Zoisite-amphibolite with corundum from Tanganyika.

By P. M. Game, B.Sc.

Department of Mineralogy, British Museum (Natural History).

[Taken as read 10 June, 1954.]

Occurrence.

The most striking rock now described occurs in the Northern Province of Tanganyika Territory, just west of the Great North road, and south of the track from Longido to Engare Naibor. A small group of specimens was collected by Mr. A. G. Clough of Industrial Minerals Ltd., and presented to the British Museum (Natural History) in 1952 (B.M. 1952,133). The outcrops occur in the highly metamorphosed Basement Complex which forms small hills (The Matabatu Mountains) descending, at their margin, by step-faulting to a peneplaned surface cut out of much younger, unconformable volcanics; the faulting in the marginal area of the basement rocks forms the eastern side of the Rift Valley. The basement rock adjacent to the zoisite-amphibolite is usually an amphibolite with conspicuous large, brown-red garnets. The occurrence of this garnet-amphibolite is usually an indication of the proximity of the zoisite-amphibolite.

The outcrops of the zoisite-amphibolite are small. The largest is just over 100 yards long and about 50 yards wide. The foliation corresponds with that of the surrounding metamorphic types. It is, therefore, difficult to determine whether the amphibolite is a highly altered intrusive rock or whether it has been formed by metasomatism or is a migmatic product. Probably each of these processes has played a part in its production.

The zoisite-amphibolite shows a continuous gradation from a very dark amphibolite containing very little zoisite to a much paler apple-green, zoisite-rich rock with little amphibole, but usually containing large, red corundum crystals. The schistosity of the zoisite-rich types is poorly defined. In thin sections under the microscope the rock shows the association of corundum, amphibole, and zoisite; a few sections show, in addition, a little plagioclase and colourless mica. There is also a secondary, partly fibrous product.

In addition to these amphibolites and zoisite-amphibolites the collection presented to the museum included one specimen of a white zoisite-rock; this is monomineralic and slightly coarser-grained than the green variety, with the same granular texture.

Corundum.—The corundum forms conspicuous ruby-red crystals up to 3 cm. in diameter, which frequently show hexagonal, idioblastic outlines. All the crystals show intense cracking and granulation, obviously the result of stress. This cracking has destroyed the otherwise gem quality of the mineral. Some crystals are riddled with small zoisite inclusions and contain, in addition, a few opaque grains, probably of iron-ore. An interesting feature is the frequent intergrowth with amphibole at boundaries of the two. The corundum grains then show no well-defined boundaries but rather a 'fretted' and complex perimeter with narrow tongues of amphibole radially arranged. The corundum shows a distinct pinkish tinge in micro-sections of the usual thickness.

Amphibole.—The amphibole usually forms irregular grains of variable size, the maximum length being about 0·4 mm. When associated with plagioclase, however, it sometimes shows small, sharply idioblastic diamond-shaped sections with the prism as the prominent form. Other grains show pinacoidal cleavages in addition to the prism cleavage, thus presenting a highly 'scarred' appearance and conspicuous relief. The mineral is pale in colour and is only faintly pleochroic.

The absorption is $\gamma = \beta > \alpha$, with γ and β blue-green, α pale yellow-green to almost colourless. The values of 2V and of $\gamma : c$ were determined on a Leitz 4-axis stage; and β by the immersion method, in sodium-light, on three selected grains showing the central emergence of an optic axis. The values of γ and α were determined by calculation from the values of β and 2V combined with the value of $\gamma - \alpha$, which was measured with a Berek compensator.

$2V\gamma = 82°$ (mean of 5 values: range 78–84½°).

$\gamma : c = 21°$ (mean of 5 values: range 19–22½°).

$\beta = 1{\cdot}648$ (mean of 3 values, 1·647, 1·648, 1·650).

$\gamma - \alpha = 0{\cdot}021$; α 1·639 (calc.), γ 1·660 (calc.); sp. gr. $d_4^{20} = 3{\cdot}13$.

These values, in conjunction with the relative lack of colour and feeble pleochroism, show that the amphibole is an iron-poor hornblende belonging to the tremolite-edenite series (about 45 molecular % edenite).[1]

[1] A. N. Winchell, Elements of optical mineralogy, 4th edit., 1951, pt. II, fig. 324, p. 433. [M.A. 11–463.]

Plagioclase.—This is only sparsely present, being observed in only one of the half-dozen sections examined. It forms highly irregular grains up to 3 mm. in diameter, fresh and unzoned, enclosing many crystals of amphibole and zoisite. The grains show one set of fine twin-lamellae intersected at a small angle by a prominent cleavage. A second cleavage, nearly perpendicular to the first, is occasionally visible as ill-defined intermittent cracks. Measurement on the universal stage showed the twinning to be on the pericline law, the prominent cleavage to be (001), and the composition to approach An_{100}.

The angular values obtained were: $\alpha\alpha$, 102°, $\beta\beta$, 56½°, $\gamma\gamma$, 104°, $2V_\alpha$ 77½°. These angles, interpreted on Tertsch's curves[1] for calcic plagioclases, confirm the composition to be that of an anorthite (about An_{97}). The values accord reasonably well with those derived from the low-temperature curves for a plagioclase of this composition. Interpolation from Tertsch's high-temperature curves gives much less consistent An values. (The $\alpha\alpha$, and $\beta\beta$, values are beyond the ranges of the high-temperature curves.) In view, however, of the necessarily approximate determinations (one set of twin lamellae being too narrow for measurement save in one or two grains) and the possible doubtful accuracy of the high-temperature determinative curves,[2] the diagnosis of the low-temperature modification can only be regarded as tentative.

Zoisite.

The abundance of the zoisite and its unusual optical properties were considered to justify detailed chemical and optical examination. The mineral occurs in two forms—a common green variety and a colourless modification, the latter represented in only one rock-specimen. A chemical analysis of a gravity-separated, hand-picked sample of the green zoisite gave the results shown in table I.

The feature of the analysis is the low value for H_2O and the high values for Al and Ca. Even after recalculation to the basis of 52(O,OH) the cation total is about 3 % higher than that required to satisfy the formula $Ca_2Al_3Si_3O_{12}OH$. On the actual (empirical) O,OH content the cation total is 5% high.

[1] H. Tertsch, Zur Hochtemperaturoptik basischer Plagioklase. Tschermaks Min. Petr. Mitt., 1942, vol. 54, pp. 193–217. [M.A. 9–270.]

[2] D. L. Reynolds, The difference in optics between volcanic and plutonic plagioclases . . . Geol. Mag., 1952, vol. 89, pp. 233–250. [M.A. 12–137.]

TABLE I. Chemical analysis of green zoisite from northern Tanganyika.

(B.M. 1952,133.) Analyst, D. I. Bothwell.

		Atomic ratios.			Empirical unit-cell contents.[1]		Cell contents on basis of 52(O,OH).	
SiO_2 ...	39·16	Si	...	0·652		12·33		12·08
Al_2O_3...	33·50	Al	...	0·657	12·42		12·17	
Fe_2O_3...	1·75	Fe'''	...	0·022	0·42	12·92	0·41	12·66
FeO ...	nil							
Cr_2O_3...	0·33	Cr	...	0·004	0·08		0·08	
CaO ...	25·02	Ca	...	0·446	8·43		8·26	
MgO ...	nil					8·43		8·26
MnO ...	0·014	Mn	...	0·0002	0·004		0·004	
Na_2O...	nil							
K_2O ...	nil							
H_2O+	0·57	O	...	2·742	51·87	53·07	50·82	52·00
H_2O-	0·06	OH	...	0·063	1·20		1·18	
TiO_2 ...	0·001							
	100·40							

Sp. gr. (d_4^{20}) 3·364±0·005

Orientation.—Crystals of both green and colourless zoisites show a single cleavage. The cleavage cracks are truly plane, though rather widely spaced. Conoscopic observations on isolated crystals showed that α (= Bx_0) is in all instances perpendicular to the cleavage plane, which therefore corresponds to the $\gamma\beta$ plane. The orientation is, therefore, that of ferriferous zoisite with 5 % or more Fe_2O_3 (the β-zoisite of Termier).[2] Iron-free zoisite has the optic plane parallel to the cleavage; yet the analysis shows less than 2 % Fe_2O_3. Preliminary measurements of $2V\gamma$ showed values of about 25° for the green and 35° for the colourless varieties. These values correspond with those usually quoted for iron-free zoisite, i.e. 30°±. Both the colourless and green zoisites were found to have extremely strong dispersion with $r > v$. This dispersion, on the other hand, agrees with that given for a ferriferous zoisite. It is thus evident that the optics do not conform (in relation to the chemical composition) with those previously published for zoisite. The orientation and the dispersion indicate a ferriferous zoisite, while the optic axial angle suggests that the mineral has little iron, as confirmed by analysis.

In order to establish with certainty the relation between the optical and crystallographic directions three single-crystal X-ray oscillation photographs were taken by G. F. Claringbull about α, β, and γ. The layer-

[1] Calculated from the determined value of the sp. gr. together with the unit-cell dimensions a 16·30, b 5·60, c 10·21 Å. (L. Waldbauer and D. C. McCann, Amer. Min. 1935, vol. 20, p. 107.) [M.A. **6**–179.]

[2] P. Termier, Bull. Soc. Franç. Min. 1898, vol. 21, pp. 148–170.

line spacings of the three photographs indicated the approximate values α 16, β 5, γ 10 Å. Comparing these values with those of Waldbauer and McCann it is evident that α coincides with a, β with b, and γ with c.

The cleavage is thus shown to be (100) and the optic axial plane is parallel to (010). At first sight the orientation of both these planes appears to differ from that of the textbook figures (for either iron-free or ferriferous zoisite), which show the cleavage as (010), and the optic axial plane as (010) for iron-free and (001) for ferriferous zoisite. However, the textbook orientations are based on axial ratios: $a : b : c = 0{\cdot}62 : 1 : 0{\cdot}34$, derived from the earlier morphological measurements.

Comparing these ratios with the X-ray parameters it is evident that:

a (from morphological measurement) = c (from X-ray measurement)
b (,, ,, ,,) = a (,, ,, ,,)
c (,, ,, ,,) = b (,, ,, ,,)

Making these transformations (giving $a : b : c = 0{\cdot}625 : 1 : 0{\cdot}344$) it is apparent that the cleavage does, in fact, coincide with the (010) plane of the textbook figures and that the optic axial plane is the (001) plane of these authors. In other words, the orientation agrees with that given in textbooks for ferriferous zoisite.

Size and arrangement of crystals.—The green zoisite usually shows distinct elongation parallel to β, with partial alignment of the crystals. The length: breadth ratio is of the order of 3 : 1, but reaches 6 : 1 in some grains. The crystal length varies from about $\frac{1}{2}$ to $1\frac{1}{2}$ mm., but is sometimes reduced in proximity to the corundum crystals. The green zoisite shows few crystal faces; many grains show sub-rounded terminations. Transverse cracks are extensively developed and are a prominent feature.

The colourless zoisite, forming virtually a monomineralic rock, shows no elongation or schistosity. The grains tend to be equidimensional; the average diameter is 2 mm. (maximum 4 mm.). The grains form a polygonal mosaic and many show partial crystal form, though crystal faces often tend to be modified due to mutual interference during growth. All grains show an extensive system of cracks, sometimes roughly perpendicular to the cleavage, but often forming an irregular network. Five of the best-developed crystals in two sections of this colourless zoisite rock were measured on the universal stage in order to determine the faces represented. Each of the five resulting stereograms was first transposed, bringing γ to the centre. The five transposed stereograms were then superimposed to bring α, β, and γ into coincidence. Indexing of faces on this final stereogram was performed by plotting the poles on a

gnomonogram, based on the X-ray parameters, with γ (c) at the centre (i.e. having the same orientation as the stereogram). The forms thus identified after transformation from the X-ray orientation ($\gamma = c$) to the morphological orientation ($\gamma = a$) are as follows:

(100) (vicinal face 8° from 100), (010), (021) (vicinal face 4° from 021), (034) (vicinal face 4° from 034), (041), (091), (140), (142), (144), (164), (311), (313), (431), (562), (971), (991), (20.5.2).

Of these observed forms only five (100), (010), (021), (041), and (140), are listed as crystal-forms by Dana and Goldschmidt. With the exception of (100) and (010), simple forms are absent and three faces are vicinal to faces having the quoted indices. (The angular differences in these instances are outside the range of experimental error.) The high indices may perhaps be due to mutual interference.

Optical properties.

Refractive indices.—The γ and β values of both the green and white zoisite were determined on selected oriented crystals, using the immersion method, with mixtures of methylene iodide and monobromonaphthalene. A Bellingham and Stanley refractometer was used to measure the refractive index of the matched liquid in sodium-light. The values of both γ and β were obtained from cleavage flakes, since the cleavage coincides with the $\gamma\beta$ plane. Cleavage flakes thus give a centred obtuse bisectrix interference figure and are easily recognizable. The value of β was determined, in addition, from grains showing the central emergence of an optic axis; grains having this orientation are also easily detected by their abnormal purple-yellow interference colours resulting from the extreme axial dispersion of the mineral.

For most of the refractive index measurements the 'control drop' method was used. The refractive index of the liquid mixture was adjusted to a value somewhat above the index to be measured in the mineral. The drop was split into two portions; the first portion remained on the glass slide (with the immersed grains) which was placed on the microscope stage. The second part of the drop was placed upon the glass prism of the refractometer which was immediately adjacent to the microscope, so that the two glass surfaces (carrying the two portions of the liquid drop) were separated by only a few inches. The operation was carried out in a room free from draughts. Owing to the more rapid rate of evaporation of the methylene iodide compared with that of the monobromonaphthalene, the refractive index of the two drops becomes

gradually lower. The liquid on the slide, therefore, slowly passed through the refractive index value at which it matched the desired index of the grain, and at this instant the refractometer reading was noted. This technique was found to give reasonably concordant values. For example, in one set of 8 measurements the difference between the maximum and minimum values was 0·0019, and was reduced to 0·0011 by omitting one reading.

The value of α was not determined directly, but was obtained by calculation from the mean values measured for γ, β, and 2V. Owing to the difficulty of finding suitable crystals having the required orientation, the theoretically derived index was considered to be more accurate.

Optic axial angle.—This was measured in sodium-light on the universal stage. Sections of about twice the normal thickness were used. Owing to the smallness of 2V the usual orthoscopic method was found to give wide fluctuations in the measurements and much more precise values were found to result from conoscopic observation (full apertures on substage diaphragms, and insertion of Bertrand lens). Four to five readings were made of the position of each optic axis. The values of 2V given in table II are the result of 12 determinations of the green zoisite and 12 of the colourless variety.

TABLE II. Optical data (mean values),

	α.	β.	γ.	$2V_\gamma$. range
Green zoisite	1·700	1·700	1·705	25° (17½–33°)
White zoisite	1·695	1·698	1·704	33½° (28–37°)

Dispersion.—It was apparent during the preliminary optical examination that the zoisite possessed extremely strong axial dispersion, since the isogyres of well-centred interference figures showed conspicuous colour fringes. It was, therefore, decided to attempt to measure the variation in the optic axial angle caused by changes in the wave-length of the light. Owing to the weak birefringence, the smallness of the crystals, and their extensive cracking, the accurate determination of 2V for light of varying wave-lengths presented some difficulty. The first measurements, made on an optic axial goniometer and on a stage goniometer, fitted to a Swift microscope, were not entirely satisfactory, although they confirmed the order of the dispersion (red to violet) to be about 10°.

It was finally found that much more reliable results were obtainable using a universal stage method. A suitably oriented crystal, giving one

almost centred optic axis, was isolated; both upper and lower surfaces were carefully ground, thus producing a parallel-sided plate about 0·7 mm. in thickness. This was mounted in a circular depression on a glass slide. A Leitz 4-axis stage was used for the measurements; the substage diaphragms were opened to give conoscopic definition. A Hilger

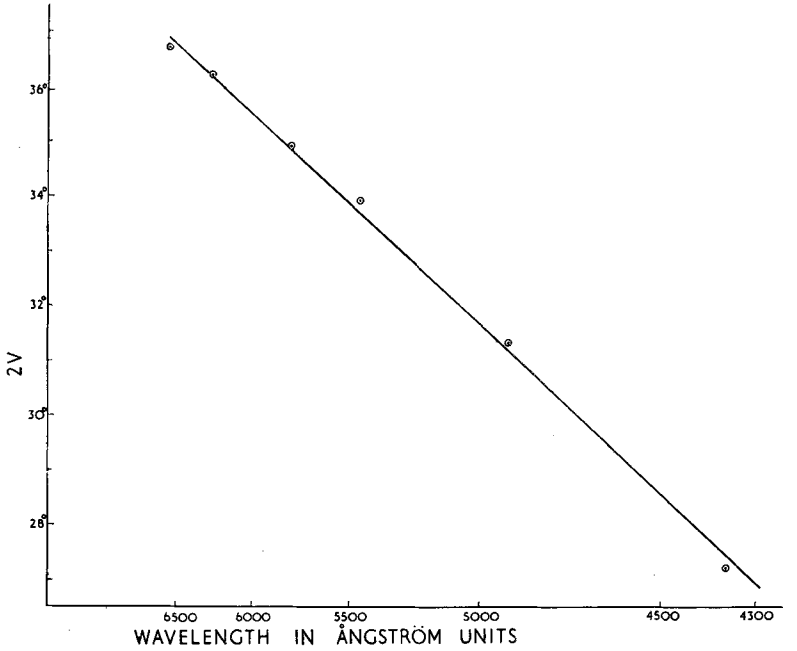

FIG. 1. Zoisite (colourless variety) from Tanganyika. Variation in optic axia angle 2V with wave-length of light.

monochromator was employed in conjunction with a high-pressure mercury-vapour 50 watt lamp, the emission from which was intense for the 'mercury violet' (4358 Å.) and 'mercury green' (5461 Å.) wave-lengths and satisfactorily strong for wave-lengths in the blue, yellow, and red orders of the spectrum. The value of 2V was determined for six different wave-lengths ranging from 4358 to 6550 Å. Using each eye alternately, 10 readings were made for the violet and blue wave-lengths and 6 readings for the remaining wave-lengths of the position of that optic axis which emerged almost vertically (A_1). Four readings were made of the other more inclined axis (A_2), which gave less precise definition of the isogyre. From these two sets of readings (for each optic axis)

the mean position of the acute bisectrix was determined. This angular value (Bx_a) was subtracted from the mean value obtained for A_1 for each wave-length, and the resulting angle was doubled, thus giving 2V. The corrections required for the difference in refractive index of hemisphere (1·649) and mineral (1·699), were very slight owing to the small inclinations. The resultant values of 2V for the six different wave-lengths are given in Table III. If a logarithmic horizontal scale (Hartmann dispersion paper) be used to plot these values, an almost straight line relationship results (fig. 1).

TABLE III. Zoisite (colourless variety) dispersion.

Wave-length.	Optic axial angle.
4358 Å.	27·2°
4916	31·3
5461	33·9
5790	34·9
6250	36·2
6550	36·7

Acknowledgements.—I wish to thank Dr. G. F. Claringbull for the X-ray data, Mr. D. I. Bothwell for the analysis, Dr. M. H. Hey for help with the indexing of the zoisite, and Mr. A. H. Weir for his assistance in some of the dispersion determinations. Details of the field occurrence were kindly supplied by Mr. N. J. Guest of the Tanganyika Geological Survey.