PLAY-OF-COLOR OPAL FROM WEGEL TENA, WOLLO PROVINCE, ETHIOPIA

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A new opal deposit was discovered in 2008 near the village of Wegel Tena, in volcanic rocks of Ethiopia's Wollo Province. Unlike previous Ethiopian opals, the new material is mostly white, with some brown opal, fire opal, and colorless "crystal" opal. Some of it resembles Australian and Brazilian sedimentary opals, with play-of-color that is often very vivid. However, its properties are consistent with those of opal-CT and most volcanic opals. Inclusions consist of pyrite, barium-manganese oxides, and native carbon. Some samples show "digit patterns": interpenetrating play-of-color and common opal, resembling fingers. The opaque-to-translucent Wegel Tena opals become transparent when soaked in water, showing a remarkable hydrophane character. White opals from this deposit contain an elevated Ba content, which has not been reported so far in opal-CT. The fire and crystal opals are prone to breakage, while the white, opaque-to-translucent opals are remarkably durable. The proportion of gem-quality material in the Wegel Tena deposit seems unusually high, and 1,500 kg have already been extracted using rudimentary mining techniques. The deposit may extend over several kilometers and could become a major source of gem-quality opal.

In early 2008, a new source of play-of-color opal was discovered by farmers near Wegel Tena in northern Ethiopia (Fritsch and Rondeau, 2009; Mazzero et al., 2009; Rondeau et al., 2009). Since January 2009, the deposit has been worked by about 200 local miners. The opals are mostly white, which is uncommon for play-of-color volcanic opal, and may resemble material from Australia or Brazil (figure 1). Some fairly large pieces have been polished (figures 2 and 3). The Wegel Tena opals differ from those found at Mezezo, in Ethiopia's Shewa Province, or in neighboring Somalia, which are mostly orange to red to brown (e.g., Koivula et al., 1994; Gauthier et al., 2004, and references therein).

Two of the authors (FM and EB) traveled to the locality on several occasions. They gathered representative gem material, as well as surrounding rocks, and discussed the opal and its extraction with the miners to develop a better understanding of this promising new deposit.

LOCATION AND ACCESS

The opal mining area lies in Wollo Province (also spelled Wolo or Welo), ~550 km north of Addis Ababa and ~200 km north of the Mezezo opal deposit (figure 4). The locality has also been referred to as "Delanta," which corresponds to a former subdivision (or "awraja") of Wollo Province. The region containing the deposit is called Tsehay Mewcha, a large area that encompasses scattered farms and a small village, about 17 km northeast of the village

See end of article for About the Authors and Acknowledgments.
GEMS & GEMOLOGY, Vol. 46, No. 2, pp. 90–105.

Figure 1. Volcanic play-of-color opals mined at Wegel Tena, Ethiopia, are mostly white, translucent to opaque, and show vivid play-of-color. The round orange cabochon in the center weighs 41.70 ct, and the white cabochon to its right is 31.30 ct. Photo by F. Mazzero.

of Wegel Tena (figure 4). Tsehay Mewcha is situated on a plateau at an altitude of about 3,200 m. The opal occurs in a horizontal layer that is exposed on a cliff above a canyon tributary of the Blue Nile River. This layer is ~350 m below the top of the plateau (figure 5). Tsehay Mewcha is accessible with a four-wheel-drive vehicle, and the various mine workings are reached by walking down the steep canyon for 30 minutes to more than one hour. Hazardous conditions are created by cliffs in the digging areas, as well as by falling rocks due to mining activities (see www.opalinda.com for more information on access conditions).

GEOLOGY

The entire region around Wegel Tena consists of a thick (>3,000 m) volcano-sedimentary sequence of alternating layers of basalt and rhyolitic ignimbrite. The layers of basalt or ignimbrite are a few meters to hundreds of meters thick. (Ignimbrite is a volcanic rock of andesitic-to-rhyolitic composition that forms sedimentary-like layers after the volcanic plume collapses and falls to the ground. The particles that form this rock are a heterogeneous mixture of volcanic glass, crystals, ash, and xenoliths.) This volcanic sequence was emplaced with the opening of the East African continental rift during the Oligocene epoch (Cenozoic age), about 30 million years ago (Ayalew and Yirgu, 2003; Ayalew and Gibson, 2009).

Over the entire volcanic series, only one very thin seam (<1 m thick), hosted by ignimbrite, is mineralized with opal (again, see figure 5). Common opal and play-of-color opal most often cement grains of volcanic debris (figures 6 and 7) or sometimes fill in fractures or cavities in the rock. As a result, the rough gem material often has an irregular shape. Microscopic examination of our samples revealed that, for the most part, the host rock consists of mixed altered material, including clays,

Figure 2. Some of the large, fine white opal specimens from Wegel Tena display vivid play-of-color, such as the 20.95 ct oval and 14.87 ct round cabochons shown here. Photos by F. Mazzero (left) and Robert Weldon (right).

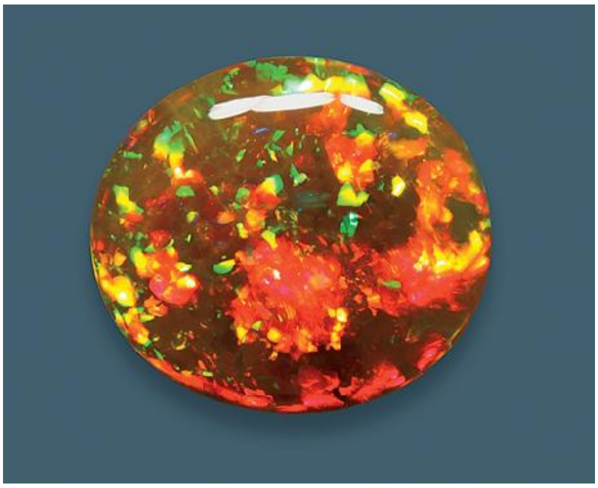


Figure 3. This 9.12 ct specimen, which measures 17 × 19 mm, is one of the few play-of-color fire opals that have been mined at Wegel Tena. Photo by F. Mazzero.

common opal, and some minor iron oxy-hydroxides. Some large crystals of alkali feldspar were unaltered, while others were transformed into clays. By comparison, the ignimbrite sampled only a few meters above the opal-bearing layer was unaltered and contained abundant quartz crystals.

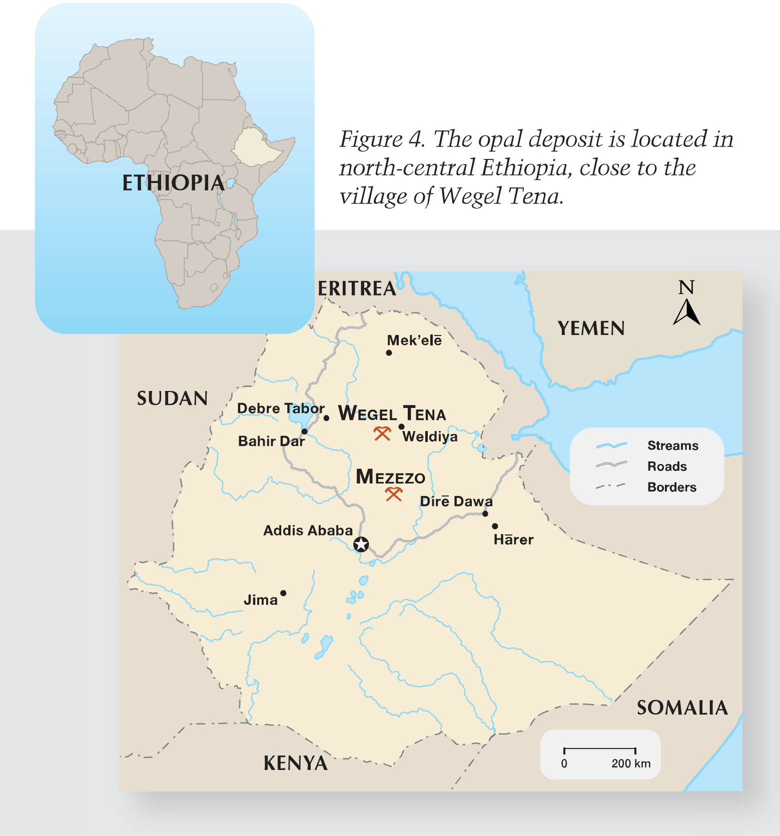


Figure 4. The opal deposit is located in north-central Ethiopia, close to the village of Wegel Tena.

MINING AND PRODUCTION

The opal is extracted by artisanal miners using homemade tools (figures 8 and 9), as well as picks, hammers, and shovels provided by the Ethiopian government. The mineralized layer extends for hundreds of meters along the flank of the canyon (again, see figures 5 and 8), but the excavations only penetrate 1–2 m into the mountain. Because the diggings are not supported by timbers or other means, mining is very dangerous in some extensively worked places. Tragically, at least 20 miners have died from collapsing rock. The miners are organized in cooperatives that control the distribution of the rough opal sold to gem dealers and eventually cutters in Addis Ababa. Opal production has been significant, with over 1,500 kg of rough extracted to date.

MATERIALS AND METHODS

We examined hundreds of rough and polished samples to determine the typical characteristics for this locality. We selected 33 samples to document the gemological properties and note interesting inclusions and growth features, hydrophane character, matrix, and the like (table 1). Eight of these were fashioned as cabochons of various shapes and colors (4.43–18.85 ct). The other 25 samples consisted of rough pieces ranging from ~4 to 965 g (e.g., figure 7), and most contained significant portions of play-of-color opal. Some had considerable matrix material. Several of these were sliced or crushed for specific testing, as detailed below.

Selected samples were examined by standard gemological methods to determine their refractive index, hydrostatic specific gravity, and microscopic features (see table 1). Play-of-color was observed with the stone against a dark background (when necessary), and spot illumination placed above, behind (when appropriate), and then perpendicular to the viewing direction (the latter to observe any contra luz effect, i.e., play-of-color revealed by transmitted light). Luminescence was observed with long- and short-wave UV radiation using 6-watt lamps.

We tested the hydrophane character of 14 samples by observing the specific gravity, transparency, and play-of-color before and after immersing the samples in water for a few minutes to one hour. For the same 14 stones, the following optical tests were conducted: Polarization behavior was studied using a GIA Instruments polariscope, absorption spectra were observed with an OPL prism-type spectroscope, and the Chelsea filter reaction was determined with illumination from a strong halogen lamp.

Fourier-transform Raman spectra were recorded on all samples using a Bruker RFS 100 spectrometer. Each spectrum included 1,000 scans to increase the signal-to-noise ratio, as opal is a poor Raman scatterer.

The microstructure of five samples (1071, 1073, 1074, 1076, and 1101) was investigated with a JEOL 7600 scanning electron microscope (SEM) equipped with a hot cathode/field-effect electron gun, and a Hitachi H9000-NAR transmission electron microscope (TEM) operated at 10 kV. TEM samples were obtained by crushing a small piece of each sample with a mortar and pestle. The chemical composition of eight representative samples (1071, 1073, 1074, 1076, 1078, 1100, 1111, and 1121), their inclusions, and accompanying minerals (in samples 1100, 1106, 1113, and 1122) was measured by energy-dispersive spectroscopy (EDS) with a Princeton Gamma Tech IMIX-PTS detector installed on a JEOL 5800LV SEM. We prepared two thin sections (30 µm thick) of the opal's host rock for petrographic microscopy and analysis of the minerals by EDS.

We conducted preliminary analyses of trace-element composition by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Institute of Geological Sciences in Bern. We investigated two rough samples representative of the marketable opal: one white translucent and the other zoned white translucent and orange transparent, both with play-of-color. (These are not listed in table 1 because they were examined apart from the other samples and only with the LA-ICP-MS technique.) The LA-ICP-MS system consisted of a pulsed 193 nm ArF excimer laser with an energy-homogenized beam profile coupled with an Elan DRCe quadrupole mass spectrometer. Laser parameters were set to 16 J/cm^2 energy density on the sample, with a pulse duration of 15 ns and a repetition rate of 10 Hz. Pit sizes were 60 and 90 µm. The laser-ablation aerosol was carried to the ICP-MS by a mixed He-H_2-Ar carrier gas. Details on the LA-ICP-MS measurement conditions are available in

NEED TO KNOW

- Play-of-color opal has been mined from volcanic deposits near Wegel Tena (Wollo Province) since 2008.
- The bodycolor is typically white, with some brown, fire, and colorless "crystal" opal.
- As with other Ethiopian opal, some of the material shows "digit patterns" of interpenetrating play-of-color and common opal.
- The opaque-to-translucent opals from Wegel Tena become transparent when soaked in water (hydrophane), are resistant to crazing, and are remarkably durable.

Figure 5. The opal deposit consists of a thin horizontal layer (see arrow) in the cliffs above a canyon. It is located ~350 m below the top of the plateau. The cliffs consist of alternating layers of basalt and rhyolitic ignimbrite. Photo by F. Mazzero.

Figure 6. The opal typically fills spaces between pieces of volcanic rock debris, acting as a cement. The black areas in this sample also consist of opal, together with Ba-Mn oxides. This 105 g specimen measures 7 × 5 × 3 cm. Photo by F. Mazzero.

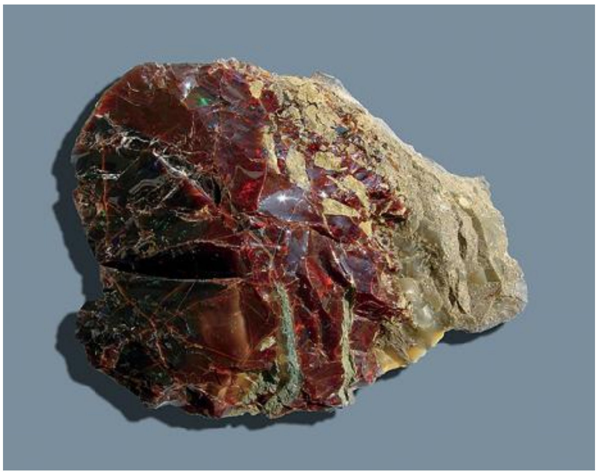


Figure 7. Some rare samples of Wegel Tena opal showed a dark "chocolate" brown bodycolor with play-of-color. This exceptional 965 g specimen, which also demonstrates how the opal occurs in matrix, is on permanent display at the Museum of Natural History in Nantes, France. Photo by F. Mazzero.

the *G&G* Data Depository (gia.edu/gandg).

Stability to crazing was assessed after cutting and preforming by one of us (FM) who has handled numerous Wegel Tena opals since their discovery. A few representative samples from various Wegel Tena parcels were kept at ambient temperature and humidity, and visually observed over time. As part of a proprietary fashioning process, about 50 high-quality play-of-color Wegel Tena opals were cycled between water and air (at room temperature) for one hour and then longer periods (up to several days).

Figure 8. Miners at Wegel Tena often use rudimentary tools, such as the hammer and chisel shown here, to extract the opal from the exposed seam along the flank of the canyon. Photo by Thomas Cenki.

We tested for toughness by dropping five fashioned opals on a concrete surface from a height of ~1.5 m, to simulate dropping a stone by accident.

RESULTS

The standard gemological properties are summarized in tables 1 and 2 and presented below.

Visual Appearance and Optical Phenomena. From observing hundreds of rough and faceted samples, we determined that most opals from Wegel Tena have a white bodycolor, while some are pale yellow and a few are darker orange (fire opal) to brownish red (again, see figures 2 and 3). Rare samples have a dark "chocolate" brown bodycolor (again, see figure 7). Some zoned samples show several layers of contrasting bodycolor and play-of-color (figure 10).

The opals range from opaque to transparent, but most are translucent. Because the material is turbid, it scatters light efficiently, creating the white bodycolor typical of this deposit. Some of the highest-quality opals are translucent and display a blue scattering bodycolor (figure 11).

Among the 33 samples tested, we observed that all opaque-to-translucent samples became more transparent when immersed in water for a few minutes to one hour, depending on the thickness of the sample. This behavior is typical of hydrophane. There were several degrees of change, the most dramatic being a transformation from opaque white to transparent colorless (figure 12). During this process, play-of-color appeared to strengthen. This phenomenon was fully reversible in one to a few hours, depending on ambient humidity and the thickness of the gem.

The opals typically displayed a mosaic of pure spectral color patches against a translucent white bodycolor. Generally all spectral colors (from red to violet) were observed in the play-of-color samples, often with large patches of red and orange. The intensity of the play-of-color varied on the millimeter scale, from intense to none, even within the same sample. We did not notice any contra luz material (which is typically transparent).

Play-of-color was commonly distributed along parallel columns that resembled fingers. We refer to such features as *digit patterns* (figure 13). The play-of-color digits were embedded within common opal of slightly different color or transparency. Their cross-section was rounded, or sometimes quite polygonal when there was little interstitial common

Figure 9. Note the carved wooden pick used by some of these miners to extract the rough opal at Wegel Tena. Photo by F. Mazzero.

opal present. The digits' tips were often rounded. Some samples showed planar zoning of common and play-of-color opal that we interpreted as horizontal. When digit patterns were observed in such samples, they were always perpendicular to these planes (figures 10 and 14). Digit patterns were seen in nine of the 33 samples (nos. 1072, 1104, 1105, 1109, 1111, 1113, 1114, 1121, and 1122).

Figure 10. The strong zoning of this exceptional 18.68 ct cabochon represents most of the opal varieties found at Wegel Tena: brownish orange to white, transparent to opaque, with and without play-of-color. The zoning probably corresponds to successive deposition of horizontal opal layers in a cavity. The white layer with strong play-of-color shows parallel columns that we refer to as digit patterns. *Note that they are perpendicular to the plane of zoning, which means they developed vertically. Photo by Robert Weldon.*

Some much rarer play-of-color features also have been observed in Wegel Tena opals. The cabochon in figure 15 (sample 1075) showed diffraction concentrated in points (not patches) that moved together in a synchronized fashion and changed color when the stone was tilted, or the intense pinpoint light source moved around. This revealed a perfect organization of the silica spheres that was distributed throughout the entire cabochon (pseudo single crystal; Fritsch and Rondeau, 2009). This "perfect diffraction" of light is seen only very rarely in natural gem opals. For a video and more comments on this phenomenon, see

Figure 11. The highest-quality opals, such as this 20.62 ct cabochon, are translucent and display a blue bodycolor due to light scattering. Photo by Robert Weldon.

TABLE 1. Characteristics of the 33 Wegel Tena opal samples studied for this report.[a]

Sample no.	Description	Size[b]	Bodycolor	POC	Hydrophane character	RI
1071	Round cabochon, then sawn; partly broken for SEM	5.07 ct	Translucent light yellow	Green to red	na	1.37, 1.38
1072	Truncated cone	8.19 ct	Nearly opaque white	All colors	Str	na
1073	Double cabochon, then sawn; partly broken for SEM	6.95 ct	Nearly opaque white	All colors	Mod	1.42, 1.44
1074	Formerly a cabochon; broken for SEM	~15 x 6.3 x 4.7 mm	Nearly opaque whitish yellow	All colors	na	na
1075	Elongated sphere	4.43 ct	Translucent white	Pinpoint diffraction	na	na
1076	Oval cabochon, then sawn; partly broken for SEM	~14 x 9 x 3.5 mm	Transparent light yellow	Violet to green	Wk	1.37
1077	Pyramidal cabochon	4.94 ct	Translucent whitish yellow	All colors	Wk	1.36, 1.40
1078	Large rough with matrix; thin section	~50 x 35 x 20 mm	Dark "chocolate" brown	All colors	None	na
1084	Rough nodule, cut in two halves	24.0 g	Transparent orange with a large white "egg" in the core	None	na	na
1099	Rough nodule	8.21 g	Translucent white rim + orange core	Violet in rim, none in core	na	na
1100	Rough, with long, tubular inclusions	3.82 g	Colorless	All colors	None	na
1101	Rough	4.44 g	Transparent orange	All colors	na	na
1103	Rough, broken because of instability	9.81 g	Transparent orange	None	na	na
1104	Rough, broken nodule with a little matrix	4.88 g	Translucent orange + opaque rim	All colors (none in rim)	na	na
1105	Rough, broken nodule with a little matrix	11.61 g	Opaque white rim + transparent orange core	All colors	na	na
1106	Rough, broken nodule with a little matrix, including black coating	4.69 g	Translucent white rim + translucent orange core	All colors	na	na
1107	Rough, broken nodule with a little matrix	16.9 g	Opaque white rim + colorless core	All colors in rim, none in core	na	na
1108	Matrix with few opal veins	28.17 g	Transparent to opaque, orange to colorless	Violet to green	na	na
1109	Rough nodule	23.83 g	Opaque white	All colors	na	na
1110	Rough, broken nodule with a little matrix	42.96 g	Transparent orange	Green to red	None	na
1111	Rough nodule with a little matrix; thin section	49.53 g	Layered, from opaque white to colorless and yellow	All colors	na	na
1112	Rough, broken nodule with a little matrix	81.33 g	Colorless	All colors	None	na
1113	Rough, broken nodule with a little matrix	34.42 g	Colorless with translucent white rim	All colors	na	na
1114	Oval cabochon	7.21 ct	Translucent yellow	All colors	na	na
1116	Rough nodule, sliced into 2 plates	19.68 g	Nearly opaque white	All colors	V str	na
1117	Rough nodule, sliced into 1 plate	16.07 g	Nearly transparent	Violet to green	Wk	na
1118	Rough nodule, sliced into 3 plates	28.67 g	Nearly opaque white	All colors	V str	1.37, 1.42, 1.52
1119	Rough nodule, sliced into 3 plates	40.0 g	Nearly opaque white	All colors	V str	na
1120	Rough nodule, sliced into 1 plate	6.71 g	Transparent	Violet to green	Wk	na
1121	Rough nodule with a little matrix; thin section	25.29 g	Layered translucent yellow to white	All colors	na	na
1122	Rough nodule with fractures filled with black material	12.65 g	Translucent yellow to orange	All colors	na	na
1123	Double cabochon with green inclusions	18.85 ct	Opaque white	All colors	na	na
1124	Rough, in matrix	~100 x 60 x 30 mm	Dark "chocolate" brown	All colors	None	na

[a] Abbreviations: Cont = continuous, inter = interference, Mod = moderate, na = not analyzed, POC = play-of-color, sec = seconds, Str = strong, V = very, Wk = weak.
[b] Weights were measured before soaking.
[c] All dominantly white luminescence is turbid by definition.

UV fluorescence[c]		Phosphorescence[c]		Chelsea filter	Polariscope	Hand spectroscope
Long-wave	Short-wave	After long-wave	After short-wave			
Wk yellowish white	Turbid, wk-to-mod whitish yellow	Inert	Inert	Red, because of green diffraction	Cont change of inter colors; no extinction	Cutoff in violet and blue
Turbid, str whitish green	Turbid, str whitish green	Inert	Inert	Red, because of green diffraction	No reaction	Cutoff in violet and blue
Mod bluish white	Wk bluish white	Wk-to-mod green, few sec	Mod green, few sec	Red, because of green diffraction	Cont change of inter colors; no extinction	No absorption
Inert	Inert	Inert	Inert	Opaque	na	Cutoff in violet and blue
Mod bluish white	Mod yellowish white	Wk green, few sec	Wk green, few sec	Red to orangy red	Reflects the inter patterns	Cutoff in violet and blue
Wk bluish white	Wk bluish white	V wk green, few sec	Wk green, few sec	No reaction	Anomalous hues	Cutoff in violet and blue
Wk yellowish white	V wk to wk yellowish white	Wk yellowish green, 10 sec	V wk	Partly red	Cont change of inter colors; no extinction	Cutoff in violet and part of blue
Inert	Inert	Inert	Inert	na	na	na
Inert	Inert	Inert	Inert	na	na	na
Rim: wk white; core: inert	Rim: V wk white; core: inert	Inert	V wk, few sec	Red to orange	No reaction, diffusion of light	Cutoff in violet and blue
Wk blue	V wk whitish blue	Str whitish blue, ~18 sec	Mod white, ~6 sec	na	na	na
Inert	Inert	Inert	Inert	Deep red	No reaction	na
Turbid, mod green	V wk green	Inert	White, 10 sec	No reaction	No reaction	Cutoff in violet and blue
Rim: yellowish white; core: inert	Rim: yellowish white; core: inert	V wk	V wk, 3-4 sec	na	na	na
Rim: str white; core: inert	Homogeneous, str bluish white	V wk	Inert	Red	Cont change of inter colors; no extinction	Cutoff in violet and blue
Rim: wk yellowish green; core: inert	Core: inert; rim: wk yellowish green	Inert	Inert	Red (rim only)	No reaction	Partly absorbs violet
Rim: str white; core: mod white	Rim: mod white; core: str green	Mod white, 10 sec	Mod green, 8 sec	No reaction	No reaction	No absorption
Wk to V wk greenish white in colorless opal, inert in orange	Wk greenish white in colorless opal, inert in orange	Inert	Inert	na	na	na
Wk-to-mod bluish white	Wk-to-mod bluish white	Mod white, 10 sec	Mod greenish white, 12 sec	Deep red	Extinction every 90°	Cutoff in violet and blue, partly absorbs green
V wk	Inert	Inert	Inert	na	na	na
Homogeneous, wk bluish white	Homogeneous, wk bluish white	Mod white, 15 sec	Wk bluish white, 20 sec	na	na	na
Wk greenish white	Wk yellowish white	Inert	Wk white, 10 sec	na	na	na
Wk bluish white	Wk bluish white	Str white, 15 sec	Greenish white, 20 sec	Partly red	No reaction	Cutoff in violet, partly absorbs blue
Turbid, mod-to-str whitish yellow	Wk-to-mod greenish white	Few sec	Few sec	na	na	na
Mod-to-str blue-white	Mod blue-white	Mod-to-str blue-white, 10 sec	Wk-to-mod white, ~5 sec	na	na	na
Mod-to-str whitish blue	Mod whitish blue	Wk white, ~2 sec	Wk white, ~2 sec	na	na	na
Mod-to-str white	Mod white	Mod white, ~7 sec	Mod white, ~7 sec	na	na	na
Mod-to-str white	Mod-to-str white	Mod white, ~7 sec	Mod white, ~7 sec	na	na	na
Wk bluish white	Wk white	Wk bluish white, ~4 sec	Wk white, ~3 sec	na	na	na
Mod-to-str white	Wk white	Mod white, ~7 sec	Mod white, ~5 sec	na	na	na
Mod white in yellow opal, inert in orange	Wk white in yellow opal, inert in orange	Mod white, ~7 sec	Wk white, ~3 sec	na	na	na
Mod white	Wk-to-mod white	Wk white, ~3 sec	Wk white, ~2 sec	na	na	na
Inert	Inert	Inert	Inert	na	na	na

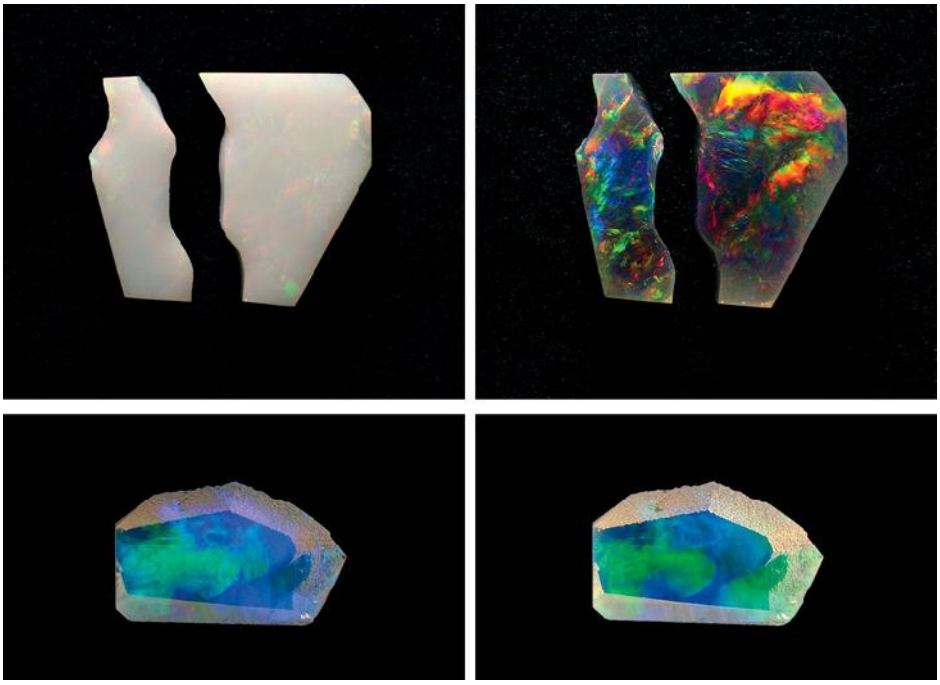


Figure 12. The opaque-to-translucent opal samples we examined became more transparent after immersion in water, as demonstrated by the top photos (samples 1118b and c; 3.96 and 4.68 ct). The sample in the bottom photos (no. 1120, 1.50 ct) showed little change, as it was already quite transparent before immersion. Photos by B. Rondeau.

www.gemnantes.fr/research/opal/index.php#reciproque.

Another rare optical phenomenon seen in one opal that we were only able to keep for a short time was the presence of small, curved rainbows of diffraction (figure 16). Usually in play-of-color opals, each patch of diffraction is homogeneous in color. Here, the spectral colors within each patch were diffracted along a small area, ranging from 1 to 5 mm. For a video of this phenomenon, see www.gemnantes.fr/research/opal/index.php#rainbow.

Figure 13. This spectacular 11.91 ct opal specimen provides a good example of digit patterns: columnar zones of transparent play-of-color opal within a network of common opal of similar bodycolor. Photo by Robert Weldon.

Specific Gravity. SG values (before being soaked in water) ranged from 1.74 to 1.89. After immersion in water for less than one hour, some samples weighed as much as 10.2% more, resulting in higher SG values of 1.90 to 2.00 (table 2). This effect, related to the samples' porosity, was fully reversible and repeatable.

Refractive Index. Because of the opals' porosity, we measured the refractive index of only five samples. In some instances, reaction with the contact liquid

Figure 14. This opal (no. 1121, 25.29 g) shows parallel zoning with the digits developed vertically, perpendicular to this layering. Photo by B. Rondeau.

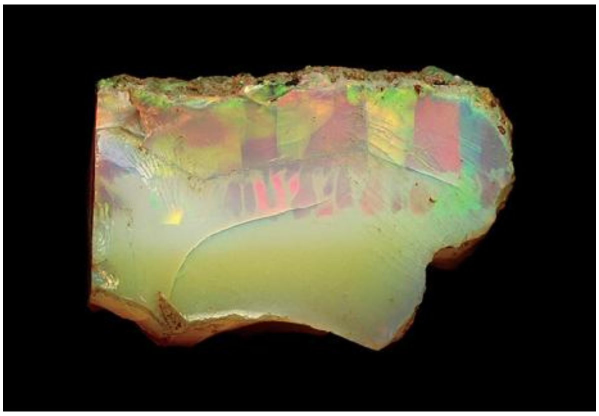


TABLE 2. Specific gravity of representative Wegel Tena opals.

Sample no.	Transparency before/after soaking	Weight (ct) before/after soaking	Weight increase (% of dry weight)	SG before/after soaking
1116a	Nearly opaque white/	2.54/2.69	5.6	1.87/1.95
1116b	transparent	0.53/0.56	5.3	1.89/2.00
1117	Nearly transparent/ transparent	5.07/5.63	9.9	1.77/1.91
1118a	Nearly opaque white/ transparent	1.95/2.17	10.1	1.74/1.90
1118b		3.96/4.38	9.6	1.80/1.91
1118c		4.68/5.17	9.5	1.79/1.91
1119a	Nearly opaque white/	8.01/8.60	6.7	1.82/1.94
1119b	transparent	5.01/5.40	7.2	1.82/1.94
1120	Transparent/transparent	1.50/1.67	10.2	1.76/1.92

caused white opaque spots to form on the opal, adversely affecting the gem's transparency and even its UV luminescence. RI values measured on sample 1073 were 1.42 and 1.44. However, we measured RIs as low as 1.36 to 1.38 on other samples (1071, 1076, and 1077). Some indices were easy to read, but most were difficult or simply impossible. Surprisingly, sample 1118a, a plate, showed an RI of 1.37 on one face and two indices on the other: 1.42 and a very sharp reading at 1.52.

Luminescence. UV luminescence was quite variable, ranging from bluish white to greenish white, yellow, and green. Luminescence intensity ranged from inert to strong. All brown samples or zones were inert. In long-wave UV, most non-brown samples had weak to very weak luminescence that was fairly turbid, and bluish to greenish white, with weak to very weak greenish white phosphorescence that lasted a few seconds. The typical short-wave UV reaction was slightly weaker, though the phosphorescence sometimes lasted longer. Some samples—particularly white opals with very good play-of-color—luminesced more strongly, with a moderate, mostly white fluorescence. One transparent, near-colorless, play-of-color opal had a strong, pure green luminescence.

Polariscope Reaction. Seven transparent light color stones, with and without play-of-color, showed no reaction viewed between crossed polarizing filters. Five translucent stones with play-of-color showed cyclic variations in diffraction colors as the stones were rotated a full 360°. Two opals (no. 1076 and 1109) showed anomalous double refraction (ADR).

Optical Absorption Spectrum. No spectrum was seen in the two lighter-color, transparent stones tested with the hand spectroscope. The remaining 12 milky or orange-to-brown stones showed absorption in the violet and blue regions, sometimes extending into the green. This absorption increased with the amount of light scattered by the stone (from slightly milky to white), the darkness of the bodycolor (from yellow to brown), and the thickness of the sample.

Color Filter. Three transparent, light-colored gems showed no reaction when viewed through the Chelsea color filter. Eleven transparent brown or strongly diffusing (milky to white) opals appeared orange to bright red.

Inclusions. One sample (no. 1100) contained elongated, cylindrical inclusions measuring approximately 800 μm × 1 cm (figure 17). Their surface was very irregular. EDS showed that these "tubes" were filled with silica, which may correspond to chalcedony. The outside surface of the inclusions also consisted of silica. They appeared more difficult to

Figure 15. This very unusual opal (no. 1075, 4.43 ct) displays a perfect diffraction pattern. Spectral colors formed small points that moved in a synchronized fashion and changed color when the light source was moved. Photo by B. Rondeau.

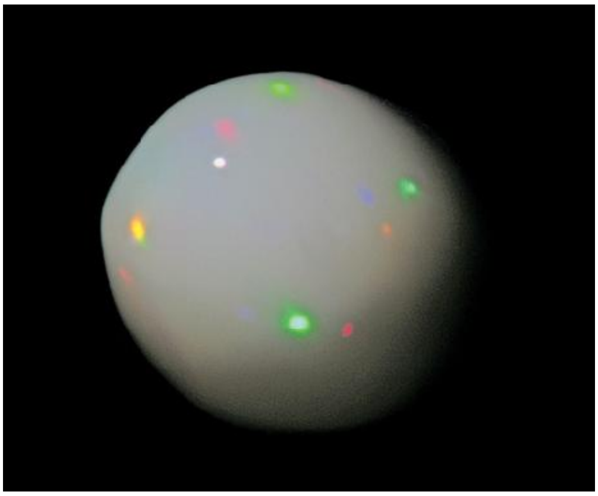


Figure 16. The diffraction of light by opal usually produces patches of pure spectral colors. On rare occasions, such as this 9.51 ct cabochon, we observed these colors diffracted from millimeter-size areas, forming small rainbows. Photo by F. Mazzero.

polish than the host opal.

Dispersed micro-inclusions of black, opaque crystals were abundant in some samples (in particular, no. 1113). EDS analyses revealed iron and sulfur, which suggests they were pyrite (pyrite usually appears black in such small dimensions).

Some of the rough opal samples were outlined by a thin layer (less than 0.1 mm thick) of black, opaque minerals. These were identified by EDS as barium-manganese oxides (probably hollandite) and native carbon (probably graphitic carbon). Also present in such layers were micrometer-sized crystals that were identified by EDS as titanium oxides (probably rutile). In rare instances, the black minerals were included in the body of the opal, filling fissures or forming dendrites.

Chemical Composition. We measured the chemical composition of several samples by EDS (both major and minor elements; see table 3) and LA-ICP-MS (trace elements; see table 4 and the *G&G* Data Depository). In addition to silica, we detected a significant proportion of Al (0.6–1.9 atomic %) and minor amounts of Ca (0.05–0.6 at.%), Na (up to 0.4 at.%), K (0.2–0.5 at.%), and Fe (up to 0.3 at.%). Iron was not detected in the white samples. These compositions are typical for opal (Gaillou et al., 2008a). Among the trace elements, white opal contained abundant Ba (140–226 ppm [by weight]), Sr (127–162 ppm), and Rb (44–73 ppm). The orange fire opal portion of one sample showed Ba, Sr, and Rb contents consistent with those of opal-CT (Gaillou et al., 2008a). For the concentrations of other elements, see table 4 and the *G&G* Data Depository.

Raman Scattering. We obtained similar spectral features for all samples (e.g., figure 18). The apparent maximum of the strongest Raman band ranged from 360 to 335 cm^{-1}. Other, sharper Raman bands were present at ~3230–3200, 2940, 1660, 1470, 1084, 974, and 785 cm^{-1}.

Microstructure. Observing the microstructure of an opal helps us characterize it and understand its growth conditions. Most often, as shown in Gaillou et al. (2008b), two main categories of structures can be observed: "smooth sphere" structure in opal-A (A for amorphous) or "lepisphere" structure in opal-CT (CT for cristobalite and tridymite; opal-A and opal-CT were originally defined on the basis of their X-ray diffraction patterns, and later on their Raman scattering patterns—see Jones and Segnit, 1971; Smallwood et al., 1997). To reveal the internal structure of an opal, one must first etch the sample in hydrofluoric acid (HF) and then observe the sur-

Figure 17. Elongated, cylindrical inclusions were present in one opal sample. This coated cylinder was made of silica, most likely chalcedony. Photomicrograph by B. Rondeau; magnified 40×.

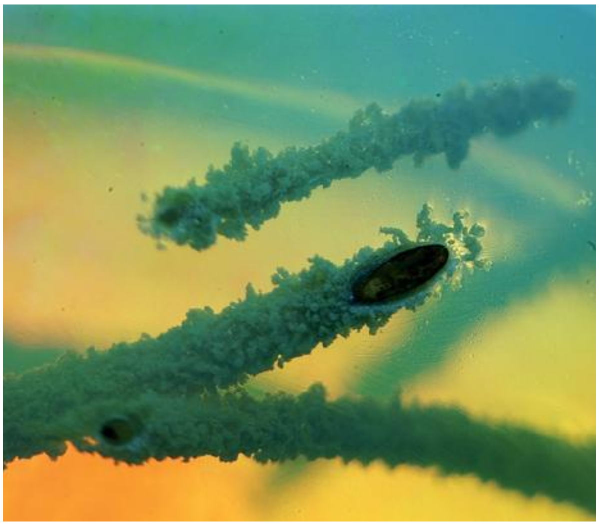


TABLE 3. Chemical composition of five opals from Wegel Tena, Ethiopia, measured by EDS.[a]

Sample no.	Color	Si	Al	Ca	K	Na	Fe	O
1100	Colorless	31.5–31.7	1.4–1.5	0.5–0.6	0.2	nd	nd	66.1–66.1
1078	Brown	32.4–32.7	0.6	0.05–0.1	0.2–0.3	nd–0.1	nd	66.2–66.4
1106	White	31.1	1.7	0.4	0.4	0.4	nd	65.82
1111	Yellow	31.9	1.9	0.4	0.3	nd	0.3	65.9
1111	White	30.9	1.2	0.3	0.2	0.4	nd	66.2
1113	Colorless	31.6	1.5	0.3	0.5	nd	nd	66.1

[a] *Values are expressed in atomic percent. O is calculated for a sum of 100%. Samples 1078 and 1100 were analyzed in three spots; others are one spot. Abbreviation: nd = not detected.*

face by SEM. Gaillou et al. (2008b) showed that etching in a 10% solution of HF for about 10 seconds can reveal the structure of opal. We encountered an unexpected reaction, however: Our samples were strongly affected by the acid, tending to flake away and develop networks of cracks. We modified both the concentration of HF (from 0.01% to 10%) and the duration of acid exposure (from 1 second to 3 minutes, with longer times using weaker acid), but we did not observe any organization of smooth spheres or lepispheres. Thus, we could not see any packing of spheres in opals from Wegel Tena using this technique.

We subsequently studied the structure of the opal using TEM, which revealed a regular network of spheres ~170 nm in diameter (figure 19). In another attempt to explore the structure, we studied the same sample using SEM with an unusually high voltage (15 kV) for a sample that was not coated to make it electrically conductive. Because the opal specimen was so thin, the electrons were able to pass through it to the backscattered electron detector. The similar image that was generated by this significantly different technique confirmed the TEM observations. Yet neither method helped us determine if the opal's structure is characterized by lepispheres (as are typical of opal-CT) or smooth spheres (typical of opal-A). Regardless, the regular network of these spheres is responsible for the diffraction of visible light that results in the play-of-color shown by the opals.

Stability and Toughness. Opals from certain localities (e.g., Querétaro, Jalisco, and Nayarit States in Mexico, and Shewa Province in Ethiopia, both opal-A and -CT) are known to destabilize, or "craze" with time. Cracks develop at the surface, and/or a white, opaque egg-like structure develops in the center of the stone (mostly in opal-CT; Aguilar-Reyes et al., 2005).

In the authors' experience, ~5% of Wegel Tena opals develop cracks after initial sawing and preforming. Until now, out of approximately 3,000 play-of-color opal cabochons from Wegel Tena released into the market during 2008–2010 by one of us (FM), only three samples were returned after

TABLE 4. Range of chemical composition of two opals from Wegel Tena, Ethiopia, measured by LA-ICP-MS.[a]

Composition	1B White	3B White	3B Orange
No. analyses	8	7	2
Element (ppm)			
Li	0.061–0.205	<0.064–0.173	0.092–0.104
B	6.97–9.55	8.12–12.1	<0.179
Cu	0.267–0.555	0.159–0.640	0.069–0.091
Zn	11.6–18.9	1.19–16.2	<0.203–0.218
Pb	0.131–0.274	0.017–0.225	0.013–0.021
Sc	1.46–2.12	1.49–2.25	1.79–2.02
V	0.060–0.152	0.024–0.069	<0.007–0.011
Co	<0.009–0.046	0.001–0.031	<0.010
Ni	0.655–1.56	0.442–1.53	0.586–0.863
As	<0.090	<0.045–0.288	0.061–0.063
Rb	58.7–73.1	43.7–73.2	38.7–43.2
Sr	127–161	128–162	72.1–75.1
Y	0.093–0.314	0.087–0.241	0.067–0.103
Zr	51.1–245	34.3–201	29.2–31.2
Nb	0.944–2.81	0.321–0.408	0.477–0.588
Mo	<0.047	<0.030	<0.017
Cd	0.475–1.84	0.446–0.608	0.240–0.345
Ba	140–166	196–226	81.8–91.8
La	0.036–0.187	0.011–0.064	0.013–0.013
Ce	0.074–0.552	0.010–0.098	0.020–0.027
Pr	0.007–0.047	<0.001–0.013	<0.001–0.004
Nd	0.032–0.222	<0.010–0.069	0.012–0.019
Sm	<0.012–0.066	<0.009–0.013	<0.020
Eu	<0.003–0.014	<0.003–0.008	<0.004
Gd	<0.011–0.029	<0.022	<0.014
Tb	<0.002–0.012	<0.002–0.005	<0.002
Dy	0.010–0.031	<0.009–0.021	<0.005–0.007
Ho	<0.002–0.015	<0.001–0.008	<0.001–0.004
Er	<0.010–0.042	<0.007–0.029	<0.006
Tm	<0.001–0.007	<0.002–0.004	<0.001
Yb	<0.010–0.047	<0.008–0.037	<0.001
Lu	<0.002–0.003	<0.002–0.008	<0.002–0.004
Th	0.008–0.064	<0.003–0.006	0.141–0.196
U	0.197–0.361	0.103–0.135	<0.001

[a] *Values are expressed in ppm by weight. For detailed analyses, see the* G&G *Data Depository.*

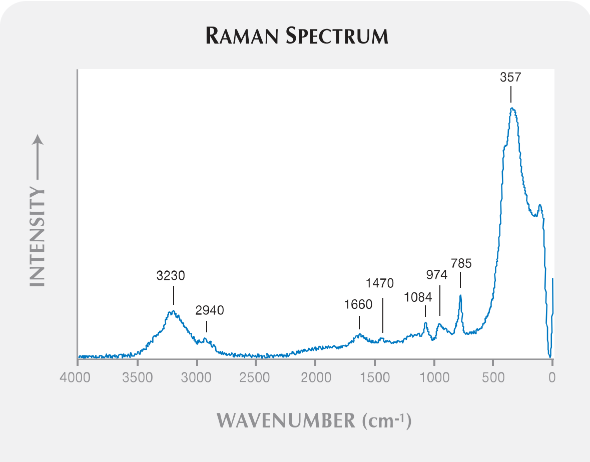


Figure 18. This Raman spectrum of sample no. 1072 is representative of opal from Wegel Tena. The main Raman bands at ~1470, 1084, 974, 785, and 357 cm^{-1} are typical for opal-CT. The bands at about 3230–3200, 2940, and 1660 cm^{-1} are attributed to water.

cracking. A parcel of seven opals (including sample 1072) thought to be from Mezezo was set aside in 2005 because of their unusual appearance; they are now known to be from Wegel Tena, and all the stones are still intact. Any crazing appears to be restricted to transparent material, in particular pale yellow to orange samples (fire opal) and near-colorless "crystal" opals. A few samples showed spectacular "egg" development (figure 20), as seen in some Mexican fire opal. In general, opaque white-to-yellow-to-brown opals from Wegel Tena appear very stable. There is no noticeable difference in crazing behavior between common and play-of-color opal.

There was no change in appearance (color, diaphaneity, crazing, or play-of-color) in the samples that were submitted to alternating periods of immersion in water. One customer who wears her opal constantly complained that it became more transparent when she took a shower, swam, or otherwise put her hands in water. She recognized, however, that the opal always returned to its original appearance after some time (depending on the duration of immersion)—which is due to its hydrophane character.

We noticed by accident that Wegel Tena opals could sustain a fall from 1.5 m onto a concrete floor with no visible damage, even under the microscope. Repetition of this test on five oval cabochons did not produce any sign of damage. The same experiment with five oval cabochons from the Mezezo deposit and three oval cabochons of white opal from Australia (including one boulder opal) led to breakage of all samples.

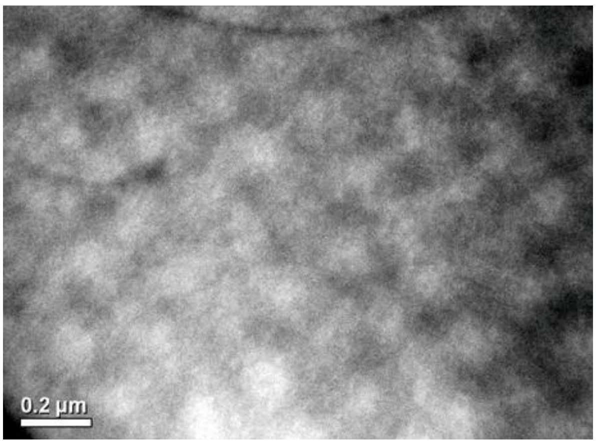
DISCUSSION

Gemological Properties. SG was in the reported range for opal (Webster, 1975). However, some samples showed large weight gains during immersion in water, up to 10.2%. This is probably related to the high porosity of these samples, detectable simply by touching a sample with the tongue to test its "stickiness." RI ranged from as low as 1.36 to 1.43, with one "secondary" reading of 1.52. Values as low as 1.36 have been previously measured in hydrophane from Slovakia (Reusch, 1865) and in opals from Mexico (Spencer et al., 1992). The RI sometimes varied strongly even within a single sample, depending on the orientation. Similar effects were seen in Shewa opals (Johnson et al., 1996). They are probably due to local physical or chemical heterogeneities, as commonly observed in opals.

The large patches of red and orange seen in some of the play-of-color Wegel Tena opals are not common in Brazilian and Australian opals. We found the digit patterns to be very common in Wegel Tena opals, though in some cases they were only visible with a microscope. Digit patterns were described previously only in opals from Mezezo (see figure 14 in Johnson et al., 1996; Gauthier et al., 2004). We know of only one non-Ethiopian opal with digit patterns; it was seen in Australia by one of the authors (EF). Also, Choudhary (2008) described another such opal from an unspecified source. In contrast, the planar zoning of common and play-of-color opal is often observed in opals from other deposits, volcanic or otherwise.

As expected, the spectroscope spectrum and

Figure 19. Transmission electron microscopy of sample 1071 reveals a microstructure consisting of spheres ~170 nm in diameter.



color filter reaction were not useful for identification. The red color filter reaction, as well as the absorption of the violet and blue regions in most stones, stems from two possible factors that may combine in a given stone. Intense light scattering (the corresponding stones were milky or white) attenuates violet and blue wavelengths, as they are scattered preferentially at an angle. Also, the yellow-to-brown bodycolor is due to a continuum of absorption, increasing from the red toward the violet region. Hence it will also contribute to blocking the violet-to-blue (and even some green) wavelengths. The resulting color in rectilinearly transmitted light in both cases is orange or red, as seen with the spectroscope or the Chelsea filter. Note that this is a good example of a bright red Chelsea filter reaction that has nothing to do with the presence of chromium in the stone.

The UV luminescence properties were typical for opal. The fluorescence is a mix of intrinsic silica surface-related violetish blue emissions and extrinsic uranium-related green emission. The latter is often more visible with short-wave UV (Fritsch et al., 2001; Gaillou, 2006; Gaillou et al., 2008a).

The observed hydrophane behavior is already known for some rare opals (Webster, 1975), particularly from Opal Butte, Oregon (Smith, 1988). In the samples studied here, there was no relationship between the capacity of opal to absorb water and the change in its visual appearance (compare figure 11 and table 2).

Raman Scattering. The main Raman peaks at ~1084, 974, 785, and 357 cm^{-1} are typical for opal-CT and distinctly differ from those of opal-A, for which the Raman spectrum displays a main band around 420 cm^{-1} (Smallwood et al., 1997; Fritsch et al., 1999; Ostrooumov et al., 1999). The bands at ~3230 and 1660 cm^{-1} are attributed to the presence of water (Ostrooumov et al., 1999; Zarubin, 2001), and the band at 2940 cm^{-1} to cristobalitic water (Gaillou et al., 2004; Aguilar-Reyes et al., 2005).

Geology. The occurrence of digit patterns remains something of a mystery, but they seem to have been vertical at the time of their formation. To date, digit patterns have been observed almost exclusively in material from the two Ethiopian deposits, Wegel Tena and Mezezo. It follows, then, that the geologic conditions under which opals formed at these areas share common characteristics. However, the disposition of opal in its host rock differs between the two localities. At Wegel Tena, opal most often cements volcanic grains, while at Mezezo it usually forms nodules filling the cavities in volcanic rock. The latter is the case for most volcanic opal localities, such as Mexico and Oregon. Also, the inclusion scenes observed in opals from Wegel Tena are different from those observed in opal from any other deposit (e.g., Gübelin and Koivula, 1986).

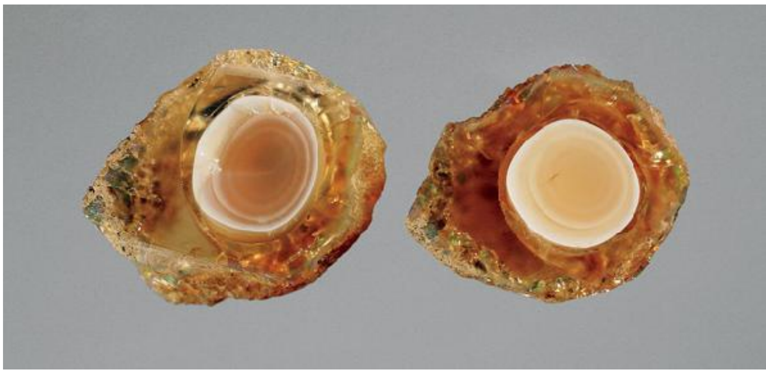


Figure 20. This orange opal (24 g total weight) from Wegel Tena was sliced to show the internal 15-mm-diameter egg-shaped zone of destabilization. Photo by B. Rondeau.

At Wegel Tena, the opal-mineralized layer is concordant with volcano-sedimentary deposits that extend for hundreds of kilometers. No systematic prospecting for opal has been conducted, but a local miner reported to one of us (EB) that opal samples have been found in the same geologic unit and at a similar depth on the flank of the Great Rift Valley, 40 km from the present workings (Yapatsu Purpikole, pers. comm., 2009). We believe, then, that the extent of the opal-bearing layer is probably much greater than what is known today.

Chemical Composition. From our preliminary measurements of two samples, trace-element composition was comparable to opals from Mezezo (Gaillou et al., 2008a), with the following notable exceptions: Y (0.07–0.3 ppm), Nb (0.3–2.8 ppm), and Th (<0.2 ppm) were lower in the Wegel Tena opals, whereas Sc (1.5–2.3 ppm), Rb (39–73 ppm), Sr (72–162 ppm), and Ba (82–226 ppm) were higher. The enriched Ba concentration in opals from Wegel Tena is surprising. Looking at opals from elsewhere (Gaillou et al., 2008a), we see that those that formed in a volcanic environment always have low Ba (<100 ppm), whereas those from a sedimentary environment contain 100–300 ppm Ba. However, we note that the relatively high Ba contents in some Wegel Tena opals are consistent with the geologic environment that

Figure 21. Opal from Wegel Tena is being incorporated into innovative jewelry designs. The Meduse Lune Clip features two opals (16.72 and 16.77 ct) that are set with diamonds and natural pearls. Courtesy of Van Cleef & Arpels, Paris.

also resulted in the presence of Ba-Mn oxides in fissures mentioned above.

Areas of different composition within single samples raise the question of their petrogenesis. The orange opal is richer in Fe and presents a typical opal-CT trace-element composition (compare with Gaillou et al., 2008a), whereas the white opal has unusually high contents of Ba, Sr, and Br compared to volcanic opals.

Identification. Digit patterns are typical of Ethiopian opal, from either Mezezo or Wegel Tena, regardless of the bodycolor. The digit patterns somewhat resemble the columnar structure observed in synthetic opals (such as Gilson), but they also have significant differences. Digit patterns are made of two materials: one transparent with play-of-color and the other more turbid, often without play-of-color. They form rounded columns, whereas the columns in synthetics are far more regular and polygonal. Hence, careful observation is sufficient to distinguish the natural from synthetic opal.

To our knowledge, white opals from Wegel Tena represent the only example of opal-CT with a Ba content greater than 100 ppm. Therefore, the combination of a satisfactory Raman spectrum with trace-element analysis makes it possible to identify white opals from this locality. The fire opals displayed a chemical composition comparable to that of opal-CT from other localities.

Stability. Translucent opals from Wegel Tena resist hydration/dehydration cycles much better than opals from Mezezo, which crack and break more easily during such tests. A stabilization process has been developed to prevent crazing of Ethiopian opal (Filin and Puzynin, 2009), but in our experience this appears unnecessary for translucent opals from Wegel Tena.

CONCLUSION

Wegel Tena, Ethiopia, is a source of significant quantities of high-quality play-of-color opal (e.g., figure 21), with a mostly white bodycolor that is more market-friendly than the mostly brown material from Mezezo, ~200 km to the south. The opals are found in a specific layer of a thick volcanic sequence of alternating basalt and ignimbrite of Oligocene age. Systematic prospecting is needed to assess the extent of the opal-containing layer and the production potential, which appears quite significant.

Many of these new opals showed what we describe as "digit patterns," a common feature in Ethiopian opals. The Wegel Tena samples typically showed the Raman spectrum of opal-CT, as do most opals that formed in a volcanic environment. Among the inclusions, we noted cylinders of silica (probably chalcedony), black microcrystals (probably pyrite), and coatings/fissures filled with barium-manganese oxides and graphite-like carbon. The combination of an enriched Ba content in the white opals (>100 ppm), a Raman spectrum typical of opal-CT, and the presence of digit patterns characterizes opals from Wegel Tena. Further trace-element analyses are necessary to strengthen the chemical criterion for Ba. The opaque-to-translucent opals from Wegel Tena are much more stable than those from Mezezo, which have a tendency to craze. Also, physically they are surprisingly tough. The Wegel Tena area has the potential to become a leading supplier of high-quality white play-of-color opal.

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ACKNOWLEDGMENTS

The authors thank Nicolas Stephant, Stéphane Grolleau, Eric Gautron, and Luc Lajaunie of the Centre de Micro-Caractérisation (IMN, University of Nantes) for their help with electron microscopy. T. Pettke is thanked for assistance with LA-ICP-MS analysis. Messrs. Mazzero and Bekele are grateful to the Ethiopian Ministry of Mines and Energy for their help with their visit to the mining area. In particular, they thank Mrs. Hadas Sherif, gemologist at the Mines Works Department, for her assistance in collecting field data and research samples, together with Thomas Cenki.

REFERENCES

Aguilar-Reyes B.O., Ostrooumov M., Fritsch E. (2005) Estudio mineralógico de la desestabilización de ópalos Mexicanos [Mineralogical study of the destabilization of Mexican opals]. *Revista Mexicana de Ciencias Geológicas*, Vol. 22, No. 3, pp. 391–400.

Ayalew D., Yirgu G. (2003) Crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites: Basalt and rhyolite geochemical provinciality. *Journal of the Geological Society of London*, Vol. 160, pp. 47–56.

Ayalew D., Gibson S.A. (2009) Head-to-tail transition of the Afar mantle plume: Geochemical evidence from a Miocene bimodal basalt–rhyolite succession in the Ethiopian Large Igneous Province. *Lithos*, Vol. 112, pp. 461–476.

Choudhary G. (2008) Gem News International: An interesting opal. *G&G*, Vol. 44, No. 2, pp. 172–174.

Filin S.V., Puzynin A.I. (2009) Prevention of cracking in Ethiopian opal. *Australian Gemmologist*, Vol. 23, No. 12, pp. 579–582.

Fritsch E., Rondeau B. (2009) Gem News International: Rare optical phenomenon in play-of-color opal. *G&G*, Vol. 45, No. 2, pp. 147–148.

Fritsch E., Rondeau B., Ostrooumov M., Lasnier B., Marie A.-M., Barreau A., Wery J., Connoué J., Lefrant S. (1999) Découvertes récentes sur l'opale [Recent discoveries about opal]. *Revue de Gemmologie a.f.g.*, No. 138/139, pp. 34–40.

Fritsch E., Mihut L., Baibarac M., Baltog I., Ostrooumov M., Lefrant S., Wery J. (2001) Luminescence of oxidized porous silicon: Surface-induced emissions from disordered silica micro-to nano-structures. *Journal of Applied Physics*, Vol. 90, No. 9, pp. 4777–4782.

Gaillou E. (2006) Relation entre Nanostructure, Propriétés Physiques et Mode de Formation des Opales A et CT [Relationship between Nanostructure, Physical Properties and Mode of Formation of Opal-A and Opal-CT]. PhD thesis, University of Nantes, 278 pp.

Gaillou E., Mocquet B., Fritsch E. (2004) Gem News International: A new gem material from Madagascar. *G&G*, Vol. 40, No. 4, pp. 339–340.

Gaillou E., Delaunay A., Rondeau B., Bouhnik-le Coz M., Fritsch E., Cornen G., Monnier C. (2008a) The geochemistry of opals as evidence of their origin. *Ore Geology Reviews*, Vol. 34, pp. 113–126.

Gaillou E., Fritsch E., Rondeau B., Aguilar-Reyes B., Barreau A., Ostroumov M., Post J. (2008b) Common gem opal: An investigation of micro- to nano-structure. *American Mineralogist*, Vol. 93, pp. 1865–1873.

Gauthier J.-P., Mazzero F., Mandaba Y., Fritsch E. (2004) L'opale d'Ethiopie: Gemmologie ordinaire et caractéristiques exceptionnelles [Opal from Ethiopia: Usual gemology and unusual characteristics]. *Revue de Gemmologie a.f.g.*, No. 149, pp. 15–23.

Gübelin E.J., Koivula J.I. (1986) *Photoatlas of Inclusions in Gemstones*, ABC Edition, Zürich, 532 pp.

Johnson M.L., Kammerling R.C., DeGhionno D.G., Koivula J.I. (1996) Opal from Shewa Province, Ethiopia. *G&G*, Vol. 32, No. 2, pp. 112–120.

Koivula J.I., Kammerling R.C., Fritsch E., Eds. (1994) Gem News: Opal from Ethiopia. *G&G*, Vol. 30, No. 1, pp. 52–53.

Mazzero F., Gauthier J.-P., Rondeau B., Fritsch E., Bekele E. (2009) Nouveau gisement d'opales d'Ethiopie dans la Province du Welo: Premières informations [New deposit of Ethiopian opals in Welo Province: Early information]. *Revue de Gemmologie a.f.g.*, No. 167, pp. 4–5.

Ostrooumov M., Fritsch E., Lasnier B., Lefrant S. (1999) Spectres Raman des opales: aspect diagnostic et aide à la classification [Raman spectra of opals: Identification aspects and help for classification]. *European Journal of Mineralogy*, Vol. 11, No. 5, pp. 899–908.

Reusch E. (1865) Ueber einen Hydrophan von Czerwenitza [On a hydrophane from Czerwenitza]. *Annalen der Physik*, Vol. 200, No. 3, pp. 431–448.

Rondeau B., Mazzero F., Bekele E., Gauthier J.-P., Fritsch E. (2009) Gem News International: New play-of-color opal from Welo, Ethiopia. *G&G*, Vol. 45, No. 1, pp. 59–60.

Smallwood A., Thomas P.S., Ray A.S. (1997) Characterisation of sedimentary opals by Fourier transform Raman spectroscopy. *Spectrochimica Acta Part A*, Vol. 53, No. 13, pp. 2341–2345.

Smith K.L. (1988) Opals from Opal Butte, Oregon. *G&G*, Vol. 24, No. 4, pp. 229–236.

Spencer R.J., Levinson A.A., Koivula J.I. (1992) Opal from Querétaro, Mexico: Fluid inclusions study. *G&G*, Vol. 28, No. 1, pp. 28–34.

Webster R. (1975) *Gems: Their Sources, Descriptions and Identification*, 3rd ed. Butterworth & Co., 938 pp.

Zarubin D.P. (2001) The two-component bands at about 4500 and 800 cm^{-1} in infrared spectra of hydroxyl-containing silicas. Interpretation in terms of Fermi resonance. *Journal of Non-Crystalline Solids*, Vol. 286, No. 1–2, pp. 80–88.