OPAL FROM QUERÉTARO, MEXICO: OCCURRENCE AND INCLUSIONS

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The Querétaro area, 200 km northwest of Mexico City, has been producing fine, unusually transparent opal with vivid red and green play of color for over 100 years. These opals occur largely in gas cavities in pink to brick-red, thinly bedded rhyolitic lava flows and are mined in open-pit quarries. After examining thousands of opals from this area, the authors selected 20 specimens containing excellent examples of both common and rare inclusions that seemed to represent the variety of inclusions found in gem-quality opals from this locality. The opals and their inclusions were then subjected to a battery of tests to ascertain their nature. These tests revealed both two- and three-phase inclusions and a variety of different mineral species.

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Mexican opal has been known since the latter part of the 18th century, but the more familiar gem-quality material has been available to the world market only since the end of the last century. At times, the beauty of Mexican opal (figure 1) exceeds that found in opal from any of the world's better-known deposits, such as Australia; yet its somewhat undeserved reputation for instability has prevented it from taking a major role in the modern jewelry trade (Sinkankas, 1959). The most important opal deposits in Mexico are in the state of Querétaro, although there are other significant deposits in the states of Chihuahua, San Luis Potosí, Guerrero, Hidalgo, Jalisco, and Michoacán. However, Querétaro is the center of opal mining and cutting in Mexico, and it is the predominantly reddish-orange fire opal from the Querétaro deposits that is addressed in this study of the locality and internal features of this material.

Although most gemologists who have examined even a small number of opals from Querétaro with a microscope are familiar with at least two or three inclusions in this material, very few inclusions have as yet been conclusively identified. In addition, with the exception of some brief general descriptions of inclusions in opal that are scattered throughout the literature, virtually nothing has been written on this subject.

This article briefly describes the Querétaro deposits and the opal they have produced and, with this as background, presents the results of a study of about 3,000 opals from this locality that were examined for inclusions.

LOCATION AND ACCESS

The opal mining and cutting center of Querétaro is also the capital city of the state bearing the same name. Querétaro is located in central Mexico, on its high central plateau, approximately 200 km northwest of Mexico City. Access to the capital city is via Highway 57, a major toll

Figure 1. This 0.95-ct cabochon shows the reddish orange body color with red and green play of color that is typical of fine fire opal from Querétaro. Photo by Mike Havstad.

road from Mexico City. The principal productive area today is in the vicinity of the Iris mine, which is reached by taking the toll road from the city of Querétaro approximately 30 km back toward Mexico City to Highway 120, and then traveling east on Highway 120 toward Cadereyta for about 6 km until the open-pit mines can be seen from the highway along a series of low ridges (Burton, 1981).

HISTORY AND MINING

According to Webster (1975), fire opal was used extensively by the Aztecs (1200–1519 A.D.) in some of their ceremonial objects. Sinkankas (1959) states that the opal was known to the Aztecs as *vitzitziltecpatl,* or "humming bird stone," an allusion to the similarity of the opal to the iridescent feathers of a humming bird. These early accounts of the Aztecs' use of opal are somewhat substantiated by one of the most famous Mexican opals in the world: the Aztec Sun God opal. Once part of the famous Hope collection (which also contained the Hope diamond), it supposedly is of Aztec origin and was taken from a temple in the early 16th century (Kunz, 1907). After being sold from the Hope collection in 1886, this opal became part of the Tiffany gem collection of the Field Museum of Natural History, in Chicago, Illinois, where it still resides today.

With the conquest of the Aztecs, the location of the Querétaro opal deposits remained a mystery for several hundred years. It was not until 1855 that a servant of the Hacienda Esperanza rediscovered them (Ramirez, 1884), and it was another 15 years before Don José María Siurob of Querétaro located the Santa María Iris mine in Hacienda Esmeralda and began commercially working the opal deposits (Foshag, 1953). Bauer (1904) states that the gem was so common in the area that "specks of opal are often seen in the stones of buildings." It is interesting to note that the Santa María Iris mine remains the most productive and famous of the Querétaro opal mines today. Since Don José's initial commercial efforts at Hacienda Esmeralda, the region has experienced widespread development. Sinkankas (1976) notes that production from the Querétaro area reached an all-time high in 1969, a result of greatly increased demand from Europe and Japan. Sinkankas lists eight mines, in addition to the famous Iris mine, active in the Querétaro area. Perhaps the most notable of these is the Carbonera mine near Trinidad, not far from San Juan del Río.

All opal mining operations in the Querétaro area are very simple open-pit quarries, and the opal recovery methods have not changed significantly in the last 100 years (figure 2). These quarries may be quite large (figure 3); Burton (1981) reported that the original Iris open-pit mine now has walls over 60 m high. Recovery initially involves the dynamiting of the opal-bearing rock from the quarry wall. The loose boulders are then stacked in a pile to be broken down by hand—into pieces 5 cm or less to improve recovery of gem-quality material—under strict supervision. The rough opal is then sorted and taken to the city of Querétaro where it is fashioned into cabochons. Because of the unusually high transparency of the material and the play of color, these cabochons are usually cut with a high dome rather than the flat ovals common to opals from other regions of the world (Foshag, 1953).

The opal occurs in a series of thinly bedded

Figure 2. Using the same methods as their 19th-century predecessors, miners remove material from the newly reopened Mina El Buey. Mine owner Joaquín Ontiveros reported that Mina El Buey was last worked over 100 years ago.

Figure 3. View looking into the Mina La Simpática. This mine is typical of the simple open-pit quarries in Querétaro.

rhyolite lava flows (Kunz, 1907). Locally these pink to brick-red rhyolites exhibit an abundance of irregular to oval lithophysal (gas) cavities common to rhyolitic lava flows. The opal occurs as a secondary filling in these cavities as well as in any other available spaces in the lava, including pumice fragments and fractures. The opal usually fills the cavities totally, but occasionally it is found as loose nodules in the open spaces. These loose nodules, which may be "as large as a hen's egg," are generally the highest quality material (Foshag, 1953). Figure 4 illustrates one of the finest matrix opal specimens found in Querétaro (Kunz, 1907).

GEMOLOGY OF THE QUERÉTARO OPAL

Opal from the Querétaro area typically has lower properties than the Australian material. The refractive index is usually around 1.42 to 1.43; the specific gravity is approximately 2.00 ± 0.05. Querétaro opal is often distinguished from other opal by its unusually high degree of transparency and by its particularly vivid red and green play of color. Although the cabochon is the most common cutting style (again, see figure 1), the transparency of the Querétaro material occasionally allows it to be faceted (figure 5), a cutting style not generally considered for opal. A reddish orange body color is most commonly seen in fine opals from this area (responsible for the term *fire opal*), with predominantly green play of color that may be in broad spangles, small flecks, or even pinfire. Black opals have been reported (Mayers, 1947), but they are probably the result of heat treatment (Sinkankas, 1959).

GENESIS OF MEXICAN OPAL: MULTIPLE CYCLES OF GROWTH

After carefully studying several Mexican opals with included acicular crystals, the authors noted that in almost all cases there seemed to be a shell

Figure 4. Fire opal in matrix. Called one of the finest specimens of its kind by Kunz (1907), this 7.5 × 6.5 cm nodule was taken from the Iris mine in Querétaro and is now part of the Harvard University Collection.

of whitish to pale yellow material surrounding the needle-like crystals. This shell, or coating, often seemed to take on a somewhat bulbous, almost botryoidal, appearance that at first was attributed to a flow structure around the included crystals. It was not until the authors examined a sample of rhyolite matrix rock that contained several partially open gas cavities lined with numerous acicular crystals coated with a near-colorless transparent material (as shown in figure 6) that a full understanding of the nature of these coatings and their origins was learned.

X-ray diffraction on the near-colorless coating material proved it to be opal. This led the authors to theorize that if the cavities containing these already-coated crystals were later filled entirely with opal, an inclusion pattern similar to the one illustrated in figure 7 could be easily explained as resulting from at least two cycles of growth. One such coated crystal included in an opal was cut through so that it could be studied in cross section. The result, as seen in figure 8, is reminiscent of tree rings and shows that several stages of deposition took place during the initial coating of the needle-like crystal and prior to its inclusion in the larger body of the orange-colored opal host.

It is not particularly surprising to have several cycles of deposition, similar to the tree-ring analogy, because studies of chalcedony in rhyolitic flows in Chihuahua, Mexico, showed similar phenomena. Keller (1977) studied agate in the Sierra Gallego area of Chihuahua and found that the nodules formed at near-surface temperatures and that their characteristically banded structure was probably the result of many years of deposition of silica due to annual fluctuations in the local water table from the wet to dry seasons. It is possible that some of the opal in the Querétaro area formed under similar conditions.

From the numerous layered and flow structures in Mexican opals, it is concluded that the silica initially introduced into the host igneous rock was in a somewhat gelatinous plastic state. Flow structures are seldom as prominent and easily observable as the one illustrated in figure 9 or the black streamers reported by Fryer et al. (1982). They are more often observed as faint, curving flow lines associated with included crystals or other pre-existing formations that tend to interfere with and/or block the flow of the opalizing gel. In a few rare cases, the flowing gel will actually break or twist extremely thin acicular crystals.

INCLUSIONS IN MEXICAN OPAL

Over 3,000 opals from Querétaro were examined with the microscope. The opals were either tumbled, polished, rough, or cut en cabochon. Many contained portions of their original rhyolite matrix. They ranged in hue from near colorless to pale yellow through orange to deep orange-brown, and the diaphaneity varied from transparent to translucent. The majority displayed at least some play of color. Those with some rhyolite matrix frequently proved the most exciting to the authors, as crystals of interest would be attached to the rhyolite and extend into the opal. Occasionally free-floating included crystals and crystal fragments were encountered in the opal.

From the original mass of opals, 20 specimens were chosen because of the size of their inclu-

Figure 5. Faceted fire opal, 3.10 ct. Photo by Mike Havstad.

Figure 6. Acicular crystals coated with a near-colorless transparent material (found to be opal) inside partially open gas cavities. Magnified 6×.

Figure 7. Opal-coated crystals included in opal. Magnified 45×.

Figure 8. A cross section of a coated crystal (in this case, a partial limonite pseudomorph after hornblende) in Mexican opal. The rings indicate that several stages of deposition occurred during the initial coating of the needle-like crystal and prior to its inclusion in the opal host. Magnified 100×.

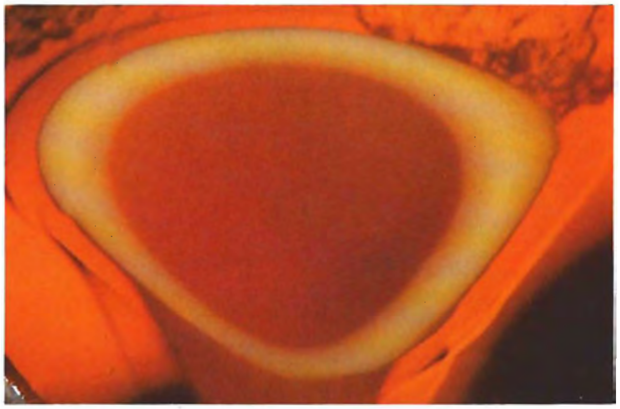

Figure 9. Flow structure in Mexican opal. Magnified 15×.

sions, the ease with which they might be analyzed, their photogenic nature, and in some cases because of their rarity and uniqueness. The following discussion reports the results of this investigation, which led to the definitive identification of a number of the included minerals and the revelation of some heretofore unreported inclusion phenomena in opals.

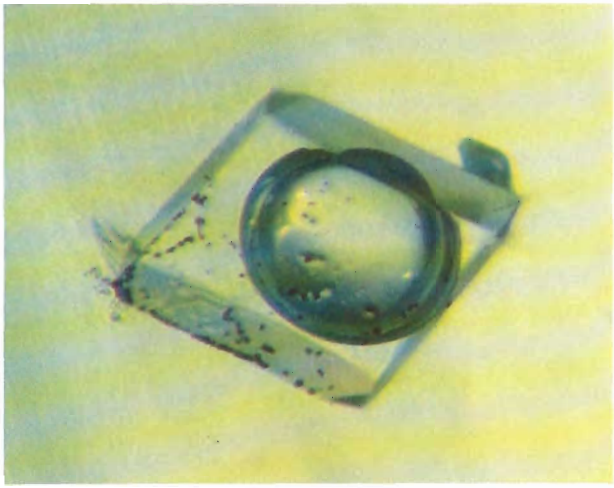

Figure 10. A three-phase inclusion in Mexican opal. Notice the tiny red solid phases attached to the surface of the void. Magnified 50×.

Three-Phase Inclusions. When we observe an inclusion that appears to be a negative crystal such as that illustrated in figure 10, one of the last gemstones to come to mind as a possible host is opal, because, by virtue of its amorphous nature, opal should not house negative crystals that contain the liquid, gas, and solid components of a three-phase fluid inclusion. Figure 10, however, illustrates just such a three-phase inclusion in a Mexican opal. The following explanation is offered for its existence. Perhaps during initial formation in its extrusive igneous host, the opal captured and included a euhedral crystal, a carbonate such as calcite or dolomite. If the opal's environment and the natural water it contains in its structure turned somewhat acidic, the rhombohedral carbonate crystal could be dissolved, leaving behind a rhombohedron-shaped cavity that would now be filled with a portion of the dissolving solution and an accompanying gas bubble. Any insoluble inclusions in the original carbonate crystal would be left behind as solids.

In addition, if the dissolving solution brought chemically suspended impurities with it, these, too, could be deposited in the void left by dissolution of the carbonate crystal in the opal host. Study of figure 10 immediately reveals the obvious liquid and gas phases present. A closer examination reveals numerous tiny red solid phases attached to the surface of the void which dent the gas bubble where they are trapped between it and the walls of the cavity, proving that they are inside the bubble with the liquid and gas phases.

Figure 11. This two-phase inclusion in Mexican opal consists of an acicular crystal of hornblende within a balloon-shaped void. Magnified 45×.

Two-Phase Inclusions. One of the opals studied contained an included acicular crystal of hornblende within the teardrop void shown in figure 11. It might be easily mistaken for an opal coating on a crystal such as the one shown in figure 7. The hornblende needle contained in the upper bulbous portion of the void was broken off and free to move about in the void, thus identifying it as a hollow space.

A void of this nature might be formed when the opalizing gel fills cavities in the host rock that contain the hornblende needles. As the gel covers the needles, gas bubbles might attach to the hornblende just as gas bubbles can be seen to coalesce on the surface of any object placed in a liquid such as water. The greater density of the gel would force the accumulating gas bubbles upward, forming a ballon-shaped tent around and over the end of the hornblende crystal. When the opal solidified, the gas would be trapped in the balloon-shaped void it had formed in the opal.

Hornblende. The crystal shown in figure 12 is typical of the black, needle-like crystals found in Mexican opals. It is also opaque and is of slightly distorted hexagonal cross section. Crystals of similar appearance that did not reach the surface of the opal host had rhombohedron-like terminations. These properties and the nature of the host rock suggested that these inclusions might be hornblende. An X-ray diffraction powder photograph of an exposed inclusion proved that the initial conclusion was correct. Note that the X-ray diffraction powder test caused no observable damage to either the hornblende inclusion or the host opal.

Figure 12. Black, needle-like crystals are commonly seen in Mexican opal. This particular inclusion proved to be hornblende. Magnified 40×.

Limonite Pseudomorphs after Hornblende. Many of the acicular crystals and crystal groups of hornblende are completely, or at least partially, altered to limonite. Limonite is a general term used for hydrous ferric iron oxides such as goethite. Alteration products composed of limonite have a rusty brownish to yellow color with an earthy appearance. During the alteration process, some of the hornblende crystals became quite cavernous on their terminations. An excellent example of partial pseudomorphic replacement of hornblende by limonite is shown in figure 8. The cen-

Figure 13. Goethite inclusion in Mexican opal. Magnified 50×.

tral core of this crystal is still fresh black hornblende, while the outside has completely altered to limonite. Notice, too, that in the pseudomorph example, the external morphology of the original hornblende remains intact.

Goethite. Another inclusion observed and studied was a columnar mass of an earthy, red-brown color showing a circular cross section and a concentric radial structure (figure 13). A tentative visual identification of this and many similar inclusions suggested that the material was goethite, FeO(OH), a common alteration product of iron-bearing minerals such as hematite, pyrite, and hornblende.

As with the hornblende, X-ray diffraction proved the visual identification to be correct: the inclusion is indeed goethite.

Hematite. Intermixed and closely associated with goethite in Mexican opals is hematite. Close microscopic examination of goethite-containing areas in the opals will often reveal small amounts of a metallic-to-submetallic black material. An X-ray diffraction pattern (done for this study) showed that the black material is hematite. Scraping similar sections that reach the surface of the opals gives the characteristic browish red streak of hematite. Occasionally, single, tabular, somewhat distorted crystals are seen.

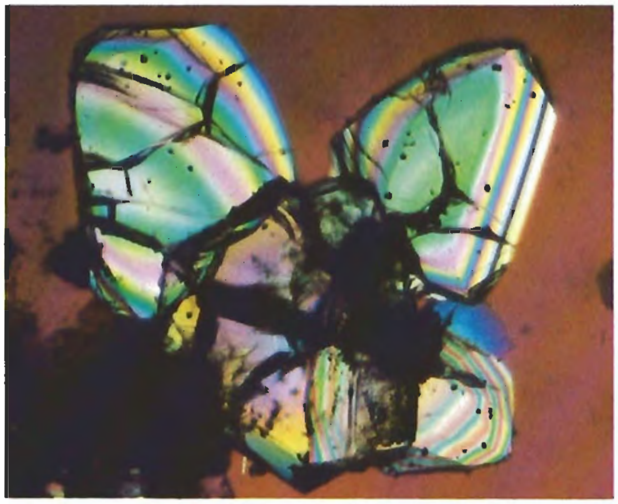

Figure 14. Euhedral prismatic crystals terminated by rhombohedral faces. Testing proved these inclusions to be quartz. Polarized light. Magnified 50×.

Fluorite. A few very small, transparent, near-colorless cubes with octahedrally modified corners were noticed by the authors. Polarized pinpoint illumination showed no evidence of double refraction. The cubes were in direct association with hematite. Two of the cubes are perched on the edge of a single tabular hematite crystal. As this opal is in a private collection, no further testing could be carried out. However, the habit, transparency, and single refraction of these inclusions strongly suggest fluorite.

Quartz. A small, tumble-polished sample of almost-colorless Mexican opal contained numerous small, essentially colorless, euhedral prismatic crystals apparently terminated by rhombohedral faces. Under polarized light with a first-order red compensator, the inclusions, as illustrated in figure 14, stood out vividly as doubly refractive solids in the singly refractive host opal. A Becke line test showed that the refractive index of the inclusions was higher than that of the opal. In transmitted light, little relief could be seen between the opal and the inclusions, suggesting that the R.I. of the inclusions was relatively close to that of the opal; but the double refraction of the in-

Figure 15. Cristobalite inclusion in Mexican opal. Magnified 110×.

clusions, their crystal habit, and their low relief suggested quartz. By grinding and polishing the specimen, we exposed one of the larger crystals. A stainless steel probe was used to extricate the crystal from the opal, and the crystal was then crushed. During crushing, no cleavage was observed. The randomly oriented fragments were then placed on a glass slide, and a small drop of clove oil, with a refractive index of approximately 1.53, was placed over the fragments which were then spread out in a thin layer. The tiny fragments of the inclusion virtually disappeared in the clove oil.

The Becke line test and the very low relief proved that the inclusion fragments were only slightly higher in refractive index than the clove oil. Under polarized light, the fragments again became readily visible. Using a tiny condensing lens, we checked the randomly oriented fragments for optic figures. One of the fragments displayed a uniaxial "bull's-eye" optic figure that positively identified the inclusion as quartz.

Cristobalite. Two opals—one a bright transparent orange and the other a near-colorless transparent specimen with attached rhyolite matrix—were found to contain translucent white crystal formations such as the one illustrated in figure 15. Since the largest of the inclusions was in the orange sample, we decided to sacrifice this specimen. The same microscopic method of study employed on the quartz was used.

Figure 16. X-ray diffraction analysis indicated that the dull, whitish, earthy masses illustrated here in association with an orangy brown prismatic crystal were kaolinite, a clay mineral. Magnified 40×.

The intricate shape and platy nature of the inclusion eliminated the possiblity of dislodging it from the opal host. A tiny cube containing the inclusion was cut from the opal and ground down on a diamond lap until it was about 2 mm in longest dimension. The sample was then crushed and placed on a glass slide. With a polarizing microscope, the inclusion fragments, which proved to be doubly refractive, were easily separated from the singly refractive opal matrix. A drop of clove oil (again, R.I. of 1.53) was then placed over a few isolated inclusion fragments, and a Becke line test showed that the inclusion had a lower index of refraction than the clove oil.

Next, a tiny drop of tetrachlorethane was placed over several of the inclusion fragments. The Becke line test showed that the inclusion fragments were very close to the refractive index, 1.48, of tetrachlorethane.

Cristobalite has refractive indices of 1.484–1.487 and is a known associate of opal in volcanic rocks such as rhyolite and trachyte.

Kaolinite. Dull, earthy masses and cloud-like globs of a white to yellowish-brown to brown material were noted on the surfaces of, and included in, several of the Mexican opals used in this study. These masses and globs could be found clinging to included crystals, as in figure 16, or in direct contact with the matrix rock in the opals that contained matrix material. These masses showed no distinctive microscopically recognizable features.

The authors, therefore, depended entirely on X-ray diffraction for possible identification of these inclusions. Study of the X-ray diffraction pattern, obtained by scraping some of the whitish material from the surface of one of the opals, revealed that it was most probably kaolinite, a clay mineral.

Pyrite. Only one sample of Mexican opal was observed by the authors to contain very tiny, brassy-yellow, opaque modified cubes and what appeared to be pyritohedrons of pyrite. As the opal embracing the pyrite(?) crystals was in a private collection and could not be fully tested, this identification of pyrite in opal is only tentative.

CONCLUSION

The opal mines of Querétaro, Mexico, have been an important source of this unique gem material for over 100 years. The opal occurs in rhyolitic lava flows and is, for the most part, mined by hand just as it was in the 19th century. Even though the mining methods remain primitive, production is at an all-time high and the future in the world market appears bright.

The inclusions found in opals from this locality reflect their volcanic provenance. This study has conclusively identified five different mineral species and tentatively identified four more, none of which was previously recorded in the literature as an inclusion in opal. Rutile, commonly noted as an acicular inclusion in Mexican opal, was not encountered in this study. In all probability, the hornblende noted here was previously misidentified as rutile. In addition, a three-phase inclusion, a two-phase inclusion, flow structures, and multiple cycles of growth have also been described and their origins suggested.

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