# The structure and optical behaviour of jadeite

SIR C V RAMAN and A JAYARAMAN

(Memoir No. 70 of the Raman Research Institute, Bangalore)

Received March 16, 1955

## 1. Introduction

Jadeite is a mineral to which much interest attaches by reason of the use which has been made of it since ancient times—especially in China—for the fabrication of works of art which have been greatly admired. It is a much rarer material than nephrite which is another mineral product to which the name jade is also commonly given; happily, the two substances are readily distinguishable from each other. In its finest forms, jadeite is known as gem-jade or imperial jade and differs from the commoner varieties in its optical characters; it exhibits a beautiful green colour resembling that of emerald and is semi-transparent instead of being cloudy or opaque. There is an extensive literature which deals with jadeite from the mineralogical point of view; works on gemmology also naturally devote a good deal of space to it. We have not however found in the literature any explanation of the optical characters which jadeite exhibits in terms of its structure. Indeed, it does not appear to have been realised that there is a problem awaiting answer in that connection. The opportunity for examining the subject presented itself to us when a collection of specimens of Burmese jade which was acquired for the Museum of this Institute became available for our studies.

## 2. The structure of jadeite

The chemical composition of jadeite corresponds to the formula $NaAl(SiO_3)_2$ and indicates that it belongs to the series of monoclinic pyroxenes of which diopside $CaMg(SiO_3)_2$ is a typical example. X-ray studies[1,2,3] support the latter conclusion, the X-ray powder diagrams of jadeite and diopside showing a close resemblance to each other. The published chemical analyses[4] show the presence in jadeite of varying proportions of other oxides, notably the oxides of calcium and magnesium, thereby indicating that diopside is present as a minor constituent in the mineral. Physically, jadeite is a polycrystalline aggregate. Examination of thin sections under the polarising microscope reveals the

presence of individual crystals which are birefringent, their greatest and the least refractive indices being 1·667 and 1·654 respectively.

When light enters a polycrystalline aggregate in which the individual grains are birefringent, it would necessarily suffer reflection and refraction at the intercrystalline boundaries. The smaller the individual crystallites, the more numerous would be such reflections and refractions. Hence, on this view, none of the incident light would succeed in penetrating through the material, if it is fine-grained and also of sufficient thickness. In the absence of any absorption properly so-called, the incident light would mostly be sent back towards the source by repeated internal reflections. In other words, a fine-grained aggregate of birefringent crystals should present a high albedo by reflected light and appear opaque in transmission.

The foregoing inferences based on geometrical optics do not however represent what is actually observed in the case of jadeite. Indeed, the converse is much nearer the truth; in other words, the specimens exhibiting a coarse structure are those which are opaque to light and reflect it strongly, while the specimens which are most readily penetrated by light are those having a fine-grained structure. Why this is so is the problem considered in the present paper.

## 3. The X-ray diffraction patterns

To establish the relationship between structure and optical characters briefly indicated above, we have recorded the X-ray diffraction patterns of specimens exhibiting diverse optical behaviour. Three of these diagrams which are representative of the rest are reproduced in plate I. The film to specimen distance was in every case 5 cm and MOK$\alpha$ radiation was employed to record the patterns.

Figure 1 was recorded with a piece of jade about half a millimetre thick cut out from one of our specimens and polished flat on both sides. The X-ray pencil passed normally through the specimen. The plate exhibited a notable measure of translucency; when placed on a printed sheet of paper, the finest print could easily be read through it. The X-ray record shows clearly that the crystallites present in the specimen are of varying sizes and that crystallites of very small sizes are the most numerous; though individual bright spots appear in the pattern, there are also numerous fainter ones which run into each other and appear as continuous rings.

Figure 2 is an X-ray diagram taken with similar arrangements, the X-ray pencil now grazing the edge of a flat ellipsoidal piece of green jade. It will be seen that the pattern is of the same general nature as that reproduced in figure 1 except that the continuity of the rings is less evident and the spottiness more conspicuous.

Figure 3 is the pattern recorded with a greenish-white specimen which was nearly opaque to light. It will be seen that the pattern consists of a number of

individual spots, some of which are very bright. But hardly anything in the nature of continuous rings can be discerned. In other words, the specimen consists of relatively large crystallites.

# 4. Theoretical considerations

To understand the optical behaviour of jadeite, we have to put aside the considerations based on geometrical optics and deal with the matter from the standpoint of the wave theory of light. It is useful, in the first instance, to think of an extreme case in which the individuals in the polycrystalline aggregate are assumed to be of very small dimensions even in comparison with the wavelength of light and are also randomly orientated. Such an aggregate could obviously be regarded as equivalent to an optically isotropic medium with a refractive index which is the average of the principal refractive indices of the crystallites. A beam of light incident normally on a slab of such material would traverse it as a coherent wave-train, and emerge from the rear surface of the slab, but not the whole of the incident energy would succeed in so emerging. For, in consequence of the varying orientations of the crystallites and their birefringence, the medium would exhibit local variations in optical behaviour, and there would therefore be a diffusion of light both forwards and backwards. In the limiting case when the grains are very small, the diffusion would extend approximately with equal strength both forwards and backwards. More generally, however, there would be a concentration of the diffused radiation in the forward directions surrounding the path of the regularly transmitted light-beam. There would also be a diffusion of light backwards towards the light-source, but this would be less conspicuous.

The situation set forth above would be modified if the grains of the medium are of dimensions comparable with the wavelength of light. Nevertheless, provided the birefringence of the individual crystallites is small, we may continue to regard the aggregate as an isotropic medium which exhibits local variations in refractive index depending on the direction of vibration in the light beam traversing the material. These variations would result in the phase of light-waves passing through an individual grain being either accelerated or retarded as the case may be. The errors in phase thus resulting when summed up over the total path would tend to cancel each other out; the residual errors in phase would be the smaller relatively to the total path, the more numerous the particles are, in other words the smaller is their size. Thus, it follows that if the birefringence is not large and the material is very fine-grained, the waves of light would succeed in penetrating the medium. Nevertheless, the residual errors in phase would result in a reduction of the absolute intensity of the transmitted beam and ultimately also its total extinction. The missing energy would appear for the most part in a cone of diffuse radiation surrounding the direction of propagation of the incident light-beam.

Wave-theoretical considerations also indicate that the proportion of the

incident energy sent back towards the source as a diffuse reflection by a fine-grained aggregate would be far less than that indicated by considerations based on geometrical optics. For, the phase of a reflected wave relatively to the incident wave depends on whether the first or the second medium on the two sides of the reflecting boundary has the higher index. The boundaries encountered by a light-wave traversing a polycrystalline aggregate would obviously be of both kinds and in approximately equal numbers. The reflection in the two cases being in opposite phases, their effects would tend to cancel each other more or less completely in all directions.

Thus we may sum up the situation by the statement that light would penetrate into a polycrystalline aggregate much more freely and would be reflected backwards much less freely than that might be anticipated in terms of geometrical optics, provided that the aggregate is sufficiently fine-grained. Thus, we have an explanation in general terms of the semi-transparency exhibited by the finest varieties of jadeite.

## 5. Summary

The phenomenon of semi-transparency exhibited by the finer varieties of jadeite is discussed. X-ray diffraction studies and theoretical considerations based on wave-optics alike indicate that this is a consequence of the very small particle size of the crystallites forming the aggregate.

## 6. References

1. Wyckoff R W G, Mervin H E and Washington H S, *Am. J. Sci.*, 5th Series, 1925, **10**, 383.
2. Warren B E and Biscoe J, *Z. Kristallogr.*, 1931, **80**, 391.
3. Yoder H S, *Am. J. Sci.*, 1950, **248**, 225.
4. Hintze Carl, *Handbuch Der Mineralogie*, Zweiter Band, 1897, p. 1175.

(1)

(2)

(3)
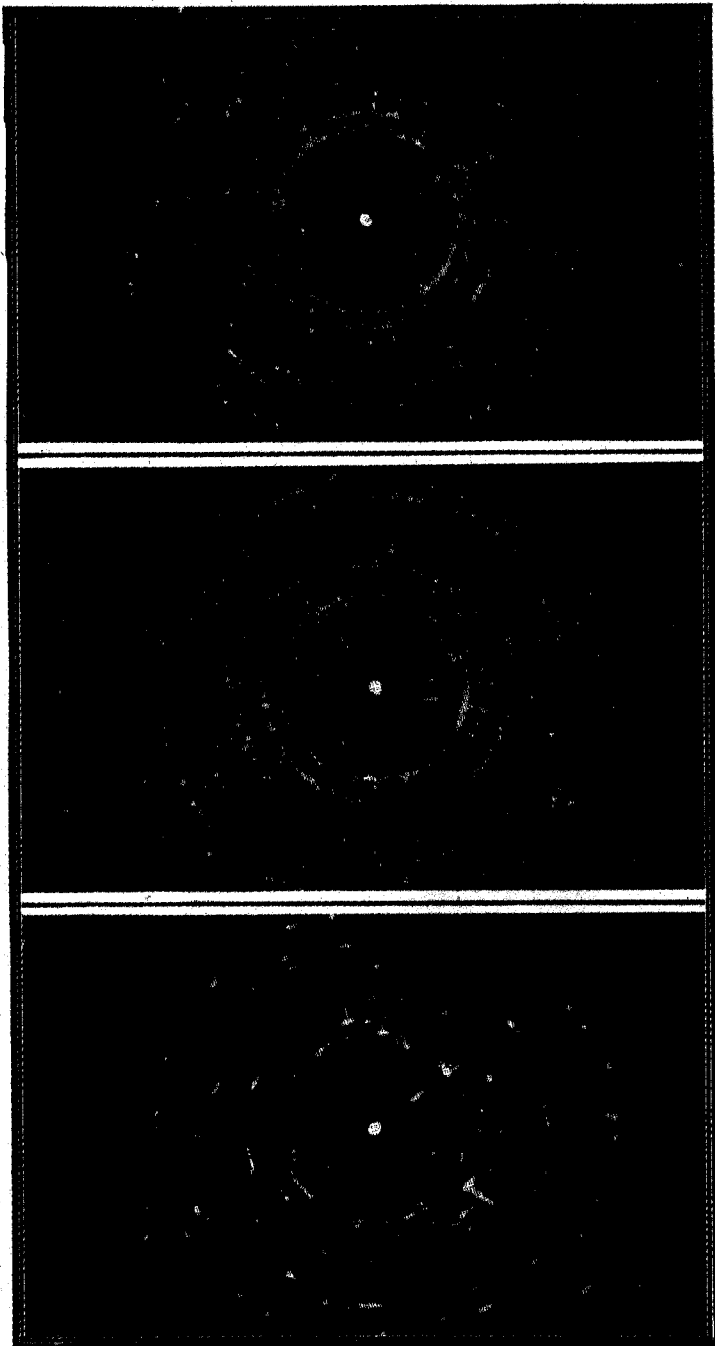
Figures 1–3. X-ray diffraction patterns of jadeite.

Plate I