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# The divided structure of crystals I. Lineage and sectoral structure in pyrite and beryl

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## Abstract

Crystals of pyrite and beryl have been found to be divided into units, perpendicularly oriented to the real faces of the crystals and herein termed lineages. As a consequence of this division and orientation, a crystal is made up of pyramids subtending its faces, each pyramid being divided in its turn into lineages parallel to one another.

In sedimentary pyrite crystals, the lineages can be seen with the naked eye after etching, whereas in beryl crystals they can be deduced as collections from the sectoral structure appearing in thin or polished sections.

## Introduction

Physicists and metallurgists, more or less independently of mineralogists, have theorized on the deviations of real crystal structures from the ideal concepts thereof. At the level between the dimension of the lattice constants and the dimension of the crystalline polyhedron, variations from ideal crystal structures have been called dislocations. These divide the structure into blocks of different form and dimensions. The literature in this field is now extensive, but application of current theories to the kind of crystals of most interest to mineralogists and geologists is still obscure.

On the other hand mineralogists have established the presence in crystals of pyramids whose bases are the crystal's real faces and whose apices coincide at the crystal's center. Becke (1894) noted that crystalline polyhedra consist of growth pyramids for each of their faces, which are physically different from one another. The corresponding mineral structure is called sectoral (Lemmlein, 1948; Grigor'ev, 1965, p. 47) or polygonal (Sahama, 1966).

Minerals for which polygonal structures have been often cited include pyrite, halite, quartz, corundum, calcite, gypsum, apatite, andalusite, staurolite, the garnets, vesuvianite, tourmaline, beryl, pyroxene, amphiboles. If we add the crystals in which the presence of the same polygonal structure determines known optical anomalies, the list includes many of the natural minerals. In artificial crystals, these structures are still more frequent (see Gaudefroy, 1919; Buckley, 1951, p. 415). According to accepted theory, the causes of polygonal structures are to be found in the differences in chemical composition of the material which makes up each pyramid. In turn, the different chemical compositions could be due either to selective adsorption during crystal growth (Grigor'ev, 1965, pp. 47–48), to isomorphic and anisomorphic substitutions, or to unmixing (Lemmlein, 1948).

The present article aims to show that the pyrite and beryl crystals are governed by lineage structure. This structure is correlated with polygonal structure which appears in thin and polished section of minerals.

## Previous work

Departures of crystals from ideally regular long-range order have been interpreted according to the following models: (1) the Laue-Darwin model, (2) the Smekal model, (3) the Zwicky model, and (4) the Buerger model. The first three models of divided structure were criticized by Buerger (1932, 1934a, 1934b) and are largely presented by Petreus (1976, p. 53).

According to the lineage model of Buerger, crystals are internally partitioned by discontinuities in such a way that the entire structure is continuous but branched. In his model (Buerger, 1932, p. 177), "subunits are not separate blocks or grains, but are continuous with each other by way of the parent crystal

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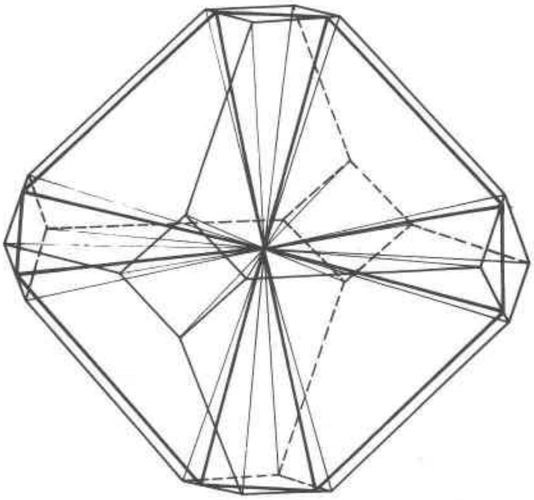

Fig. 1. The growth pyramids of a pyrite crystal {111} {100} (thin lines). Thick lines represent the tracing of the section parallel to (100) near the growth center.

nucleus, forming a rudely spherical–symmetrical tree-like structure. The term *lineages* is introduced to cover such crystal subdivisions," and (Buerger, 1934a, pp. 206–207), "A radial "block," followed back in the direction of the original nucleus, usually departs less and less from parallelism with its neighboring "blocks" and finally, under appropriate circumstances, "blocks" may be seen to join neighboring "blocks" to become continuous cleavage surfaces toward the center."

Because of the linear and continuous character of the blocks in the structure, Buerger's model represents a fundamental advance over preceding ones. It has been adopted without criticism by modern textbooks and manuals. However, until now, the geometrical forms of the lineages as well as the model according to which they are distributed in three dimensions in the crystal have remained unresolved. The present study suggests that a different model of lineages governs the structure at least of some crystals.

## Present model of the divided structure of crystals

We have tried to verify in natural crystals the lineage model of Buerger. Our results show that the structure of crystals is indeed divided, but that the blocks of which it is composed exhibit surprisingly regular distribution. The model of the divided structure resulting thus consists of the following:

A crystalline polyhedron is constituted of pyramids whose bases are the crystal's real faces. At the microscopic and mesoscopic levels, the crystalline structure is divided into units, which are aligned normal to the crystal faces. For these units we adopt the term "lineage" proposed by Buerger (1932)[1]. The symmetry of the face which makes up the base of the pyramid is the symmetry of the lineages which form the pyramid. In other words, the pyramids of the simple crystallographic form—and hence their lineages—will be identical. The pyramids of a combination of forms—and, therefore, of its lineages—will be different in each simple form.

For example, as the present study will show, a pyrite crystal with forms {111} and {100} is made up of 14 pyramids whose apices coincide with the growth

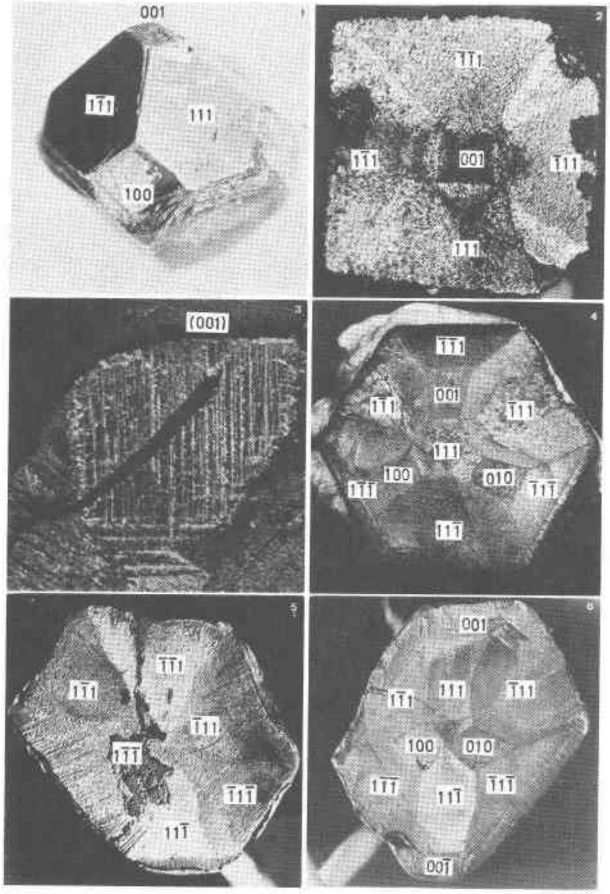

Fig. 2. 1: Sedimentary pyrite crystal used in the present study, 4×; 2: polygonal pattern resulting from electrolytic etching of a section parallel to (001), 8.4×; 3: parallel lineages displaying perpendicularity to real cube face, 32×; 4: The polygonal structure resulting from the electrolytic etching of a surface, cut parallel to (111) at half the distance between the center and (111), 6.5×; 5: The dividing structure resulting from the electrolytic etching of a surface cut parallel to (111) and containing the growth center of the crystal, 6×; 6: Polygonal pattern resulting from electrolytic etching of a section parallel to (110) cut near the growth center of a crystal {111} {100}, 6.5×.

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[1] The form and the orientation in structure of the lineages in the present model is, of course, different from Buerger's model.

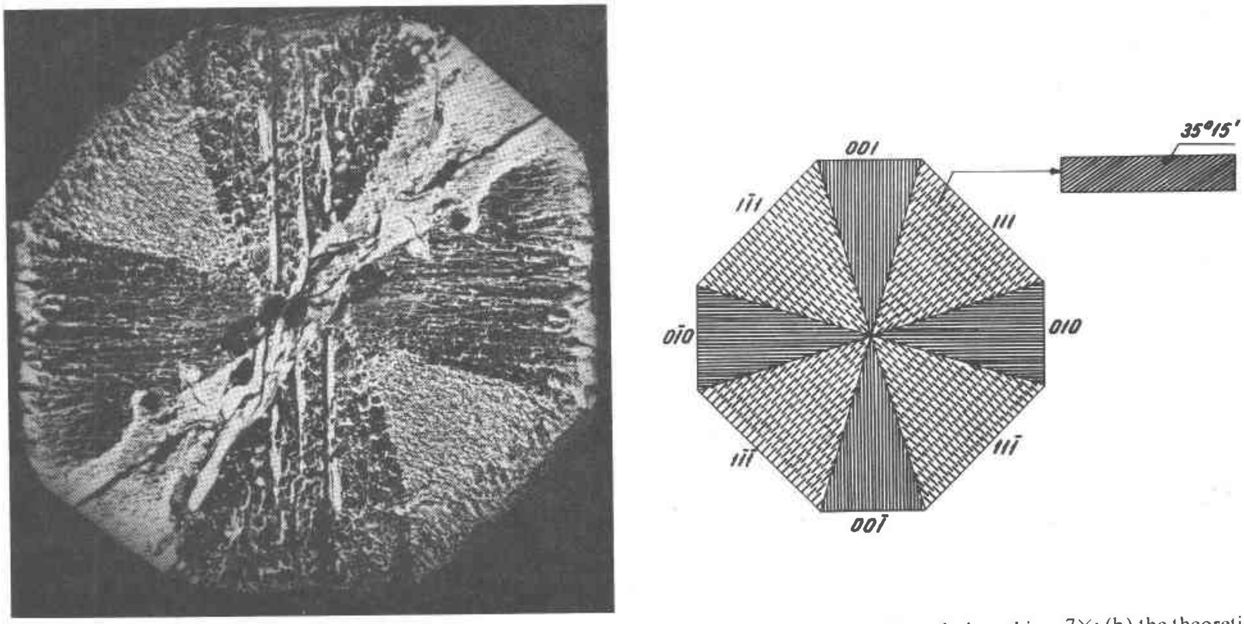

Fig. 3. The divided structure in a section parallel to (100): (a) the image resulting from the electrolytic etching, 7×; (b) the theoretical image.

center of the crystal (Fig. 1). The pyramids on {111} are made up of lineages parallel to each other and perpendicular to the faces corresponding to the pyramids' bases. There is along these lineages a 3-fold axis of symmetry. The {100} pyramids are formed of identical lineages perpendicular to the cube faces; along these lineages there is a 2-fold axis of symmetry.

## Method and apparatus

For purposes of demonstration two very different substances were used—crystals of sedimentary pyrite and of beryl. The crystals of pyrite (Photo 1 in Fig. 2), which have the {111} {100} combination, originated in a saliferous formation of the Romanian Carpathian foredeep. We collected these samples from a sequence of salty clays of Aquitanian age, showing no trace of hydrothermal or metamorphic activity.

For beryl we used the excellent polygonal structure presented in plate IId of Sahama's work, "Polygonal growth of beryl" (1966); its lineages, though invisible to the naked eye, should be detectable as collections which determine a polygonal structure in sections viewed under microscope.

The pyrite crystals were cut parallel to (100), (111), and (110), both through the crystal center and at various distances from the crystal center. The resulting fragment was wrapped with a conducting wire and embedded in plastic, except for the cut surface. This surface was ground with fine carborundum and the fragment was subsequently introduced as a cathode in an electrolytic bath; HCl concentrations of 0.5 percent, 5 percent, and 25 percent were used as electrolyte. The electrolytic etching of the exposed surfaces exhibited characteristic polygonal structures. Details concerning the method and the apparatus can be found in Petreus (1972).

## Results

*Sedimentary pyrite*

If one cuts the crystal along suitable chosen planes and etches the resulting surface electrolytically, structures composed of polygons appear, corresponding to the pyramids intersected by the section. These polygons, called "sectors", are indicated by using the indices of the real face that constitutes the pyramid's base. For this purpose we follow Lemmlein (1948, p. 6) in placing the indices in angular brackets, ⟨*hkl*⟩.

(a) *The crystal sectioned parallel to (100) near the growth center.* Figure 1 shows the three-dimensional image of the crystal as well as the section tracing. The heavy line represents the polygonal structure expected to appear after the electrolytic etching. Figure 3a shows the results from the electrolytic etching of the surface parallel to (100)[2]. The polygonal structure consists of the following sectors: ⟨001⟩, ⟨111⟩, ⟨010⟩, ⟨11$\bar{1}$⟩, ⟨00$\bar{1}$⟩, ⟨1$\bar{1}\bar{1}$⟩, ⟨0$\bar{1}$0⟩, and ⟨1$\bar{1}$1⟩. It very closely approaches the theoretical image presented in Figure 3b.

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[2] During the experiment, the crystal broke into two pieces, one of which was lost. The picture shows two images of the half preserved, one image rotated 180°, joined to the other along the line of division and then photographed together again.

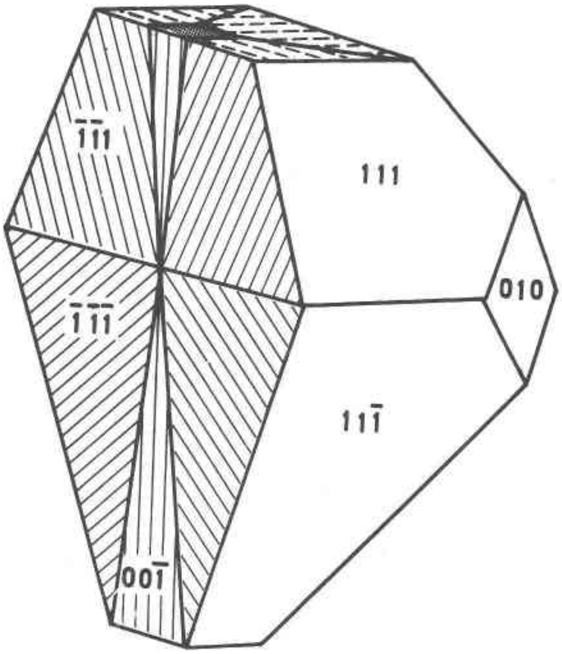

Fig. 4. The divided structure of a section parallel to $(1\bar{1}0)$ containing the center of a crystal {111} {100} and of a section parallel to (001), at half the distance between the center and (001).

In the cube sectors, lineage collections are visible, parallel to each other and perpendicular to faces (001), (010), $(00\bar{1})$, and $(0\bar{1}0)$, respectively. This image was expected, since the section surface was parallel to the lineages of the sectioned cube pyramid.

The octahedral sectors ⟨111⟩, $\langle 11\bar{1}\rangle$, $\langle 1\bar{1}\bar{1}\rangle$, and $\langle 1\bar{1}1\rangle$ distinguish themselves by the lack of lineages: their surface exhibits a rather mosaic-like aspect. This phenomenon was expected as well, for the surface resulting from the cutting of the crystal has intersected the lineages of the octahedral sectors at an angle of 35° 15′.

(b) *The crystal cut at half the distance between the center and the real face (001), parallel to this face* (Fig. 4). Photo 2 of Figure 2 shows the divided structure resulting after the electrolytic etching. A central square-shaped sector ⟨001⟩ appears surrounded by four trapezoid-like sectors: $\langle\bar{1}\bar{1}1\rangle$, $\langle\bar{1}11\rangle$, ⟨111⟩, and $\langle 1\bar{1}1\rangle$. The whole surface displays a mosaic-like aspect. The sectors appear because of the angle at which the surface intersects the collections of lineages, and also because of the different nature of the lineages occuring in the octahedral collection as compared with the cube ones.

This interpretation becomes clearer if we consider a vertical profile in the crystal studied (Fig. 4). As seen in the figure, the profile shows the intersection between the surface etched electrolytically and the lineages of the $\langle\bar{1}\bar{1}1\rangle$ and ⟨111⟩ octahedral sectors at an angle of 35° 15′, while the lineages of the ⟨001⟩ sector meet the surface at a right angle.

The striking outline of the central mosaic cube sector is caused by this lineage distribution, which also induces, in section, variations of properties from one sector to the other. The uniformity of the central cube sector suggests that all the lineages which compose it are identical, parallel to each other and perpendicular to the real (001) face. The identical behavior of the lineage collections in the adjacent octahedral sectors demonstrates the same phenomenon for the respective sectors.

A direct, more manifest proof appears in a detail presented in Photo 3 of Figure 2: the parallel lineages displaying perpendicularity to a real cube face are seen very clearly. This finding modifies Buerger's conception (1934a, p. 206), according to which the lineages generally extend in a radial direction, starting from the center or, at least, from the same point within the crystal.

(c) *The crystal cut through the growth center, parallel to (111).* Photo 5 of Figure 2 shows the following sectors: $\langle\bar{1}\bar{1}1\rangle$, $\langle\bar{1}11\rangle$, $\langle\bar{1}1\bar{1}\rangle$, $\langle 11\bar{1}\rangle$, $\langle 1\bar{1}\bar{1}\rangle$, $\langle 1\bar{1}1\rangle$. The lineage collections are oriented perpendicular to faces $(\bar{1}\bar{1}1)$, $(\bar{1}11)$, $(\bar{1}1\bar{1})$, $(11\bar{1})$, $(1\bar{1}\bar{1})$, and $(1\bar{1}1)$, respectively. The orientation of the lineage collections to the electrolytically etched surface may be followed in a vertical profile through the crystal, shown in Figure 5.

The electrolytically etched surface intersects the six octahedral sectors at an angle of 19°28′14″. In the $\langle 1\bar{1}\bar{1}\rangle$ sector, the section surface becomes parallel to the lineages, because this angle could not be exactly controlled during cutting and grinding of the surface. The deviation from the theoretical angle is fortunate,

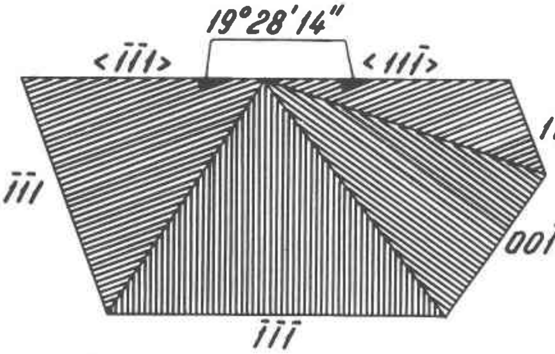

Fig. 5. The orientation of the lineage collections with regard to the electrolytically etched surface, in a section parallel to (111) and passing through the growth center.

however; for in this sector the lineages, parallel to each other, are once again visible.

(d) *The crystal cut parallel to (111), at half the distance between the center of the crystal and (111).* The result of the electrolytic etching is presented in Photo 4 of Figure 2. The lineage orientation in each sector with respect to the surface of the electrolytically etched section may be observed on the vertical profile cut into the crystal (Fig. 6). This profile shows that the line of the electrolytically etched surface intersects the lineages of the octahedral sectors $\langle\bar{1}\bar{1}1\rangle$ and $\langle 11\bar{1}\rangle$ at an angle of 19°28′14″, the lineages of the cube ⟨001⟩ sector at 35°15′ and the lineages of the central octahedral sector at a right angle. That means that the polygon ⟨111⟩ delimits a mosaic surface in the strictest sense of the term (Buckley, 1934; Buerger, 1934a). In order to check still further this conception of divided structures, we cut the crystal at half the distance between the center and the face (111), but along a plane not parallel with this face. The pattern resulting from the electrolytical etching (Fig. 7) corresponds to the theoretical model.

(e) *The crystal cut parallel to (110) near the growth center* (Photo 6 in Figure 2). The cube sectors ⟨100⟩ and ⟨010⟩ are distinguished near the section center. There are also four large octahedral sectors: $\langle\bar{1}11\rangle$, $\langle\bar{1}1\bar{1}\rangle$, $\langle 1\bar{1}\bar{1}\rangle$, and $\langle 1\bar{1}1\rangle$. In sector $\langle\bar{1}1\bar{1}\rangle$ lineages parallel to each other and perpendicular to $(\bar{1}1\bar{1})$ are observed. In the upper and lower parts of the image a lineage structure appears, with lineages perpendicular to faces (001) and $(00\bar{1})$ respectively, lineages which vanish as they go closer to the section center. The lineaged portions occurring at the upper and lower ends of the sections represent the cube sectors ⟨001⟩ and $\langle 00\bar{1}\rangle$, respectively, which pass toward the section center into two octahedral sectors ⟨111⟩ and $\langle 11\bar{1}\rangle$ respectively. In the ⟨001⟩ and $\langle 00\bar{1}\rangle$ sectors the lineages are parallel to the plane of electrolytically etched surface, whereas in the sectors ⟨111⟩ and $\langle 11\bar{1}\rangle$ the lineages intersects this plane at an angle of 54°45′ (Fig. 8).

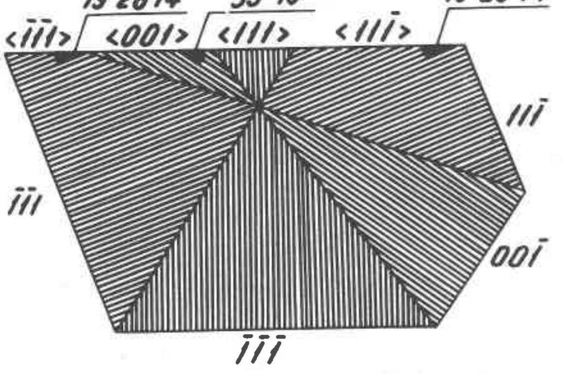

Fig. 6. The orientation of the lineage collections with regard to the etched surface in a section parallel to (111), at half the distance between the center of the crystal and (111).

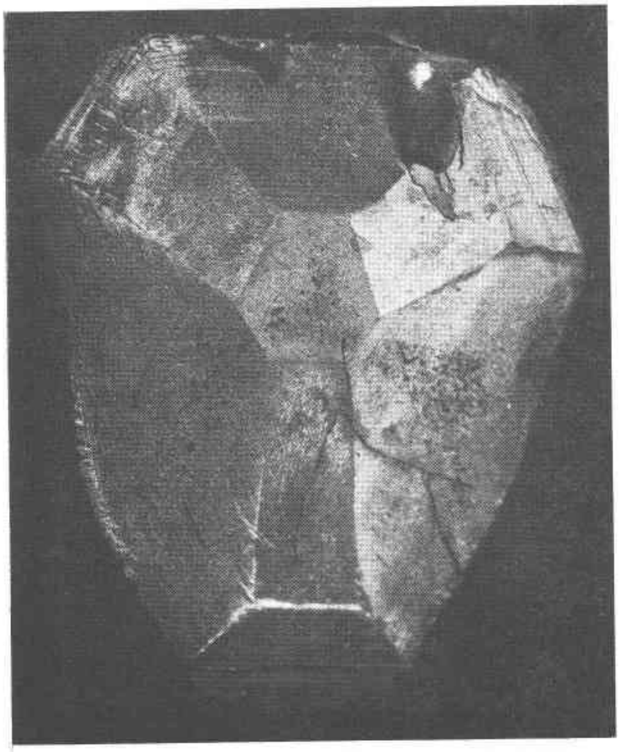

Fig. 7. Polygonal structure in a surface not parallel to (111), 9×.

### *Beryl*

Beryl with excellent polygonal internal structures was noted by Sahama (1966); one of his photographs is reproduced in Figure 9. Sahama explained the

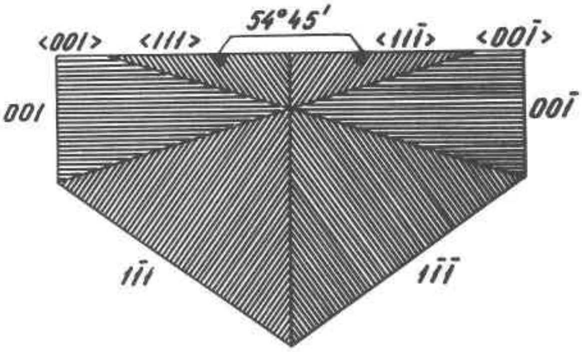

Fig. 8. The orientation of the lineages of a crystal {111} {100} with respect to a surface (110).

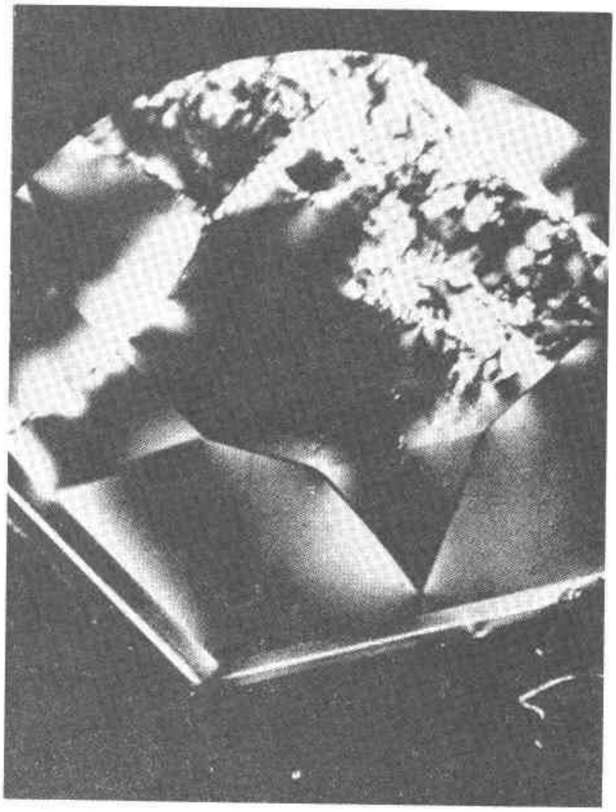

Fig. 9. The polygonal structure in a section cut perpendicular to the $c$ axis of a beryl crystal (from Sahama, 1966, pl. II, d).

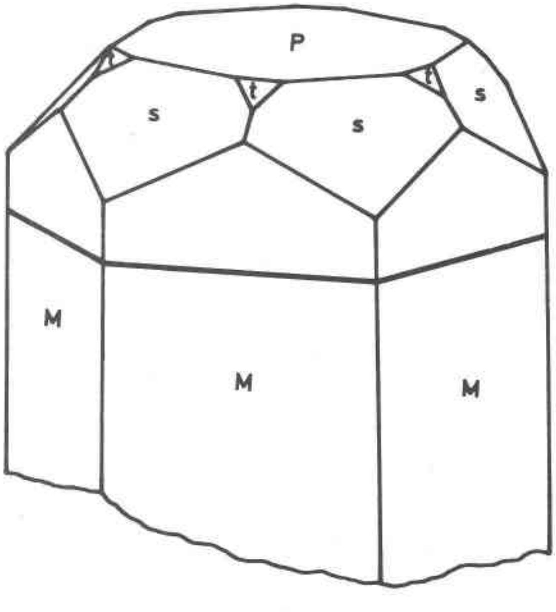

Fig. 10. The morphology of the beryl crystal and the trace of the section (heavy line) cut perpendicular to the $c$ axis.

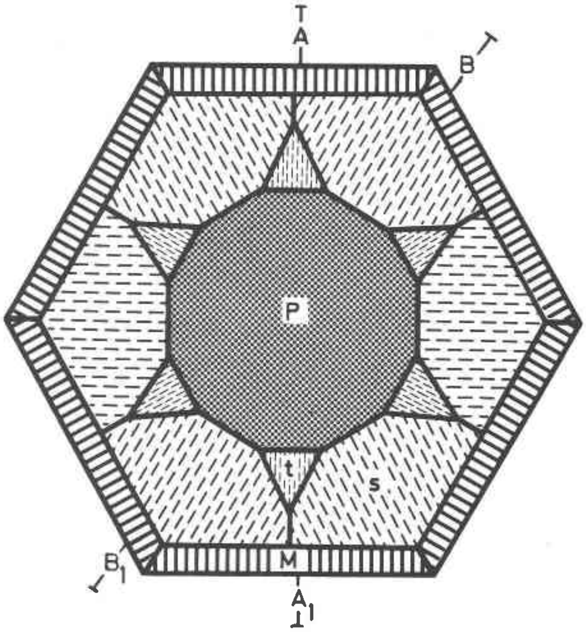

Fig. 11. The theoretical pattern of the polygonal structure in a section perpendicular to the $c$ axis of a beryl crystal of combination $\{10\bar{1}0\}$ $\{0001\}$ $\{10\bar{1}\bar{1}\}$ $\{11\bar{2}1\}$. A–$A_1$ and B–$B_1$ label the traces of two vertical profiles in the crystal, presented in Fig. 12.

polygonal structures as being due to the growth layers of the crystals. This explanation was the first one which was not based upon a (supposedly) different chemical composition of the material building up each separate polygon. However, we propose that the polygonal structure of beryl, as well as its optical abnormalities, may be better correlated with the lineage structure of the crystal. Evidently, this is only a simple prediction.

In this case the lineages cannot be observed, but can be deduced as collections from the sectoral structure. The two-dimensional polygonal (plane) structure is presented first and we search for its cause, eventually seeking to reconstruct the crystal's entire morphology, always under the guidance of the theory of lineages arranged perpendicular to the crystal faces.

Examining the morphology of beryl crystals from Goldschmidt's (1913) *Atlas der Kristallformen*, we find that the polygonal structure presented above may correspond to a beryl crystal composed of the following simple forms: *M* $\{10\bar{1}0\}$, *P* $\{0001\}$, *t* $\{10\bar{1}1\}$, and *s* $\{11\bar{2}1\}$ (Fig. 10).

If we cut the crystal according to Sahama's technique into plates perpendicular to the $c$ axis (the section mark is shown on the crystal by a heavy line, Fig. 10), one of the sections, namely the one closest to the prism end, should demonstrate the polygonal

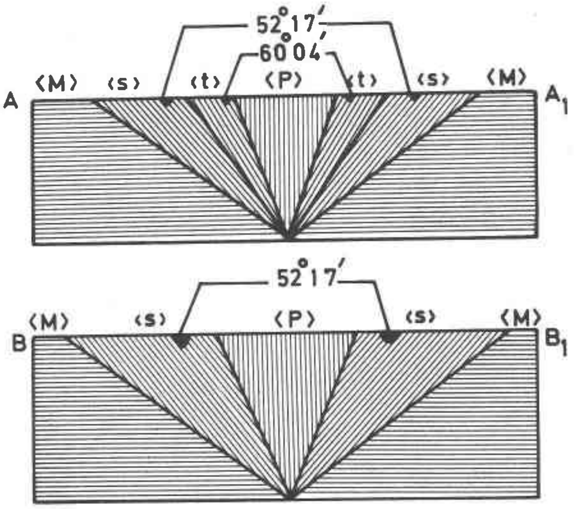

Fig. 12. The orientation of the lineage collections with respect to a section perpendicular to the *c* axis of a beryl crystal.

structure theoretically deduced and represented in Figure 11. In the plates cut parallel to this, but progressively farther from the end of the prism, the *P*, *t* and *s* polygons will grow smaller as the apex of their pyramids is approached; and at the same time, of course, the area of prism *M* will grow larger.

We can make two profiles through the crystal parallel to the *c* axis (Fig. 12). The first profile, (A–A$_1$ in Fig. 11) shows that the plates cut perpendicular to the *c* axis intersect the lineages of sector ⟨10$\bar{1}$0⟩ at an angle of 0°, *i.e.*, it is parallel with its lineages. (Note that the lines with which Sahama marks the optic axial plane are always parallel with the direction of these lineages.) The surface of the plates meets the lineages of sector ⟨11$\bar{2}$1⟩ at an angle of 52° 17′, the lineages of sector ⟨10$\bar{1}$1⟩ at an angle of 60°04′, and the lineages of sector ⟨0001⟩ at a right angle.

The second vertical profile (B–B$_1$ in Fig. 12) shows once again that the polygonal surface is parallel with the lineages of sector ⟨10$\bar{1}$0⟩ and perpendicular to the lineages of sector ⟨0001⟩, and that it intersects the lineages of sector ⟨11$\bar{2}$1⟩ at an angle of 52° 17′.

## Conclusions and implications

(1) A crystal is made up of the growth pyramids of its faces.

(a) A growth pyramid constitutes a collection of lineages parallel to each other and all perpendicular to the growth pyramid base (*i.e.*, to the real face of the crystal).

(b) The growth pyramids of the simple crystallographic forms display the same properties. In a composite crystal, each pyramid has properties distinct from the properties of the others.

(2) A thin or polished section of a crystal will be non-homogeneous, since it will contain collections of lineages variously oriented and displaying different properties.

(3) The cause of polygonal structure of crystals is their divided structure.

(a) In a plane, the polygonal structure results from the intersection of the section plane with the growth pyramids constituting the polyhedron.

(b) A polygon of a divided section represents a collection of identical lineages, sectioned at the same angle to their common direction.

(4) If, in a thin or polished section, the polygonal structure of a grain is given, the morphology of that grain can be deduced by means of the geometric relations of lineage structures to crystal faces.

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