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BENITOITE FROM THE NEW IDRIA DISTRICT, SAN BENITO COUNTY, CALIFORNIA

By Brendan M. Laurs, William R. Rohtert, and Michael Gray

Commercial quantities of gem-quality benitoite are known from a single location in the world, the Benitoite Gem mine in the New Idria district of San Benito County, California. A barium titanium silicate, benitoite is typically colorless to blue, and is noteworthy for its high refractive indices, moderate birefringence, and strong dispersion. Benitoite occurs in altered blueschist within serpentinite. The gem crystals formed within fractures as a result of the alteration of blueschist by hydrothermal fluids derived from the regional metamorphism of the serpentinite. An extension of the historic deposit at the Benitoite Gem mine was discovered in the spring of 1997, which should contribute to continued stability in price and supply. The gemological properties of benitoite readily identify it from similar-appearing gems.

Gem-quality benitoite has been mined intermittently from only one region in the world, the New Idria district of San Benito County, California. Benitoite was first discovered there in 1907; it was named after the county, as well as the San Benito River, which runs through the property, and the nearby San Benito Mountain (Louderback, 1909). Stones are strongly dichroic, typically violetish blue and colorless. Exceptionally rare gemstones are colorless and pink. A few orange benitoites have been produced by heat treatment of colorless material. Benitoite has high refractive indices, moderate birefringence, and strong dispersion (exceeding that of diamond in some directions), which render the faceted gems comparable in appearance and price to fine sapphire and tanzanite (figure 1). Although production has been sporadic throughout the life of the deposit, hundreds of carats of faceted material are currently available, in sizes up to 2–3 ct.

Benitoite is a barium titanium silicate ($\text{BaTiSi}_3\text{O}_9$) that forms under unusual conditions. At the New Idria district, benitoite is found exclusively in bodies of blueschist within serpentinite. During 1995, the senior author conducted a detailed study of blueschist bodies throughout the New Idria district on behalf of the Kennecott Exploration Company. The main occurrence, the Benitoite Gem mine, was mapped in detail, and other known benitoite occurrences at the Mina Numero Uno and Victor prospects were examined. Microscopic benitoite crystals were detected for the first time in a blueschist body on Santa Rita Peak. After nearly a decade of inactivity, a small prospect containing minute amounts of gem-quality benitoite was rediscovered along a tributary of Clear Creek; this locality is now known as the Junnila claim. More recently, an extension of the Benitoite Gem mine deposit was found in spring 1997, during exploration down slope of the historic pit.

The Benitoite Gem mine was referred to as the "Dallas mine" until the mid-1960s, but it has been variously called the "Benitoite mine," "Dallas Benitoite mine," and "Dallas

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Please see acknowledgments at end of article.

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Figure 1. Because of its beauty, rarity, and singularity of occurrence, benitoite was declared the official California State Gemstone in 1985. This assortment of stones from the Benitoite Gem mine (1.10–4.77 ct) shows the range of colors that are typically encountered in benitoite. All stones were faceted by Elvis (Buzz) and Michael Gray. From the collection of Michael M. Scott; photo © Harold © Erica Van Pelt.



Gem mine" (Wise and Gill, 1977). Today the locality is designated as the Benitoite Gem mine by the mine owners, after the notation on topographic maps of the U.S. Geological Survey which identify the site simply as the "Gem mine."

HISTORY

Although there is general agreement in the literature that benitoite was discovered in early 1907, there is considerable controversy about who actually discovered it. Louderback (1907) originally attributed the discovery to L. B. Hawkins and T. E. Sanders. However, two years later, he identified J. M. Couch (figure 2), a prospector who was grubstaked by R. W. Dallas, as having first found a number of mineral deposits that merited further investigation (Louderback, 1909). Dallas "induced" Hawkins to accompany Couch back into the mountains. According to Louderback (1909, p. 333), "While out to examine some copper deposits they happened upon the benitoite deposit and each claims to be responsible for the discovery." In 1961, Couch's eldest son, Oscar, published *The Benitoite Story*, in which he outlined the reasons why his father should be given sole credit finding the deposit. Austin (1988) provides further evidence for Couch being the sole discoverer of what, at the time, he thought was a sapphire deposit. Frazier and

Frazier (1990a) reviewed the controversial history surrounding the discovery and development of the mine without making any judgment, and provided a comprehensive bibliography (1990b).

The first documented piece of benitoite to be faceted was brought to a lapidary in the San Francisco Bay area by Sanders' brother. While an expert from the Los Angeles area proclaimed the new material "volcanic glass," this lapidary called the stone spinel: "It was too soft for a sapphire, so I decided it must be a spinel; [since] that's the only other stone there is of that color" (Marcher, 1939). The lapidary showed some of the stones to George Eacret, the manager of Shreve & Co., one of the largest jewelry stores in San Francisco at that time. According to Marcher (1939), Eacret checked the stone with a dichroscope and found that it was doubly refractive, so he delivered a sample to Dr. George Louderback, a mineralogist at the University of California (Berkeley) who determined that it was a new, undescribed mineral.

In the company of Mr. Eacret, Dr. Louderback made his first visit to the mine on July 19, 1907, and confirmed the discovery. He revisited the deposit on October 11 of that year to study the geology. When Louderback returned to the mine with Eacret on August 12, 1908, he took the first photographs of benitoite for use in his 1909 full-length

Figure 2. Although there has been considerable controversy surrounding who actually discovered benitoite, much of the evidence supports the claim of J. M. Couch, shown here at a campsite near the Benitoite Gem mine. Photo from the Dallas Mining Company archives.



article describing the mineral. Louderback's documentation of the ditrigonal-dipyramidal crystal habit finally proved the natural existence of this crystal form, which had been predicted mathematically 77 years earlier (Hessel, 1830).

Soon after the discovery, the Dallas Mining Company was formed to finance the development of the deposit, which was then called the "Dallas mine." Cabins and corrals were built nearby, and mining equipment was hauled in by horse and wagon over tortuous roads from Coalinga, the nearest town. According to a diary of the Dallas Mining Company, active mining began in July 1907. An open cut and a series of underground workings were developed during the first few years of mining (figure 3), and numerous plates of gem-bearing rock were recovered.

Most of the benitoite crystals were covered with natrolite, which could have been dissolved in acid without harming the benitoite crystals. However, it was decided that this process was too time-consuming, so the "knobs" formed by benitoite crystals lying underneath the natrolite were initially broken off the rock matrix by use of hammer and chisel or a punch press. As a result, few well-crystallized mineral specimens were recovered during the early period of mining, as the main focus was on the production of gem rough. The Dallas Mining Company diary records quantities of rough measured in "quart jars" and "cigar boxes" that were sent to Dallas's offices in Coalinga.

The Dallas Mining Company continued opera-

tions until 1912, when it ceased being economical (Bradley et al., 1917). In October 1913, the mining equipment was auctioned off and the property was vacated. The mine was issued mineral patent papers in 1917, five years after active mining ceased. The ownership of the mine remained in the Dallas family until 1987.

Between 1920 and 1940, little activity took place at the locality, except for occasional unauthorized mining by various parties, including enterprising teenagers Edward Swoboda and Peter Bancroft (Bancroft, 1984). Miller Hotchkiss, from the nearby San Joaquin Valley town of Firebaugh, leased the mine in the 1940s. Hotchkiss was the first to take a bulldozer to the mine, which he used to rework the mine tailings. From 1952 to 1967, a lease was held by Clarence Cole, a mineral dealer from Oakland, California. Cole used a bulldozer and dynamite to enlarge the historic pit. In 1966, Cole granted a sublease to Gerold Bosley, of San Diego, California (Sinkankas, 1976). Backed by noted mineral collector Josephine Scripps, Bosley used a bulldozer to expose more of the open pit near the entrance of the original tunnels. Bosley ultimately found very little gem rough, but he did recover some notable mineral specimens.

Cole died in 1967, and the lease subsequently was transferred to William "Bill" Forrest, of Fresno, California, and Elvis "Buzz" Gray, currently of Missoula, Montana. They purchased the mine from the Dallas family in 1987, and they remain the sole owners today.

LOCATION AND ACCESS

The Benitoite Gem mine is located 32 km (20 miles) northwest of the town of Coalinga, California, at approximately 1,380 m (4,520 feet) above sea level. Paved county roads provide access to the New Idria district from the southwest via Coalinga, or from the northeast via Panoche Road along Interstate 5 in the San Joaquin Valley (figure 4). These roads lead 63 km (39 miles) and 85 km (53 miles), respectively, to a network of four-wheel-drive trails that are infrequently maintained by the U.S. Bureau of Land Management. Both routes require an additional 30 to 40 km of travel over rough dirt roads to reach the mine.

The Benitoite Gem mine is located on 16.2 hectares (40 acres) of private patented mining property, which is secured by a locked gate. The site is patrolled regularly by law enforcement officers, and visitors must obtain written permission from the owners to enter the mine area. Four other benitoite prospects in the district are claimed as follows: (1) The Junnula claim, owned by Leza Junnula of Fresno, California; (2) The Mina Numero Uno claim, owned by Sharon and Eugene Cisneros of San Jose, California; (3) The Victor claim, owned by Craig Stolberg of San Jose, California; and (4) The Santa Rita Peak property, controlled by Kennecott Exploration Company. All of these mineral prospects are closed to the public.

WORLDWIDE OCCURRENCE OF BENITOITE

Benitoite has been confirmed from nine locations around the world, but only the historic Benitoite Gem mine and the Junnula claim have produced gem-quality material. All of the commercial gem production has come from the Benitoite Gem mine. At the three other deposits in the New Idria district, benitoite has been found only as small, platy (non-gem quality) crystals, up to a few millimeters in diameter (see descriptions of the Mina Numero Uno claim, Victor claim, and Santa Rita Peak property in the Geology section, below).

Outside the New Idria district, benitoite has been found *in situ* at four areas. At Big Creek–Rush Creek—in the Sierra Nevada foothills of eastern Fresno County, California—small grains of benitoite are found in gneissic metamorphic rocks near a type of igneous rock known as granodiorite (Alfors et al., 1965; Hinthorne, 1974). This occurrence is located nearly 160 km (100 miles) northeast of the



Figure 3. This photo, taken around 1910, shows benitoite miners and an adit at the Benitoite Gem mine. Photo from the Dallas Mining Company archives.

Benitoite Gem mine, and is not geologically related to the New Idria district. In Japan, benitoite was noted from albite-amphibole rock in a serpentinite body, along the Kinzan-dani River, at Ohmi in the Niigata Prefecture (Komatsu et al., 1973; Chihara et al., 1974; Sakai and Akai, 1994). At Broken Hill, New South Wales, Australia, Dr. Ian R. Plimer reported benitoite as a rare mineral in high-grade granite gneiss (Worner and Mitchell, 1982). Most recently, crystals of colorless, blue, and pink benitoite averaging 1–2 mm in diameter were detected in gas cavities in syenite at the Diamond Jo quarry in Hot Springs County, Arkansas (Barwood, 1995; H. Barwood, pers. comm., 1997).

Detrital grains of benitoite (not *in situ*) were recovered from Pleistocene lake sediments at the Lazzard estate, a few kilometers west of Lost Hills, in the San Joaquin Valley, Kern County, California (Reed and Bailey, 1927). On the basis of geologic considerations, sediments from this location could not have been derived from the New Idria district or from the Big Creek–Rush Creek area.

Two previously reported benitoite locations should be discredited. Anten (1928) probably

misidentified benitoite in a thin section from Owithe Valley, Belgium (Petrov, 1995). Lonsdale et al. (1931) tentatively identified benitoite in sediments from the Eocene Cook Mountain formation of southwest Texas; Smith (1995) suggested that the locality should be discredited because the authors confused the spelling of bentonite (a clay mineral) with benitoite, but we recommend discreditation because the available data provided by Lonsdale et al. suggest that they misidentified grains that were actually sapphirine. Rumors of benitoite from Korea have not been confirmed.

GEOLOGY

Geologic Setting. The New Idria district is located in the southern Diablo Range of the California Coast

Range geologic province. Since 1853, the district has been mined and prospected for numerous mineral resources, including mercury, chromium, gold, asbestos, gems, and mineral specimens. The district encompasses a serpentinite body that was tectonically emplaced into surrounding sedimentary and metamorphic rocks. During the late Jurassic, when two of the earth's plates collided (see, for example, Hopson et al., 1981), the relatively low-density serpentinite rose through the overlying layers of rock, which included the Franciscan Formation. Slices of the Franciscan Formation were incorporated into the highly sheared serpentinite body during its emplacement; these are called tectonic inclusions (see Coleman, 1957). The serpentinite breached the paleo-surface in the mid- to late-Miocene (Coleman,

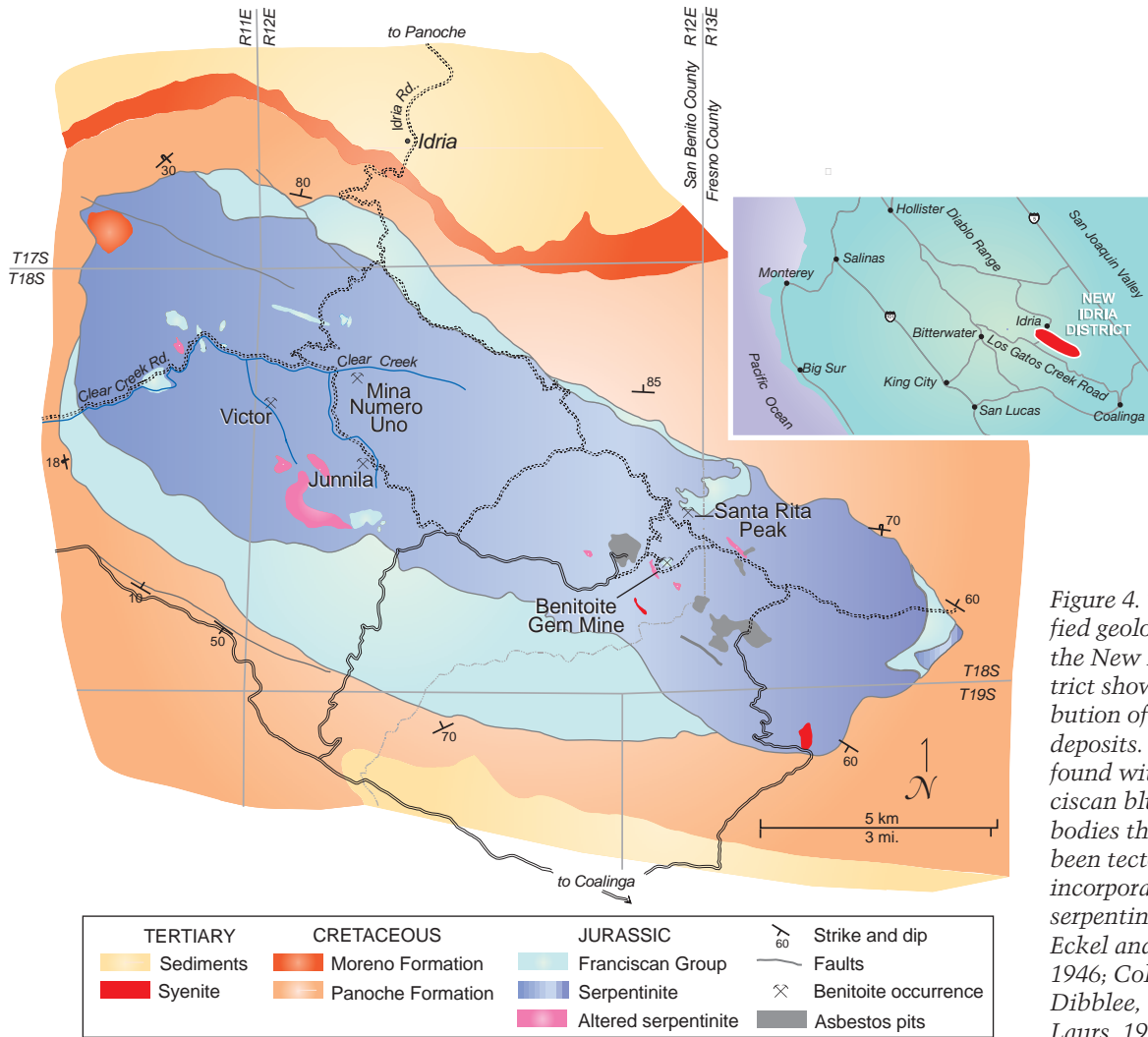


Figure 4. This simplified geologic map of the New Idria district shows the distribution of benitoite deposits. Benitoite is found within Franciscan blueschist bodies that have been tectonically incorporated into the serpentinite (after Eckel and Myers, 1946; Coleman, 1957; Dibblee, 1979; and Laurs, 1995).

1961). It is now exposed along the crest of the Diablo Range (figure 5) over an area 23 km by 8 km, elongate to the northwest.

Tectonic inclusions of Franciscan rocks within the serpentinite consist dominantly of blueschist and graywacke, with lesser mica schist, greenstone, and amphibolite schist (Coleman, 1957; Laurs, 1995). All of these rocks are derived from oceanic crust and overlying sediments that were accreted onto the continental margin during the Jurassic period. Two blueschist protoliths (parent rocks) may be differentiated on the basis of texture and composition: (1) metavolcanic, which are largely basaltic lavas and volcanoclastics; and (2) metasedimentary, which are largely marine sediments. Depending on the composition of the protolith, the blueschist contains variable amounts of very fine-grained albite, glaucophane-crossite, actinolite-tremolite, aegerine-augite, and titanite, with or without stilpnomelane, quartz, K-feldspar, epidote, and apatite. Benitoite is found in blueschist derived from both protoliths (Laurs, 1995).

Prior to breaching the surface, the New Idria serpentinite was intruded by small bodies of igneous rocks, predominantly syenite (Coleman, 1957; again, see figure 4). The mid-Miocene age of the syenite correlates well with Neogene magmatism in the California Coast Range, which is associated with the plate tectonic reconfiguration of western California (Van Baalen, 1995). Metamorphism associated with this reconfiguration is probably responsible for forming calc-silicate vein assemblages that are scattered through the serpentinite, as well as benitoite-bearing veins in the blueschist bodies (Van Baalen, 1995). Tentative age data suggests that the benitoite crystallized about 12 million years ago (M. Lanphere, pers. comm., in Van Baalen, 1995), so it is much younger than the enclosing blueschist, which formed about 100 to 160 million years ago (see, for example, Lee et al., 1964).

Benitoite Gem Mine. *Previous Work.* Arnold (1908) and Sterrett (1908, 1911) summarized the early mining activity. Coleman (1957), Van Baalen (1995), and Wise and Moller (1995) wrote district-wide geological reports, which include discussions of the Benitoite Gem mine. Geologic maps of the mine were prepared first by Coleman (1957), and later by Rohtert (1994) and Laurs (1995). Laird and Albee (1972) made physical, chemical, and crystallographic measurements on benitoite and associated minerals from the district, and Wise and Gill (1977) provided

a detailed description of the complicated mineralogy.

Geology. The mine is situated on a low hill (figure 6), which is underlain by Franciscan rocks emplaced into serpentinite (Coleman, 1957; Wise and Gill, 1977). These rocks consist of blueschist and greenstone, which are locally sheared (figure 7). The blueschist is dark bluish gray where unaltered, and lighter blue-green within the mineralized zone. This zone is at least 60 m long, strikes N60°W, dips moderately northeast, and is about 3 m thick. Recent field observations by the authors suggest that the deposit is offset along two north- to northwest-trending faults (again, see figure 7). All of the historic lode production was obtained from the central section of the deposit. However, in the spring of 1997 an extension of the mineralized zone was discovered in the western offset portion. The faulting apparently down-dropped a portion of the mineralized blueschist, which lay buried beneath up to 10 m of unconsolidated eluvium and dump material.

Mineralization. Benitoite mineralization is confined entirely to the blueschist, in a hydrothermally

Figure 5. This low-altitude oblique aerial photograph, looking northeast, shows the Benitoite Gem mine workings (small brown cut). The large open pit on the left is an active asbestos mine being worked by the King City Asbestos Corp. Santa Rita Peak, where benitoite has also been found, is visible above the Benitoite Gem mine and forms the highest point on the skyline. Photo courtesy of Kennecott Exploration Company.



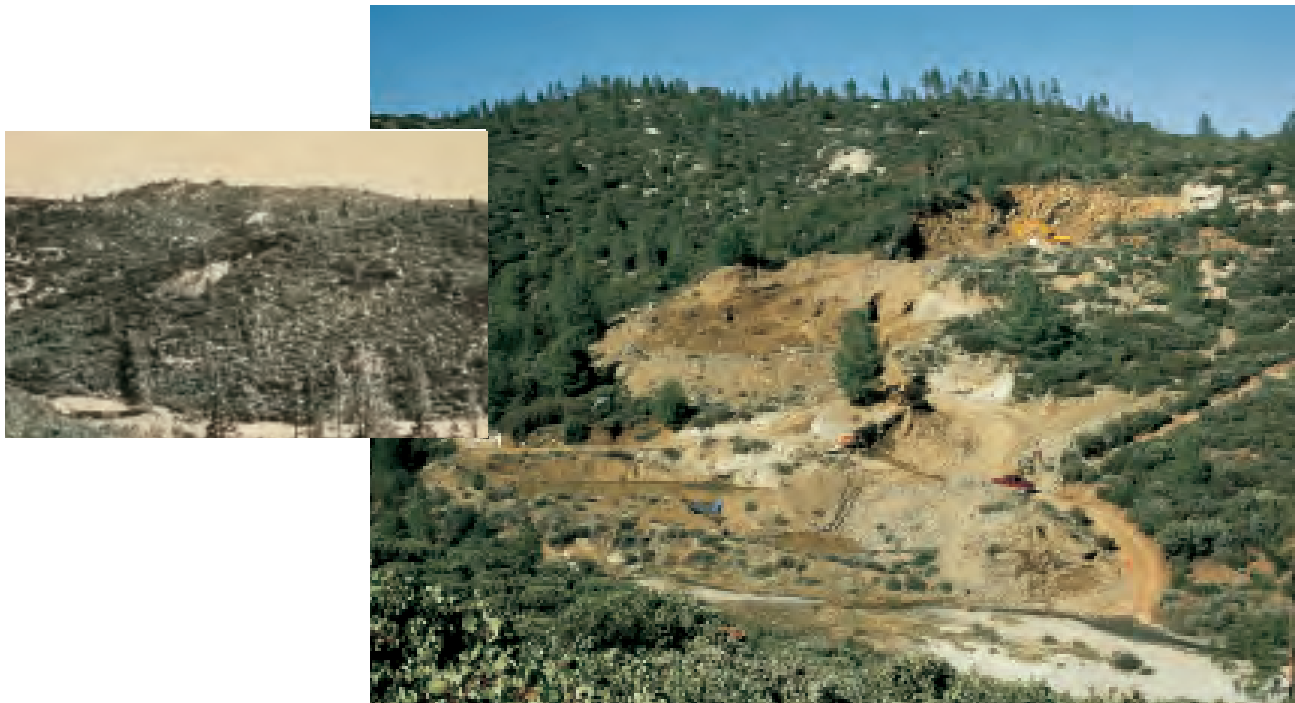
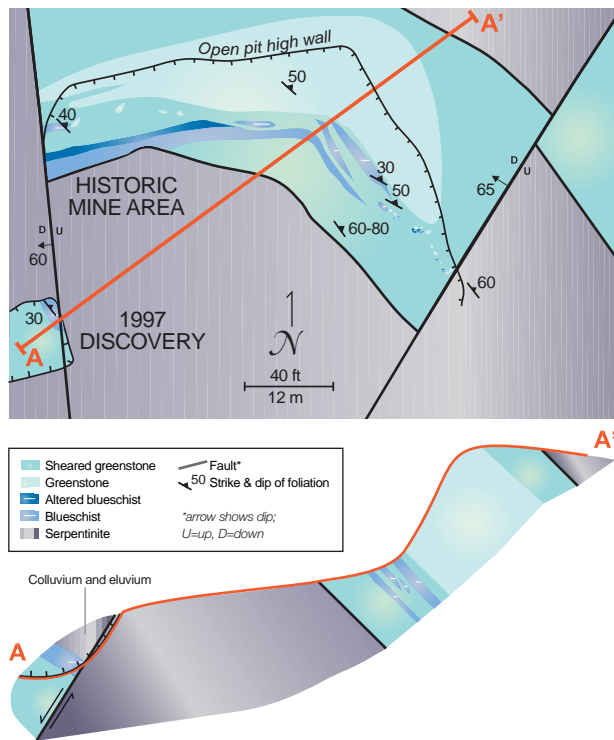


Figure 6. In this 1997 photo (by Michael Gray) of the Benitoite Gem mine, a backhoe sits in the main open cut, and the equipment processing colluvial material can be seen in the center, just below the single pine tree. Two settling ponds are visible below this equipment. Water is pumped from the San Benito River at the base of the workings into the ponds, from where it is recirculated through the processing equipment. The inset (after Louderback, 1909) shows a view of this same area in 1907, shortly after the discovery of the deposit.

Figure 7. This simplified geologic map (top) and cross-section (bottom) of the Benitoite Gem mine show the altered blueschist where benitoite is found, in lenses that are tectonically incorporated into the sheared greenstone. After Coleman (1957), Rohtert (1994), and Laurs (1995).



altered zone, which is characterized by: (1) recrystallization of fibrous amphibole and pyroxene, (2) local albite dissolution, and (3) veining and pervasive infiltration by natrolite. Benitoite formed during the first two stages of the alteration (inasmuch as many crystals contain amphibole and pyroxene inclusions), but prior to the formation of natrolite—which coats benitoite in the veins (figure 8). The natrolite veins average less than 1 cm wide, and contain benitoite only locally, commonly where the veins narrow or terminate.

The benitoite forms as euhedral crystals (figure 9) up to 5.6 cm in diameter, 1–1.5 cm on average, that are attached to the vein walls. Other minerals on the blueschist vein walls include neptunite, silica pseudomorphs after serandite, joaquinite group minerals, apatite, albite, jonesite, and the copper sulfides djurleite, digenite, and covellite (Wise and Gill, 1977), as well as traces of other minerals described by Van Baalen (1995) and Wise (1982). Natrolite coats all of the vein minerals and, in most cases, completely fills in and closes the veins. Natrolite also has infiltrated the altered blueschist adjacent to the veins, filling interstitial space that was previously occupied by albite.

Two types of benitoite were noted by Wise and Gill (1977): (1) gem-quality crystals attached to the walls of cross-cutting veins; and (2) disseminated, euhedral, non-gem benitoite with abundant amphi-

bole and pyroxene inclusions that formed within the altered blueschist. Some crystals show both characteristics, since they apparently grew into both the vein and the adjacent host-rock substrate. Benitoite in the veins commonly forms simple triangular crystals with dominant π {01 $\bar{1}$ 1} faces (Wise and Gill, 1977; figure 10). The crystals typically show a frosty appearance on the π faces due to natural etching, whereas the μ faces are mirror smooth. Color zoning is common, with a milky white or colorless core grading outward into transparent blue corners. However, gem-quality blue crystals recently discovered in the western offset portion of the deposit typically lack color zoning and show only π faces (A in figure 10). In general, the relatively small size of faceted material is due to the abundant cloudy areas and the flattened morphology of the crystals.

The disseminated non-gem benitoites closely resemble the host rock in color, because of the abundant fibrous inclusions from the altered blueschist. As described by Wise and Gill (1977), such crystals commonly show dominant c faces, as well as variably developed pyramid (π and p) and prism (μ and m) faces, resulting in tabular crystals with triangular to hexagonal outlines (D and E in figure 10). Rarely, the non-gem crystals form star-shaped twins caused by penetration twinning due to a Dauphiné-type 180° rotation about the c -axis (W. S. Wise, pers. comm., 1997; figure 11). The mine owners know of

Figure 8. On May 1, 1997, this remarkable boulder of benitoite-bearing blueschist was excavated from the newly discovered extension of the Benitoite Gem mine. Knobs on the surface of the natrolite (which covers 40 cm × 70 cm of the boulder) indicate the presence of benitoite and neptunite crystals, which are attached to the vein wall and overgrown by natrolite. Several gem-quality pieces were removed from the outside edge of the vein. Photo by Michael Gray.

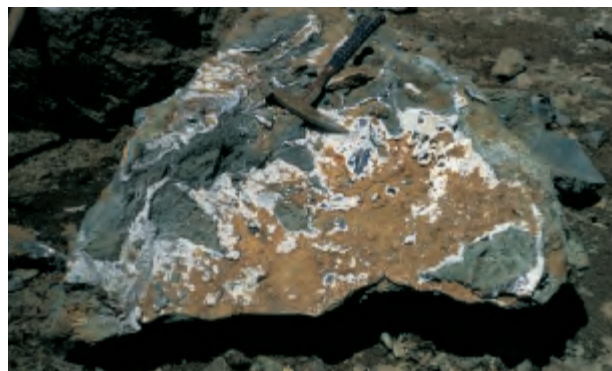
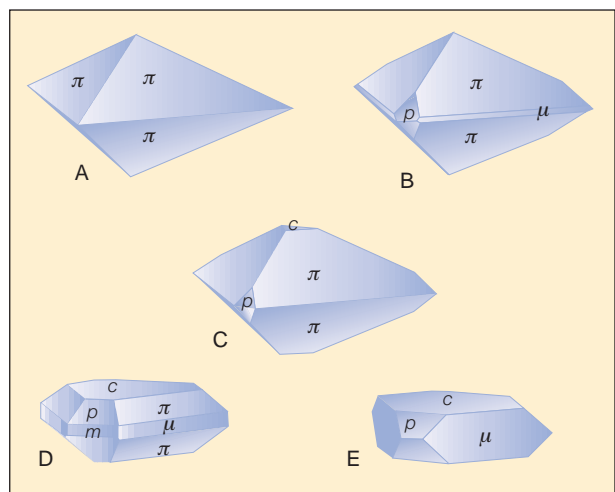


Figure 9. This specimen, which was mined during the late 1980s, shows an unusually transparent benitoite crystal on a matrix of white natrolite and light green altered blueschist. The natrolite originally covered the benitoite crystals as well, but it was removed with dilute hydrochloric acid. Photo © Harold & Erica Van Pelt.

only nine twinned crystals recovered thus far (E. Gray, pers. comm., 1997).

Junnila Claim. The Junnila claim is located 7 km northwest of the Benitoite Gem mine, on a low hill overlooking a tributary of Clear Creek (again, see

Figure 10. The common crystal habits of benitoite are redrawn from Louderback (1909) and Wise and Gill (1977). The π face decreases in importance in the sequence from (A) to (E). The morphology of the gem-quality crystals generally resembles (C), except for crystals from the recently discovered western extension of the deposit, which resemble (A). Non-gem crystals typically resemble (D).



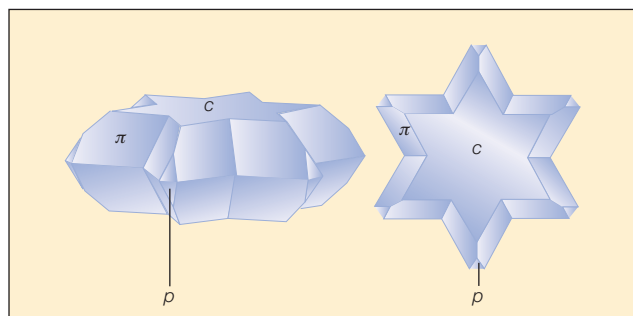


Figure 11. Twinned benitoite crystals show a 180° rotation about the *c*-axis. In this drawing (courtesy of William S. Wise), the *c* faces of the two crystals are merged and indistinguishable from one another, resulting in flat, star-shaped faces. The photo shows some of the twinned benitoite crystals (2–3 cm wide) recovered from the Benitoite Gem mine. Note the characteristic opaque appearance, resulting from abundant inclusions of fibrous amphibole and pyroxene. Photo © Harold & Erica Van Pelt.

figure 4). The claim was worked intermittently by A. L. McGuinness and Charles Trantham from 1982 to 1986. The deposit lay forgotten after the death of Mr. McGuinness in the late 1980s, but was rediscovered in 1995 by the Kennecott Exploration Company and almost simultaneously by L. Junnilla of Fresno, California. At the time of rediscovery, thick brush covered the area and only a small benitoite-containing prospect pit was found (Lauris, 1995). In fall 1995, the property was excavated using a D-8 tractor (figure 12) in a cooperative effort by Junnilla and several mineral dealers (Moller, 1996; Ream, 1996). Although only small amounts of benitoite were found, a few crystals (figure 13), up to 2.6 cm in diameter (Ream, 1996), reportedly contained material suitable for faceting; it is from this material that the two stones (0.42 ct and 0.21 ct) shown in figure 14 were cut.

As at the Benitoite Gem mine, benitoite at the Junnilla claim is found in a body of blueschist within the serpentinite. The blueschist crops out over an area approximately 50 m by 20 m; it is brownish gray and weathered into platy fragments (Lauris, 1995). Near the center of the body is a zone of altered blueschist that contains benitoite. This vertical zone is resistant to weathering, massive in texture, and has a distinctive light grayish blue color; it strikes northeast and ranges from 1 to 2 m thick over a length of 6 m. Sparse amounts of benitoite form along vertical tension gashes (commonly less than 1 cm wide), and also along foliation and cross-fractures. In contrast to the natrolite gangue present at the Benitoite Gem mine, the benitoite-bearing veins at the Junnilla claim are filled with a calcium-rich mineral assemblage consisting mostly of thomsonite, pectolite, calcite, and stevensite; neptunite and joaquinite-group minerals are present locally (Lauris, 1995).

The benitoite crystals are translucent (rarely transparent), tabular (see, e.g., figure 10D), and average 1 cm in their longest dimension. The crystals are intergrown with other vein minerals, and therefore they rarely show more than two or three faces. Blue, colorless, or color-zoned crystals (typically with colorless cores and blue rims, as at the Benitoite Gem mine) have been found.

Mina Numero Uno Claim. Located along upper Clear Creek, 7.8 km northwest of the Benitoite Gem mine, the Mina Numero Uno claim consists of boulders and rare outcrops of blueschist scattered through dense brush over an area approximately 20 m by 100 m, elongate to the east-northeast. Benitoite mineralization was noted in boulders at opposite ends of the deposit (Lauris 1995). The boulders at the eastern end contain rare vugs, up to 6 cm long and 3 cm wide, that are elongated parallel to foliation. The vugs are commonly lined with albite and silvery gray fibrous amphibole; in places, they contain benitoite, neptunite, or joaquinite-group minerals (Wise, 1982; Lauris, 1995). Benitoite forms pale blue, platy, euhedral crystals that are up to 5 mm in diameter. Less common are tan grains, previously reported as “pink” by Chromy (1969).

In the boulders at the western end, benitoite and neptunite form along narrow, randomly oriented fractures less than 1 mm wide (Lauris, 1995). These fractures typically contain no gangue minerals except for minor amounts of quartz locally (there is no albite). Benitoite forms pale blue or colorless, tabular, pseudo-hexagonal plates and rosettes up to 10 mm in diameter, with most crystals averaging 2 mm in diameter. The crystals occur with neptunite and lay flat against the fracture walls.



Figure 12. The Junnila claim was excavated with heavy equipment in 1995. Benitoite was recovered from the narrow, vertical zone of resistant blueschist that is visible here beneath the slender pine tree. Photo by William Larson.

Victor Claim. The Victor claim is located along a tributary 1 km south of Clear Creek, and 9.2 km northwest of the Benitoite Gem mine. According to documentation at an old claim marker on the property, the Victor claim was first staked in 1974 as the Franciscan mine by Steven M. Dwyer of Palm Desert, California. During the early 1980s, the claim was owned by Ed Oyler of the San Francisco Bay area; in 1991, the deposit was acquired by Craig Stolberg of San Jose, California. Outcrops of blueschist up to 3 m in diameter are surrounded by a sheared tremolite-chlorite zone within the serpentinite (Laurs, 1995). Millage (1981) inferred that the blueschist body measures 150 m × 100 m. The central blueschist outcrops contain small (up to 5 mm in diameter) colorless benitoite platelets and rosettes, in thin veinlets along the foliation.

Santa Rita Peak Property. This occurrence is located 1.2 km north-northeast of the Benitoite Gem mine, on the southeast flank of Santa Rita Peak (elevation



Figure 13. This is one of the largest benitoite crystals (2.2 cm wide) recovered from the Junnila claim during the 1995 excavation. The benitoite is intergrown with thomsonite and actinolite. The irregular surface texture is due to intergrowth with calcite, which was removed from the specimen by acid dissolution. Specimen courtesy of William Larson; photo © Jeffrey Scovil.

5,165 feet, 1,574 m). The blueschist is exposed as a field of boulders, at least 30 m wide, that is surrounded by a sheared tremolite-chlorite-jadeite zone within the serpentinite (Laurs, 1995). Some of the boulders are hydrothermally altered and cut by natrolite veins up to 2 cm thick. In places, the altered blueschist shows a nodular texture similar

Figure 14. These two benitoites (0.42 and 0.21 ct) were reportedly faceted from material found at the Junnila claim. Stones courtesy of William Larson; photo © GIA and Tino Hammid.





Figure 15. With 52 faceted benitoites weighing a total of about 33 ct (the largest stone is 2.84 ct), this benitoite and diamond necklace is unique in the world. All of the benitoites were cut and matched by E. (Buzz) Gray, and the necklace was designed by William McDonald of McDonald's Jewelry, Fresno, California. Necklace courtesy of Michael M. Scott; photo © Harold & Erica Van Pelt.

to that observed at the Benitoite Gem mine; electron microprobe analysis revealed microscopic crystals of benitoite in this altered blueschist (R. L. Barnett, pers. comm., in Laurs, 1995).

ORIGIN OF BENITOITE

Ever since benitoite's discovery, its origin has been a persistent enigma. The formation of benitoite at the New Idria district has been generally ascribed to hydrothermal processes that caused the unusual combination of barium (Ba) and titanium (Ti). Coleman (1957) suggested that Ti was derived from fluids associated with the crystallization of small syenite intrusions in the district; Ba was liberated from the alteration of blueschist. However, Ti is relatively immobile in hydrothermal fluids (Van Baalen, 1993), and the closest syenite to any of the

benitoite deposits in the district is 1 km. Wise and Gill (1977) proposed that fluids derived Ti, Fe, and rare-earth elements from the serpentine, and Ba from the blueschist, to form benitoite and the associated vein minerals. Most recently, Van Baalen (1995) proposed that benitoite formed as a result of metamorphism localized along the contact between blueschist and greenstone, in the presence of sodium-rich, low-silica metamorphic fluids. He suggested that more than enough Ba and Ti were present in the blueschist and greenstone to produce the inferred amount of benitoite and neptunite.

We generally concur with Van Baalen's (1995) model, subject to some modification. Van Baalen (1995) stated that benitoite formed along the contact between blueschist and greenstone at the Benitoite Gem mine; it is actually contained entirely within the blueschist, regardless of proximity to the greenstone. Greenstone is not required for benitoite formation, as indicated by its absence at the Junnila and Mina Numero Uno claims, although it is possible that it contributed to Benitoite formation at the Benitoite Gem mine. Throughout the New Idria district, there is also a strong correlation between the amounts of blueschist alteration and benitoite mineralization. We suggest that benitoite formed at the Benitoite Gem mine when Ba and Ti were released by the alteration of blueschist, and possibly greenstone, in the presence of magnesium- and calcium-rich fluids generated during the regional metamorphism of serpentinite (rather than in the presence of sodium-rich fluids, as postulated by Van Baalen [1995]). This model is based on detailed geologic mapping and the collection of chemical data on blueschist minerals and whole-rock samples at all the known benitoite occurrences in the district (Laurs, 1995).

MODERN MINING

The present owners of the Benitoite Gem mine, Forrest and Gray, initially worked the open pit for mineral specimens, including neptunite and jonesite. One boulder produced a small quantity of pink benitoite, which yielded gems of one-quarter carat to just over one carat, but overall the amount of gem material recovered from the lode was not substantial. In 1970, Forrest and Gray began washing the mine-dump material by pumping water uphill through a fire hose. Then (as now) they worked only during the spring months, to take advantage of the favorable weather as well as the water available from the headwaters of the San Benito River, which

runs through the property. After washing the dump materials, they picked out mineralized blueschist and loose pieces of benitoite by hand (Gray, 1986). Using this very simple method during the early 1970s, they recovered significant quantities of faceting rough that produced some fine stones. Among these was the flawless 6.53 ct pear-shaped brilliant that was the center stone of the pendant to the famous benitoite and diamond necklace that was stolen in Europe in 1974. The necklace (figure 15) was recovered in 1975, but the pendant was never found.

After working through most of the mine dump, the two owners processed the underlying colluvium and eluvium using the same mining methods. The natrolite coating protected many of the benitoite and neptunite crystals during weathering and transport, so many fine mineral specimens were recovered. The gem rough recovered during this mining operation was generally of high quality, since the crystals that weathered out of the veins had typically broken along existing fractures to isolate the gemmy tips and nodules.

Since 1982, the owners have used a more systematic and mechanized recovery method (Gray, 1992). A front-end loader feeds dirt and rock through a grizzly, to separate out boulders, into a hopper (figure 16), where water is used to wash the material down a chute to a layered screening apparatus fitted with high-pressure water jets (figure 17). Material larger than 25 mm (1 inch) moves over the top screen, where it is again cleaned by water jets and checked for specimen potential. Material smaller than 25 mm falls onto a lower screen with a 3



Figure 16. The mine owners at the Benitoite Gem mine process colluvial and alluvial material using mechanized equipment. Here a loader dumps material through a grizzly and into a hopper. Rocks larger than 15 cm roll off the grizzly and are examined individually; stones smaller than 15 cm are washed down a chute to the apparatus pictured in figure 17. Photo by Brendan M. Laurs.

mm (1/8 inch) mesh. Pieces smaller than 3 mm are discharged into settling ponds, and material between 3 and 25 mm is washed into a gravitational separation jig, where the heavier benitoite is trapped in several parallel trays. Rough gem benitoite (figure 18) is removed from the trays by hand at the end of each work day. In the late 1980s, Forrest and Gray recovered a piece of rough from which the 10.47 ct gem pictured in figure 19 was cut. The largest,

Figure 17. At the Benitoite Gem mine, material is fed first into a layered screening apparatus fitted with high-pressure water jets, and then into a gravitational separation jig. Pieces over 25 mm are separated by the screening apparatus and checked for specimen potential, while material between 3 and 25 mm is washed into the jig where the heavier benitoite is trapped in several parallel trays. Photo by Brendan M. Laurs.



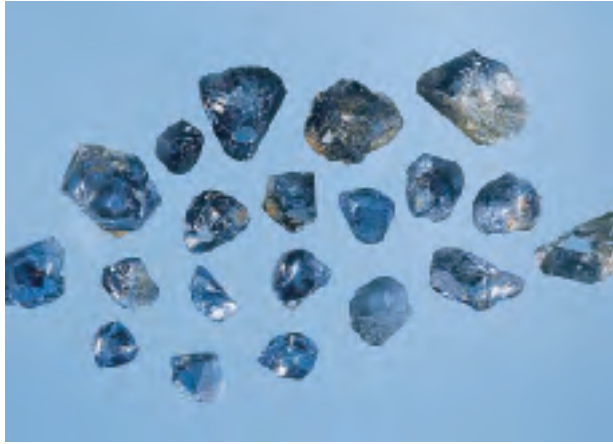


Figure 18. Rough benitoite gem nodules and crystal fragments, such as these, are removed from the gravitational separation jig by hand. The largest stone on the upper right is 1.0 cm wide. Photo by Maha DeMaggio.

finest rough found to date was recovered in the early 1990s; it was cut into a 15.42 ct gem (see cover of this issue).

By the end of the 1996 mining season, the colluvium and eluvium were largely exhausted. Using larger machinery, mine owners Forrest and Gray found a new productive area down slope of the open pit during spring 1997 (figure 20). Excavation during the 1997 season (March through May) revealed mineralized lode material that contained fine mineral specimens, as well as colluvium and eluvium with abundant gem rough. Mining of this new area will continue in 1998.

PRODUCTION

The Benitoite Gem mine is the only commercial source of gem-quality benitoite in the world. From the time of its discovery in 1907 until 1967, when Forrest and Gray began working the mine, it is estimated that about 2,500 carats of faceted benitoite were produced (E. Gray, pers. comm., 1997). Of that amount, nearly 1,000 carats were produced during the period of active mining between 1907 and 1911, based on the amount of rough reported in the Dallas Mining Company's account books. It was during that time that the gem rough that produced the 7.6 ct gem pictured in Louderback's 1909 report was recovered; this was subsequently recut to the 7.53 ct stone that is now in the Smithsonian Institution. Few other stones exceeded 3 ct, however, and most of the gems weighed less than 1 ct.

The balance of 1,500 carats believed to have been recovered between 1911 and 1967 was estimated from verbal information provided by previous miners (E. Gray, pers. comm., 1997). Most of these stones were faceted by cutters in the United States, and weights of up to 5 ct were obtained. Clarence Cole retrieved most of the rough during the interval from 1952 to 1962.

Since 1967, Forrest and Gray have produced approximately 2,000 carats of faceted benitoite. According to E. Gray (pers. comm., 1997), this inventory can be divided into six weight classes: (1) About 2,000 pieces were cut in commercial factories, and generally finished to less than 0.25 ct each; (2) another 1,500 pieces ranged between 0.25 and 1 ct; (3) some 500 stones weighed between 1 and 2 ct; (4) a total of 50 stones ranged between 2 and 3 ct; (5) only 25 stones weighed between 3 and 4 ct; and (6) the 15 largest stones exceeded 4 ct. Thus, 89% of the stones were under 1 ct; 9% were between 1 and 2 ct; and 2% were over 2 ct. All but the commercially cut stones were faceted by the families of the current owners or in their own facilities. Forrest and Gray have not marketed cuttable rough except, in a few cases, as mineral specimens.

Forrest and Gray also estimate that about 500 carats of finished goods have entered the market through informal channels and other sources, such as the cutting of older rough and the faceting of mineral specimens. Thus, a total of about 5,000 carats of faceted benitoites have been produced over the life of the mine. Because of this small produc-

Figure 19. This exceptional faceted benitoite weighs 10.47 ct. From the collection of Michael M. Scott; photo © Harold & Erica Van Pelt.



tion, benitoite is a collector's gem, one of the rarest in the world.

PHYSICAL AND CHEMICAL PROPERTIES

Materials and Methods. We examined a total of 139 benitoite samples, of which 83 were faceted stones and four were cabochons. With the exception of two faceted stones reportedly from the Junnula claim, all of the benitoites examined were from the Benitoite Gem mine. The rough stones (52) were all of gem quality, and were provided by Forrest and Gray from their gravity-separation apparatus. The fashioned samples were selected for their various internal features; consequently, they were not as clean as benitoites typically seen in the marketplace.

The faceted stones in our study ranged from 0.10 to 1.46 ct (see, e.g., figure 21), and the cabochons ranged from 1.06 to 5.31 ct. All of the sam-

Figure 20. The backhoe is excavating the newly discovered western extension of the deposit at the Benitoite Gem mine. Boulders of altered blueschist, some bearing benitoite, are piled near the left rim of the pit. The high wall of the main pit can be seen on the skyline. Photo by Brendan M. Laurs.



Figure 21. These faceted benitoites from the Benitoite Gem mine, which show a range of tone and saturation, were among the samples studied for this investigation. Clockwise from the top, the stones weigh 0.95 ct, 0.87 ct, 0.49 ct, and 0.54 ct. Photo by Maha DeMaggio.

ples—both rough and fashioned—were examined with magnification to locate and describe inclusions and color zoning. Refractive index measurements were made on the 21 faceted stones that were larger than 0.20 ct. Specific gravity, fluorescence, and visible absorption spectra were also determined for these faceted stones, as well as for the four cabochons.

Refractive indices and birefringence were measured on a GIA GEM Instruments Duplex II refractometer, using a 1.815 contact liquid and a monochromatic sodium-equivalent light source. Because the upper R.I. of benitoite (1.804) is close to the upper limit of the Duplex II (1.810), we also measured the four benitoites pictured in figure 21 with a specially designed refractometer fitted with a cubic zirconia hemicylinder. Specific gravity was measured by the hydrostatic method (three measurements per sample) with a Mettler CM1200 digital balance. All of the samples were examined with a standard gemological microscope, a Leica Stereozoom with 10× to 60× magnification; the rough specimens were immersed in methylene iodide. Absorption spectra were observed with a Beck spectroscope on a GIA GEM Instruments base.

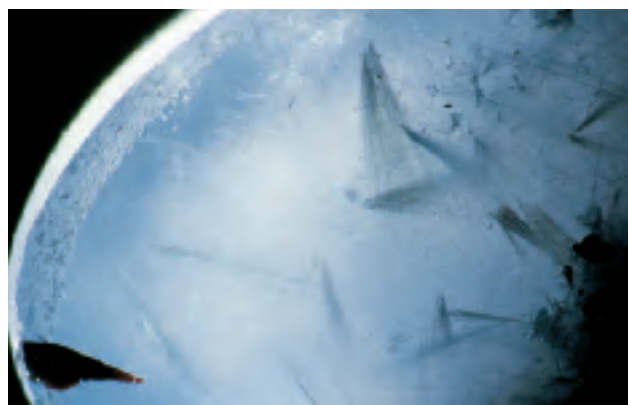
Electron microprobe analyses of some of the mineral inclusions in benitoite were performed at the University of Manitoba in Winnipeg, Canada, on two gem-quality pieces of rough that contained inclusions visible with 10× magnification.



Figure 22. Weighing from 0.30 to 1.70 ct, these benitoites show a range in size, color, and faceting style that is representative of commercially available benitoite. Courtesy of Edward Swoboda; photo © Harold & Erica Van Pelt.

Visual Appearance. The samples ranged from blue to violetish blue in color, and from very light to medium dark in tone. This color range is representative of the stones commonly marketed (figure 22).

Figure 23. This benitoite cabochon (5.31 ct) displays strong dichroism and contains fibrous inclusions of amphibole and/or pyroxene. The dark reddish brown inclusion on the lower left is neptunite. Darkfield illumination; photomicrograph by John I. Koivula.



Dark colors were seen in melee (less than 0.20 ct), as well as in larger stones. Most of the gems were medium to medium-dark in tone, with strong saturation, a color range sometimes referred to as “cornflower” blue. A green tinge was evident in some of the paler cabochons due to inclusions of fibrous green amphibole or pyroxene (discussed below). Strong dichroism (figure 23), from colorless to blue or violetish blue, was evident when the stones were viewed through a dichroscope in any direction. To the unaided eye, pleochroism was visible as light and dark tones that mingled with the brilliance and dispersion. The dispersion is masked somewhat by the blue body color. Color zoning was common.

As described previously, colorless and pink faceted stones are extremely rare; consequently, they were not included in this portion of the study. Heat treatment of lighter colored material may result in an orange hue similar to that associated with Imperial topaz (see, e.g., figure 24); the dichroic colors of this material are pink and orange. The orange color has not been observed in untreated benitoite. Heat treatment has been successful for only a small portion of the material treated, and some of the crystals have exploded in the furnace because of differential expansion of inclusions. The heat-treatment procedure is proprietary, and experiments were not performed as part of this study.

Physical Properties. The standard gemological properties of benitoite are shown in table 1 and discussed below.

Refractive Indices. Most of the stones showed $n_{\omega} = 1.757$ to 1.759, and $n_{\epsilon} = 1.802$ to 1.804. The accura-

Figure 24. Shown here, clockwise from the top left, are some of the more unusual benitoites that have been found at the Benitoite Gem mine: a 0.79 ct light blue round brilliant, with unusually large two-phase inclusions; a 1.29 ct pinkish blue round brilliant; a 1.07 ct nearly colorless lozenge-shaped mixed cut, with a slight blue tint; a 0.34 ct dark purplish pink round brilliant; a 0.53 ct heat-treated pinkish orange oval mixed cut; a 0.61 ct heat-treated particolored (pinkish orange and blue) rectangular modified emerald cut; and a 0.91 ct heat-treated particolored shield shape mixed cut. The particolored stones resulted from heat treatment of material that was originally colorless and blue. All stones were faceted by Elvis (Buzz) and Michael Gray. From the collection of Michael M. Scott; photo © Harold & Erica Van Pelt.



cy of the upper measurements was compromised by their proximity to the upper limit of the refractometer. Nevertheless, these measurements compare favorably to the published values of $n_{\omega} = 1.757$ and $n_{\epsilon} = 1.804$ (Webster, 1994). In addition, the four stones tested with the cubic zirconia refractometer showed $n_{\epsilon} = 1.804$ to 1.805. The measured birefringence ranged from 0.043 to 0.047, which compares favorably to the published value of 0.047 (Webster, 1994). Because of the high birefringence, doubling of pavilion facet junctions is easily seen through the table with 10× magnification.

Specific Gravity. The measured values for the faceted stones ranged from 3.65 to 3.80. In most of the stones larger than 0.40 ct, the S.G. values were near 3.70. This differs somewhat from the published *measured* value of 3.65, but it is close to the published *calculated* value of 3.68 (Anthony et al., 1995). The largest scatter in measured values was noted for the smaller stones, which is due to measurement error. The S.G. of the cabochons ranged from 3.31 to 3.69; the lighter measurements were obtained for stones containing abundant fibrous inclusions (described below).

Ultraviolet Fluorescence. Similar to the descriptions by Wise and Gill (1977) and Mitchell (1980), the sample blue benitoites fluoresced strong blue to short-wave UV radiation, and appeared inert to

long-wave UV; the colorless benitoite fluoresced slightly stronger blue to short-wave, and showed dull red fluorescence to long-wave. Some light-colored samples examined in this study also fluoresced dull red to long-wave UV. Moderate chalkiness is characteristic of the fluorescence to both short- and long-wave UV. Because of benitoite's conspicuous fluorescence, miners have recovered some crystals by scanning the ground surface at night with a portable UV lamp.

Internal Features. Inclusions. Microcrystals, "fingerprints," and fractures are commonly seen in benitoite. Many of the 83 faceted stones examined for this study contained white needles as disseminations and intergrown clusters (figure 25). We did not note any preferred orientation of the needles. The needles are probably actinolite-tremolite, as suggested by petrography and by electron microprobe analyses of similar crystals in the host rock (Laurs, 1995). Because the needles are so small (typically less than 0.5 mm long), they are rarely visible with the unaided eye unless they are abundant. With 10× magnification, they resemble lint particles in appearance and texture. Also present in heavily included samples were dark blue and green needles that formed elongate tufts on the order of several millimeters long (again, see figure 23). Electron microprobe analyses of benitoite inclusions showed the presence of aegerine-augite and diopside, which

TABLE 1. Properties of benitoite.^a

Composition	BaTiSi ₃ O ₉
Color	Colorless, and blue to violetish blue (commonly zoned); rarely pink. Heat treatment may (rarely) cause colorless → orange hue. Light to medium dark in tone, typically strong in saturation.
Pleochroism	Strongly dichroic; colorless (ω) and blue to violetish blue (ϵ)
Clarity	Translucent to transparent
Refractive indices	$n_{\omega} = 1.757$, $n_{\epsilon} = 1.804^b$ $n_{\omega} = 1.757\text{--}1.759^*$, $n_{\epsilon} = 1.802\text{--}1.805^*$
Birefringence	0.047 ^b ; 0.043–0.047 [*]
Optic character	Uniaxial positive
Specific gravity	3.65 (measured); 3.68 (calculated) ^c 3.65–3.80 (measured, this study)
Dispersion	$\epsilon = 0.039$, $\omega = 0.046^d$ (diamond is 0.044)
Hardness	6–6.5 ^c
Polish luster	Vitreous to sub-adamantine ^e
Fracture luster	Vitreous on conchoidal to uneven surfaces ^e
Cleavage	None
Toughness	Fair; brittle
UV Fluorescence	
Short-wave (254 nm)	All stones—moderately chalky, strong blue
Long-wave (365 nm)	Blue stones—inert Pale blue to colorless stones—moderately chalky, dull red
Cathodo-luminescence	Intense blue ^f
Morphology	Hexagonal system; crystals are triangular, flattened on the c-axis, and pyramidal or tabular
Inclusions	Minerals (actinolite-tremolite, aegirine-augite, diopside, serandite pseudomorphs ^g , neptunite ^g , joaquinite ^g , albite ^g , apatite ^g , djurleite ^g), “fingerprints,” ^h fractures, two-phase ^h
Typical size range	Cut stones, 10 points to 1 ct; rough crystals, 1 cm in diameter
Largest cut stone	15.42 ct
Stability ^e	Sensitive to rapid temperature changes and ultrasonic vibration. Insoluble in hydrochloric and sulfuric acids. Easily attacked by hydrofluoric acid.
May be confused with	Sapphire, tanzanite (depending on orientation), blue diamond, iolite, blue tourmaline, blue spinel, saphirine, blue zircon

^aProperties as obtained in this study unless otherwise noted.

^bWebster (1994). ^cAnthony et al. (1995). ^dPayne (1939). ^eGemological Institute of America (1993). ^fLaird and Albee (1972). ^gWise and Gill (1977). ^hGübelin and Koivula (1986).

^{*}Values obtained in this study from measurements taken on the tables of faceted stones.

are both pyroxenes (F. Hawthorne, pers. comm., 1997).

Silica pseudomorphs after serandite form prismatic euhedral inclusions in benitoite, but these

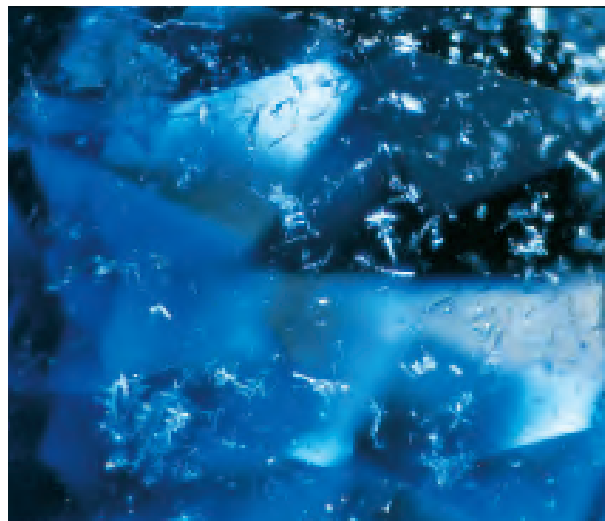


Figure 25. Lint-like needles of amphibole (probably actinolite-tremolite) are the most frequently encountered mineral inclusions in benitoite. Dark-field illumination, magnified 20 \times ; photomicrograph by John I. Koivula.

are seldom seen in faceted stones (see the center right photomicrograph in Gübelin and Koivula, 1986, p. 416; these crystals were apparently misidentified as neptunite). Other inclusions seen only rarely were anhedral to euhedral dark reddish brown neptunite and euhedral honey-colored joaquinite-group minerals (specific species not determined). Albite, apatite, and metallic greenish gray djurleite crystals have been reported as inclusions in benitoite (Wise and Gill, 1977), but they were not observed in this study. Two-phase (liquid and gas) inclusions (figure 26) were noted in only two samples, along healed fractures. The “fingerprints” are commonly planar, but they appeared curved in several stones. Unhealed fractures typically showed step-like conchoidal break patterns.

Color and Growth Zoning. Color zoning was most apparent in emerald-cut stones, which commonly displayed a gradation from blue to colorless when viewed face-up with the unaided eye. When the stones were viewed from different angles at 10 \times magnification, sharp planar boundaries between the blue and colorless areas were eye-visible in one or more directions. These boundaries are situated near the core of the rough crystals.

Growth zoning was seen at 10 \times magnification in some stones as multiple bands that showed variable tones and spacing (figure 27). Such growth zon-



Figure 26. Two-phase inclusions are not commonly seen in benitoite. The larger inclusions in the healed fracture of this 0.95 ct stone contain vapor bubbles of variable shape and size. Darkfield illumination, magnified 25 \times ; photomicrograph by John I. Koivula.

ing is much less regular or apparent than that typically seen in corundum. Less commonly than planar growth zoning, our samples showed irregular, patchy, diffuse areas of color.

A distinctive characteristic of benitoite, noted in more than half the samples examined for this study, were sharp planar features that closely resemble the internal graining seen in some diamonds. This "graining" appeared as shadow-like planes that, at 10 \times magnification, were commonly seen along the boundaries of color zones. It also truncated color zones at oblique angles (again, see figure 27). The graining was almost always uniform and straight, but in some stones it was step-like or jagged. No surface graining or other polishing irregularities were noted where the internal graining reached the surface of the stone.

Chemistry and Spectroscopy. A tabulation of previous data and recently acquired compositions of benitoite is shown in table 2. No new analyses were obtained for this study, because routine electron microprobe analyses have shown a constant composition, and the data reported by Laird and Albee (1972) are considered very reliable (G. Rossman, pers. comm., 1997). The measured amounts of Ba, Ti, and Si are remarkably constant, regardless of color or locality, and fall near the ideal values that are calculated from the chemical formula. The

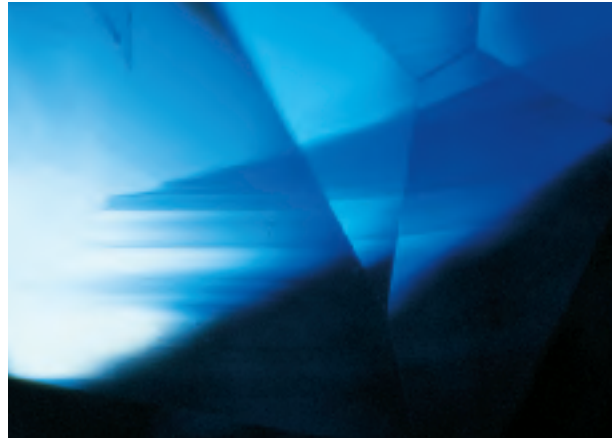


Figure 27. Planar color zoning is commonly visible at some angles within benitoite. The color zones appear curved in this 0.81 ct stone, because of refraction through adjacent facets. Shadow-like internal graining bounds and truncates the color zones, and is visible as the stone is tilted from side to side. Darkfield illumination, magnified 15 \times ; photomicrograph by John I. Koivula.

greatest chemical variation in benitoite was reported by Gross et al. (1965) for samples from the Big Creek–Rush Creek area in Fresno County, California, which contained up to 4.1% tin oxide. A zirconium-bearing blue benitoite from Japan was found to contain 1.77 wt.% ZrO₂, and up to 1.51 wt.% ZrO₂ was measured in a colorless benitoite from Arkansas (H. Barwood, pers. comm., 1997). It is not surprising that Sn and Zr show the greatest variations, since these elements form barium silicate minerals analogous to benitoite that are called pabstite and bazirite, respectively (Hawthorne, 1987). Other elements show minor variations, most notably Nb, Na, Ca, K, and Fe.

Numerous investigators have attempted to link the chemical composition of benitoite to its coloration. Louderback (1907) initially attributed the blue color to traces of reduced Ti, but in 1909 he reported that no reduced Ti could be measured. Coleman (1957) suggested that trace impurities of V, Nb, and Cu might cause the blue coloration. Laird and Albee (1972) noted slightly higher concentrations of Fe in blue than in colorless benitoite. Burns et al. (1967) suggested that the coloration is caused by crystal defects due to an oxygen deficiency. Burns (1970) suggested that the pleochroism of benitoite and other minerals might be caused by Fe²⁺→Fe³⁺ charge transfer. Millage (1981) also proposed metal-metal charge transfer, such as

TABLE 2. Chemical compositions of benitoite from California, Arkansas, and Japan.^a

Oxide (wt.%)	Benitoite Gem mine ^b	Benitoite Gem mine ^b	Victor ^c	Diamond Jo ^d	Diamond Jo ^d	Diamond Jo ^d	Ohmi ^e	Ohmi ^e	Ohmi ^e
	California Colorless (6)	California Blue (6)	California Colorless (1)	Arkansas Colorless (3)	Arkansas Blue (6)	Arkansas Pink (3)	Japan Colorless (1)	Japan Blue (1)	Japan Blue (1)
SiO ₂	42.62	43.10	43.66	43.52	43.55	43.49	43.55	43.16	41.05
TiO ₂	19.44	19.51	19.29	17.90	18.47	18.99	19.30	19.11	19.82
ZrO ₂	0.108*	0.016*	nd	1.16	0.33	0.08	nd	nd	1.77
Al ₂ O ₃	0.04*	0.20*	0.30	0.29	0.22	0.21	0.18	0.10	nd
FeO	0.01*	0.05*	0.01	0.15	0.04	0.01	0.081 [†]	0.033 [†]	nd
MnO	nd	nd	0.03	0.03	0.04	0.03	0.05	0.11	nd
MgO	trace*	trace*	nd	nd	nd	nd	0.12	0.14	0.16
CaO	0.006*	0.10*	0.11	nd	nd	nd	0.28	0.24	0.12
BaO	37.27	37.23	36.48	36.70	36.21	36.36	34.82	36.04	36.78
SrO	0.003*	0.004*	nd	nd	nd	nd	nd	nd	nd
Na ₂ O	0.14	0.13	0.20	0.23	0.22	0.18	0.84	0.75	0.27
K ₂ O	nd	nd	nd	0.01	0.20	0.13	0.44	0.21	nd
Nb ₂ O ₅	0.20*	<0.10*	nd	bdl	0.74	0.34	nd	nd	nd
V ₂ O ₅	0.002*	0.003*	nd	nd	nd	nd	nd	nd	nd
S	nd	nd	nd	nd	nd	nd	0.06	0.02	—
Cl	nd	nd	nd	nd	nd	nd	0.28	0.10	—
Total	99.84	100.34	100.08	99.99	100.02	99.82	100.00	100.01	99.97

^aComments: Ideal formula concentrations (wt.%): SiO₂ 43.59, TiO₂ 19.32, BaO 37.09 (Laird and Albee, 1972). Values determined by electron microprobe, except: * – emission spectroscopy, and † – atomic absorption. Total iron is reported as FeO. Number of samples in parentheses.

Looked for by Laird and Albee (1972), but not detected: Ag, As, Au, B, Be, Bi, Cd, Co, Cr, Cu, Ga, La, Mo, Mn, Nd, Ni, Pb, Pt, Sb, Sc, Sn, Ta, Th, Ti, W, Y, Yb, and Zn. The abbreviation "nd" = not determined; "bdl" = below detection limit.

^bLaird and Albee (1972). ^cMillage (1981). ^dH. Barwood, pers. comm. (1997).

^eSakai and Akai (1994).

Fe²⁺→Ti⁴⁺ or Fe²⁺→Fe³⁺, as a coloring agent, but then negated this possibility because these atoms are separated too far from one another in the benitoite lattice. Instead, Millage attributed the blue coloration to traces of Zr in the Ti site. The compositions of colorless and blue benitoite from Arkansas and the Benitoite Gem mine contradict this, however, since more Zr is present in the colorless samples than in the blue material (again, see table 2).

In this study, no spectral characteristics could be resolved in any of the samples tested, regardless of color, with a desk-model type of spectroscope. Spectral data have been collected by means of a spectrophotometer for blue, pink, and heat-treated orange benitoite (Burns et al., 1967; Rossman, 1997). Blue benitoite shows a broad peak at about 700 nm (figure 28), most of which appears in the near-infrared region. Infrared spectra have also been collected, but the data in this region are inconsistent and of little use (G. Rossman, pers. comm., 1997). In spite of much effort to interpret the spectral data, the cause of color in benitoite remains elusive.

Synthesis and Scientific Use. Synthetic benitoite has been successfully grown in the laboratory (Rase

and Roy, 1955a and b; Hinthorne, 1974; Christophe et al., 1980), but only in minute crystals that are colorless and too small to facet. Natural benitoite has an important industrial application in electron

Figure 28. The absorption spectra for blue benitoite from the Benitoite Gem mine, shown here in the range from UV to near-infrared at orientations parallel (red line) and perpendicular (blue line) to the c-axis, do not provide any clues to the cause of color in this material. Courtesy of George R. Rossman.

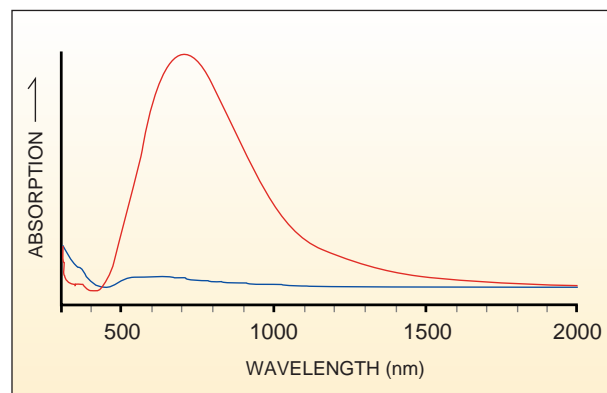


Figure 29. This 1.16 ct modified pear shape benitoite mimics the shape of the perfect 1-cm-wide rough crystal; both are from the Benitoite Gem mine.

The specimen was recovered from the upper portion of the main pit by the present owners. It is one of only three found in which the benitoite apparently crystallized contemporaneously with albite crystals. From the collection of Michael M. Scott; photo © Harold & Erica Van Pelt.



microprobes: Because it fluoresces strongly to an electron beam, benitoite is used to align and adjust the beam size. Benitoite is also employed as an analytical standard for Ba and Ti, because of the constancy of its chemical composition. Webster (1994) suggested that benitoite could be used as a known standard for measuring dispersion in gemstones.

Identification. Benitoite may be distinguished from sapphire by its greater birefringence, strong dispersion, and its strong blue-and-colorless pleochroism. When set in a piece of jewelry, benitoite also will abrade more easily than sapphire. Natural and irradiated blue diamonds can also give the appearance of the lighter shades of benitoite because of similarities in color and dispersion, but the separation is easily made because diamond is singly refractive and has a much higher R.I. Benitoite can be distinguished from tanzanite on the basis of pleochroism, since benitoite lacks the purple trichroic component that is almost always apparent at some angle within tanzanite. In addition to the differences in gemological properties, sapphirine is too dark to be confused with benitoite, and zircon does not occur in the same hue. Iolite and blue tourmaline have much lower dispersion, refractive indices, and birefringence than benitoite. As described previously, benitoite also commonly has distinctive growth-zoning patterns and lint-like mineral inclusions.

CUTTING

Benitoite is one of the easiest gemstones to facet. There are no directional weaknesses (e.g., cleavage). At 6.0–6.5 on the Mohs scale, benitoite is about as hard as tanzanite and peridot, harder than sunstone and other feldspars, and softer than quartz and tourmaline. Benitoite can be oriented so that color zoning is rarely evident in the face-up direction (figure 29). Since the dichroic colors of blue benitoite are blue and colorless, there are no ancillary hues to mix through optical orientation. As a result, the alignment of the rough crystal for faceting requires only the placement of the desired color within the culet of the finished stone. In most cases, however, this is not important, since blue coloration is evident regardless of the direction in which the stone is oriented.

One of the authors (MG) has cut thousands of benitoites. Because of the typically small finished sizes, faceting can generally be accomplished using a single lap—in most cases, 1200 grit. Polishing is so rapid that the lapidary has to be careful not to enlarge a facet by overpolishing. The best grit is 0.04 micron aluminum oxide, generally known as Linde B, which is a hundred times finer than the more common Linde A. It works very well on a tin or tin/lead polishing lap. The fineness of the powder helps eliminate the polishing lines that are typically imparted to softer gemstones.

The critical angle of benitoite is 34.7°. Successful makes have crown angles that range from 30° to 40°, with optimum results obtained at 38°. The pavilion angle range is narrower, from 40° to 42° with the optimum at 41°. Benitoite is amenable to all styles and makes (see again, figure 22), but it tends to show maximum dispersion when finished as a round brilliant or a trilliant.

CONCLUSION

It is likely that future production of faceting-quality benitoite will come solely from the Benitoite Gem mine. The recent discovery of additional mineralized material down slope from the historic open pit is highly encouraging for the stability of price and future supply. Although rare, faceted stones and mineral specimens of benitoite are commercially available, and mining is ongoing. The formation of relatively large, locally abundant, gem-quality crystals at the Benitoite Gem mine resulted from a combination of unusual geologic processes. The distinctive gemological properties of benitoite make it readily identifiable from other gem materials.

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