LEOPARD OPAL: PLAY-OF-COLOR OPAL IN VESICULAR BASALT FROM ZIMAPÁN, HIDALGO STATE, MEXICO

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"Leopard opal" consists of vesicular basalt impregnated with play-of-color opal, and is known only from Zimapán, Hidalgo State, Mexico. The formation of this ornamental stone was made possible by an abundance of silica derived from the chemical breakdown of overlying volcanic ash layers, the permeability of the underlying basalt, and the presence of pores in the basalt of an aesthetically pleasing size. The even distribution and small size of the opal-filled vesicles makes the rock attractive when cut or carved and polished. Veinlets and irregular masses of play-of-color opal showing various bodycolors (red, white, and colorless to pale blue) have also been deposited along joints and fractures within the basalt flow. This opal deposit, which may have been worked in pre-Columbian times, has been explored only by a number of small test pits in recent years, and significant potential remains for its future development.

One of the authors (ARZ) spent much of his youth as a *gambusino*, or prospector, exploring remote areas of the Mexican countryside on horseback. In 1965, while investigating some bushes where a fox was hiding, he noticed flashes of color in a lump of vesicular basalt that proved to contain opal. Further prospecting led to the discovery of the deposit itself higher on the hillside. However, it is possible he had only *re*discovered it, as an old shallow trench suggested that the deposit could have been worked for opal much earlier, perhaps by pre-Columbian inhabitants of the region. (There are no records of opal having been found in this area by the Spaniards, nor are the authors aware of any recent opal mining other than that of ARZ.) Shortly thereafter (in 1965), ARZ staked the mining claims that are known today as Gemma and Desiré.

Because of the striking spotted appearance of the opal against its black basaltic host, this unique material became known as "Leopard opal." Word spread, and soon the material attracted the attention of an American, Foster Conton, who visited the prospect and returned to the U.S. with a 6 kg sample given to him by ARZ. He gave the specimen to Albert Eugene Upton, who after months of research and study decided to have the stone carved into an art piece that would have historical significance for Mexico: a likeness of Cuauhtémoc, the last emperor of the Aztecs (figure 1). Artisan Rafael Tapia of Taxco, Mexico, was commissioned to undertake the carving, which took seven months to complete and had a final weight of 3.375 kg. The silver headdress and mounting were made by Alejandro Gómez. The complete statue stands approximately 48 cm high and weighs a total of 8.2 kg (E. Littig, pers. comm., 1999). Photos of this carving were published in *Lapidary Journal* (Leipner, 1969), which also advertised rough and cabochon-cut pieces of "black matrix opal" from this deposit. In 1970, Mr. Upton donated the carving to Sacred Heart College (now Newman University), in Wichita, Kansas. Apart from some samples cut and polished locally in Mexico or by foreign lapidaries over the years (e.g., figure 2), and an

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See end of article for About the Authors and Acknowledgments.

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Figure 1. Leopard opal, vesicular basalt impregnated with play-of-color opal, can be polished into cabochons for use in jewelry or employed as a carving material. This bust (3.375 kg) shows the likeness of Cuauhtémoc, the last emperor of the Aztecs. The carving is by Rafael Tapia, and the silver work is by Alejandro Gómez; it is part of the Newman University collection in Wichita, Kansas. Photo by Charles Rasico, courtesy of Newman University.

appearance of the material at the 1996 Tucson gem shows (Johnson and Koivula, 1996), there has been little public exposure of Leopard opal, and the deposit has lain in relative obscurity for the last several years.

This is the only known opal deposit in the Zimapán area. The historical significance and geologic setting of the site, as well as the small-scale mining activities carried on there, have not been described previously in the literature. To date it has been explored only by a number of small test pits, but the authors believe significant potential remains for its future development.

A History of Mexican Opal. Long before its rediscovery in modern times, opal was mined and appreciated as a gem material by the pre-Columbian

Figure 2. This pre-classical-style jaguar head (44.76 × 42.45 × 11.30 mm) carved from Leopard opal was fashioned by Kevin Lane Smith of Tucson, Arizona. Photo by Maha Calderon.

peoples of Mexico and Central America. There are two terms in Nahuatl, the Aztec language, that are used to describe opal: *quetza litzle pyolitli*, meaning "stone which changes color in movement" (or "bird of paradise stone") and *huitzitziltecpatl*, "stone like a bird of a thousand colors" (or "hummingbird stone"). Some of these Mexican opals were taken to Europe and the present United States by the Spaniards in the early 16th century (White, 1998). The Spanish monarchy, however, had more of an interest in finding Mexican gold, and opal is not mentioned on the invoices of precious objects sent by the Spanish *conquistador* Hernán Cortés to Charles V of Spain during this period (Leechman, 1961).

Eventually, many of the pre-Columbian opal mines were closed and their locations lost. It is interesting to note that Zimapán is indicated as the source of many old opal specimens in museums around the world (see, e.g., Leechman, 1961; Heylmun, 1984b). One such example is a ring containing a "fire opal of Zimapán" (Ball, 1931) worn by Antonio Eusebio de Cubero in a 17th century portrait by Diego Velázquez.

In the mid-1800s, the opal deposits in the state of Querétaro were rediscovered (see, e.g., Koivula et al., 1983). Numerous small open-cut mines began operating in the district (Heylmun, 1983a), and the capital, Querétaro City, became Mexico's most important cutting and polishing center (Webster,

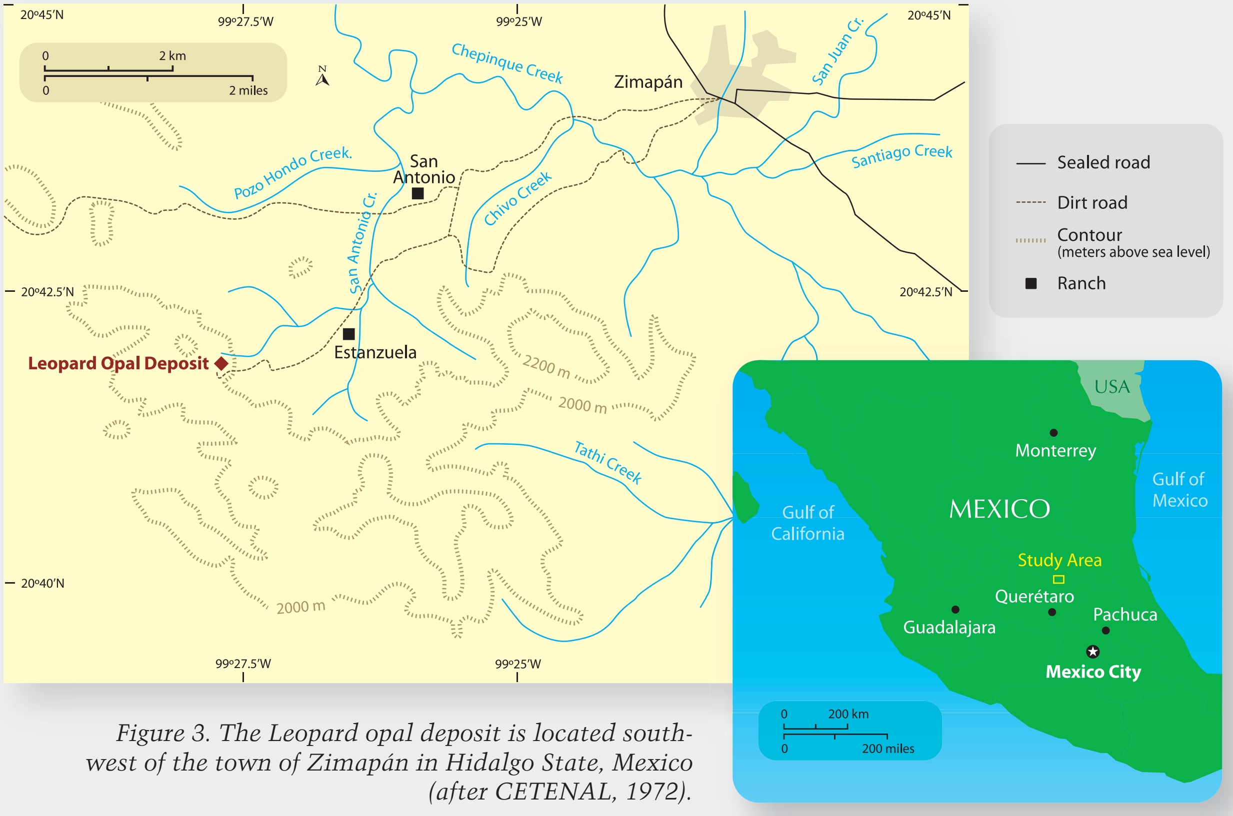


Figure 3. The Leopard opal deposit is located southwest of the town of Zimapán in Hidalgo State, Mexico (after CETENAL, 1972).

1983). The region has made Mexico famous for its fire opal, an orange-red (fiery) opal that often displays play-of-color. Most Mexican fire opal is open-pit mined from hard pink-to-red Cenozoic rhyolite using labor-intensive hand methods (see, e.g., Mallory, 1969a,b; Zeitner, 1979).

In the last 150 years, opal has been found throughout Mexico's Central Volcanic Belt (Heylmun, 1984a) in the states of Querétaro, Hidalgo, Guanajuato, San Luis Potosí, Guerrero, Michoacán, Jalisco, and Nayarit. Detailed locality maps and descriptions of the mines were published in a series of articles by Heylmun (1983a,b,c). The wide variety of opal types found in Mexico and their local nomenclature are described by Heylmun (1984a).

Other Mexican opals, in addition to fire opals, show play-of-color, and some of these are legendary among early Mexican production. The Aztec Sun God opal, a 36 × 34 × 15 mm, 94.78 ct stone, is believed to originate from Mexico; it has a transparent pale blue bodycolor and displays blue, green, yellow, and red play-of-color (White, 1998). This opal is carved into an image of the sun with a human face. Another notable opal, *El Águila Azteca* (The Aztec Eagle), was discovered in an excavation in Mexico City around 1863 and is believed to have been part of the treasures of the Aztec ruler Moctezuma II (1502–1520). This 32 ct eagle's head was said to "exhibit an infinite series of prismatic colors from a pale lavender to deep ruby red" (White, 1998, p. 46); its present whereabouts are unknown.

LOCATION

The Leopard opal deposit is located 14 km southwest of the town of Zimapán in Hidalgo State at 20°41.8′ N, 99°27.7′ W (figure 3). The site is not open to the public, and permission to visit must be obtained from the second author (ARZ). The mine is accessed by a rough dirt track that winds its way to the base of *La Piedra Grande* (The Big Rock, or *Tandhé* in the local Otomhé language), a peak that forms part of a NW-SE trending range. The last kilometer of the track must be negotiated using a 4-wheel drive vehicle or on foot. The mine is located at an elevation of about 2000 m, at a break in slope caused by a change in rock type (figures 4 and 5). A number of small pits and trenches that have produced opal-bearing material may be seen here lying in a trend that follows the geologic contact (figure 6).

Figure 4. The Leopard opal workings are located at 2000 m on a ridge that projects eastward from the side of the peak known as La Piedra Grande *or* Tandhé *(right, background). The workings (yellow arrow) are located along the contact between the softer white tuffs and breccias above and the harder dark vesicular basalts below. The road leading to the mine can be seen as a light line on the darker unit. Photo by R. Coenraads.*

GEOLOGIC SETTING

The geology of the region around Zimapán was described by Carrillo and Suter (1982). The opal deposit is hosted by a sequence of undifferentiated Tertiary-Quaternary age volcanic rocks. On the northeastern slopes of the range (again, see figures 4 and 5), the lower portion of the sequence consists of intercalated lava flows, the most dominant being a massive red-brown quartz porphyry that is clearly visible in the field as a cliff-forming unit. Above these lava flows, and extending to the top of the range, is a series of light-colored units ranging from fine ash-fall tuffs and breccias to layers of pyroclastic blocks (solid rocks blown out of an erupting volcano) up to 50 cm across. The entire volcanic sequence has been tilted about 20° southwest and has been offset locally by faulting.

At the mine site, a discontinuous unit of vesicular basalt is found along the contact between the lava flows and overlying pyroclastic layers (again, see figure 5). Vesicular basalt forms when water vapor and gases such as carbon dioxide cannot escape quickly enough from the cooling lava, thus leaving open cavities, or vesicles. The basalt erupted as a lava flow that probably filled a small valley. The vesicles are typically stretched into cylindrical shapes, formed as the hardening (but still plastic) lava continued to flow downhill. There are more

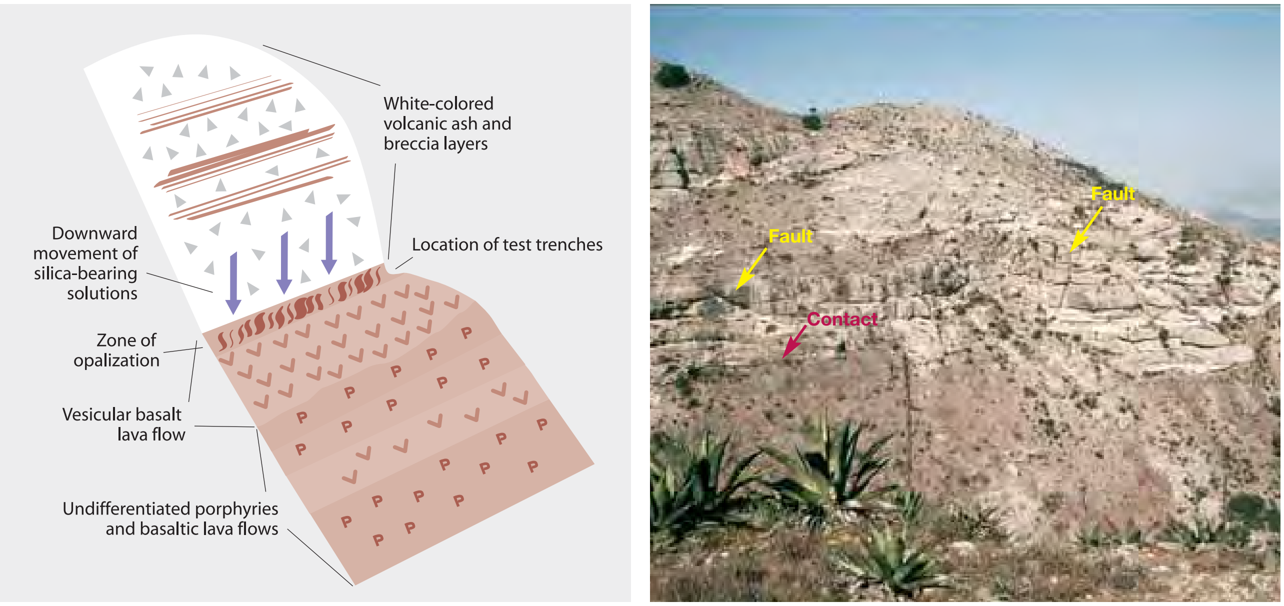


Figure 5. The zone of opalization occurs within the top few meters of a vesicular basalt that is overlain by ash and breccia layers, as seen in the cross-section on the left. The entire sequence dips about 20° southwest. In the photo on the right, looking across the valley to the north of the exploration area, the contact between the well-bedded, whitish volcanic tuffs and breccias, and the underlying darker, featureless basalts is clearly visible. The bedding and the contact are folded and displaced by faulting (visible as diagonal lines). Photo by R. Coenraads.

gas bubbles toward the top of the lava flow because the gases that slowly rose through the still-molten interior remained trapped below the hardened upper skin. Here, the vesicles are sufficiently numerous that the rock has become quite porous and permeable to groundwater. The basalt was, in turn, overlain by ash-fall tuff and breccia units deposited during a series of explosive volcanic eruptions. The ash-fall units are also very porous, and the feldspar and silica glass–rich portions have largely weathered to clay. The presence of abundant cryptocrystalline silica films coating the surfaces of faults and fractures in the lower units suggests that the reaction associated with this weathering process liberated significant quantities of silica, which migrated downward and precipitated into any available open space.

The elongated vesicles or gas cavities in the basalt are filled with transparent colorless opal to semi-opaque opal of various bodycolors ranging from white to pink or pale blue. In some hand specimens, the different bodycolors appear to run in parallel bands or patches (figure 7). The opal displays play-of-color ranging from red to violet.

Together with the vesicle-filling opal, two distinct generations of play-of-color opal are also found filling fractures in the basalt. These are a translucent reddish orange opal (figure 8) typical of the fire opal for which Mexico is renowned, and a colorless, transparent to pale blue translucent variety similar to the opal found in the basalt vesicles.

EXPLORATION AND MINING

Since 1965, occasional activities by one of the authors (ARZ) and his family have left several small shallow exploration and mining pits spread out along the geologic contact for a distance of several hundred meters. The section of the old trench found by ARZ, and thought by the authors to be pre-Columbian workings (again, see figure 6, right), also follows the contact. The excavations by ARZ show that opal has permeated the top of the basalt flow, but with a patchy and discontinuous distribution parallel to the contact. Exposures in the pit shown in figure 6, left, reveal that the concentration of opal in vesicles and along fractures is highest at the upper surface of the basalt, which is in direct contact with the overlying tuffs. The concentration of opal falls off rapidly within several meters. At greater distances from the contact, the basalt vesicles are empty. Approximately 1,500 kg of Leopard opal have been removed from these excavations using simple hand-mining techniques, and almost all of this production has been sold in the U.S. The 6 kg piece used for the Cuauhtémoc carving (again, see figure 1) is the largest found to date. Most pieces recovered weigh less than 1 kg.

Figure 6. At left, one of a series of mining pits and trenches is located along the contact between the white tuffs and the vesicular basalt. The top of the black basalt lava flow has been exposed, with the hollows and depressions of its surface still filled by white tuff. The opal is concentrated in the vesicles and fractures in the top of this basalt flow. In the photo on the right, the surface expression of the contact between the white tuff (left) and the darker basalt (right) is clearly visible, and a shallow depression can be seen running along the contact. This trench may represent pre-Columbian workings of this opal deposit, as the types of opal recovered here are consistent with those used in pre-Columbian pieces. Photos by R. Coenraads.

The fire opal and pale blue opal is found in thin veins (again, see figure 8) crisscrossing the deposit. The veins thicken in places up to about 2 cm, but the opal tends to fragment into small pieces when dug out. Most is milky and sun-damaged, but it recovers its original appearance and play-of-color when wet. To date, there has been no exploration for this vein opal at depth, where unweathered material may exist. It is possible that this was the type of opal being sought in the pre-Columbian workings, as it closely matches descriptions of the above-mentioned historic pieces, and it is the only known locality of such material in the Zimapán area.

More extensive exploration and deeper mining of the geologic contact in the vicinity of the earlier workings could yield good quantities of opal. The geologic contact also needs to be followed along strike, beyond the known area of opal occurrence, where it may have the potential to produce similar opal-bearing material on adjacent hillsides.

Figure 7. This sample of vesicular basalt (15 cm) was collected near the contact of the lava flow and overlying tuffs and breccias. Most of the vesicles in this sample are filled with transparent-to-translucent opal, and a distinct zonation in opal bodycolor is visible. Photo by R. Coenraads.

Figure 8. Translucent opal displaying an orange-red bodycolor (fire opal) fills cracks and fractures in the vesicular basalt near the contact. The opal appears to have deposited at the narrowing ends of fractures; some of it shows play-of-color. A Mexican coin (2.5 cm) is provided for scale. Photo by R. Coenraads.

Figure 9. Samples of opal from Zimapán used for this study include a 205 ct polished sample (top), a 100 ct polished sample (center), and a 6.87 ct cabochon (center left) of Leopard opal; 9 g of fire opal (bottom right); and 5 g of colorless to pale blue opal (bottom left). Photo by R. Coenraads.

MATERIALS AND METHODS

About 2 kg of Leopard opal and chips of opal from the veins were collected by the authors for study. The material, shown in figure 9, includes 9 g of reddish orange fire opal, 5 g of colorless to pale blue opal, and a 6.87 ct cabochon from the personal collection of ARZ. Prior to gemological testing, flat faces were polished on several of the vein opal chips, and two pieces of the rough Leopard opal were ground smooth and polished on one side, yielding final weights of 205 ct and 100 ct. These two Leopard opal samples were prepared according to the guidelines recommended for this porous material (Leipner, 1969). The material was soaked in water prior to slabbing, sawn using a water-soluble mixture (i.e., not oil), and was polished with darker polishes rather than light-colored polishes that are difficult to remove from the pores. Excessive wheel speed and pressure were avoided, as these can generate heat that might damage the opal. The 6.87 ct cabochon showed minor undercutting of the opal spots, since opal, with a Mohs hardness of slightly less than 6, is softer than the feldspar of the basalt matrix, which has a hardness of 6–6.5. Specimens with a more careful sample preparation showed no variation in surface relief.

All samples were examined with a 45× binocular microscope and viewed in a darkened room with a Raytech short- and long-wave UV lamp. Spot refractive index (R.I.) readings were conducted using a Topcon refractometer, and specific gravity (S.G.) was determined for opal pieces without matrix using an Oertling R42 hydrostatic balance. A standard thin section (0.03 mm) of the Leopard opal was cut at New South Wales University in Sydney for study with a polarizing petrologic microscope.

Small pieces of fire opal and colorless "crystal" opal from veins within the Leopard opal deposit, both exhibiting good play-of-color, were crushed for X-ray diffraction (XRD) analysis at the Australian Museum laboratory in Sydney, and the results were compared to standard scans by Diffraction Technology, Canberra, Australia. Other samples from the veins were etched in hydrofluoric acid vapor for times varying between 90 seconds and several minutes to reveal their internal structure, gold coated, and then imaged using the scanning electron microscope (SEM) at the University of Technology, Sydney.

RESULTS

In hand specimens, the black basalt takes a high polish, thereby providing a good background for the "leopard spots" of play-of-color opal. The loupe and binocular microscope provide conclusive identification of the material. In figure 10, the 205 ct sample shows a distinct elongation and orientation of its opal-filled vesicles, and also a marked opal bodycolor zonation from blue to white, similar to that visible in some of the rough hand specimens (again, see figure 7). Figure 11 shows several views of the vesicles of the 100 ct sample; these are filled with transparent opal displaying play-of-color domains that are continuous over several vesicles. Detailed examination (figure 11, center) revealed that the vesicles are highly irregular in shape. Although some have remained empty (see the bottom right corner of the photo), most appear connected to one another by channels along which the silica-bearing fluids could migrate. The inside walls of the vesicles are white, which suggests that a thin coating of another mineral was deposited before the vesicles were filled with opal (again, see figure 11). At higher magnification (figure 11, right), long thin colorless feldspar crystals are visible in the dark basalt matrix.

The thin section (figure 12) revealed that the basalt in this specimen is unweathered and consists of abundant microscopic (0.1–0.2 mm) euhedral

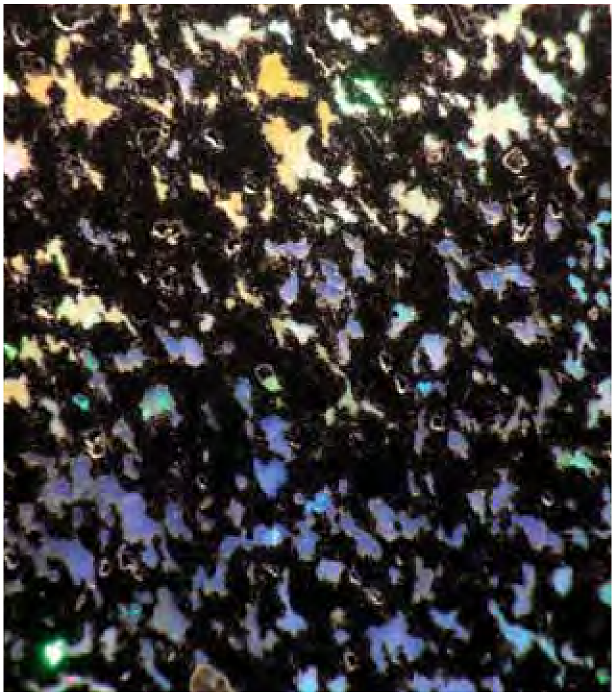
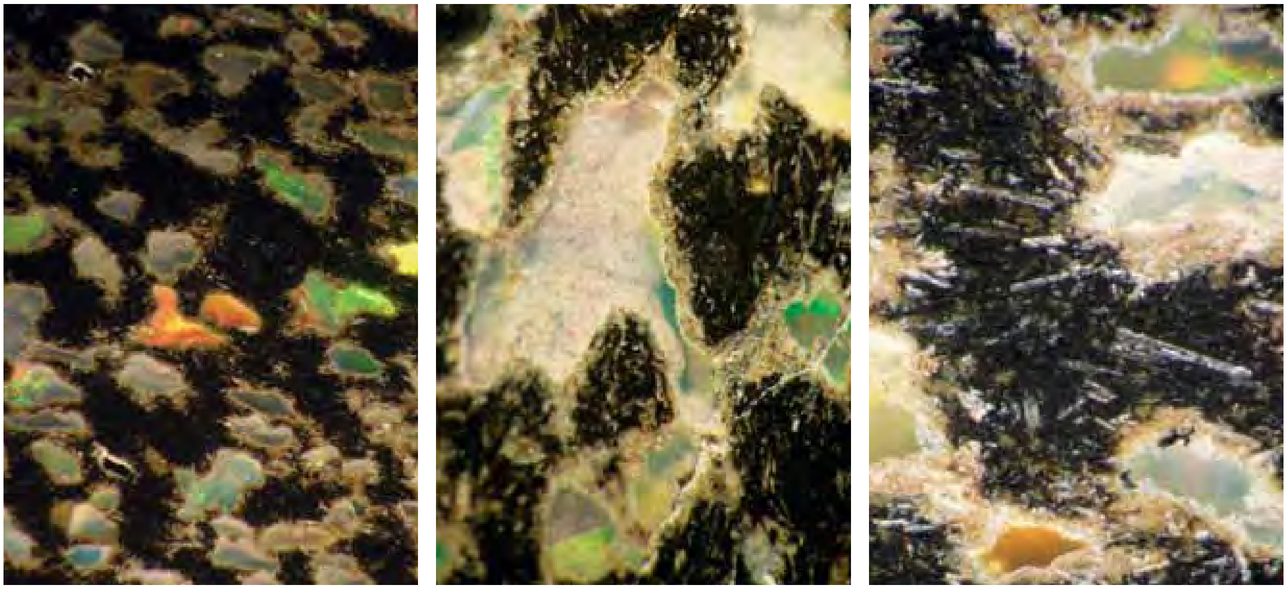


Figure 10. This detail from the 205 ct polished sample in figure 9 displays oriented (bottom right to top left) irregularly shaped vesicles filled with opal that varies in bodycolor from blue (bottom) to yellow, pink, and white (top). Photo by Graham Henry; field of view is 18 mm high.

Figure 11. In this series of photomicrographs, the 100 ct polished sample in figure 9 also shows oriented vesicles filled with colorless opal displaying play-of-color. A domain displaying red play-of-color continues over two vesicles (left). At higher magnification (center), this sample shows an irregular-shaped vesicle that illustrates the interconnected channelways through which the silica-bearing fluids originally migrated. At right, the basalt host reveals numerous elongated transparent feldspar crystals oriented parallel to the direction of elongation of the vesicles. These would have been parallel to the original flow. Photomicrographs by Graham Henry; height of field of view is 11 mm (left), 4 mm (center), 3 mm (right).



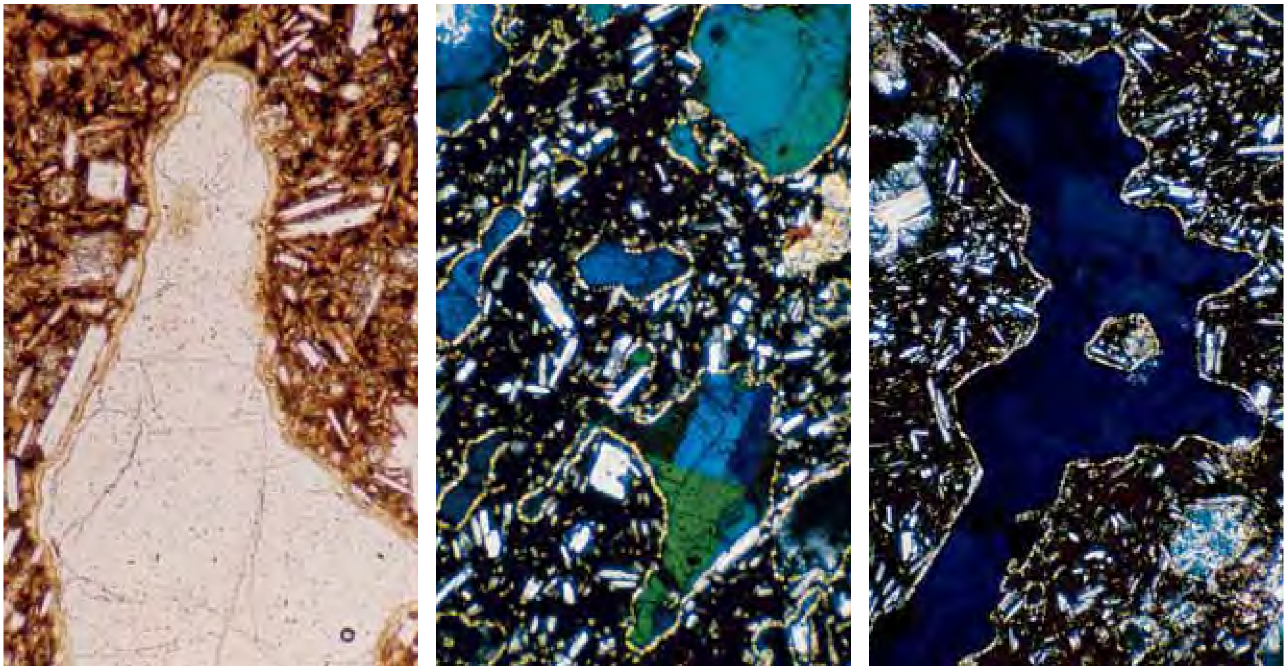


Figure 12. This thin section shows details of the opal-filled vesicular cavities within the basalt. At left, in plane-polarized (normal) light, the opal in the cavities appears colorless. A thin yellowish line (appearing white in hand specimens) is visible around the opal in each cavity. This unknown fibrous mineral lined the inside of the vesicles prior to deposition of the opal. The basalt is comprised of abundant well-formed rectangular crystals of white feldspar together with minor opaque minerals (black grains) in a brown glassy groundmass. At center, the thin section of Leopard opal is viewed between crossed polarizers. The elongated feldspar crystals show a preferred orientation approximately parallel to the lava flow direction, and the opal displays blue and green diffraction colors. In some cases, the opal diffraction color is consistent across several vesicles, while in others several opal domain boundaries lie within a single cavity. At right, the homogenous blue color indicates that the opal precipitated as a single domain of ordered spheres across the large irregularly shaped vesicle. Photomicrographs by R. Coenraads; height of field of view is 0.9 mm (left), 2.2 mm (center and right).

feldspar crystals; these are oriented more-or-less parallel to the direction of the original lava flow (figure 12, center). The vesicles vary in size up to ~1–3 mm, and are also elongated in the direction of flow (again, see figure 12, center). When viewed between crossed polarizers, some of the opal in the vesicles remained dark upon rotation through 360°, as would be expected from an amorphous material, while some displayed diffraction colors (figure 12, center and right). Such colors are typical in thin sections of opal showing play-of-color (R. Flossman, pers. comm., 1999) because of the pseudo-crystalline nature of the material caused by the regular arrangement of its silica spheres. Consistent colors are often visible over several adjacent vesicles, indicating that the orderly deposition and arrangement of silica spheres proceeded unimpeded within the framework of the host basalt.

Viewing Leopard opal with UV radiation highlights the inhomogeneous nature of the material. The basalt matrix is inert to UV, while the opal stands out as bluish white spots (stronger under long-wave than short-wave UV) against the black background (figure 13).

Determinations of S.G. and R.I. are not meaningful for Leopard opal, since they will invariably reflect a mixture of basalt, opal, and porosity (for example, the 6.87 ct cabochon showed a 4% weight gain when left in water overnight). The S.G. range of small pieces of opal without matrix was 2.05–2.15. A spot R.I. of ~1.46 was obtained from pieces of opal with polished faces, which is consistent with prior tests (Johnson and Koivula, 1996).

The XRD scans for the reddish orange and colorless opal showed them both to be opal-CT, that is, having a disordered cristobalite-like structure with varying degrees of tridymite stacking (Elzea and Rice, 1996).

Etching of the opal for SEM imaging proved to be more difficult than expected, implying that etch rates for both the spheres and their matrix are more uniform than those seen in most other opal. We were

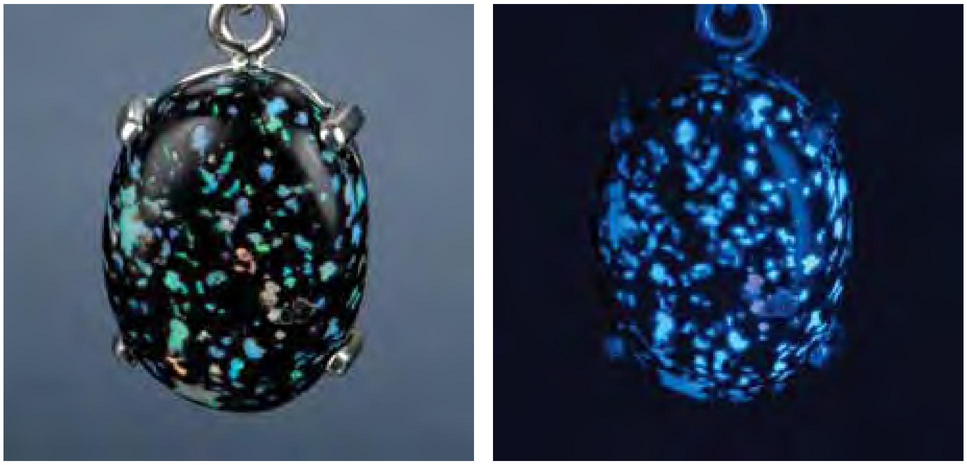


Figure 13. When this 6.87 ct cabochon (left, under normal lighting) is exposed to long-wave UV radiation (right), the basalt matrix is inert, while the opal stands out as bluish white spots (stronger under long-wave than short-wave UV) against the black background. Photos by Robert Weldon.

therefore unable to use the SEM to discern the internal structure responsible for the opal's play-of color.

DISCUSSION

Opal-CT is typical of volcanic opal from Mexico (Smallwood, 2000; Fritsch et al., 2002), and this identification indicates that the Zimapán opal formed at reasonably low temperatures, probably between 100°C (Elzea et al., 1994) and 190°C (Rondeau et al., 2004). According to Elzea et al. (1994), it may have precipitated originally at even lower temperatures (~45°C; Rondeau et al., 2004) as opal-A (i.e., with an amorphous pattern) from silica-rich solutions due to water interacting with silica-rich volcanic ash and tuff, and then converted to opal-CT during heating associated with regional tectonic uplift. There appear to have been at least two phases of opal deposition, as indicated by the presence of opal of two distinct bodycolors in the veins. As the orange-red bodycolor of fire opal is caused by iron-rich nanoinclusions (Fritsch et al., 2002), some of the silica-bearing fluids undoubtedly were iron-bearing.

The simultaneous occurrence of a number of factors, all critical to the formation of opal showing play-of-color in a vesicular basalt, highlights the rarity of this Mexican Leopard opal and the low likelihood of finding a similar deposit elsewhere:

1. **Availability of silica.** It is reasonable to assume that the silica-bearing solutions responsible for the deposition of the opal in the vesicles and fractures within the basalt flows percolated downward from the immediately overlying felsic tuffs and breccias.
2. **Permeability of the vesicular basalt and porosity with an advantageous size.** Permeability is essential for the silica-bearing solutions to penetrate the basalt and reach most of the open spaces. The size of the vesicles is also important, since the abundant, but small, vesicles and their uniform distribution, are necessary for an appealing product. Fractures in the basalt have allowed accumulations of pale blue opal and fire opal that are also of interest.
3. **Environmental factors.** These would have favored the formation of opal instead of cryptocrystalline silica, and also favored formation of play-of-color opal over common opal (potch). The silica-bearing waters would need to be introduced over a sufficiently long period of time and at relatively low temperatures to lead to the precipitation of opal-CT (Elzea et al., 1994). We can assume that the deposit has not been subject to a significant heating event, which would have led to recrystallization of the opal into a more common cryptocrystalline silica product.

CONCLUSION

Significant potential for Leopard opal exists within the upper portion (top few meters) of the vesicular basalt flow, adjacent to the contact with the overlying tuffs and breccias. There is also potential for the recovery of play-of-color opal and fire opal from cracks and fractures in the upper surface of the basalt. Apart from the shallow trenches that may represent pre-Columbian workings and the small exploration pits opened up by one of the authors (ARZ), the Zimapán deposit of Leopard opal has not been developed and few in the gemological community are aware of the potential of this material. At least several hundred meters of contact exposed on the hillside remain unexplored.

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REFERENCES

Ball S.H. (1931) Historical notes on gem mining. *Economic Geology*, Vol. 26, No. 7, pp. 681–738.

Carrillo-Martínez M., Suter M. (1982) Tectónica de los alrededores de Zimapán, Hidalgo y Querétaro [Tectonics around Zimapán, Hidalgo, and Querétaro]. In M. Alcayde and Z. De Cserna, Eds., *Libro Guía de la Excursión Geológica a la Región de Zimapán y Áreas Circundantes, Estados de Hidalgo y Querétaro [Guidebook of the Geologic Excursion to the Zimapán region and Surrounding Areas, Hidalgo and Querétaro States]*, Geological Society of Mexico, Sixth National Geologic Convention, Mexico City, pp. 1–20.

Comisión de Estudios del Territorio Nacional [CETENAL] (1972) Topographic map sheet, 1st ed., Tecozautla F-14-C-68 HGO.QRO, 1:50,000 scale, Mexico City.

Elzea J.M., Odom I.E., Miles W.J. (1994) Distinguishing well ordered opal-CT and opal-C from high temperature cristobalite by X-ray diffraction. *Analytica Chimica Acta*, Vol. 286, pp. 107–116.

Elzea J.M., Rice S.B. (1996) TEM and X-ray diffraction evidence for cristobalite and tridymite stacking sequences in opal. *Clays and Clay Minerals*, Vol. 44, No. 4, pp. 492–500.

Fritsch E., Ostrooumov M., Rondeau B., Barreau A., Albertini D., Marie A.-M., Lasnier B., Wery J. (2002) Mexican gem opals: Nano- and micro-structure, origin of color, comparison with other common opals of gemmological significance. *Australian Gemmologist*, Vol. 21, No. 6, pp. 230–233.

Heylmun E.B. (1983a) Map of the Queretaro opal mines, Mexico. *Lapidary Journal*, Vol. 37, No. 2, pp. 344–345.

Heylmun E.B. (1983b) Opal localities in west central Mexico. *Lapidary Journal*, Vol. 37, No. 4, pp. 598–602.

Heylmun E.B. (1983c) Four opal localities in Mexico. *Lapidary Journal*, Vol. 37, No. 6, pp. 880–882.

Heylmun E.B. (1984a) Varieties of Mexican opal. *Lapidary Journal*, Vol. 38, No. 5, pp. 746–747.

Heylmun E.B. (1984b) Zimapan opal: Are the mines lost? *Lapidary Journal*, Vol. 38, No. 6, p. 794.

Johnson M.L., Koivula J.I., Eds. (1996) Gem News: "Leopard opal" from Mexico. *Gems & Gemology*, Vol. 32, No. 1, pp. 54–55.

Koivula J.I., Fryer C., Keller P.C. (1983) Opal from Querétaro, Mexico: Occurrence and inclusions. *Gems & Gemology*, Vol. 19, No. 2, pp. 87–96.

Leechman F. (1961) *The Opal Book*. Lansdowne Press, Sydney.

Leipner H.N., Ed. (1969) About our cover: Cuauhtemoc, last Aztec Emperor. *Lapidary Journal*, Vol. 23, No. 2, pp. 299, 340.

Mallory L.D. (1969a) Opal mining in western Mexico, part 1. *Lapidary Journal*, Vol. 23, No. 3, pp. 420–428.

Mallory L.D. (1969b) Opal mining in western Mexico, part 2. *Lapidary Journal*, Vol. 23, No. 4, pp. 570–579.

Rondeau B., Fritsch E., Guiraud M., Renac C. (2004) Opals from Slovakia ("Hungarian" opals): A re-assessment of the conditions of formation. *European Journal of Mineralogy*, Vol. 16, No. 5, pp. 789–799.

Smallwood A. (2000) A preliminary investigation of precious opal by laser Raman spectroscopy. *Australian Gemmologist*, Vol. 20, No. 9, pp. 363–366.

Webster R. (1983) Opal from Mexico. In *Gems, Their Sources, Description and Identification*, revised by B.W. Anderson, 4th ed., Butterworth, London, p. 234.

White J.S. (1998) Hope's wonderful opal. *Lapidary Journal*, Vol. 52, No. 5, pp. 44–46, 59.

Zeitner J.C. (1979) The opal of Queretaro. *Lapidary Journal*, Vol. 33, No. 4, pp. 868–880.


CHARACTERISTICS OF HPHT-GROWN SYNTHETIC DIAMONDS
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SPECIFIC FEATURES


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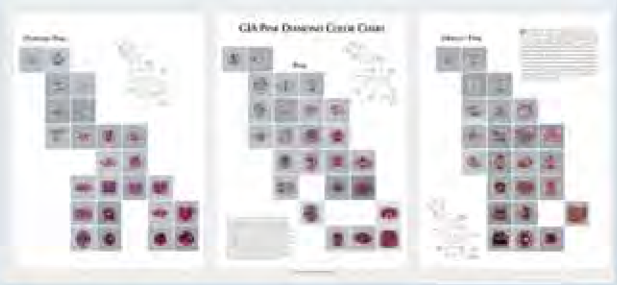
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