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ARTIFICIAL AND NATURAL PHOTOELASTIC EFFECTS IN QUARTZ AND FELDSPARS

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ABSTRACT

Optical disturbances occur in quartz and feldspars around stress centers as caused by impact from carborundum grains during preparation of thin sections. This photoelastic phenomenon is described and compared with the optical disturbance observed around stress centers produced in various substances such as cellophane paper, photographic film, plexiglass and common glass. The interference figures observed with crossed nicols show that the stress fields have cylindrical or spherical symmetry, the stress decreasing rapidly with distance from the centers. Similar photoelastic effects are seen around inclusions in quartz and feldspars, showing that inclusions are sometimes surrounded by stress fields with maximum compressive stress parallel to the radius. Some piezo-optical properties of quartz and potash feldspar are measured qualitatively in order to interpret the character of the stress fields. For these minerals the deformation of the indicatrix under unidirected compressive stress is similar to the deformation of the strain ellipsoid in the sense that the indicatrix becomes elongated, relatively, in directions normal to the stress. Plexiglass behaves in an opposite manner, its indicatrix being relatively elongated parallel to the direction of compressive stress.

CENTERS OF PHOTOELASTIC DISTURBANCES IN QUARTZ AND FELDSPARS AS PRODUCED DURING PREPARATION OF THIN SECTIONS

Quartz grains cut quasi-normal to the optic axis often show a faint grating texture when observed with crossed nicols at moderate magnification. At the first glance the texture usually appears as a set of somewhat irregular extinction bands making about a 45° angle with the vibration directions of the nicols, crossed by a quasi-normal set of irregular bright bands. Being invisible when the quartz grain is in position of extinction, the grating texture shows up at only a few degrees deviation from this position and remains visible at any angular deviation from extinction of the quartz grain, provided that the optic axis is quasi-parallel to the microscope axis. Rotation of the thin section makes the dark bands and the complementary bright ones alternate between the first—third and the second—fourth quadrants, bisecting symmetrically the vibration directions of the nicols.

This apparently common texture seems so far to have failed to arouse sufficient interest among petrographers and mineralogists to motivate publication. During thin section work on gneisses from Brazil the writer studied the feature in some detail and found that it represents an interesting example of photoelasticity in minerals, a phenomemon hardly dis-

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cussed in geological literature. Although recognized as chiefly caused by stresses produced during preparation of the thin sections, the feature may serve as a model for the optical disturbances induced by stresses around inclusions and some lattice defects in minerals.

The feature appeared most distinctly at moderate magnification, *e.g.* between 50 and 200X, the dark and bright bands generally being too fine for less magnification, whereas higher power (say 500X) made the pattern very diffuse.

The appearance of the grating is produced by numerous little separate crosses consisting of two hourglass shaped bars, one dark, one bright, intersecting orthogonally and bisecting symmetrically the vibration direction of the nicols (Fig. 1).

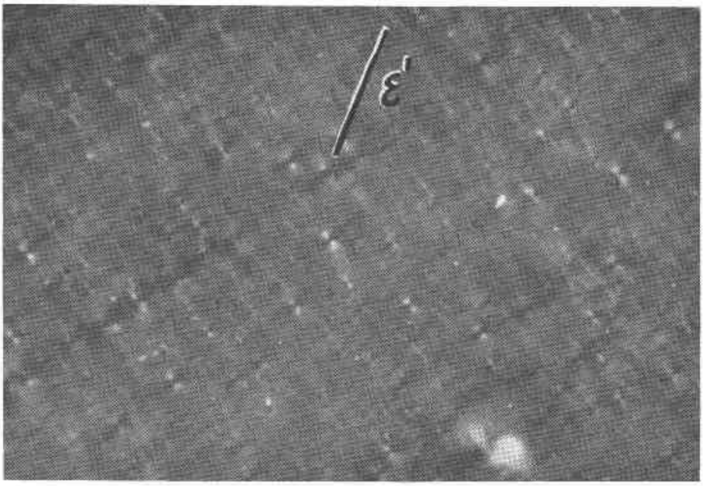

FIG. 1. Microphotograph of interference crosses around stress centers in quartz cut quasi normal to c. The vibration direction ϵ' of the quartz is marked by ink. The extinct bars of the crosses strike NE, the bright bars NW. Crossed nicols parallel to the edges of the photo whose length is 0.4 mm.

The maximum length of the bars was about 0.03 mm., but most were less than one third that size. All the little crosses were parallel, the dark bars constituting one set of parallel features, the bright bars another parallel set. The crosses were mostly scattered randomly, but occasionally occurred in rows.

In all sections studied the crosses changed consistently as follows when rotating the sections clockwise starting with the extraordinary ray of the quartz vibrating in NS direction:

A few degree rotation produced simultaneously and rather suddenly an appearance of numerous crosses with dark bars bisecting at about 45° the first–third quadrants, and bright bars or elongate regions bisecting the second–fourth quadrants, the vibration directions of the nicols being the reference coordinates. This pattern remained immobile, except for minor variations in the brightness and darkness of the bars, until ϵ' —the vibration direction of the extraordinary ray—is lined up with the EW direction when the uniform extinction is interrupted only by hardly visible small areas of light in the regions where the largest crosses had been.

A few degree further rotation caused a sudden reappearance of the crosses, but in a reversed position *viz.* with the dark bars bisecting the second–fourth quadrants and the bright ones in the first–third quadrants. The crosses remained in this position during the next 90° rotation of the quartz, *i.e.* until uniform extinction when ϵ' became parallel to the NS direction after 180° rotation from the starting point.

Checks with $\frac{1}{4}$ λ quartz plate showed that, within the circular regions swept out by the bars of the little crosses, the intersection of the indicatrix with the plane of the thin section was deformed (or rotated) in the manner shown in Fig. 4.

The variation of the brightness and darkness of the bars indicated that in general the magnitude of indicatrix deformation increased toward the centers.

This indicates a photoelastic effect created by local concentric distribution of anisotropic stress in the quartz lattice, the intensity of the stress increasing toward the center.

Before discussing some tests made to check this assumption, we shall describe the optical disturbances around the few centers of exceptionally strong deformation inasmuch as these showed details not visible in the little crosses.

When the quartz grains were in the position of extinction, some interference light passed through a few scattered small regions. In these regions the extinction was complete only along the arms of an orthogonal cross parallel to the vibration directions of the nicols, leaving a sector of faint light in each quadrant.

Clockwise rotation from a position $\epsilon' \parallel$ NS made the bars of the crosses bend, the north end of the vertical bar and the east end of the horizontal bar bending into the first quadrant at the same time as the south end of the vertical bar and the west end of the horizontal bar bent into the third quadrant. The cross thus changed into a figure 8 pattern, the longest axis of which bisected symmetrically the first–third quadrants while the section was rotated until ϵ' became parallel to EW. During this rotation, however, the long axis of the figure 8 "isogyre" changed, its length continuously decreasing during the first 45° rotation of the section and increasing again until ϵ' was parallel to EW, at which point the figure 8 pattern opened up to an orthogonal cross. Further clockwise rotation produced a figure 8 pattern in the second–fourth quadrants. A similar interference pattern occurs in glass, Fig. 2.

Insertion of a $\frac{1}{4}$ λ quartz plate with ϵ vibrating in the first quadrant gave additive interference color within the "eyes" of the figure 8 when it fell in the second–fourth quadrants, and subtractive color when the figure 8 fell in the first–third quadrants. Outside the figure 8 pattern, but close to its center, additive interference color stronger than in the rest of the quartz grain occurred when the figure 8 occupied the first–third quadrants. In these same regions outside the figure 8, substractive

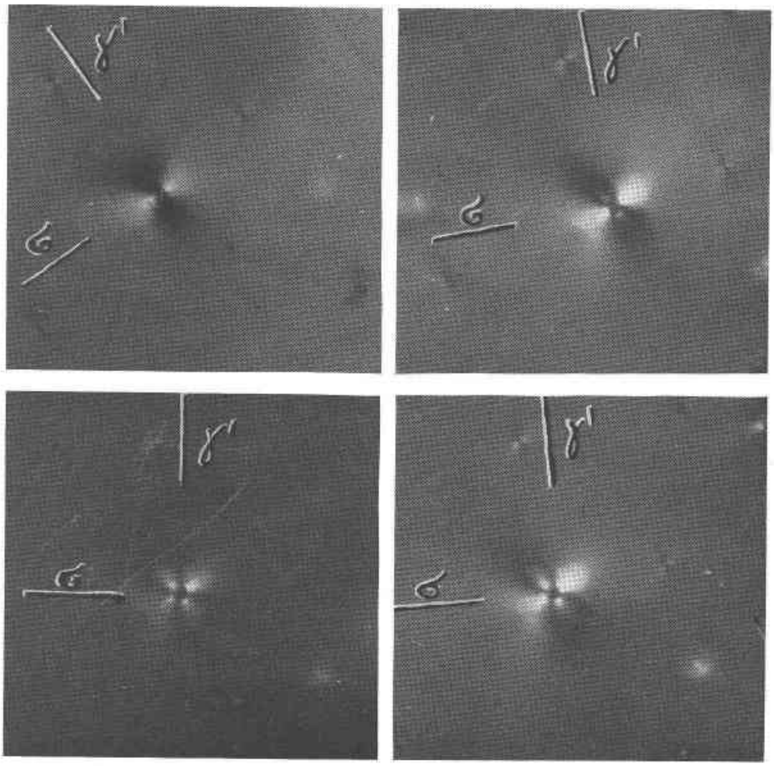

FIG. 2. Microphotograph of interference figures in stress fields caused by little grains of carborundum pressed between cover glass and objective glass made double refracting by application of compressive stress in direction σ. The vibration direction of the high-index ray is marked γ'. Crossed nicols parallel to edges of photos. Note how the central figure-8 pattern changes with varying angle between γ' and the nicols. Length of photos 0.2 mm.

interference color lower than the rest of the crystal occurred when the figure occupied the second–fourth quadrants.

When the bulk of the crystal was in the position of extinction such that a dark cross with four small sectors of light occurred at points of exceptional strong optical disturbance, the $\frac{1}{4}\ \lambda$ quartz plate gave always additive color for the light sectors in the second and fourth quadrants, and substractive color in the first and third quadrants.

These observations on the regions of strong disturbances verified the notion that the quartz indicatrix was significantly deformed within more or less circular (spherical, cylindrical?) regions, the general pattern of deformation being as shown in Fig. 4.

The figure 8 extinction pattern may perhaps not seem an obvious consequence of such radial distribution of indicatrix deformation, but a closer study will reveal that a pattern of this kind is exactly what should be expected if the indicatrix is deformed in a field of anisotropic stress with spherical or cylindrical symmetry.

A grating texture similar to that described from the quartz was sometime seen in plagioclase and potash feldspar. In the feldspars, however, the pattern was rarely developed as clearly and as symmetrically as in the quartz. The bright and dark elongate regions were rather diffuse, they were not always quasi-normal to one another but appeared somewhat controlled by the tricline structure of the feldspars, and often one set of linear regions showed up much better than the other.

In quartz as well as in feldspars the feature here described would become less and less visible the more the optic axis deviated from the microscope axis. For large angular deviation of these axes the optical disturbances could only be seen when the crystals in bulk were close to the position of extinction.

Experimental Tests

It is generally true that transparent solids show photoelastic effects in the sense that their indices of refraction vary with magnitude and geometry of the stresses applied, the piezo optical coefficient being the measure of the relationship between stress and indices of refraction. An excellent discussion of this phenomenon is found in Nye (1957). Unfortunately nothing seems to be known with reference to the piezo optical coefficient of quartz and feldspar.

As an interpretation of the described optical disturbances to the first approximation does not require a quantitative knowledge of piezo optical coefficient (the sense of the change of double refraction with stress is sufficient) the experiments were limited to qualitative stress tests on small polished samples of quartz and feldspars.

Rectangular plates some 2–4 mm. thick were cut and polished normal to the c-axis of quartz, and other plates of similar thickness were cut parallel to this axis. The plates were subjected to compressive stress in direction parallel and normal to the c-axis in the plane of the plates, and the variation of the double refraction noted in the microscope by help of compensating quartz wedges. It was found that in all cases the double refraction changed in such a fashion as to show that the indicatrix was deformed in a manner similar to the elastic strain ellipsoid, *i.e.* dimensions of the indicatrix which were parallel to the applied compressive stress decreased relative to dimensions normal to the stress.* When compressive stress was applied parallel to c on the plates cut parallel to this axis the double refraction $\Delta n = \epsilon' — \omega'$ decreased; when stress was applied normal to c on the same plates the double refraction increased. Stress applied normal to the trigonal axis on the plate cut normal to this axis made the plate distinctly double refracting with the smaller axis of the deformed indicatrix parallel to the stress. In the latter case the indicatrix became a triaxial ellipsoid.

The significance of these tests is to show that for quartz the photoelastic distortion (*i.e.* the deformation of the indicatrix under stress) is similar to the deformation of the elastic strain ellipsoid. This was necessary to check inasmuch as there exist solids whose indicatrix distortion under stress is opposite to the deformation of the strain ellipsoid. In other words the indicatrix becomes elongated (relatively) in the direction of the highest compressive stress. It is, however, possible that all axes of the indicatrix increased under uniaxial compression, but to different degree. Potassium chloride is an example of a crystalline solid with this character (Nye, 1957, p. 255); plexiglass, which was used in the model tests below, is an example on an amorphous substance with such photoelastic character.

Because of low symmetry the number of piezo optical coefficients necessary to describe fully the photoelastic character of feldspars is great—36 different coefficients for triclinic feldspars and 20 for monoclinic (Nye 1957, p. 250) as compared with 8 for low quartz. No attempt was made to determine fully the photoelastic character of feldspar, but a few tests were made on cleavage fragments parallel to (001) and parallel to (010) of potash feldspars (adularia and orthoclase of the type characteristic of charnockite rocks).

When the basal cleavage fragments were compressed in direction parallel to the a- and the b-axes respectively, and the change in double

* The experimental tests did not give information about the absolute variation of the indices of refraction; it may well be, for example, that all three indices increased with increasing uniaxial compressive stress.

refraction observed on basal cleavage flakes, it was found that the indicatrix cross section was relatively compressed in direction of the stress.

Cleavage flakes parallel to (010) showed a similar deformation of indicatrix cross section, *i.e.* the indicatrix was elongated normal to the compressive stress when applied parallel to *a* as well as when applied normal to (001). It appeared, however, that the effect was sensibly less when stress was applied normal to (001) than when applied parallel to *a*.

It appears then, at least for stress applied in the direction noted above, that adularia and orthoclase behave photoelastically similar to quartz (but opposite to plexiglass) in the sense that the distortion of the indicatrix under stress is qualitatively similar to the distortion of the strain ellipsoid under the same stress.

In light of these tests of the photoelastic character of quartz and feldspars, it follows that the concentric optical disturbances as described from thin sections are caused by a spherical or cylindrical stress field with the highest principal stress parallel to the radius, a stress distribution to be expected if caused by a nucleus of high pressure.

To obtain more detailed information about the photoelastic effect of a spherical or cylindrical stress field in an optically anisotropic medium such fields were artifically produced in various transparent solids which either possessed permanent double refraction (cellophane paper, photographic film, plexiglass), or were made double refracting by application of directed uniform stress (common glass), superimposed on the spherical or cylindrical stress field.

In sheet-shaped samples of these substances smaller or larger regions of quasi-concentrically distributed stress were developed by pressure from a pointed instrument (on cellophane paper, photographic film, plexiglass), by hitting the surface with a pointed metal tool (glass), or by drilling tiny holes in which plugs of lead were stampted (plexiglass, film). The points of pressure or impact, and the plugs of lead acted as centers about which the concentric stress is distributed with the largest principal stress parallel to the radius and decreasing rapidly with distance from the center as given by equations (1) to (3) below.

This stress pattern simulates the condition to be expected for example around mineral inclusions with small compressibility enclosed in more compressible mineral if exposed to increasing external pressure. If an inclusion is more compressible than its host, release of confining rock pressure (*e.g.* elevation of a rock complex from depth due to surface erosion) may result in the same kind of stress pattern around the inclusion. Variable temperature combined with unlike thermal expansion of inclusion and host could also give stress distribution of this type. Similar stress distribution may moreover result from an inclusion growing in a mineral, the inclusion executing a certain "force of crystallization."

In some instances the stress pattern was reversed during the tests in such a fashion that the largest principal compressive stress was made normal to the radius. This was achieved by subjecting a circular sheet of plexiglass with a small open hole to planar compressive stress acting in radial direction around the circumference. In the vicinity of the hole, maximum principal compressive stress is then normal to the radius, and decreases with increasing distance from the hole.

This situation would serve as a model for the stress distribution around an inclusion whose compressibility is greater than that of the host mineral provided the mineral is exposed to increasing rock pressure. If an inclusion is less compressible than its host, release of rock pressure may cause a stress distribution as here mentioned. Unmixing of alkali feldspar should create a similar stress pattern around the albite lamellae inasmuch as the unit cell of albite is considerably less (about 10% by volume, Laves, 1952, p. 551) than that of microcline.

All the thus prepared samples showed at crossed nicols under the microscope interference pattern essentially similar to that around the described disturbances in quartz and feldspars. The pertinent feature common to the disturbed little regions in all samples was an area of extinction in each of two diametrically opposite quadrants of the crossed nicols and areas of brightness in the two other quadrants. The fields of extinction and brightness would alternate among the quadrants upon rotation of the microscope stage. Indeed, in common glass, texture indistinguishable from that in quartz was produced simply by grinding a sheet of glass as if it were a mineral section, applying canada balsam and cover glass. When this section was put under homogeneous plane stress, such as to give it a faint double refraction, and observed under crossed nicols its grating structure of optical crosses looked identical to that of quartz. During grinding, impacts of the carborundum grains on the surface of the quartz creates the same kind of stress centers as they do on the ground glass.

The most ideally symmetrically interference figures were developed around plugged holes in the plexiglass (Fig. 3). This substance was therefore best suited for a detailed study. One must note, however, that plexiglass (at least the piece that was used in these experiments) has photoelastic properties of opposite character to quartz, feldspars and the other substances (glass, cellophane paper, film) tested. Independent stress checks on plexiglass showed that its indicatrix becomes relatively elongated in the direction of maximum compressive stress.

The deformation of the indicatrix is essentially determined by the difference between radial and tangential stresses around the stress center, and by the orientation of the stress ellipsoid relative to the original indicatrix. The difference of radial and tangential stresses $\sigma_r - \sigma_\theta$, about the cylindrical hole (pressure = 0) varies with distance r from the center thus

1) $$\sigma_r - \sigma_\theta = \Delta\sigma_1 = \frac{2a^2b^2}{b^2 - a^2}\frac{P_c}{r^2}$$

where a is radius of the hole, b radius of the disk and P_c pressure on the circumference of the disk. As a and b are constant for a given test disk it is seen that the stress difference decreases rapidly with distance from center.

For a plugged hole in which pressure is P_h and pressure on the circumference on the disk is zero, the stress difference at distance r from center is

2) $$\sigma_r - \sigma_\theta = \Delta\sigma_2 = -\frac{2a^2b^2}{b^2 - a^2}\frac{P_h}{r^2},$$

(see Jaeger 1956, p. 126). If the disk is large relative to the hole the equation reduces to

3) $$\Delta\sigma_1 = 2a^2\frac{P_c}{r^2}; \qquad \Delta\sigma_2 = -2a^2\frac{P_h}{r^2}.$$

Fig. 3 shows a sequence of microphotos of the interference figure around a plugged hole in plexiglass.

In analyzing the interference figure of the plexiglass let us for simplicity assume that the stress is distributed with cylindrical symmetry around the plugged cylindrical hole whose axis is normal to the surface of the sheet. The conditions that the radial compressive stress decreases with distance from the center, and that the relative elongation of the indicatrix increases with increasing intensity of stress difference, *i.e.* difference between radial and tangential stresses, result in the following pattern of indicatrix deformation: Along the radial direction from the stress center which is parallel to the long axis of the indicatrix in the undisturbed plexiglass, the elongation of the indicatrix simply increases as the center is approached. Along the radial direction which is parallel to the small axis of the undisturbed indicatrix, the elongation of the indicatrix decreases as one approaches the stress center until at a certain distance the indicatrix cross section becomes circular. At this distance the stress is exactly sufficient to neutralize the optical anisotropy of the plexiglass. This happens at two diametrically opposite points about the stress

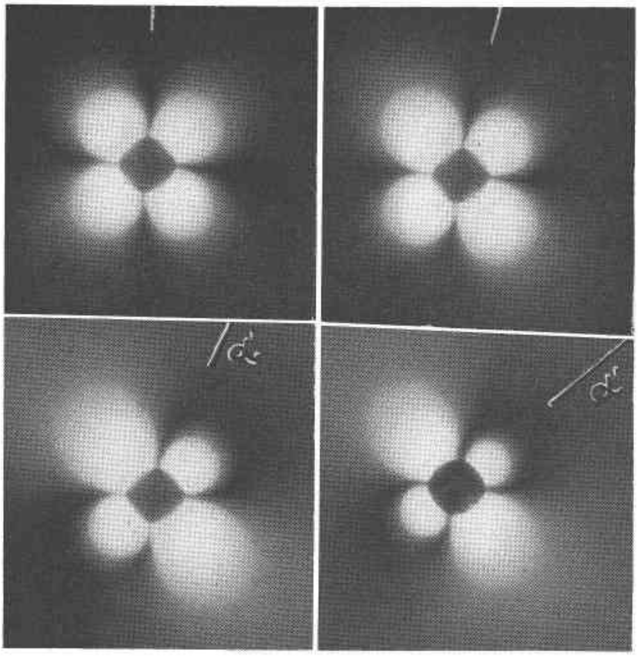

FIG. 3. Microphotographs of interference figures in stress field around plugged hole in a plate of plexiglass. The lines in upper middle and upper right sides of the photos give the vibration direction of the low-index ray in the plexiglass, and indicate the angular deviation of the sample from the crossed nicols which are parallel to the edges of the photos. Diameters of photos 1.3 mm.

center. These points are extinct at any angular position of the sheet relative to the nicol directions, and the figure 8-shaped "isogyre" must always pass through these points.

In the region between the two "isotropic points" and the center of stress the indicatrix becomes increasingly elongated in direction parallel to the radius as the center of stress is approached.

For quartz and orthoclase cut quasi-normal to the optic axis, for cellophane paper and photographic films whose indicatrix respond to stress in a sense opposite to that of plexiglass, the indicatrix deformation around a stress center is as indicated in Fig. 4. This figure is also valid for common glass made double refracting by application of an uniform planar directed stress superimposed on a stress center.

In the quadrants between the coordinate axes x and y the deformed indicatrix is rotated because the principal axes of stress are inclined to the original indicatrix. As we do not know accurately the piezo optical

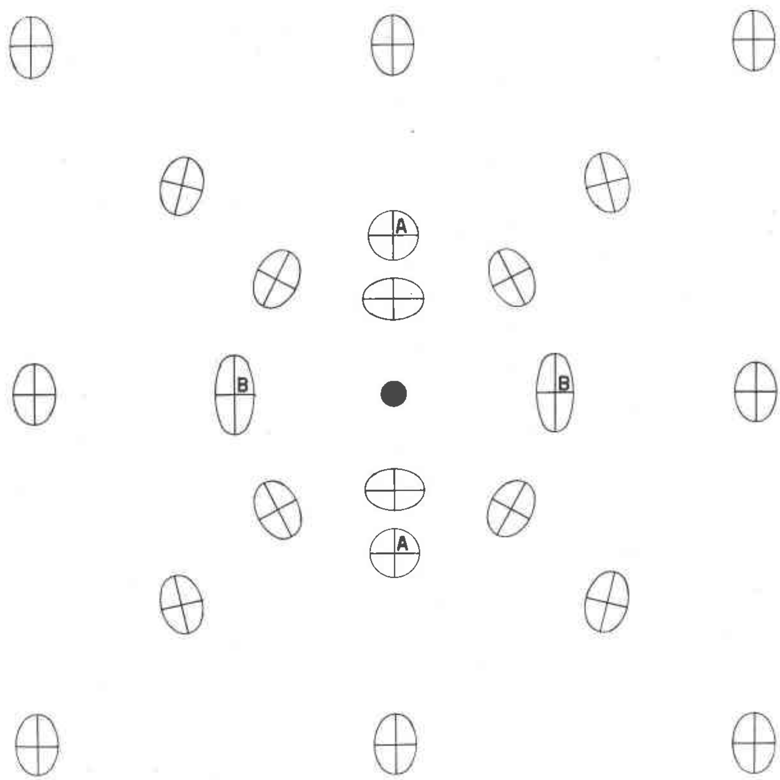

FIG. 4. Schematic map of indicatrix cross sections around a center of stress in plexiglass, or quartz cut quasi normal to the *c* axis. The ellipticity of the undisturbed indicatrix (along the edges of the figure) is considerably exaggerated. If the figure refers to quartz maximum compressive stress is parallel to the radius from the stress center; if referring to plexiglass maximum compressive stress is normal to the radius.

coefficients of either plexiglass or quartz and feldspars, it is not possible to determine quantitatively the degree of strain and rotation of the indicatrix, but it is plain that the vibration direction of the light rays must follow a pattern similar to that shown in Fig. 5. This figure can be thought of as representing plexiglass as well as quartz cut quasi normal to the *c* axis, containing a center around which the decreasing maximum compressive stress is either parallel to the radius or tangential to the circumference. If the figure is to refer to plexiglass with a center of radial maximum compressive stress or to quartz with a center of tangential maximum compressive stress the lines indicate the vibration directions of the low-index ray. If the figure is to refer to plexiglass with a center of tangential maximum compressive stress, or to quartz with a center of radial maximum compressive stress the lines represent the vibration of the high-index ray.

When one of the crossed nicols vibrates parallel to the y axis, it is seen that a peripherial field of the figure as well as an orthogonal cross through the center of stress will be extinct. If rotated clockwise until one nicol is parallel to line 2, a loop shaped area marked by heavy lines and the num-

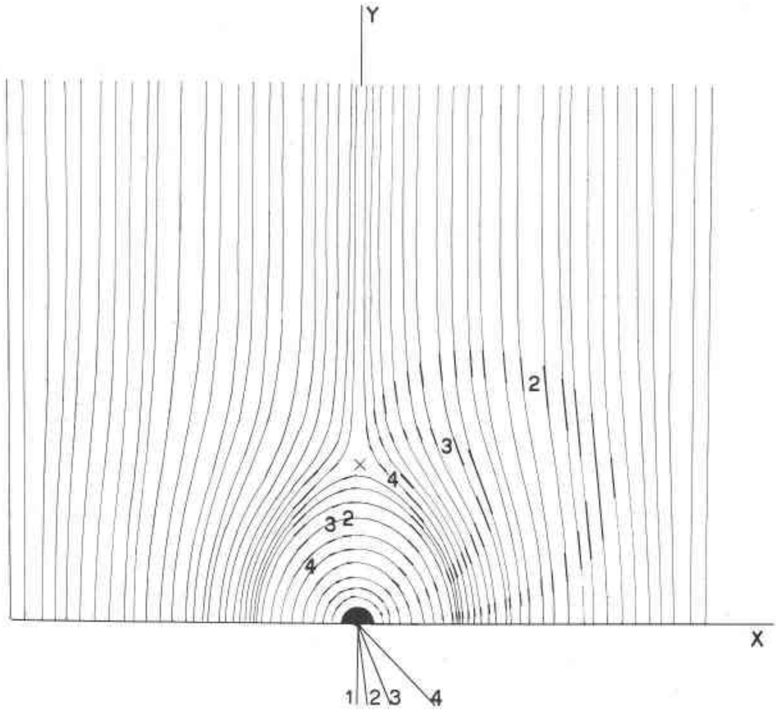

FIG. 5. Map of vibration direction of one of the two polarized rays around a stress center in a double refracting solid. Only half of the stress field is shown, rotation of the figure 180° about the stress center produces the other half. The loops indicated by heavy lines and marked 2, 3, and 4 represent regions of extinction when one of the crossed nicols vibrates parallel to the lines 2, 3 and 4 respectively. The cross slightly below the center of the figure represents one of the "isotropic" points of no double refraction.

ber 2 will become dark. Further rotation makes the loop shrink continuously to the areas marked 3 and 4, respectively when one nicol is parallel to line 3 and 4. Stage 4 represent 45° rotation of the sample. The reader may convince himself that further rotation makes the loop of extinction (*i.e.* the locus for the points at which the vibration directions in the sample is parallel to the nicols) expand out in the region between the positive y axis and the negative x axis. This continues until 90° rotation at which y is parallel to the horizontal nicol. Further rotation makes the loop of extinction redevelop in the region between the positive y- and x-axes (*i.e.* now in the 4th quadrant of the crossed nicols). One also realizes that the loop of extinction at all times is symmetrically situated in the quadrants of the vibration direction of the crossed nicols.

The explanation above is valid for cylindrical stress distribution around a center such as will essentially prevail if the stress center is linear and normal to the test plate, the stress in this direction being zero (or constant) throughout. In such a stress field the vibration directions remain fixed through the entire thickness of the plate along any given ray normal to the surface. Extinction is then limited to points where the vibration directions of the test plate coincide with those of the crossed nicols. (We note that the double refraction of both the stressed and unstressed parts of the tested materials—including the thin sections of quartz and feldspar—is too low to produce other than first order gray.)

At other stress distributions the conditions for extinction are less simple. Suppose for example that the stress is distributed with spherical symmetry about a center in a test plate sufficiently thick to leave the indicatrix undisturbed over the entire surface. None of the rays which have passed through the plate are therefore polarized normal to the analyzer (unless of course the whole sheet is in position of extinction), and extinction of the rays passing the internal field of stress must be caused by interference rather than parallelism with the nicols.

Without attempting to determine the extinction figure quantitatively which follows from an enclosed stress field of spherical symmetry, it may be of some interest to compare it qualitatively with the above considered cylindrical stress field. Consider two test plates with the same thickness and double refraction, one with a cylindrical stress field around a circular plug normal to the plate, the other with a spherical stress field around an inclusion, the stress of the latter not reaching out to the surface.

For simple comparison let us assume that the strength of the two stress fields, measured in terms of σ_r and σ_θ is the same for given radial distance from the centers. If these two fields are observed under the microscope at crossed nicols one finds that the extinction pattern is very similar, both showing the figure-8 pattern described above. This was verified with simple tests on plexiglass. However one essential difference is that the extinct figure 8 is always considerably smaller for the spherical field than for the cylindrical one of the same strength. This is a consequence of the fact that a light ray which passes the spherical stress field must cross thicker and thinner layers of optically undisturbed material above and below the field of stress. Moreover, through the field itself the indicatrix controlling the ray changes continuously. For the cylindrical stress field no such effect is theoretically present, or in reality (because of imperfect cylindrical symmetry) the effect is much less than for the spherical field.

The photoelastic disturbances which were observed around inclusions in quartz and feldspars (see below) did not produce the distinct figure-8 pattern shown by the plexiglass and some stress centers in ground quartz and common glass. Around inclusions in quartz and orthoclase only rather small differences in extinction angle and intensity of interference light appeared: diffuse region of excess darkness in the first–third quadrants and complementary region of excess light in the second–fourth-quadrants, or vice versa. Such effects seem a reasonable result of weak stress fields, everywhere too weak to reverse the elongation of the natural indicatrix in the stressed medium. In such fields the two "isotropic" points (Fig. 5) do not appear, and the whole central region of elliptical traces of the optical vibration direction as shown in the figure fails to develop. Only the outer diffuse pattern will appear under the microscope at crossed nicols, giving diffuse regions of extinction in one of the sets of diametrically opposite quadrants and regions of brightness in the other. This pattern was common around the stress centers caused by impact or point pressure on cellophane paper and photographic film. The pattern was also produced around holes without plugs drilled part way through a sheet of plexiglass, Fig. 6. The pressure from the drill at the bottom of

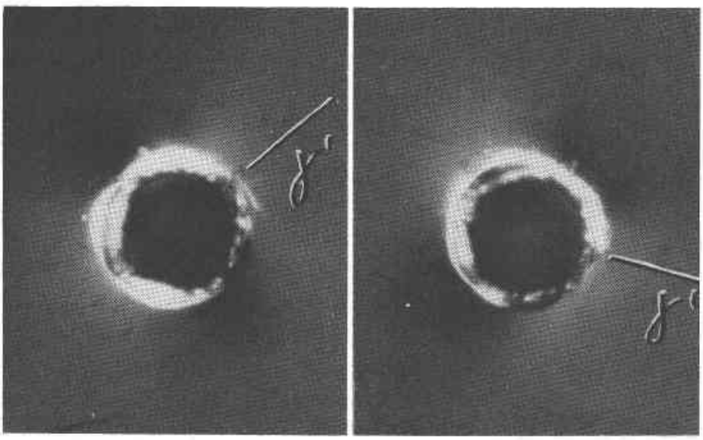

FIG. 6. Microphotographs of diffuse interference figures produced by a weak stress field around a hole drilled 1 mm down in a 5 mm thick plate of plexiglass. The lines marked γ' indicate the vibration direction of the high-index ray. Crossed nicols parallel to the edges of the photos. Diameter of hole 0.4 mm.

the hole probably produced the weak elastic or plastic field necessary to produce the diffuse interference pattern.

Photoelastic Effect Around Inclusions in Quartz and Feldspars

In several of the thin sections examined from Brazilian gneisses, optical disturbances were seen around inclusions in quartz and feldspars. Much of these features showed interference patterns of a kind to be expected if the inclusions function as centers of stress.

Inclusions in quartz

In quartz visible photoelastic effect around inclusions was rather rare, and when observed it was always faint, considerably less clearly developed than the best ones in orthoclase.

Inclusions surrounded by visible stress in quartz were zircon, apatite and hornblende. The effect always appeared as diffuse regions of faint excess light in two diametrically opposite quadrants and shaded regions in the two other quadrants when referring to the vibration directions of the nicols as the reference coordinates.

The interference disturbance usually appeared when the grains were within limited angular deviation from bulk extinction. Without exception ϵ' of the quartz proved to vibrate in the quadrants which contained the shaded regions, the shaded and bright regions consequently alternating among the quadrants when the sections were rotated. This condition, in combination with the tested piezo optical character of quartz (see above) shows that in all observed cases the inclusions functioned as centers of relatively high pressure, or that the concentric stress field was formed as a result of increased pressure or anisotropic stress affecting the rock after the inclusions were emplaced. Since quartz is considerably more compressible than all common minerals reported for example by Birch in Handbook of Physical Constants, 1942 (including zircon, apatite and actinolitic hornblende, see Table I) increasing external pressure on a quartz grain will create a field of intensified radial stress around inclusions of almost any kind of common mineral.

Inclusions in orthoclase

The optical disturbances around inclusions in orthoclase was much more common and more intense than in quartz. (The orthoclase was of the type characteristic of charnockite gneisses and granulite facies rocks; *i.e.* it did not show distinct twinnings, was usually microperthitic, and often showed a type of wavy extinction perhaps caused by submicroscopic microcline-type twinning, see below.) Inclusions of apatite, zircon,

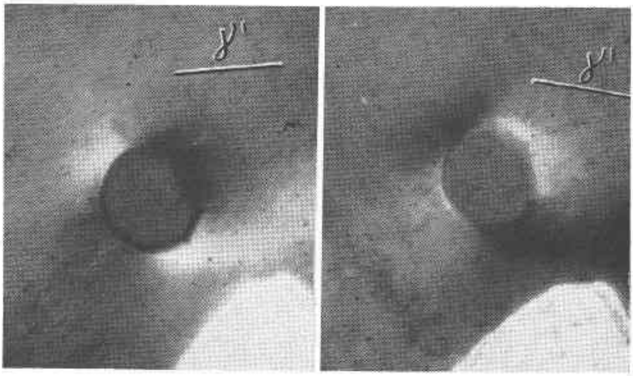

FIG. 7. Microphotographs of interference pattern in orthoclase around inclusion of quartz. The vibration direction γ' shown by ink lines. Crossed nicols parallel to edges of photos. Diameter of inclusion 0.009 mm. Section 65b–60.

ore minerals and plagioclase in orthoclase were more often than not surrounded by a region of disturbance of similar characters as described from quartz. Figs. 7 and 8 show examples of this feature. Also in orthoclase the lower index ray (α') was consistently found to vibrate in the bright quadrants and the higher index ray (γ') in the shaded quadrants. This observation, combined with the piezo optical character of orthoclase indicates that the inclusions were surrounded by stress fields with maximum compressive stress in radial directions. According to Table I or-

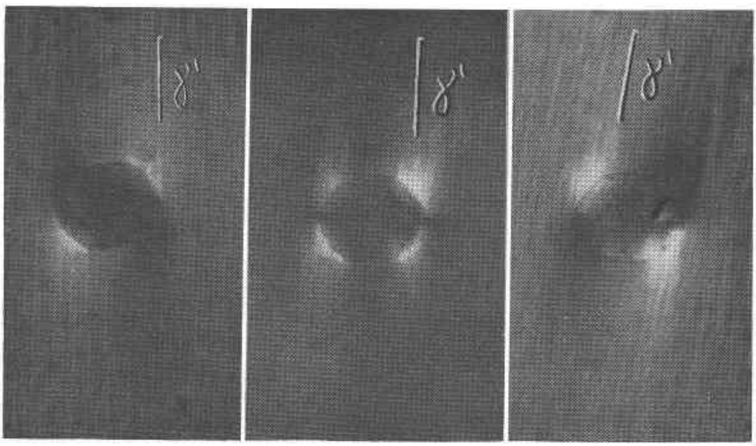

FIG. 8. Microphotographs of interference pattern in orthoclase around inclusion of apatite. Note the small angular deviation between γ' and the vertical nicol in A and C. In B, γ' is parallel to the vertical nicol. Crossed nicols parallel to the edges of photos. Longest diameter of inclusion 0.02 mm. Section 3–60.

thoclase has higher compressibility than oligoclase, labradorite, zircon, oxide ore minerals and apatite. The observed photoelastic effects could therefore be taken to indicate that the stress field around the inclusions was developed during a period of increased isotropic or anisotropic stress affecting the rock in bulk. This conclusion is not contrary to other features in the studied rocks. Undulatory extinction of orthoclase, plagioclase and quartz, so common in the granulite facies gneisses under study certainly shows that the rocks were subject to intense stress during their later period of evolution.

In closing, let us point out that there are features of the optical disturbances around inclusions in orthoclase which perhaps indicate that they do not represent a simple photoelastic phenomenon, but that sub-

TABLE I. VOLUME COMPRESSIBILITIES AFTER FORMULAE—$\Delta V/V_0 = aP - bP^2$ (Handbook of Physical Constants, 1942)

	$-\Delta V/V_0$		Temp. ° C.
	10^7a	$10^{12}b$	
α-quartz	27.06	24.0	30
Fe_2O_3	6	—	0
$FeTiO_3$	5.6	—	0
Apatite	10.91	4.1	30
TiO_2	4.83	0.92	30
Zircon	8.6	—	0
Orthoclase	21.23	14.5	30
Labradorite	15.0	9.8	25
Actinolite	13.0	—	25

microscopic twinning may be involved, facilitated by the stress field. Firstly, it is surprising that the optical disturbances caused by inclusions is without comparison more abundant and intense in orthoclase than in quartz, not to mention plagioclase in which the effect is all but lacking. Yet the tests of the piezo optical properties of quartz and orthoclase did not indicate orthoclase to be more sensitive to stress than quartz. Secondly, it was sometimes seen that the optically disturbed regions around inclusions in orthoclase were structurally controlled in the sense that the light and dark regions tended to be limited by directions closely parallel or normal to (010) (see Fig. 8), *i.e.* directions parallel to the cross-hatch twinnings in microcline. Thirdly, some tendency to microclinization of the orthoclase, chiefly adjacent to fractures, albite lamellae and inclusions, was evident in many thin sections. It is not unreasonable that the stress fields around the inclusions have facilitated the transition from orthoclase to microcline, giving rise to submicroscopic twinning or continuous variation in "triclinity" in regions were the stress field had a proper orientation for twinning production. That twinning in potash feldspars is produced by stress is not a new idea (see Alling 1921–24). However, if the cases described above are examples on incipient microclinization, it is interesting that they show an indicatrix reorientation of a type to be expected on purely photoelastic grounds, *i.e.* without a phase transition but rather continuously varying stress (and strain) in concentric stress field.

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