# OPAL

Opal, considered a separate entity among gems and minerals since times of antiquity, on the basis of its outward characters, became classed in most eighteenth century mineralogical works as a type of *silex* or *kiesel*. It was usually placed in the category of translucent fine-grained types of silica then given by many the general name agate, in distinction to the opaque types classed under jasper, and now known as chalcedony or chalcedonic silica. In modern works opal has been classed as a separate species. In general it has been characterized as an amorphous mineral gel. In recent years, however, x-ray diffraction study has shown that opal is not amorphous but is a sub-microcrystalline aggregate of crystallites of cristobalite, containing much non-essential water. Opal is here considered as a variety of cristobalite, standing to that species much in the same relation that chalcedony does to quartz. It is described, however, as if it were a species.

**OPAL.** Upala *Sanskrit.* Opalus, Paederos *Pliny (Nat. Hist.,* **37,** 21, 23, A.D. 77). Quartz résinite *Haüy (Traité de min.,* **2,** 1801). Hyalite (Hyalit, Hialit, Müller's Glass) *Werner* (Hoffmann: *Min.,* **2a,** 134, 1812; Karsten: *Min. Tab.,* 22, 1800). Glasopal *Hausmann* (*Handb. Min.,* 424, 1813). Menilite *de Saussure* (Delamétherie: *Théor. de la terre,* **2,** 169, 1797; Delarbre and Quinquet: *J. phys.,* **31,** 219, 1787). Leberopal *Karsten (Min. Tab.,* 24, 1800). Jasp-Opal *Karsten (Min. Tab.,* 26, 1808). Eisenopal *Hausmann (Handb. Min.,* **428,** 1813). Semi-Opal, Halb-Opal *Werner* (Emmerling: *Min.,* **1,** 248, 1793; Hoffmann: *Min.,* **2a,** 134, 1812). Wood-Opal, Holz-Opal *Germ.* Cacholong *Mongolian name* (? from *kaschtschilon,* beautiful stone). Mother-of-pearl-opal, Pearlmutter-Opal *Karsten (Min. Tab.,* 1808).

Jenzschite *Dana (Syst. Min.,* 201, 1868; 194, 1892). Passyite *Marchand (Ann. chim. phys.,* **1,** 393, 1874). Grossouvréite *Meunier (Bull. soc. géol. France,* **2,** 250, 1902). Granuline pt. (?) *Scacchi (Rend. acc. Napoli,* **21,** 176, 1882). Forcherite *Aichhorn (Wien. Ztg. Abendbl.,* July 11, 1860; Maly: *J. prakt. Chem.,* **86,** 501, 1862). Neslite *Leymérie (Stat. min. de l'Aube,* 116, 1846).

Sinters and Tripoli; Diatomite. Fiorite, Siliceous Sinter, Kieselsinter *Santi (Crell's Ann.,* **2,** 589, 1796; Thomson: *J. phys.,* **39,** 407, 1791, and **1,** 108, 1796; Pfaff: *Crell's Ann.,* **2,** 589, 1796); Kieselsinter *Karsten (Min. Tab.,* 24, 1808). Kieseltuff *Klaproth (Beitr.,* **2,** 109, 1796); Geysirite *Delamétherie (Leçons Min.,* 1812; Damour: *Bull. soc. géol. France,* 157, 1848). Geyserite. Michaelite *Webster (Am. J. Sci.,* **3,** 391, 1821). Pealite *Endlich (U.S. Geol. Surv.,* 6th Ann. Rpt., 1873, 153; *Am. J. Sci.,* **6,** 66, 1873). Viandite *Goldsmith (U.S. Geol. Surv.,* 12th Ann. Rpt., Pt. 2, 407, 1883). Tripoli; Bergmehl (pt.), Kieselmehl, Kieselguhr (*Germ.*). Tripoli slate, Polishing slate; Tripelschiefer, Saugkiesel, etc., (*Germ.*). Randannite *Salvétat (Ann. chim. phys.,* **24,** 348, 1848; Lacroix: *Bull. soc. min.,* **39,** 85, 1916); Ceyssatite *Gonnard (Min. Puy-de-Dôme,* 1876, 14); Lassolatite *Gonnard* (1876). Vierzonite *Grossouvre (Bull. soc. géol. France,* **1,** 431, 1901). Floatstone, Schwimmstein *Germ.,* Silex nectique *Haüy (Traité de min.,* **2,** 1801).

## MODE OF AGGREGATION

Opal occurs as crusts with a botryoidal, globular, reniform, or ropy surface; small-stalactitic to coralloidal; as concretionary masses with a tuberose or irregular shape. Commonly as a cavity-filling and as veinlets. The siliceous sinters and geyserites are porous to firm in texture; sometimes filamentous, fibroid, or in leathery or sponge-like forms; in cauliflower-like forms; scaly-massive to compact massive. Also massive, rock-forming, poorly compacted (diatomites) to hard and dense.

## X-RAY STUDIES

The earliest[1] x-ray powder diffraction studies of opal indicated that the substance was amorphous, as earlier thought on physical and optical grounds. Later work[2] by superior experimental techniques, however, has shown that opal is in general a crystalline aggregate, composed of submicroscopic crystallites of a substance, here called opal-cristobalite, with a more or less disordered internal structure. The large and variable content of non-essential water characteristic of the aggregate is primarily a consequence of the extremely small particle size, or large internal surface, and the manner of formation in nature. In the older literature the crystalline substance present usually was called high-cristobalite, in the ideal sense, but recent x-ray and thermal studies[3] have led to a characterization as a disordered type of low-cristobalite. In this, the one-dimensional disorder present can be broadly described in terms of a layer-like linkage of $(SiO_4)$ tetrahedra, approximately 4.1 Å thick, which can be recognized in the structure of the three classical polymorphs of $SiO_2$. In quartz these layers are arranged parallel to $(10\bar{1}1)$, in cristobalite parallel to $(111)$, and in tridymite parallel to $(0001)$. The idealized structure of tridymite consists of two geometrically distinguishable kinds of alternating layers, A and B, with the stacking sequence ABAB . . . The idealized structure of cristobalite, which is taken at high temperatures of formation, is based on the stacking sequence ABCABC . . . At lower temperatures of formation, and in the presence of alkalies and other cations as noted beyond, an interstratification of both two-layer and three-layer sequences may take place. The interstratification may be periodic, giving rise to superstructures (polytypes), or, more commonly, may be random. In opal the three-layer sequences are dominant (opal-cristobalite). With increasing disorder the x-ray pattern becomes diffuse with the appearance of the stronger diffraction lines of low-tridymite. The high-low inversion temperature also decreases, and the dilatometric curves of highly disordered material show less sharp volume changes.[4]

The disordering is caused by the entrance of cations such as Al, Ca, Mg, and alkalies and probably also of $H_2O$ and (OH) into solid solution. Opal-cristobalite thus is not pure $SiO_2$ but is a stuffed derivative thereof.

In addition to the diffraction lines of opal-cristobalite, x-ray patterns of opal and especially of opaline rocks may show distinct lines of quartz, chiefly representing chalcedonic material, and of feldspar, clay minerals, and other admixed material. Some opals, especially material of biochemical origin, give faint and very diffuse x-ray patterns. A low, extremely broad peak centering at about $21°$ $2\theta$ is characteristic. The availability of cations that can stabilize cristobalite may be a factor, in addition to the temperature of formation.

Submicrocrystalline opal-cristobalite also forms in artificial silica gels[5] on ageing at ordinary temperatures and more rapidly on hydrothermal treatment. At higher temperatures in water or superheated steam the gel may convert to quartz, depending on the temperature and pressure, with cristobalite appearing first as a metastable, transient phase. The conversion is sensitive to the presence of alkalies and other cations in the wet gel. When heated in air, silica gels or dried, powdery $SiO_2 \cdot nH_2O$ lose water at low temperatures and in the range 800–1400° crystallize rapidly to cristobalite, tridymite, or high-quartz,[6] depending on the amount and kind of alkalies and other cations present.

## PHYSICAL PROPERTIES

In its purest form, opal is white to colorless and transparent, commonly milky white or bluish white; also, through admixture of pigmenting material, ranges from yellow and yellowish brown to brown, reddish brown, orange, green, and blue, but usually in pale shades; also gray to black. Opal is sometimes found colored red by disseminated cinnabar[7] or orange-yellow by orpiment; frequently brown or reddish brown by iron oxide. It sometimes shows a rich internal play of colors by reflected light (precious opal). Streak white. Three different color mechanisms occur in opal: pigmentation by finely divided foreign material; interference of light, giving the color play of precious opal; and scattering of light, causing a pale bluish tint in reflected light and a brownish tint in transmitted light. The third mechanism is dominant in the turbid, milky types of opal. Two or all three mechanisms can coexist in a given specimen, but intensive pigmentation by dispersed, opaque foreign material may so reduce the optical transmission that observation of scattering or interference effects may be precluded. In the transparent and subtransparent types of precious opal interference of light is the dominant coloring mechanism, although a weak body-color caused by a foreign pigment also may be apparent. In the hyalite variety of opal, pigmentation, interference, and scattering effects are lacking. Opaque to transparent; generally subtranslucent to subtransparent.

Fracture conchoidal in varying degree; also flat-conchoidal to smoothly undulatory or broadly ribbed, in some types splintery to irregular. Moderately brittle, occasionally markedly so. May spontaneously crack by sudden change of temperature and, more generally, by partial dehydration. Density variable, depending primarily on the water content and on porosity and cracks; usually 1.99–2.25, but ranging down to about 1.8 in sinters and porous material. The density increases with absorption of water, markedly in the case of hydro-phane and other very porous, dehydrated types (see *Dehydration*). Hardness $5\frac{1}{2}$–$6\frac{1}{2}$. Some opal, especially hyalite, shows a greenish yellow fluorescence in ultraviolet radiation because of traces of the uranyl ion.[58] Not changed in color by irradiation with x-rays.[73]

## OPTICAL PROPERTIES

Opal usually is isotropic, but may show weak anomalous birefringence because of strain and is then uniaxial negative. The index of refraction of different specimens varies with the water content and usually is in the range 1.435–1.455 (Tables 37, 38, and 39). These values are much below the mean index of refraction of coarsely crystallized low-cristobalite, 1.485. The index of refraction of individual specimens increases as additional water is taken up and decreases below the original value as water is removed to leave voids (see *Dehydration*). Minute fibers or bundles of chalcedony are sometimes seen in opal, especially in opaline cherts and other rock-forming types. Fibrous cristobalite, lussatite, sometimes occurs associated with or admixed with opal, but most opal that yields an x-ray diffraction pattern of low-cristobalite does not show such fibers. Microscopic crystals of tridymite were said[51] to be common in opal, probably through confusion with lussatite or chalcedony.

The origin of the color play in precious opal is not well understood. The display of colors is seen in reflected light, not in transmitted light, or very weakly, and the individual colors often are of considerable spectral purity and strength. A spectral line width of about 20 Å has been measured for some red colors. The color play does not appear in monochromatic illumination. Although the colors are caused by the interference of light, the nature of the structure that gives rise to the effect is problematic.[8] It may be an open, regularly spaced grid-work of crystallites of cristobalite. Some specimens of precious opal, however, give an x-ray powder pattern, whereas others do not. Thin lamellae with an index of refraction different from that of the adjoining material, and systems of cracks or fissures, perhaps filled with opal of slightly different index of refraction, also have been postulated. The high saturation of the colors requires that the structure be periodic over a considerable thick-ness. Strains set up during the drying of the initial gel and of the opal may be a factor.

Table 37. Index of Refraction of Opal

| Locality | $n$, Original | $n$, after Immersion in $H_2O$ | Ref. |
|---|---|---|---|
| Hyalite, Waltsch | 1.458 | | 9 |
| Hyalite, Waltsch | 1.455 | | 10 |
| Hyalite, Waltsch | 1.4374 | | 10 |
| Hyalite, Mexico | 1.451 | | 12 |
| Hyalite, North Carolina | 1.418–1.425 | | 16 |
| Hyalite, Guanajuato | 1.456–1.458 | | 17 |
| Hyalite, California | 1.420 | | 18 |
| Hyalite, Austria | 1.457 | | 56 |
| Hyalite, Austria | 1.437 | | 56 |
| Hydrophane | 1.406 | 1.446 | 10 |
| Hydrophane | 1.266 | 1.406 | 10 |
| Hydrophane | 1.387 | 1.439 | 10 |
| Hydrophane | 1.368 | 1.443 | 13 |
| Hydrophane | 1.2290 | 1.3961 | 15 |
| Hydrophane | 1.398 | 1.4344 | 15 |
| Tabasheer | 1.119 | 1.364 | 10 |
| Tabasheer | 1.111 | | 14 |
| Opal, plant cells | 1.430–1.452 | | 78 |
| Diatomite | 1.440–1.448 | | 20 |
| Diatomite | 1.441 | | 19 |
| Geyserite, Iceland | 1.428–1.445 | | |
| Opal, milky | 1.442 | | 10 |
| Opal, milky | 1.4536 | | 9 |
| Opal, milky, Austria | 1.466 | | 56 |
| Opal, milky, Austria | 1.439 | | 56 |
| Opal, milky, Austria | 1.431 | | 56 |
| Opal, white, Austria | 1.473 | | 56 |
| Opal, bluish, Austria | 1.439 | | 56 |
| Opal, yellow, Austria | 1.444 | | 56 |
| Opal, yellow, Austria | 1.458 | | 56 |
| Opal, Brazil | 1.428–1.436 | | 55 |
| Opal, Styria | 1.431–1.473 | | 56 |
| Opal, Italy | 1.440–1.446 | | 57 |
| Opal, brownish, Queretaro | 1.418–1.422 | | 16 |
| Opal, wood | 1.415–1.423 | | 16 |
| Opal, yellow, Virgin Valley | 1.414 | | 16 |
| Opal, milky, Camp Verde, Ariz. | 1.448 | | 16 |
| Opal, fire, Guatemala | 1.450 | | 10 |
| Opal, Guatemala | 1.446 | | 10 |
| Opal, colorless, Guatemala | 1.442 | | 10 |
| Opal, fire, Mexico | 1.440 | | 11 |
| Opal, fire, Mexico | 1.433 | | 12 |

TABLE 38. SOME CORRELATED PROPERTIES OF OPAL

| Locality | Specific Gravity | Index of Refraction | Water Content | Ref. |
|---|---|---|---|---|
| Opaline chert, California | 1.983 | 1.445 | 7.34 | 21 |
| Opaline chert, California | 1.992 | 1.444 | 7.08 | 21 |
| Wood opal, California | 2.068 | 1.448 | 5.96 | 21 |
| Hyalite | 2.028 | 1.444 | 8.35 | 21 |
| Hyalite, Honduras | 2.111 | 1.456 | 4.93 | 21 |
| Wood opal, California | 2.098 | 1.451 | 5.05 | 21 |
| Opal, in rhyolite | 2.009 | 1.441 | 8.70 | 21 |
| Opaline chert, California | 2.080 | 1.448 | 6.3 | 21 |
| Opaline chert, Nevada | 2.067 | 1.451 | 5.34 | 21 |
| Opaline chert, California | 2.016 | 1.448 | 4.75 | 21 |
| Opal, Hungary | 2.096 | 1.4531 | 6.33 | 22 |
| Hyalite, Hungary | 2.036 | 1.4465 | 8.97 | 22 |
| Hyalite, Japan | 2.139 | 1.4567 | 4.71 | 22 |
| Hyalite, Bohemia | 2.160 | 1.4592 | 3.55 | 22 |
| Opal, fire, Zimapan | 2.008 | 1.4410 | 9.16 | 22 |
| Opal, green, Moravia | 2.038 | 1.4445 | 7.40 | 22 |
| Opal, yellowish, Moravia | 2.074 | 1.4491 | 7.05 | 22 |
| Opal, milky, Moravia | 2.046 | 1.4528 | 5.36 | 22 |
| Opal, milky, Moravia | 2.075 | 1.4499 | 6.27 | 22 |
| Opal, milky, Moravia | 2.116 | 1.4525 | 5.30 | 22 |
| Opal, milky, Moravia | 2.098 | 1.4518 | 5.36 | 22 |
| Opal, milky, Moravia | 2.056 | 1.4499 | 6.05 | 22 |
| Opal, milky, Moravia | 2.070 | 1.4478 | 6.17 | 22 |
| Opal, milky, Moravia | 2.055 | 1.4496 | 5.58 | 22 |
| Opal, milky, Moravia | 2.122 | 1.4501 | 5.25 | 22 |
| Opal, milky, Moravia | 2.104 | 1.4512 | 4.76 | 22 |
| Opal, milky, Moravia | 2.025 | 1.4425 | 8.36 | 22 |
| Hyalite, Waltsch | | 1.4590 | 3.4 | 23 |
| Hyalite, Germany | | 1.4562 | 4.84 | 23 |
| Opal, fire | | 1.4514 | 8.5 | 23 |
| Opal, Hungary | | 1.4459 | 9.73 | 23 |

TABLE 39. VARIATION IN INDEX OF REFRACTION OF PRECIOUS OPAL[24]

| Locality | Original Index (white light) | After Immersion in $H_2O$ for 48 hr. | After Heating at 74°C. for 48 hr. |
|---|---|---|---|
| Hungary: girasol, bluish | 1.433 | 1.451 | 1.421 |
| Querétaro: fire opal, red brown | 1.441 | 1.443 | 1.432 |
| Virgin Valley: transparent, pale brown | 1.447 | 1.448 | 1.442 |
| White Cliffs: milky, green and blue color play | 1.456 | 1.457 | 1.449 |

The Virgin Valley and Querétaro material gave strong, broad x-ray powder lines of cristobalite; the other material, a extremely faint and diffuse pattern.

## CHEMICAL COMPOSITION

Opal is hydrous silica, $SiO_2 \cdot nH_2O$. The water content is quite variable, ranging up to 20 per cent or more in some natural material, but commonly is in the range from 4 to 9 per cent. A small part of the water may be held structurally in interstitial positions in the cristobalite crystallites that compose the material. The great bulk of the water, however, is adsorbed or capillary and is readily lost on strong desiccation or heating or, in part, by exposure to a dry atmosphere (see *Dehydration*).

Over 100 chemical analyses of opal and sinters have been reported,[25] and a selection is cited in Table 40. Aside from $SiO_2$ (which on an anhydrous basis generally ranges well over 90 per cent) and $H_2O$, the principal constituents are $Al_2O_3$, $Fe_2O_3$, CaO, MgO, and alkalies. The role of these constituents is not well established, but in many instances they must be ascribed in part or entirely to admixed clay, coprecipitated gels of $Al_2O_3 \cdot nH_2O$ and $Fe_2O_3 \cdot nH_2O$, and other physical impurities. The analyses are in general similar to those of flint, chert, and chalcedony. In part, especially with regard to the Al and alkalies, these constituents may represent material held in solid solution in cristobalite, and are responsible for the (metastable) crystallization of this phase, but there is no proof of this plausible supposition.

The content of Al usually ranges from a few tenths of a per cent of $Al_2O_3$ up to a few per cent, with $Fe_2O_3$ ranging to somewhat higher values, 5–7 per cent, and in red or brownish opals, evidently admixed with iron oxide, up to large amounts. Although CaO and MgO vary widely, they generally are present below 1 per cent or are lacking. Alkalies, not always reported in analyses of opal, are generally in the range of a few tenths to 1 weight per cent. There is no correlation of the alkalies with the amount of Al present. Organic material is found in some opals, such as those of Virgin Valley, Nevada, and $SO_3$ may be present (see *Melanophlogite*). An opal incrustation on sodalite-syenite from the Kola Peninsula, Russia,[59] contained much Na and F, apparently as admixed NaF. Opal and siliceous sinter has been found[60] to have a relatively high ratio of $Si^{28} : Si^{30}$ (30.09). An opal pseudomorph after gypsum has been found[61] to contain $0.0X$ per cent Ge, and up to 0.03 per cent Ge has been found in opal in fumaroles.[79]

Opal is readily and completely soluble in hot, strongly alkaline solutions.[26] An insoluble residue of admixed clay, chalcedonic silica, sand grains, iron oxide, etc., may be left. Hyalite is less rapidly attacked. Opal also may be partly or completely decomposed by hot, concentrated HCl, affording a gelatinous residue on evaporation, and it is more readily soluble in HF than is chalcedony or powdered quartz. The more rapid attack on opal by acids and alkalies is caused by the high porosity and relatively small particle size of this

TABLE 40. ANALYSES OF OPAL

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 85.80 | 91.89 | 88.73 | 92.31 | 89.55 | 86.54 | 92.67 | 96.48 | 43.60 | 96.46 |
| $Al_2O_3$ | 3.22 | 1.40 | 0.99 | | 0.49 | 1.73 | 0.80 | Tr. | Tr. | |
| $Fe_2O_3$ | 1.85 | | | 0.36 | | | | 0.30 | 52.16 | 0.08 |
| $CaO$ | 0.96 | | 0.49 | 0.22 | 0.63 | 0.55 | 0.14 | | | 0.09 |
| $MgO$ | 1.08 | 0.92 | 1.48 | 0.18 | 0.57 | 0.74 | 0.05 | | | Tr. |
| $Na_2O$ | Not det. | | | | | | 0.18 | | | |
| $K_2O$ | Not det. | | 0.34 | | | | 0.75 | | 0.08 | |
| $H_2O$ | 6.95 | 5.84 | 7.97 | 5.31 | 8.03 | 9.40 | 5.45 | 3.33 | 3.75 | 3.26 |
| Rem | | | | | | | | Tr. | 0.37 | |
| Total | 99.86 | 100.05 | 100.00 | 98.46 | 99.27 | 98.96 | 100.04 | 100.11 | 99.96 | 99.92 |
| $d$ | 2.07 | 2.07 | | 2.198 | 2.01 | 1.97 | | 2.13 | 3.18 | 2.06 |

1. Precious opal. Virgin Valley, Nev. (?).[27] 2. Fire opal. Washington County, Ga.[28] 3. Fire opal. Faroe Islands.[29] 4. White opal. Rákos, Hungary.[30] 5. Hyalite. Elba.[31] 6. Milk opal. Elba.[31] 7. Siliceous sinter. Steamboat Springs, Nev.[32] 8. White opal. Nikolaevsky mine, Altai, Russia.[54] With trace $SO_3$. 9. Red opal. Nikolaevsky mine, Altai, Russia.[54] Rem. is $SO_3$, $Na_2O$ tr. 10. Opal. Yugoslavia.[62] $H_2O(+)$ 1.34, $H_2O(-)$ 1.92.

material.  This behavior has led to the belief that chalcedony, which is soluble in hot alkalies to a certain extent, contains opaline silica as an interstitial material (see further under *Chalcedony*).


## DEHYDRATION

The variation in the water content of different opal specimens as found in nature presumably is connected with both initial differences during formation and with dehydration during later history.  It has been shown that the dehydration of artificial silica gels is accompanied by a decrease in bulk volume up to a more or less well-defined point, beyond which further loss of water is accompanied by the development of voids.  Whether or not a natural opal has formed in this way, it is found that natural material in general has reached a point in which the internal structure has become so established that artificial dehydration over short periods of time is accompanied by the development of voids with little or no change in bulk volume.

In general, the lower the content of water in different specimens of untreated natural material, the higher the specific gravity and the index of refraction. This is shown[21] by the data of Table 38.  On the other hand, if an individual specimen is treated under laboratory conditions, it is found that dehydration is accompanied by a decrease in the specific gravity and the index of refraction.  An opposite change is produced by hydration.  Since natural material in general contains some voids, at least in specimens preserved under museum conditions, hydration by immersion in water may increase the content of water, and also the specific gravity and index of refraction, over the initial values of the specimen.

The water is lost continuously on dehydration, and definite hydrates are not present (as has been claimed[34]).  A very small part of the water may be held to high temperatures,[35] perhaps representing $H_2O$ in interstitial solid solution or (OH) in substitution for O in the $(SiO_4)$ tetrahedra.  Bound (OH) has been identified in some opal by infrared absorption study.[17]  The rate at which water is lost under laboratory conditions varies considerably in different specimens.[36]

Dehydration of large pieces usually is attended by cracking, and on large loss of water initially transparent or translucent material becomes white, opaque, and porous.  Desiccated, porous natural material readily imbibes water, in instances up to 50 per cent or more of its volume.[33]  Hyalite has been observed to convert to quartz under shear at high confining pressures.[47]  The hydrophane variety of opal, in its natural state white or yellowish and virtually opaque, by the absorption of water becomes almost transparent,[33] and some specimens acquire the play of color of precious opal.  Organic liquids also are absorbed,[15] as are index-liquids and wax, and ammonia.[63]  Cacholong opal

also is very porous and adheres to the tongue but does not become transparent on immersion in water.

## SYNTHESIS

Hard, opal-like masses of hydrous silica, sometimes transparent, or showing a color play, have been obtained experimentally by reaction of fluosilicic acid with glass,[37] by precipitation of sodium or potassium silicate or ethyl silicate solutions in various ways,[38] by the decomposition of silicon chloride or silicon fluoride,[39] and in other ways.

## VARIETIES

The varietal nomenclature of opal, like that of the fine-grained varieties of quartz, has been greatly extended by trivial terms that refer to variations in color, gross structure, state of aggregation, and other secondary characters. A few of these terms have been preserved in the synonomy, which see. Other names or terms of more specific reference that are in general use are mentioned below.

**Precious Opal; Noble Opal.** Exhibits a play of brilliant colors, variously red, orange, green, or blue, appearing as spangles, wavy or flame-like bands, sheets, etc., usually set in a translucent to subtransparent matrix of a milky white or other body-color. Black opal has a black or other very dark body-color with a play of color. Harlequin opal has a variegated appearance, with a mosaic-like pattern of color in rounded, angular, or roughly rectangular patches of about equal size. Pin-fire opal exhibits closely spaced specks or pinpoints of color. The terms matrix opal and mother-of-opal are applied to matrix material containing closely spaced veinlets or specks of opal, sometimes cut as cabochons or plates.

**Fire Opal.** A type of precious opal with a dominantly red or orange play of color usually set in a relatively transparent background with a pale yellowish, to yellowish red, orange, or brownish red body-color. The name is also improperly extended to transparent or highly translucent opals with an orange-red, brownish red, or red body-color that do not show a play of color. Chiefly from Mexico.

**Girasol or Girasol Opal.** A kind of precious opal, relatively transparent, with a rather uniform bluish or reddish floating or wavy type of internal light.

**Common Opal.** In general, opal without a play of color; also opal without a body-color, degree of translucency or markings to make it of value as an ornamental material. Includes milk opal, hyalite, opaque to semi-translucent opal of various ordinary colors, wood opal, rock-forming opaline silica, etc.

**Hyalite.** A hyaline type, colorless and clear as glass. Often occurs as crusts with a botryoidal, globular, or reinform surface, also stalactitic. Sometimes faintly tinted, usually blue, green, greenish yellow, or yellowish, and passing into translucent milky or white material. Hyalite tends to have a higher index of refraction and lower water content than most opal. Named from ὕαλος, *glass*.

**Hydrophane.** A white or light-colored translucent to opaque type of opal that becomes virtually transparent when placed in water.

**Tabasheer or Tabaschir.** A milky white opaline silica deposited within the joints of bamboo. Density 0.5–0.6, with $n$ about 1.12. Dried material very strongly absorbs water and becomes transparent.[40]

**Cacholong.** An opaque, white to yellowish type of opal with a mother-of-pearl luster; rather porous, but does not become transparent in water.

**Milk Opal.** A translucent to opaque type of common opal with a milk white, pale bluish white, or greenish white color.

**Wood Opal.** Common opal, generally yellowish or brownish in color, sometimes dark brown to brownish black, found as the petrifying material of wood and often preserving the details of the woody structure.

**Moss Opal.** Contains dendritic or other imitative inclusions, in appearance and origin similar to those in moss agate.

## OCCURRENCE

Silica formed at or near the surface of the Earth's crust by the action of biochemical processes, which are dominant in the deposition of silica from sea water and lakes, and by inorganic precipitation either directly from solution or by chemical reaction at essentially ordinary temperatures and pressures, is in general deposited in a form variously called opal, opaline silica, or "amorphous silica." These types of silica chiefly consist of submicroscopic crystallites of cristobalite with a more or less disordered structure and are believed to contain significant amounts of $H_2O$, Al, alkalies, and other elements in interstitial solid solution (see further under *Cristobalite*). The cristobalite is metastable relative to quartz in these surficial geological environments and tends to convert to the stable form, quartz, or to microfibrous varieties thereof, with time and more rapidly with increasing temperature.[72] The chemical and structural nature of the cristobalite and the composition and $p$H of the aqueous solutions with which it is in contact are other factors in this conversion. It may be noted that the solubility of silica in natural surface and near-surface waters at ordinary temperatures and pressures is primarily determined against this type of cristobalite as the solid phase (giving solubilities of about 120 p.p.m.) rather than against quartz (about 7 p.p.m.).

The great bulk of the opaline silica found in nature is constituted of sedimentary accumulations of the tests of silica-secreting organisms such as

diatoms, radiolaria, and sponges. These may form very extensive geologic formations, the diatomaceous rocks of the Monterey formation in California, e.g., reaching a thickness of many thousands of feet. The opaline silica of such deposits may be reconstituted during diagenesis or low-grade metamorphism into chalcedonic or microgranular quartz, forming chert, sedimentary jaspers, flint nodules, etc. Opaline silica also is secreted by some forms of terrestrial plant life, especially by the Gramineae. Concretions of opaline cristobalite have been found in the urinary tract of animals.[78]

Opaline silica also is formed inorganically in a variety of ways. These include chemical weathering processes, direct deposition from hot springs and from low-temperature hypogene solutions at shallow depths, and deposition from the meteoric circulation. Among the important sources of dissolved silica in deep natural waters not of igneous origin are opaline organic remains in sediments, and the chemical alteration, with release of silica (desilication), of glassy material and of silicates in volcanic ashes and tuffs. Cristobalite, presumably present as disseminated opaline silica, is a characteristic constituent, together with montmorillonite, of bentonite.[50] Opal forms by the solfataric alteration[66] of basaltic and other rocks, the acid solutions leaching the alkalies, alkaline earths, Al, and Fe and leaving a siliceous residue. Opal has been found as pseudomorphs after augite on Vesuvius.[76] A deposit of kaolin containing cristobalite and alunite formed by the hydrothermal alteration of volcanic tuffs occurs in west Texas.[75] Kaolin with alunite, sulfur, and cristobalite occurs around fumaroles in andesite tuff in the Ibusuki caldera, Kyushu, Japan.[80] The siliceous sinters and geyserites formed about the orifices of hot springs and geysers may be largely opaline and formed both by precipitation from the siliceous waters, through the action of organisms, and in part, especially about fumaroles and along the deeper channels of hot springs, by the chemical alteration of the wall rocks. The opaline silica formed during weathering also is chiefly produced by the chemical breakdown of silicates. Tripoli is a residual deposit, consisting of friable, very fine-grained chalcedonic and opaline silica, formed by the weathering of siliceous limestones and calcareous cherts.

The varieties of opaline silica of mineralogical rather than geological interest, including precious opal, fire opal, milk opal, hyalite, and the like, are formed principally by inorganic deposition in cavities and veinlets, either in association with igneous activity or in the meteoric circulation. Opal, including precious opal, is found frequently, sometimes in association with zeolites, in igneous flow rocks, especially those of an acidic and alkalic character, such as rhyolites and trachytes, and in their tuffaceous equivalents. It also occurs in basalts and other basic effusive rocks, but agate and other types of chalcedonic silica are more typical of this type of environment. In these occurrences the opal is found in cavities and veinlets as a postconsolidation product formed by hydrothermal activity or, especially in tuffs and ash beds, by the

entrance of meteoric waters. Both opal and chalcedony very commonly occur
as the petrifying material of wood in volcanic ash, tuffaceous rocks, and sedi-
ments. Also as irregular masses, nodules, and veinlets in cherty calcareous
rocks and sandstones, often replacing bones, shells, and other fossil material.
At some occurrences the formation of the opal appears to be a near-surface
effect related to weathering processes under arid conditions in rock types of
favorable composition. Opal also is found as an alteration product in serpen-
tine,[71] where it may be associated with magnesite or garnierite. It may occur
as a cementing material, as in sandstones,[70] or may form veinlets.

In some types of occurrence, especially those in the cavities of igneous
rocks, the silica appears to have been initially deposited in gelatinous form
and later to have hardened into opal; the process may continue with con-
version into chalcedonic silica. In a generalized hydrothermal sequence, opal
forms and remains metastably as such in the lowest range of temperatures,
below roughly 100–150°. Chalcedony forms either directly or by relatively
rapid conversion from opaline silica at somewhat higher temperatures, and
coarsely crystallized quartz is deposited at still higher temperatures. In some
instances fibrous cristobalite (lussatite) apparently forms by crystallization of
opal and has been observed to convert in turn to chalcedony.[42] Gelatinous
silica itself has been found[41] in some igneous and sedimentary occurrences, as
in the diabase sills of New Jersey, in the Chalk formation of England, in
cavities in flinty and marly rocks in France, in solfataras, and with hydrophane
in porphyry at Hubertusberg, Saxony. On exposure to air, as has been obtained
with artificial silica gels, it dries out, hardens, and sets to a hyaline mass or
whitens and falls to a powder which under the microscope is seen to be
opaline.

## LOCALITIES

The principal localities for opal of gem quality and a few other localities
for material of specimen interest are mentioned beyond. A traditional locality
for opal that has supplied fine gem material since Roman times is in the neigh-
borhood of Červenica, notably on Mount Simonka and Mount Libanka, in
Saros Comitat in northern Hungary. This was the principal source of precious
opal until the development of the Australian occurrences in the latter 1800's.
Here precious opal occurs as nests and rounded masses in altered and bleached
zones in an andesite associated with much milk opal and other types of
common opal. The formation of the opal has been ascribed to ascending
hydrothermal solutions. The precious opal largely occurs as thin seams and
bands in massive milk opal; also as nodules in cavities. Remarkable gem
pieces up to 600 grams in weight have been found. Hungarian opal, often
accepted as a standard of comparison, has a rather characteristic appearance,
showing a display of brilliant colors, chiefly reds, greens, and violet-blues,

that are irregularly distributed as relatively small patches and spangles against a more or less milky or whitish background. The most valued material is relatively translucent, with only a slight milky appearance, and a strong color play. Other European localities for opal yield chiefly the common varieties, which occur abundantly in the basaltic rocks of northern Ireland, the Faroe Islands, and Iceland; at numerous localities in Germany, as in the trachytes of the Siebengebirge; a milk white and bluish white opal in serpentine at Kosemütz in Silesia; in the Puy-de-Dôme, Plateau Central, France.

Fire opal and precious opal are found at various places in the state of Querétaro, Mexico. The opal occurs there[64] as nodular masses and patchy areas in a reddish brown to pinkish rhyolite. Cavities may be only partly filled with opal, often banded as milky, hyaline, and other types, or they may contain loose nodules. Mexican or Querétaro opal varies considerably in detail. The fire opals range in body-color from pale brownish yellow, straw yellow, and reddish brown shades through orange and orange-red to brown, deep brownish red, and red. These opals, which in general are relatively transparent, may show color play, usually red and green. Uniformly colored types are sometimes cut as faceted stones. The reddish and brownish body-tints are caused by iron oxide. Other types of Querétaro gem opal are virtually transparent with a bluish white haze or brilliant spangles of color, or have a milky white appearance with bright flakes of color and resemble Hungarian opals. Fine fire opal also has been obtained at Zimapan, Hidalgo, and was brought to Europe in the early 1800's; an analysis was reported by Klaproth in 1807. The Querétaro opal is said to have been first worked in the latter 1800's. Opal was used for mosaics and other purposes by the Aztecs. Opal, including gem types, is found widely in Honduras, notably near Erandique, as veins and which may show an interlamination of platy masses, or streaks of precious opal and common opal, in trachytic rocks. The deposits have been known since the early nineteenth century.

Numerous important localities for precious opal are known in Australia.[65] In New South Wales, the Lightning Ridge area afforded fine black opals showing a gray to black body-color with a lively play of red, green, and deep blue or purple, or with uniform deep blue to dark purple background play of color and intercalated green and red flames At this place and at White Cliffs opal and precious opal occur as thin veinlets and seams often trending along bedding planes and joints in sandstones and conglomeratic rocks, the Desert Sandstone, of Upper Cretaceous age. The opal workings are shallow. At White Cliffs opal with color play was found as pseudomorphs after large groups of glauberite crystals[43] resembling pineapples; also opalized fossils, including belemnites, brachiopods, gastropods, and animal bones. Many gem localities are known in Queensland in a similar geologic setting. The Queensland opal usually is of a milky or bluish white body-color with flashes of blue and green, and also red. Gem opal also is obtained at Andamooka, Coober

Pedy, and other localities in South Australia and in western Australia. Some of the Australian opal, especially that from White Cliffs, shows a patterned arrangement of the color play; the valued Harlequin opal has a variegated display in more or less regular arrangement of round, angular, or roughly rectangular areas, and the pinpoint opals have minute flecks of color. Much Queensland and other Australian opal is found in relatively thin veinlets or sheets and is cut as flat plates, often backed with other material, rather than *en cabochon*. Australian opal in general shows colored areas of larger size than Hungarian opal, as well as relatively large areas of uniform color, although not as marked as in most Virgin Valley opal; in many instances two colors predominate, usually either red and green or green and blue.

In the United States, common opal and wood opal are very widely distributed. Precious opal has been obtained notably in the Virgin Valley in Humboldt County, Nevada. These deposits, found about 1906, contain opal chiefly as the petrifying material of wood embedded in Tertiary ash and tuff beds with interstratified coarse detrital material. The wood shows all stages of petrifaction by precious or common opal or chalcedony, from partly silicified lignitic material to completely replaced masses. The precious opal usually occurs in cracks or seams in the more or the completely silicified wood, or envelops such material; also as solid masses or limb sections of wood, often having a zonal structure but not preserving the cellular structure of the wood, and possibly representing casts. The Virgin Valley precious opal occurs in pieces of relatively large size, and remarkable specimens have been preserved.[49] Most of the precious opal ranges from nearly colorless or faintly brownish or yellowish with a limpid appearance to brownish black or black, then of diminished transparency. The color play typically is red, often with orange and yellow, and is developed over relatively broad areas; also shades of green and, less commonly, blue and purplish tints which may be disposed as a rather uniform glow. Translucent bluish and white or milky white types of opal sometimes with color play also are found. The Virgin Valley opal is particularly subject to cracking and to surface crazing by dehydration, with internal strains accentuated by zones of varying water content concentric to the outline of the wood sections; this behavior has limited its application as a gem material.

Precious opal has been found in a number of minor occurrences elsewhere in the United States, as near Opal Mountain in San Bernardino County, California; near Whelan in Latah County and in Lemhi and Owyhee counties, Idaho; and in Oregon. Notable localities for opalized wood include Yellowstone Park, Wyoming; localities in Socorro and Sierra counties, New Mexico; Clover Creek, Lincoln County, Idaho; the Latah formation over a wide area in Klickitat, Yakima, and Benton counties, Washington. Opalized termite pellets have been found in fossil wood.[52]

Colorless opal, hyalite, is of very wide occurrence. Found particularly as

crusts and stalactitic masses in cavities in basaltic rocks, as at Waltsch, Bohemia; the Puy-de-Dôme, France; numerous localities in the Columbia River basalts of the northwestern United States; Iceland; the Faroe Islands. Also as spherules at Tateyama and Sankyo, Japan;[44] at Querétaro and Guanajuato, Mexico; etc. Hyalite often occurs as crusts and films along fracture and joint surfaces in pegmatite, granites, and other rocks; it often shows a bright lemon-yellow fluorescence in ultraviolet radiation because of traces of uranyl compounds released from accessory minerals during weathering. Fine specimens have been found in Mitchell County, North Carolina. Hyalite also is found associated with precious opal, especially in occurrences in volcanic rocks. Opaline siliceous sinters are found in regions of hot spring and geyser activity, as in Yellowstone National Park, Wyoming; Steamboat Springs, Nevada; Iceland; and New Zealand. Hyaline opal is a product of the decomposition of a Roman cement in the hot springs of Plombières, France.[45] Opal has been found in hollow spherulites in perlite at Hosaka, Iwashiro Province, Japan.[53] Opal and chalcedony occur as hydrothermal alteration products of pitchstone and volcanic ash on Specimen Mountain, Rocky Mountain National Park, Colorado.[67] Opal containing dendritic enclosures occurs as nodules in limestone in Morrill County, Nebraska.[68] Reniform, tuberose, and other concretionary forms of opal (menilite, pt.),[69] usually of grayish or grayish brown appearance, or black, and dull in luster, are found in argillaceous limestone and marls, as at Limagne and Aurillac, Plateau Central, and in the Paris basin, France.

## HISTORICAL

The name opal is believed to have derived from the Sanskrit *upala, precious stone* or *gem*. Opal is said to have been obtained in ancient times from India, with material of lesser quality from Egypt, Arabia, and various localities in the Mediterranean region, but from Roman times almost to the twentieth century the principal source of supply was Hungary. In Byzantine time Constantinople was the center of distribution of Hungarian opal. Opal (*opalus, paederos*) was the favorite gem of the Romans. Pliny termed precious opal of incomparable beauty and elegance, and relates the story of Nonius, a Roman senator who gave up house and country rather than yield a ring containing an opal the size of a hazelnut to the demand of Marcus Antonius. According to a modern authority, the finest opals were then worth over $20,000 a carat in present-day exchange. The high rank of the precious opal was long continued. B. de Boodt (1647) acknowledged it the most beautiful of gems, and Dutens (1779), who gave the same opinion, said that the finest opals were valued as high as diamonds. Ure (1853)[81] said, "In modern times fine opals of moderate bulk have been frequently sold at the price of diamonds of equal size: the Turks being particularly fond of them."

The popularity of opals decreased during the nineteenth century, partly because of a foolish superstition that they were unlucky (said to have been started by a romantic novel, *Ann of Geierstein, or, The Maiden of the Mist*, written in 1829 by Walter Scott, in which an opal talisman appears). The traditionally high value of opal, especially the milky precious opals from Hungary, also declined in this period with the appearance of abundant fine material, particularly black opal, from Australian deposits. Black opals and opals with a patterned display of color, such as Harlequin opals, are today among the most highly valued types. Black opal from an unstated source was known in Europe in the eighteenth century. In fact, as opposed to superstition, the principal ill fortune associated with opals is their tendency to crack by exposure to a dry atmosphere or to undergo dimunition of the color play and translucency, either by dehydration or by contact with grease and oil. Sudden temperature changes, e.g., during lapidary operations, should be avoided. The tendency to crack varies considerably in material from different localities, and even from a given locality, and is said to be least marked in Hungarian opal and more marked in that from Central America, Mexico, and especially the Virgin Valley, Nevada.

Girasol, from the Italian *gira-re, to turn*, and *sole, the sun*, is a name of relatively recent origin. It was early applied to precious stones that display fire when turned in sunlight, and also to fire opal, but now generally refers to opal with a uniform, diffuse bluish or reddish play of color, usually in a slightly milky background.

## ALTERATION

Opal occurs very commonly as a replacement of wood, as already noted, and has been found as pseudomorphs after glauberite,[43] gypsum,[46] calcite, aragonite, apophyllite,[74] siderite, and apatite.

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