ANOMALOUSLY ELONGATED RUTILE IN ECLOGITE-FACIES PYROXENE AND GARNET*

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Garnet and pyroxene from some kimberlite eclogites and from eclogites and anorthosites of the Bergen Arcs contain highly birefringent acicular inclusions with inclined extinction. Microprobe and X-ray studies have identified the inclusions as rutile, elongated in an unidentified anomalous direction. The anomalous habit is inferred to reflect exsolution during cooling at high pressures.

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Petrographic descriptions of eclogites from kimberlite pipes contain several references to unidentified acicular inclusions of a high-birefringence phase within the garnet. Williams (1932, specimen 501, plates 82 and 83) described an eclogite from the Dodoma mine, Tanzania, showing complex mutual exsolution textures between garnet and clinopyroxene. The garnet contains 'numerous fine needles as inclusions arranged in certain directions and crossing each other at definite angles; these give oblique extinction and bright polarization, and may be acicular amphibole or pyroxene, or conceivably kyanite'. O'Hara & Yoder (1967, p. 80) noted similar inclusions in the garnet of another Dodoma eclogite, and concluded 'These may have been produced by exsolution and may be rutile, but if so the needles are elongated parallel to some axis other than (001)'. The pyroxene of this rock contains small inclusions of rutile with straight extinction. The unidentified needles were also described by Williams (1932, plate 89) in the garnet of an eclogite from Roberts-Victor mine, and by Nixon et al. (1963, p. 1101) from eclogite garnets in Basutoland kimberlites.

The purpose of this note is to identify the acicular phase, report further occurrences, and suggest the possible significance of such inclusions.

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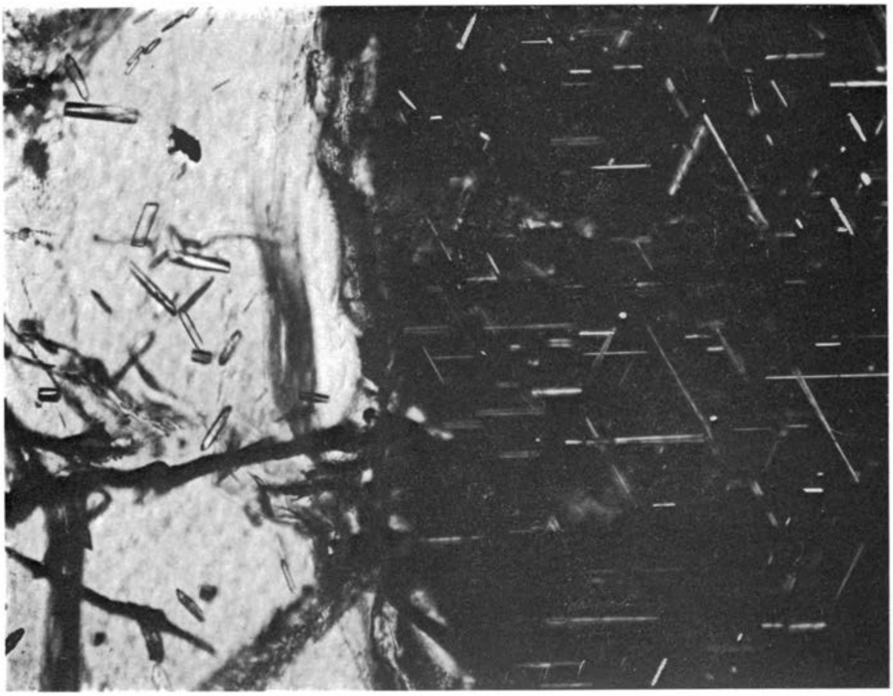

Fig. 1. Eclogite KA64–5, Bultfontein Mine. Crossed nicols. Garnet (left) shows acicular rutile inclusions; the horizontal set would be in extinction if needles were elongated parallel to X as in normal rutile. Larger anomalous rutile prisms are present in clinopyroxene (right). Width of photo equals 1 mm.

Identification

Acicular inclusions similar to those described above are abundant in both garnet and pyroxene of an eclogite nodule (KA64–5) from the Bultfontein pipe, South Africa (Fig. 1). The rock is petrographically very similar to Williams's (1932) specimen 501, and the features shown in his plates 82 and 83 are duplicated in this rock. The eclogite is a very fresh coarse-grained equigranular mosaic having roughly equal portions of dark green clinopyroxene and wine-red garnet. Microprobe analyses of these phases are given in Table 1; they are very similar to the analyses of pyroxene and garnet from Dodoma (O'Hara & Yoder 1967). Local amoeboid patches and elongate rods of garnet in clinopyroxene suggest an exsolution relationship. Large (to 1 mm) droplike interstitial grains of rutile occur rarely. Both garnet and clinopyroxene contain abundant acicular to prismatic inclusions of a yellow, highly birefringent mineral having high relief and inclined extinction. The inclusions are tiny and well-oriented in three sets within garnet grains; they are larger, more prismatic, less well-oriented and less abundant in the pyroxene (Fig. 1). None of the inclusions appear to be twinned. The

Table 1. Analyses of pyroxenes and garnets containing anomalously elongated rutile.

	37039		KA64–5		69–113A		69–119A		69–108	
	CPX	GNT	CPX	GNT	CPX	GNT	OPX	GNT	CPX	GNT
SiO_2	52.04	39.04	51.5	40.0	49.8	39.3	51.4	39.5	54.7	39.2
TiO_2	0.54	0.21	0.2	0.0	1.2	0.0	0.1	0.0	0.2	0.0
Al_2O_3	6.93	21.85	7.1	22.3	9.2	22.9	3.8	21.9	11.3	21.9
Fe_2O_3	2.59	0.13	–	–	–	–	–	–	–	–
FeO	4.10	18.42	6.3	18.6	7.2	17.6	20.6	21.5	6.0	23.8
MnO	0.09	0.47	–	0.5	–	0.6	–	0.9	–	0.7
MgO	11.65	9.04	11.8	6.8	11.1	11.3	21.8	9.6	7.9	7.7
CaO	19.49	10.63	19.8	11.5	19.3	7.3	0.3	5.3	12.9	6.1
Na_2O	2.22	0.06	2.2	–	2.2	–	–	–	6.9	–
Σ	99.67	99.93	98.9	99.7	100.0	99.0	98.0	98.7	99.9	99.4

37039 from O'Hara & Yoder 1967. All other microprobe analyses by W. L. Griffin. Cell parameters of CPX KA64–5: a_o 9.692 ± 0.006, b_o 8.856 ± 0.005, c_o 5.240 ± 0.003, ß 106.62 ± 0.002 (A. E. Edgar, pers. comm. 1967).

maximum length is about 300 microns (in the pyroxene), but there may be a great range in size within a single garnet or pyroxene grain.

The rutile needles show strong preferred orientation in three directions within the pyroxene. In addition, groups of grains with a common orientation tend to be arranged parallel to crystallographic planes (Fig. 2). Thus the first group lies in the plane (010) with the axes of elongation perpendicular to c, the second group lies in the plane (100) with the axes of elongation perpendicular to $[1\bar{1}0]$, and the third group in the plane (111) with the axes of elongation perpendicular to a (Fig. 2).

Within the garnet the needles define three sets at 60° angles to one another. All needles in one set do not extinguish together, but over a range of extinction angles from zero to 33° (very rarely up to 47°), and commonly there exist two 'subsets' which extinguish at equal angles on either side of the parallel position. Examination of thinly sliced needles with relatively low birefringence shows that the smallest extinction angle is to the X direction in each case. There is no evidence of twinning in any of the grains observed.

Microprobe scans were made over several of the inclusions in both garnet and pyroxene, though only a few (in the pyroxene) were large enough to get analyses relatively free from interference by the surrounding mineral. These analyses showed the inclusions to be at least 99.5% TiO_2, relative to a pure rutile standard. The following elements were sought but not found: Si, Al, Cr, Mg, Ca, Na, K. A trace for FeKα showed a level just above background, but may have resulted from secondary excitation in the pyroxene.

A single large inclusion was recovered intact by crushing several pyroxene grains under a high-power binocular microscope. This rod-like fragment measured approximately 200 × 40 microns and had a morphology similar

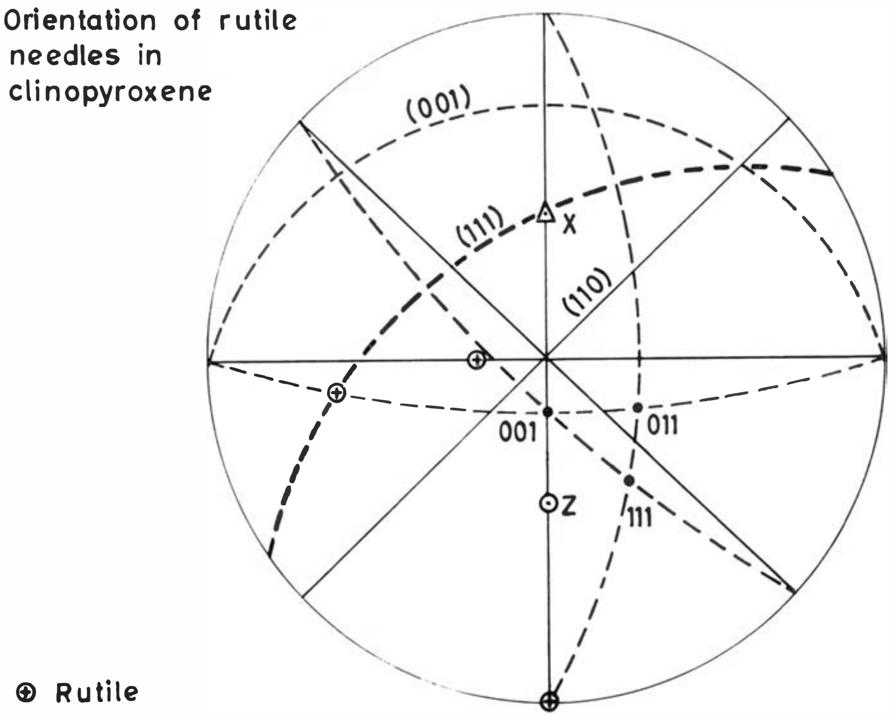

Fig. 2. Orientation of three sets of rutile needles in clinopyroxene from KA64–5. The diagram is a composite, as it was not possible to measure the orientation of all three sets in one pyroxene grain.

to the grain in Fig. 3B. Extinction paralleled the apparent prism faces in one orientation; when the rod was rotated 90° about the long axis an extinction angle of 32 ± 1° was observed. A Debye-Scherrer powder film of this fragment showed five strong lines and three weak ones, all corresponding exactly to the ASTM rutile pattern. We conclude that the inclusions in the garnet and pyroxene of KA64–5 are rutile, elongated in an anomalous direction as proposed by O'Hara & Yoder (1967). The acicular phase described by the authors mentioned above is also inferred, from the similarities of properties and occurrence, to be anomalously elongated rutile.

The morphology of some inclusions from the clinopyroxene of KA64–5 is illustrated in Fig. 3. The grain in 3D shows striations, which are parallel to the extinction direction and to one terminating face, and presumably are identical to the vertical striations commonly seen on the prism faces of rutile crystals.

Curved cracks, resembling percussion fractures, curve outwards from some of the largest rutile grains in the clinopyroxene of KA64–5 (Fig. 3A, 3B). These may be related to differences in contraction rates between host pyroxene and rutile grain during cooling, or may be related to later deformation of the eclogite nodule.

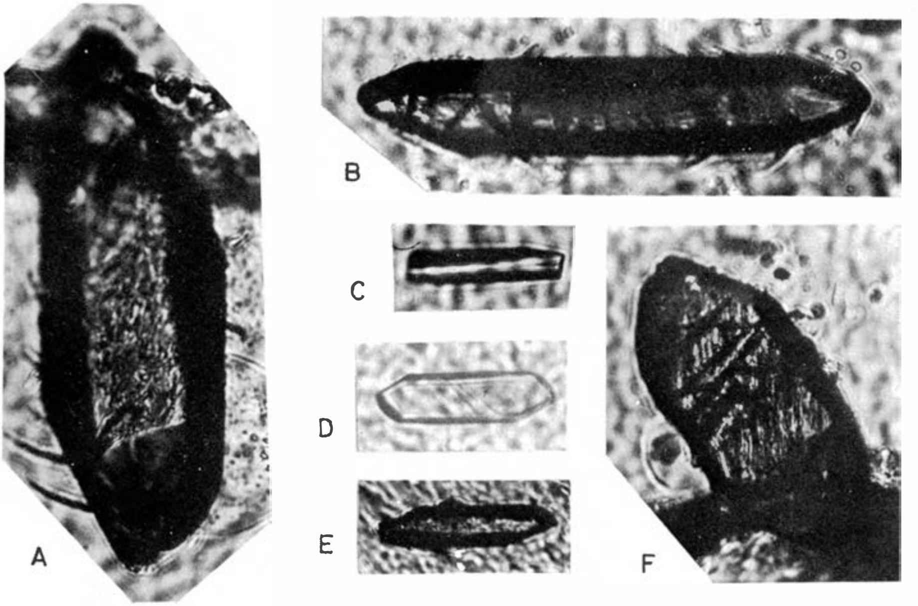

Fig. 3. Rutile grains from the clinopyroxene of KA64–5. All are to the same scale; the grain 3D is 100μ long. Striations parallel to the extinction direction are clearly shown in 3D.

The morphology of the needles in the garnet is less clear because of their smaller size. Many of the larger needles appear to resemble Fig. 3B, but many are terminated essentially by a single face which makes an angle of 20–25° to the direction of elongation. Preliminary studies of the morphology have proved unable to index most faces present. Studies by transmission electron microscopy have been initiated to determine the orientation of the rutile lattice relative to the morphology, and relative to the lattice of the host mineral.

Norwegian occurrences

During a study of pyroxene-garnet-feldspar relations in anorthositic rocks from the Bergen Arcs, Norway, numerous examples of anomalously elongated rutile have been noted. The anorthositic rocks are complexly interlayered group of anorthosites, anorthositic gabbros and pyroxenites; the widespread occurrence of thin eclogite layers suggests the entire complex has passed through eclogite facies conditions during protracted cooling and burial. The anorthosites contain lenses and pods of aluminous pyroxenes, typically jacketed by garnet granules. Brief descriptions of three typical samples are given below.

69–113A: Clinopyroxene pod in anorthosite, Skjelanger, Holsenøy. The pod consists of randomly oriented pyroxene grains up to 1 cm across. A row of rounded garnet grains about 5 mm in diameter is clustered at the border of each pod, and some send thin finger-like extensions into the pyroxene pod along the grain boundaries. Small irregular garnets also occur between clinopyroxene grains in the interior of the pod. The pyroxene is heavily pigmented with very small prismatic rutile inclusions oriented in three sets. Near the small irregular garnet grains the rods become fewer and larger. The birefringence of the pyroxene made a detailed measurement of the extinction angle impossible, but by finding rods which lie parallel to the cross hairs when the host pyroxene is in extinction, it is possible to see that at least some rutile grains do have inclined extinction.

Both the large and the small garnet grains contain elongated needles with inclined extinction, resembling those in the garnet of KA64–5 but with an even greater length/width ratio. Microprobe scans verify the identification of the inclusions in garnet as TiO_2. Small garnet euhedra also occur within strained zones in the pyroxene. These garnets contain rutile needles, but only with straight extinction.

69–119A: Mafic pod in anorthosite, Alverstraumen. The interior of the pod consists of coarse-grained (5 mm) granular orthopyroxene with anhedral interstitial scapolite, ilmenite and garnet, and some 1 mm anhedral to subhedral rutile grains which appear to have inclined extinction. The outer part of the pod is a coarse-grained mixture of orthopyroxene, clinopyroxene and garnet. The garnet, where unstrained, contains three widely-spaced sets of rutile needles with inclined extinction; they are up to 500μ long, with a length/width ratio $\approx$ 100/1. The orthopyroxene is strongly pleochroic and typically contains abundant inclusions of high relief and birefringence with inclined extinction. They are oriented in three sets at about 60° angles to one another. Some inclusions are acicular like the inclusions in garnet, but many are in the form of thin elongate blades which vary in width, curve and even bifurcate along their length (Fig. 4). These blades are yellowish in color; some show geniculate twinning, though not at the angle characteristic of rutile. Microprobe traces across them, however, show a concentration of Ti and support their identification as rutile. In most orthopyroxene grains the rutile blades are intergrown with thin plates of a brown isotropic material tentatively identified as spinel. The spinel-rutile interface commonly makes a 20–25° angle with the elongation of the rutile. Associated with these intergrowths there are thin-film patches of a low-birefringence material. The clinopyroxene is heavily clouded with small rods and granules of both a birefringent yellow phase and an isotropic brown phase. In some zones these coalesce into larger red-brown translucent to opaque plates and lesser numbers of randomly oriented rutile rods with oblique extinction. The intergrowths of the two exsolved phases resemble those in the orthopyroxene, and the opaque plates may be oxidized spinel.

69–108: Eclogite, Landsvik, Holsenøy. The eclogite occurs as conformable

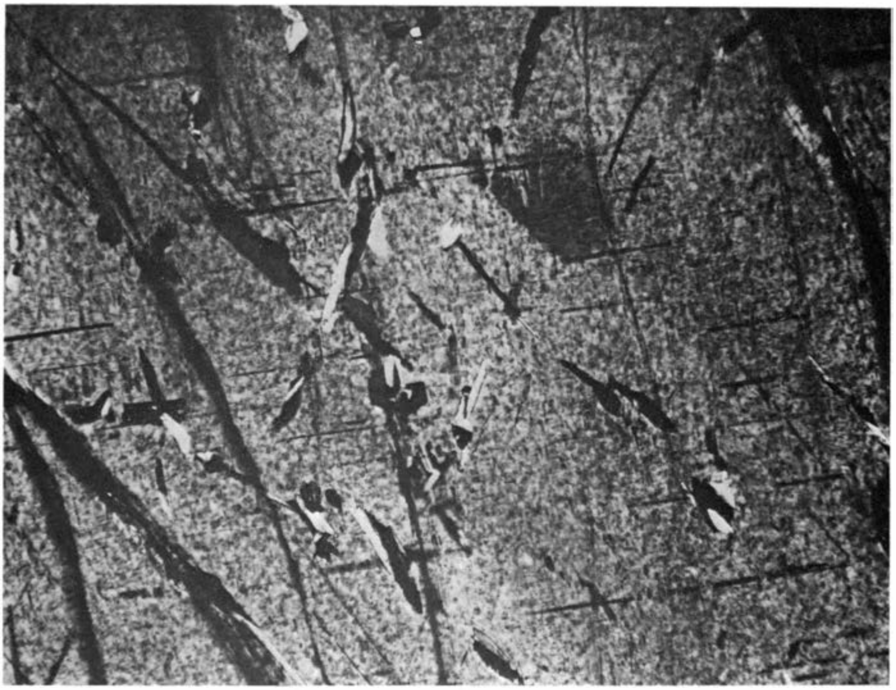

Fig. 4. Orthopyroxene from 69–119A, Bergen. Nicols partially crossed. Orthopyroxene contains exsolved needles and blades of anomalous rutile (light color) and exsolved blades and plates of brown spinel (dark color). Width of photo equals 1 mm.

bands within a coarse opx-cpx-garnet-plag 'gabbro'. It has a gneissic texture, with large rounded garnet grains set in a foliated mass of clinopyroxene (now largely converted to hornblende-diopside-plagioclase symplectite), rutile and quartz. The large rutile grains have straight extinction. The garnets contain three sets of acicular rutile needles (verified by probe scans) with inclined extinction but the inclusions are considerably less abundant than in KA64–5. Where the garnets are slightly strained the rutile needles are absent.

The garnet peridotite body at Lien in Almklovdalen contains layers of eclogite which have gradational contacts with the surrounding peridotite (R. K. O'Nions, pers. comm.). The garnet of both rocks contains stubby to needle-like prisms of rutile with inclined extinction. Long leaf-like blades of a low-birefringence mineral are associated with the rutile inclusions; this phase has not been identified. Both types of inclusions are far more abundant in the eclogite garnets. A sample of this eclogite was heated at 900 °C and at 1 atm for eight days, with no visible effect on the inclusions.

Finally, B. A. Sturt (pers. comm.) has identified rutile needles with inclined extinction, and rutile grains showing only the pyramid faces, in quartz which was subjected to high stress from thermal expansion during incorporation into a peridotitic magma on Sørøy, North Norway.

Discussion

Brief references to anomalously elongated rutile can be found in some mineralogical text books. Mügge (1903), discussing parallel growth of rutile on hematite, describes and pictures rutile elongate in the [$\bar{1}$01] direction. Rutile needles are common in the garnets of other Norwegian eclogites, but we have observed none with inclined extinction.

The various modes of occurrence of anomalously elongated rutile in or on host minerals as diverse as hematite, quartz, garnet, clinopyroxene and orthopyroxene indicates that this type of elongation is fairly readily adopted by the rutile structure and our studies suggest that development of the anomalous elongation is somehow favored by certain environmental conditions.

The eclogite nodules in kimberlites are generally agreed to have a high-pressure, high-temperature origin. The high Al_2O_3 contents of the pyroxenes from Bergen suggest a high-P origin also.

Corona structures around olivine in the Bergen anorthosites imply initial crystallization at $P < 9$ kb, followed by burial and cooling to eclogite-facies conditions. The garnet-pyroxene relations in these rocks are thus believed to result from exsolution and reaction with plagioclase at high-P, high-T conditions. The pyroxenes of samples 69–113A and 69–119A have high Ts/Jd ratios and have probably equilibrated at higher T than the eclogite sample 69–108. It is notable that no rutile needles were found in the garnets in the anorthosites of Sognefjord (Griffin 1971); these rocks appear, from studies of the coronas, to have had a geologic history similar to those in Bergen, but involving lower pressures of formation.

We suggest that the anomalous elongation of rutile in the Bergen rocks and in the kimberlite nodules reflects exsolution processes operating at high temperatures and pressures; we further suggest the pressure factor is the more important. O'Hara & Yoder (1967) observed that the rutile inclusions in the Dodoma eclogite minerals disappeared in runs at 30 kb. This is consistent with a high-P exsolution origin, though we do not wish to imply 30-kb pressures for the Bergen rocks.

Moore (1968) has described rutile needles, with straight extinction, exsolved from orthopyroxene in the Gosse Pile ultramafic intrusion, Australia. He suggested that the exsolution took place at high pressures, following high-T incorporation of Ti into the pyroxene structure. However, the initial coexistence of olivine and plagioclase in these rocks limits the depth of emplacement to < 9 kb (Green & Hibberson 1970). The development at Gosse Pile of pyroxene-spinel coronas around olivine, but without the further development of garnet coronas, implies that cooling of the rocks took place with no further increase, or perhaps a decrease, of pressure (cf. Griffin 1971). The Gosse Pile complex probably, then, had a lower-P cooling history than the Sognefjord anorthosites (Griffin 1971) and was thus never at P equivalent to that reached by the Bergen rocks. We suggest therefore that the 'normal' rutile observed by Moore resulted from exsolution at high T, but at lower P than the anomalously elongated rutile reported here.

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