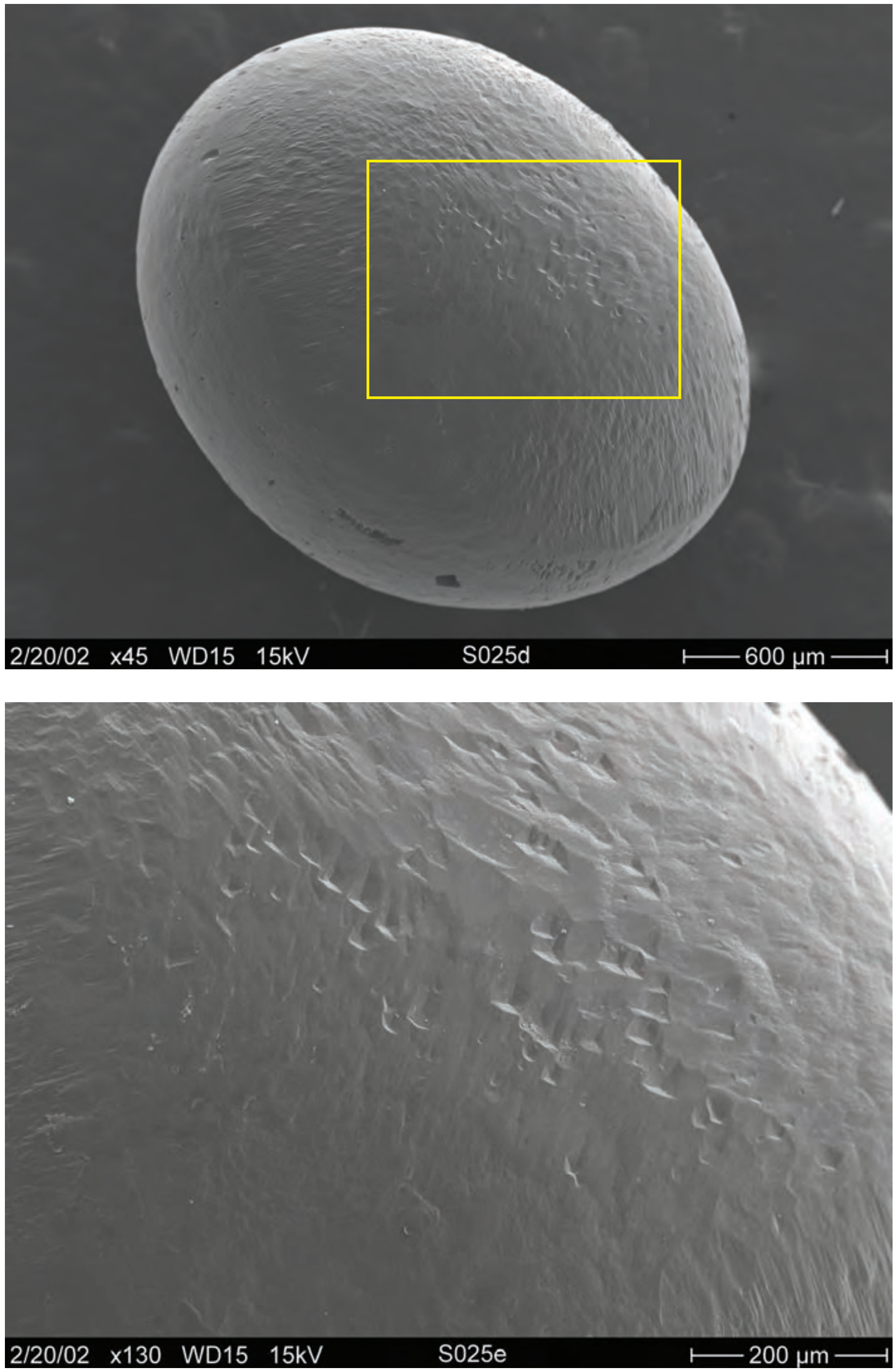
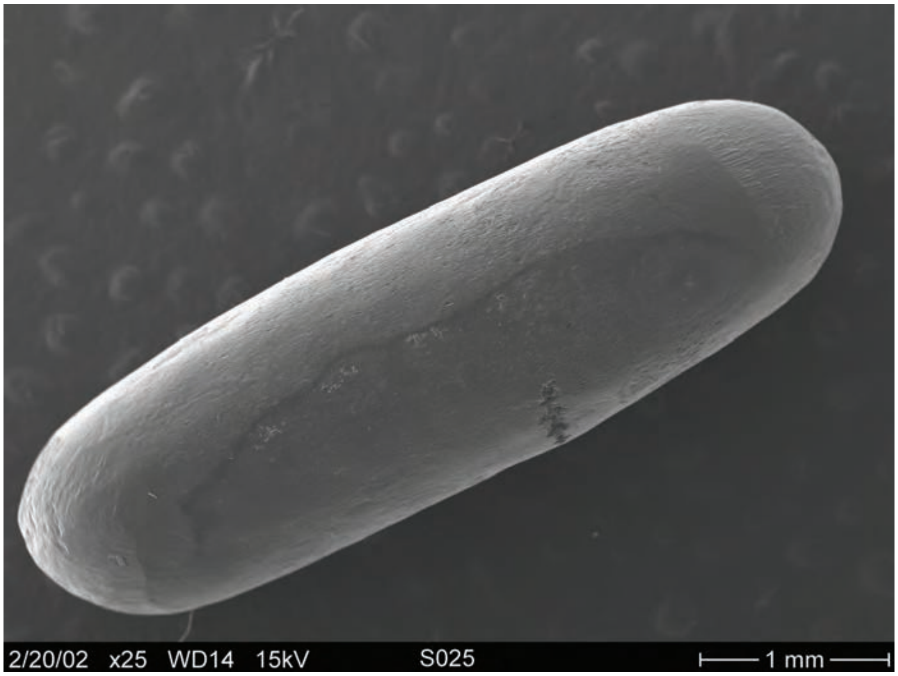


Figure 22A. **Observation**—Steps on surface of spherical sapphire.

Figure 22B. **Observation**—Enlargement of steps. **Interpretation**—Generally when examined closely the spherical sapphires show some indication of crystallographic control. **Source**—John Rex, who mined along the upper part of the South Fork of Dry Cottonwood Creek where American Gem, Inc. mined in 1995 and 1996, from parcel S026.

A



B

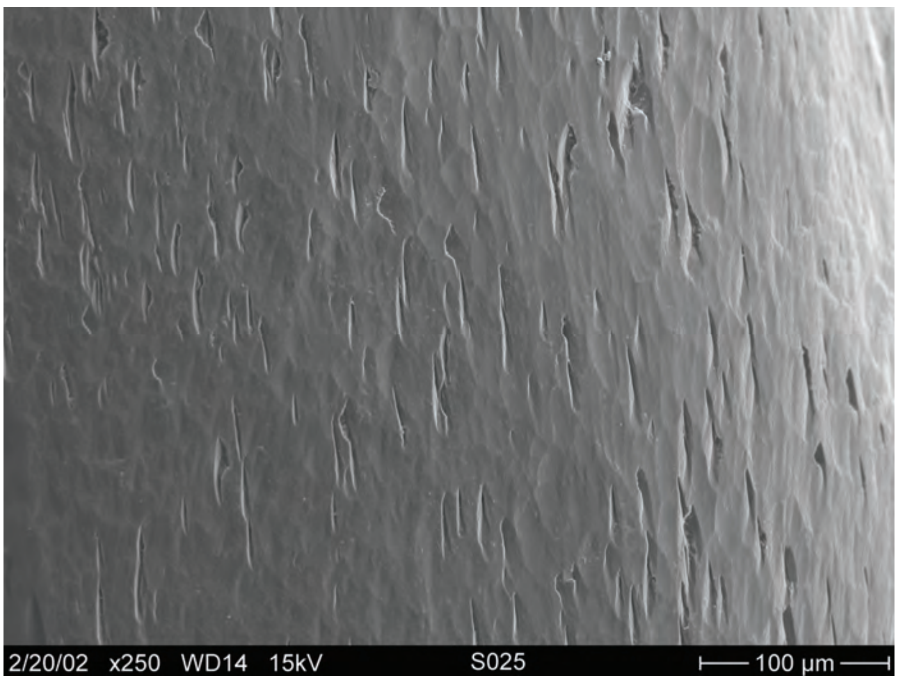


Figure 23A. **Observation**—Elongate, rod-shaped sapphire.

Figure 23B. **Observation**—Enlargement of the surface of this sapphire with long vertical axis showing elongate pits parallel the length, which is probably the C axis. **Interpretation**—Elongate pits caused by resorption parallel to the C crystallographic axis. **Source**—John Rex, who mined along the upper part of the South Fork of Dry Cottonwood Creek where American Gem, Inc. mined in 1995 and 1996, from parcel S025.

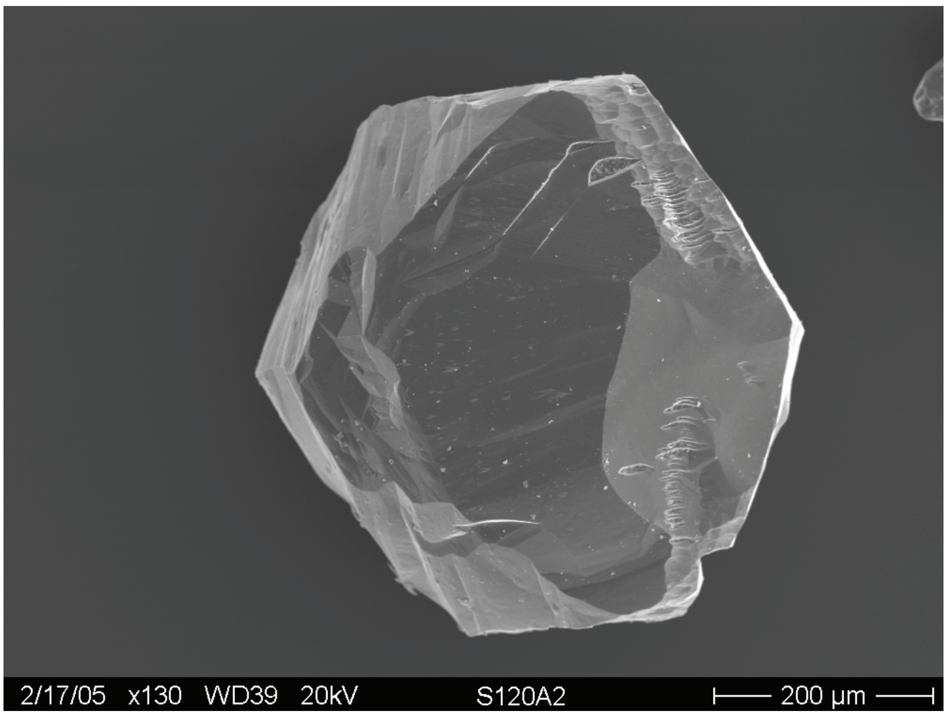


Figure 24. **Observation**—Small sapphire with unusually well-defined hexagonal form and grooves on the right side. **Interpretation**—The closely spaced grooves formed by resorption in the magma. The other surfaces appear finely frosted. **Source**—Sapphire from black sand from the North Fork of the South Fork of Dry Cottonwood Creek, provided by Marc Bielenberg. I am not certain what Marc Bielenberg meant by the North Fork of the South Fork of Dry Cottonwood Creek. Perhaps this indicates another sapphire locality, from parcel S120.

A

B

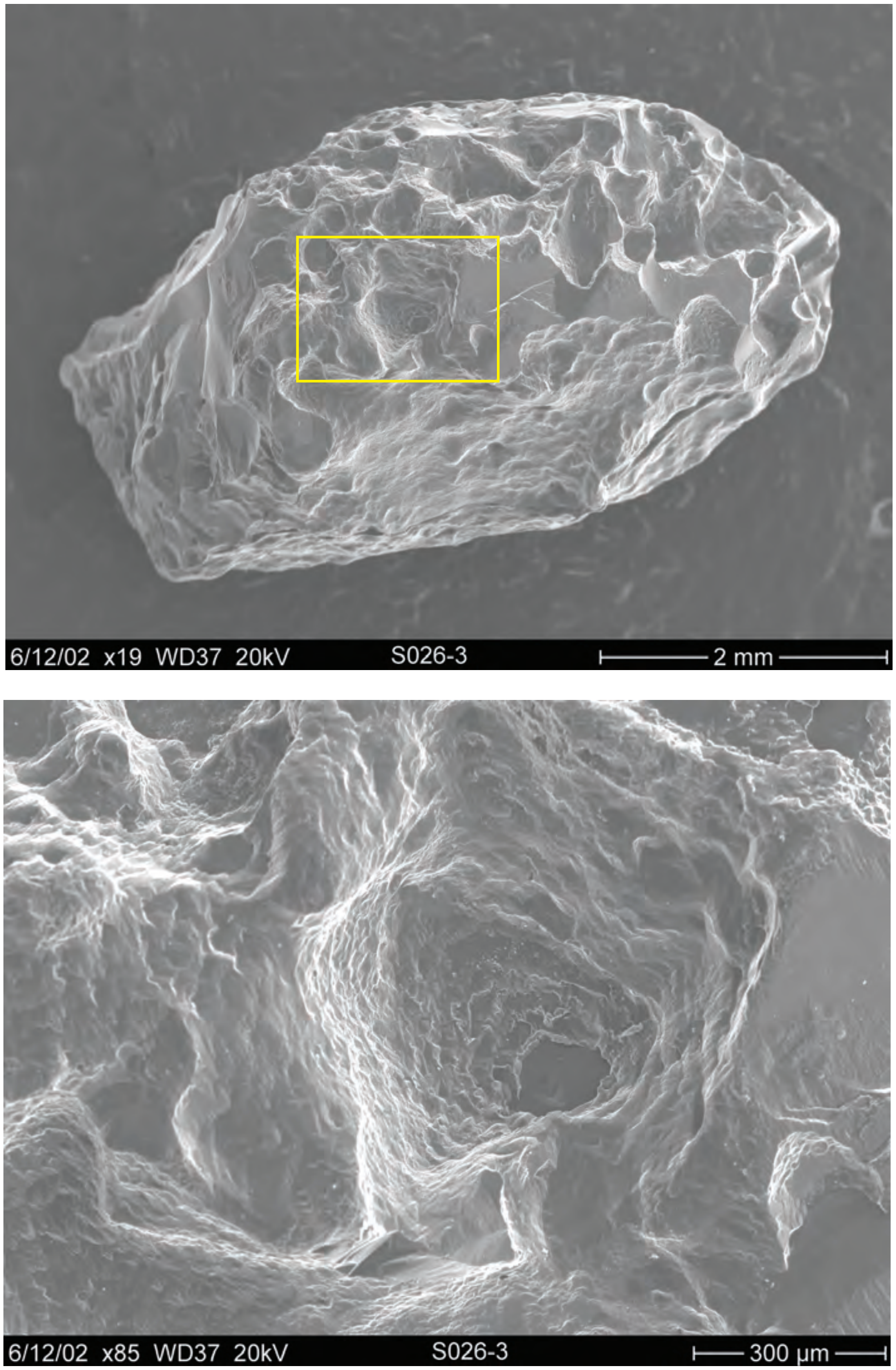


Figure 25A. **Observation**—Sapphire with numerous depressions and craters.

Figure 25B. **Observation**—Enlargement of crater. **Interpretation**—Craters like this are rare on sapphires from the South Fork of Dry Cottonwood Creek, but are more common on sapphires from Eldorado Bar along the Missouri River (fig. 35) and have been recognized on sapphires from the Yogo deposit. As shown here, this sapphire has a highly sculpted surface. The crater may have resulted from resorption initiated by a mineral inclusion in the sapphire or crystal lattice defects. **Source**—John Rex, who mined along the upper part of the South Fork of Dry Cottonwood Creek close to the fork where American Gem, Inc. mined in 1995 and 1996, from parcel S026.

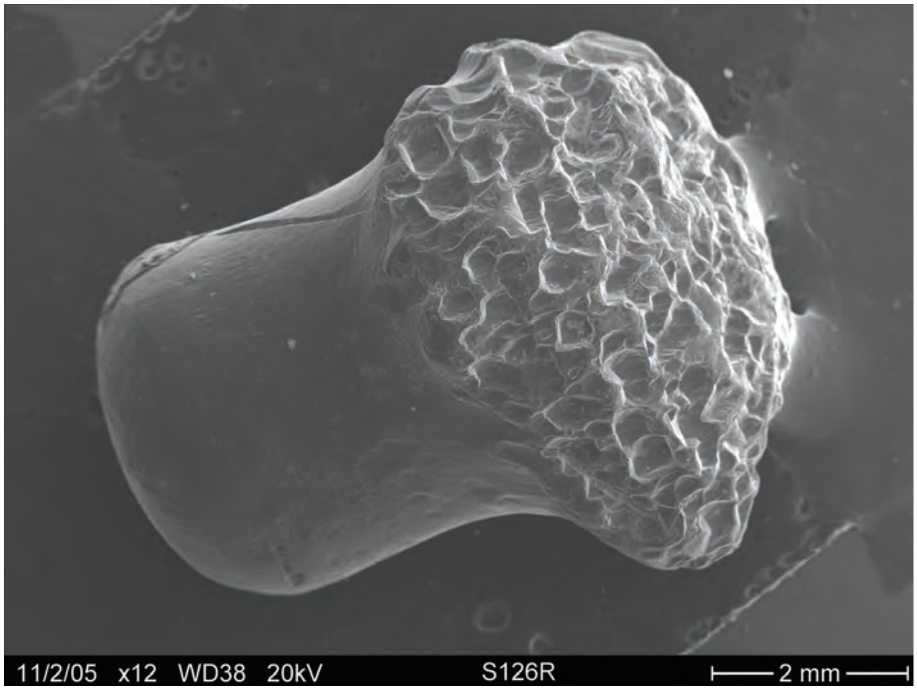


Figure 26. **Observation**—This unusual sapphire is probably elongate parallel to the C axis, with a faintly recognizable rhombohedral groove along the upper surface. **Interpretation** (speculative)—When the sapphire was incorporated in magma it was partly enclosed in a xenolith that contained a sapphire that had grown next to many small crystals. During much of the sapphire's journey in the magma the left side of the sapphire was exposed to the magma and significantly resorbed with the formation of the groove. It appears that there may be limited resorption along the ridges between the crystal impressions, indicating that the sapphire was entirely liberated from the xenolith shortly before crystallization of the magma. **Source**—From Marc Bielenberg probably from Grand Pre Flat, from parcel 126.

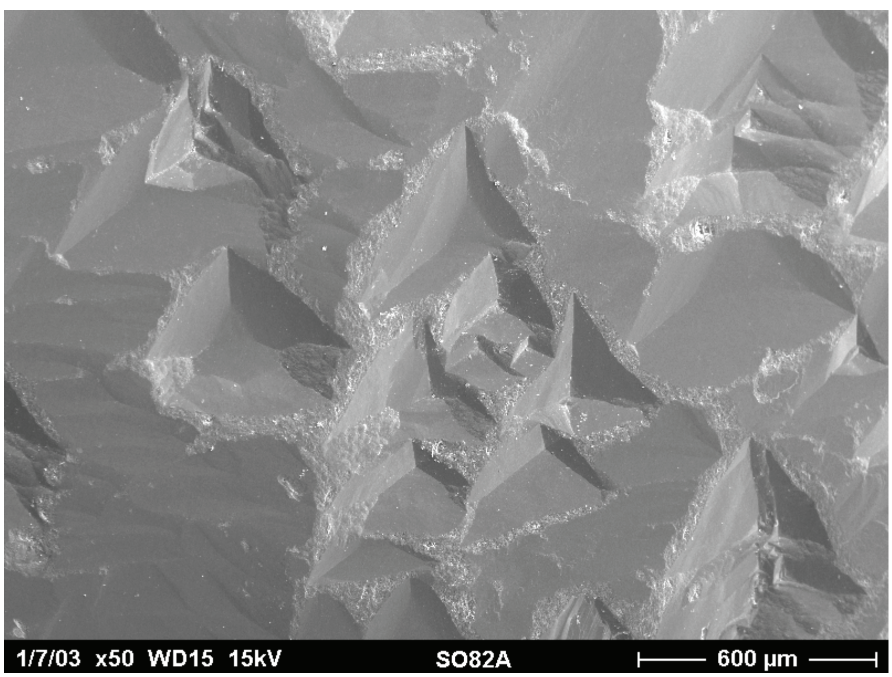


Figure 27. **Observation**—The sapphire surface is covered with many steps of similar orientation. **Interpretation**—Because the steps are of similar orientation, they must be crystallographically controlled, unlike the crystal impressions shown in figure 26 that are not of similar orientation. The chips on the ridges were abraded during fluvial transport or, less likely, during recovery in the washing plant. **Source**—Dale Siegford, from parcel S082.

MISSOURI RIVER SAPPHIRES

Sapphires from Deposits along the Missouri River near Helena

Introduction

Sapphire deposits extend for at least 24 km along the Missouri River near Helena, where sapphires are mined from strath terraces along Hauser Lake (fig. 28).

Specimens were selected for scanning electron microscopy from approximately 1,600 sapphires examined using the binocular microscope. Many of the sapphires from this area have features that are not found on sapphires from the other secondary deposits.

Remnants of black spinel occur in small depressions on the surfaces of at least 25 percent of the sapphires examined. Spinel was not identified in mineral inclusions and is thought to have formed by reaction of the transporting magma with the sapphire. Also, some sapphires have distinctive flat surfaces surrounded by stepped surfaces. On a microscopic scale, these features are somewhat similar to lakes surrounded by a series of shorelines. Figures 29–40 are images of the Missouri River sapphires.

For additional information on the geology and sapphire deposits see Berg and Landry (2018). Sapphires were provided by Tim Beard, Mac Mader, Blaze Wharton, Bruce Scharf, and Neal Hurni. Their generosity is very much appreciated.

Most Distinctive Features

1. The occurrence of small remnants of spinel in depressions on the surfaces of sapphires is the most distinctive feature of Missouri River sapphires (fig. 29). Spinel was not found on the surfaces of sapphires from the other secondary deposits.
2. Depressions with flat bottoms of basal orientation are prominent on some sapphires (figs. 33A–33C).
3. Generally, resorption on sapphires from the Missouri River deposits was more prominent along a basal surface than on a rhombohedral surface.
4. Deep craters occur on Missouri River sapphires (figs. 34A–34C). Although not shown here, a sapphire from the Yogo deposit also has similar deep craters.

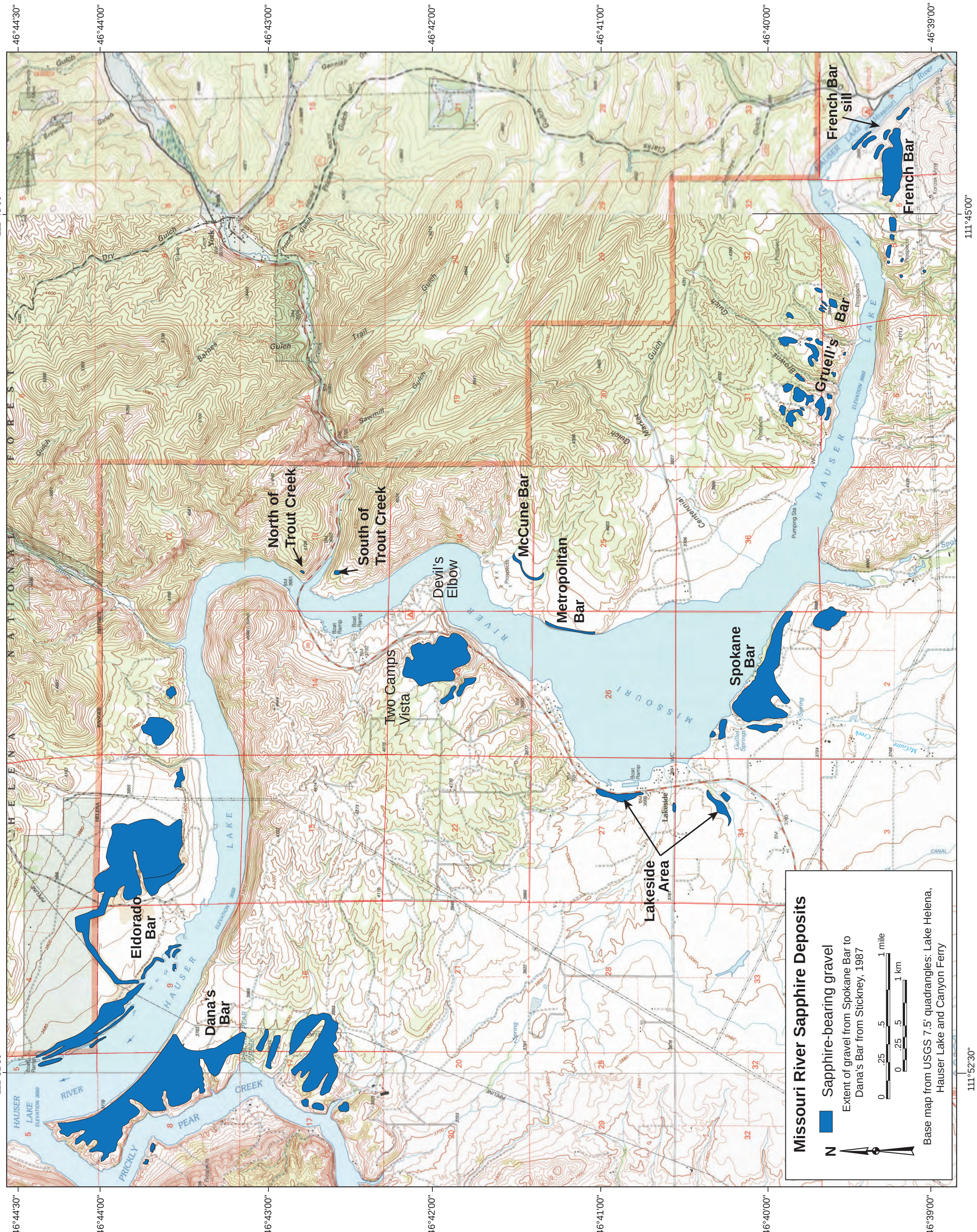


Figure 28. Sapphire-bearing gravel deposits along Hauser Lake from Berg and Landry (2018) and Stickney (1987).

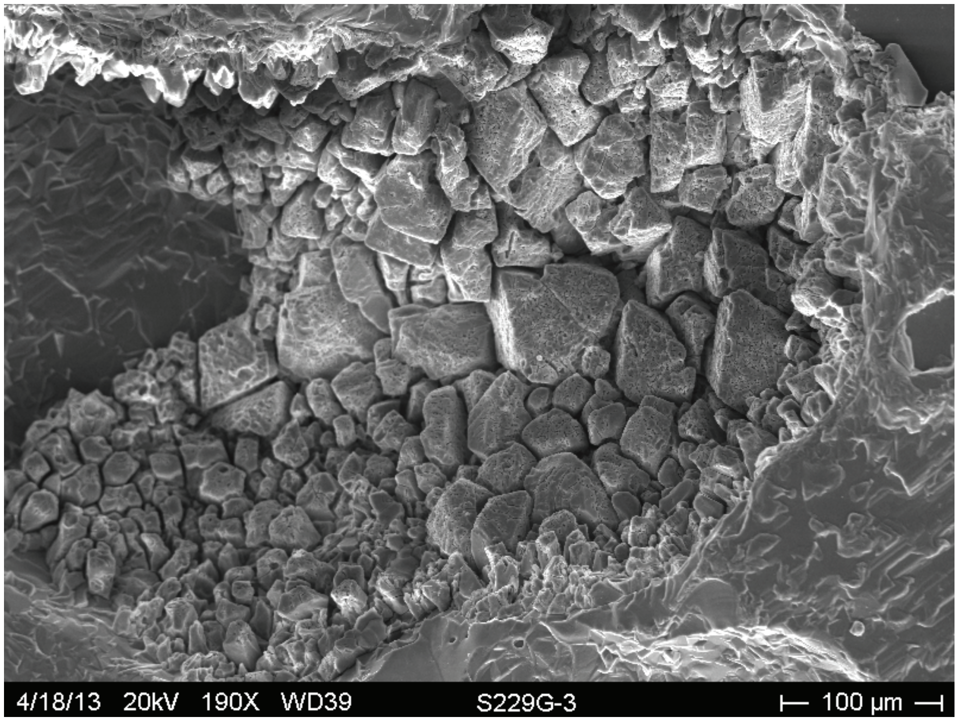
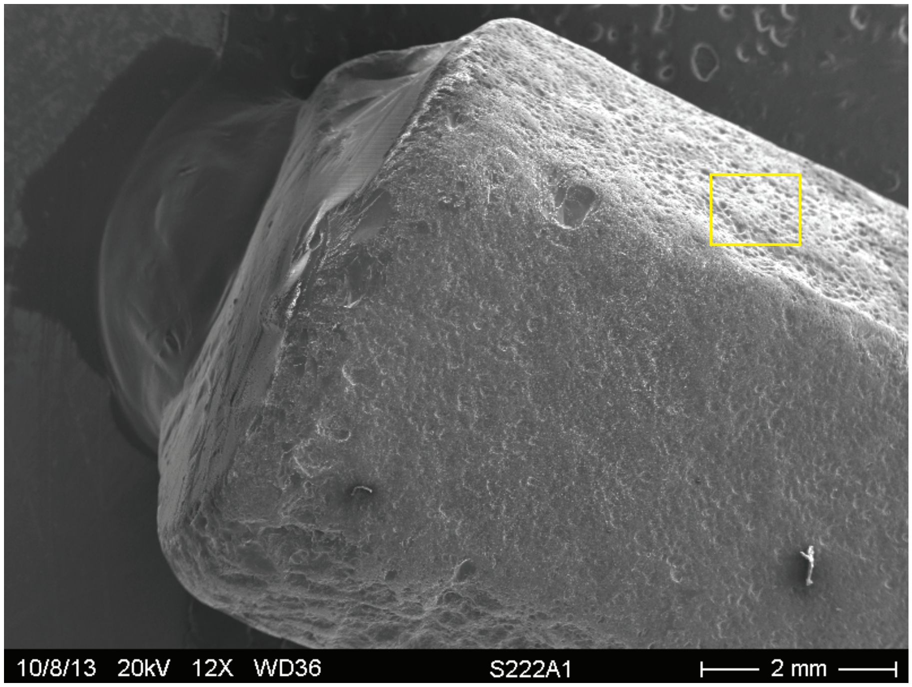


Figure 29. **Observation**—Many of the sapphires from the Missouri River deposits have remnants of spinel preserved in depressions on the surface of the sapphire. The spinel appears black when examined with a hand lens; however, when examined in thin section with a petrographic microscope it is very dark green. Octahedral spinel crystals can usually be recognized with a hand lens. I estimate that at least 25 percent of the sapphires from the Missouri River localities have remnants of spinel on the surface. Spinel inclusions were not identified in sapphires from the Missouri River deposits. **Interpretation**—The bedrock source of the Missouri River sapphires has not been recognized (Berg and Landry, 2018, p. 43). However, the spinel remnants on the surface of these sapphires are interpreted to have formed by reaction of Fe and Mg in the magma that brought the sapphires to the surface with the Al of the sapphire. A similar reaction has been recognized for sapphires from the Yogo deposit, some of which are partially coated with spinel (Fe variety hercynite) as a result of reaction of the sapphire with the enclosing lamprophyre (Claubaugh, 1952, p. 18). In another spinel occurrence, sapphires from the Siebengebirge Volcanic Field in Germany are coated with a very thin reaction rim of spinel (Baldwin and Ballhaus, 2018). Interestingly, spinel was not recognized on the surfaces of any of the sapphires from the Rock Creek district, the South Fork of Dry Cottonwood Creek, or the French Bar sill along Hauser Lake. This suggests transporting magma of lower Fe and Mg content than the unidentified magma that brought the Missouri River sapphires to the surface. **Source**—From Mac Mader, who recovered sapphires using a hand-held suction dredge from Hauser Lake down river from Canyon Ferry Dam and just offshore from French Bar, from parcel S229.

A



B

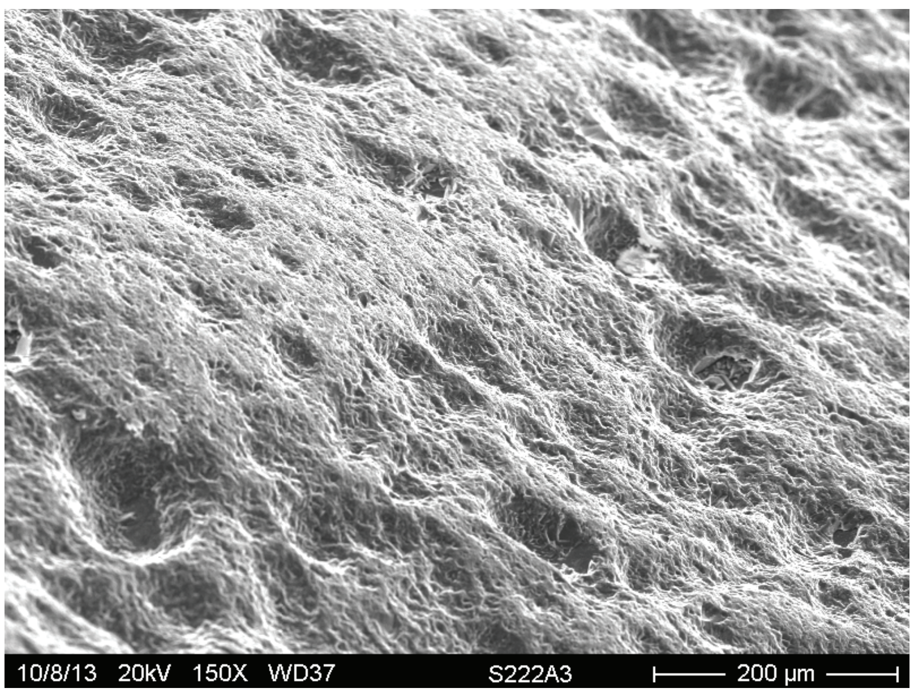
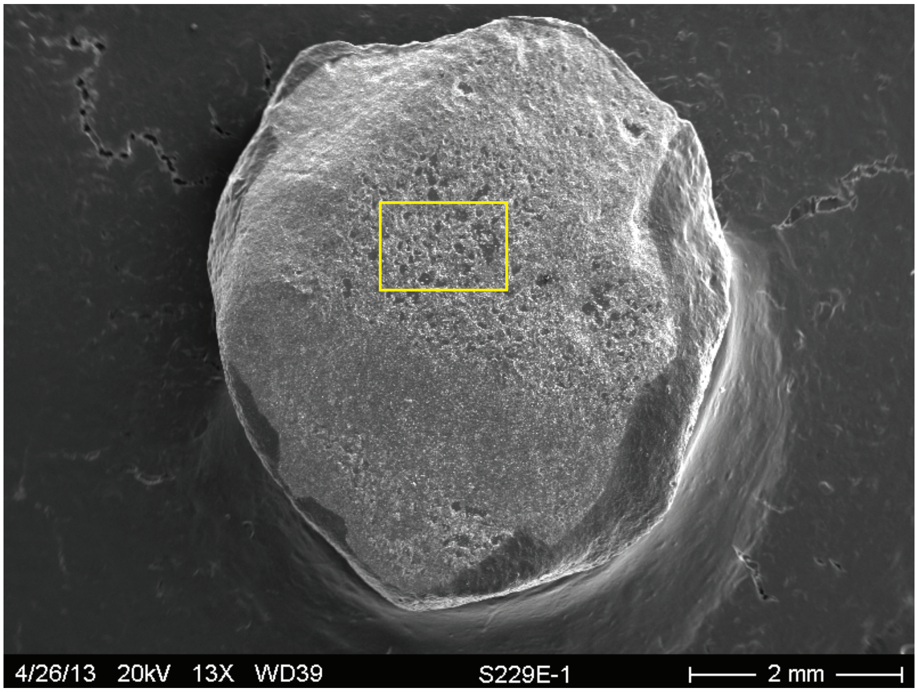


Figure 30A. **Observation**—This sapphire shows the relict form of a hexagonal prism covered with small pits. The surface to the left is a conchoidal fracture partly coated with the mounting medium.

Figure 30B. **Observation**—Enlarged image of the upper surface shown in figure 30A. Note the scattered, relatively large pits surrounded by much smaller irregular pits. However, upon rotation of this image the pits appear as irregular raised knobs that may be a better interpretation. **Interpretation**—Caused by resorption in the magma that doesn't appear to be crystallographically controlled. **Source**—From Tim Beard from the eastern lobe of Gruell's Bar, from parcel S222.

A



B

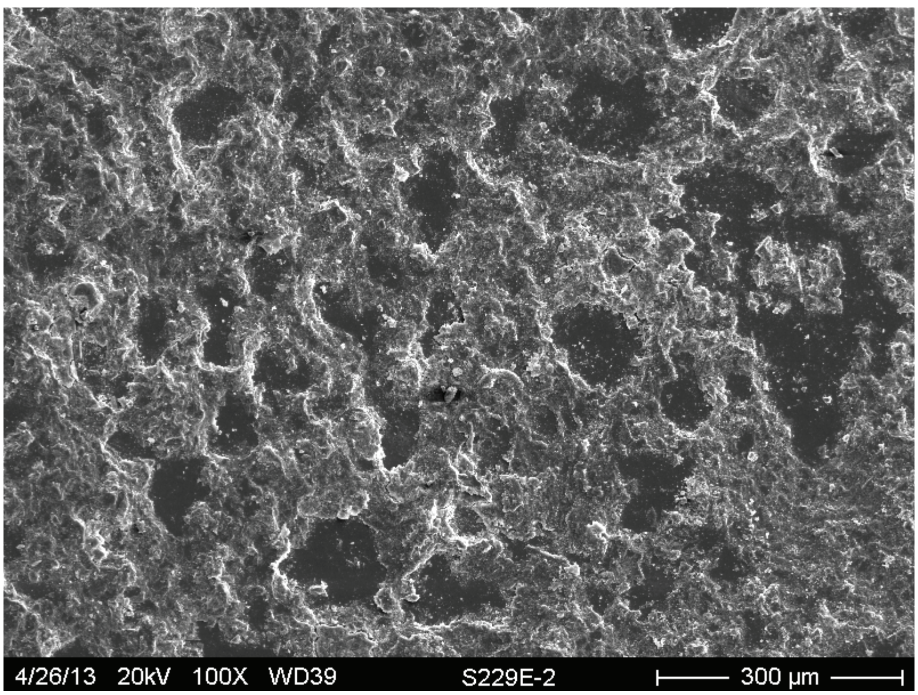


Figure 31A. **Observation**—Partly preserved remnant hexagonal outline of a tabular sapphire. Most of the visible surface of this sapphire is typical of many sapphires from the Missouri River deposits.

Figure 31B. **Observation**—Greatly enlarged image of the surface in Fig. 31A shows the pitted and irregular textures of a typical surface. Note small flat areas surrounded by irregular surface. **Interpretation**—Resorption during magmatic transport. **Source**—From Mac Mader, who recovered sapphires using a hand-held suction dredge from Hauser Lake downriver from Canyon Ferry dam and just offshore from French Bar, from parcel S229.

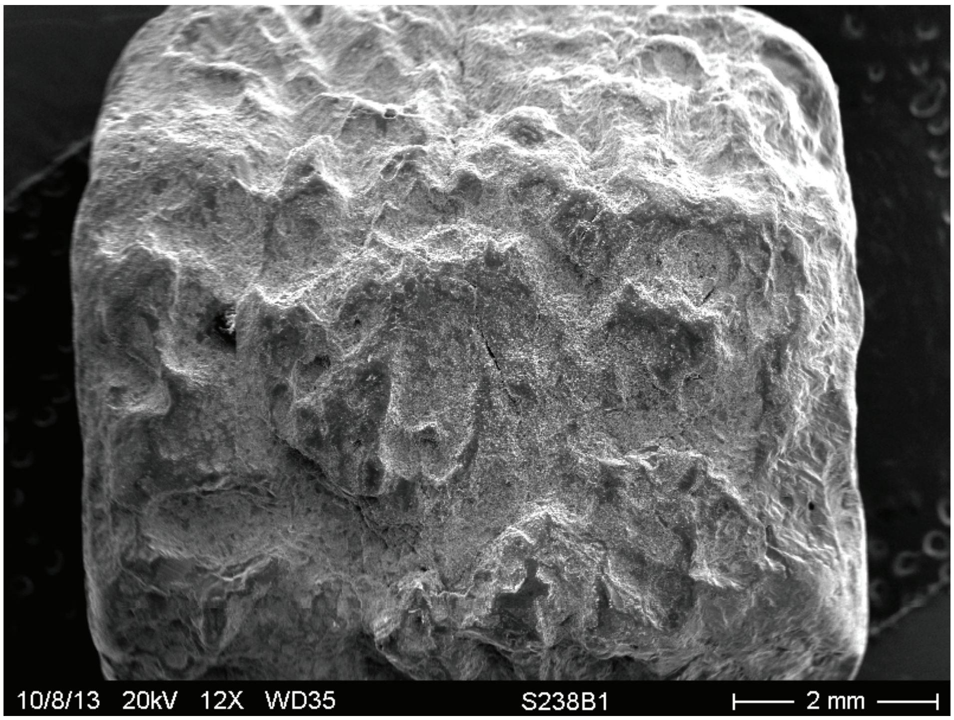


Figure 32. **Observation**—Surfaces of Missouri River sapphires range from smooth (fig. 40) to this very irregular surface. **Interpretation**—This surface was caused by resorption. Speculative conjecture is that this sapphire had a greater than usual density of lattice defects that contributed to resorption at numerous sites. **Source**—From the Lewis and Clark Sapphire mine where Neal Hurni mines gravel uphill on Eldorado Bar above the dredge tailings, from parcel S238.

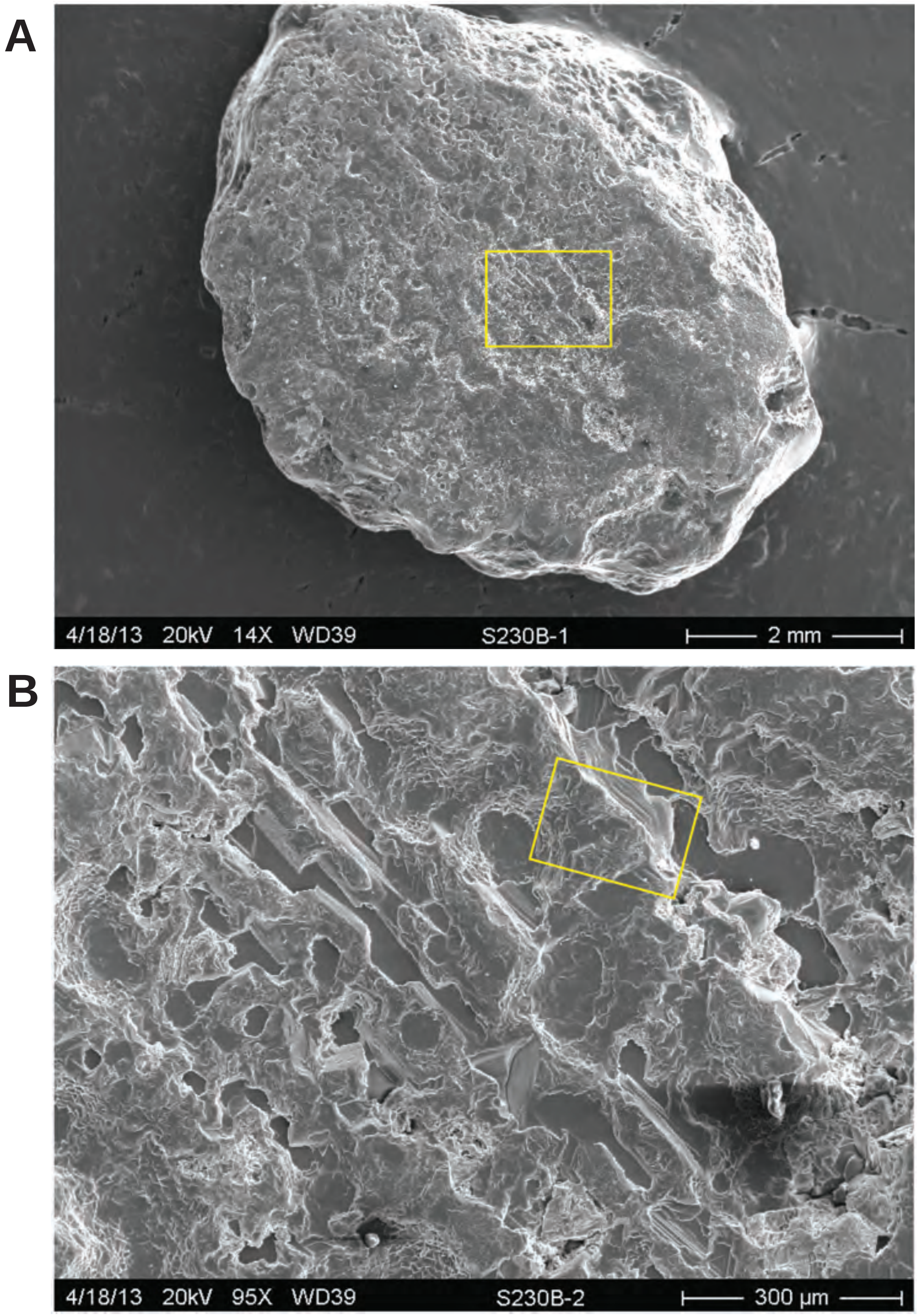


Figure 33A. **Observation**—Even at low magnification numerous small flat areas can be seen on the basal surface of this sapphire.

Figure 33B. **Observation**—Enlarged image of the same surface showing in detail these depressions with flat bottoms. Although the flat surfaces are of basal orientation, they are not coplanar. Similar features occur on sapphires from Eldorado Bar and Gruell's Bar, in addition to this sapphire dredged from Hauser Lake. Similar depressions with flat bottoms occur on some sapphires from the Rock Creek district and the South Fork of Dry Cottonwood Creek, but they are not surrounded by the stepped surfaces shown on this sapphire from the Missouri River deposits.

C

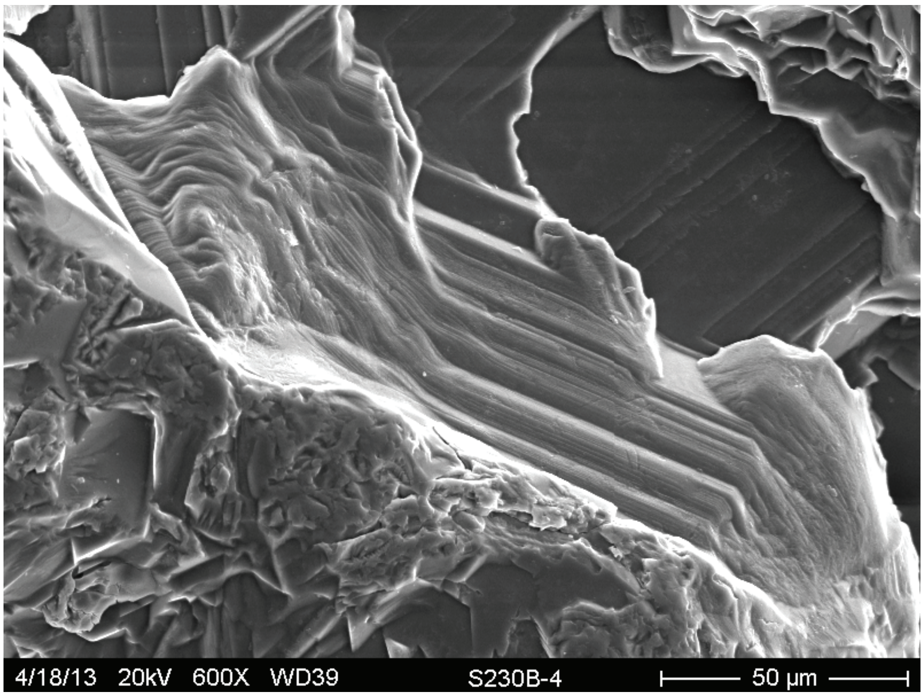
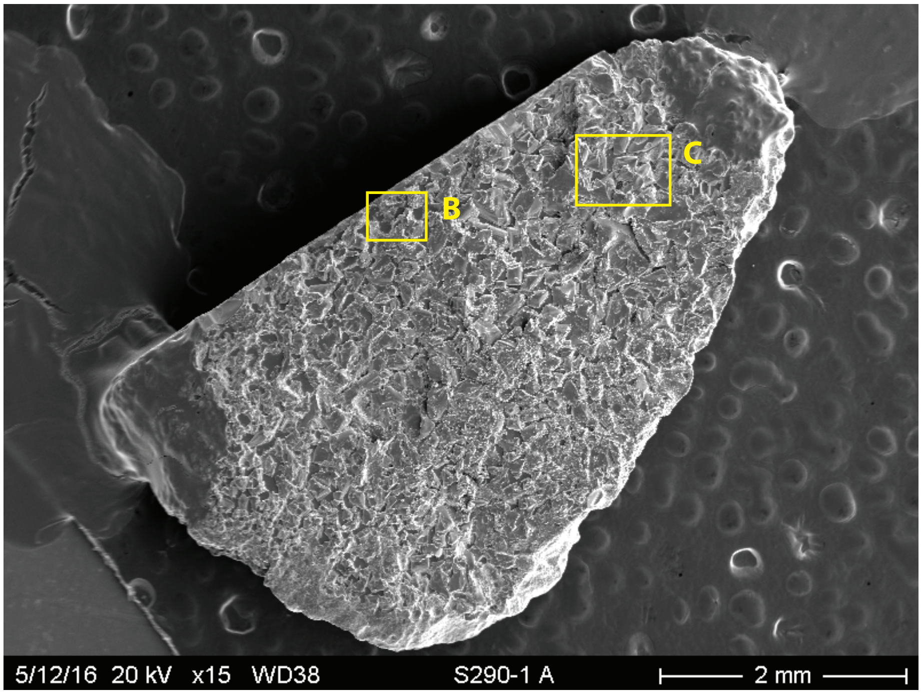


Figure 33C. **Observation**—Further enlargement showing stepped surfaces analogous to shorelines on a lake that here are of basal orientation. Compare to figure 34 of sapphire showing similar features from French Bar sill. **Speculation**—See section on crystallography for unsuccessful attempt to demonstrate that these stepped features were controlled by twinning of basal orientation. Although crystallographically controlled, the mechanism has not been identified. **Source**—From Mac Mader, who recovered sapphires using a hand-held suction dredge from Hauser Lake near Canyon Ferry Dam and just of shore from French Bar, from parcel S230.

A



B

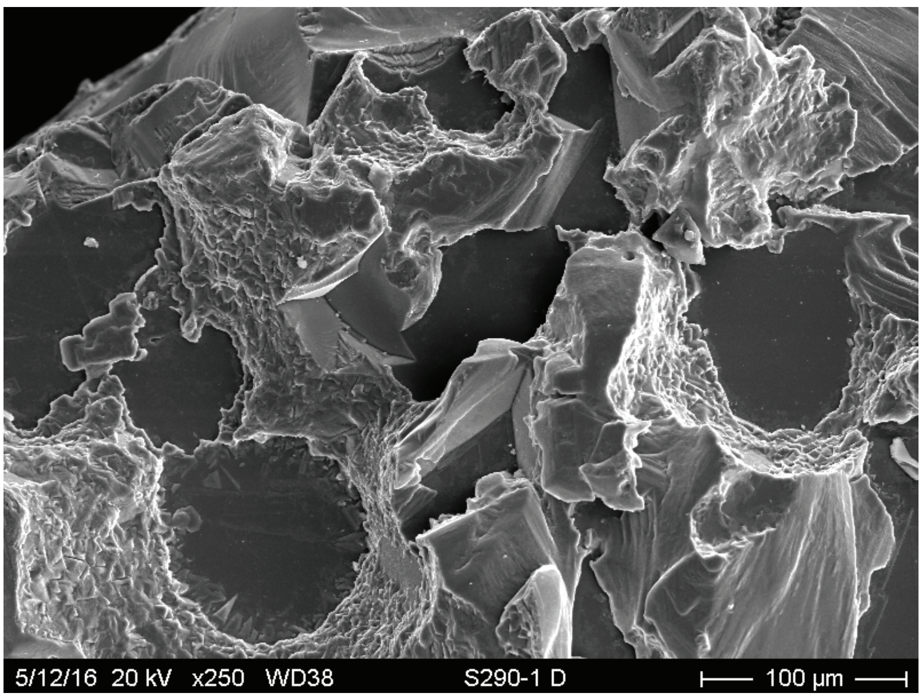


Figure 34A. **Observation**—Except for the sapphire shown in these three images, all of the sapphires described in this compilation are from secondary deposits in southwestern Montana. This sapphire is from the French Bar sill exposed above the west bank of Hauser Lake that contains sparse sapphire xenocrysts (Berg and Dahy, 2002: Berg and Palke, 2017). Although this sill contributed sapphires to the Missouri River deposits, because of the sparse occurrence of sapphires in it and its limited extent, it is not a significant source of the sapphires in the Missouri River deposits. This sapphire was carefully removed from the sill by first chipping away almost all of the enclosing rock and then removing the remaining adhering rock by soaking it in HF for several days.

Figure 34B. **Observation**—Enlarged image showing flat-bottomed depressions on the surface of this sapphire.

C

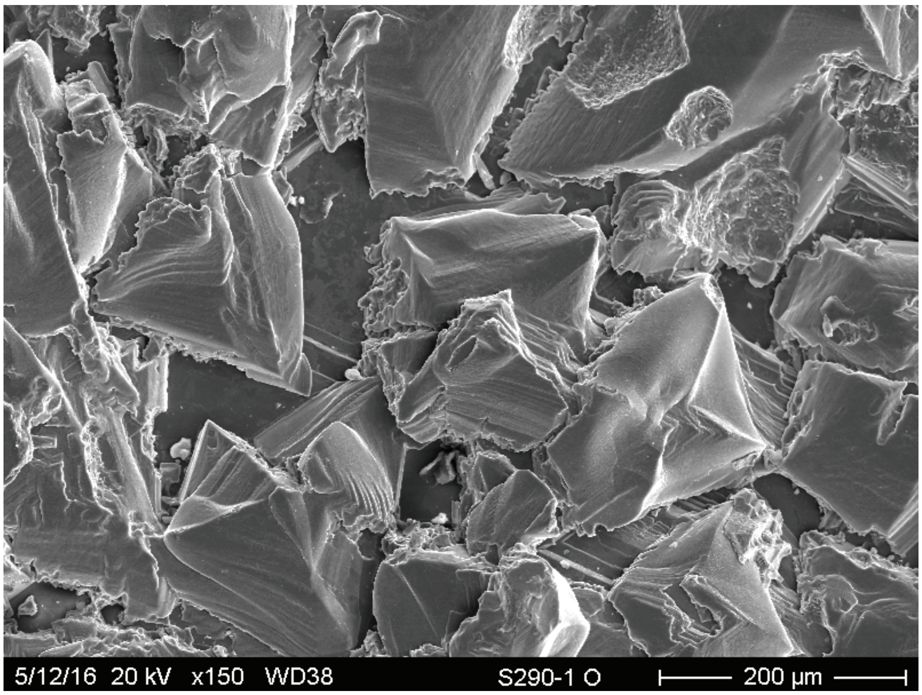
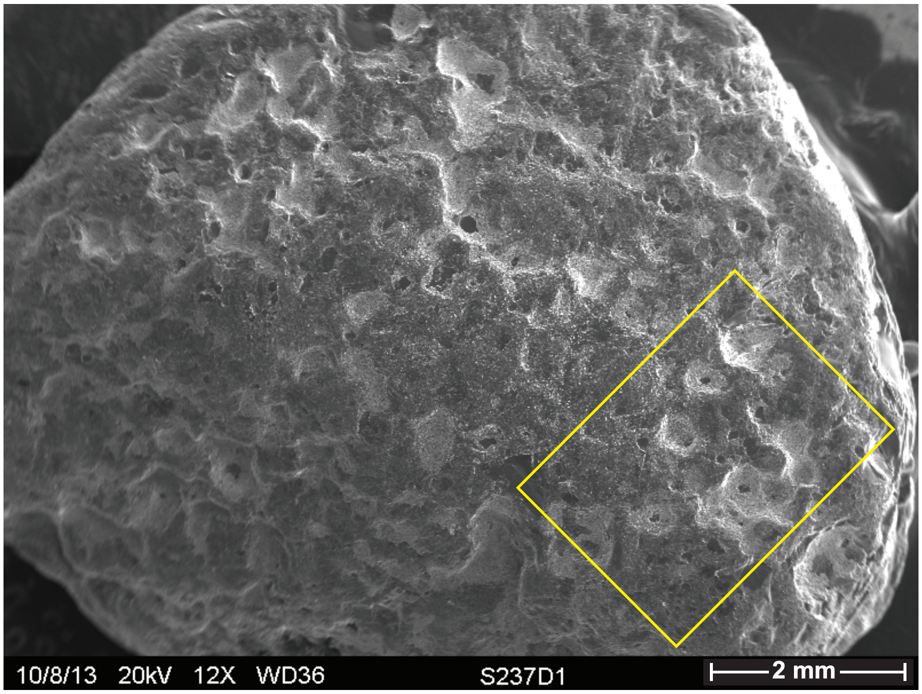


Figure 34C. **Observation**—Another area showing the impressive relief developed on the surface of this same sapphire. **Interpretation**—Same as for sapphire shown in figure 33, where resorption was controlled by crystallography. **Source**—Collected from French Bar sill by R.B. Berg, from parcel S290.

A



B

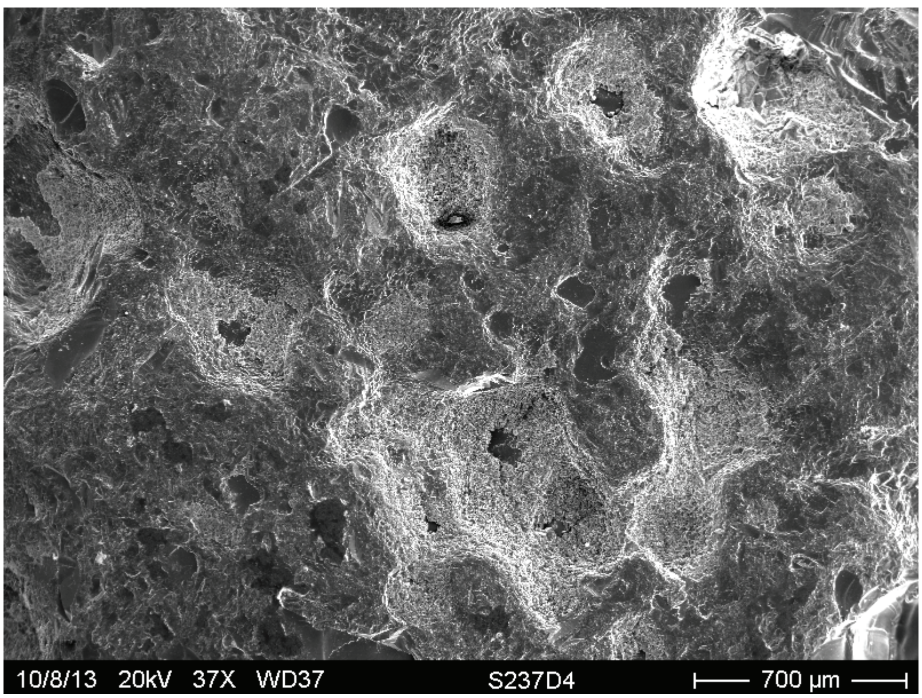
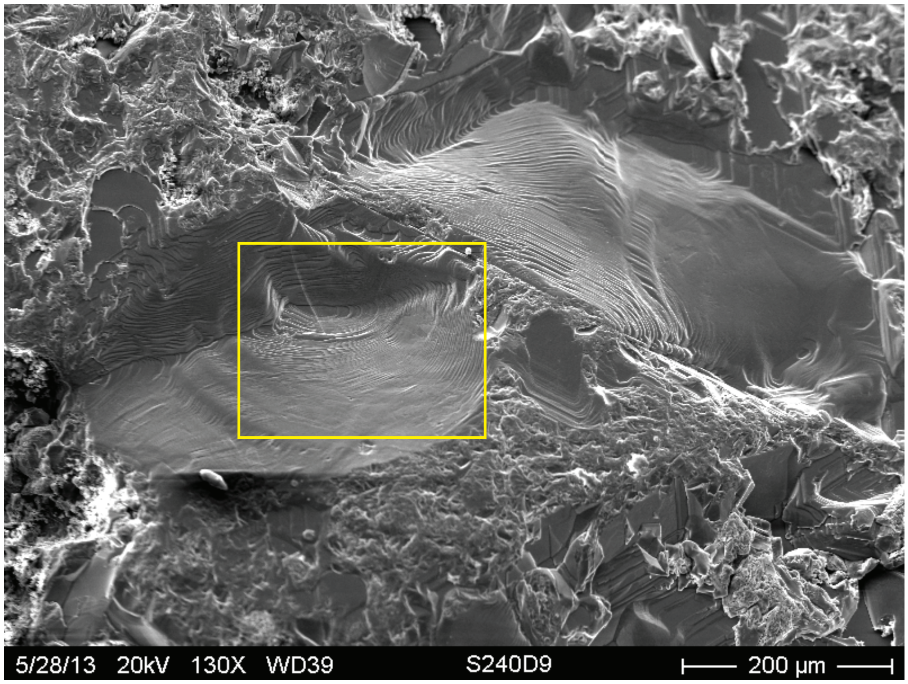


Figure 35A. **Observation**—The surface of this sapphire is covered with small craters surrounded by an irregular surface.

Figure 35B. **Observation**—This enlarged image shows the approximately circular form of the craters and finely pitted surfaces. **Interpretation**—Formed by resorption in the magma, perhaps initiated by mineral inclusions or defects in the sapphire lattice. Similar craters have been observed in a sapphire from the French Bar sill, South Fork of Dry Cottonwood Creek, and also a sapphire from the Yogo lamprophyre dike. **Source**—From Neal Hurni, who mines sapphires at the Lewis and Clark Sapphire mine located uphill from the dredge tailings on Eldorado Bar, from parcel S237.

A



B

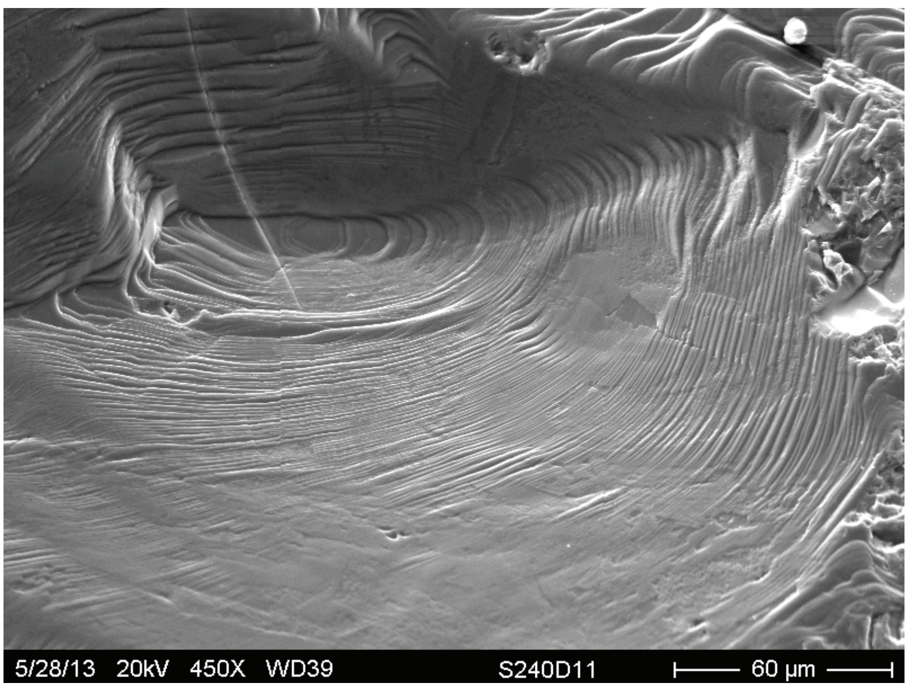


Figure 36A. **Observation**—The contrast in the surface of this sapphire is unusual, from the irregular surface to the finely sculpted surfaces.

Figure 36B. **Observation**—Enlargement of the crater showing the regular grooves on the surface of the depression and the flat bottom. **Interpretation**—This unusual crater may have been caused by resorption in the magma initiated by a mineral inclusion in the sapphire. The white line in the upper left of the image may be an incipient fracture in the sapphire. **Source**—From Neal Hurni, who mines sapphires at the Lewis and Clark Sapphire mine located uphill from the dredge tailings on Eldorado Bar, from parcel S240.

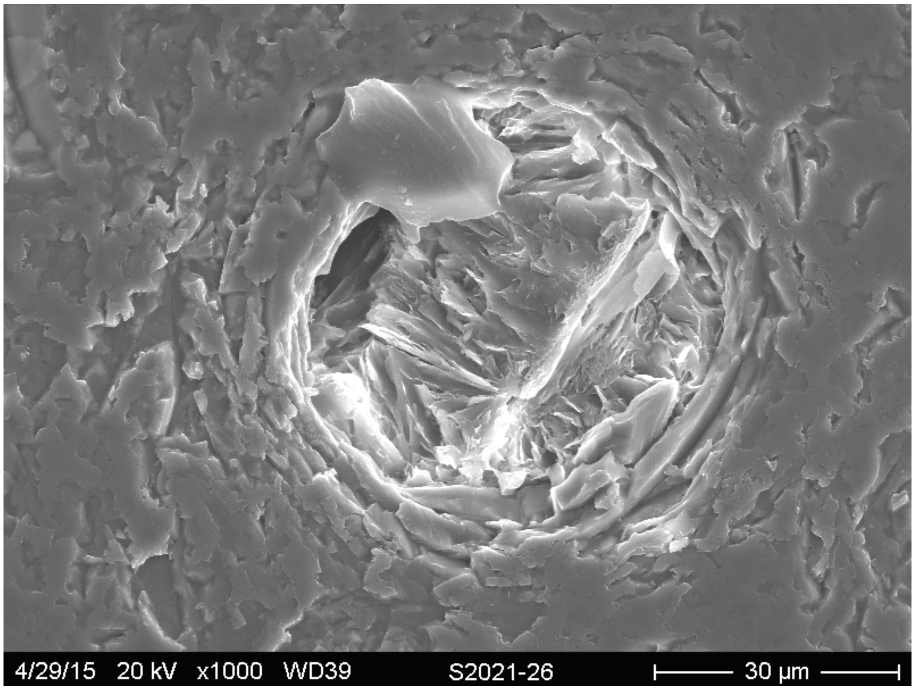


Figure 37. **Observation**—Some sapphires, particularly from Eldorado Bar, have these relatively deep, shaft-like pits. **Interpretation**—The pits were formed by resorption while in the magma, perhaps caused by a mineral inclusion that localized resorption or a lattice defect. **Source**—Mined by Blaze Wharton at his Blaze N' Gems mine on Eldorado Bar. This sapphire may have been recovered from the dredge tailings or previously unmined gravel that he mined at the same location, from parcel S202.

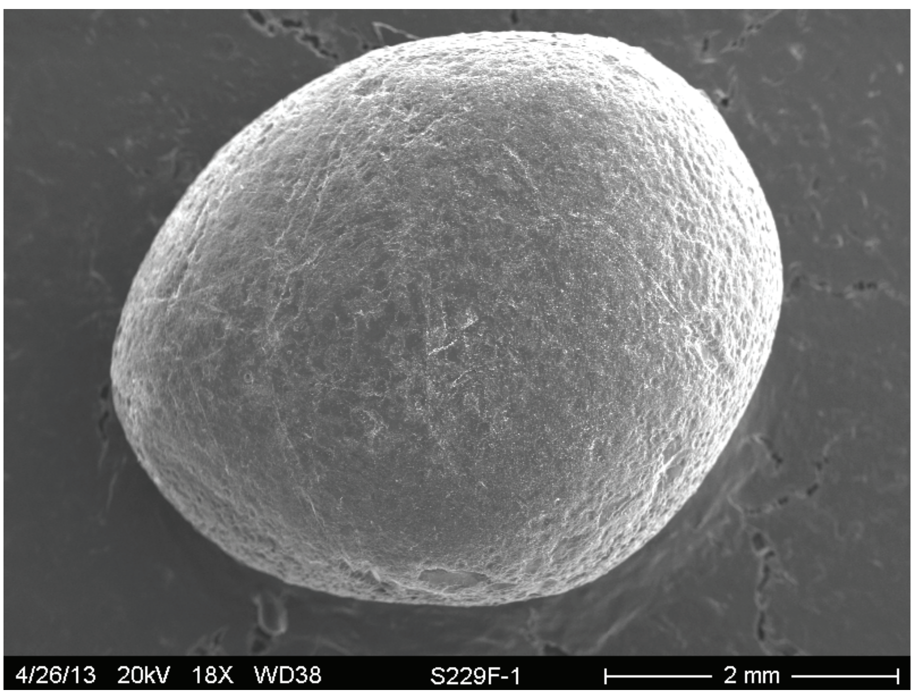
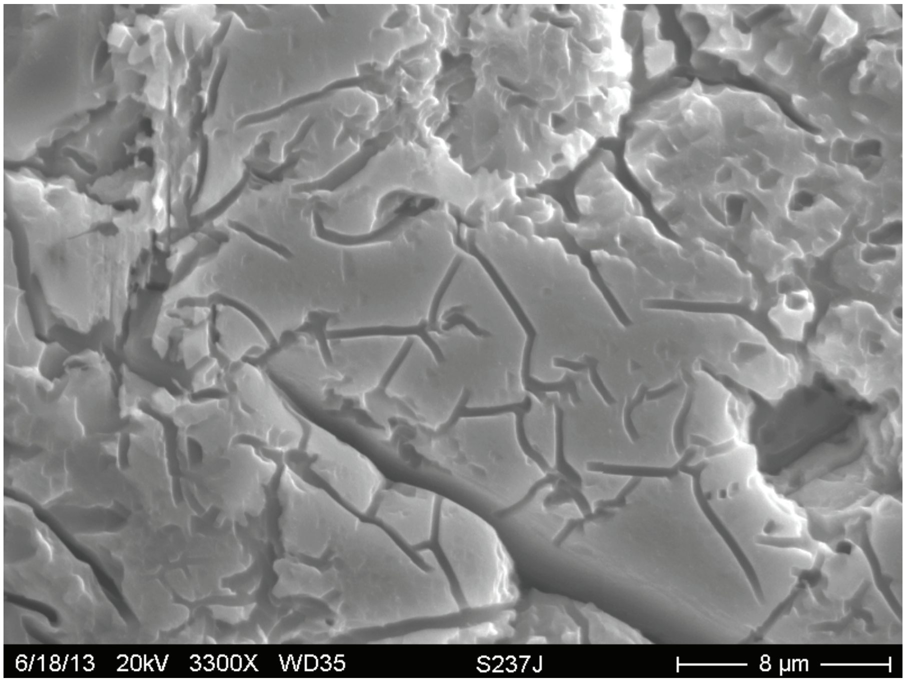


Figure 38. **Observation**—Rare sapphires from the Missouri River deposits are almost spherical, which has led some to think that they are stream rounded. However, this image shows a pitted surface and careful examination shows several faint grooves. **Interpretation**—These features indicate resorption in the magma. The almost spherical form is difficult to explain. Clearly there is no indication of crystallographic control. Compare this image to figure 9, which shows small rounded sapphires from the Rock Creek district. **Source**—From Mac Mader, who recovered sapphires using a hand-held suction dredge from Hauser Lake downriver from Canyon Ferry Dam and just offshore from French Bar, from parcel S229.

A



B

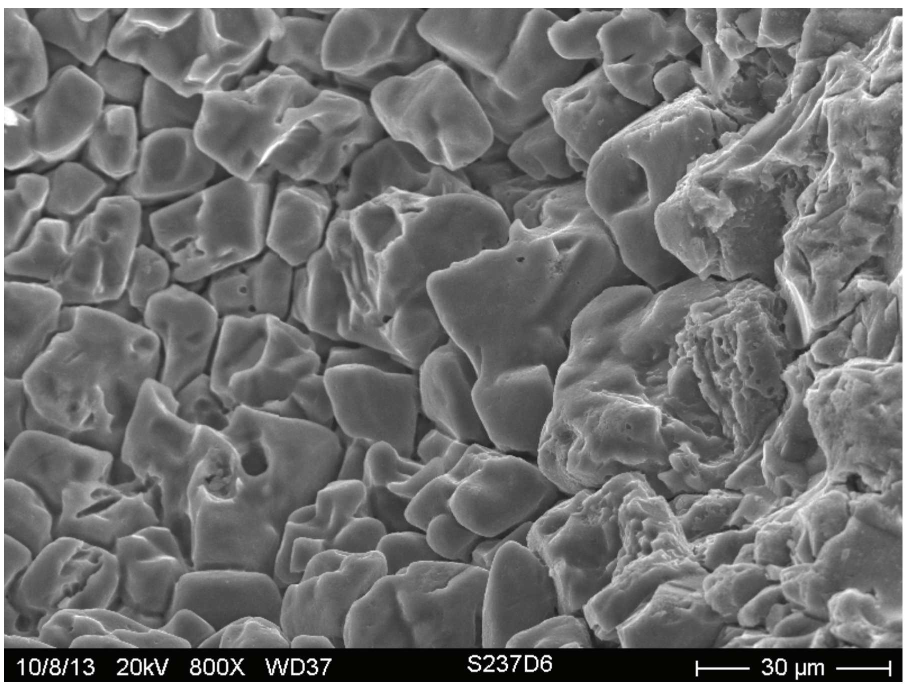


Figure 39A. **Observation**—This highly enlarged image shows shallow grooves cut by deeper grooves on the surface of this sapphire.

Figure 39B. **Observation**—Another image of the same sapphire shows irregular deep channels that produce what has sometimes been called a broken-brick surface. **Interpretation**—I have only recognized this surface on some of the sapphires from the Missouri River localities, but not on sapphires from the other deposits. Like other surface features, these are attributed to resorption by the magma that carried these sapphires to the surface. Initial resorption produced the grooves as shown in figure 39A that, with continued resorption, formed a surface that appears to consist of sapphire fragments. **Source**—From the Lewis and Clark Sapphire mine, where Neil Hurni mines sapphires from gravel uphill from the dredge tailings on Eldorado Bar, from parcel S237.

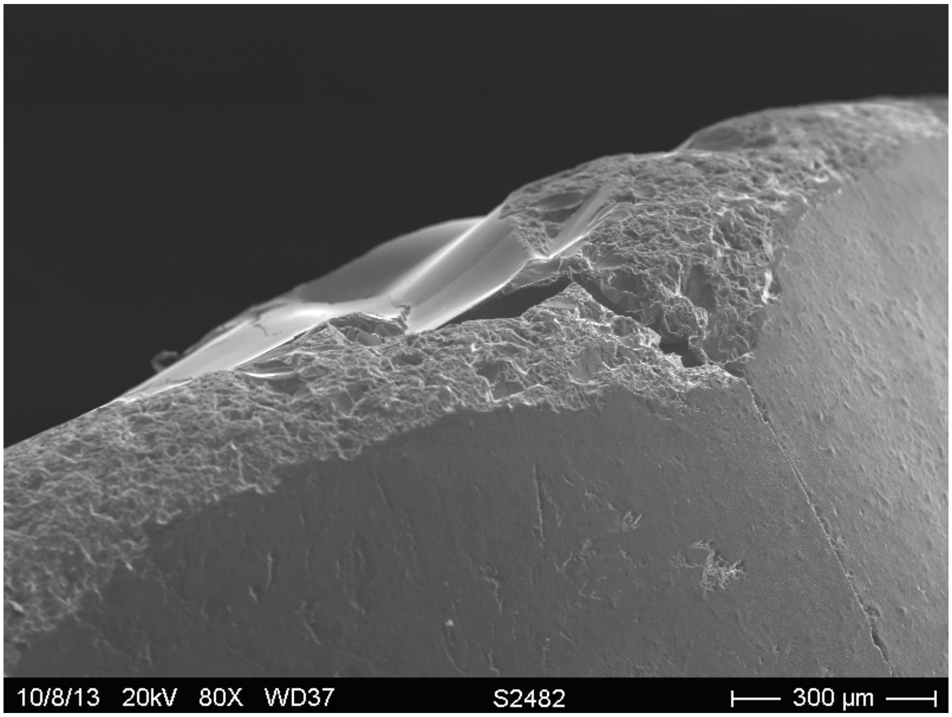


Figure 40. **Observation**—This image illustrates the difference in texture between the smooth surface formed by resorption and the jagged surface on the ridge formed by abrasion. **Interpretation**—Ridges and high points on some sapphires from all three of the secondary deposits (Rock Creek, South Fork of Dry Cottonwood Creek, and Missouri River) present a chipped surface that is attributed to abrasion either during fluvial transport or, less likely, in the washing plant. **Source**—From Bruce Scharf, who recovered it at his Blue Jewel mine, where he mines the dredge tailings on Eldorado Bar, from parcel S248.

CONCLUSIONS

Features Formed by Growth of the Sapphire before Incorporation in Transporting Magma

Surface features on sapphires from the three major deposits in southwestern Montana can be divided into three categories. First are features that are formed by growth of the sapphire before its incorporation in the transporting magma. These include rare, partly preserved hexagonal crystals and also hexagonal tablets. Although rare, some sapphire surfaces have preserved impressions of the crystals the sapphire grew against (see fig. 26, a sapphire from the South Fork of Dry Cottonwood Creek).

Features Formed by Partial Resorption in the Magma and also by Chemical Reaction between the Sapphire and Magma

Two assumptions have been made that bear on the following discussion. One is that there has not been growth of the sapphire in the transporting magma. This assumption is based on the lack of textural evidence as shown by scanning electron microscopy or optical microscopy of sapphire overgrowths. This assumption is further supported by the chemical composition of the transporting magma. It is very likely that the bedrock source and transporting magma for both sapphires from the southwestern part of the Rock Creek district and the South Fork of Dry Cottonwood Creek was rhyolite or dacite (Berg, 2007, 2014). Sapphire (Al_2O_3) is not in chemical equilibrium with magma of these compositions and would be slowly dissolved. The source bedrock for the Missouri River sapphires has not been recognized (Berg and Landry, 2018).

The second assumption is that most of the features shown on these sapphires formed by resorption during magmatic transport. Garland (2002) suggested that most of the surface features of the alluvial sapphires from the Rock Creek district and the South Fork of Dry Cottonwood Creek formed by mechanical processes in the weathering environment and not resorption in the magma. This suggestion is based on an experiment in which a rod of AI_2O3 was immersed in a basic melt for 75 h. Evidence of solution of the rod was not recognized. Suffice to say, it could have been a long time, thousands or even millions of years, that sapphires were subjected to magma. It is generally accepted that the surface feature of sapphires from volcanic rocks formed by resorption in the magma. See Coenraads (1992) for examples of the surface of sapphires from volcanic rocks in Australia and Thailand. Compared to studies of surface features formed by resorption of diamonds, published studies on sapphire morphology are very limited.

Very little is known about the conditions that sapphires experienced during their magmatic transport from a source (the mantle, lithosphere, or lower crust) to the surface, where they were liberated by weathering and formed the secondary deposits of southwestern Montana. Chambers and others (2020) provided some insight into the time involved in the crystallization of megacrysts that may have application to magmatic reactions with xenocrysts. On the basis of the geochronology of included zircons in the core and in the rim of a large K-feldspar megacryst in a granitoid pluton, they concluded that this crystal grew over a period of at least 0.5 Ma. Palke and others (2017) observed what they classified as secondary melt inclusions in sapphires from the Rock Creek district and the South Fork of Dry Cottonwood Creek, but did not observe any in the Missouri River sapphires. They concluded that these inclusions contained samples of the transporting magma that, based on their chemical compositions, were indicated to be felsic.

It is very likely that some sapphires were completely dissolved in the transporting magma. Because of the difficulty in recovering small sapphires, there is no record of the smallest sapphires in these deposits. The smallest sapphire that I have recovered is from a gravel deposit on a strath terrace, just south of Trout Creek on the east side of Hauser Lake. This sapphire is somewhat elongate and 270 mm in maximum dimension. See section on laboratory procedure for techniques used in the recovery of very small sapphires.

Many of the surface features of sapphires from all three districts can be explained by resorption along planes of specific crystallographic orientation: rhombohedral ($10\bar{1}0$) and basal (0001). Figure 4, an image of a Rock Creek sapphire, illustrates the importance of surfaces of basal orientation in forming the mesas and surrounding stepped surfaces on these sapphires. Sapphires from the South Fork of Dry Cottonwood Creek have well-developed smooth grooves along the rhombohedral parting and also some of basal orientation. Figure 18A, an image of a sapphire from the South Fork of Dry Cottonwood Creek, illustrates that the smooth surfaces on a groove developed along an unidentified crystallographic orientation that contrasts with the irregular surrounding surface (fig. 18B). I speculate that the coarser etching formed while the magma was at a higher temperature and proceeded more rapidly than the etching that appears smoother at this magnification, which was produced when the magma had cooled and resorption proceeded more slowly.

Remnants of spinel are preserved in depressions on the surface of Missouri River sapphires, where it was protected from abrasion during river transport (fig. 29). Because spinel was not identified as a mineral inclusion in these sapphires (Berg and Landry, 2018), it is interpreted to have formed by reaction between the sapphire (Al_2O_3) and Fe and Mg in a mafic magma. Spinel variety hercynite adheres to some of the sapphires from the Yogo deposits (Clabaugh, 1952) where sapphires are mined from a lamprophyre dike. Also, sapphires from a basalt in the Siebengebirge Volcanic Field in Germany have spinel coronas (Baldwin and Ballhaus, 2018).

Spinel was not recognized on sapphires from the Rock Creek district or from the South Fork of Dry Cottonwood Creek, where the transporting magma was inferred to be of rhyolite or dacite composition (Berg, 2007, 2014). Similarly, spinel was not observed on the surfaces of sapphire xenocrysts in the French Bar sill exposed along Hauser Lake, which is a basaltic trachyandesite (Berg and Palke, 2017). However, spinel on sapphires from the Missouri River deposits suggests that these sapphires may have weathered from a mafic igneous bedrock source that has not been recognized.

Features Formed in the Weathering Environment

Small chips on ridges and projections on sapphires, best recognized by scanning electron microscopy, are attributed to abrasion during fluvial transport (figs. 15, 27, and 40). It is likely that most of these small chips formed by tumbling in the sediment load of the Missouri River as compared to the washing plant, because these sapphires were subjected to fluvial action for a much longer time than in the washing plant and jigs.

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The interpretations, some quite speculative, are the author's sole responsibility. I hope that future researchers will be able to explain some of the features that puzzled me.

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