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Stratiform magnetite crystals of abnormal morphology from volcanic carbonatites in Tanzania, Kenya, Greenland, and India

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SUMMARY. Magnetite is common in carbonatites, and usually has octahedral habit. Abnormal crystals from Galapo, Tanzania, were long thought to be unique, but such crystals are now known to occur at seven localities in four countries. The magnetite is titaniferous, but not unusual in composition for its provenance. The abnormal crystals typically have large growth pyramids extending in one direction (occasionally in two or more directions). They appear to be formed by superimposition of macroscopic growth sheets, parallel to octahedral and other planes, giving a planar structure to the growth pyramid. The edges of the sheets may form low-index or more complex surfaces. Some sheets project beyond the bounding planes of the growth pyramid, which is not repeated in crystallographically equivalent orientations. This unusual mode of growth will be called stratiform. Recognition of these distinctive crystals elsewhere might reveal the presence of hitherto unsuspected carbonatites.

MAGNETITE is a common accessory mineral in carbonatites, usually forming simple octahedral crystals. The abnormal crystals illustrated in fig. 2 were discovered by T. C. James and the first author in 1953 at Galapo, Tanzania, during a brief inspection of carbonatite occurrences. At Galapo the carbonatite exposures were very puzzling, often suggestive of bedded limestone, and as the first author encountered nothing comparable in later years, the occurrence remained problematical. Recently, however, searches in museums and informal enquiries have led to identifications of similar magnetites from four localities in Kenya, one in Greenland, and one in India. Despite the striking appearance of the crystals there is no mention of this feature in the literature, apart from comments on the Greenland occurrence. These seven occurrences are all from volcanic carbonatites, i.e. from extrusive carbonatite tuffs or carbonatite intrusions located high in the volcanic diatreme, but as detail on most of them is very limited, their significance still remains rather obscure. It is hoped that this account will prompt others to seek and record similar crystals, in both old localities and new, and thereby lead to their better understanding. In this paper the first author is responsible for the general account, and the second for the crystallographic aspects.

Field relations

Five occurrences have been found in association with the Neogene volcanic carbonatites of the East African Rift areas, and their locations are shown in fig. 1.

Galapo, Tanzania. Galapo (4° 14′ S. 35° 50′ E., also spelled Galappo) lies at the foot of the volcano Kwaraa (also Kwaraha, or Ufiome), one of several Pleistocene-Recent nephelinite-tuff/carbonatite volcanoes situated near the Eastern (Gregory) Rift fault-line towards its southern termination. Gittins (Tuttle and Gittins, 1966, p. 478) gave brief notes and a map of the area, based on early unpublished reports by T. C. James. Later information from an unpublished prospecting report of 1959 by A. F. Cluver (kindly provided by Gold Fields of South Africa Ltd.), and from the 1:125000 geological map, Quarter Degree Sheet No. 85, Babati (Mineral Resources Division, Tanzania, 1966) has been useful in preparing the following synopsis.

Kwaraa (alt. 2415 m) is capped by nephelinitic lavas and tuffs, but the upper slopes on the eastern side are formed of basement quartzite and kyanite schist, domed up by the volcanic intrusion some 600 m above their level on the surrounding plateau.

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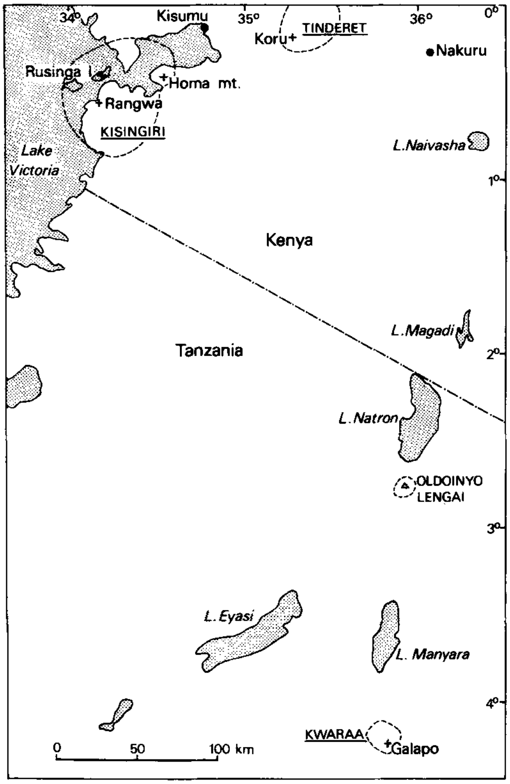

FIG. 1. Map showing locations of stratiform magnetites (+) and associated nephelinite/carbonatite volcanoes (underlined) in Tanzania and Kenya.

The carbonatites occur at the south-eastern foot of the mountain, around Galapo Mission, in a broad belt of nephelinitic agglomerates, tuffs, and lavas. Prospecting work in 1957 established the presence of four bodies of sövite to the north-west of the Mission, the largest 500×80 m in area. About 500 m to the south of this group there is a remarkable 'bedded carbonatite' extending for some 1500 m in an east-west direction along the north side of the Endanuk stream. It is this rock that contains the abnormal magnetites, whereas the writer believes that the intrusive sövites contain predominantly normal magnetite octahedra, although this has not been fully investigated. The bedded carbonatite outcrops as a flat ledge in the slopes just above the stream, and is usually from 0·5 to 1·3 m thick, but up to 3 m in pits, dipping gently to the south-east at about 3°. It overlies an old land surface of weathered agglomerates and tuffs, encrusted with calcrete and locally succeeded by a thin layer of impure limestone containing a few fossil land snails (named by W. W. Bishop as *Limicolaria sp.* and an internal plate of a Urocyclid slug) and fragments of fossil wood. The overlying bedded carbonatite is a grey fine-grained calcite rock containing numerous well-spaced subangular inclusions of fenitized quartzite and schist, usually 1–5 cm across, smaller fragments of carbonatite (not easily discernible in the field), and sparse, but conspicuous, abnormal magnetite crystals about 5 mm in size. Near the base, here and there, a brownish rock containing coarse poikilitic calcite was noticed, and appears to be a calcified tuff. It seems most probable that the bedded carbonatite is in fact a carbonatite tuff. A suggestion that it might be a sill of carbonatite tuffisite, injected into the agglomerates, seems less likely. It underlies at least 50 m of agglomerates and tuffs. At outcrop it is overlain by dark-red soil from which magnetite crystals can be extracted with a hand magnet, and most of the figured crystals were obtained in this way. Small patches of phosphorite (ferruginous francolite) also occur in the soil, and it was H. Bassett's discovery, in 1952, of pyrochlore in this regolithic material that first indicated the presence of carbonatites.

Numerous explosion craters occur around the foot of the volcano, mainly disposed circumferentially about 7–10 km from the centre. They are 200–350 m in diameter, and appear to have been essentially gas vents, active much later than Kwaraa itself. In some of these craters abnormal magnetite crystals were noted among the tuffs, and at the Marongwe crater, 10 km north-east of Galapo, a second small occurrence of 'bedded carbonatite' with similar magnetites was seen.

The Kavirondo Rift area, Kenya. The four occurrences known in Kenya are associated with the alkaline volcanoes Kisingiri and Tinderet (see fig. 1). Their geological history has been reviewed by King *et al.* (1972) and Le Bas (1977), and selected magnetite crystals are shown in fig. 3. Rusinga Island and Rangwa are situated on the Kisingiri volcano, which had a diameter of at least 80 km, and dates from early to middle Miocene (Bishop *et al.*, 1969). The Kenya 1 : 125 000 geological map and Report No. 45 (McCall, 1958) describe this area.

Rusinga Island. This island (0° 25′ S. 34° 10′ E.) is noted for its Miocene mammalian fossils, including early hominoids. Magnetite from Rusinga resembling that from Galapo was found in the British Museum collections (Rocks 1942, 48 (37), and Minerals 1942, 52) among specimens collected by P. E. Kent in 1934–5. They comprise five abnormal magnetite crystals, and four 'pebbles from the base of the Upper Agglomerate Series NNW of Kiahera Hill' showing similar crystals set in medium-grained white calcitic carbonatite. Kent's reports do not mention these specimens, but later investigators recorded the presence of carbonatite

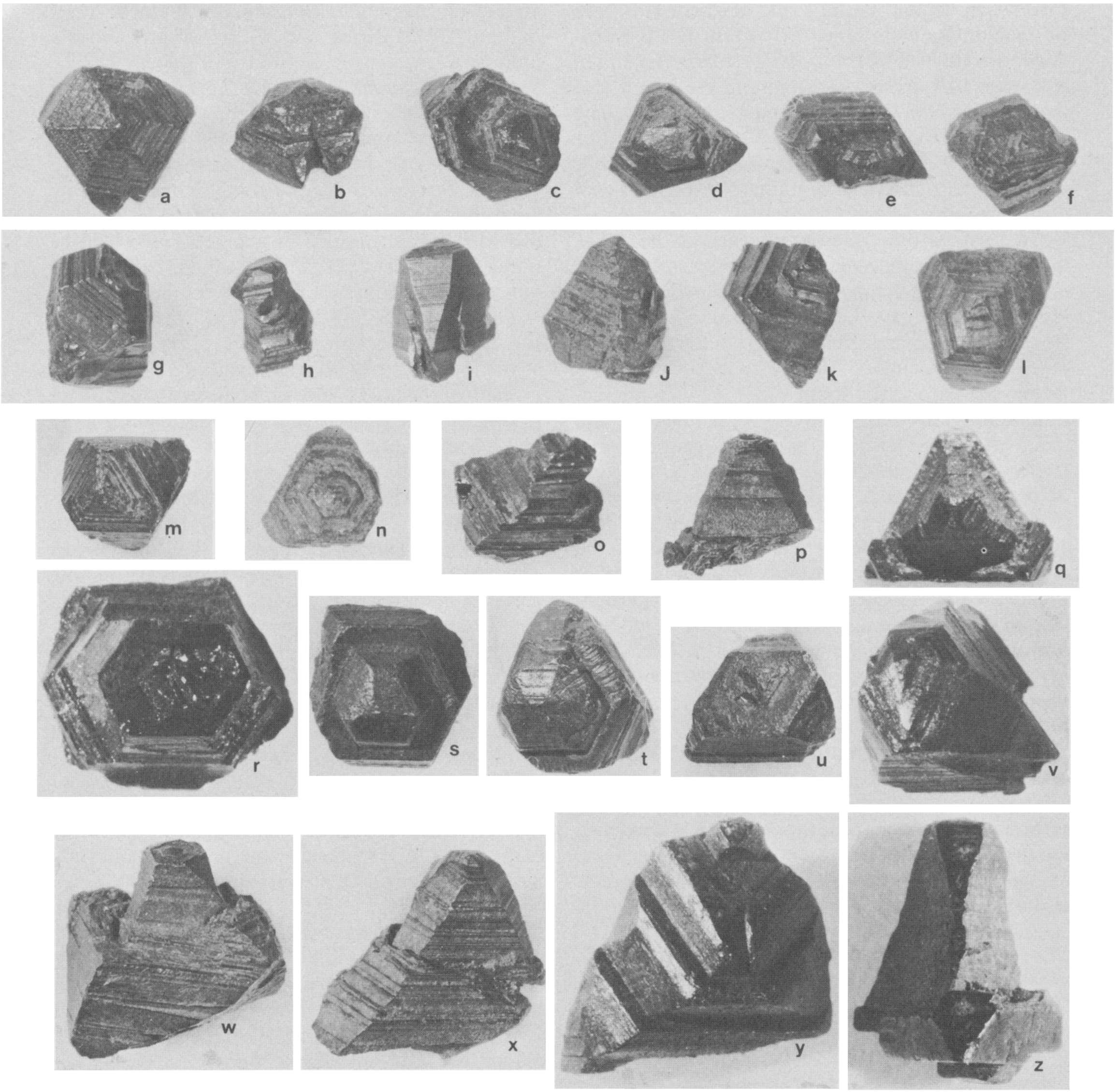

FIG. 2. Stratiform magnetite crystals, Galapo, Tanzania. Magnification a–n, ×2·8; o, p, s, t, u, w, x, ×3·1; q, r, v, y, z, ×5·7.

blocks (Shackleton, 1951, and Whitworth, 1953). McCall noticed similar crystals of magnetite during his survey, both in Rusinga and on the adjacent mainland coast, where a ridge of Kisingiri pyroclastics extends southwards for 8 km from Mbita Point (pers. comm., 1977).

In 1967–8 J. A. Van Couvering reinvestigated the stratigraphy of Rusinga (Van Couvering and Miller, 1969). He has kindly provided a grab sample of magnetite crystals from surface soil in the Gumba area, at the western end of the island, 3 km west of Kiahera Hill. Of the 60 crystals and fragments, at least 50 show the distinctive morphology, and only 6 or 7 are normal octahedra. The magnetite, often associated in the rock with biotite altered to vermiculite, has weathered out from carbonatite boulders and blocks present in conglomerates and agglomerates at four horizons in the varied sequence of volcaniclastic sediments. They are most plentiful in the 'Brown Breccia' of the Lower Kiahera

Formation around Gumba and Kiahera Hill, and in conglomerates interbedded within the Rusinga Agglomerate near Mbita. These places lie in an east-west belt 9 km long spanning the island (see map fig. 1 in Van Couvering and Miller, 1969). The magnetite in these carbonatite blocks is not all of this type, however. In one case it is largely subhedral, with normal octahedra as numerous as abnormal crystals among the few euhedra.

On Rusinga only one or two carbonatite dykes intrude the volcaniclastic strata, and these are much younger than the magnetite-bearing boulders, which are believed to have been washed down the talus slopes, perhaps partly in lahars, from the up-domed core of the Kisingiri volcano, which centred on Rangwa, 15 km to the south.

Rangwa. This centre (0° 34′ S. 34° 09′ E.), the main caldera of Kisingiri, exposes a ring of pyroclastics 4 km in diameter, surrounding a central area of carbonatites and breccias 2 km in diameter (Findlay and Rubie, in Le Bas, 1977, chap. 8). Here at least three carbonatite intrusions marked the final igneous activity, the youngest being a plug of foliated magnetite-carbonatite, with minor pyrochlore, in the Kinyamungu area. Portions of Findlay's Kinyamungu specimens were obtained from Bedford College, London, and of the three containing magnetite, one shows only octahedral crystals, up to 3 mm across, without surface features. The other two are grey carbonatites containing scattered crystals of magnetite, 1-10 mm across, which are all abnormal in their morphology. Since the carbonatite boulders of Gumba and Kiahera Hill, Rusinga, appear to represent the earliest activity of the Kisingiri volcano, and the Kinyamungu carbonatite belongs to its closing stages, the abnormal magnetites must have formed intermittently over a long period, of perhaps about a million years.

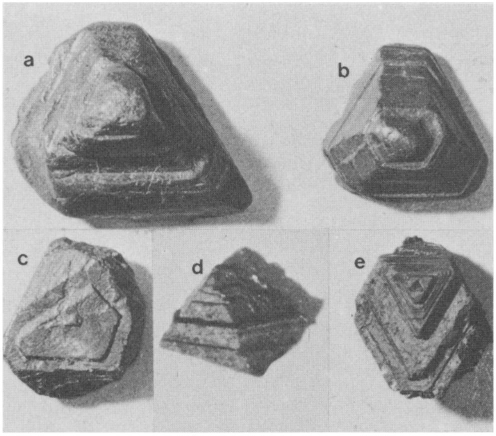

FIG. 3. Stratiform magnetite crystals, Kenya. a, b Kiahera Hill, Rusinga Island. c Koru. d, e Kinyamungu, Rangwa complex. Magnification a-c, e, ×2; d, ×4.

Homa Mountain. Near the eastern margin of Kisingiri lies Homa Mountain (0° 23′ S. 34° 31′ E.), an up-domed complex of carbonatite cone sheets and breccias of Miocene and Late Pliocene age (Le Bas, 1977, pp. 208-54). From minor carbonatite intrusions on the southern flank, M. J. Le Bas has provided specimens rich in magnetite in which he noticed a few crystals similar to those of Rusinga, although the majority are simple octahedra.

Koru (0° 10′ S. 35° 17′ E.). This Miocene fossil site lies at the eastern end of the Kavirondo Rift, at the foot of the Tinderet volcano, built of nephelinitic agglomerates and tuffs (King *et al.*, 1972, p. 191). In 1932 A. T. Hopwood collected magnetite and hornblende 'washed out of lava at Koru'. The thirty-six small magnetite crystals and grains now in the British Museum (1932, 93) include four stratiform crystals (see fig. 3c). In 1977 M. H. L. Pickford (report in preparation) mapped the fossiliferous area and recognized sheets of extrusive carbonatite, confirming earlier suggestions (Le Bas and Dixon, 1965) that the 'Koru Limestones' include carbonatite. He collected magnetites from the soil at eight points, of which 40 % (120 crystals) are stratiform, and only 4 % simple octahedra, the rest being rough fragments or dodecahedron/octahedron combinations.

Qagssiarssuk, Greenland. In the Gardar alkaline province, at 61° 09′ N. 45° 29′ W., adjacent to the Igaliko nepheline syenite intrusions, a small down-faulted area of volcanic carbonatite flows and tuffs has been described by Stewart (1970). The volcanics occupy more than 1 km^2, and comprise calcareous tuffs (with pyroclasts of carbonatized melilite rock), dolomitic tuffs, and alnöitic lapilli tuffs. A rock described (p. 41) as a martite tuff contains euhedral crystals of martite up to 1 cm in length, and small apatite euhedra, in a matrix of hematite-stained dolomite, with subsidiary fluorite and baryte. Stewart stated that the martite crystals 'showed the stepped faces commonly found in magnetite crystals from carbonatite', and this led to the loan of a specimen of the rock from the Geology Department, University of Durham. It closely resembles Rusinga specimens. Stewart has mentioned (in lit., 1976) that when describing this rock the few magnetite-bearing carbonatites available to him for comparison were largely from Kenya, including the Rusinga area!

Amba Dongar, Gujarat, India. R. N. Sukheswala recently examined magnetites, at our suggestion, from Amba Dongar (21° 59′ N. 74° 04′ E.) and surrounding areas of this Eocene carbonatite province. He found specimens resembling those described in this paper, and kindly sent us sixteen crystals. These are rather small (*c.* 2 mm), but similar in detail to Kenya specimens. They have been found in both the sövite ring-dyke and younger ankeritic plugs at Amba Dongar (Deans *et al.*, 1972 for map and references), and also in sövites near Siriwasan, 8 km to the north-west (Sukheswala and Borges, 1975), where they are perhaps a little more frequent. Their distribution appears to be rather patchy, and they occur with normal magnetite octahedra. Structurally the Amba Dongar finds are high in the large volcanic diatreme, whereas the Siriwasan sövites form pockets near the top of an extensive (11 km) sill of carbonatite breccia, injected along the junction between sandstone and overlying Deccan Trap basalts.

Petrographic notes and chemical analyses

Petrographic work has been largely confined to the Galapo rocks. The typical carbonatite tuff is fine-grained, but contains numerous conspicuous angular and sub-rounded fragments of fenite (2–50 mm across), fewer fragments of basement quartzite and amphibolite, and numerous, but less conspicuous, rounded fragments of carbonatite (1–10 mm across). The latter contain accessory amounts of biotite, sodic amphibole, and magnetite. These coarse fragments usually make up less than 20% of the rock. The groundmass consists of finer calcite (down to 0·1 mm), with minor amounts of biotite, sodic-amphiboles and feldspars, magnetite, and traces of pyrochlore. Some of the biotite is partly exfoliated, perhaps as result of weathering before incorporation in the tuff. The magnetite is usually an accessory or minor constituent, from 1–5 mm in size, occasionally slightly larger, and varying from anhedral to platy to euhedral equidimensional. In thin sections the magnetites are variable in appearance, often irregular and rather featureless, and the examples seen in fig. 4 are selected rather than typical. Some (e.g. 4a) show pronounced internal dissolution, comparable with the 'highly corroded' and 'skeletal' martite described by Stewart from Qagssiarssuk. The cavities are infilled with granular calcite. Others have thin layered inclusions parallel to external faces (e.g. 4b). In this example the magnetite has evidently grown around a crystal of biotite (b), and in fig. 4c the large prismatic inclusion appears to have been an apatite crystal, now replaced by calcite. The Rusinga and Kinyamungu carbonatites have not been studied in detail, but do not appear to be abnormal. In both cases biotite is a common associate, and some Kinyamungu magnetites form unusual aggregates (fig. 4d).

Samples of the bedded Galapo carbonatite tuff, and a carbonatite pebble from Rusinga (Kiahera Hill), have been analysed for the trace-elements characteristic of carbonatites, and the results, shown in Table I, are quite normal for these rocks. The fossiliferous calcareous tuffs of Koru (analyses 4 and 5) also carry the same trace elements as carbonatites, and in similar proportions. This indicates that they derived their calcium from carbonatitic tuffs and ashes, and, as Bishop (1968) has pointed out, such carbonatitic ash-falls may have been particularly favourable to fossilization of mammalian remains. Thus the association of terrestrial fossils and stratiform magnetites at Koru and Rusinga is not fortuitous.

Five analyses of abnormal magnetites are shown in Table II. The first two are of whole crystals, which appeared to be essentially homogeneous. Similar crystals dissolved in hydrochloric acid left only trace amounts of flaky ilmenite. Prins (1972), using the electron-probe, reported exsolved ilmenite in Galapo magnetites, but his specimen D321 contains more titanium (4·58% TiO_2) than the others. The Rusinga magnetite is quite similar in composition to that from Galapo, apart from slight oxidation towards martite. Martite also replaces the magnetite

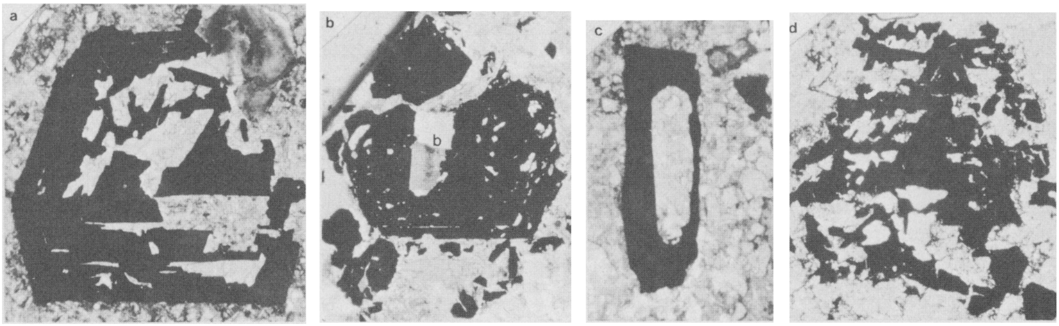

FIG. 4. Stratiform magnetites seen in thin section. a–c in carbonatite tuff, Galapo, ×15. d in intrusive carbonatite, Kinyamungu (Rangwa), ×9.

TABLE I. *Trace element contents of carbonatites and tuffs from Galapo, Rusinga Island, and Koru. (X-ray fluorescence analyses, in ppm)*

	La	Ce	Y	Sr	Ba	Rb	Zr	Nb
1 Carbonatite tuff, Galapo DT93	250	450	60	1990	1000	20	70	150
2 Carbonatite tuff, Galapo DT94	350	650	60	3300	1750	10	10	80
3 Carbonatite, Kiahera Hill, Rusinga Island BM1942-48	220	300	60	3940	1400	10	10	20
4 Pink fossiliferous tuff, Koru, No. 24/2*	nd	na	50	1800	900	40	nd	40
5 Grey fossiliferous tuff, Koru, No. 26/2E*	400	na	100	3000	3000	nd	nd	300

na = not analysed nd = not detected.

Analysts: A. Livingstone and D. J. Bland, Institute of Geological Sciences.

* See Bishop (1968, p. 30).

to a variable degree at other localities, and for the most part probably results from weathering, but in some cases the possibility of oxidation during eruption cannot be ruled out.

Prins (1972), and others to whom he refers, have discussed the chemistry of magnetites from carbonatites in some detail. There is evidently considerable variation in composition, but the present analyses are all rather similar, and characterized by a moderate content of titanium (2–4·6% TiO_2), and appreciable amounts of vanadium and manganese, whereas magnesium and aluminium (enriched in some other carbonatite magnetites) are distinctly low.

Crystallography of the magnetite

Characteristics of the abnormal morphology. The authors are not aware of any description in the literature of this mode of growth in magnetite. The morphology of magnetite crystals from volcanic carbonatites shows considerable variation at each of the localities mentioned above, but several features of the growth of these abnormal crystals distinguish them from normal magnetite:

The development of steep or very steep growth pyramids, which are not normally repeated in equivalent crystallographic orientations.

The abnormal growth pyramids are often developed on only one face or plane. When developed on more than one face or plane, these faces or planes are not usually crystallographically equivalent.

Only one growth pyramid is developed on an individual face or surface; it is often situated within the boundaries of the face and makes a large re-entrant angle with it. The growth pyramids are bounded, in part, by planes with rational indices, but also by surfaces that are probably irrational.

The surfaces of many growth pyramids are very strongly striated, developing prominent ridges in the more extreme examples. The ridges on several adjacent faces are often coplanar: this will be called 'planar structure'. The word 'stratiform' will be used to refer to this unusual mode of growth and to crystals that exhibit it.

The characteristics summarized above, and other features of the abnormal morphology, are illustrated by descriptions and figures of crystals from four localities in three countries, representing typical occurrences. Several of these characteristics are usually present in each abnormal crystal. Some of the features are so aberrant that conventional

TABLE II. *Analyses of magnetites from Galapo and Rusinga Island*

	Galapo				Rusinga
	DT94	DT 105	D323	D321	No. 37
FeO	32·44	31·49	91·28*	90·13*	25·9
MgO	0·41	0·19	0·28	0·19	0·22
MnO	0·80	0·91	0·36	0·46	
CaO	0·90	0·45	0·06	0·09	0·05
Fe_2O_3	61·60	63·84			70·5
Al_2O_3	0·05	0·14	0·09	0·14	
V_2O_3	0·16	0·11	0·44	0·59	
Cr_2O_3	nd	nd			
TiO_2	3·91	2·64	2·27	4·58	2·24
SiO_2	0·03	0·04			
H_2O	0·04	0·06			
Acid insol.	(0·11)	(0·07)			
Total	100·34	99·87			98·91

* Total Fe expressed as FeO. nd = not detected.

DT 94 from carbonatite tuff, Galapo
DT 105 from soil over carbonatite tuff, Galapo
} anal. E. A. Vincent (1955, unpublished)

D 323 phenocrysts from carbonatite, Galapo
D 321 phenocrysts from carbonatite, Galapo
} anal. (electron probe) P. Prins, see Prins (1972, p. 235)

No. 37, BM 1942-48 magnetite (slightly altered to martite) from carbonatite pebble, Kiahera Hill, Rusinga Island. Anal. N. Cogger morphological terminology is either inadequate or would require lengthy descriptions. In such cases limited use will be made of colloquial terms, for the sake of brevity.

Fig. 5a. This crystal is an extreme example of the abnormal morphology and illustrates many of its characteristics. The broadest part of the crystal will be called the 'base', from which arises an exceptionally tall and steep growth pyramid, elongated in approximately the direction of a triad axis. The base consists of a triangular face beneath $(\bar{1}\bar{1}\bar{1})$, surrounded by six other octahedron faces, which appear entirely normal, apart from some flattening parallel to (111), and the presence of a crystal in parallel growth, which causes a re-entrant angle on the growth pyramid. The upper face of the base, (111), has a slightly raised rim, formed by the six lateral faces, resembling hopper structure. Fig. 2*z* is another view of the same crystal, rotated 60° about the axis of elongation. This also shows the normal character of the faces forming the base. The growth pyramid arises within the boundary of (111) and has trigonal symmetry, with three broader, coarsely striated surfaces alternating with three narrower and smoother faces. The planest parts of the latter are the three octahedral faces, near the upper termination or 'apex', which make the smaller interfacial angle with (111). One such face is in front (fig. 5a). The crystal is terminated by a very obtuse growth pyramid, with equilateral triangular layers slightly truncated at the corners.

Fig. 5b. This crystal has a base, in which planar structure is developed, about the same height as the growth pyramid above. The latter arises abruptly within the boundaries of a nearly plane surface, which appears to be an octahedron face. However, growth sheets crop out slightly obliquely upon this surface. Moreover, the growth pyramid, which appears to have a regular hexagonal outline, actually has adjacent inter-edge angles of 55°, 60°, and 65°, with opposite pairs of angles equal. This also suggests that the upper surface of the base is not an octahedral plane, although it is a remarkably flat surface macroscopically. The growth pyramid has three steep, rough surfaces alternating with three less steep and smoother surfaces. The former, which appear to be composed of aggregates of growth layers, make unequal angles with the base, having one surface nearly normal to it and another forming a re-entrant angle. Two of the less steep surfaces are smoother, but are not equally inclined to the base. Above each of the six steep surfaces a curved region leads into an obtuse termination, which appears to be composed of forms {*hhl*} and {*hkk*}.

Fig. 5c. Beneath this crystal is an apparently normal octahedron face $(\bar{1}\bar{1}\bar{1})$. Subsequent preferential growth in the direction [111] developed an abnormal growth pyramid, from the large upper (111) face of which another small abnormal growth pyramid arose. (111) is surrounded by three nearly plane octahedral faces, at *c*. 70°, alternating with three very coarsely striated surfaces. These striations all have plane upper surfaces parallel to (111) and many elements of {111} planes at *c*. 70° to $(\bar{1}\bar{1}\bar{1})$, and some narrow striations of {100}. The coarse striations, parallel to (111), are an excellent example of planar structure, which can also be traced across the three smoother octahedron faces. On them it is indicated by a ridge bounded by three octahedral planes, or simply by an interruption of the growth layers.

Another crystal from Galapo (fig. 5d, e) has a nearly normal octahedron face on the base $(\bar{1}\bar{1}\bar{1})$, free of striations but with slight domain structure (fig. 5e). Throughout the rest of the crystal planar structure is very strongly developed (fig. 5d). Above the six steep lateral surfaces is a (111) face, on which is situated an obtuse trigonal growth pyramid with truncated corners. The lateral surfaces somewhat resemble those in fig. 5c; the three alternate surfaces making the smaller interfacial angle with (111) are relatively smooth (such as the face in the centre of fig. 5d), but the intervening surfaces are very coarsely striated, as on the left and right sides of the fig. Some of the striations do not appear to be exactly co-planar, as in the striation just below the centre of the crystal, in which the outgrowth seems to be slightly lower on the central face than on the lateral ones. This may be explained by the normal mode of growth of magnetite octahedra, the growth layers of which are equilateral triangles with their edges parallel to those of the face. The central surface in fig. 5d is approximately octahedral, and a growth layer should spread faster downwards than upwards. Conversely, layers on the lateral surfaces should spread more rapidly upwards; however, they cannot extend far due to the topography of the striated surface, but are slightly above the layer on the front face. The latter shows two other features related to the planar structure. The strong striation just below the centre, with nearly parallel sides, has not developed into a triangular layer, and the growth layers forming the striation just above the centre have proceeded from left to right, along the trace of the planar structure. This was also observed on the crystal in fig. 5c. Planar structure is strongly developed in the growth pyramid of fig. 5a and the fine detail well preserved in the re-entrant angle, which was protected by soil. Striations on the lateral faces can be traced into the re-entrant angle, where those on adjacent faces meet precisely. The striations are sharply defined ridges, bounded by (111) above and another octahedral plane below. There is no apparent offset of the ridges, as in fig. 5d, because two surfaces of like crystallographic character meet each other.

A crystal with planar structure in two orientations is shown in figs. 5f–h. In the top view a small, steep growth pyramid is situated on a shallow 'plinth' on a (110) face (fig. 5f). The latter is bounded on the left by an octahedron face (pale-grey triangle) and on the right by an irregular surface (very dark grey) with traces of layers parallel to an octahedron face. The growth pyramid is terminated by (110) and two octahedron faces (one parallel to the pale-grey face) and bounded by four steep surfaces, which have elements parallel to octahedral planes. Coplanar ridges on the four octahedron faces normal to (110) are parallel to it, but no other

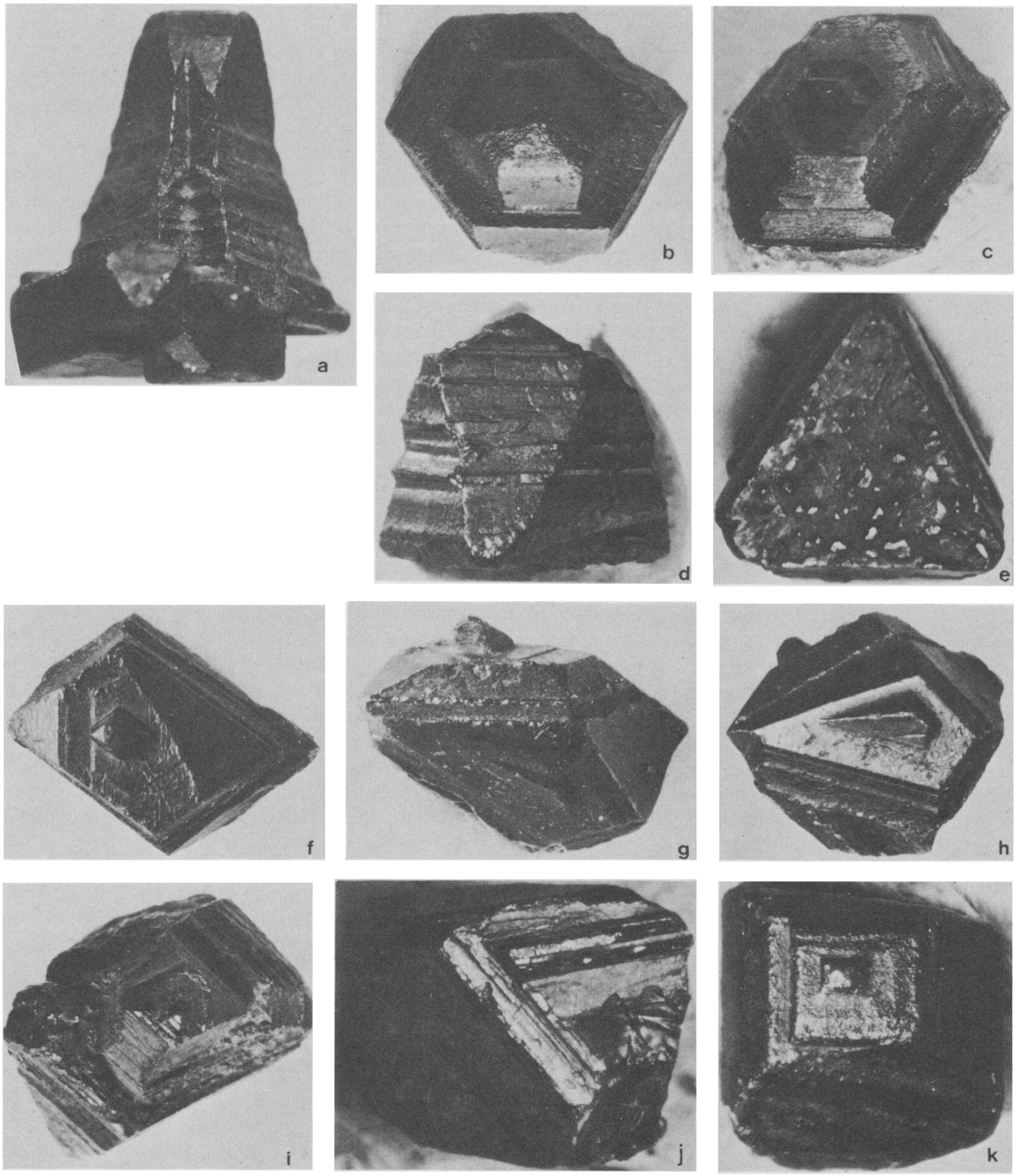

FIG. 5. Stratiform magnetite crystals, Galapo, Tanzania. b, i, ×4; f, h, ×5; g, ×6; c, d, e, ×7; a, k, ×9; j, ×11.

rhombic dodecahedron faces are present on the crystal. In the front view of the crystal (fig. 5g) the triangular octahedron face is again on the left, the steep growth pyramid projects above the *(110)* face, below which pronounced planar structure is visible. Beneath the lower ridge is a surface with a shallow growth pyramid, based on a planar structure, which is viewed normally in fig. 5h. This surface, which will be designated 'A', is the only one of its kind present on the crystal. The interfacial angles between A and three adjacent octahedron faces suggest it belongs to the form {12.9.2}. Since the surface A is somewhat uneven it is reasonable to consider approximations to this symbol, such as {641}, {651}, and {861}, the last of which has been recorded as rare or doubtful. It is conceivable that the plane is irrational.

The crystal in fig. 5i superficially resembles that in fig. 5f, having well-developed planar structure and a growth pyramid 5 mm high, which appears to have diad symmetry. However, the slightly weathered terminal surface, which is parallel to the planar structure and lies in zone with the octahedron faces to the left and right of it, makes angles of *c.* 27° and *c.* 42° with them. The planar structure is thus approximately parallel to a face of {551} or {661}, the first of which has been recorded as rare or doubtful. This plane is not repeated elsewhere on the crystal and may or may not be rational. Hopper or solution structures are present on the growth terraces.

The crystal in fig. 5j resembles an octahedron, and has planar structure in two orientations. The two sets of lamellae meet, but do not intersect, on the right- and left-hand faces at angles of *c.* 55° and *c.* 40° respectively, therefore the surfaces cannot all be octahedral. The right-hand, lower front, and left-hand faces belong to {111}, but the upper 'face', to which one set of lamellae is parallel, does not. This is an irregular sloping surface, composed of stepped growth sheets, which often occur on these crystals.

The major part of the crystal in fig. 5k is a nearly normal octahedron, which has developed planar structure in one orientation, somewhat inclined to a cube plane. The weathered surface makes goniometry impracticable.

A crystal from Gumba, Rusinga Island (fig. 6a), is the only abnormal crystal of magnetite, among the large number studied from seven carbonatite localities, that appeared to show partially the repetition of faces required by the symmetry. Planar structure was not visible, but other crystals from Gumba exhibited it, as well as abnormal growth pyramids typical of magnetite from Galapo. The crystal in fig. 6a resembles the morphology of zircon. The interfacial angles between opposite pairs of terminal faces are 91° and 93° (compared with $(101)_{\wedge}(\bar{1}01) = 84°$ in zircon and $(111)_{\wedge}(\bar{1}\bar{1}1) = 109°$ in magnetite). No unambiguous faces are present on the crystal, from which the symbol of this 'form' can be determined. It could be part of an octahedron distorted in a fairly symmetrical manner. Other crystals from Gumba have growth sheets with irregular edges and plane, strongly reflecting octahedral surfaces. Each successive layer has spread less far than the one beneath, forming an irregular sloping surface. Fairly regular growth of this kind, with very thin layers, may account for the morphology of the crystal in fig. 6a. This came from a soil sample, and growth features have been obliterated.

The crystal in fig. 6b is a good example of the 'castle, moat, and rampart' structure. Formally it is a steep growth pyramid, surrounded by a depressed area, beyond which the surface rises steeply, and falls away again still further from the growth centre. A similar structure is also visible in fig. 5i and appears to be present in the crystal in fig. 5a. Evidence has been sought to decide whether these are growth or solution structures. The deepest part of the moat is a strongly reflecting plane, parallel to the growth layers, and is so smooth that it appears more likely to have been produced by growth than by etching, although the latter has not been ruled out.

A single crystal of martite is exposed on the sawn carbonatite surface in fig. 6c. Very thin parallel bands of martite are separated by other minerals. This almost certainly represents differential dissolution along a parallel set of growth horizons with subsequent infilling, rather than dendritic growth, which would have a different morphology. (The saw marks, which are virtually invisible in the martite, are at *c.* 35° to its linear structure, and do not account for it.) On an adjacent uncut surface of the rock the same crystal shows very pronounced growth striations. Planar structure and steep growth pyramids have also been observed on crystals from Qagssiarssuk. Stewart (1970) noted the 'stepped' faces of the magnetite crystals and that 'In section these grains prove to be highly corroded, and many are dendritic skeletons'.

Many crystals of magnetite from Kinyamungu, Rangwa, have well-developed planar structure and abnormal growth pyramids. This crystal (fig. 6d), which was released from its matrix with hydrochloric acid, has extensive planar structure in one orientation, parallel to an octahedron face, extending over its entire width. The thin plates that project are bounded by octahedral planes above, below, and on their outer edges. The false impression of planar cavities is due to the shadows below projecting growth sheets.

Fig. 6e and f gives two views of a crystal from

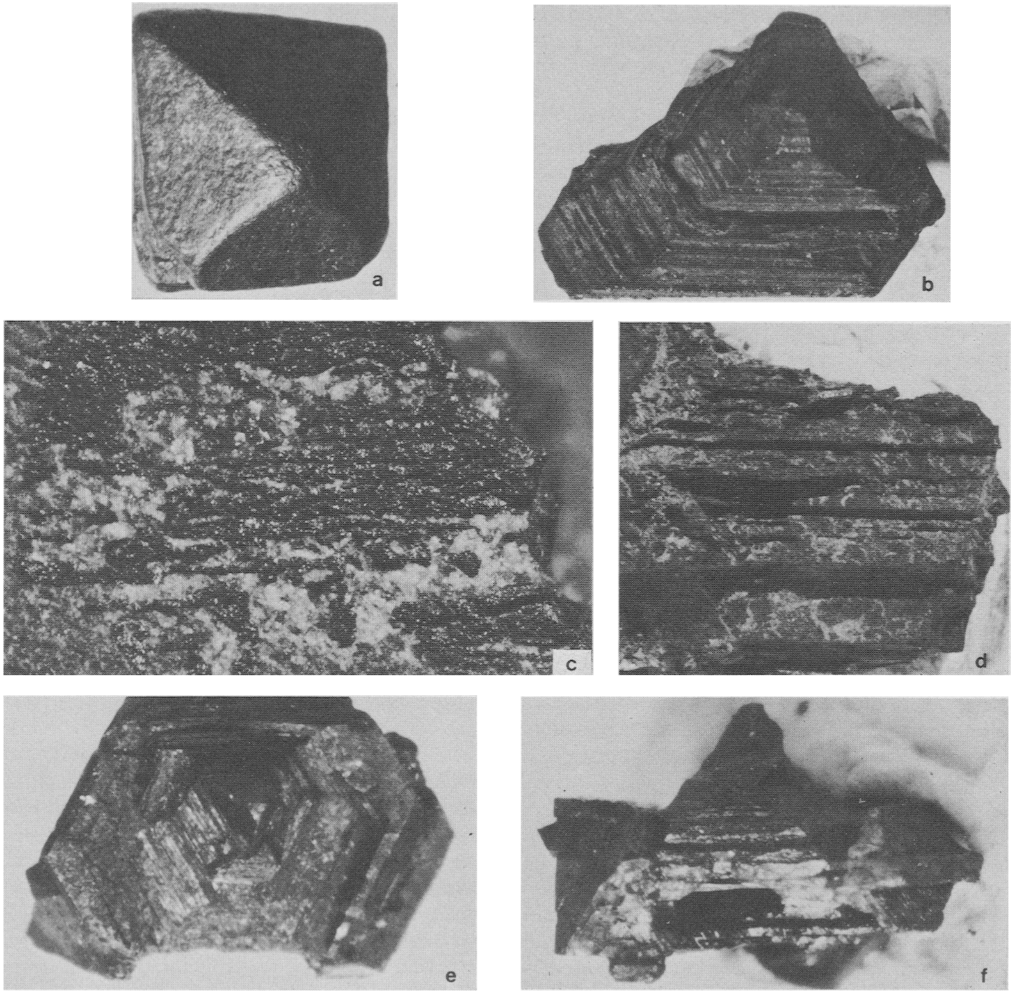

FIG. 6. Stratiform magnetite crystals. a: Gumba, Rusinga Island, Kenya, ×4. b: Galapo, Tanzania, ×4. c: Qagssiarssuk, Greenland (magnetite converted to martite), ×18. d: Kinyamungu, Rangwa, Kenya, ×6. e, f: Galapo, Tanzania, two views of the same crystal, ×22.

Galapo, along a triad axis and normal to it respectively. The crystal has a broad base parallel to (111) and a steep growth pyramid arising within its borders. It is one of the best examples of the 'castle, moat, and rampart' structure. This crystal was liberated from the carbonatite with hydrochloric acid and suffered etching, the extent of which is uncertain. The moat may have been formed simply by solution of layers from the sides of the growth pyramid, or conversely by enclosure, due to formation of the rampart by hopper growth, or by a combination of these processes. The well-developed planar structure has almost certainly been made more conspicuous by the etching. Above the cavity (fig. 6f) a thick resistant layer extends across most of the crystal, projecting on the right. Below the planar cavity is another resistant layer parallel to (111). The pointed projection on the left is a partially enclosed octahedron of magnetite in random orientation.

On stratiform crystals of magnetite from carbonatites at the localities mentioned above it has been noted that:

Planar structure occurs in as many as four orientations in one crystal.

When planar structures of different orientations meet they never intersect.

Crystals that are geometrically almost normal octahedra may, rarely, exhibit planar structure, without developing any abnormal growth pyramid.

Twinning was not observed in any of the magnetite studied.

Apparently normal octahedra may occur in close association with stratiform crystals.

Stratiform crystals sometimes partially enclose small octahedra of magnetite.

Some crystals of magnetite from Nordmark, Sweden, and Traversella, Italy, develop steep growth pyramids on all octahedron faces, formed by an oscillatory combination of {111} and {110}. These crystals differ in many respects from the abnormal magnetite described here, particularly in the simple rational indices of the planes and in the formation of growth pyramids in all crystallographically equivalent orientations.[1]

Etching of magnetite. Some crystals have been etched naturally, in the volcanic environment, and others may have been affected in the soil. Crystals have also suffered artificial etching by hydrochloric acid during liberation from their carbonatite matrix (fig. 6e, f).

Stratigraphic etching of cleaved or broken crystals can reveal the trace of growth horizons, due to differential rates of etching along adjacent planes, which have slight variations of chemical or physical properties (Patel and Tolansky, 1957). When etching is extensive, solvents may gain access to the interior of crystals, which happened to some normal octahedra of magnetite in HCl. The interior could be seen through superficial cavities, and the alternation of more and less soluble growth horizons parallel to octahedron faces caused narrow, parallel-sided cavities to be formed between thin remnant laminae of magnetite.

A crystal from Gumba strikingly illustrated zonal variations of properties. It had been fractured recently, and the matching surfaces were slightly etched, revealing incipient stratigraphic etching parallel to the crystal edges, and hence presumably to the growth horizons. However, the appearance was enhanced in incident light, because the fracture had slight undulations coincident with the stratigraphic etch pattern, causing variations in the intensity of reflected light. In this crystal there were clearly some physical differences along successive growth horizons, which affected both the etching and the mechanics of fracturing.

Artificial etching of a stratiform crystal from Galapo produced very wide planar cavities in one orientation (fig. 6f). Naturally etched linear cavities almost the width of the crystal occur in martite in matrix (fig. 6c); these are probably planar in three dimensions. Etching could produce the moat and rampart structure found in some crystals, by differential solution of growth layers parallel to the sides of the steep growth pyramids, if growth took place on them. In fig. 6f there definitely appears to have been some solution of lateral growth layers beneath the crystal, invisible in the figure, but it has not necessarily occurred above the base, where planar structure is well developed. The evidence for the mechanism of formation of all the moat and rampart structures, whether by growth or etching, is still ambiguous. Hopper type growth seems to have occurred on the crystals in figs. 5a and 2q.

Mode of growth of the stratiform crystals. It is difficult to reconcile the manner in which some of these crystals *appear* to have grown with current ideas on crystal growth, so emphasis has been placed on recording observations. Now the evidence will be assessed for the mode of growth of the stratiform crystals, without seeking the cause, which will be considered later. The discussion will be limited, initially, to crystals having a growth pyramid in one orientation. One of the most striking characteristics is the morphological 'polarity' of the crystals, which is very apparent in figs. 5a–d and 6f; they appear to have grown from the 'base' upwards. The initial growth of some crystals (e.g. fig. 5a) seems to have been normal. In this example there is an appreciable development of octahedral faces before the abnormal growth begins. In other crystals the extent of normal growth is very slight; the crystal in fig. 5d shows no sign of it, except on the 'base' (fig. 5e), which must be quite thin. It seems virtually certain that all crystals had an initial phase of normal growth, however slight, otherwise the abnormal growth might be expected to take place in at least two opposite directions, thus destroying the typical polarity. No such crystal has yet been observed. Planar structure appears to have been initiated more or less rapidly after nucleation, and dominated the subsequent growth of the crystals, which never reverted to normal growth. The planar growth and dissolution structures both provide evidence that growth pyramids were formed by the superimposition of sets of parallel growth sheets,

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[1] The authors are grateful to Mr. P. G. Embrey for drawing their attention to three specimens in the mineral collection of the British Museum (Natural History) that have well-developed tapering, stepped, growth pyramids: Uraninite, Uluguru Mts., Tanganyika; bröggerite, Råde, Norway; and microlite, Rutherford No. 2 mine, Virginia. It is difficult to decide whether individual specimens are examples of the type of abnormal morphology described above unless sufficient criteria are fulfilled. It is probably present in the specimen of uraninite, which has three well-developed plane cube faces and a large stepped growth pyramid, the layers of which are inclined at large angles to all the cube planes.

which had slight differences in their physical or chemical properties, or both. Since the properties of individual growth sheets appear to be so homogeneous, with regard to both growth and etching, it is probable that they extended the whole width of the crystal, and their rapid succession caused the growth pyramid to increase in height, with no increase in width, or very little.

Planar structure may develop in two or more orientations, which are almost invariably non-equivalent crystallographically. When this occurs, the later growth in each orientation appears to proceed in the manner described for crystals having planar structure in a single orientation.

The symmetry of growth pyramids corresponds to that of the surface on which they have grown; it is therefore governed by the crystal lattice and not by the external environment.

The origin of the abnormal growth features. The following discussion is largely speculative, but may suggest a direction for future research. Two features of the growth pyramids give some indication of the kind of property that may be responsible for their development: The planar structure and the typical lack of repetition of this structure on crystallographically equivalent planes.

One relevant property of crystals that is not rigorously controlled by symmetry is the orientation of dislocations. A large dislocation, or group of dislocations, approximately normal to an octahedron face might initiate the kind of growth that is so characteristic of these crystals. The physico-chemical conditions in the volcanic environment could fluctuate markedly, causing surges of growth of slightly different character, forming the planar structure and abnormal growth pyramids. The growth pyramid on a large (110) surface (fig. 5f), on a crystal that has no other rhombic dodecahedral faces, could be due to dislocations approximately normal to (110). Since dislocations can exist in a number of directions unrelated by symmetry, it is possible that they account for the occurrence of planar structure in several non-equivalent orientations.

In conclusion, it may be noted that the stratiform crystals of magnetite described above were found in volcanic carbonatites, but do not occur in all such rocks. Normal octahedra are often associated with the stratiform crystals. It seems probable that their abnormal mode of growth is due to some aspect of their very unusual physical and chemical environment. Since euhedral crystals of apatite and biotite, as well as small normal octahedra of magnetite, occur as inclusions in the abnormal crystals of magnetite, the latter may have grown rapidly at a late stage of crystallization.

Concluding remarks

Seven occurrences of abnormal magnetite crystals have so far been discovered in association with volcanic or high-level subvolcanic carbonatites, and it is probable that further occurrences will be found. It is desirable that they should also be sought in more deep-seated carbonatites, as well as other rocks. It is known that very similar crystals occur in the mineralized alkaline granites of the Jos Plateau of Northern Nigeria and of Niger (J. A. Bain, private communication). He reports that these crystals are quite common in some of the tin-bearing alluvials, and can also be extracted from the weathered mantle overlying the granites. Their distinctive morphology distinguishes them from various other spinels (Al, Cr, or Zn-rich) that may accompany them, as the latter are invariably octahedra with plane faces.

The mechanism and conditions of growth need more study. As yet evidence of conditions of growth of the crystals is very scanty, as most specimens have been derived from tuffs (Galapo) or transported blocks (Rusinga). It is tentatively suggested that the abnormal magnetite crystals grew rather rapidly in the carbonatite magma, crystallizing after biotite and apatite, at relatively low temperatures (perhaps much less than 500 °C) and pressures. The discovery of such distinctive crystals of magnetite elsewhere may indicate the presence of carbonatites in new areas, of volcanic phases of carbonatite activity not previously known, or the existence of other unusual rock types.

The magnetite specimens described and figured in this paper are now preserved in the Mineral Department, British Museum (Natural History), and additional material is housed in the Geological Museum, Institute of Geological Sciences, London, S.W.7.

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Notes added in proof:

p. 464: Kavirondo has recently been renamed Nyanza.

p. 473, Etching of magnetite: Extensive natural stratigraphic etching of analcime has been recorded by A. F. Seager (*Mineral. Mag.* 1978, **42**, 245-9).