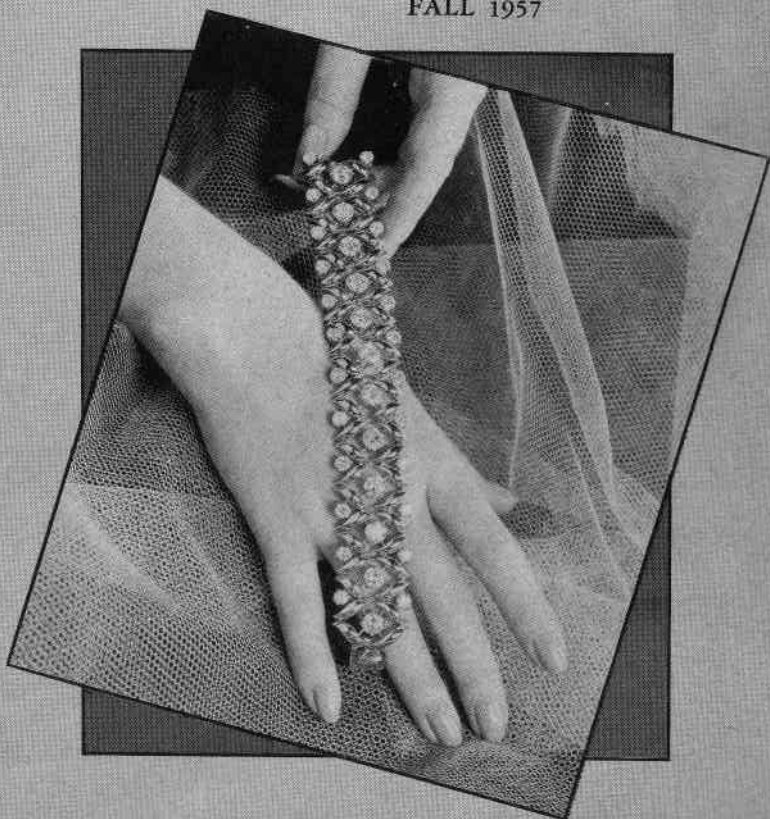


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On the Cover

An award-winning diamond bracelet by Julius Cohen, New York City. The criss-cross design, adapted from Middle East motifs, combines flowing lines in 18-karat gold with 36 choice diamonds set in decorative prongs.

*Photo courtesy Dorothy Dignam
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The Phase-Contrast Method

Yields Fascinating Knowledge in Gemological Microscopy

by

DR. EDWARD J. GUBELIN, C.G., F.G.A.

In 1932 F. Zernike*, the Dutch scientist, showed that differences in the optical path, causing what generally are referred to as *phase differences*, could be made visible in transmitted-light microscopy as differences in intensity. Zernike's idea, generally known as the *phase-contrast method*, and its further development may be considered as one of the greatest advances made in the field of modern microscopy, although until recently it has not been widely applied in mineralogy, let alone in gemology. The reason for this probably lies in the difficulty and expense of modifying the polarizing microscope for the application of phase-contrast microscopy. It also was believed that only thin sections of heterogeneous material with but slight differences in refractive index would yield good contrast pictures. It was necessary to have special phase-contrast equipment constructed (*Figure 2*) to be used in combina-

tion with a polarizing microscope, and these improvements in equipment and the writer's own work have proved it possible that even in gemology, with its relatively "bulky" objects, a wealth of contrast can be revealed with the Zernike Method, and that a profusion of new knowledge on the endogenesis of gemstones can be gathered.

Theory and Principles

Fundamentally, the phase-contrast method is employed whenever the worker wishes to secure contrast between object details that cannot be satisfactorily distinguished by the eye or on the photographic film under normal observing conditions. The desired contrast can be obtained wherever there are slight differences, either in thickness or in refractive power, among the materials that are viewed.

For proper interpretation of the images

obtained, it is necessary to understand the principle of the phase-contrast technique. It is not intended, however, to discuss the theory of phase contrast in full detail here; those readers who are further interested can obtain all desired information from the extensive literature* that already has been written on the subject. The essential aim of the method is to make visible those details of the transparent objects that are hardly or not at all visible in the ordinary bright field.

The bright-field illumination that is in most general use depends on the phenomenon that different parts of an object absorb and/or refract light in varying degrees; and thanks to absorption, refraction, or to both of these in combination, the object becomes visible as a definite image. In gemstones and their inclusions the contrast is often due to different coloration, which simply reflects selective absorption of different parts of the visible spectrum by the contrasting materials. Different degrees of absorption of all parts of the visible spectrum leads to contrast in the form of relative lightness or darkness. It is well known that where slight differences in index of refraction are involved, contrast between adjacent objects can be increased by closing the aperture of the condenser-iris and by additional de-focusing. With such operations, however, the effective resolving power of the microscope is seriously reduced.

A more satisfactory method of emphasizing contrast is dark-field illumination, as beautifully developed in the *Diamondscope**. The field of vision is dark, and a brilliant image of the structure is formed by the light diffracted along its contours. In dark-field illumination, however, only sharp borders between portions of different thickness or different refractive power generally are made visible, whereas soft transitions or interior details of inclusions are hardly visible or show up unsatisfactorily.

With the phase-contrast method normal

*Trademark

relief, as perceived between constituents of heterogeneous material, can be diminished — yet part or all of the object can be made to appear in strong contrast with the neighboring part or with the background. This method, which offers an enormous improvement in emphasizing contrast, has resulted from a development of Abbe's classical experiments on the visibility of images under the microscope. Abbe limited his studies mainly to light-absorbing objects, whereas Zernike investigated the formation of the microscopic image of nonabsorbing objects in terms of their influence on the phase of the passing light. He noticed that their diffraction image showed very characteristic differences as compared with images due solely to contrasting absorption effects:

- a) With absorption effects alone, the phases of the light waves coming from the virtual image do not differ from the phases of the waves coming from the secondary images. With effects due to differences in thickness and for refractive index of the materials being viewed, the light waves from the secondary images show a very definite phase difference ψ from the light waves of the main image. This kind of "retardation" depends, in a constitutional way, on the phase difference that the light waves undergo while passing through the object. Designating this latter phase difference φ , then the phase difference ψ between virtual image waves and secondary image waves is expressed by the equation:

$$\psi = 90^\circ \pm \frac{\varphi}{2}$$

- b) In general the differences in amplitude, and hence in intensity of the light waves coming from the main image 0 and the secondary images -1 and $+1$ are relatively small with absorbing effects but very great with "retarding" effects.

It is to Zernike's great credit that, while investigating the process, he recognized that the diffraction image of the light source, as is formed by phase effects, can be assimilated to the diffraction image caused by absorption effects through obliteration of the phase difference and assimilation of the intensity of the main image to that of the secondary images. The image involving phase effects must then assume the appearance of the corresponding image involving absorption effects only. By means of the phase-contrast method the phase differences (differences of the state of vibration) are converted into differences of intensity (brightness) and thus become visible — the range of phase-shifts caused by the differing parts of the object is thereby translated into a range of the most varying gradations of brightness. This means nothing else than the formation of an image that is rich in contrast through an artificial interference in the path of light (*Figure 1*).

In order to apply the phase-contrast method it is necessary to install a special contrivance in place of the image of the light source (that is, in the plane of the condenser iris), altering the phase of the virtual image wave against the phase of the secondary image wave in a desired manner and thus causing intensity balance between the two wave groups through absorption. The device consists of an annular iris in the level of the condenser diaphragm and an annular phase plate built into the back focal plane of the objective.

With positive or "dark" phase contrast, optically dense parts of the object (i.e., those of higher refractive power) are darker than the adjacent parts or background of lower refractive index, whereas with negative or "bright" phase contrast, the conditions are reversed. Whether one obtains positive or negative phase contrast depends on the particular make of the phase objective or phase plate used.

Phase-Contrast Equipment

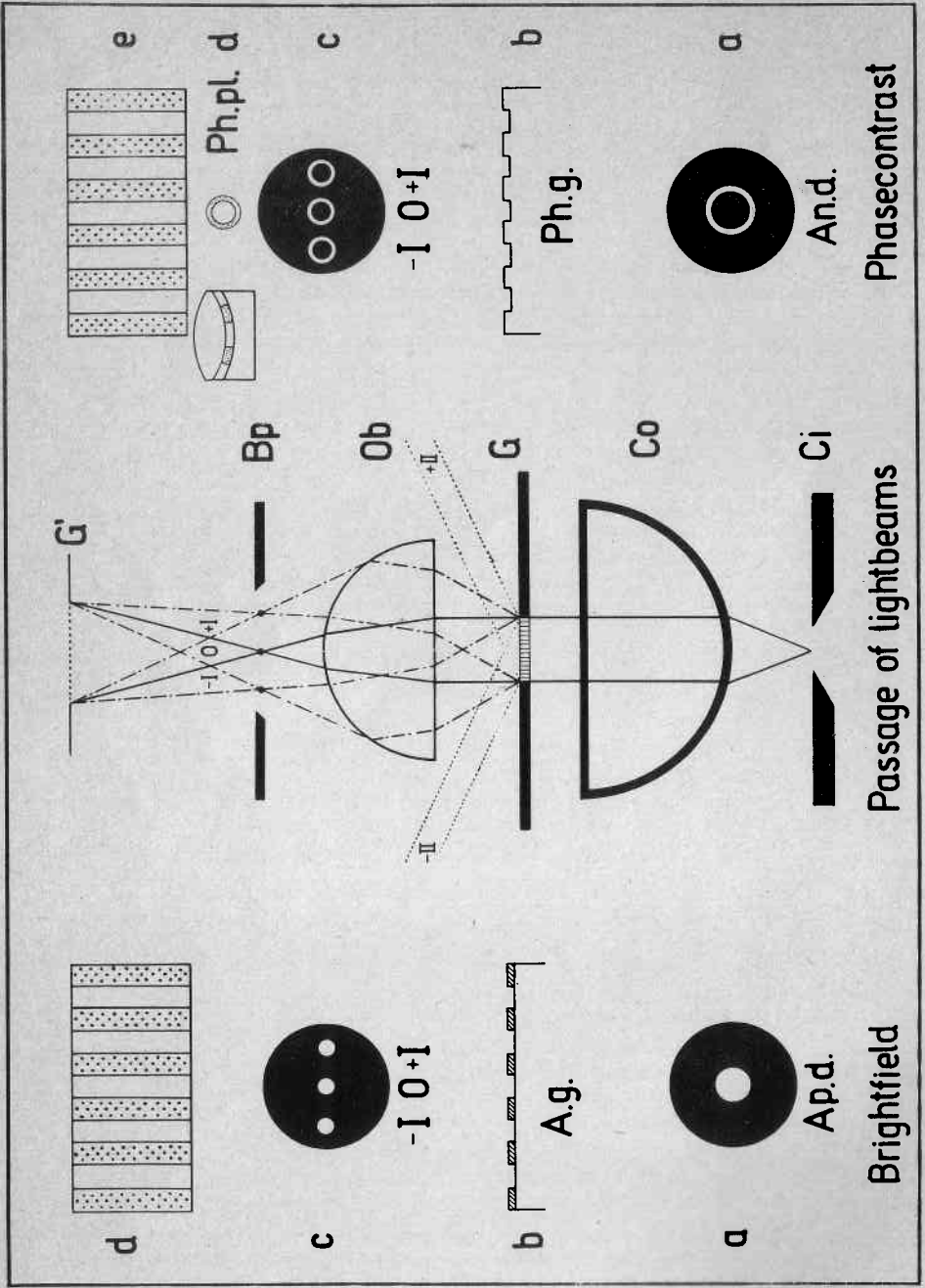
Right at the outset of the writer's experi-

ments difficulties were experienced in applying the normal phase-contrast accessories to gemological studies because

- a) Phase contrast, by its principle, works best with ultra-thin objects (e.g., biological preparations, mineralogical thin sections) or relatively at surface (which incident light in ore microscopy, metallurgy, etc.); and
- b) All commercial phase-contrast objectives were of the high-power type with extremely short focal distance and minimum focal depth, both facts making it impossible in most cases to "reach" inhomogeneities or inclusions in the depth of a gemstone.

Fortunately, the writer received valuable assistance from Dr. H. Piller, scientific consultant of the Zeiss-Winkel Works at Göttingen, who showed keen interest and undertook on his own responsibility to design and construct a special phase-contrast arrangement in order to meet gemological requirements. The special equipment that was thus developed consisted of the following (refer to corresponding numbers on accompanying illustrations):

1. A special collector lens with adjusting screws, which was placed into the foot of the microscope;
2. A tube-shaped condenser with an annular diaphragm that was to be placed upon the collective lens and used with or without the disc-condenser;
3. The disc-condenser, which was fixed in place of the normal substage condenser and which contained a range of annular diaphragms corresponding to Ph₂ 25/0.45, Ph₃ 40/0.65 and Ph₄ 90/1.25 phase-contrast objectives;
4. A set of various phase-contrast objectives Ph₁ 6.3/0.16, Ph₁ 10/0.25, Ph₂ 25/0.45 of low magnifying power, long working distance and greater focal depth: and



Explanation of Diagram Figure 1

The central part of the diagram demonstrates in lateral section the path of light and the formation of the microscopic image as explained by Abbe's theory. A decreased image of the aperture diaphragm Ap.d. in the plane Ci is formed by the condenser Co and the objective Ob in the back focal plane Bp of the objective. Through the intervention of an object (in the present case the grating G) in the path of light, the image of the aperture diaphragm gets disturbed. In passing this object G the incident beam of light is diffracted into many diffraction beams (so-called maxima). Apart from the direct maximum O, more rays of the diffracted beams (e.g., the maxima -1 and $+1$) may enter the objective Ob. In the same way as the direct beam forms an image of the aperture diaphragm at O, the diffracted beams also form images of the Ap.d. in the plane Bp—the so-called diffraction images -1 and $+1$.

However, in order to understand the phase contrast, the image of the grating G is of greater purport. Abbe proved that the image of the grating G in the plane G' consists of the effect of interference of the light vibrations from all the aperture images in the plane Bp, and that the structure of a microscopic object appears more accurate when more diffraction beams (caused by the object) participate in the formation of the image in the plane G'. The actual image formed in the plane G' is observed through the magnifying ocular.

The left side of the diagram depicts this process in overhead sketches.
From below to top:

- a) The aperture diaphragm Ap.d.
- b) The amplitude grating Ag, being the object G.
- c) The diffraction images -1 , 0 , $+1$ of the aperture diaphragm formed in the plane Bp above the amplitude grating.
- d) The image G' of the amplitude grating A.g.

If a phase grating is placed into the light path at G instead of an amplitude grating, all diffracted images (e.g. -1 and $+1$) of the aperture diaphragm show a phase difference of $\frac{1}{4}$ of a wavelength in the plane Bp, as compared with the corresponding diffracted aperture images of an amplitude grating. The virtual aperture image O formed by the direct beam, however, is identical in both cases. Yet, in order to produce the phase contrast, its phase must also be shifted by $\frac{1}{4}$ wavelength. This can be achieved by inserting a phase plate into the path of light.

The right side of the diagram demonstrates this event also in overhead sketches.
From below to top:

- a) Annular diaphragm An.d.
- b) Phase grating Ph.g.
- c) Above this are the three images of the annular diaphragm formed by diffraction; i.e., the central direct image O and left and right of this the diffracted images -1 and $+1$ shifted in their phase.
- d) Ph.pl. designates the phase plate in cross section (left) embedded between the objective lenses, and in top view (right).
- e) Image of the phase grating in which, according to the principle of the phase-contrast method and on account of the inserted phase plate, the phase of the entire image O has also been shifted by $\frac{1}{4}$ wavelength. Thus the phase difference of the direct and the diffracted images is $\frac{1}{4}$ wavelength, rendering the image of the phase grating visible.

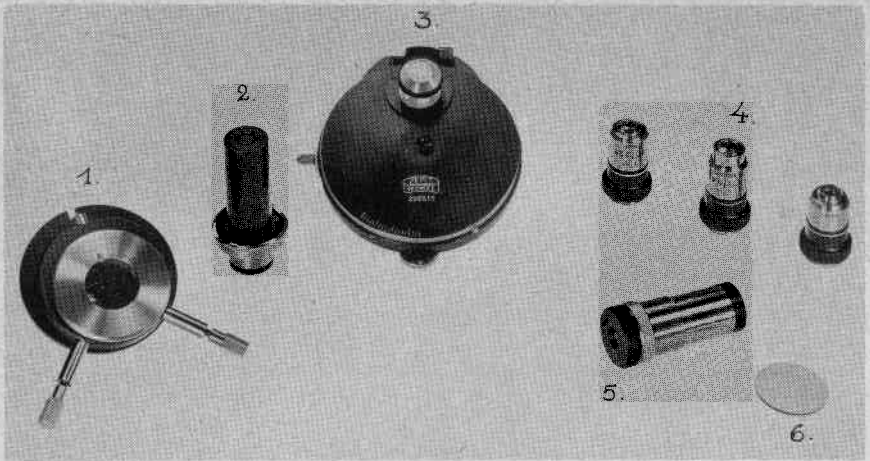


Figure 2

5. An auxiliary microscope that was to be inserted in the tube (in place of the eyepiece) in order to control coincidence of the absorption ring with the circular diaphragm aperture (Figure 2).

For practical work it is of great convenience to be able to change from phase contrast to conventional bright- or dark-field microscopy without complicated manipulations, so that the different images can quickly and easily be compared and differences of details best interpreted. This was accomplished merely by either rotating the revolver plate of the disc-condenser or the objective revolver (holding Ph- and normal objectives alternatively) or both. No special oculars were required, examinations being made with the normal eyepieces of 8x, 10x, or 20x, for best resolving results. This phase-contrast equipment was used with the latest model of a Zeiss-Winkel binocular polarizing research microscope.

The Images of Phase Contrast

Inhomogeneities and inclusions distinguish themselves from their background mainly by

their refractive difference and their differences in thickness; therefore, they appear homogeneous with the surrounding structure if these differences are extremely minute. However, their visibility is also determined by the differences in the path and the phase of the light waves that pass through the heterogeneous object. The constitutional rule of these associations among differences of refractive index, thickness, phase and path is well understood and has been defined mathematically. However, such calculations are usually very complicated, and hence are beyond the scope of this article. The result of the various interactions is that the difference of contrast is, on the average, about five times greater with the phase-contrast method than with the ordinary transmitted light of the bright field, provided that the differences in refractive index between enclosing substance and inhomogeneities or inclusions, as well as the thickness of the latter, be sufficiently minute.

In geological investigation the application of the phase-contrast method is not so much a matter of determining the refractive index of an inclusion (since it still does not extend beyond the possibilities

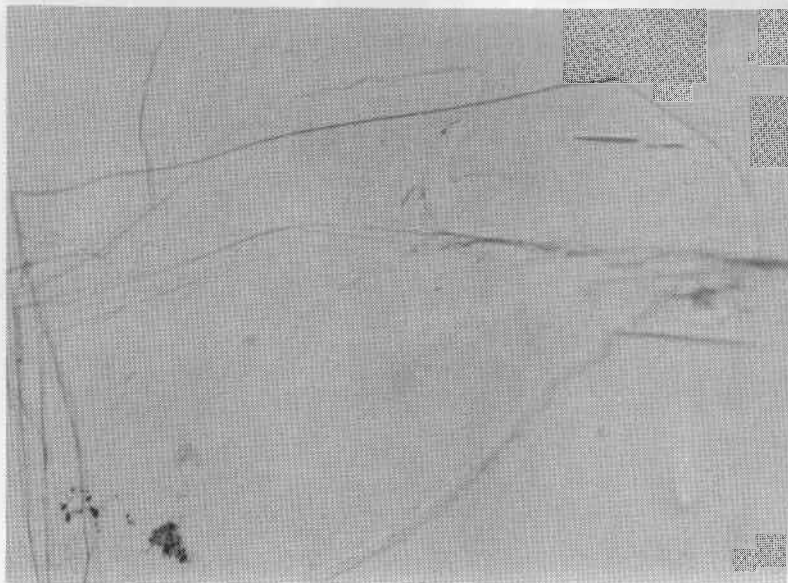
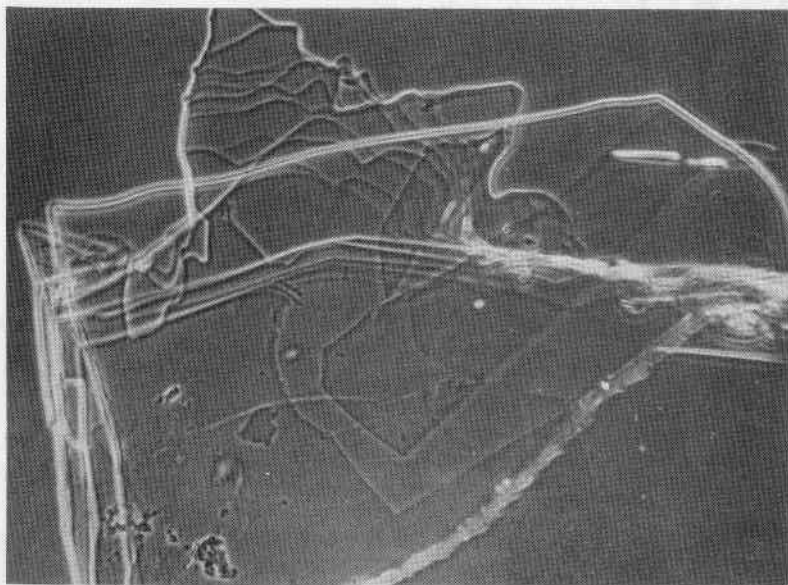


Figure 3a. Book of muscovite flakes in a yellow beryl from Madagascar photographed in bright-field illumination. The contours are hardly visible and no details show in the interior. Photo ocular pol. 10x. Achromatic objective pol. 6.3/0.16 Huygens. Magnification 63x.

Figure 3b. Same book of muscovite in the same position photographed with phase-contrast optics. White fringes show remarkably well towards the optically rarer medium (\equiv beryl) and the smallest details are visible in the interior of the object. Photo ocular pol. 10x. Achromatic objective Ph₁ 6.3/0.16. Magnification 63x.



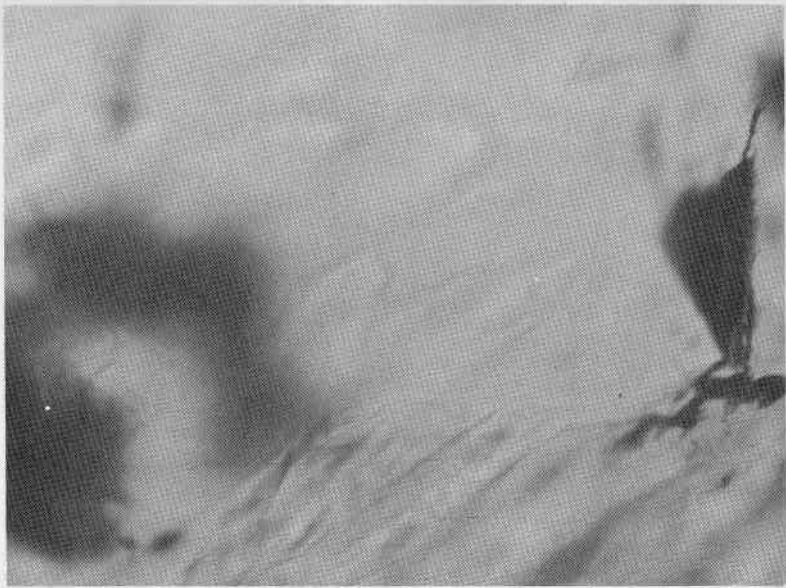
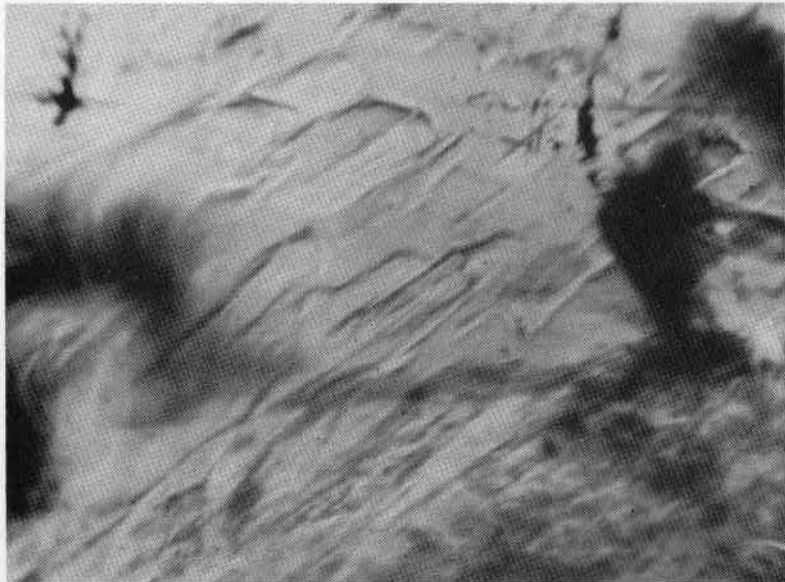


Figure 4a. Indistinct swirly interior of an emerald from the Muzo mine in Colombia photographed in bright field. From this picture very little or no knowledge can be derived with regard to internal structural peculiarities. *Photo ocular pol. 10x. Achromatic objective pol. 6.3/0.16 Huygens. Neutral filter, condenser iris closed to half and extra-focal position of microscope tube. Magnification 63x.*

Figure 4b. Same portion of the same emerald photographed with phase contrast. The irregular details of the structure appear very distinctly, betraying incomplete ex-solution of calcite, which is often the cause of the "oily" interior of so-called oil-drop emeralds. *Photo ocular pol. 10x. Achromatic objective Ph₁ 6.3/0.16. Magnification 63x.*



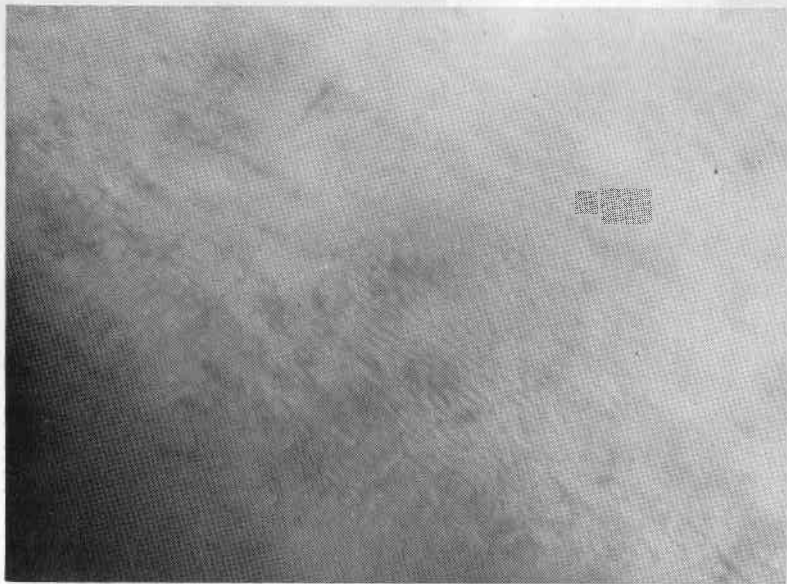
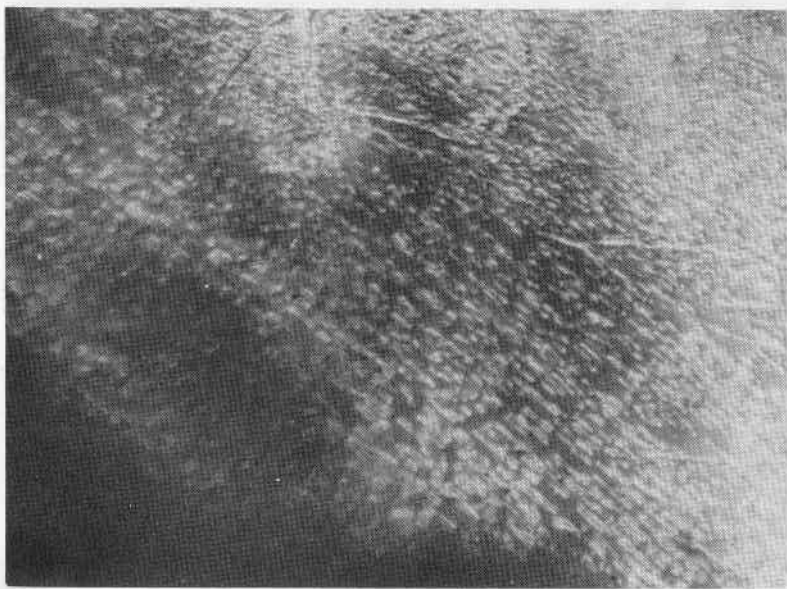


Figure 5a. The softly rippled field of this picture photographed in bright field does not yield any valuable information about the details of the interior of this iolite from Ceylon. *Photo ocular pol. 10x. Achromatic objective pol. 6.3/0.16 Huygens. Contrast filter. Magnification 63x.*

Figure 5b. In phase contrast the same area of the same iolite discloses fascinating information of its structure, which suffers from an advanced stage of pinitisation (=alteration into pinite). *Photo ocular pol. 10x. Achromatic objective Ph₁ 6.3/0.16. Magnification 63x.*



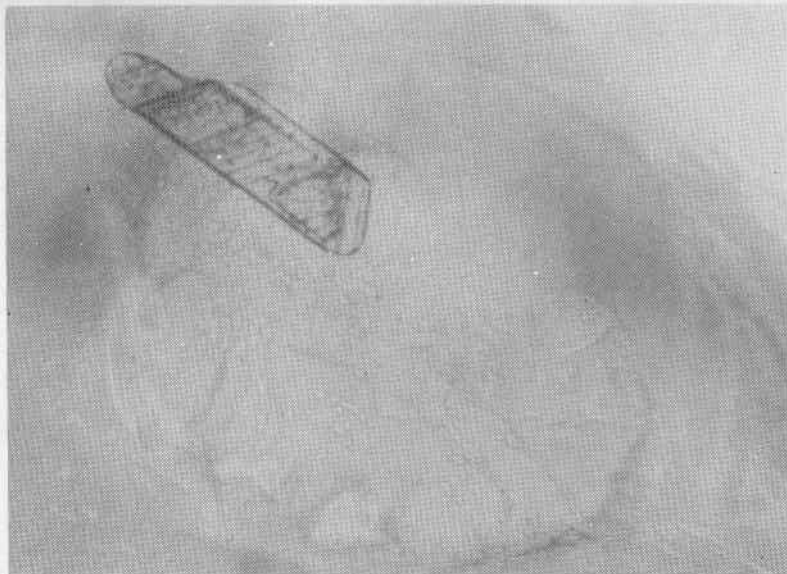


Figure 6a. Characteristic inclusion portrait of a sapphire from Ceylon photographed in bright field. It shows a slab of partly resorbed mineral (probably muscovite) above a partly healed crack that is hardly visible and does not enable one to discern clearly between healed areas and residual drops. *Photo ocular pol. 10x. Achromatic objective pol. 6.3/0.16 Huygens. Magnification 63x.*

Figure 6b. Photographed in phase contrast, the healed crack in this same Ceylon sapphire manifests itself as well as all its details very distinctly. The white rims within the hose-shaped and bubble-shaped formations betray them indisputably as the residual liquid, whereas the fields between and around them are the healed parts. *Photo ocular pol. 10x. Achromatic objective Ph₁ 6.3/0.16. Magnification 63x.*

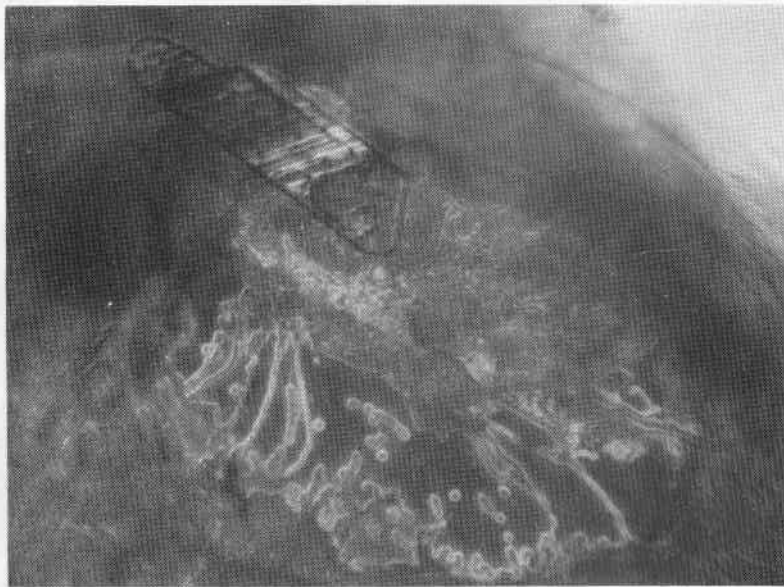




Figure 7a. This picture photographed in bright field lets the microscopist only vaguely guess some faint structural peculiarities in a yellow fluorspar from Switzerland. Photo ocular pol. 10x. Achromatic objective pol. 6.3/0.16 Huygens. Magnification 63x.

Figure 7b. Phase contrast, however, reveals excellent information on the subject details of the healed fissure in this yellow fluorspar, clearly marked by the residual drops of the healing fluid. Photo ocular pol. 10x. Achromatic objective Ph₁ 6.3/0.16. Magnification 63x.

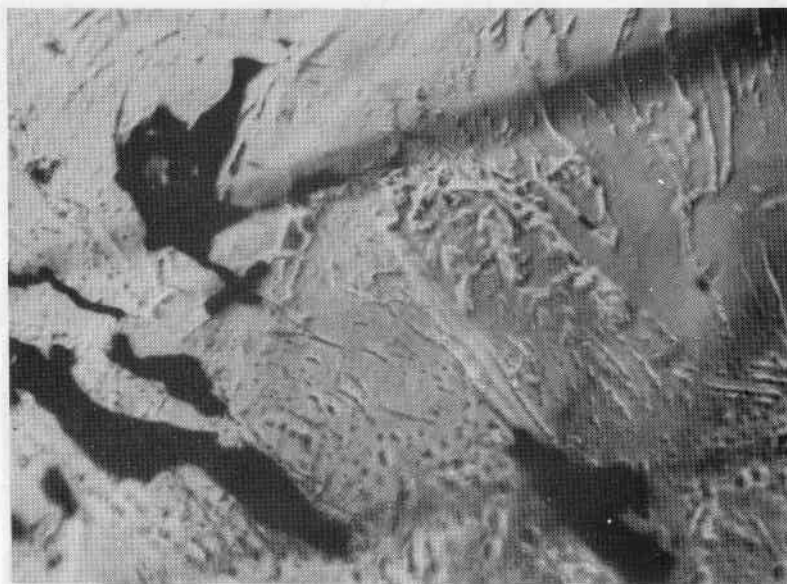
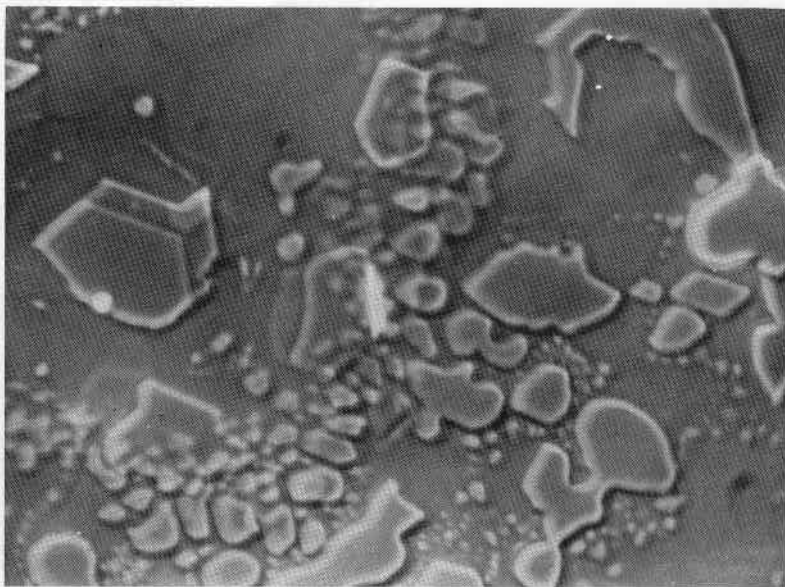




Figure 8a. Partly healed flat fissure in a yellow beryl from Madagascar photographed in bright field shows inhomogeneities very faintly, making it almost impossible to understand their nature. *Photo ocular pol. 10x. Achromatic objective pol. 25/0.45 Huygens. Magnification 250x.*

Figure 8b. Thanks to phase contrast, a wealth of dramatic contrast enables one to recognize the white fringed patches in this yellow beryl as residual drops of lower refractive index, some with gas bubbles with even stronger and broader white borders. *Photo ocular pol. 10x. Achromatic objective Ph₂ 25/0.45. Magnification 250x.*



Comparison of these photomicrographs clearly shows the great advantage of the phase-contrast method even in gemological microscopy, since the same or many similar inhomogeneities and inclusions could not be observed, let alone properly studied, in the ordinary bright field.

of the Becke line and will merely show whether its refractive index is higher or lower than that of the host, although this is always a valuable indication), but is especially important in increasing the degree of visibility of inhomogeneities and inclusions, so as to enable the observer to gain a better knowledge of the internal structure and perfection of the homogeneity of a particular gemstone.

Discussion of Illustrations

Figure 3a to Figure 8b depict some characteristic examples of the advantageous application of the phase-contrast method for a much more subtle investigation of the details of the internal structure of gemstones.

The work carried out thus far shows that the phase-contrast method can be used favorably in gemological microscopy and provides a wealth of new and fascinating knowledge. It is well known that the relative boldness of relief of a foreign mineral enclosed in a gemstone gives some indication of its refractive index as compared with its host. Differences of mean refractive indices from little less than about 0.1 to approximately 0.2 produce a "moderate" to "high" relief, respectively. However, the phase-contrast equipment causes these phenomena to appear with very much lower differences of refractive power. Thus a muscovite flake, while hardly showing in any variety of beryl, becomes very con-

spicuous with phase-contrast (see *Figure 3a* and *Figure 3b*)—a difference of about 0.03 ± 0.005 .

Structural disturbances appear with increased sharpness, and zoning may sometimes betray itself by alternate dark and light bands. Where there is heterogeneity of composition within a gemstone caused by perfect or incomplete ex-solution, precipitation, alteration, or healing, resulting in slight differences of refractive index in adjacent parts, the phase-contrast method reveals this feature in light and shade (see *Figure 4a* and *4b*; *Figure 5a* and *5b*).

However, phase-contrast microscopy is of little use with the normal types of inclusions (such as many solid, liquid or gaseous enclosures) whose refractive indices differ greatly from their embedding substance (*Figure 6a* and *6b*). Also, any strain or structural deformation caused by stress is not revealed by phase contrast.

It is hoped that this paper has explained the basis and use of the phase-contrast method, which has many advantages and is a great aid to those who are interested in investigating the inclusions in gemstones.

The author takes great pleasure in expressing his gratitude to Dr. H. Piller for his interest and valuable help in developing phase-contrast equipment suitable for gemological use.

*Literature

For those who are interested in studying more about the phase-contrast method or its various possibilities of application, ample information can be obtained from the *List of Literature Dealing with Phase-Contrast Microscopy, Series ZW115-S*, issued by R. Winkel G.m.b.H., Göttingen.



Recent Gem Mining At Pala, San Diego County, California

by

CAPTAIN JOHN SINKANKAS, U.S.N.
Certified Gemologist, AGS.

Introduction

From within the broad pegmatite region encompassing the principal part of San Diego County and a portion of Riverside County, the mines of Pala have probably provided the major portion of the gemstones which made California so famous in the early part of this century. Undoubtedly, the Himalaya-San Diego mining group at Mesa Grande yielded more gem-quality tourmaline, but taking morganite and kunzite into consideration along with tourmaline, the total production from Pala surely exceeded that of any other district.

In the past fifteen years at Pala, frequent attempts at gem mining have taken place, some successful and some not. Very few of these operations have been more than modest efforts by one or two individuals; the full-scale mining of the early part of the century is a thing of the past. Two individuals have enjoyed a considerable measure

of success in their efforts: Mr. George Ashley of Pala and Mr. Charles Reynolds of Lilac. The first resides on his mining property at the southern foot of the fabulously rich Hiriart Hill, and his small ranch has become a mecca for collectors and connoisseurs who pass through San Diego County in the course of their travels. Mr. Reynolds resides in the small community of Lilac, which is about ten miles south of the Pala district and is conveniently reached by road. When time away from other business interests permits, he spends several months each year mining his San Pedro Mine, located on Hiriart Hill.

The locale of the Pala mines is a series of low rounded hills north and northeast of the Indian community of that name in the northern part of San Diego County. The position of these hills and the most prominent of their mines is shown on the map (*Figure 1*).

The most productive hill has already been

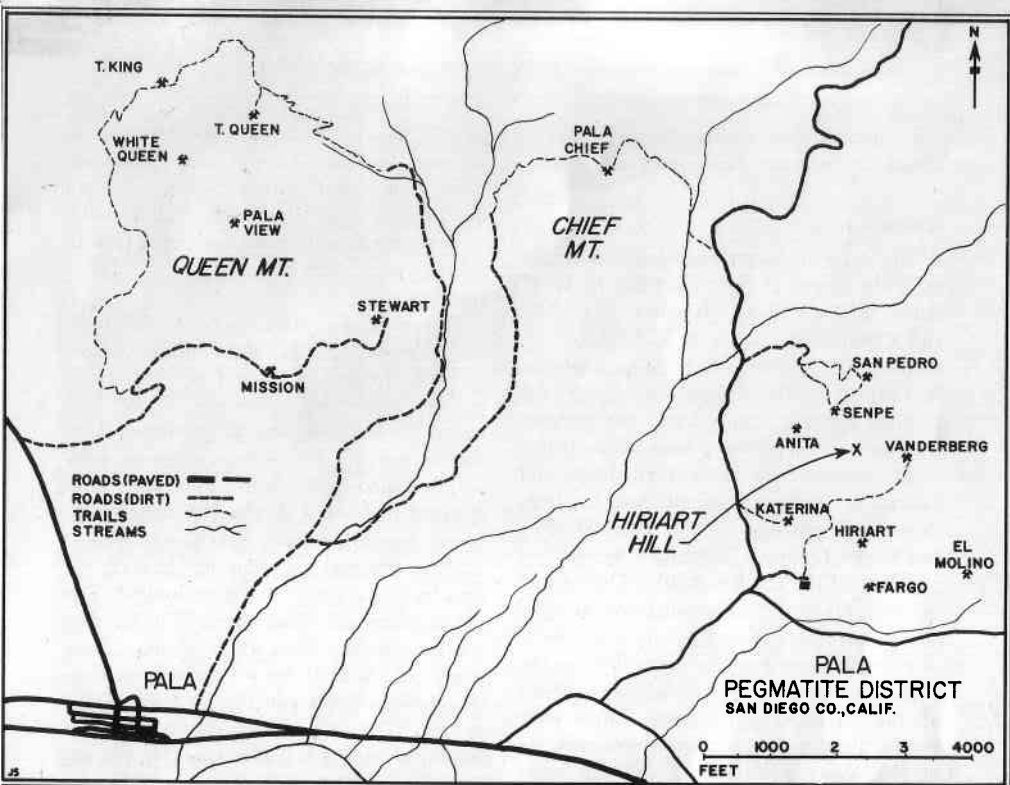


Figure 1

mentioned: Hiriart Hill, named after one of the "oldtimers" among the early discoverers of gem deposits in the Pala district. Hiriart Hill is a rounded prominence of oval outline, 2.3 miles northeast of Pala. Its elevation is 1766 feet above sea level, rising to about 900 feet above the shallow sloping alluvial fan at its base. Its appearance is made conspicuous by the prominent whitish pegmatite dikes which crisscross its densely vegetated slopes. Another famous hill is Tourmaline Queen Mountain, located several miles directly north of Pala. Rising to 1922 feet, it is also smoothly rounded and uniformly brush-covered. Pegmatites are far less numerous on its flanks, however, and at first it appears to be devoid of all characteristic features. However, several mine workings are prominent along its southeastern flank, a small one belong-

ing to the Mission Mine and several large light-colored dumps further to the east belonging to the Stewart Mine. Near the summit may be seen several small dumps, marking the Pala View and White Cloud mines.

Between Tourmaline Queen Mountain and Hiriart Hill is still another famous prominence, the Pala Chief Mountain. Somewhat sharper crested and covered by a multitude of outcropping pegmatites, it is the home of the Pala Chief Mine, noted for its marvelous spodumenes and tourmalines. Its elevation is 1502 feet.

The three hills just described contain what is surely one of the outstanding concentrations of gem-bearing pegmatites in the world. Intensive prospecting activities on these hills in the heyday of mining resulted in the staking of at least seventy-four claims or prospects honored with names. There

are a number more which were too minor in nature to warrant the dignity of a title.

History

The early discovery and development of the Pala district is fully described by G. F. Kunz in his "Gems, Jewelers' Materials, and Ornamental Stones of California," issued by the California State Mining Bureau in 1905 as Bulletin 37. More recently, the detailed geology, mineralogy, and productions of the Pala district have been exhaustively described by Richard H. Jahns and Lauren A. Wright in "Gem- And Lithium-Bearing Pegmatites of the Pala District, San Diego County, California," Special Report 7-A of the California State Division of Mines. This report culminated several years of intensive field investigations and laboratory work, and must be regarded as the authoritative publication on the subject of the Pala pegmatite dikes. Since little would be gained by repeating the substance of the above publications, only the most recent developments will be treated here.

After a period of hectic development, the Pala mines lapsed into quiescence when dwindling markets and reduced prices made further mining unprofitable. Resurgence of activity took place soon after Mr. George Ashley acquired a series of claims on Hiriart Hill from Mr. Fred Sickler, one of the original discoverers and the heir to many of the properties. Included were the San Pedro to the north, the Anita about midway to the south of Hiriart Hill, the Katerina at the extreme south end, and the Vandenberg near the middle and to the east. The acquisition of the Fargo, K. C. Naylor, Hiriart, El Molino, and the White Queen rounded out the entire hill except for the Senpe Claim, which had been previously disposed of to another party and did not come into Ashley's possession until some time later. The date of transfer of titles to Mr. Ashley was July, 1947.

In 1948 the San Pedro, Anita, and the recently acquired Senpe were sold as a group

to Mr. Charles Reynolds. Mr. Norman E. Dawson of San Marcos also purchased three claims and during 1948-49 worked the Fargo and White Queen. Mr. Dawson has also worked the El Molino from time to time in recent years but without conspicuous success.

Following his acquisition of the three claims mentioned, Mr. Reynolds proceeded to work the San Pedro and in 1951 struck a large pocket of spodumene. In 1955 he leased the Senpe to several gentlemen from San Diego who did some exploratory work without successful results. This mine later changed hands and is now reported as sold to an individual from San Diego who is actively engaged in working one of the opencast pits above the main tunnel. The Senpe Mine was leased or sold to an electronics company for a short period during the World War II for the purpose of mining quartz crystals suitable for piezoelectric purposes. This operation had little success insofar as quartz was concerned, but it did open up several pockets containing finemorganite beryls. Many of these were thrown over the dumps in ignorance of their value but, needless to say, they did not stay there long when local collectors got wind of it. The third claim owned by Mr. Reynolds, the Anita, was sold to Messrs. Harold Noble, William Woynar, and William Granzow, all of San Diego, who have not done much more than preliminary exploration of the claim. There are no extensive workings of any kind, and the ultimate worth of this claim remains to be proved.

The mines which have been most productive will be treated individually in following paragraphs, along with an account of their yield.

Katerina Mine

The workings of this mine penetrate a thick, strongly banded pegmatite on the southwestern base of Hiriart Hill, just a few feet above the alluvial fan. It outcrops in striking fashion a short distance east of the



Figure 2. The Vanderberg Mine atop Hiriart Hill, Pala, San Diego County, California. The rock exposed is part of the huge pegmatite which has been mined for kunzite and quartz crystals. Photo courtesy George Ashley.

tunnel openings, where it crosses a gully and forms a small steep cliff. Commencing work in 1947, Mr. Ashley struck a series of five small pockets, each yielding about a "hatful" of spodumene, principally of fair-to good-grade kunzite. The last pocket was the best, furnishing above-average material of good amethystine tints. The typically corroded and etched crystal fragments were of all sizes but some larger pieces reached as much as two pounds weight. From one of the larger and better-colored specimens a fine gem of $93\frac{1}{2}$ carats was cut.

Accompanying the spodumene were found numbers of magnificent clear quartz crystals of very pale straw-yellow color and curiously crystallized in a series of turreted over-

growths. Some small quantities of beryl were also found adjacent to pockets but not within the pockets proper. The quartzes rival Swiss specimens in clarity, smoothness of faces, and in the mode of growth. Their large size makes them eminently suitable for spheres and for carving into various decorative articles.

As in all of the pockets found in Hiriart Hill, quantities of red and pink clay filled the spaces between walls and supported the loose shards and splinters of spodumene.

Vanderberg Mine

Shifting his attention to the Vanderberg, Mr. Ashley launched upon an extensive program of exploitation and was rewarded by



Figure 3. A stupendous find of gem quality kunzite from the Vanderberg Mine, Pala, San Diego County, California. The pile of etched crystals and crystal fragments totals 130 pounds! These all came from a single pocket. *Photo courtesy George Ashley.*

several pockets yielding the most spectacularly beautiful kunzites that the world has ever known. The finest Madagascar and Brazil spodumenes cannot compare either in sizes, clarity, or color with the breathtakingly beautiful crystals found in this mine. For the first time, kunzite appeared in definitely bluish shades as well as in a peculiar greenish color strongly reminiscent of dark greenish-blue aquamarine. This last type of material was found only in one pocket, and the quantity as well as the size of individual pieces was not great.

The Vanderberg Mine is located on the eastern crest of Hiriart Hill and is reached by a narrow, steep jeep trail from Mr. Ashley's ranch. The large pegmatite in which

the workings are driven appears to be identical to that containing the San Pedro Mine. *Figure 2* shows the opencut and tunneling of this mine. The great thickness of the dike prevents economical removal of barren covering rock, and all operations are conducted by means of head-high drifts following the pocket zone. Mr. Ashley generally devotes several months each spring to intensive work on this property.

The richness of pockets in large spodumene-bearing dikes at Pala is attested by *Figure 3*, which shows approximately 130 pounds of gem-quality spodumene extracted in the summer of 1952 from the Vanderberg. All of this material was above average color, and much of it truly exceptional. About ten



Figure 4. George Ashley's helper holds some of the finer kunzite crystals from the Vanderberg pocket. The largest crystal in the center weighs $2\frac{1}{2}$ pounds and has never been cut. Photo courtesy George Ashley.

percent was exceptionally flawless gem stock suitable for faceting. From selected specimens in this lot, a deep amethystine gem of 177 carats has been cut, a magnificent 215-carat gem, and another of 107 carats. Like all kunzites, however, continued exposure to daylight results in rapid fading of color; cases are on record of such gems having bleached to almost colorless. Bluetinted stones from the Vanderberg first fade to the normal amethyst hue thence to pink and finally to colorless. It is necessary to protect vividly colored kunzites from daylight if the original color is to be preserved. This defect is absent in yellow-green stones such as those obtained in recent years from Brazil. This type has not been found at

Pala in such strong colors.

Some of the outstanding crystals obtained from the large Vanderberg pocket are shown in *Figure 4*. To the rear is the entrance to the mine, which serves as an effective background for the crystals displayed by Mr. Ashley's helper. The large crystal in the center weighs $2\frac{1}{2}$ pounds, is of deep color, and remains uncut to this day. Many sections are completely flawless. The largest piece of flawless gem stock obtained from this pocket measured about seven inches in length, three inches in width, and about seven-eighths inches in thickness. The weight was estimated at three-quarters of a pound.

Cut and rough Vanderberg specimens of outstanding quality have been sold to promi-

ment museums and private collectors; other rough has been disposed of to dealers everywhere for specimen and cutting purposes.

In addition to spodumene, some excellent quartz crystals were mined from the Vanderberg, although not in connection with spodumene-bearing pockets. Mr. Ashley states that cloudy crystals are found lining the walls of gem pockets and that when clear crystals of quartz are found, it is a discouraging sign, since most such pockets prove to be barren of all minerals except quartz. The crystals are very similar to those from the Katerina, except for their almost total absence of color. Accessory minerals occurring at the Vanderberg were bluish translucent apatites crystallizing in flat hexagonal prisms, some fine peach-colored morganite, and various rare pegmatite minerals, including a number of phosphates. Some of the morganites contained clear sections capable of yielding cut stones of six to eight carats.

San Pedro Mine

The acquisition of the San Pedro Mine proved a fortunate event for Mr. Charles Reynolds, for shortly after commencing work he struck an enormous pocket which yielded at least 300 pounds of spodumene in all shades of color from colorless to pink and very pale green. Only a few specimens were richly colored, the majority being quite pale.

This mine is located atop a ridge formed by the exposure of the dike itself and is a prominent feature of the north slope of Hiriart Hill. The dike dips rather steeply to the southwest and mining is therefore difficult. Mr. Reynolds attacked the dike from a shelf on the northern side of the outcrop and was forced to tunnel downward at an angle of about twenty degrees. Extraction of debris proved a most irksome and laborious task. The dike is very thick at this point (about twenty feet) and shows a confused zoning. The line of pockets is marked by a crumbly mixture of feldspar, mica and

black tourmaline, and, where pockets were encountered, by a core of blocky feldspar and quartz. Mining at another place in the dike some fifty feet toward the northwest from former workings was resumed in the fall of 1956. This new location does not appear to be promising, but perhaps favorable mineralization may be met with in depth.

The pocket which yielded the enormous quantity of spodumene proved to be an elongated oval of quartz and feldspar, shaped somewhat like a loaf of French bread and dipping at an angle of about twenty degrees. The roof was lined with extremely large milky-gray quartz crystals as well as pocket feldspars showing the usual corroded faces, and partly impregnated with reddish clay. Many of the quartz crystals showed imprints of large spodumene crystals, with the cavities filled by pinkish clays and occasional slivers of transparent spodumene. The majority of spodumenes were found in the central pocket filling of very dark reddish-brown clay. A number of fine, clear, pale straw-yellow quartz crystals were found in this clay also, some doubly terminated, representing the last stages of quartz crystallization. All of the spodumenes were typically etched and corroded into lathlike crystals, rectangular splinters and crude tablets. The floor of the pocket contained solid growths of cleavelandite, together with small crystallizations of greenish muscovite mica. Numerous specimens of various rare phosphates were found as well as minor quantities of morganite and aquamarine. As is typical of all Hiriart Hill localities, tourmaline was conspicuous by its absence, appearing only rarely as small pencils of very dark violet-blue color.

The largest spodumene crystal, still in the possession of Mr. Reynolds, weighs almost five pounds. It measures approximately 12 inches x 4 inches x 1 inch. It is pink at one end and fades to a very pale, almost colorless, yellowish green at the other. It is deeply striated along the sides and the termi-

nations are rounded by etching. Other large crystals exceeding a pound in weight were found, as well as an abundance of those ranging from $\frac{1}{4}$ to $\frac{1}{2}$ pound in weight. Bucketsfull of slivers were also obtained, many reaching lengths of about four inches and thicknesses of about $\frac{1}{4}$ inch to $\frac{1}{2}$ inch.

A fine pendeloque stone of rich color and weighing several hundred carats was cut for Mr. Reynolds by Mr. Fred Rynerson from one of the better pieces. This handsome and brilliant gem, along with the enormous crystal described above, serves as a central attraction in the exhibits of the San Diego County Fair each year.

Senpe Mine

The dike of the Senpe mine begins at the base of the northwestern slope of Hiriart Hill and rises steeply to the crest and thence over to the other side. The claim proper covers only the first part about halfway up the slope. A number of tunnels and open-cuts mark the exploration of this dike which, by and large, has not been as productive as other mines in the immediate vicinity. Its chief claim to fame has been the occurrence of morganite beryl, many very clear and with large flawless areas. These were taken from narrow lens-shaped pockets adjacent to cores of blocky quartz and feldspar. Better specimens have yielded cut stones of about 48 carats.

The latest workings near the top of the claim are aimed at clearing out an old open-cut filled with huge blocks of pegmatite and slumped topsoil. A steel mast has been erected at the opening and by means of a power driven whip, sleds are loaded and slid out to the dump. The dike at this point appears to dip steeply to the southwest; it is about ten feet in thickness. The pocket zone is marked by streaks of clayey material, masses of feldspar intimately mixed with scales of mica, and an occasional small core unit of blocky feldspar and quartz. Morganite appears as smooth tabular prisms implanted upon radiated growths of cleavelandite and

associated with small, clear, very pale straw-yellow quartz crystals. Tourmalines are occasionally found; however, as with others on this hill, they are always deep violet-blue. The dike appears to have been subjected to several epochs of injection and the structure is far from clear.

Other Mines

The famous Tourmaline Queen and Pala Chief Mines are on patented ground and are being held for sale by the Salmons estate at a substantial sum. There has been no formal mining carried on in them for many years, although considerable favorable ground still remains. Both are situated atop their respective hills and no easy method exists to deliver equipment, personnel and supplies to the mine entrances. The Tourmaline King Mine, about one-half mile to the west of the Queen, is also dormant, and has been since the mining last carried out by R. M. Wilkie. The ground does not appear to hold much promise for successful future mining.

The Stewart Mine, at the southern base of Tourmaline Queen Mountain, is famous for its production of lepidolite mica, at one time supplying the principal part of the world's needs for lithium ores. Several years ago it was placed under lease for resumption of lepidolite mining but after considerable bulldozing of accessways and some sporadic shooting in the open-cuts, further mining ceased and it too has lapsed into dormancy. Although noted for the production of many tons of pale-pink lepidolite specimens shot through with sprays of rubellite, it has occasionally produced some fine peach-colored morganite, small pencils of beautiful green tourmaline, and crystals of warm-pink tourmaline whose hue is quite unlike that from any other locality. The latter show under the dichroscope a saturated pink color in one window and a pale yellow in the other. In contrast, most pinks from Southern California are decidedly purplish and usually

(Continued on page 95)

"Green" Amethyst From Four Peaks, Arizona

by

CAPTAIN JOHN SINKANKAS, U.S.N.
Certified Gemologist, AGS.

The appearance of "greened" amethyst from Brazil several years ago aroused considerable interest in gemological circles, because this hue had not been reported in previous literature. As the story goes, the peculiar properties of this amethyst were discovered by a prospector in some material that he had used to make a camp fireplace. Later, he noticed the effect of the heat had altered the amethyst to green. The source is near Montezuma, about 37 miles from Rio Pardo, Minas Geraes (1). An occurrence of similar material in the Four Peaks region of central Arizona is reported in this paper.

Perhaps the most thorough recent investigation into the cause of color in amethyst was conducted by Edward F. Holden, who published his results in an extensive article in the *American Mineralogist* (2). In this work, Holden gathered together amethyst

samples from thirteen localities and subjected five samples to a variety of heating tests, tabulating his results in accordance with temperature, time of heating, color before and after, etc. In none of these tests, nor in any by previous investigators whose results Holden had studied and, at times, freely commented on, did any final color other than colorless, yellow, or milky white appear. That extensive heat-treatment experiments had taken place many times before Holden's is borne out by his referencing similar work by Heintz (3), Berthelot (4), Hermann (5), Simon (6), and Wild & Liesegang (7). To these scientific investigations we may add the long history of commercial decolorization as still practiced in Brazil and elsewhere. However, since commercial processes were aimed at the production of yellow colors, occasional freakish variations that undoubtedly

occurred from time to time were probably dismissed as unfortunate and no particular significance attached to them. Nevertheless, the overwhelming mass of evidence points to green as being a most rare resultant color in the heat treatment of amethyst. It is for this reason that the occurrence at Four Peaks, Arizona, is considered worthy of being placed on the record.

The circumstances leading to the discovery of greening propensities in the Four Peaks material were, as in the Brazilian, entirely accidental. It seems that a mineral dealer in California who had mined a considerable quantity of the material had stored his supply in a building next to his home. One day, a fire of unknown origin totally destroyed this building, and the amethyst, presumably ruined, was dug from the ashes. It was then found that much of it had turned to various shades of apple green, reminiscent of certain aquamarines. Deeper colors, such as noted occasionally in the Brazilian material, were absent, but the fact that the resultant color was green is far more significant than the fact that its suitability for gemstones may not be as great. Furthermore, since the temperature obviously was not controlled in this accident of mixed blessings, deeper greens might possibly result under controlled firing conditions. Through the courtesy of Drs. William T. Pecora and David B. Stewart of the United States Geological Survey, controlled heat-treatment experiments were conducted on Four Peaks samples and the results appear later in this paper.

Little is known about the Four Peaks deposit and apparently no systematic mineralogical investigation of the amethyst and its accessory minerals has ever been undertaken. The general geology of the area has been studied by Eldred D. Wilson (8). According to F. W. Galbraith of the University of Arizona, the deposit was worked to small extent about 1921 and some amethyst of good grade produced, but much was ruined through heavy blasting. When seen in 1935,

all of the good material in sight had been mined out (9). However, it is known that the deposit has been worked in recent years by the same mineral dealer alluded to before and that a considerable quantity of cutting- and specimen-grade amethyst was obtained. This last operation is said to have extended underground workings to as much as several dozen feet along the dip of the stratum containing the deposit.

The Four Peaks, named after a like number of prominent individual mountains aligned in a row north to south, are part of the Mazatzal Mountains of central Arizona. The area is about 45 statute miles on a direct line from Phoenix, bearing east by northeast, and about $9\frac{3}{4}$ miles almost due west of Roosevelt Dam. The area is extremely rugged, sparsely vegetated, and, of course, quite arid. The elevation of the highest peak is 7,691 feet above sea level, and the deposit of amethyst, lying at the base of a cliff on the western slope of the second peak from the south, is approximately 6,500 feet above sea level. The deposit can be reached only by trail after an initial approach by automobile along a Forestry Service road leading from Roosevelt Dam.

Geologically, the Four Peaks are considered to be roof pendants of pre-Cambrian rocks resting upon a vast granitic batholith that has been denuded elsewhere of covering rock formations. The steep sides of the peaks can be attributed in part to the relative resistivity of the Maverick shale and Mazatzal quartzite of which they are composed. Both formations dip about 45° to the southeast and include numerous small masses of a partly altered schistose rock. The entire formation has been strongly affected by drag-folding. The quartzite in which the amethyst occurs is typically very hard and vitreous. Microscopic examination shows it to consist of a closely packed aggregate of angular to subangular quartz grains in finely granular, siliceous, somewhat limonitic cement (8). The amethyst deposits consists of crystal-studded geodes or cavities

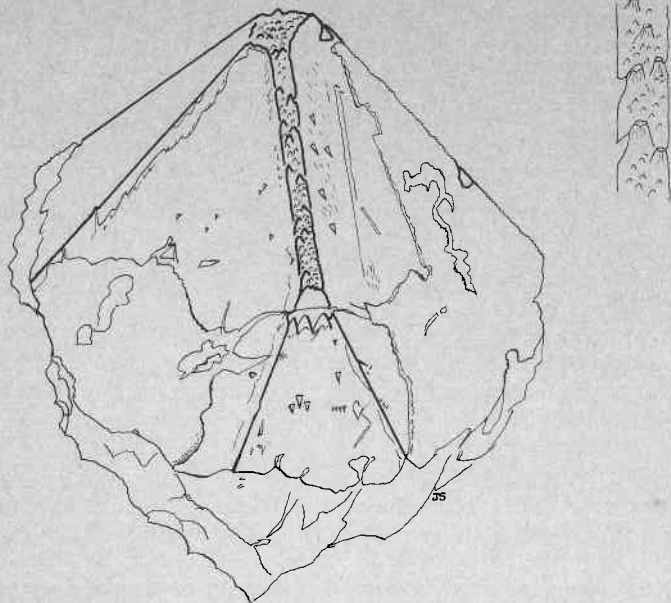


Figure 1. A typical Four Peaks amethyst crystal showing extensive etching and partial overgrowth by apatite. The smaller illustration depicts the etching figures between adjacent rhombohedral faces. This crystal is about three inches in diameter.

of irregular form and generally less than ten feet in maximum dimension. According to one visitor to this locality, the cavities range in height from a few inches to as much as four feet. The majority of these cavities are associated with fissures in the quartzite, which is here intruded by granite (9). Presumably, the deposit formed from mineralizing solutions emanating from the crystallizing granite.

Some cavities show fillings of solid material in narrow places, often interlocked from wall to wall, whereas in thicker areas amethyst appears as druses or as loose individual crystals suspended in a peculiar, gritty vug-filling material. Mineralization extends laterally along the strike of the quartzite bed for a considerable distance but only a portion shows good cavity development, and it is here that mining has taken place (10). This observer also stated that similar mineralization crops out on the eastern slope of the peak, indicating persistence over a long and as yet unexplored distance along the quartzite bed. The potential of this de-

posit appears to be great, but inasmuch as hard-rock tunnelling must be resorted to and since all water, food, and supplies must be brought in by pack train, it is likely that production will never be large.

The effects of extensive hydrothermal activity are apparent from the form of the amethyst specimens examined and from descriptions of the cavities in which they were found. In such places, crystals no longer adhere to the walls of cavities but are found completely detached and suspended in a vug-filling material of a pale grayish-purple color, or of a rusty-brown color in places where surface waters penetrated. This filling is not coherent and crumbles readily at the slightest touch. Under a microscope, it appears to consist wholly of hematite and apatite in the form of minute, much flattened, euhedral crystals. The hematite and apatite are both hexagonal in outline, with the latter being completely transparent and colorless. The ratio between the two in terms of quantity is roughly ten to one in favor of the apatite. The hematite is ordi-

narily opaque but shows a deep red in thinner crystals. The apatite has refractive indices suggesting that it is fluorapatite.

In addition to the vug-filling material just described, small isolated patches of a talcose mineral have been observed from time to time. This material has been described as being soapy or greasy in feel and "dead" white in color. It has not been identified, but is probably a clay mineral.

Many of the loose amethysts are coated with thin, tenacious overgrowths of the same kind of apatite crystals as are found in the vug-filling material. The individuals are thickly sprinkled over the surface of the crystals and partially imbedded; their interstices are filled with very fine crystals of hematite of a steel-gray color and metallic luster, but coatings of reddish clay obscure these appearances except in isolated cases. The apatite crystals are uniformly set on edge and create a reticulated pattern of wonderful regularity. In a few specimens of amethyst from fresh, unaltered vugs, bright hematite crystals are present as inclusions just beneath the surface on rhombohedral faces. In these, the brilliant color and glassy faces, among other features, make them strikingly similar to amethysts from the Thunder Bay region of Lake Superior.

Four Peaks amethyst crystals have the common habit of amethyst noted from other localities; that is, they consist primarily of rhombohedral terminations with prism faces either poorly developed or lacking altogether. Crystals from altered vugs are so extensively etched that only rhombodedral faces are distinguishable.

Figure 1 shows a representative crystal several inches in diameter and somewhat more in length. The point of attachment is a mere vestige, deeply corroded and extensively coated with apatite and hematite. This overgrowth extends over the edges and also covers much of the termination. The general form of this crystal, as well as many others, indicates that dissolution took place along joints between adjacent crystals, loosening

each one until all connections were severed. The most interesting solution phenomena, however, are to be noted on the rhombohedral faces, where symmetrical etching figures, as well as curiously corroded edges, can be observed. The smaller drawing in *Figure 1* shows an enlargement of the corroded edge between a pair of rhombohedral faces and shows the vicinal faces left behind by a solution of the material. The larger prominences are roughly hexagonal in outline when viewed from the top. This form of corrosion is strikingly similar to that observed in quartz from Madagascar by Lacroix (11).

The distribution and quality of color in Four Peaks amethyst is extremely variable. In general, twinning has taken place between rather large individuals; consequently, the resulting color zoning is apt to be coarse, with pronounced variation in intensity and distribution of color. In broken specimens, the "ripple" fracture that is typical of many Dauphine twinning cycles is largely absent, only widely spaced sutures showing here and there. A cross section taken from the base of many crystals shows typical 60° sector-color development. In other specimens, the lateral distribution of color is far less regular and indicates juxtaposition of another mode of twinning in addition to the Dauphine. The net effect in most crystals is extreme patchiness of coloration, with boundaries between intensely tinted and colorless areas altogether too sharp to be useful for faceted gems of any size. One fragment of amethyst inspected, for example, was so deep in hue that it was nearly opaque. As a consequence, specimens containing such coloration are most difficult to cut into satisfactory gems. It has been estimated that only about two percent of all material mined can be classed as good faceting material in respect to intensity of color, its distribution, and freedom from flaws and inclusions.

Many crystals show milky patches that are sometimes slightly amethystine in color. Examinations with a microscope fails to

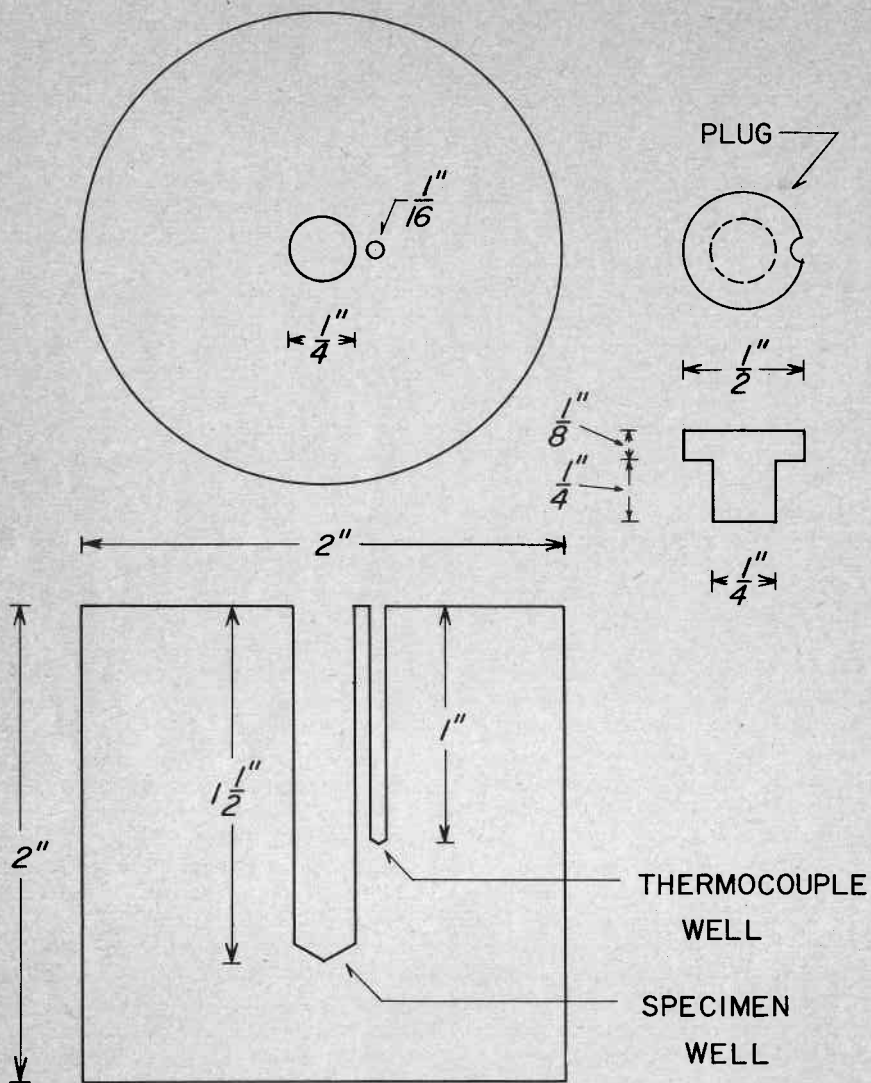


Figure 2. The copper block used for the heat treatment of amethyst. Specimens are crushed just enough to fit in the central cavity and covered by means of a plug. A chromel-alumel thermocouple is used to determine temperatures.

reveal any discrete inclusions and consequently leaves the exact nature a matter of speculation. Similar milky patches have often been noted in Brazilian amethysts that have been fired to produce the "Rio Grande topaz" color.

The size of Four Peaks amethyst crystals varies from individuals of about one inch in diameter to those reaching as much as eight inches. As noted in many similar cases elsewhere, the large crystals are often badly flawed and produce suitable material only from small areas near the tips. Because of the intensity of the color and lack of transparency of crystal faces, quality can only be determined by sawing or breaking apart the crystals. In the past, much of this hand cobbing has been done at the mine to avoid carrying down unnecessary weight. For this reason, good crystals suitable for mineralogical specimens are not commonly obtainable. As far as is known, no gems have been cut from any of these large badly flawed crystals.

Heating Experiments

(Conducted by Dr. David B. Stewart)

Small fragments of amethyst from this deposit were heated under controlled conditions to determine the most favorable temperature for decolorization. It was realized that high temperature would have a tendency to fracture the crystals, whereas low temperatures would not affect the color perceptibly. Although crude, these experiments indicate the time required for the change to take place at a given temperature. The results suggest the possibility that other deposits exist where original amethyst has been decolorized by natural thermal heat treatment.

Pairs of samples, about one-quarter inch in size, were selected so that they had the same intensity of coloring and zoning. One fragment was retained as a standard of comparison and the other was placed in the sample well of a two-pound block of copper that had been preheated to the

temperature of the run. The starting time was recorded as the time the sample was placed in the sample well; runs made at high temperature and corresponding short times are in error to the extent that it takes some time for the sample to reach the temperature of the block. The runs were terminated by quenching the block in cold water. The heating was performed in a pot furnace operated from a Variac. The atmosphere in the furnace was air. The temperature was measured with a calibrated chromel-alumel thermocouple inserted in the copper block to a point about one-sixteenth of an inch from the sample. The dimensions of the heating block are given in *Figure 2*.

After the run, the heated sample was compared with the reference sample and a visual estimate of the amount of bleaching was made. A value of 1.0 means that no difference in coloring was noted, and a value of 0.0 means that the sample was completely bleached. A more precise method of making these measurements with a densitometer or photometer could be devised, but the present rough measurements indicate the pertinent region. Results of runs are tabulated in *Table 1*.

Examination of the results indicates that five minutes at 450° C., two hours at 400° C., or one week at 350° C. will decolorize this amethyst. It is evident from these data, and from thermodynamic calculations based on these runs, that much longer times at lower temperatures will also decolorize amethyst, but longer runs are desirable to place numbers on the points. There is an upper "time-at-temperature" limit for this amethyst, and if other amethysts are like it (and there is evidence that they are), then it is possible that in some geologic occurrences this upper limit may have been exceeded. Since it is known that decolorized amethyst is easily recolored by irradiation [(12) for example], it is at least theoretically possible that some quartz now found as clear or slightly greenish material represents decolorized amethyst and can be recolored by irradiation. Favor-

Table 1

Heat-Treatment Experiments on Four Peaks, Arizona, Amethyst

Sample No.	Color	Deg. C.	Time	Results
A 1	medium	135	67 hours	1.0
A 1	medium	345	30 minutes	1.0
A 1	medium	345	1½ hours	0.9
A 1	medium	345	25½ hours	0.7
A 2	dark	400	17 hours	0.0 pale greenish white
A 3	dark	400	2 hours	0.1 certain strong zones still pink
A 4	medium	375	4 hours	0.6
A 5	dark	450	1 minute	fractured; chip 0.6, mass 0.9
A 6	medium	450	3 minutes	fractured; chip 0.1, mass 0.3
A 7	dark	450	6 minutes	fractured; chip 0.0, mass 0.0
A 8	medium, zoned	400	45 minutes	0.1 strong zones still pink
A 9	dark	400	30 minutes	0.4
A 10	medium	400	45 minutes	0.2 run made with Fe in evacuated tube
A 11	dark	345	66½ hours	0.3

Note: Under "results," the value 1.0 means that no change has occurred, whereas a value of 0.0 means that the sample has been completely decolorized.

able sites for such localities would be quartz veins or vugs with quartz in the contact-metamorphosed zones surrounding igneous intrusions.

Heating rapidly to the temperature of the run fractured the samples in all of the runs at 450° C. Obviously, this problem would be more severe at higher temperatures or even at lower temperatures with larger samples. Probably the best procedure with this material is to start with a cold furnace and increase the temperature gradually until a temperature of 350° C., is reached, and then maintain this temperature for about a week. No relation between depth of green color and heat treatment was noted, providing that overheating was avoided. Slightly green fragments became nearly colorless after heating to a red heat.

One run was made in an evacuated silica-glass tube containing metallic iron in addition to the amethyst fragments. Reaction of the iron with any remaining oxygen sets up an equilibrium between the iron and its oxidation products, so that only an extremely small pressure of oxygen (10^{-26} atmos-

pheres) can be present. No differences were noted between results of this run and a run made in air, so the decolorization seems independent of the pressure of oxygen.

The color change observed is confined largely to the original amethystine bands. The depth of green color seems proportional to the depth of the original amethystine coloration. The material with the darkest green coloration was examined under a microscope with a magnification of 1,000 times. Only a few spherical voids (former bubbles?) and a few flecks of reddish material, presumably iron oxide, were noted.

When the data in *Table 1* are plotted on a graph together with the estimated values for bleaching, based on the results of Holden (2), both sets of data are analogous and are compatible. The most advantageous coordinates for plotting these data are the logarithm of the time against the reciprocal of the absolute temperature, since this makes the points for a rate reaction like this one plot on a straight line. Such a plot makes it clear that Holden's conclusion that the change takes place at 260° C. is not correct

unless a time at this temperature is also specified.

Specimens of Brazilian amethyst that turn green upon heating were supplied by Dr. F. H. Pough. The color change in this material takes place at approximately the same times and temperatures obtained for the Four Peaks amethyst.

One consequence of the recognition of the "time-at-temperature" stability limit of amethyst is a maximum-reading geologic thermometer. If we knew how long it took to deposit amethyst in a deposit and how long the amethyst stayed at the temperature of deposition after deposition stopped, then we could specify the maximum temperature of the depositing fluid. It follows that points determined above indicate times and temperatures above which it will not be possible to manufacture synthetic amethyst even after the nature of the pigmenting substance is known.

Acknowledgments

The assistance of Dr. David B. Stewart in carrying out the heat-treatment experiments on the Four Peaks amethyst is gratefully acknowledged. Several important revisions by him to the first part of the text, as well as the identification of the colorless mineral adhering to the amethyst crystals, are also deeply appreciated. The author's thanks are due to Mr. Norman E. Dawson of San Marcos, California, for supplying specimens for use in experimentation and for furnishing personally acquired information on the general nature of the deposit at Four Peaks. Similarly, thanks are due to Dr. F. W. Galbraith of the University of Arizona, who supplied important data on this deposit.

Bibliography:

1. Webster, R. *Some Newer Gem Problems*. Journal of Gemmology, Vol. 5, No. 3, July 1955, p. 181.
2. Holden, Edward F. *The Cause of Color in Smoky Quartz and Amethyst*. American Mineralogist, Vol. 10, No. 9, September 1925, p. 203-252.
3. Heintz, W. *The Coloring Constituents of Flint, Carnelian, and Amethyst*. Annales Physik. Chem., 60, p. 519-527, 1860.
4. Berthelot, M. *Synthesis of Amethyst Quartz*. Compt. Rend., 143, p. 477-488, 1906.

5. Hermann, W. *The Effect of Oxidizing and Reducing Gases on the Color of some Minerals*. Zeit. Anorg. Chem., 60, p. 369-404, 1908.
6. Simon, Karl. *Mineral Color*. Neues Jahrb. Min. Geol., Beil. Bd., 26, p. 249-295, 1908.
7. Wild, G. O. & R. E. Liesegang. *The Color of Amethyst and Beryl*. Centr. Min. Geol., p. 737-740, 1923.
8. Wilson, Eldred D. *Pre-Cambrian Mazatzal Revolution in Central Arizona*. Bull. Geol. Soc. America, Vol. 50, p. 1113-1164, July 1, 1939.
9. Galbraith, F. W. Personal communication. May 22, 1956.
10. Dawson, Norman E. Personal communication. July, 1956.
11. La Croix, A. *Mineralogie de Madagascar*. Tome I, p. 208 et seq., 1922.
12. Cohen, A. J. *Color Centers in the Alpha-Quartz Called Amethyst*. American Mineralogist, Vol. 41, Nos. 11 & 12, Nov.-Dec. 1956, p. 886.

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show an intense purplish pink in one window and pale pink to colorless in the other.

Future Prospects

The potential of the Pala mines as a group is very great. Only a cursory examination of the various dikes is needed to see that much attractive ground remains undisturbed. However, very few persons with the time and the means to carry on sustained operations have appeared on the scene. In several instances, properties are being held for sale by owners for high figures, along with steadfast refusals to enter into any leasing arrangements. Access to many of the properties is made difficult by the steep terrain and lack of roads, and the isolation of certain properties within areas of private property poses legal complications which lessen substantially their attractiveness. Roads can usually be bulldozed but costs are high for this service, although the removal of much debris accumulated over years of previous mining makes mere access only one of the problems. In spite of all these drawbacks, the day may soon come when the prices demanded for Brazilian gemstones will make reopening of selected mines in this region a profitable venture. If this should happen, the world of gemologists and mineralogists will be treated again to a display of material unique for its size and beauty—masterpieces in stone by the greatest of all artists.