DEVELOPMENT AND GROWTH OF CORDIERITE IN PARA-LAVAS*

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ABSTRACT

Several specimens of para-lavas from Bokaro coalfield formed by fusion and recrystallization of sedimentary rocks due to the burning of underlying coal seams, show numerous crystals of cordierite. The size, shape, development and growth of these crystals are here described and four general types have been distinguished: (*a*) small symmetrical hexagonal grains, (*b*) clusters of spiral shaped grains, (*c*) linked parallel clusters of hexagonal grains or rings, and (*d*) large, imperfect grains with tentacles or multiple terminations.

The conditions and rate of growth, responsible for the formation of these four general types and influencing the size, shape, idiomorphism, perfection, symmetry and pattern of twinning of these crystals are discussed.

The preferred and easy growth towards the solid angles and edges and along the prism faces of the pseudohexagonal prism, and the sluggish growth towards the prism face in rapidly grown cordierite crystals, are explained as being due to the degree of saturation of the atoms or molecules at these spots which afford the greatest or least total co-ordination, and also probably due to the development of lineages in earlier stages. The peculiarities of the atomic structure may influence this preferred growth by controlling the location, number and angular relations of these sites of easy and quick growth.

It is shown that slow, symmetrical mode of growth favors the formation of small star shaped twins and symmetrical concentric twin patterns, while rapid growth in preferred directions yields an irregular concentric twin pattern.

INTRODUCTION

In 1916, L. L. Fermor collected from the Bokaro coalfield several specimens of fused shale and sandstone. These and the rocks from a coalfield in Korea (Madhya Pradesh) originally described as the Chirimiri volcanic series, he termed para-lavas on the analogy of para-gneiss, para-schist, etc. They are known to be produced by the fusion of sedimentary rocks by the burning of coal seams (13). Crystals of cordierite are very common in some of these specimens and it is the purpose of this paper to describe these crystals with special reference to their size, shape, growth and development.

Rocks similar to these and formed by fusion and subsequent recrystallization of sedimentary and even metamorphic rocks may be produced by the agency of heat, either artificial or derived from the burning of coal or oil, magmatic intrusions or lavas. When the heat is of magmatic origin the resulting rock is usually termed a buchite (or basalt-jasper), which is essentially composed of glass and one or more characteristic crystalline phases. Mutual transfer of material between the sedimentary and igneous reactants is often recognized (28).

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Numerous references to these fused and recrystallized rocks are found in literature. The earliest papers are in German by Zirkel (32), Mohl (22), Hussak (21) and Prohaska (24) to name a few. Harker (19) and Flett (15) recognized buchites formed by the fusion of sandstones and phyllites, respectively, near the contacts of igneous intrusions. Thomas (28) and more recently Tomkeieff (29) have described buchites formed by fusion of aluminous xenoliths in a thoelitic magma and of sandstone by the intrusion of a dolerite plug.

Indian examples of buchites and vitrophyric rocks, formed in sedimentary strata by the burning of underlying coal seams at the outcrops, have been described by Chatterjee and Ray (10) and Sharma, Misra and Bhatnagar (26). Both papers give a general petrographic description of these rocks and their mode and temperature of formation. Rocks produced in a similar way have also been recorded by Bastin (1), Rogers (25) and Brady and Greig (2). Fused spent shale from a retort with similar mineral and textural characters as the buchites have been studied by Phemister (23).

Cordierite forms an important and persistent crystalline phase in most of the buchitic rocks described, but so far no attempt seems to have been made to study in detail the stages of growth of this mineral.

A detailed petrographic account of the rock collection under study does not appear to have been published and a mere mention of the minerals recognized in these rocks by Hayden (20) and a short description of the pleochroic iron cordierite by Fermor (14), were the only references located.

PETROGRAPHY

Three of the specimens from Fermor's collection, 23/855 Cordierite-pyroxene vitrophyre, 23/951 Cordierite vitrophyre and 23/952 Cordierite-labradorite vitrophyre, showed a better development of cordierite and over two dozen sections cut from these were studied in detail. Half the number of the thin sections were also examined with the help of a Fedorov stage.

Of the three specimens chosen, 23/951 and 952 are dark grey to black, fine grained and tough rocks resembling basalts. Small vesicles coated with some yellowish material are sometimes found on closer examination. The third is also quite similar to these but shows a vesicular structure more prominently. Blocks of unfused shaly matter are seen enclosed in the molten material (2) which has a rough reniform appearance on the surface.

Under the microscope they show a vitrophyric texture with dark brownish grey glass in which cordierite, labradorite, enstatite and magnetite have been recognized occurring as different assemblages in each specimen. Some corundum (?) and sillimanite have also been observed in other specimens from the same collection.

The cordierite generally occurs as pseudohexagonal prisms which vary from euhedral to anhedral and irregular shapes. In prismatic sections they are rectangular and show negative elongation. All the grains examined are optically negative and the optic axial angle ranges from 68°–75°. Twinning is almost of universal occurrence and inclusions are sometimes present. The light yellowish brown enstatite is seen to build laths or square prisms showing good prismatic cleavage, and straight extinction. Skeletal crystals and prisms with forked terminations are also observed. Rough rosettes comprising small slender laths of labradorite which are generally built of two or three twinned lamellae are quite abundant in the glass. Skeletal shapes are also fairly common. Magnetite occurs as skeletal, dendritic or microlitic growths and is distributed throughout the groundmass. It is very abundant in specimen 23/855. Large irregular crystals and octahedral grains are also common when it occurs in large proportions. Spherulitic growths are quite common in specimens 23/855 and 952.

The glass varies from a light yellowish brown transparent variety to a dark brownish grey, nearly opaque variety. In some places it is completely isotropic and in others it shows signs of devitrification and carries microlites and spherulites.

The general sequence of crystallization deduced from a study of the inter-relation of the minerals shows that magnetite was perhaps the earliest to start crystallizing followed soon by cordierite. Labradorite probably appeared towards the end of the growth of cordierite. Some little magnetite also started separating at this stage. The pyroxene (enstatite) and corundum(?) are among the last to crystallize.

DESCRIPTION OF CORDIERITE CRYSTALS

The cordierite crystals in these specimens can be roughly divided into four general types depending upon their size, shape, perfection and grouping. It will be seen that some of the types grade into others. A short description of each of these four different types is given below:

I. *Small symmetrical hexagons:*

These have generally perfect hexagonal outlines though, in a few, some of the sides are not fully grown. They are small in size, 0.05 mm. to 0.17 mm. across the base and .09 mm. to 0.25 mm. in length. Usually they are about one and a half times as long as broad and form perfect rectangles in longitudinal sections with a tendency in some to be more equidimensional. These crystals occur usually singly and not in clusters

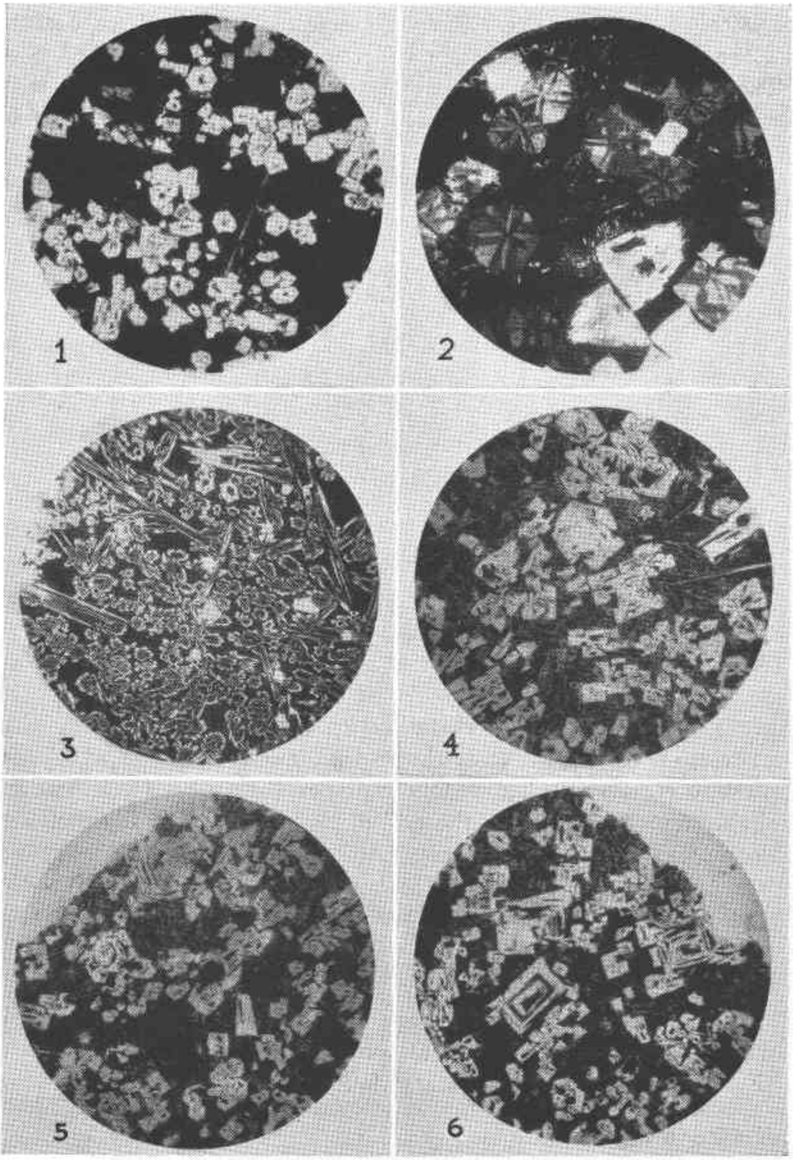


Plate 1. Photomicrographs of cordierite crystals in para-lavas.

Fig. 1. Small symmetrical hexagonal crystals with cavities at the centre embedded in glass. ×10.

Fig. 2. Star shaped radial twinning in small cordierite crystals. Crossed nicols. ×32.

Fig. 3. Crystal clusters and wreaths of types II and III exhibiting early stages of growth. ×10.

Figs. 4 and 5. Rapidly grown crystals of type IV showing the multiple terminations and preferred growth. ×10.

Fig. 6. Prismatic sections showing the preferred growth towards the corners. ×10.

with the individual crystals attached or linked with one another. Voids or glassy inclusions and growth lines are rare but some specks of magnetite are sometimes seen. Radial twinning producing star shaped forms (under crossed nicols) are prevalent and only occasionally does a concentric twin lamella occur. Some of these are pleochroic, colorless to pale mauve. This type is the only one present in specimen No. 23/855 and similar rocks and it is not very common in the others.

Similar haxagonal grains of a slightly larger size measuring 0.15 mm. to 0.24 mm. across in basal sections, are present in specimen 23/952 where large irregular crystals and different types of crystal shapes and clusters are predominant. Radial twinning is occasionally seen in these but a concentric pattern is much more frequent, though in a few cases radiating star-shaped cores are present in the grains showing concentric twinning. These crystals occur in small clusters with overlapping boundaries. Dusty inclusions and hexagonal glassy enclosures at the centre are commonly observed (Fig. 1).

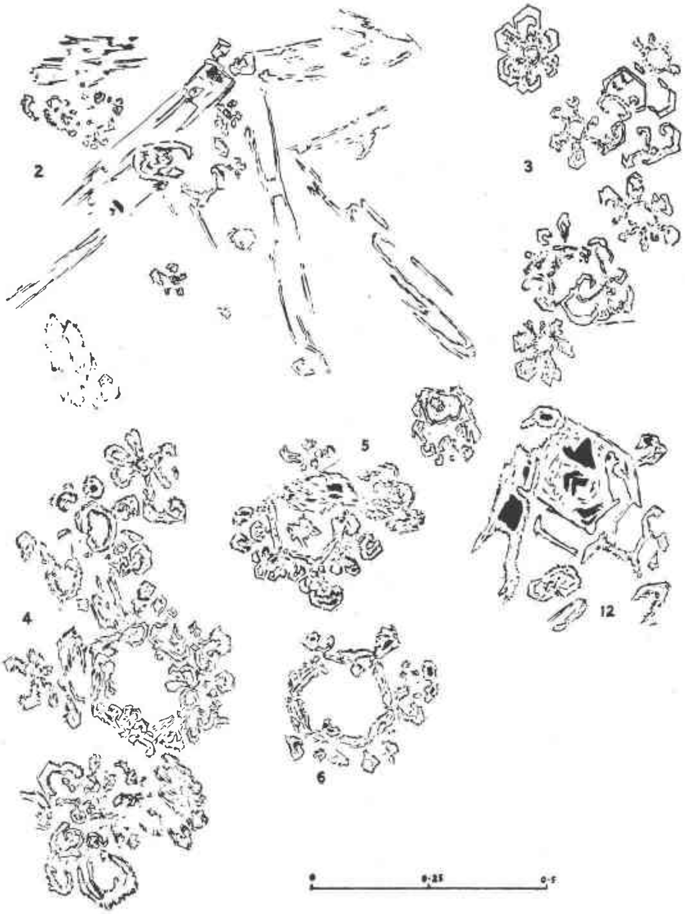
II. *Spiral clusters:*

In specimen 23/951 and to some extent 23/952, the cordierite tends to form hexagonal spirals as viewed in basal sections (Pl. II, Figs. 3, 9). These spirals occur in clusters, overlapping one another when small but when sufficiently big, the individuals might merge together and form a large spiral (Fig. 7), or a partially formed hexagon (Figs. 10, 12). The arms of the spirals have dusty and glassy inclusions either permeating evenly or more commonly concentrated as parallel streaks along their length. The arms often show twinning with the trace of the twin planes usually parallel to the arms or sides. The spiral type is probably an early stage of crystal formation and is closely allied in many respects to the succeeding type.

III. *Linked, parallel clusters of hexagonal rings and grains:*

These generally occur in groups and clusters with fairly well developed hexagonal outlines which are parallel for all individual crystals in the same cluster. The surrounding smaller individuals are grouped around a central one which itself might be a spiral, hexagonal ring or partly formed hexagon, like the satellites. This type of wreath-like arrangement of cordierite grains is very characteristic of specimen 23/951. There is a tendency for the subsidiary individuals to prefer the corners of the central hexagonal framework, though sometimes they also grow along the sides, both inside and outside of the central ring. (Figs. 3–6). These are perhaps the earliest stages of crystal growth, probably contemporaneous with the spiral type.

Twins are not so well developed, but the twin lamellae are often parallel to the sides. Usually the crystals are spirals, skeletals, or rings containing



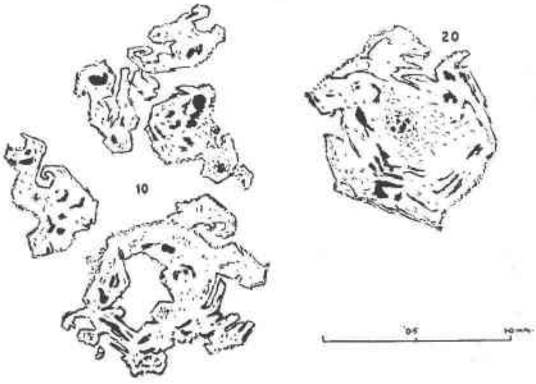
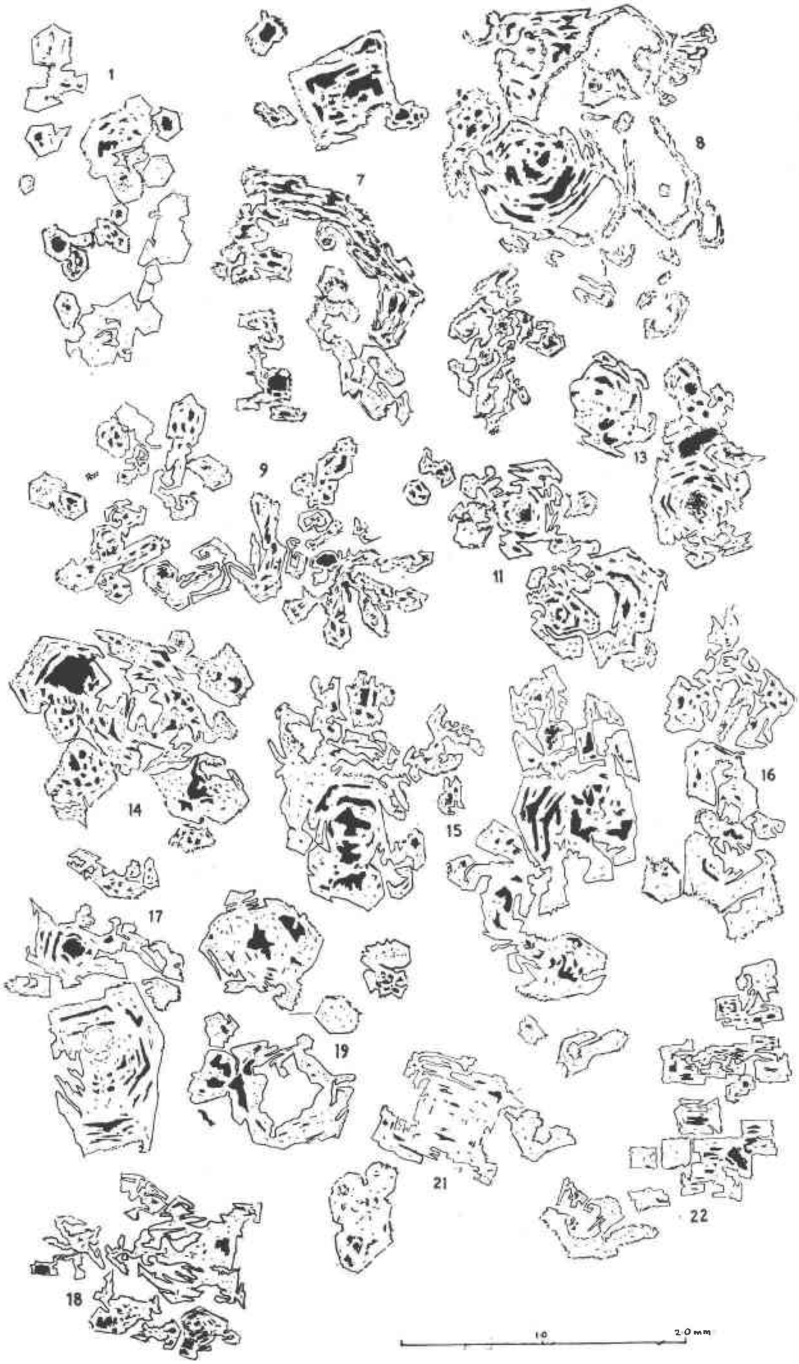


PLATE 2. Camera Lucida drawings of cordierite crystals illustrating the stages of growth and mode of development.

FIG. 1. Small symmetrical hexagonal grains. Type I.

FIGS. 2 to 6. Clusters and wreaths of small crystals in early stages of growth. Note parallelism of boundaries, mode of attachment to central grain, and ring and spiral shaped grains. Types II & III.



FIGS. 7 to 9. Later stages of growth of the crystal clusters producing large spirals or imperfect hexagonal grains.

FIGS. 10 to 20. Rapidly grown imperfect grains showing tentacles or multiple terminations. Note the rapid growth towards the hexagonal corners and the secondary branches parallel to the hexagonal sides. Type IV.

FIGS. 21 & 22. Prismatic sections showing the preferred and rapid growth towards the corners.

inclusions of glass at the nucleus or along growth layers. When the grains are small and euhedral, radial twinning producing stars is occasionally seen.

The outer crystals are attached to the central grain by means of thin channels of minute specks of the same mineral. Sometimes, the channels or arms are seen to be discontinuous or indistinct and in a few cases there are no connecting channels at all. These links connect generally the corners of the crystals but often also the sides of the central frame-work and the corners of the outer individuals. Spirals are commonly seen growing from the central parent with their sides welded together (Figs. 3, 4 and 7).

These linked clusters grow very long parallel to the *c* crystal axis and form bunches or bundles of rod or pencil-like crystals which have many hollows filled with glass along their length (Fig. 2). They have the shape of the letter *H* or of a bobbin, so characteristic of skeletal growth. The boundaries of the grains are rather hazy and indistinct.

An entire wreath or cluster varies in size from .08 mm. to 0.25 mm. in a basal section. The central crystal, when ring shaped, measures .01 mm. to over 0.2 mm. across. Surrounding grains attached to this central one are generally .01 mm. or less to over .05 mm. These are usually smaller if the central framework is large and *vice versa*. The bundles are 0.8 mm. to 2.5 mm. in length.

IV. *Hexagons with tentacles or multiple terminations:*

These are of much later stages of growth where the clusters described above have grown filling the glassy enclosures to form large sized irregular grains measuring .05 mm. to even 1.0 mm. across the basal sections. The larger size is partly due to the numerous branching outgrowths, but different sizes are not uncommon in the same microsection. In this type the arms grow out from the central parent towards the six hexagonal corners but not towards the sides or prism faces. These arms then send out secondary branches parallel to the hexagonal sides and thus try to build a crystal first along the corners and later along the sides from the adjacent corners as is well illustrated in Figs. 8–20. These arms and branches separate out from the parent stalk at angles of 60°. Numerous, fairly big glassy enclosures are present in the central portion of the grain as well as between and within the arms and branches. Their arrangement is, obviously, roughly parallel to the growth layers. These grains with the different branches of growing parts having multiple terminations resemble spread out tentacles.

Sections roughly parallel or slightly inclined to the *c* crystal axis show numerous rectangular prisms of cordierite grouped together in clusters.

In each cluster the long directions of the individual prisms are all roughly parallel thereby showing that they are all parts of a single growing unit. Some of these rectangular prismatic sections show a pronounced growth along the corners and slower and inadequate addition of material along their sides (Fig. 7, 21 and 22). A slender needle of a different mineral is sometimes seen lying in a diagonal direction pointing to the corners of these rectangles.

The prisms vary a great deal in size even within a single thin section. The whole cluster with smaller individual prisms in parallel alignment, measures 0.15 mm. to 2.0 mm. and the smaller individuals 0.17 mm. to 0.7 mm.

All the prismatic sections show traces of twinning planes roughly parallel to the *c* crystal axis (15). In the basal sections the twinning is seen to be mostly distorted and rather complex. Radial, concentric and mixed tendencies (30) are all present. The composition planes are irregular, zigzag and indistinct and the crystal looks like a mass of intricate inter-growth or an aggregate of oddly shaped angular grains fitting as in a jig-saw puzzle. Occasionally there is a small radiating star at the core around which the twinning has developed rather irregularly and indistinctly. When a hexagonal cavity or glassy inclusion is recognizable at the centre, the twinning is more likely to be concentric in pattern reminding one of a spiral or ring shaped parent. Towards the periphery and along the secondary branches from the growing arms, there is a strong tendency for the twin lamellae to lie parallel to the hexagonal sides.

Stages and mode of Development of the Crystals

The earliest forms of crystal formation are the second and third types where skeletal crystals and smaller sizes are common. These are also in clusters, each small grain being attached or linked to another and aligned parallel to one another (Pl. II, Figs. 3–6). They represent the different centres of formation of spontaneous nuclei around which crystal growth starts in an area. It is well known that there is a field of attraction around nuclei and nuclei agglomerates (18). The atomic structure of the earlier nuclei influence and guide the later ones to align themselves in parallel position so as to form a single continuous and homogeneous unit, and this arrangement gives the maximum bonding, cohesion and stability for the later nuclei, especially when they have similar atomic structure. Thus clusters with individuals in parallel alignment are formed.

At this early stage, two modes of growth are possible for the newly formed crystal nuclei. They can grow along their sides, in course of time producing spirals or rings, or they may grow as normal pseudohexagonal prisms adding successive concentric hexagonal layers to the nuclei. In the former case, growth lines, inclusions and irregularities of twinning, shape and size are more common than in the latter. The rings and spirals are very similar since the ring gets formed when the growing arm of a spiral reaches back to its tail but if it overshoots or undershoots to miss the tail, it becomes a spiral awaiting a further opportunity to grow and coalesce with the inner or outer layers eliminating the whorls.

In later stages, the rings, spirals and whorls may grow to quite large sizes with all their irregularities and imperfections, or alternately give rise to a tentacled hexahedron or even to an imperfect pseudohexagonal prism. But the small sized symmetrical hexagons with perfect star shaped radial twins formed by slow, regular growth do not reach large sizes.

These smaller, well developed, six sided crystals are generally confined to specimen No. 23/855 in which no other types are seen. They are however, occasionally met with in specimens 23/951 and 952. The clusters with individual rings and spirals of small dimensions are very characteristic of 23/951 which shows the initial stages of development of the crystals. In 23/952, these clusters grown to slightly larger sizes are observed, but the much larger irregularly grown hexagons (type IV) are much more common. It has not been possible to say whether the small radially twinned perfect hexagons (type I) have grown from these clusters; but it appears very unlikely. They have probably grown from nuclear stages with ordered and uniform-growth in all directions by addition of symmetric layers all round. However, the small crystals with perfect concentric twin patterns appear to have grown from types II and III. On the other hand, it seems quite clear that the crystals of type IV have developed from types II and III.

The size of a crystal depends on two factors, viz. the rate of formation of nuclei and the velocity of growth, and the crystal size equals (31):

$$\text{Constant} \times \sqrt[4]{\text{Velocity of growth/rate of formation of nuclei.}}$$

The well-known curves of Tamman and Miers correlating power of spontaneous crystallization (or nuclei formation) and super-cooling show that the former is maximum at the later labile stage when numerous centres of crystallization develop, than at the earlier metastable stage. This affords the classical explanation of the coarse-grain size of the slowly cooled rocks as compared to the fine-grained nature of the quickly cooled ones. Davey (12) shows how crystallization from a melt is quite analogous to crystallization from a solution; melt becoming synonymous with solution, freezing with precipitation and undercooling with supersaturation. He mentions how Von Weimarn has shown that the size of crystals obtained from pure solution by spontaneous crystallization is a function of the solubility (S), degree of supersaturation (P) and co-efficient of the viscosity of the solution (n) related to the dispersion co-efficient (δ), by the formula $\delta=(P/S)n$. When δ is small the crystallization would be slow and crystals probably perfect, and when it is large, the number of spontaneous nuclei is great and it is very likely that crystals are less perfect.

The perfection and symmetry of a crystal form depends on its rate of growth and it is recognized that the slower the rate of growth, the more perfect a crystal is. Thus, the two controlling conditions of the size and perfection of crystals are the rate of nuclei formation and velocity of growth which in turn depend upon (*a*) the degree and rate of undercooling, (*b*) the viscosity of the melt controlling the rate and ease of diffusion, and (*c*) the molecular concentration or proportion of the crystallizing material in the melt.

It is evident that the para-lavas were formed by the fusion of sedimentary rocks which were cooled relatively rapidly being exposed to atmospheric conditions. Specimen No. 23/855 showing the small, well formed symmetrical crystals of type I has cooled comparatively less rapidly than the others. The total volume percentage of cordierite in this rock is also less in comparison to the other specimens. Both these factors have influenced the formation of relatively few nuclei, and slow rate of growth producing the small and more perfect crystals. Specimen No. 23/951, on the other hand, shows a large quantity of crystals of types II & III which are small skeletal shapes in the form of rings, spirals, etc., building clusters or hexagonal wreaths. It is evident that this specimen, also comparatively fine grained, has cooled rapidly, reaching the labile stage quickly and giving rise to numerous nuclei but the growth was stopped abruptly soon after. In the last specimen, i.e. 23/952, where the crystals are mainly of type IV, the growth was carried on rapidly on account of the concentration of requisite material as indicated by the high volume percentage of cordierite in the rock. During this rapid growth, the crystals developed irregularly and in preferred directions, yielding the large, imperfect crystals with many glassy enclosures and a grotesque and often unrecognizable twin pattern showing wavy and zig-zag twin planes. But growth was perhaps moderate and slower even for these in earlier stages as evidenced by some of the small, more perfect crystals with good twin patterns and few inclusions, occurring separately, or as cores of the bigger imperfect grains.

Imperfections and irregularities in crystals are very normal and common, as remarked by Davey (12). Dendritic shapes and imperfect crystals are the results of rapid growth. When there is a quick shower of the atoms or molecules on a growing crystal, there is not enough time for the impinging atoms or molecules to adjust themselves and fit into the right positions which becomes more and more difficult as it grows to larger sizes as pointed out by Bragg (3); and after a stage growth may be difficult and may even cease on account of the cumulative irregularities and of structural disorder on the rapidly growing surface. Hence, the incoming atoms and molecules place themselves roughly in positions which allow of quick and comparatively easy attachment giving rise to imperfections, irregularities and distortions. But in the case of a crystal growing at a slow and steady pace, it is easier (within limits and up to a stage) for the molecules and atoms to seek out proper places and orient themselves suitably to fit in more exactly as there is more time available. The result is a small well formed, more perfect crystal with well defined boundaries, smooth faces and a symmetrical twin pattern. The presence of smaller perfect crystals occurring either separately or as cores in 23/952, probably represent the few earlier, small perfect crystals in 23/951 which have grown at a moderate pace keeping as perfect as possible, as pointed out earlier.

It seems quite clear that the crystals of type II and III are results of growth in the labile stage and the perfect, well-formed crystals of type I probably of the metastable stage; but it is not quite definitely known to which stage, the growth of the large, irregular crystals of type IV in specimen 23/952, should be ascribed. It is also very likely that during the later stages of cooling the conditions of crystallization alternated between the metastable and labile states probably due to the heat liberated by rapid crystallization and the changes in molecular concentration. Chevalier (11) has shown that these different states can even coexist in the different parts of a single drop due to the changes in molecular concentration by rapid crystallization. The persistence of the skeletal crystal clusters (though slightly larger in size) in specimen No. 23/952 and the presence of smaller, perfect crystals support this alternation of the labile and metastable states to some extent. The inclusion of spherulitic growths, characteristic of labile state (11), in the large irregular crystals of type IV and the enveloping of the small perfect crystals of type I by spherulitic growths are also in favor of the above suggestions. It is however, inexplicable that the spherulites are rare in specimen 23/951.

We have therefore reasons to believe that the smaller, more symmetrical and perfect crystals grew slowly, probably in the metastable state while the large irregular hexagonal crystals with multiple terminations grew very rapidly and that the skeletal crystal clusters and wreaths represent growth in the labile state. A more detailed picture of the various physico-chemical factors relating to the formation and growth of these crystals, will have to depend on more precise knowledge of other data besides the mere shape, size and perfection of crystal grains.

Differential Rate of Growth

From the foregoing description of the growth and shape of the crystals, it can be seen very easily that a growing crystal has certain preferential directions along which growth takes place more easily and quickly as is specially brought out in the rapidly grown crystals. The long, slender pencil-like, hollow crystals forming bundles in types II and III and the general elongation of the prisms parallel to the *c* crystal axis in almost all crystals of cordierite, the arms in the tentacled hexagons, the secondary branches from these arms, and the spirals and rings, all indicate these directions of rapid growth. The following are the preferred directions of growth from the centre:

(*a*) towards the solid angles of the pseudohexagonal prism i.e., where the prism edges meet the base, as shown by the step wise growth of prisms along their corners and the hollow transversely elongated bobbin or *H* shaped skeletal crystals (Pl. II, Figs. 2, 21 and 22);

(*b*) towards the edges of the prisms i.e., the corners of the hexagonal outline as seen in basal sections (Figs. 10, 11, 13, 14 and 15); and

(*c*) parallel to the sides of the hexagon which is also a parallel direction to *b*. The secondary branches from the arms of the tentacled hexagon (Figs. 9, 10, 11, 14 and 17) and the spirals and rings (Figs. 3, 4, 5, 7, 8, 9) exhibit this tendency very well.

This leaves one significant direction towards which growth is very slow and sluggish i.e., towards the prism face or hexagonal side, which consequently shows embayments or enclosures.

The general prevalence of the hexagonal motif in all the crystal forms of cordierite described here and the preferred growth in particular directions, may probably be explained as being the characteristic manifestation of the crystal structure of cordierite. Gossner and Mussgnug (cited by Bragg and Bystrom), perhaps the first to investigate the crystal structure of cordierite, suggested a psuedohexagonal structure of the beryl type for the mineral, from the facts that the formula written as $Mg_2Al_4Si_5O_{18}$ was similar to that of beryl and the ratio $a{:}b$ was close to $\sqrt{3}$. Bragg (4) has supported this view and writes the formula as $Al_3Mg_2(Si_5Al)O_{18}$, and recently Bystrom (9) has further confirmed the close similarity between the orthorhombic (pseudohexagonal) structure of cordierite and the hexagonal structure of beryl. While on the structure of beryl which shows such close similarity to that of cordierite, Bragg and West (5) observe that the hexagonal rings formed by the six silicon oxygen tetrahedra are stacked on each other along the hexagonal axis forming a series of open channels parallel to the *c* crystal axis. This honeycomb-like arrangement and the striking open channels in the structure, they remark, might confer on the crystal some special properties. Folinsbee (16) makes particular reference to these hollow central channels in the structure as possible spaces for the location of alkalies, in discussing the variability of optic properties of cordierites in relation to their alkali content. Bystrom also recognizes these channels as the probable spaces for the location of water and alkalies. It is now interesting to note the remarkable extent to which the hollow, slender needles and the spirals and rings, simulate and reflect the structural peculiarities.

It is well known that the different crystal faces of a particular mineral have different rates of growth indicating the difference in the ease with which molecules can slip into their places on different growing faces. This is sometimes influenced by the difference in force of molecular attraction or cohesion in different directions—evidenced by the differential bonds in the case of bismuth and its homologues—as observed by Bragg (3) who further remarks that "without a more detailed knowledge of the active forces localised at various points of atoms and molecules, we cannot build up a complete theory of cohesion." No attempt is being made in this paper to show the exact nature of the interatomic or molecular forces in different directions in the cordierite structure which may influence this differential rate of growth. It is also not known whether such nonuniform bond density exists in cordierite or not.

Besides the unequal bond strength in different directions controlled by the peculiarities of atomic structure, other explanations are also possible for this preferred growth of cordierite in particular directions. These explanations of course are also ultimately related to the structural pattern in the crystal.

Buerger (8) has attempted to explain the relative ease of growth of crystal faces by such considerations as co-ordination and surface energy. It is shown that the preferred site is the one which affords the greatest decrease in surface energy for the incoming molecules. In other words, a preferred site affords a molecule the greatest total coordination or greatest bonding energy which is complementary to surface energy. This would of course be modified and influenced by the location and strength of strong bonds in a molecule or atom possessing non-uniform bond density (as in bismuth?).

In seeking an explanation for the cause of mineral incrustations upon the corners and edges of crystals, Frondel (17) remarks that these are the parts of a crystal having greater adsorptive powers and the cause for this is sought from the work of Taylor (27) on metallic hydrogenation catalysts. Taylor states that, "the atoms in the edge of a granule have one less degree of saturation than those in the surface proper; atoms at a corner have two less than those in the surface and one less than those at an edge." Preferred adsorption or growth at corners and edges of a crystal are thus caused by the low degree of saturation of the atoms or molecules placed at these points.

This rapid rate of growth along the corners and edges of a crystal is not wholly dependent on the peculiarities of crystal structure and it is more likely to be a general result of the low degree of saturation at these points as explained by Taylor, and all rapidly grown crystals should show similar growth irrespective of their crystal structure. In this connection it is pertinent to quote the observations of Flett (15) concerning the unequal growth of augite in some Scottish buchites: "Very often the corners of the crystals have grown outwards so rapidly as to form projecting spikes while depressions correspond to centres of pinakoidal faces."

During the early stages of growth of a crystal, there are certain thermal stresses set up on the surface of the crystal due to factors such as the latent heat of crystallization (Zwicky), impurites (Buerger), etc. This would lead to the formation of certain cracks (referred to as Zwicky cracks) whose spacing and width are mostly a function of the atomic structure of the crystal. These cracks would cause irregularities and slight deviations in the orientation of the different growth layers on the blocks bounded by these cracks, the final result being the development of lineages or block structure in crystals (6 and 7). The orientations of the lineages or blocks descend continuously from a parent nucleus but differ mutually, the degree of difference being proportionate with the distance from the nucleus. Buerger (6) observes that crystals in parallel positions and dendrites are special cases of lineage growth and form by more rapid rate of growth. He says "The essential difference between simple lineages and exaggerated cases of parallel growth is that in the former the structure is bathed by a solution of more or less uniform concentration on all sides, so that the space between the lineages is kept filled with precipitated material and the lineages are able to keep pace with the growth of one another while in the latter case, the rapid growth allows material to be added only to the growing ends of the separated lineages, the region of interlinear boundaries not receiving much material for growth because it is all precipitated on the leading tips." The interlineage boundaries obviously form the loci for negative crystals or cavities.

Davey (12) has also drawn attention to the rapid needle-like outgrowths from the corners of blocks formed by the intersection of the Zwicky cracks, resulting from the least potential energy at these spots which helps to hold tightly the incoming material. The development of these needle-like outgrowths are common in the earlier stages of all rapidly grown crystals. The interspaces between this net work of needles are filled at a later stage to form single, smooth faced crystals. These needle like skeletons probably correspond to the initial stages of Buerger's lineages.

The figures of spectroscopically pure zinc grown from vapor, given by Davey show fin-like outgrowths branching off from the stem at angles of 30° and 60° characteristic of the hexagonal close packed structure of zinc. These fins represent later stages of growth of the secondary and tertiary needle-like projections from a growing surface. The figures closely resemble some of the cordierite crystals of type IV. So, it appears quite likely that these projections and outgrowth on a large, quickly grown cordierite grain would be caused by the Zwicky cracks and development of lineages.

Thus the sites of rapid growth are more likely to be conditioned by simple, general considerations such as surface energy, total co-ordination, degree of saturation and development of lineages than by the peculiarities of the atomic structure. This contention is supported by the similar shapes of skeletal crystals, of parallel growths, of rapidly grown grains and of dendrites in different minerals. The ultimate influence of the distinctive atomic structures of different minerals, in determining the angular relations, location and number of the sites of easy and quick growth cannot however be disregarded.

Twinning and Its Relation to Growth

A genetic relationship between twinning and mode of growth in these cordierite crystals is apparent as the latter is the most important if not the sole controlling and modifying factor of the former. Two general types and patterns of twinning—the 'radial' giving rise to sixlings and stars, and the 'concentric' with twin lamellae mostly parallel to the hexagonal sides—are recognized (30). Combinations of both are also observed.

The sixlings (trillings are very rare) and star shaped (with twelve pointed rays) twins are generally associated with the smaller, well-formed, symmetrical individual crystals. There is no cavity or inclusion at the centre and the nucleus itself starts as a twinned individual and encouraged by slow, steady and orderly growth, a perfect radial twin pattern is built. In rapidly grown crystals of bigger sizes this orderliness, or symmetry, is partly lost due to lack of time for proper orientation of the added material, and an unsymmetrical confused pattern of twinning is produced. The sixlings are almost always twinned on (110) planes which connect the corners of the hexagonal outline. A twelve pointed star is produced by the presence of (130) twin planes in alternate positions with the (110) planes.

A concentric twin pattern on the other hand is very characteristic of cordierite developed from skeletal crystals, spirals and rings. Here the crystal growth does not proceed methodically and equally in all directions, but in preferred directions which are usually parallel to the hexagonal sides and thereby promoting the development of concentric twin lamellae parallel to the hexagonal faces or sides. They develop so naturally in a hollow ring, or spiral, or an outgrowth building the prism faces, all of which grow in directions parallel to the twin lamellae. A few radial twin planes may also get formed normal to, or at high angles to, the prism faces, possibly due to the meeting of two growing surfaces; but the predominant pattern is still concentric.

In a few cases growth may be slow and moderate in the early stages giving rise to a star shaped twin around which a concentric or irregular pattern may develop as the growth becomes rapid. Glassy enclosures and cavities are common in these rapidly grown concentric or irregular twins, but not in the slowly grown radial and star shaped twins.

Thus the twin pattern is fully conditioned and controlled by the mode and speed of growth, yielding small symmetrical radial twins or concentric or irregular patterns of poor symmetry. In para-lavas which have formed by fusion and quick cooling, the duration of conditions suitable for crystal growth is short and hence all the large grains have grown very rapidly causing imperfections and distortions in the symmetry of twin patterns. But in a magmatic or metamorphic environment, conditions favoring crystal growth may be very prolonged and large crystals with beautiful and symmetrical twinning may be produced even with moderate and slow rate of growth. Such crystals are, however, not very common even under the latter conditions.

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