THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY

No. 242 September, 1958 Vol. XXXI

The alteration of pyrochlore to columbite in carbonatites in Tanganyika.[1]

(With Plates XX and XXI.)

By T. C. James, B.Sc., A.R.C.S.,
and Duncan McKie, M.A., B.Sc., A.R.I.C., F.G.S.
Geological Survey, Dodoma, Tanganyika.

[Read 7 November 1957.]

Summary. The formation of columbite has been observed in two carbonatites in south-west Tanganyika where it is due to autometasomatism following the emplacement of the bodies. Disoriented aggregates of columbite crystallites are formed as pseudomorphs after cubo-octahedra of pyrochlore in sövite. This alteration is accompanied by the addition of Fe, conversion of amphibole and biotite in the sövite to a ferruginous talc, the formation of an iron-bearing carbonate, and the introduction of colloform silica; Ca and Na are lost in part. The general alteration of the sövite can be ascribed to the influx of iron-bearing solutions at relatively low temperature and high pressure.

Columbite is not a primary mineral in carbonatites, except perhaps at Fen (Sörum, 1956), and in each of its occurrences in Tanganyika it has been formed by the replacement of pyrochlore as part of the general alteration of the host rock. So far it has been found in only the Mbeya (Fawley and James, 1955) and Ngualla[2] carbonatites which are situated in south-west Tanganyika; pyrochlore from carbonatites in the coastal and northern volcanic provinces does not exhibit such alteration.

The Mbeya carbonatite lies in the floor of the southern end of the Rukwa trough (a rift valley) and is possibly Jurassic in age; it is thought

---

[1] Published by permission of the Director, Geological Survey of Tanganyika.

[2] Described by T. C. James in unpublished reports of the Geological Survey of Tanganyika, 1954.

to be in the core of an eroded volcano. The Ngualla carbonatite is about eighty miles to the north-west of the Mbeya carbonatite and about twenty miles to the east of the Rukwa trough. It is principally sövite with minor amounts of rauhaugite, and is a circular body some two miles in diameter within a rim of fenitized brecciated quartz-porphyry. Its age is apparently older than late Cretaceous and may be similar to that of the Mbeya carbonatite.

Detailed descriptions of these carbonatites have not been published and it would seem desirable to outline their petrography before giving an account of the alteration of pyrochlore and some associated reactions, and, finally, considering the significance of these late-stage effects.

In the Mbeya carbonatite the alteration of pyrochlore to columbite is confined to certain bands of altered sövite within the body. The alteration of the sövite is shown by the formation of large porphyroblasts of what was probably a ferruginous carbonate, which has been subsequently converted either by weathering or low-grade autometamorphic effects to hematite, limonite, and quartz. Alteration is also shown by the development of secondary quartz, often in colloform masses, in the carbonates forming the matrix of the rock. In such rocks rims of columbite are developed by replacement around the pyrochlore crystals and large cracked crystals are infiltrated by veins of columbite. Fluorite is developed in and around the altered crystals.

One specimen of sövite from near the centre of the Ngualla carbonatite contains disoriented aggregates of columbite pseudomorphous after pyrochlore crystals. In other aspects the rock appears to be a normal sövite, but there is some alteration in the other members of the accessory mineral assemblage.

Museum zone, Mbeya carbonatite.

The apatite–sövite forming the Museum zone is unaltered and is regarded as typical of the carbonatite (Fawley and James, 1955). It is a medium-grained (1 to 2 mm.) equigranular aggregate, shown by partial chemical analysis to be composed of 71 % calcite, 17 % dolomite, and 12 % of accessory minerals of which apatite amounts to about 10 % and the remaining 2 % represents amphibole, biotite, quartz, pyrochlore, magnetite, and pyrite. Modal analysis of thin sections stained with Alizarin Red S (Mitchell, 1956) shows dolomite to be less abundant than the chemical analysis indicates, suggesting that the calcite may be magnesian. Magnesian calcite has been recorded from Fen by Goldsmith *et al.* (1955). Calcite grains locally contain a dust of minute hematite inclusions, whereas dolomite is always clear. Dolomite appears to have crystallized after calcite and is concentrated around bands of the accessory mineral assemblage. Apatite in rounded grains (up to 0·5 mm.) forms schlieren of granular aggregates and occasional single grains scattered throughout the rock.

The accessory minerals are all euhedral, although amphibole and biotite are more or less carbonated and pyrochlore is corroded and embayed by carbonates. A relatively abundant accessory mineral is an *alkali-amphibole*, with $2V_\alpha$ about 70°, $\gamma \wedge c$ 25°, γ 1·625, β 1·612 and an alkali content of 5·31 % Na_2O and 2·29 % K_2O. Some crystals are up to 2 mm. in length and 1 mm. in width, but most are smaller and rather fibrous. They cut directly across the matrix of granular calcite and across the bands of granular apatite. Carbonation is often intense and in large crystals starts along the cleavages. Small crystals within the carbonates are usually completely replaced, only ghosts of the crystal outlines remaining. The amphibole and its carbonated relics tend to occur in bands, and where alteration is intense the surrounding carbonate is clear dolomite. Campbell Smith (1953) does not mention the occurrence of any amphibole in the sövites of the Chilwa Series; neither did von Eckermann (1948) find any in the Alnö sövites, but his description of the carbonation of sodic pyroxene in the Smedsgården dyke is reminiscent of the alteration of alkali-amphibole in the Mbeya carbonatite. At Iron Hill, however, potash-rich amphiboles with optics resembling tremolite are abundant in the carbonate rocks; they are composed principally of the soda-tremolite, ferri-glaucophane, and hastingsite end-members (Larsen, 1942). An amphibole of similar composition and optics has recently been described from the type sövite of Söve, Fen, by Sæther (1957). Riebeckite and crocidolite on the other hand occur as late cross-fibre veins in many carbonatites.

A constant accessory is *biotite* with $2V_\alpha$ 13°, γ 1·609, reversed pleochroism α deep orange-red, β, γ pale orange-red, and an X-ray powder diffraction pattern corresponding to the 1M or 3T polymorph of Smith and Yoder (1956); crystals are elongated parallel to c, are zoned with more intensely coloured rims, and are more or less replaced by carbonate along the cleavages and marginally. Phlogopite with similar pleochroism has been described without chemical analysis from Alnö, Fen, Iron Hill, and Mountain Pass; von Eckermann (1948, p. 69) points out that the material from Alnö is low in Mn and is not manganophyllite as Högbom had suggested.

Pyrochlore is yellowish to reddish-brown, often concentrically zoned, and slightly anisotropic in thin-section. Small crystals and the inner zones of large crystals exhibit only {111} faces, whereas large crystals tend to develop {100} faces as well in the later stages of their growth (pl. XX, figs. 10, 12) and examples are known of the development of {011} faces on the octahedra (pl. XX, fig. 13). A not uncommon habit is produced by the preferential development of a diametrically opposed pair of octahedral faces to give a tabular crystal (pl. XX, fig. 11). Inclusions of euhedral apatite are common at the margins of large crystals; crystal outlines usually transgress the zoning, indicating corrosion after the completion of crystallization as euhedral crystals; and embayment by calcite is common. Size varies from 5 mm. to 0·1 mm. between cube faces. The specific gravity of fresh material is 4·43. The unit-cell edge is *a* 10·405 Å. for brown pyrochlore from the Museum zone and 10·428 Å. from the rather similar Mstari zone.

Quartz occurs as small grains, interstitially and in secondary veinlets. Magnetite occurs in octahedra and pyrite in cubes, both occasionally corroded. The alteration and corrosion of the euhedral minerals of the accessory mineral assemblage suggest that they were not in equilibrium with the crystallizing carbonates and may be to some extent xenocrystic.

Chini zone, Mbeya carbonatite.

Altered sövite containing pyrochlore altered to columbite is found at the north-east end of the Chini zone (Fawley and James, 1955). The rock is a fine-grained sövite composed mainly of calcite with prominent bands of granular (up to 1 mm.) apatite, large crystals of altered pyrochlore, large pseudomorphs of quartz and platy limonite after a carbonate that was probably chalybite, and occasional disseminated grains of apatite. The rock has undergone extensive changes, but its original composition may have been similar to that of the Museum zone sövite. The large pseudomorphs after chalybite are absent from the Museum zone sövite and are considered to be the product of an iron metasomatism affecting the Chini zone. The accessory mineral assemblage has undergone considerable alteration: amphibole and biotite are extensively carbonated; much more quartz, some of it obviously secondary, is present; pyrochlore is cloudy and opaque around its edges and along cracks, and in this partially altered material have grown disoriented crystallites of columbite, in many instances coalescing into massive columbite, which completely replaces the pyrochlore; magnetite and pyrite do not appear and have presumably been altered to the hematite and limonite that are common in the partly weathered specimens used for this description.

Staining tests show that the large equigranular crystals of carbonate forming the bulk of the rock are calcite although a partial chemical analysis of the rock indicates 5 % dolomite and 73 % calcite. Small inclusions of dolomite occur in many of the calcite grains and are oriented parallel to the calcite cleavage (pl. XXI, fig. 5). Some of the inclusions are limonite, which may be interpreted either as original inclusions of limonite in the calcite crystals or as due to the subsequent alteration of a ferruginous dolomite or ankerite. Large pseudomorphs composed of platy limonite and quartz, up to 1 cm. in size, are apparently after chalybite; a box-work of limonite follows the {100} cleavage directions and the intervening carbonate has been replaced by quartz (pl. XXI, fig. 6). In weathered specimens increased development of limonite obscures the box-work.

Amphibole is unaltered only where it occurs in bands of apatite. It has not been analysed, but appears to be similar to the alkali-amphibole of the Museum zone. A number of linear zones of fine-grained carbonate in the matrix of the rock may represent altered amphibole. The reddish *biotite* is partly carbonated and one large euhedral crystal can be seen to have recrystallized in minute disoriented flakes.

Pyrochlore occurs in crystals up to 1 cm. in size, usually zoned and with little sign of embayment by carbonates. Alteration to columbite is preceded by a change in the pyrochlore, which becomes cloudy and opaque (pl. XXI, figs. 1, 3); an X-ray powder photograph of this material shows that it is still pyrochlore, possibly with some amorphous material, and that the unit cell edge a 10·405 Å. remains constant. It is evident that pyrochlore in carbonatites is easily attacked by carbonate solutions and it is often embayed and veined by calcite. In the example shown in pl. XXI, fig. 2, calcite is replacing partially altered pyrochlore along its junction with columbite veins.

Columbite (pl. XX, figs. 7, 8, 9) replaces pyrochlore around its edges and along cracks in the larger crystals. Both the development of the opaque phase in the pyrochlore and the growth of columbite are shown in pl. XX, fig. 14, and pl. XXI, figs. 1, 2, and 3. The opaque phase is always developed in pyrochlore before alteration to columbite but in many cases only small individual grains of columbite are developed within it. The growth of columbite around the edges of the pyrochlore crystals is usually not uniform, massive aggregates being developed only at a few points. Occasionally the zoning of the pyrochlore is reproduced in the pseudomorphous columbite aggregates in which definite bands parallel to and replacing zones in the pyrochlore can be seen. Within the pyrochlore crystals the veins of columbite are generally massive aggregates. An unusual variation is shown in pl. XXI, fig. 2, where carbonate is interposed between the columbite veins and the opaque phase of the pyrochlore. Often fluorite is developed within or adjacent to the columbite pseudomorphs.

Ngualla carbonatite.

Columbite pseudomorphs after pyrochlore are found in apparently unaltered sövite from near the centre of the Ngualla carbonatite. The sövite is composed of equigranular calcite, scattered grains of dolomite containing oriented rhombs of calcite (the inverse of the intergrowth observed in the Chini zone), granular apatite associated with amphibole and talc in schlieren, grains of apatite disseminated throughout the rock, and an accessory mineral assemblage of amphibole, talc, biotite, columbite, and occasional pyrite and magnetite. The rock shows little sign of alteration although some has presumably taken place since the amphibole is altered to a disoriented aggregate of talc, biotite is altered to talc, and disoriented aggregates of columbite have completely replaced cubo-octahedral crystals of pyrochlore. The *amphibole* of the columbite-bearing sövite appears to be similar to that of the Museum and Chini zones of the Mbeya carbonatite. A coarse-grained calcite-rich sövite contains a deep green alkali-amphibole (up to 10 mm.) with 5·90 % Na_2O and 2·18 % K_2O.

Both amphibole and biotite alter to a pleochroic green mineral which was identified by its X-ray powder pattern as *talc*. Alteration has in both cases often gone to completion, to produce pseudomorphs composed of a disoriented aggregate of minute flakes of talc. Occasional flakes are dispersed among the carbonates. The talc is unusual in having moderately strong pleochroism with α colourless, β, γ olive-green; its refractive index is rather high, γ 1·605, and $2V_\alpha < 10°$. These optical properties are associated with the remarkably high iron content of 6·76 % total iron (calculated as FeO). Talc does not normally contain more than 2·5 % FeO, and then according to Gruner (1944) there is a gap in the Fe–Mg replacement series until minnesotaite is reached, with 33·66 % FeO and 6·26 % MgO. No member of the talc-minnesotaite series has hitherto been recorded in a sövite.

A red *biotite* is common in the Ngualla sövites. It has $2V_\alpha < 10°$, γ 1·638, and a pleochroic scheme, α foxy-red, β, γ colourless; its X-ray powder pattern is consistent with either the 1M or 3T polymorph. Crystals are elongated in the *c* direction and the pleochroism is blotchy.

Alteration to talc is extensive and may develop at various points within the crystals, invariably forming a wide rim around their edges (pl. XXI, fig. 4); the talc is interleaved with and feathers out into the biotite it is replacing. Magnetite occurs in grains elongated parallel to the cleavage of the talc, and where it is adjacent to calcite, talc is rimmed with limonite, probably a product of secondary alteration.

Unaltered *pyrochlore* has only been found in a magnetite segregation in the sövite. It occurs in pale yellow transparent octahedra and cubo-octahedra, less than 0·5 mm. in size, and with *a* 10·425 Å.

Pseudomorphs of *columbite* after pyrochlore have been extracted from the rock by treatment with dilute hydrochloric acid. The original habit of the pyrochlore was clearly octahedral modified by {100} faces (pl. XX, figs. 4, 5, 6), the characteristic habit of pyrochlore in the Mbeya carbonatite and in sövites in general. The columbite is black in colour, metallic in lustre, and completely replaces the pyrochlore. Its X-ray rotation pattern shows that it is an aggregate of disoriented crystallites (pl. XX, fig. 3). A partial chemical analysis[1] of the columbite shows the presence of 2 % MnO, 19 % FeO (total iron), 67 % Nb_2O_5, and 3 % TiO_2.

The alteration of pyrochlore to columbite.

In the Mbeya carbonatite the alteration of pyrochlore to columbite can be traced through various stages (pl. XX, fig. 14; pl. XXI, figs. 1, 3). The pyrochlore crystals are zoned and, although the edges may be partially embayed by carbonates, the general outline of the crystals is euhedral. Columbite replaces pyrochlore along the crystal margins and anastomozing veins, which tend to be parallel to the poor octahedral cleavage. The first stage of alteration is the development in the pyrochlore crystals, usually along the margins, of a white opaque material containing a few minute black grains. The X-ray powder pattern of this material shows that it is still essentially pyrochlore although the diffuse lines suggest incipient breakdown of the pyrochlore structure. Continued alteration gives rise to the growth of small grains of columbite in this cortex, which may eventually coalesce to form a columbite rim. A single crystal rotation photograph (pl. XX, fig. 2) of a portion of the rim attached to residual pyrochlore shows the normal pyrochlore pattern of discrete reflections with a superimposed 'powder' pattern of θ-curves corresponding to columbite; the columbite is therefore present as a disoriented aggregate of minute grains. It was necessary to heat this material at 450° C. in nitrogen for two hours to produce a sharp columbite

---

[1] Analyst: T. D. Rees, formerly Geochemist, Geological Survey of Tanganyika.

pattern. In fact before heat treatment the columbite pattern was too diffuse to be recognizable.

At Ngualla pyrochlore is completely replaced by columbite; the intermediate stages in the process of alteration are not seen and the original presence of pyrochlore is inferred from the cubo-octahedral shape of the pseudomorphs. Unaltered pyrochlore has, however, been found in another part of the carbonatite. A single-crystal rotation photograph of one of these pseudomorphs rotated about a [111] axis shows a pattern of θ-curves of columbite that is quite sharp even in unheated material.

The rotation photographs, pl. XX, figs. 2 and 3, show that the columbite crystallites in the pseudomorphs are completely disoriented and quite small.

In general, pseudomorphous minerals can occur in three types of aggregation:

A completely disoriented aggregate or 'powder', of microscopic or submicroscopic crystallites. Examples are common and occur even where there is some structural similarity between the pseudomorphous mineral and its host, if the transformation requires the breaking of bonds in such a way that those parts of the structure that persist have some choice of orientation in the new structure.

A microscopic or submicroscopic aggregate of crystallites completely or partially oriented with respect to the morphological symmetry, and therefore to the lattice, of the replaced mineral. Epitaxic replacement as defined by Kostov (1956) produces this type of pseudomorph. In the transformation bonds are broken in such a way that units of the structure persist continuously in at least one direction, as for instance in the linking of pyroxene chains to form double amphibole chains in the homoaxial intergrowths of tremolite in diopside.

A single crystal, twinned or untwinned, with the morphology of the replaced mineral. Examples occur among the products of polymorphic inversions, but are rare where a change in composition is involved in the pseudomorphing process.

The chemical similarity between pyrochlore, essentially $(Ca,Na)_2Nb_2O_6(O,OH,F)$, and columbite, $(Fe,Mn)Nb_2O_6$, might suggest the likelihood of some degree of orientation in the columbite crystallites of the pseudomorphs. A consideration, however, of the structural changes involved in the pseudomorphing process shows why complete disorientation is observed.

An important factor in the replacement of pyrochlore by columbite is the reduction in size of the ions in the *A* position, when Fe^{2+} and Mn^{2+} replace Ca^{2+} and Na^{+}. The latter are in eightfold coordination in pyrochlore (Rosén and Westgren, 1938), and their replacement by the smaller Fe^{2+} and Mn^{2+} ions, which can only coordinate six oxygen atoms, results in collapse of the Nb–O framework of pyrochlore to produce the less symmetrical Nb–O framework of columbite. This collapse involves breaking of strong Nb–O, largely covalent, bonds and complete disruption of the structure. The rearrangement can only be propagated over short distances before the distortion of the Nb–O framework becomes too great and a new sequence of adjustments must be begun, that is, a new columbite crystallite. The size of the columbite crystallites has not been determined, but the absence of spottiness on the θ-lines of the rotation photographs of the Ngualla pseudomorphs (pl. XX, fig. 3) indicates an average diameter of less than 10^{-4} cm. The inability of the pseudomorphs from the Mbeya carbonatite to give a sharp pattern without previous heat treatment (pl. XX, fig. 2) indicates rather shorter-range order.

The significance of the alteration of pyrochlore to columbite.

The changes accompanying the alteration of pyrochlore to columbite differ considerably in the Mbeya and Ngualla carbonatites. In the Mbeya carbonatite it appears that large crystals of an iron-bearing carbonate probably crystallized during the formation of the columbite. Limonite and hematite were produced by the subsequent exsolution and decomposition of the carbonate, and by alteration of magnetite and pyrite. Some quartz has been introduced into the sövite. The iron content of such sövites in the Chini zone (2·7 % Fe_2O_3) considerably exceeds that of the Museum zone sövite (1·1 % Fe_2O_3).

At Ngualla the columbite occurs in an apparently unaltered sövite. However, a high proportion of the original alkali-amphibole is completely converted to ferruginous talc. Biotite is also altered both around its margins and at centres within the crystals to ferruginous talc and magnetite. There is no evidence of appreciable quantities of iron in the carbonate minerals nor is there any limonite in the rock. It is believed that the alteration of amphibole and biotite took place at the same time as the alteration of pyrochlore to columbite. All the processes involve the introduction of iron into the rock but in rather smaller amount than in the Chini zone of the Mbeya carbonatite.

The alteration of pyrochlore to columbite involves only the addition of iron, or iron and manganese, and the removal of calcium, alkalis, and fluorine. The niobium content of both minerals is similar and the high niobium to tantalum ratio characteristic of pyrochlore in carbonatites is inherited in the columbite. In the Mbeya carbonatite many of the partially altered pyrochlore crystals have a core containing purple fluorite. It seems reasonable to suppose that the fluorite is a by-product of the alteration, both calcium and fluorine being expelled from pyrochlore during the formation of columbite.

The alteration of amphibole and biotite to talc at Ngualla provides a clue to the physico-chemical conditions operative during the pseudomorphous alteration of pyrochlore to columbite. However, there is little exact information about the stability field of talc in the presence of calcite and, moreover, data relating to the composition $Mg_3Si_4O_{10}(OH)_2$ will be somewhat modified by the high iron content of the Ngualla talc, although such modification is likely to be well within the limits of precision of the data available. The lowest temperature at which talc can form is controversial. It has been reported as a weathering product, but the lowest well-authenticated temperature for natural talc formation is apparently of the order of 100° C. for authigenic growth in the Permian evaporites of Eskdale, Yorkshire (Stewart, 1949), under conditions of considerable hydrostatic pressure. The upper temperature limit of talc formation in the presence of an adequate supply of calcium appears to lie near the top of the greenschist facies (Turner and Verhoogen, 1951) or in the lower grades of the albite–epidote–amphibolite facies (Ramberg, 1952); thus the upper limit is of the order of 200° C. to 300° C. at pressures of about 2000 bars (Rosenqvist, 1952). Such conditions are consistent with what may be expected in a volcanic neck after active volcanism has ceased and before erosion has removed the overlying pile. In the Mbeya carbonatite talc formation has not been observed and the alteration of the sövite amounts to the formation of an iron-bearing carbonate and the introduction of colloform quartz. In this case the physico-chemical conditions cannot be estimated; the sövites exposed at surface lie near the base of the original volcanic pile. The alteration processes both at Ngualla and Mbeya may be regarded as autometasomatic.

Acknowledgements. Our colleague Mr. R. Halligan very kindly devoted much time and trouble to the careful preparation of the photographs. We have also to thank Mr. A. J. Radford for a number of chemical analyses and Dr. A. E. Wright for staining the thin-sections. It would not have been possible to have produced this paper without the active support of Mr. A. M. Quennell, Director of the Geological Survey of Tanganyika.

References.

von Eckermann (H.), 1948. Sveriges Geol. Undersök., no. 36.

Fawley (A. P.) and James (T. C.), 1955. Econ. Geol., Chicago, vol. 50, p. 571.

Goldsmith (J. R.), Graf (D. L.), and Joensuu (O. I.), 1955. Geochimica Acta, vol. 7, p. 212.

Gruner (J. W.), 1944. Amer. Min., vol. 29, p. 363.

Kostov (I.), 1956. Min. Mag., vol. 31, p. 333.

Larsen (E. S.), 1942. U.S. Geol. Surv. Prof. Paper 197–A.

Mitchell (J.), 1956. Colon. Geol. Min. Resources, vol. 6, p. 182.

Ramberg (H.), 1952. The Origin of Metamorphic and Metasomatic Rocks. Chicago.

Rosén (O.) and Westgren (A.), 1938. Geol. För. Förh., vol. 60, p. 226.

Rosenqvist (I. Th.), 1952. Univ. Bergen Arb. Naturv. R., no. 4.

Sæther (E.), 1957. Kgl. Norske Vidensk. Selskab. Skrifter, no. 1.

Smith (J. V.) and Yoder (H. S.), 1956. Min. Mag., vol. 31, p. 209.

Smith (W. C.), 1953. Bull. Brit. Mus. (Nat. Hist.), Min., vol. 1, p. 97.

Sörum (H.), 1956. Kgl. Norske Vidensk. Selskab. Forh., bd. 28, p. 112.

Turner (F. J.) and Verhoogen (J.), 1951. Igneous and metamorphic petrology. New York.

Explanation of Plate XX.

Fig. 1. X-ray powder pattern of pyrochlore from Museum zone, Mbeya carbonatite, taken with Cu-$K\alpha$ radiation in a 6 cm. diameter camera.

Fig. 2. X-ray rotation pattern of a fragment of pyrochlore partly altered to columbite, from Chini zone, Mbeya carbonatite, taken with Cu-$K\alpha$ radiation in a 6 cm. diameter camera. The discrete reflections are due to pyrochlore. The powder lines are due to a completely disoriented aggregate of crystallites of columbite to which the pyrochlore is altering.

Fig. 3. X-ray pattern produced by a pseudomorph of columbite after pyrochlore, from Ngualla carbonatite, rotated about a [111] axis, radiation Cu-$K\alpha$, camera diameter 6 cm.

Figs. 4–6. Cubo-octahedral pseudomorphs of columbite after pyrochlore from Ngualla. Fig. 4 shows a tabular crystal formed by the preferential development of a pair of opposed {111} faces. Magnification ×4.

Figs. 7–9. Cubo-octahedral pseudomorphs of columbite after pyrochlore from Chini zone, Mbeya carbonatite. Figs. 7 and 9 show tabular crystals. In the crystals shown in figs. 7 and 8 pits produced by the solution of apatite crystals are visible. Magnification ×2.

Figs. 10–13. Pyrochlore crystals from Museum zone, Mbeya carbonatite. Fig. 10 shows the forms {111} and {100} in equal development. Fig. 11 shows a tabular crystal exhibiting the forms {111} and {100} with preferential development of a pair of opposing {111} faces; the crystal is shown in the same orientation as that in fig. 10. Fig. 12 shows the common habit of pyrochlore in the Mbeya carbonatite. Fig. 13 shows the forms {111} and {011}—a rare habit of pyrochlore in the Mbeya carbonatite. Magnification ×2.

Fig. 14. Thin-section showing the alteration of zoned pyrochlore (transparent) to columbite (opaque), from the Mbeya carbonatite. The prismatic crystals on the right-hand side are apatite. Columbite forms a rim to the crystal and anastomozing veins in the body of the crystal tend to follow {111} cleavage directions. Magnification ×14.

EXPLANATION OF PLATE XXI.

FIG. 1. Polished section illuminated by inclined light showing the development of columbite around the margin of a pyrochlore crystal and the coalescence of columbite veins in the interior. Bordering the columbite veins is a white incipient alteration product of pyrochlore. Chini zone, Mbeya carbonatite. Magnification ×16.

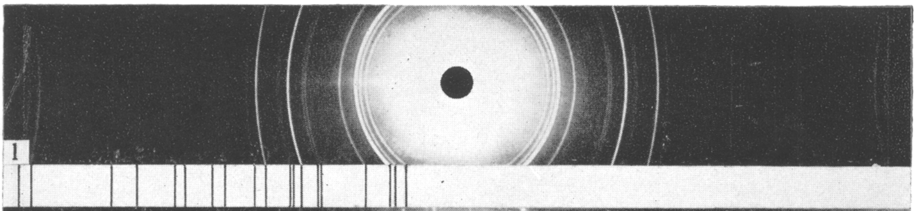
FIG. 2. Thin-section showing the development of a carbonate at the junction of columbite veins and unaltered pyrochlore, replacing the white alteration product. Chini zone, Mbeya carbonatite. Magnification ×16.

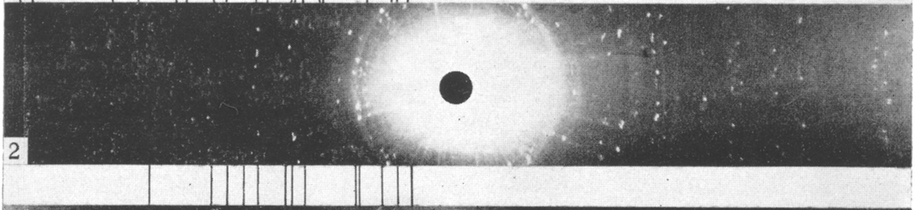
FIG. 3. Thin-section illuminated by inclined light showing the extensive development of the white alteration product of pyrochlore and marginal development of columbite. Chini zone, Mbeya carbonatite. Magnification ×32.

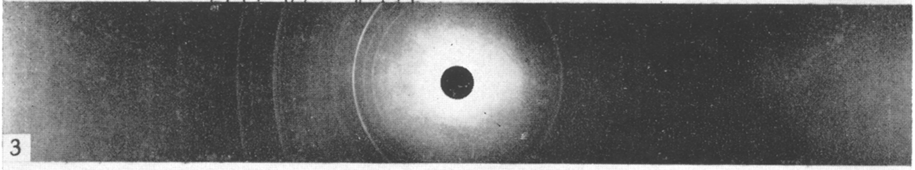
FIG. 4. Thin-section showing the marginal alteration of biotite to ferruginous talc. Blotchy pleochroism can be seen in both of the large crystals of biotite. The matrix of the rock is calcite. Apatite needles are visible in the top right-hand corner. Ngualla carbonatite. Magnification ×14.

FIG. 5. Thin-section of calcite with oriented rhombs of dolomite. The calcite is stained with Alizarin Red S. Chini zone, Mbeya carbonatite. Magnification ×200.

FIG. 6. Thin-section of a box-work of limonite in secondary quartz after a ferruginous carbonate. Chini zone, Mbeya carbonatite. Magnification ×100.

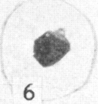

1


2


3


4

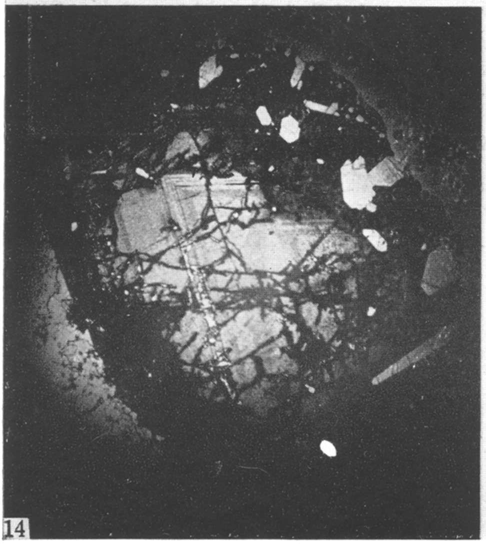

5

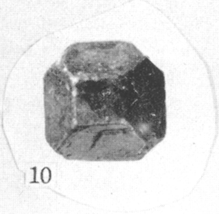

6

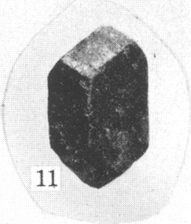

7

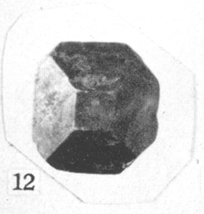

8


9


14

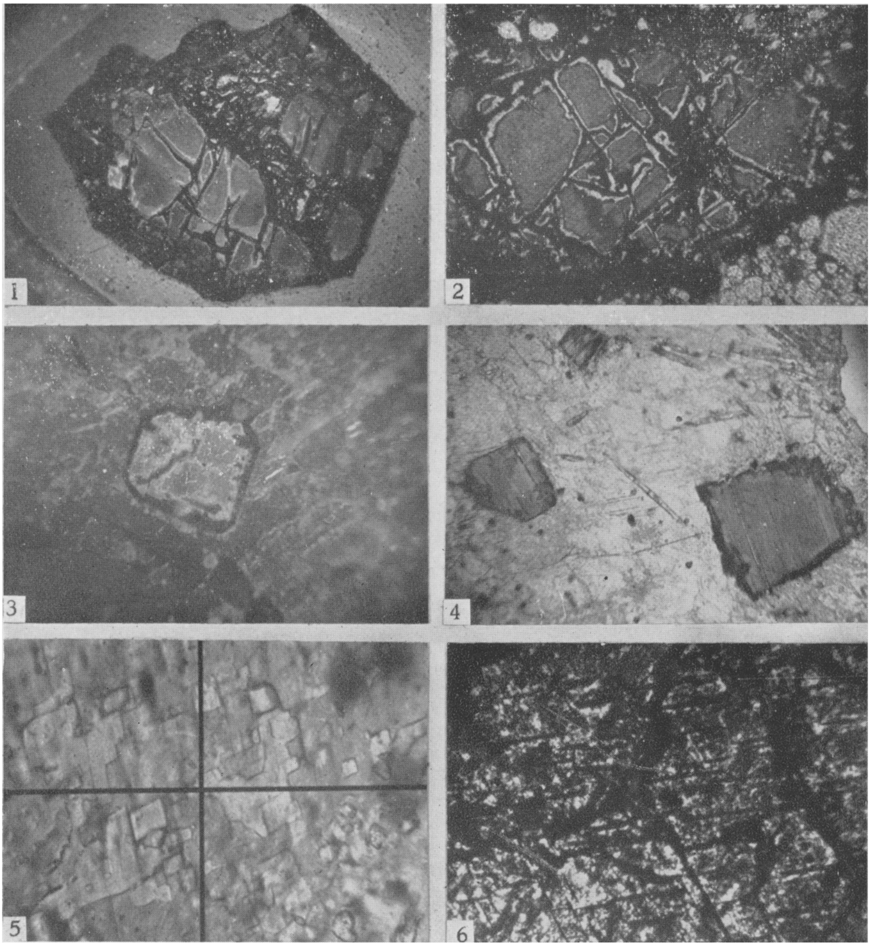

10


11


12


13

T. C. JAMES AND DUNCAN MCKIE: PSEUDOMORPHS OF COLUMBITE AFTER PYROCHLORE



T. C. James and Duncan McKie: Pseudomorphs of columbite after pyrochlore