

# THE CAUSE OF COLOUR OF THE BLUE QUARTZES OF THE CHARNOCKITES OF SOUTH INDIA AND THE CHAMPION GNEISS AND OTHER RELATED ROCKS OF MYSORE

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## *Introduction*

The nature of mineral colours has been a subject of much study especially during the last few decades. Investigations of the cause of colour of minerals, and its variation with physical and chemical properties as well as with temperature, were carried out systematically only in recent years. Such investigations were carried out mainly with the common coloured quartzes, smoky quartz, amethyst and rose quartz, and some other coloured minerals, prominent among which are zircon, topaz, tourmaline, fluorite, garnet, sapphire, emerald, ruby, etc. But the charnockite blue quartz, which is as abundant as any of the other coloured quartzes, has not received much attention from mineralogists or physicists so far.

Holland<sup>1</sup> investigated the greyish-blue charnockite quartz from South Africa and observed the presence of acicular inclusions which he considered to be rutile. He reported that the colour of the quartz was probably due to these inclusions, but he does not appear to have either isolated the inclusions or carried out a chemical investigation of the quartz specimens.

The blue quartzes of Nelson and Co., Virginia, which were investigated by Dunnington<sup>2</sup> and Robertson<sup>3</sup> possess a colour which is unaffected by heating, but showing at the same time some relation to their  $TiO_2$  and  $Fe_2O_3$  contents, while those of Pfaffenreuth show a very unstable blue colour which according to Weinschenk<sup>4</sup> is due to the manganese and iron content of these quartzes. The colour of these quartzes, which is of a yellowish-red tone in transmitted light and blue by reflected light, disappears even on gentle heating. The colour is found to be unstable even in direct sunlight. Further, the Pfaffenreuth quartz is found to contain inclusions of needles with high birefringence and weakly birefringent droplets. Finally Weinschenk

comes to the conclusion that there is a possibility of dilute dyes playing a rôle in the colouring of this quartz. The cause of the blue colour in the quartz from Rumberg in Bohemia, described by Von Cotta<sup>5</sup> could not be determined microscopically. Robertson<sup>6</sup> and Iddings<sup>7</sup> hold the view that the colour of blue quartz is due only to the microscopic acicular inclusions of rutile, and Postelmann<sup>8</sup> also comes to the same conclusion. Watson and Beard<sup>9</sup> observe that the blue quartz of the Virginia rutile area owes its colour to the presence of acicular inclusions of rutile, the phenomenon being attributed to the behaviour of light reflected from the surface of these inclusions.

The present paper describes the results obtained by chemical and microscopic examination of the specimens and the light they throw on the problem of colouration of minerals.

*Physical and Chemical Properties.*—

Specimens of charnockite quartz with varying intensity of blue colour as well as the opalescent blue quartz from the champion gneiss and related rocks of Mysore were examined in the course of this work. The colour of these quartzes which is of an yellowish tone by transmitted light and blue by reflected light was found to be greatly affected by heating, the charnockite quartz losing its colour completely even at 300° C.

The charnockite quartz occurs as crystal aggregates in the acid charnockites. The crystal mass shows considerable cracking and granulation. The colour of this quartz is not very dark, but it is definitely blue with a greyish tint.

Boiling with hydrochloric acid was found to free the crushed specimens totally from the iron present as an impurity, but since the blue colour of the specimen persisted even after this treatment, it appears that iron compounds do not contribute to the colour of the specimen.

Specific gravities of the various quartzes :

(i) Pallavaram charnockite blue quartz (B) " Type Specimen " .. .. .	..	2.660
(ii) Pallavaram charnockite colourless quartz (F)	..	2.665
(iii) Pallavaram charnockite blue quartz (A) ..	..	2.662
(iv) Colourless glassy quartz from Nellore ..	..	2.661

*Microscopic examination of the blue quartz specimens with varying intensities of colour.*—

*The Charnockite quartz specimens*—(A) *Specimens coloured more intensely than others.*—These were collected from the Pallavaram Hill and are few

in number. In their microscopic properties they are similar to (B), described below, excepting for the intensity of the colour of the turbid medium which is more prominent than in (B). The distribution and arrangement of the various inclusions are exactly the same as in (B).

(B) *The common charnockite blue quartz.*—“*Type Specimen*”—This was collected from the so-called “Charnockite-pegmatite” of Holland, a coarse grained rock composed mainly of blue quartz and microperthitic microcline occurring as contemporaneous or segregation veins in the type mass of charnockite which forms a low hill on the western side of the St. Thomas Mount.

When a thin section of this quartz is examined under the microscope it shows an enormous number of inclusions which can be classified under two heads, *viz.*, (a) *regularly arranged acicular inclusions* (Microphotographs 1, 2) and (b) *the more or less irregular drop-like and dust-like inclusions showing much variation in size* (Microphotographs 3, 4). When sections cut perpendicular to the C-axis are examined between crossed nicols the acicular inclusions are highly birefringent while the others are almost isotropic, a few of them, however, being weakly birefringent. The quartz grains which appear to be homogeneous shapeless crystals are found, when examined under the microscope between crossed nicols, to be made up of many crystal grains in different orientations. Thus, this definitely shows that the quartz has undergone fragmentation at some stage or other. Further, most of the individual grains show strain shadows. Often, the acicular inclusions extend through adjacent fragments of the quartz in unbroken continuity indicating thereby either a secondary origin for these acicular inclusions or a secondary arrangement not along cracks produced by orographic movements as suggested by Johannsen<sup>10</sup> due to molecular movement of titanium when the magma was in a plastic condition.

A thin section of this quartz shows between parallel nicols a pale brownish-yellow turbidity which is not so prominent as in the Mysore blue quartz A. 762 described below. The presence of this coloured turbid medium can be easily detected even in fairly thick sections under low power. The dust-like and drop-like inclusions are found either scattered uniformly throughout the quartz or congregated in patches or lines like strings of pearls (Microphotographs 5, 6).

The arrangement of the acicular inclusions in two different sections of the quartz is as follows :

*In sections parallel to the prism (110).—*

NEEDLE GROUPS	REMARKS
(1) Parallel to the axis of minimum optical elasticity, <i>i.e.</i> , parallel to the <i>C</i> or vertical axis.	One set of needles of equal length lying almost in the plane of the section. 50 to 100 $\mu$ in length.
(2) Parallel to the fast direction, <i>i.e.</i> , parallel to one of the lateral crystallographic axes and exactly at right angles to system (1).	One set of needles lying in the plane of the section. Average length is about 100 $\mu$ . Needles varying in length from 200 to 300 $\mu$ are also met with.
(3) Parallel to a direction which makes an angle of 38° with system (2) and 52° with system (1).	One set of needles of almost equal length lying in the plane of the section. Length 50 to 100 $\mu$ .
(4) Parallel to a direction which makes an angle of 38° with system (1) and 52° with (2).	One set of needles similar to system (3) but lying not exactly in the plane of the section.
(5) Parallel to a direction which makes an angle of 15° with system (2) and 75° with system (1).	Only a few needles—not exactly in the plane of the section. Needles are comparatively short—25 to 50 $\mu$ in length.
(6) Parallel to a direction which makes an angle of 30° with system (2) and 60° with (1).	Needles fairly long but not in the plane of the section. They are also few in number. Length 100 to 200 $\mu$ .
(7) Parallel to a direction which makes an angle of 30° with system (1) and 60° with (2).	Similar to system (6). Length 100 to 200 $\mu$ .
(8) Parallel to a direction which makes an angle of 15° with system (1) and 75° with system (2).	Similar to system (5). Do not lie in the plane of the section. Length 10 to 50 $\mu$ .
(9) Parallel to a direction which makes an angle of 5 to 10° with system (1).	Very short needles—not in the plane of the section. Length 10 to 25 $\mu$ .
(10) Parallel to a direction which makes an angle of about 5° with system (2).	Similar to system (9). Length 10 to 25 $\mu$ .

The section was also studied under dark-field-illumination to search for needles perpendicular to the section examined. The cut ends of needles were then found to stand out as bright points of light showing the presence of needles perpendicular to the section, that is, needles lying in a direction parallel to the secondary planes of symmetry of quartz crystal.

*In a section perpendicular to the C-axis.—*

Here the sets of needles are less in number and they are easily made out. Their characters can be studied without much difficulty owing to the isotropic nature of the section which is cut perpendicular to the optic axis of the crystal. There are seven well-defined sets of needles which can be easily recognised in thin sections and they are as follows :

(1), (2), (3).—These three sets of needles are almost of equal length (about 100  $\mu$ ) crossing one another at an angle of  $60^\circ$ . All these needles lie in the plane of the section.

(4), (5), (6).—These three sets are almost similar to sets (1), (2) and (3) but they exactly bisect the angle ( $60^\circ$ ) formed by the latter sets. They cross one another at an angle of  $60^\circ$ . Average length is about 75  $\mu$ .

(7) There is one set of needles lying almost parallel to one of the three above-mentioned sets, but not lying in the plane of the section. These needles vary in length from 100 to 150  $\mu$ .

There are also two or three other sets of very short needles (5 to 10  $\mu$ ) not lying in the plane of the section. These sets comprise only very few needles.

The above observations regarding the arrangement of the needles in the two sections can be summarised and classified as follows :

(a) There is one set of needles parallel to the vertical or C-axis.

(b) There are three sets of needles parallel to the three lateral crystallographic axes of the quartz and thus lie in the principal planes of symmetry.

(c) There are three sets of needles lying parallel to directions which bisect the angles formed by the lateral crystallographic axes, that is, they lie in the secondary planes of symmetry.

(d). There are two sets of needles parallel to the faces of the unit rhombohedron.

(e). There are six other sets of needles in a section cut parallel to the prism and about three in a section cut perpendicular to the C-axis which do not lie in the plane of the section and therefore could not be identified with any of the crystallographic directions.

While referring to the set of needles which is supposed to be parallel to the face of the unit rhombohedron, Holland<sup>1</sup> remarks that this set meets the vertical axis at an angle of  $52^\circ$  instead of at  $38^\circ$  and the trace of the basal plane at an angle of  $38^\circ$  instead of at  $52^\circ$ . As found out by Holland the needles lying in the basal sections of the quartz show straight extinction and are highly birefringent.

(C) *A blue quartz from Pallavaram Charnockite less intense in colour than (B).*—The acicular and dust-like and drop-like inclusions are as abundant as in (B). The brownish-yellow turbidity is slightly less intense and the arrangement and distribution of the inclusions are exactly the same as in (B).

(D) *A blue quartz from Pallavaram Charnockite less intense in colour than (C).*—The abundance and distribution of the inclusions are similar to both (B) and (C) excepting for the faintness of the brownish-yellow turbid medium.

(E) *A very faintly coloured blue quartz from the Pallavaram Charnockite.*—The abundance and distribution of the inclusions are almost similar to B, C and D. The brownish-yellow turbidity is almost absent in thin sections and is very faint in thick sections.

(F) *A colourless quartz from the Pallavaram Charnockite area.*—This specimen contained the acicular inclusions described above but was almost free from the innumerable specks of dust-like material and weakly anisotropic droplets present in the blue varieties. The acicular inclusions were as abundant as in some of the blue varieties, but the brownish-yellow turbidity was not noticeable. Like the blue variety this quartz also shows fragmentation and strain shadows. The grains of this quartz show extensive longitudinal cracking, almost parallel to the vertical crystallographic axis but the cracks are too widely spaced to mask any colour effect. Even individual grains which exhibit no cracking are found to be colourless, whereas in the blue varieties, the colour persists even in the highly cracked portions.

(G) *A colourless quartz from Bodi Charnockite, Maduva (from Karattu Petti Hill).*—When examined under the microscope, this specimen was found to be almost free from the acicular inclusions, but the dust-like and drop-like inclusions were present as in the blue varieties. Further, no brownish-yellow turbidity was noticed nor any signs of fragmentation or wavy extinction. This specimen also is traversed by longitudinal cracks which run more or less parallel to the vertical crystallographic axis. Here also, as in (F), the cracks are fairly widely spaced.

(H) *An ignited sample of blue quartz (B).*—The specimen (B) was heated for 13 hours at 300°, when it was found that it had lost its colour. Examination under the microscope revealed that the turbidity originally present was no longer noticeable, but in other respects the specimen appeared to have retained all its characteristics.

A. 762. *A quartz-porphry from Kadur District (Mysore).*—This rock shows the presence of both blue as well as almost colourless quartz grains. When a thin section of the rock is examined in transmitted light the blue quartz grain is found to be coloured by an almost uniform brownish-yellow tint which is absent in the colourless grains. The intensity of this brownish-yellow colour is found to be directly proportional to the intensity of the blue colour of the quartz when it is seen in reflected light. This colour, like the blue colour, is destroyed by heat. Like the charnockite quartz this quartz also shows the presence of acicular inclusions. The microscopic dust-like and drop-like inclusions are also found in abundance.

Very fine acicular inclusions are found crowded in the regions coloured brownish yellow showing, as it is now definitely known that these inclusions are rutile needles, that those regions are rich in titanium. The yellow colouration is mostly produced, judging from the chemical analyses given below, by a titanium compound and not by the acicular inclusions owing to the dispersed nature of the colour film in the areas between needles. Further, *there are also found some grains of quartz which show the strong brownish-yellow tint in transmitted light and blue in reflected light and yet are completely free from inclusions of any type even when observed under oil-immersion magnification.*

The acicular inclusions are not so prominent in size as in the charnockite blue quartz, but they are definitely more in number and more closely packed. The colour of this quartz is more prominent than the charnockite quartz and the turbid medium is also denser than in the charnockite quartz. In most of the colourless quartz grains of the same rock section both the acicular inclusions and the brownish-yellow colouration are absent. But there are present in such grains very small yellow coloured patches in which a few needles of rutile are present congregated. There are also present a few colourless quartz grains showing the presence of acicular inclusions which are as densely packed as in the coloured grains and at the same time are devoid of the brownish-yellow turbidity.

The acicular inclusions in this quartz are, in general, extremely fine and a very high magnification is required even to observe them. These inclusions unlike those of the charnockite quartz, are not arranged with crystallographic regularity within the body of their host. The dust-like

and drop-like inclusions are as abundant in the colourless grains as in the coloured ones and their arrangement is also similar to those present in the coloured ones. As in the charnockite quartz, these dust-like and drop-like inclusions appear to be strained acidic glassy matter. Some of them also appear to consist of opaque iron compounds. As the powdered specimen suffers some loss of weight on ignition some of the drop-like inclusions are perhaps liquid inclusions in cavities.

Z 4/539. *An opalescent blue quartz of Champion Gneiss from the E.S.E. spur of the 3803 near S.U.N. Se, Mudgere Taluk (Kadur District, Mysore).*— Unlike A.762 a thin section of this quartz shows zoning parallel to the outer margin of the crystal. The colour of this quartz suffers considerable paling when heated, but is not completely destroyed even on heating to nearly 1000° C. The brownish-yellow to grey turbid medium is very dense along definite parts of the crystal forming as it were bands which give rise to the zoning effect. The acicular inclusions are very crowded towards the bands leaving the interspaces between the bands almost free or only with a few scattered needles. The interspaces between the bands are also faintly coloured by the brownish-yellow turbid medium which, however, is slight.

A comparison of this blue quartz with A. 762 reveals some interesting points. The blue colour of A. 762 is more intense than that of this quartz. The acicular inclusions in A. 762 observed under microscope are found to be smaller in size and less prominent than Z4/539. In A. 762 the brownish-yellow turbid medium is more intense than in Z4/539. In Z4/539, the microscopic dust-like and drop-like inclusions are as abundant as in A. 762. In Z4/539, the colour of the turbid medium is slightly modified by a greyish-tint, perhaps due to the predominance of the inclusions of rutile needles. Perhaps, this is also responsible for the greyish tint observed in this quartz and also in the charnockite quartz specimens when they are examined in reflected light.

A number of sections of champion gneiss and other rocks with opalescent blue quartz from the Mysore Geological Survey Department, kindly lent by the Director of the Department, were studied by me and the results are given below :—

J5/65. *Champion Gneiss. K.G.F.*—The quartz grains exhibit the unmistakable opalescent blue colouring in reflected light. The rock as a whole looks highly granulated and the quartz occurs as large patches which between crossed nicols show innumerable grains of quartz having different orientation. Both the acicular inclusions and the dust-like and drop-like inclusions are present. The brownish-yellow turbidity is not very prominent. The



acicular inclusions of rutile are not present as abundantly as the charnockite or A. 762 or Z4/539.

Number of needles per c.c. of quartz	..	350,000
Average length of the needles	.. ..	40 $\mu$
Thickness	.. .. ..	about 0.5 $\mu$

M<sub>1</sub>/349. *Champion Gneiss (?) from Holenarsipur.*—The quartz grains in this rock exhibit the characteristic opalescent blue colour. The brownish-yellow turbidity in this quartz is easily perceptible. *The quartz grains are completely free from acicular inclusions but they contain the dust-like and drop-like inclusions.*

H<sub>11</sub>/946. *Champion Gneiss, Shimoga District.*—This is a fine grained specimen with porphyritic blue opalescent quartz. The quartz grains show clearly the presence of the brownish-yellow turbid medium. *Excepting for a very few scattered needles of rutile the acicular inclusions are completely absent.* It is noteworthy that this quartz which shows such intense blue colour is almost completely free from acicular inclusions. The dust-like and drop-like inclusions are present.

The quartz loses its colour on heating but does not show the development of cracks. The milky blue colour of the quartz in reflected light is very prominent.

M<sub>1</sub>/560. *Basic Xenolith in Banavar Granite.*—The quartz grains in this rock show a striking resemblance to the charnockite quartz. They are almost rounded in shape. The abundance and distribution of dust-like and drop-like and the acicular inclusions are almost similar to the charnockite quartz excepting that the acicular inclusions are smaller in size. Like the charnockite quartz the brownish-yellow turbidity is rather faint and the colour in reflected light is an opalescent greyish blue.

Number of acicular inclusions per c.c. of quartz	..	= 455,000
Average length of needles	.. ..	= 40 $\mu$
Thickness	.. .. ..	= 0.5 $\mu$

M<sub>2</sub>/233. *Chitaldrug Granite.*—Quartz occupies sufficiently large areas. *It is almost free from acicular inclusions, but contains the drop-like and dust-like inclusions to the same extent as most of the charnockite quartzes.* The quartz has suffered the same amount of granulation as the charnockite quartz. The dispersed brownish-yellow turbid medium is clearly seen and the milky blue opalescent colour could be easily detected.

*Chemical analysis of the impurities present in the various specimens of quartz.*—

*Method of procedure.*—The impurities in the blue quartz were analysed before and after washing the roughly powdered material with hot concentrated

hydrochloric acid and finally with water. The faint blue colour which is also visible in the roughly ground wet material is not lost by this treatment showing thereby that the colour of this quartz is not affected by this acid treatment. This further shows that the impurities detected in the acid-treated samples alone should be responsible for the colouration of this quartz. Loss of weight on ignition was determined in all cases but it showed no relation to the depth of colour of these quartzes.

*Estimation of Iron and Titanium.*—Iron and titanium were determined colorimetrically as follows: The dried and weighed quartz powder from the hydrochloric acid treatment was fused with potassium bisulphate and the melt after cooling was taken in dilute hot  $H_2SO_4$  and the silica was removed by filtration. The iron and titanium were then independently determined colorimetrically in the filtrate using potassium thiocyanate as reagent for iron and hydrogen peroxide for titanium.

For the estimation of other constituents about five to ten grams of material were taken and fused with  $Na_2CO_3$ . The cooled melt was dissolved in dilute HCl and the silica was removed completely by two evaporations. The third group metals (Fe, Al, Ti) were removed by filtration after precipitating them with ammonia and ammonium chloride. Calcium and magnesium were determined in the filtrate. Calcium was precipitated as oxalate and the precipitate was ignited and weighed as oxide. Magnesium was determined as usual as pyrophosphate.

To find out the real nature of the impurities present in the quartz (*B*) the quartz was chemically analysed before and after washing it with hot concentrated hydrochloric acid.

*Results of analysis*

TABLE I

*The composition of the impurities in the blue quartz B*

Oxides	Before washing with HCl	After washing with HCl
	per cent.	per cent.
Fe <sub>2</sub> O <sub>3</sub> ..	0.150	0.008
TiO <sub>2</sub> ..	0.024	0.024
CaO ..	0.120	nil
MgO ..	trace	nil
Total ..	0.294	0.032

TABLE II

*Ti and Fe content of various specimens of quartz and the loss of weight suffered by them on ignition*

Quartz	TiO <sub>2</sub> %	Fe %	Loss on ignition %
(i) The blue quartz from Mysore (A. 762) (The average composition of the coloured and the colourless grains) .. ..	0.030	0.005	..
(ii) The Pallavaram (charnockite) blue quartz (A) .. ..	0.030	0.011	0.18
(iii) Do. do. (B) .. ..	0.024	0.006	0.11
(iv) Do. do. (C) .. ..	0.020	0.005	0.12
(v) Do. do. (D) .. ..	0.018	0.004	0.15
(vi) Do. do. (E) .. ..	0.014	0.004	0.19
(vii) Colourless quartz from Pallavaram (charnockite) (F) .. ..	0.002	0.001	0.11
(viii) Colourless quartz from Bodi (charnockite) (G) .. ..	..	0.002	..
(ix) Z4/539 Opalescent blue quartz from Champion gneiss .. ..	0.025	0.010	..
(x) J5/65 Blue quartz of Champion gneiss from K.G.F. .. ..	0.024	0.012	..
(xi) H 11/946 Blue quartz from Champion gneiss from Shimoga District .. ..	0.028	0.005	..
(xii) M <sub>1</sub> /349 Blue quartz from Holenarsipur .. ..	0.017	0.015	..
(xiii) M <sub>2</sub> /233 Blue quartz from Chitaldrug granite .. ..	0.025	0.005	..
(xiv) M <sub>1</sub> /560 Blue quartz from the basic xenolith in Banavar granite .. ..	0.024	0.004	..

Samples (i) and (ix) to (xiv) were kindly lent by the Department of Geology, Mysore.

Postelmann has devised an easy method for separating from the quartz the needles of rutile present therein. The method consists in dissolving out all the quartz from the roughly crushed specimen in hydrofluoric acid at ordinary temperature. To find out whether in the charnockite quartz also these inclusions are rutile the following procedure was adopted:

About 15 to 20 grams of the roughly crushed quartz was treated with about 25 c.c. of 40% hydrofluoric acid in a platinum dish at the room temperature for about 60 hours. Finally the excess of hydrofluoric acid was poured out by careful decantation and 50 c.c. of water was added to the residue which contained about 5 grams of undissolved quartz and a dark slimy deposit. Then the water was stirred till it was somewhat turbid and this turbid solution was allowed to settle for 8 hours and then carefully poured out by decantation so that the sediment at the bottom was not disturbed.

This process of washing was repeated twice again so that most of the acid was removed. Finally about 25 c.c. of water was added to the residue and stirred well. 5 c.c. of concentrated hydrochloric acid was then added and the dish heated for 4 hours on a water-bath and then allowed to settle for 4 hours. The original process of washing was again repeated to remove the excess of hydrochloric acid. The residue which was thus freed from iron was then washed thrice with cold water and finally stirred vigorously in about 20 c.c. of cold water. This liquid was at once poured into small evaporating dishes and evaporated to dryness over a water-bath. The dried residue was then mounted on a glass slide with canada balsam and examined under a microscope in the dark-field with oblique illumination (Microphotograph 7). The slide shows numerous perfectly detached needles scattered throughout the field. From their general character it was easily ascertained that they were rutile needles. The dried residue was also found to contain titanium.

#### *Discussion*

A careful count of the needles in the thin section of the charnockite quartz (B) showed that there were only about 405,000 needles of rutile per cubic centimetre of the quartz, the average length of the needles being about 100  $\mu$ . By assuming that all the titanium shown by the chemical analysis is present as rutile, the thickness of these needles could be calculated, and it is found to be almost 2  $\mu$ . But when the thin section of the quartz is examined under very high magnification (oil-immersion) most of the needles appear to be about 1  $\mu$  in thickness. This shows definitely that there is some titanium present other than as rutile and this is not accounted for. This additional titanium is far in excess of the titanium content of the acicular inclusions and this is also illustrated by the following example. The colourless quartz from Pallavaram, which contains about 450,000 needles of rutile per cubic centimetre of quartz with an average needle length of 60  $\mu$ , shows a titanium content of 0.002% ( $\text{TiO}_2$ ). If all this  $\text{TiO}_2$  is present as rutile, then, calculation yields a needle thickness of 0.7  $\mu$  to 0.8  $\mu$ , which is of the observed order. In the Mysore blue quartz (A. 762) which shows 0.03% of  $\text{TiO}_2$  the number of needles per cubic centimeter of quartz is about 2,000,000 and their average length is about 30  $\mu$ . This would give a needle thickness of 1.8  $\mu$  if all the  $\text{TiO}_2$  existed as rutile needles observed. But when the thin section is examined under oil-immersion magnification, the needles appear to be only about 0.8  $\mu$  in thickness, indicating the existence of additional  $\text{TiO}_2$ , as pointed out earlier. Dr. Postelmann's observations on the Hindenburgstein<sup>8</sup> reveals that the calculated thickness of needles is slightly more than 1  $\mu$ , which appears to be larger than the observed thickness.

Since the colour of these quartzes was lost on heating them, carefully prepared thin sections of these quartzes were examined under the microscope both before and after heating them with a view to ascertain whether the needles of rutile suffered any change either in the number or in their size. The results given in the following table show that the number and size of the acicular inclusions were not affected by heat and thus they do not serve to explain the loss of colour on heating.

To estimate the number and size of the rutile needles same areas in all the specimens were examined under the microscope both before and after heating. All the specimens were heated for 13 hours at a temperature of 300°.

TABLE III

Quartz	Before heating			After heating		
	Average No. of needles per c.c. of Quartz	Length	Thickness	Average No. of needles per c.c. of Quartz	Length	Thickness
A	445,500	85 $\mu$	1-5 $\mu$	445,500	80 $\mu$	1-5 $\mu$
B	405,000	100 $\mu$	1-5 $\mu$	405,100	100 $\mu$	1-5 $\mu$
C	405,000	80 $\mu$	1-5 $\mu$	405,100	85 $\mu$	1-5 $\mu$

The results shown in the above table indicate that the number and size of the acicular inclusions are not affected by heat. Even heating at very high temperatures has produced the same results.

While working on the "opalescent quartz gneiss" (Champion gneiss of Kador District, Mysore) Sampat Iyengar<sup>11</sup> examined rocks Z<sub>4</sub> 539 and Z<sub>4</sub> 540 which are characterised by the presence of the bluish opalescent quartz. After a careful study of this quartz he comes to the conclusion that the pale brown colour of this blue quartz in thin sections in transmitted light is due to the presence of either rutile or amphibole prisms crossing each other at an angle of 60°. He adds further that the bluish opalescent colour of this quartz seems to be the effect of diffraction of light by such minute inclusions in the mineral. Smeeth<sup>12</sup> while referring to Sampat Iyengar's work remarks that the opalescent quartz grains are of a milky-blue appearance by reflected light and pale brownish-yellow in transmitted light in thin sections. He adds that in the majority of slides of rocks which he examined from localities other than those referred to by Sampat Iyengar *inclusions of this character are not noticeable and the optical effect appears to be due to microscopic dust-like inclusions*. He points out at the same time that *this is perhaps merely an*

*association and the opalescent effect may really be due to an ultramicroscopic cause.*

From a spectroscopic analysis of a blue corundum Islamov and Talmacev<sup>13</sup> have recently concluded that titanium is responsible for the production of blue colour in corundum. Though the specimens used were not examined microscopically, it supports the idea that titanium is responsible for the production of blue colour in quartz.

While working on specimens of amethyst, rose and blue quartz, Watson<sup>9</sup> observes that the blue quartz of the Virginia rutile area owes its colour to the presence of the acicular inclusions of rutile, the phenomenon being attributed to the behaviour of light reflected back from the surface of these inclusions. In support of this view is put forward the fact that heating does not destroy the blue colour of the quartz. This quartz however differs from those of Pfaffenreuth and those of the charnockites. Watson and Beard, in the same paper, state that in many sections of blue quartz examined by Watson the substance of this quartz was found to be crowded with hair-like inclusions of rutile, which were frequently arranged with more or less crystallographic regularity. But they also add that "*quartz of light colour or colourless to dark smoky colour often shows inclusions of rutile needles, with no indication whatever of blue colour*". Wetzel<sup>4</sup> while dealing with blue quartz in general, remarks that it is questionable from observed facts whether these acicular inclusions contribute to the production of dilute colours, *since in those quartzes whose colour was specially intense the number of needles was relatively small.*

The titanium content of the various quartz specimens shown in Table II presents clearly that there is a definite relationship between the  $\text{TiO}_2$  content and the intensity of colour of these quartzes, the amount of  $\text{TiO}_2$  increasing with the increase in the intensity of colour. In the case of the iron impurity it is not so apparent. Perhaps the trace of iron shown by these quartz specimens is merely a remnant of the unwashed original iron impurity. The amount of iron thus present is so small that it need not be taken into consideration. The loss of weight on ignition is not very striking as it is found to be more or less the same in all the specimens of quartz. Even in the colourless specimens it is of the same magnitude.

Postelmann<sup>8</sup> found that the iron shown by chemical analysis is only an external impurity, which coats the quartz grains and very fine fissures either brown or green, "*Es tritt nur als ausserliche verunreinigung auf und stammt aus braunlichen (Nelson Co.) oder grunlichen (Cojehnen) Zarten Hautchen, die, stellenweise die Quarzkorner und deren feinste Risse uberziehen.*" The analyses of the charnockite blue quartz both before and after washing

with hot concentrated hydrochloric acid (Table I) also show this point clearly, namely, that most of the iron is only an external impurity and has nothing to do with the colour of the quartz. The iron is washed away by the acid and further the colour of the quartz is not affected by such washing. The trace of iron shown by the material after washing with acid is perhaps due to some residual unwashed iron left out due to incomplete washing or it might be in the body of the quartz forming the material of the dust-like inclusions. Thus it is more or less definite that titanium is the only element which is responsible for the colouration of the blue quartz.

Recently Postelmann has published a memoir on blue quartzes, but he has made no reference to the heat treatment of these quartzes. Heat treatment being an important item in the investigation of these quartzes it would be desirable to study the effect of heat on these quartzes. A colour stable to heat may mean either that it is due to some inclusions unaffected by heat or due to some stable pigment. An unstable colour may be due to various other causes. It may be due to colloidal particles of some element as proposed for the colour of smoky quartz or it may be due to an organic dye which decomposes on heating or it may be due to some inorganic compound the physical state of aggregation of which within the quartz alters on heating. If it is assumed that the colour is due to the needles alone, then the loss of colour on heating can be explained only in one way, and that is, these needles should have possessed an unstable blue colour. But it seems to be very uncertain. It cannot be argued that the quartz enclosing the rutile needles is affected by heating it even up to  $400^{\circ}$  and destroys thereby the blue colour effect produced by these needles, because the blue colour of the quartz from Nelson and Co., Virginia, is found to be unaffected by heat. Further, the charnockite quartz suffers no change on heating it up to  $400^{\circ}$  C. excepting that it loses its colour. So in those quartzes in which the colour is affected by heat the acicular inclusions are not responsible for the production of the colour. Even in the case of the blue quartz from Nelson and Co., the author considers it possible that the colour may not be due to the rutile inclusions but due to some stable inorganic pigment.

#### *Conclusion*

A study of previous work shows clearly that no single general theory has been developed to account for the origin of mineral colours. The mode of origin of these mineral colours, as well as their constitution appear to depend upon the mode of origin and constitution of the coloured mineral and also on the impurities present in it. Doelter<sup>14</sup> has shown that mineral colours fall under two main categories, that is, (i) produced by colloidal and liable matter

and (ii) produced by a substance which is stable and isomorphous with the mineral. The minerals belonging to the second category offer no trouble as they are easily detected and differentiated from those of the first. The problem of the colour of minerals belonging to the first category is complicated owing to the inclusion under this head of minerals which assume dilute colours due to the presence of some inclusions either solid, liquid or even gas, or due to some structural abnormalities in their crystal structure as that of blue halite. Further, under this head are also included all dilute colours produced by intermixture of foreign materials present in such a fine state of division that they cannot be detected even with the highest magnification.

It is gathered from earlier works that a study of mineral colours offers considerable difficulties and it appears that no method proposed so far to investigate this problem has been found to be complete and convincing. W. Hermann<sup>15</sup> used a method which consisted of a study of the behaviour of a number of minerals and glasses artificially coloured with metallic substances and oxides, when subjected, at a given temperature, to the influence of different oxidising and reducing gases. He drew the following conclusions from the observed results: (i) The oxides of iron are the most important colouring agents. (ii) Manganese and chromium are next in importance. (iii) The rare earths uranium, cerium, thorium, etc., are practically of no importance as colouring agents. (iv) Certain organic substances may be present and act in conjunction with the metallic oxides as in the case of topaz. Brauns<sup>16</sup> after studying the influence of radium rays on the colour of some tinted minerals arrives at the conclusion that the colours must be due to some as yet unknown inorganic impurity in a diffused condition.

The literature about the coloured quartzes is rather enormous. Prominent amongst the coloured quartzes are smoky quartz, amethyst, rose quartz and blue quartz. The colour of smoky quartz is supposed to be due to atoms of free silicon. The cause of colour of amethyst and rose quartz is still unknown, but it is generally believed that they owe their colour to a metallic impurity, perhaps manganese, in a diffused condition. The colour of blue quartzes has been attributed to the presence of microscopically detectable inclusions in some cases and in others to the presence of metallic impurities in a fine state of division. It is held by many that the acicular inclusions observed in many of the blue quartzes are alone responsible for the blue colour.

The metallic impurities detected in the quartz specimens now under study are only two, *viz.*, titanium and iron. The Iron compound which occurs in these quartzes, as it is easily washed off by acids and as this washing by acids does not destroy the colour of the specimens, evidently does not contribute to the colour. The iron exists only as an external impurity, probably



as a hydrated oxide coating the individual grains of quartz and also filling in the cracks present both in the coloured and in the colourless specimens. The loss of weight suffered by the various specimens of quartz on heating them does not appear to signify anything as it is very slight and more or less the same in all the specimens, whether coloured or colourless. So now it is more or less definite that the colour of the charnockite and other quartz specimens studied here is due to the presence of titanium.

The acicular inclusions present in these quartzes were separated by hydrofluoric acid and on microscopic and chemical examination was found to be fine needles of rutile. To find out whether all the titanium detected in the individual quartz specimens was present in the form of rutile needles alone or also in some other state, the quantity of rutile present in the various specimens was estimated microscopically and was found to be roughly the same even in specimens of different intensities of colour. Since chemical analysis revealed that the intensities of colour was proportional to the titanium content of the specimens and as this titanium content was in great excess over that required by the amount of rutile present in it, it follows that the coloured specimens contained titanium not only in the form of rutile but also in some other form. Colourless quartzes which contained acicular inclusions showed only the amount of titanium corresponding to the amount of rutile present in them.

All the blue coloured quartzes invariably show the presence of a pale brownish-yellow turbidity in transmitted light the intensity of which varies with the intensity of the blue colour of the specimens in reflected light. It is also observed that this brownish-yellow turbidity is completely absent in all the colourless quartzes without any exception. Now it is interesting to note that the brownish-yellow colour observed in transmitted light is complementary to the blue colour observed in reflected light and both colours are destroyed by heat. It can be gathered now that the blue colour observed in these quartzes is due almost entirely to the existence of a brownish-yellow turbid medium which contains the excess titanium mentioned above, perhaps in a colloidal condition.

The brownish-yellow turbidity was not noticeable in the colourless quartz specimens from the Pallavaram (Madras) charnockites which contain the acicular and drop-like and dust-like inclusions in an exactly similar manner as the coloured specimens. Another colourless quartz obtained from Bodi (Madura) charnockite contained the drop-like and dust-like inclusions, but did not reveal the presence of either the acicular inclusions or of the brownish-yellow turbid medium. Further, a sample of fine opalescent blue quartz from a champion gneiss (H<sub>11</sub>/946) of Kolar Gold Fields, Mysore, is

almost free from acicular inclusions, but shows the brownish-yellow turbidity to a marked degree and a titanium content (0.03%  $\text{TiO}_2$ ) equal to that of the charnockite blue quartz. Two other samples of quartz, one from Chitaldrug granite ( $M_2/233$ ), and the other from an unidentified gneissic rock from Holenarsipur ( $M_1/349$ ), are completely free from acicular inclusions but contain the brownish-yellow turbid medium. They show a titanium content equal to those of the other coloured quartzes and their opalescent blue colour in reflected light is also sufficiently strong. So, from the observations given above, it can be gathered that the acicular inclusions are not responsible for the production of the brownish-yellow turbidity observed in the coloured specimens.

From general considerations of the theories of light scattering it is found that the opalescent blue colouring of such intensity as is met with in these quartzes would be prominent only when the particles producing it are of the order of thickness of 0.05 to 0.2  $\mu$ . The particles of such size cannot be seen clearly even in high power oil-immersion magnifications. No doubt particles finer than this are incapable of producing this type of opalescent colour which is partly a true opalescence and partly a colloidal colour. Thus, as the needles are of the average thickness of 0.8  $\mu$ , they will not be capable of producing the opalescent blue colour observed in these quartzes.

In the blue quartzes now under study the colour is only an opalescent colloidal one produced not by very fine particles of the order of molecular dimensions of titanium, but by considerably bigger colloidal particles of the magnitude of 0.2 to 0.05  $\mu$  in diameter. The colour produced is thus an almost intermediate one between a true colloidal colour and a true opalescent colour. Further, the colour produced would be modified to a very great extent by the absorption coefficient of the titanium compound composing these colloidal particles. Thus the presence of such big colloidal particles of the titanium compound in the quartz, no doubt, is responsible for both the brownish-yellow turbidity in transmitted light and the blue colour in reflected light.

The titanium compound composing these particles is perhaps capable of undergoing a physical or a chemical change on heating, interfering thereby with its capacity to scatter light in a particular manner and thereby changing the nature of the scattered light. Thus the colour in this particular case would be lost on heating.

The dust-like and drop-like inclusions appear to be none other than some congealed glassy matter. It is definitely ascertained that they contain no titanium as these inclusions were found to occur with equal prominence in some of the colourless quartzes, like those from Bodi charnockite in which

titanium was completely absent. Perhaps a detailed study of these inclusions will reveal the exact origin of the charnockites.

*Summary*

Specimens of charnockite quartz with varying intensities of blue colour as well as specimens of opalescent blue quartz from the Champion gneiss and associated rocks of Mysore were examined both microscopically and chemically. The colour of these quartzes was found to be greatly affected by heating, the charnockite quartz losing its colour completely even at 300°.

All the coloured specimens and some of the colourless specimens show under the microscope two types of inclusions, (i) regularly arranged acicular inclusions, and (ii) drop-like and dust-like inclusions scattered throughout the quartz without much arrangement.

Invariably, all the coloured quartzes show a brownish-yellow turbidity in transmitted light, the intensity of which varies with the intensity of the blue colour in reflected light. This turbidity is destroyed by heat in the same way as the blue colour.

All the colourless quartzes, even those which contain all the other inclusions, are completely free from this turbidity.

The acicular inclusions were separated out from the quartz by dissolving the latter in hydrofluoric acid and they were then examined both microscopically and chemically. They are found to be very fine rutile needles.

Almost all the iron present in these quartzes is discovered to be only an external impurity and so appears to have nothing to do with the colour of these quartzes.

Titanium is the element which is responsible for the production of the turbid medium and the consequent colouration of the quartz. The intensity of colour is proportional to the titanium content of the specimen.

The amount of rutile is calculated from the micrometric estimates of the number and size of the rutile needles and thus the amount of titanium required to form these needles is also derived. It was found that the quantity of rutile present was the same in specimens of quartz with different intensities of colour.

The titanium content of all the coloured specimens is in great excess over that due to the amount of rutile present in them.

There are found some coloured specimens of quartz which are completely free from any acicular inclusions, but at the same time exhibit the presence of the brownish-yellow turbid medium.

It was found that the acicular inclusions present in these quartzes was not responsible for the production of either the blue colour or the brownish-yellow turbidity, in these quartzes.

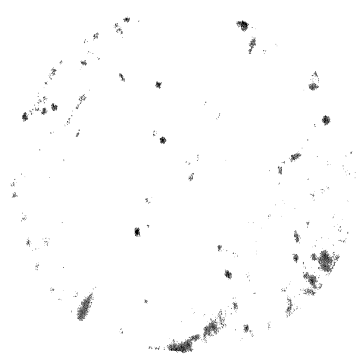
It is suggested that in these blue quartzes the colour is only an opalescent colloidal one produced by colloidal particles of the size of  $0.2$  to  $0.05 \mu$  in diameter. The colour produced is intermediate between true colloidal colour and true opalescent colour and it is modified to a great extent by the absorption coefficient of the titanium compound composing these colloidal particles.

The presence of these colloidal particles is responsible for the brownish-yellow turbidity as well as the blue colour. The loss of colour brought about by heating the quartz is due to a change in the physical or chemical properties of the titanium compound on heating.

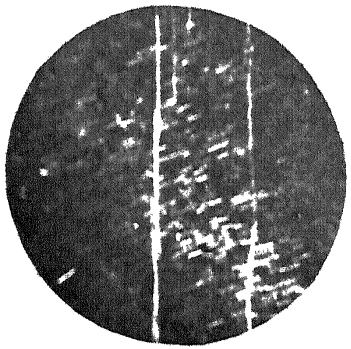
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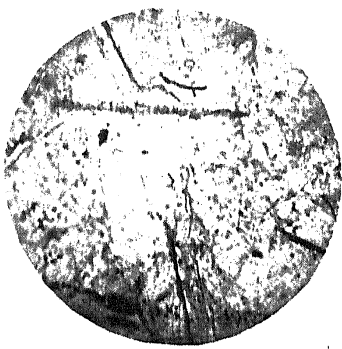
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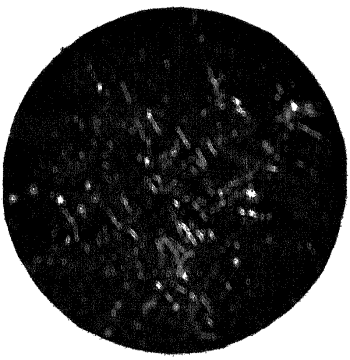
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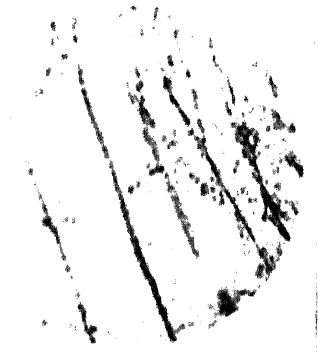
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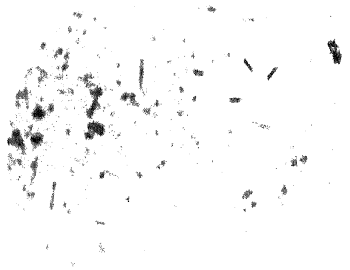
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