"Contra Luz Opal:" Structure and Optical Properties

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Introduction

"Contra luz" means in Spanish "against the light." This opal is so named because it displays its diffraction colors, "play of color," not like precious opal by illuminating and observing its face, but by passing light through the stone. A weak expression of this characteristic of contra luz opal can be seen in a small percentage of the Mexican opal known as hyalite opal when a small chunk, especially if wet, is held toward a light. Hyalite opal is defined in the Funk and Wagnalls Dictionary as "a pellucid glassy variety of opal of no commercial value."

This author has collected a considerable number of pieces of such opal because it is important in unravelling the puzzle of the natural formation of opal (1, 2, 3). In cutting small slices off the rough faces of such opal, in order to see the structural features within, vivid interference colors were encountered in perhaps half of the hyalite opal nodules. These vivid colors were visible only in thin slices. Cursory examination of this opal suggested that the colors may have an origin similar to that of play of color in precious opal.

The structure of precious opal which gives rise to characteristic brilliant and pure interference colors was elucidated by a group of collaborating Australian scientists: Darragh, Gaskins and Sanders (2), who employed scanning electron microscopy to show that precious opal contains a regular lattice of closely packed silica spheres of uniform size and spacing, appropriate to cause color separation of visible light by optical interference.

The distance between layers in the lattice, d-values, were found to be approximately one half the wave length of visible light in a medium of refractive index of opal, 1.45. The dimensions found also correlated with the dimensions required to produce the predominant wave length of the play-of-color of different stones. The change of color with changing angle of illumination and observation correlated well with the expectations for such a diffracting system. They also studied Mexican precious opal which occurs in cavities of igneous rocks and an Australian opal of similar form. Using scanning electron microscopy, they studied such opal only enough to establish that these opals also contain a regular lattice structure of similar dimensions.

To my knowledge, no comparable study has been reported on the structure or optical properties of contra luz opal, perhaps because of its relative non importance as a gem stone. Interest in this stone also has been limited by the failure to recognize the importance of thin slicing. The facility of an electron microscope has not been available to me. It was, therefore, decided to determine if the observed play of color and optical properties could be explained on the basis of a regular lattice structure by analogy to the understanding of the structure of precious opal.

Observations

For comparison purposes, several Australian precious opals were sliced flat and the face ground flat by lapping in a direction and at a level to coincide with a layer of play of color in its face. After grinding with a 600 mesh diamond lap, a microscope cover slip was cemented over the flat face with epoxy 330 cement. Such flat faces simulate a well polished flat face.

These faces were illuminated with near parallel white light and observed and photographed at various angles. As the angle between illumination and viewing increases, the interference colors move to shorter wavelengths. For instance, an area which is green when illuminated and viewed at 10° from normal to the surface is blue at 30° and colorless at 70°. FIGURE 1 shows the geometry of this arrangement.

Representative thin slices of contra luz opal, generally less than 1 mm thick, were cut from hyalite opal nodules. Unlike the situation with Australian precious opal, the hyalite opal generally was sliced in a vertical orientation, that orientation being evident by the existence of a natural flat top on the nodule. These slices also were ground flat on a diamond lap and had a microscope slide and a cover slip cemented with epoxy 330 onto their faces. This results in very little scattering at the faces.

Optical arrangements were made to view and photograph the slices at varying angles when illuminated with a parallel beam of high temperature incandescent light. The observed colors against-the-light contrast with a total absence of play of color when these slices are observed under face illumination even under ideal conditions, for instance, when they are backed with a black plate. The observation and photography of these contra luz slices were made by the geometry shown in FIGURE 2. It is to be noted that the angle between the incident beam and the diffracted ray -within the stone - is much greater than the maximum angle achievable between incident light and diffracted rays in the system shown in FIGURE 1.

The play of color seen in such slices is generally less well separated into zones of a single color than is seen generally in Australian precious opal. The colors generally stream or grade into one another. It may well be that this distinction would be less prominent if the contra luz opal had been sliced generally along the horizontal direction as is generally done with Australian precious opal.

The play of color in a slice of contra luz opal shifts to shorter wavelength, entirely as expected, as the angle between the incident beam and the diffracted rays increases in these experiments. This is documented in photographs which can not be reproduced in this report. When the colors seen at specific angles between the incident and observed directions were employed to calculate d-values, the values were, of course, much greater than those calculated from observations on precious opal. Colors all the way from red to blue are seen in contra luz opal.

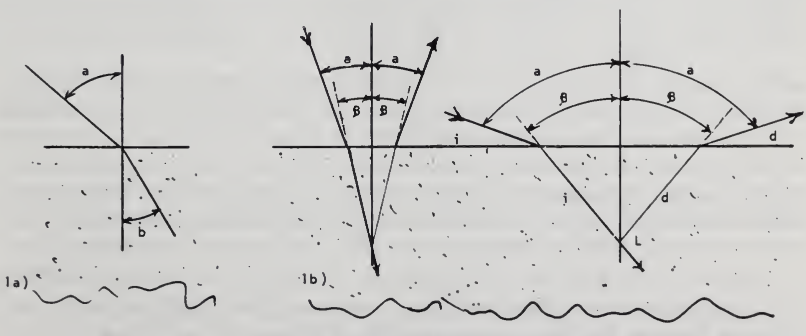

FIGURE 1—*a—Path of a ray entering or leaving opal, n = 1.45*
b—Scheme 1 face illumination (for precious opal)

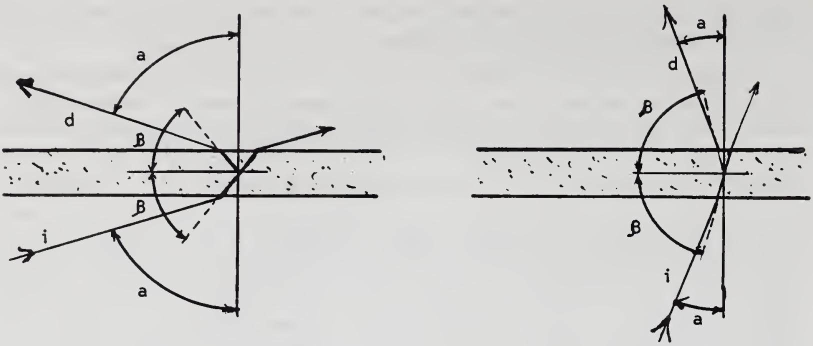

FIGURE 2—*Scheme II against-the-light viewing (for contra luz opal)*

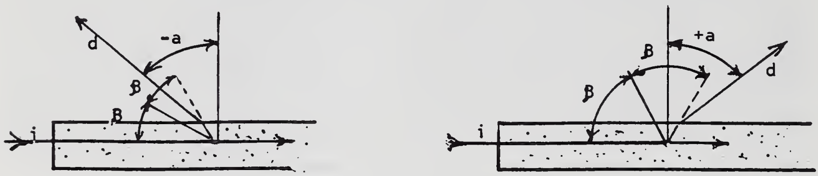

FIGURE 3—*Scheme III side light illumination (for medi opal).*

Some of the slices of hyalite opal prepared as above were found to produce little play of color when illuminated as in FIGURE 2. They were seen to: 1) show more color when illuminated at minimum angles in scheme 2; and 2) show intense play of color when the light was allowed to enter the edge of the stone and the face of the stone was observed. Analysis of this situation led to the understanding of the scheme of observation shown in FIGURE 3 and discussed in the later section.

Optical Considerations

When light enters a transparent solid from air at any angle other than normal to the surface, it is bent by an angle which depends on the refractive index of the solid and the incident angle. The refractive index of air is approximately 1.00 and that of opal is 1.45. The relation of the internal angle to the external angle is given by the formula $\frac{\sin a}{\sin b} = n_s$ where a is the angle between the incident direction in air and the normal to the surface, b is the corresponding angle between the incident ray inside the stone and an extension of the normal to the surface into the solid, and n_s is the refractive index of the solid, here 1.45. When a ray leaves the solid and enters air, it is bent identically at the surface, a and b having the same meaning as above. FIGURE 1 portrays the path of an incident ray i and that of a diffracted ray d which originates at a point L in the solid. In the first scheme of observation of interference colors used in viewing precious opal, this geometry is employed.

In the present treatment, the angles for entering and for emerging rays are kept equal to one another for simplicity of treatment. This restriction on viewing the stone does not limit the arguments which follow.

In the simplest case of illuminating and viewing the stone, both at normal angle to the face where a = O (and b = O) the relation of d, the distance between plates or layers of a diffracting system, to the wavelength of light giving constructive interference (λ_{air} and λ_{opal}) is simply:

$$1)\ d = \frac{\lambda_{opal}}{2} = \frac{\lambda_{air}}{1.45 \times 2}$$

Since diffraction occurs inside the stone, the angles between the incident and diffracted rays *inside the stone* are used for calculations. One half the angle between incident direction and the direction of the diffracted ray is designated as β in all schemes of observation.

In the more general case where the angle β is anything between 0° and 43.5°, the theoretical maximum value corresponding to a = 90°, the relationship of d, the angle β, and the wavelength of the diffracted ray in air or opal is given by the expressions which hold also for Schemes 2 and 3.

$$2)\ \frac{\lambda_{air}}{1.45} = \lambda_{opal} = 2\ d \left(\frac{1}{\cos\beta} - \tan\beta \sin\beta\right)$$

$$d = \frac{\lambda_{air}}{2 \times 1.45 \left(\frac{1}{\cos\beta} - \tan\beta \sin\beta\right)}$$

TABLE 1 contains the results of calculations of the d-values for typical interference colors when incident and diffracted rays are assumed to take several values of a and the consequent values of β. Note that the values at a = 0° and a = 90° are *theoretical* limits. *Feasible* limits of observation are more nearly a = 20° and a = 70°. Calculated d-values for these angles are also given in TABLE 1. This scheme of viewing is applicable to precious opal and is referred to as scheme 1.

The geometry of observations of contra luz opal - by looking through a thin slice of stone - is illustrated in FIGURE 2. In this case the angle between the incident and diffracted rays within the stone is greater than in scheme 1, having values between 2 x 46.5° and 2 x 90°. β the half angle, is between 46.5° and 90°. The feasible limits on viewing angles a are approximately 70° and 20°, corresponding to angles β = 49.6° and 76.4° respectively. Thus neither the feasible nor the theoretical values of β for schemes 2 and 1 overlap.

TABLE 1 contains the results of calculations of d-values for contra luz opal showing interference colors at feasible angles of observation. The theoretical minimum angle β is 46.5° and the theoretical maximum of β is 90°. But at β = 90° the value of d is infinite for all wavelengths and is not significant. Since the β ranges for schemes 1 and 2 do not overlap no lattice giving interference color by scheme 1 viewing can give the same color by scheme 2 viewing, and the reverse is true.

Of course a given stone might have lattices of widely varying d-values at different places. Different colors exhibited at different locations in a given stone at one angle of observation are an indication of this fact. In gemology a precious opal exhibiting different areas of color from red to blue at one angle is exceptional and is most highly prized.

If an opal had a lattice with a spacing d between the feasible ranges for precious and contra luz opals, it would not show interference colors by these schemes of viewing. Fortunately, a third scheme of viewing was discovered as

TABLE 1. *Calculated Lattice d-Values for Interference Colors at Feasible Angles for Precious and Contra Luz Opal*

Colors	Wave Length (nm) In Air	Wave Length (nm) In Opal	Precious Opal at Angles			Contra Luz at Angles		
			a* β** 0° 0°	a β 20° 13.6°	a β 70° 40.4°	a β 70° 49.6°	a β 45° 60.8°	a β 20° 76.4°
Blue	470	324	162	166	179	250	333	689
Green	520	358	179	183	198	276	368	762
Yellow	580	400	200	205	221	308	411	850
Orange	600	413	206	211	227	318	425	876
Red	650	448	224	229	247	348	460	952

* a is the external angle between normal to the surface and the viewing direction

**β is one half the angle between incident and diffracted rays within the opal.

In scheme 1, β = b; In scheme 2, β = (90° - b)

The relation $\frac{\text{Sin a}}{\text{Sin b}} = 1.45$ relates the internal angle of viewing to the external angle of viewing. See Figure 1a.

referred to earlier. We shall call it scheme 3 and represent it as in FIGURE 3. This scheme permits observation at β angles intermediate between and overlapping those of scheme 1 and scheme 3. The observation of vivid interference colors by this scheme, which may be referred to as "side light illumination," evidences continuity of d-values in ordered lattices through the range between those of precious opal and contra luz opal.

In scheme 3, the slice is illuminated through its edge and viewed through its face. In this case β has feasible values from 29° to 60.5°, corresponding to viewing angles between about 50° on each side of the normal to the face. TABLE 2 contains the results of calculating d-values for various colors viewed at feasible viewing angles relative to the incident direction by scheme 3. The author suggests the name medi opal for Mr. Opal of intermediate d-volumes.

Conclusions

These observations on three classes of opal support the conclusion that the sizes of silica spheres which form regular lattices in opal capable of producing interference colors vary widely outside those sizes observed by Darragh and coworkers for precious opal, and extend to at least double the diameter and interlayer spacing for precious opal. An extension of the electron microscope studies of Darragh *et al.* to hyalite opal would be pertinent.

While no statistical study was made of the distribution of d-values in a significant number of hyalite opal nodules, the spread of values in ten nodules ranged from approximately 300 nm to 800 nm. It may be supposed that opals do exist having d-values higher than those which show interference at feasible high angles of viewing by scheme 2. The highest d-values which one would be able to detect by this kind of viewing would give a blue interference near a = 0° in scheme 2.

To test this idea, an optical system is being put together to extend the feasible limit of observation to β values close to 90° in scheme 2. The upper limit of d-values which could be determined in this way depends only on how close to β = 90° one can make observations.

Perhaps the most significant question raised by these conclusions is: What process of natural formation leads to such wide ranging d-values, notwithstanding the regularity of the lattice required for the production of interference colors? This question was discussed by the author in reference 3.

TABLE 2: *Calculated Lattice d-Values for Interference Colors at Feasible Angles for Medi-oPal (side lighted)*

	Wavelength	MEDI-OPAL AT ANGLE		
	(nm)	a* β**	a β	a β
COLORS	IN AIR	-50 29°	0 45°	+ 50 60.5°
Blue	470	185	229	333
Green	520	204	253	368
Yellow	580	228	282	410
Orange	600	236	292	425
Red	650	256	317	460

* a is the external angle between the normal to the surface and the viewing direction. This angle is measured in a plane including the direction of the incident light. It is considered negative when it makes an acute angle and positive when it makes an obtuse angle with the direction of the incident light. See FIGURE 3.

** β is here: $\beta = (45° - \frac{b}{2})$ and $\beta = (45° + \frac{b}{2})$

Literature Cited

1. DARRAGH, P. J. and A. J. GASKIN. 1966. The Nature and Origin of Opal. Australian Gemmologist #66 p. 5-9.
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3. DAVIS, W. W., Indiana Academy of Science, Proceedings. 1978. p. 237-241.