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THE GENESIS OF PEGMATITES

I. OCCURRENCE AND ORIGIN OF GIANT CRYSTALS

RICHARD H. JAHNS, *California Institute of Technology, Pasadena, California*

ABSTRACT

Some masses of pegmatite contain individual crystals that are truly enormous in size, with dimensions measurable in feet or tens of feet, and weights that commonly amount to hundreds or even thousands of pounds. Such giant crystals are formed mainly by beryl, potash and sodaclase feldspars, quartz, spodumene, and the micas biotite, muscovite, and phlogopite, and to lesser extents by allanite, amblygonite, apatite, columbite-tantalite, fluorite, hornblende, hypersthene, monazite, petalite, median and calcic plagioclase, topaz, tourmaline, triphylite-lithiophilite, triplite, and other species.

Most of the giant crystals show rough external faces and are morphologically simple. Some are regular in form, whereas others are tapered or are marked by less systematic variations. Most of the crystals occur singly, but some others are grouped in irregular clusters, and many of those with prismatic or tabular habit form groups in which the individuals are parallel, radiating, or diversely oriented. A few species, notably quartz, beryl, and amblygonite, also occur as huge anhedral crystals.

Nearly all the giant crystals occur in pegmatite bodies that are zoned, i.e., that comprise lithologically distinctive units whose more or less concentric disposition within each body tends to reflect its shape and structure. In general the grain size of the zones in such a pegmatite body increases inward from its walls to its center, though not at a uniform rate. The giant crystals thus are most abundant in the interior parts of the body. They occur chiefly in rock with giant pegmatitic texture, which is characterized by extremely large, euhedral to anhedral crystals that are of nearly uniform size or tend to reflect a continuous variation in size.

The giant crystals show systematic trends in their distribution and size, and these trends are in full accord with all systematic trends and textural variations within the pegmatite body as a whole. Like the lithologic zones that contain them, they appear to have developed successively from the outer parts of a given pegmatite body inward toward its center. Many individual crystals of elongate habit plainly grew in the same general direction.

Convincing direct evidence that the giant crystals grew by replacement of other minerals appears to be lacking; instead, the excellent evidences of replacement that are widespread and clearly displayed in so many pegmatites apply to attack and replacement of the giant crystals by aggregates of younger, generally much finer-grained minerals. The problem of support during growth from a liquid, so often cited as an argument for a replacement origin of very large crystals, is readily resolved in most occurrences, where some type of effective support can be demonstrated. Several other features that are com-

patible with the replacement theory seem equally well explainable in terms of primary crystallization of the giant individuals from a solution.

Many investigators have concluded that pegmatite zones were formed by fractional crystallization of a magma, with incomplete reaction between successive crops of crystals and rest-liquid. The giant crystals in pegmatites are here considered to be primary constituents of these zones, mainly on the basis of their systematic distribution, age relations, textural and structural relations, and variations in composition. They are thought to have crystallized directly from pegmatite liquid that was rich in hyperfusible constituents, probably under restricted-system conditions involving rather delicate thermal and chemical balance.

Contents

Introduction

The very coarse development of minerals in most masses of pegmatite makes this rock type a particularly inviting one for detailed examination and study. Even casual scrutiny, however, soon dispels any original impression of simplicity, but reveals instead many fine-grained constituents, as well as variations of structure, texture, or mineralogy that generally suggest a complex history of crystallization. Moreover, the interpretation of these features rarely is a simple matter, as demonstrated, for example, by the many conflicting opinions to be found in the extensive literature on pegmatite genesis.

The term pegmatite is applied by geologists mainly to those intrusive igneous rocks that are holocrystalline and at least in part very coarse grained. Marked irregularities in grain size are characteristic, and in some masses of pegmatite the coarsest crystals are enormous. The very size of such giant crystals is most provocative, and brings first to mind the oft-repeated question of just how large a crystal can grow. More than this, though, it provokes further thought as to what physical and chemical conditions are required for such spectacular nourishment of a relatively few crystal nuclei during the period of growth. And was this growth accomplished solely in a fluid environment, or was each new crystal lattice developed wholly or in part at the expense of pre-existing solid material? Before these and other questions can be approached effectively, however, the general features and relations of such giant crystals to the enclosing pegmatite must be known and, so far as possible, understood.

The writer's personal experience with giant crystals dates from a springtime day in 1932, when he spent several hours in collecting a well-faced 284-pound individual of potash feldspar from a mass of pegmatite in northwestern Riverside County, California. He clearly recollects his chagrin in discovering, a few weeks later, that this was by no means the largest known crystal of feldspar! In the years following, however, he had opportunity to observe and study many crystals of considerably greater size, and was especially fortunate in participating, during the period 1942–48, in an extensive program of pegmatite investigations by the U. S. Geological Survey. A specific study of exceptionally large crystals has been made since 1946, chiefly in the pegmatites of the Southwestern States; this work was supported by a research grant from the California Insitute of Technology.

The studies were greatly facilitated by Dr. D. F. Hewett of the U. S. Geological Survey, who supplied information on several pegmatite localities in southeastern California; by Mr. W. J. Alexander of the Whitehall Company, Inc., who introduced the writer to several areas of interesting pegmatite deposits in western Arizona; and by Dr. Arthur Montgomery of Lafayette College, who kindly furnished data and suggestions relating to results of his operations at the Harding mine in northern New Mexico. The writer also has profited from discussions in the field with Mr. L. A. Norman, Jr., of the California Division of Mines, and from later discussions, based on critical reviews of this manuscript, with his colleagues, Drs. Ian Campbell and A. E. J. Engel of the California Institute of Technology. Thanks also are due to Ellen Powleson, who drafted most of the sketches and diagrams, and to Florence Wiltse, who aided in the preparation of other parts of the manuscript.

Some Outstanding Occurrences

Spodumene and the potash feldspars form the largest crystals thus far reported from masses of pegmatite, and particularly well known are the gigantic spodumene "logs" from the Black Hills region of South Dakota. Blake (4; 5, p. 608) long ago described a spodumene crystal 36 feet long and 1 to 3 feet thick from the Etta pegmatite; Hess (17, p. 651) and Ziegler (42, p. 654) later noted one that was 42 feet long and approximately 3 by 6 feet in section, and Schaller (34) described and pictured an immense crystal that was 47 feet in exposed length. Some-

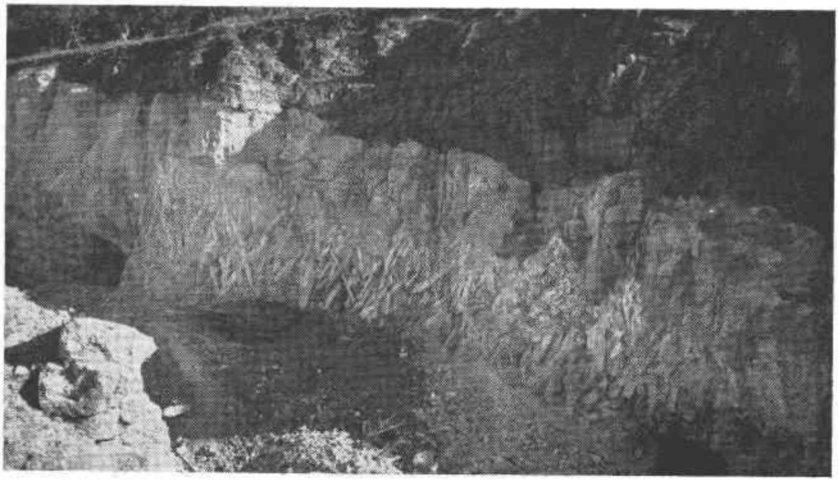

FIG. 1. Fringe-like aggregate of giant, lath-shaped spodumene crystals, Harding mine, New Mexico. The largest crystals are about 12 feet long. The quarry face here exposes the upper one-third of the thick, gently dipping pegmatite dike.

what smaller, though still giant, crystals of spodumene are present elsewhere in the Black Hills region, at several localities in eastern Manitoba, in the Kings Mountain region of North Carolina, in the Harding pegmatite of Taos County, New Mexico (Fig. 1; 8, Fig. 8), in a small area of pegmatites northeast of Wickenburg, Arizona, and in the Stewart pegmatite of San Diego County, California (24, Fig. 22). Similar occurrences have been reported from other parts of the world, and appear to be uncommon but by no means rare.

Giant crystals of perthite (mainly microcline with intergrowths of sodaclase feldspar) are more widespread in their occurrence, although fewer careful measurements seem to have been made of the largest ones. Most often quoted are the "individual feldspars more than 10 meters in length" that were noted by Brögger (6, p. 231) in pegmatite dikes south of Moss, in Norway. Olaf Andersen, in a letter to Hess (19, p. 455), mentioned a crystal 7 by 12 by 30 feet from the Iveland district, north of Kristiansand, and Lindgren (30, p. 754) noted that in the Ural Mountains of Russia a quarry was opened in a single orthoclase crystal! Bastin (2, p. 13), in his early report on feldspar deposits of the United States, mentioned single crystals 20 feet across, and a 20-foot crystal was described from the American mine, at Groton, New Hampshire, by Crosby and Fuller (10, pp. 154–155). Cleavage surfaces 20 to 23 feet across were observed by the writer in underground workings of the Coats and Kiawa mines, near Petaca, New Mexico, and crystals only slightly smaller are known from many other occurrences in the southwestern United States. Five- to 10-foot individuals are mentioned in published descriptions of pegmatites and pegmatite deposits too numerous to mention individually.

Well-faced crystals of pegmatite quartz, some of them a foot or more in diameter, have been recorded by Crosby and Fuller (10, p. 336), Kemp (26, p. 706), Frondel (13, p. 473), and many others, and Hess (18, p. 289) has remarked that "quartz crystals from a number of pegmatites have weighed more than 1,000 pounds each." Evidently overlooked by most observers, however, are the anhedral individuals of similar or even much greater size that form aggregates of so-called massive quartz, or "bull quartz." Such aggregates are conspicuous in the interior parts of many pegmatite bodies, and commonly contain anhedral crystals that weigh several tons. The writer has seen rhombohedral cleavage surfaces 2 to 9 feet across in the quartz cores of several large pegmatite masses in western Arizona and southern California, and such coarse textures are by no means rare in many other areas.

The micas, as represented by muscovite and phlogopite, can take their place among the real giants of pegmatite crystals. Well-known sources of very large crystals include the pegmatites of Brazil, Ceylon, India, Madagascar, Russia and Siberia, the Transvaal, eastern Canada, and the southeastern United States. Two of the most outstanding occurrences are at the Purdy mines in Mattawan Township, Ontario, from which Spence (38, p. 547) recorded a muscovite crystal $9\frac{1}{2}$ feet by 7 feet in plan and nearly 3 feet thick, and at the Lacey mine in Loughborough Township, Ontario, whence Ellsworth (quoted in 32, p. 363) described an enormous crystal of phlogopite 14 feet in diameter and 33 feet long, with an estimated weight of "not less than 90 tons!"

Beryl, a widespread though not particularly abundant accessory constituent of many pegmatite bodies, forms some crystals of truly exceptional size. One of these was partly exposed for several years in the Ingersoll No. 1 pegmatite, in the Black Hills region of South Dakota; a gigantic hexagonal prism (39), it was measured at different times by Hess (18, p. 289), who reported a basal diameter of 45 inches, and by Connolly and O'Harra (9, p. 254), who reported the diameter of another section as 46 inches. Although its length never was determined accurately, this prism probably weighed more than 30 tons. A mass of beryl weighing approximately 100 tons is reported from the same pegmatite by Page,* who also notes a tapering prismatic crystal, once exposed in the Bob Ingersoll No. 2 mine, that was 18 feet long and 6 feet in maximum diameter. Another immense crystal, 18 feet long, 4 feet in diameter,

* Page, L. R., Personal communication, 1952.

and weighing about 18 tons, was noted from Albany, Maine, by Gedney and Berman (14, p. 79).

Several large "logs" of beryl were taken from partly kaolinized feldspathic pegmatite at the Herbb No. 2 mine, in Powhatan County, Virginia, during operations for sheet mica in 1944. This interesting occurrence has been described by Brown (7, p. 265). One of the crystals, as "reconstructed" by the writer from huge segments on the dump, must have been about 14 feet long and 17 to 23 inches in diameter. A somewhat different but no less spectacular occurrence was encountered at the Harding mine in northern New Mexico, where a 23-ton lens of beryl was mined in 1944 by Arthur Montgomery (31, p. 33). This irregular mass appeared to consist of several very large anhedral crystals.

Fluorite, a rather common accessory mineral in some pegmatite bodies, forms rudely faced crystals as much as 7 feet in diameter in several dikes of the Petaca district, New Mexico (Fig. 2; 21, p. 62). Dodecahedral crystals with somewhat smoother faces are scattered through the massive quartz of many dikes and pod-like masses of pegmatite northeast of Congress Junction, Arizona, where they reach diameters of 3 to 4 feet. Hess (16, p. 289) has reported crystals a foot across from the Baringer Hill, Texas, pegmatite.

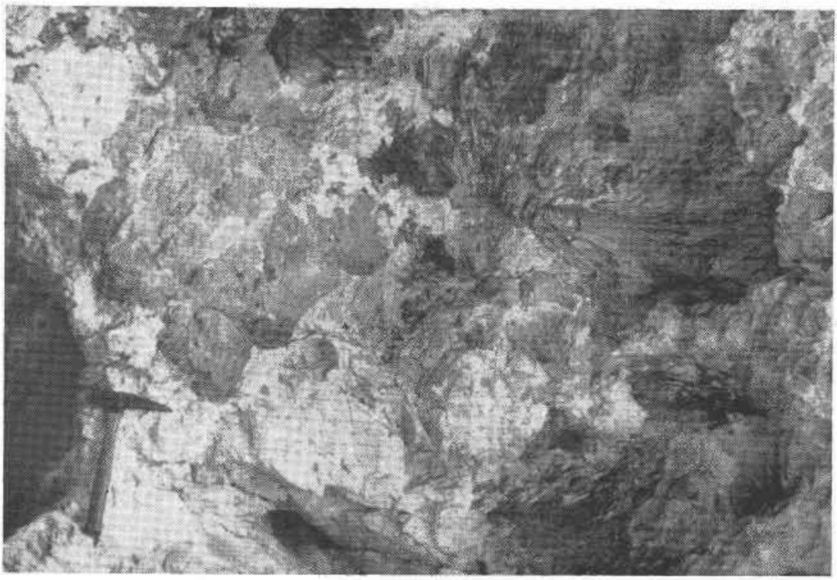

Fig. 2. Giant subhedral crystal of fluorite (dark gray, above hammer) in very coarse-grained quartz—perthite—muscovite—albite pegmatite, Globe mine, Petaca district, New Mexico. White albite veins and corrodes this crystal, as well as several large books of muscovite (upper right).

Rough crystals of amblygonite 4 to 5 feet in diameter are present in several pegmatite bodies near San Domingo Wash, northeast of Wickenburg, Arizona. Masses of amblygonite weighing tens of tons have been reported from the Black Hills region (18, p. 289), from the Stewart mine in San Diego County, California (24, p. 40), and from many other localities, but these appear to be very coarse-grained aggregates, rather than single giant crystals.

Other examples of unusually large crystals include the 9-foot prisms of black tourmaline that were exposed for many years in the walls of the Southern Pacific silica quarry near Nuevo, in Riverside County, California; strips of biotite 3 to $5\frac{1}{2}$ feet long in several other southern California pegmatites; a book of biotite 6 feet wide, 9 feet long, and 2 feet thick reported by Andersen (19, p. 455) from a locality near Arendal, Norway; topaz crystals "up to 3 feet long" noted by Bandy (1, p. 521) from Portuguese East Africa; and a gigantic, smooth-faced, 596-pound topaz crystal, obtained from Minas Gerais, Brazil, that is now in the collection of the American Museum of Natural History. A columbite crystal, in part interleaved with several thin sheets of quartz, was reported from the Ingersoll No. 1 pegmatite in the Black Hills area by Blake (3, p. 341), who described it as 20 inches square, 24 inches long, and at least a ton in weight. A crystal of monazite, $6\frac{1}{2}$ inches by $9\frac{1}{2}$ inches by 11 inches in size, was described and pictured by Schaller (36, pp. 435-436) from a pegmatite deposit in Madison County, North Carolina. A 75-pound crystal of allanite was once collected by W. C. Brögger from pegmatite in Norway (26, pp. 707–708), and a mass of allanite weighing more than 300 pounds was reported from the Baringer Hill, Texas, pegmatite by Hess (16, p. 291).

This brief catalog of outstanding occurrences, though far from complete, should suffice as a background for more detailed consideration of the individual crystals. It is evident that many different mineral species form these unusually large individuals in pegmatite, and that such giant-textured pegmatite is widespread in its geographic distribution. No attempt will be made in this paper, however, to outline or to analyze the trends in geographic occurrence of various species of giant crystals. The principal aim of the following discussion is to summarize the characteristics of such crystals and the features of their occurrence within masses of pegmatite, and to consider these features in broad genetic terms.

General Features

Chief among the pegmatite minerals that form crystals of exceptional size are quartz, beryl, potash and sodaclase feldspars, spodumene, and the micas biotite, muscovite, and phlogopite. Such other minerals as amblygonite, apatite, fluorite, petalite, and tourmaline are less widespread, and among the rarer species should be listed allanite, columbite-tantalite, monazite, topaz, triphylite-lithiophilite, and triplite. Most of these minerals occur in pegmatite of granitic to monzonitic composition, but many also occur in quartzdioritic and granodioritic pegmatite. Hornblende, hypersthene, plagioclase, and a few other species are characteristic of very coarse-grained pegmatites that are more basic in composition, but in general do not form individuals of such great size as the minerals noted above.

The numerous examples of giant crystals already cited will give some idea of the maximum sizes that are attained. The dimensions of such individuals are measurable in feet or even in tens of feet, and their weights commonly amount to hundreds of pounds. Some of the largest individuals of beryl, feldspar, mica, and spodumene weigh many tons. In general, the ranges of size and weight vary considerably from one mineral species to another, and, for a given species, from one pegmatite body to another.

Most of the crystals show external faces, and ordinarily their form is typical for the species involved. Thus prismatic crystals are characteristic of most apatite, beryl, spodumene, and tourmaline, whereas crystals of amblygonite, fluorite, and monazite are stubby or equant. Some giant individuals of perthite are equant, but in other occurrences the crystals are much elongated parallel to the *a*-axis. The micas also show some variation in habit. Most characteristic are thick tablets, but a few crystals are greatly elongated parallel to their *c*-axis and form rough prisms, some of which taper markedly. Other crystals, notably of biotite, form thin strips and blades whose flat surfaces are parallel to the principal cleavage direction. Columbite and allanite generally occur as thick tablets and rough, nearly equidimensional masses, but long blades and prisms also have been observed.

Some of the individual crystals, particularly the largest ones of elongate habit, are distinguished by gross variations of form. Spodumene and tourmaline commonly taper from one end to the other, as traced along the *c*-axis of the crystal, and the perthite crystals in many pegmatite bodies show similar tapering along the *a*-axis. Tapered crystals of beryl are somewhat less common. Most of these show a progressive cross-sectional thinning along the *c*-axis from one end to the other, the remainder a thinning toward both ends from a central maximum. Less regular variations of form are known from crystals of both these and other mineral species.

Most of the giant anhedral crystals are equidimensional or nearly so.

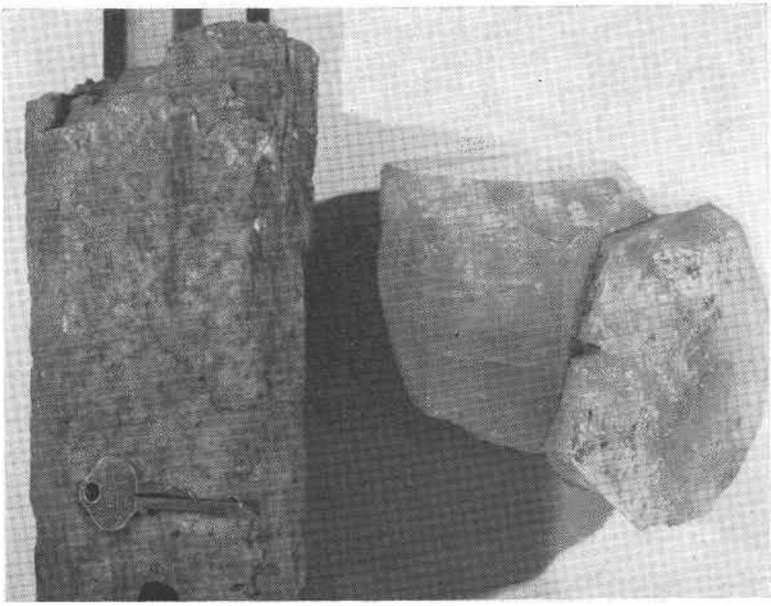

FIG. 3. Contrast in form and surfaces of crystals of pale blue beryl, San Pedro mine, Pala district, California. Large, rough prism at left is from very coarse-grained quartz—perthite pegmatite; stubby, smooth-faced, partly transparent prisms at right are from a pocket at the center of the same dike.

Quartz is most abundantly represented among such crystals, but this form also is developed by some beryl and several of the lithium-bearing phosphates. Nearly all the anhedral crystals have rough, highly irregular surfaces.

Those giant crystals that are euhedral tend to be morphologically simple, with development of a relatively few broad faces that are characteristically rough in detail. In marked contrast are the much more nearly perfect, mirror-like faces so commonly found on smaller, morphologically more complex crystals of the same mineral that occur elsewhere in the same pegmatite body (Fig. 3). Moreover, the giant crystals are nearly everywhere milky or opaque, whereas the smaller and more smoothly faced crystals typically are much more transparent.

Many of the giant crystals are single, separate individuals that are scattered through the enclosing pegmatite like plums in a pudding. Others, particularly those of elongate habit, form groups in which the individuals are parallel, radiating, or diversely oriented. Some of the spodumene "logs" in the Etta pegmatite of the Black Hills region form a mesh-like aggregate of gigantic, randomly disposed jackstraws, whereas others extend radially outward from masses of much finer-grained pegmatite, as pointed out by Hess (18, p. 295). Huge, lath-shaped crystals of the same mineral, where exposed in the gently dipping Harding dike of northern New Mexico, are arranged in a fringe-like aggregate whose principal elements are vertical or nearly so (Fig. 1). Most of the crystals are tapered, and have been described by Hess (18, p. 295) as "pointing upward." Similar arrangements are characteristic of much tourmaline, muscovite and other micas, and allanite, as well as some quartz and beryl. Preferred orientation of prismatic or tabular crystals generally occurs at or near the walls of a pegmatite body, and the crystals that are present in the more central parts of the body ordinarily show diverse attitudes.

Relations to the Pegmatite Framework

Nearly all the crystals of giant size occur in pegmatite bodies that are zoned, i.e., that comprise lithologically distinctive units that are more or less concentrically disposed within a given pegmatite body and reflect, at least to some degree, its general shape and structure (Fig. 4). These systematically arranged units have drawn the attention and comments of pegmatite investigators for many years, and recently were described, classified, and discussed in considerable detail by Cameron, Jahns, McNair, and Page (8, pp. 11–70). As recognized from the walls of a given pegmatite body inward toward its center, these units have been termed border zone, wall zone, intermediate zone (or zones), and core. In general, the coarsest minerals occur in cores and intermediate zones (Fig. 4), but the wall zones of some pegmatite bodies also contain giant crystals.

Ordinarily there is some correlation between the size of a pegmatite body and the size of giant crystals within it, and Cameron, et al. (8, p. 59) have noted, for example, that "the larger the body in question the larger the crystals in the core." Most of the giant crystals cited in the first part of this paper occur in pegmatite bodies with minimum dimensions of at least several tens of feet, and in general are present only in certain parts of these bodies. The correlation of sizes is only a rough one, however, and it cannot be applied to all occurrences. Thus many very large pegmatite bodies contain no giant crystals, and, in contrast, some fairly small bodies do contain such crystals. Outstanding examples of the latter are several dikes at the Purdy mine in Ontario, in which enormous books of muscovite extend nearly from wall to wall.

Of particular significance in the sequence of lithologic units within a zoned pegmatite body is a characteristic sequence of textures. By far the most widely represented are granitoid, prophyritic, and giant peg-

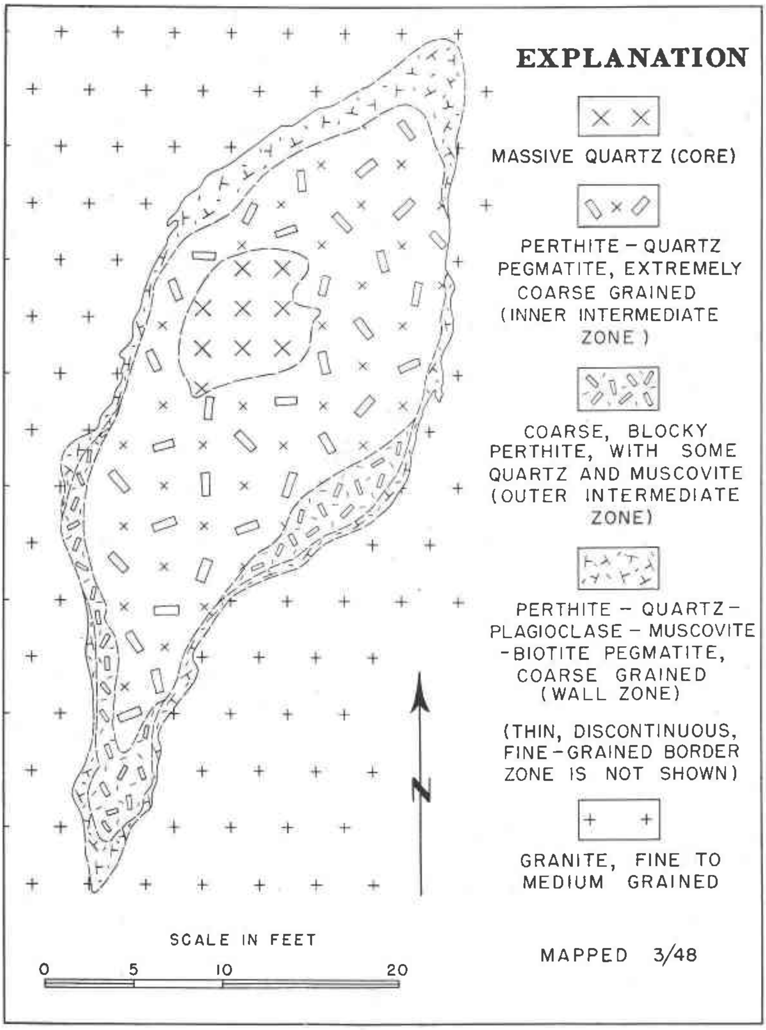

FIG. 4. Geologic map of a small, pod-like pegmatite body, showing typical concentric arrangement of zones. Relative coarseness of the pegmatite units is indicated diagrammatically by the map patterns. Robbins silica prospect, San Bernardino County, California.

matitic textures, which generally appear in this order from the walls of a pegmatite body inward to its center.

Granitoid, as used in the standard sense of the term, refers to pegmatite in which the mineral grains are dominantly anhedral and approximately the same size (Fig. 5). In nearly all granitoid pegmatite they are 8 inches

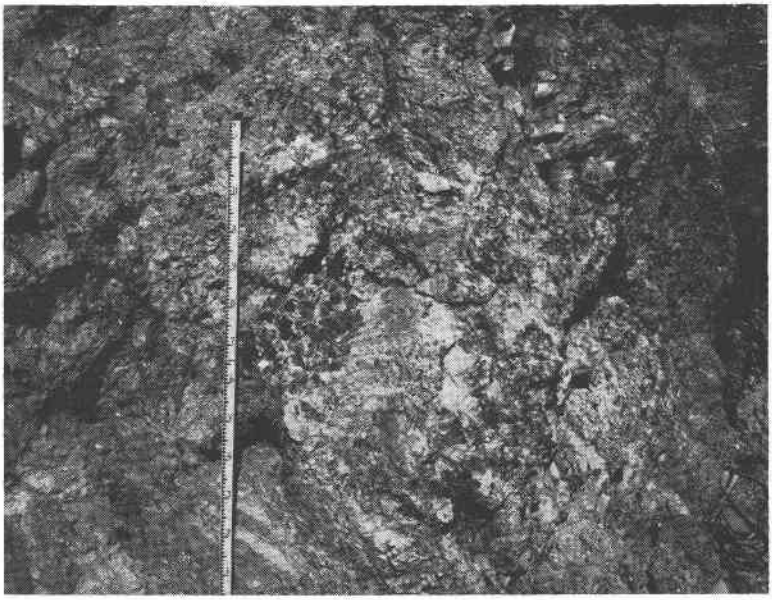

FIG. 5. Coarse-grained perthite—quartz—muscovite—albite pegmatite, Joseph mine, Ojo Caliente district, New Mexico. The texture of this rock is granitoid in the vicinity of the stadia rod, but several very large masses of perthite and quartz appear in the right-hand part of the exposure.

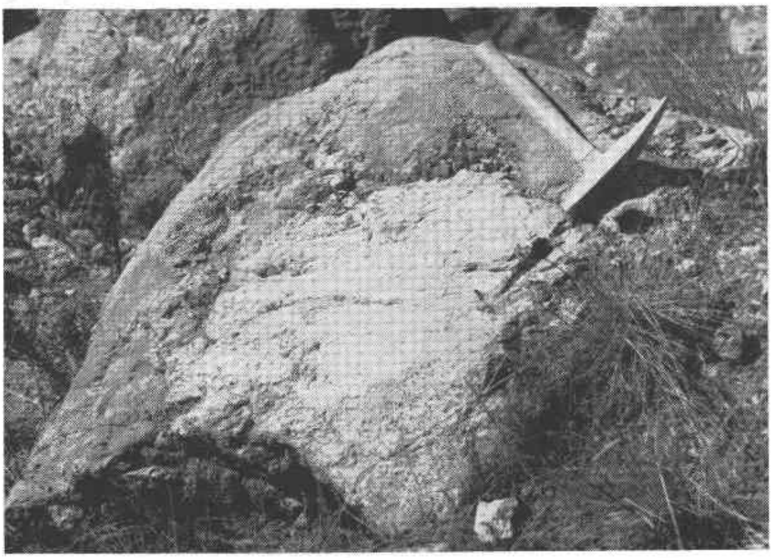

FIG. 6. Porphyritic perthite—plagioclase—quartz—muscovite pegmatite, Senpe mine, Pala district, California. In foreground light is reflected from large, ragged phenocryst of perthite, which contains much graphically intergrown quartz.

or less in maximum dimension. Departures from the normal texture are caused mainly by the tendency of some minerals, notably the micas, to develop crude crystal faces, and by the occurrence in some pegmatite of scattered crystals that are larger than the others. No such crystals reach giant size, however.

Porphyritic texture, as typically developed in pegmatite, results from the occurrence of very large, prominent crystals, or phenocrysts, in a groundmass of distinctly smaller crystals (Fig. 6). The phenocrysts are

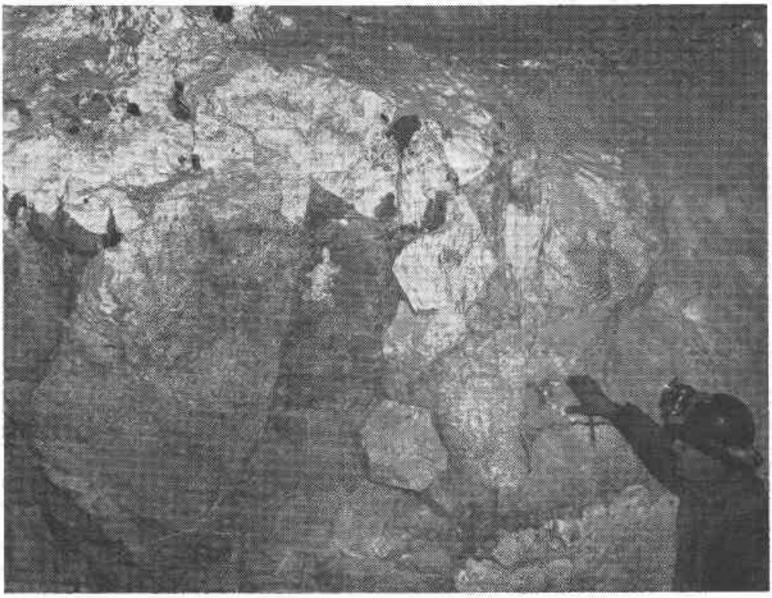

FIG. 7. Exposure showing giant pegmatitic texture, Cribbenville mine, Petaca district, New Mexico. The giant, subhedral crystals of perthite are not phenocrysts, as the enclosing quartz (dark gray) is equally coarse grained. The large, white masses at the upper left and lower right are cleavelandite, in which are scattered books of muscovite (very dark gray).

subhedral or euhedral, with very rough and irregular faces, and most are 1 to 4 feet in maximum dimension. The most abundant phenocryst constituent is perthite, with or without graphically intergrown quartz. Apatite, beryl, garnet, and tourmaline also occur as very large crystals in some varieties of porphyritic pegmatite. The beryl crystals commonly are anhedral, in contrast to the phenocrysts of the other minerals.

Giant pegmatitic texture, as herein applied to the coarsest parts of many pegmatite bodies, is characterized by extremely large, euhedral to anhedral crystals that are of nearly uniform size or show a more or less continuous variation in size (Fig. 7). Such pegmatite is therefore

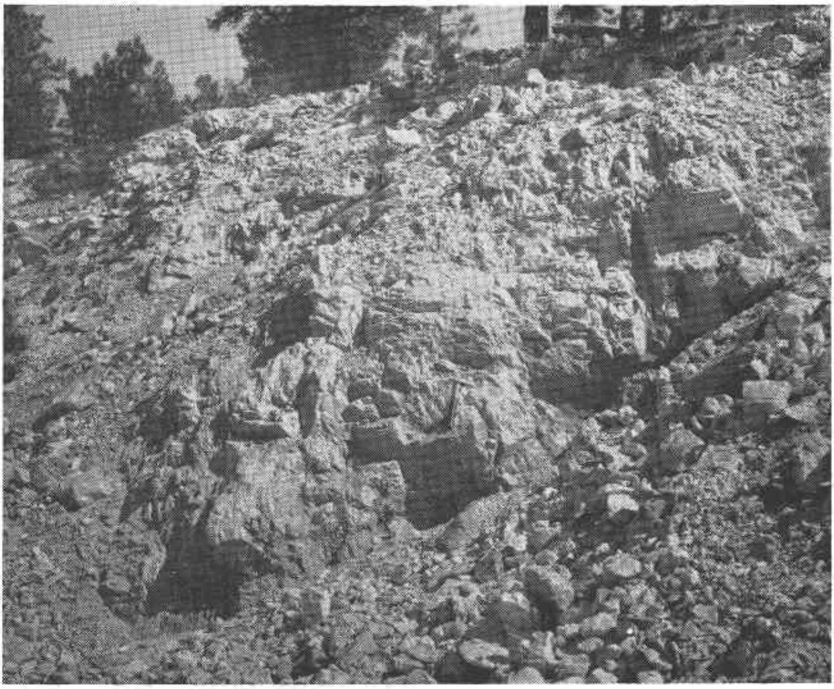

FIG. 8. Typical massive quartz in the central part of a pegmatite body, Kiawa mine, Petaca district, New Mexico. The quartz forms anhedral crystals that are 1 foot to 8 feet in diameter, and hence the rock is much coarser grained than it appears to be. Note the many closely spaced fractures.

non-porphyritic, though not necessarily even grained. Pecora, et al. (33, p. 250) have aptly designated this texture in Brazilian pegmatites as "a gigantesque variation of the granitic pattern." The terms pegmatitic and micropegmatitic have been applied by some authors to certain geometrically regular intergrowths of minerals, but such alternate terms as graphic, micrographic, and granophyric seem more appropriate in this connection. These intergrowths are relatively fine grained, and hence texturally quite distinct from giant pegmatitic aggregates, which contain most of the largest crystals to be found in pegmatites.

Giant pegmatitic textures are most commonly developed in zones of massive quartz (giant anhedral crystals) (Fig. 8), quartz-perthite pegmatite (Fig. 7), quartz-spodumene pegmatite (Figs. 1, 10), and quartz-perthite-tourmaline pegmatite. The mineralogy of these extremely coarse-grained rock units ordinarily is very simple, and rarely are more than three species represented among the large crystals of a given unit.

Other kinds of texture are present in many masses of pegmatite, but

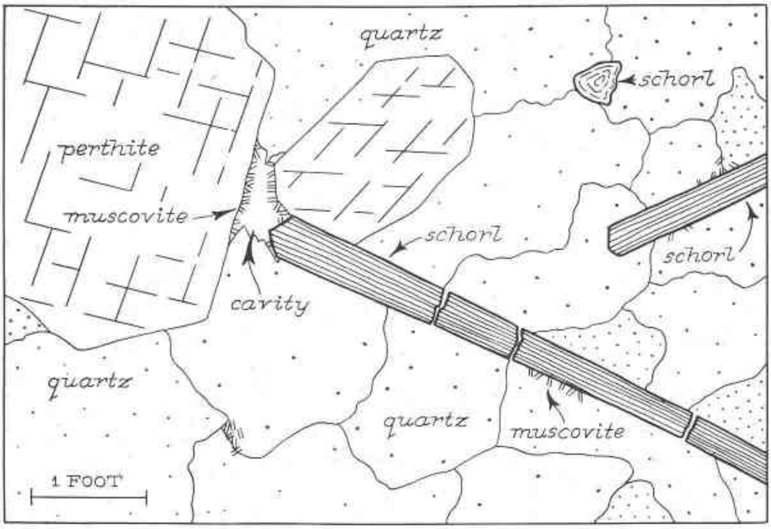

FIG. 9. Giant pegmatitic texture in quartz—perthite—schorl core of large pegmatite dike near Sage, Riverside County, California. The large crystals show smooth faces where they form the walls of the small cavity. Contacts between anhedral quartz crystals are diagrammatic, but positions of most are correct to within an inch.

are subordinate to the three principal types described above. Graphic intergrowths, chiefly of quartz in potash feldspar (graphic granite), are widespread, and the host crystals commonly are phenocrysts in porphyritic varieties of pegmatite (Fig. 6), or occur in varieties with giant pegmatitic texture. Some pegmatite shows miarolitic texture, and contains irregular cavities or pockets that are walled with well-faced crystals. Most of these cavities occur in the very coarse-grained central parts of zoned pegmatite bodies, but some others, generally smaller ones, lie in the outer parts. Crystals of considerable size are present in some cavities, but rarely are they as large as other crystals of the same minerals that occur in nearly solid rock. These other crystals generally lie entirely outside the cavities, but a few terminate as parts of the cavity walls (Fig. 9).

Textural complexities are characteristic of pegmatite bodies that contain fracture fillings or masses of replacement material. Thus giant crystals of one mineral commonly show fracturing and subsequent healing by another mineral (Fig. 10), or are veined and corroded by aggregates of much finer-grained material (Figs. 2, 11). All degrees of replacement can be observed in some giant crystals, ranging from thin, fracture-controlled stringers to stockworks or widespread disseminations of the younger material in the older. Common end-stage products are huge pseudomorphs and partial pseudomorphs of sugary albite after perthite, albite after muscovite, muscovite or hydrous mica and clay minerals after spodumene, fine-grained muscovite after topaz, fine-grained muscovite and clay minerals after tourmaline, and hureaulite after lithiophilite, to name only a few. These and other products of fracture-filling and replacement processes have received much attention in the literature on

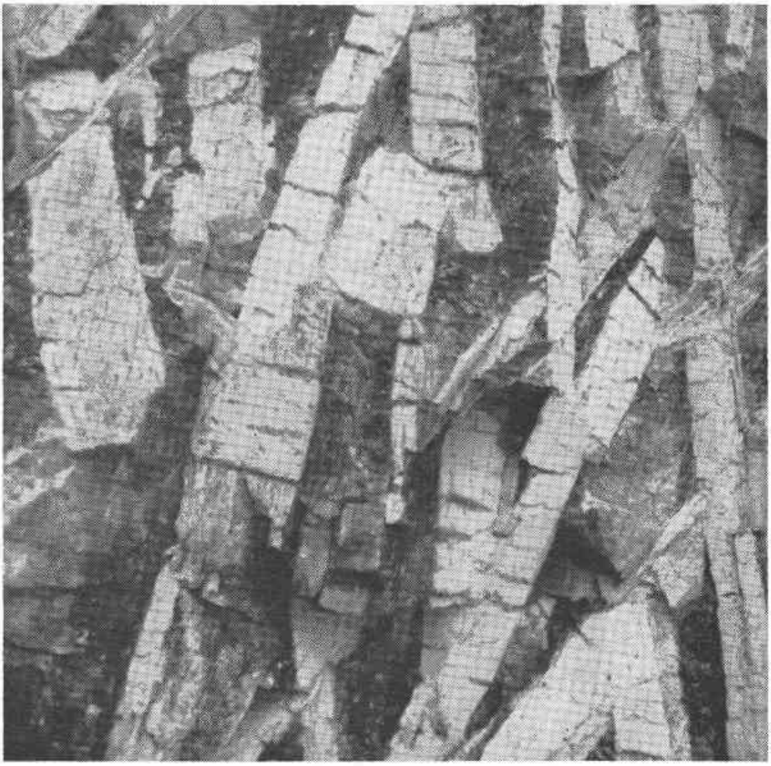

FIG. 10. Detail of giant laths of spodumene showing "healed-fracture" structure, Harding mine, New Mexico. Note matching walls of fractures, which are filled with gray quartz like that enclosing the laths. Width of largest spodumene crystals is about 10 inches.

pegmatites, and recently have been summarized and discussed by Cameron, et al. (8, pp. 70–97).

In general the grain size of a pegmatite body that contains giant crystals increases from its walls to its center, or from its border zone to its core. As shown in Fig. 12, the rate of increase is far from uniform. In most occurrences the average grain size increases gradually inward from the walls, thence very markedly and abruptly, and thence very slightly into the core. In some pegmatite bodies, especially very large ones, there is a slight decrease at the center, and in those pegmatite bodies with cavities or much replacement material there is a considerable final decrease.

The narrow region of marked increase in grain size reflects the generally sharp boundary between granitoid or porphyritic pegmatite, on the one hand, and the giant pegmatitic aggregate that forms the interior part of

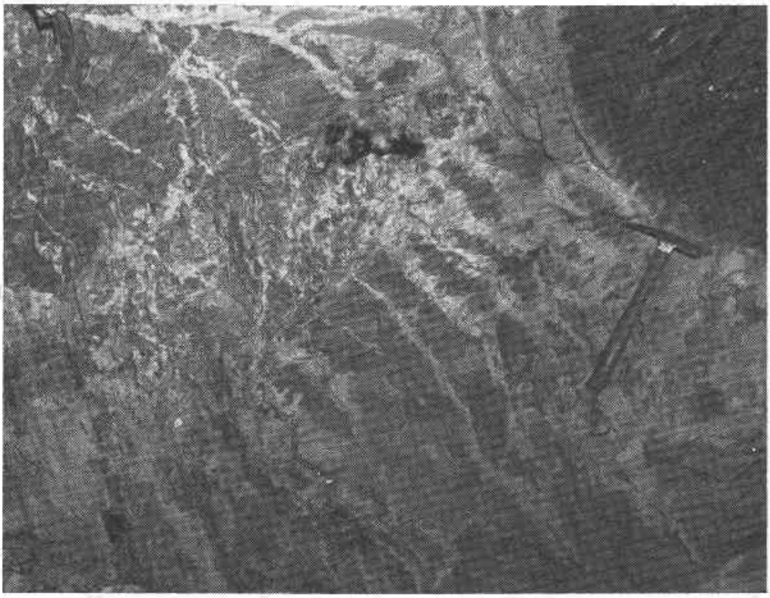

FIG. 11. Gigantic crystal of perthite (dark gray), veined with cleavelandite and encroached upon by fine-grained aggregates of quartz, albite, and muscovite. Globe mine, Petaca district, New Mexico.

the mass, on the other. If a plot of grain size is made on the basis of the largest crystals, rather than the average crystals, the major break in the curve is moved to the left and softened somewhat (Fig. 12), particularly for those pegmatite bodies that contain a porphyritic zone.

The curves shown in Fig. 12 are derived from the pegmatites of only one region, but in general shape they are applicable to most other pegmatites that contain giant crystals. Indeed, the abrupt increase in grain size is one of the most characteristic features of such pegmatite bodies. It occurs nearer the walls of some, nearer the centers of others, but invariably it can be correlated with a marked change in the rock fabric, involving especially the strong tendency of certain minerals to develop crystal faces. There is an accompanying tendency, at least in some pegmatites, toward a much simpler mineralogy immediately inside this textural break.

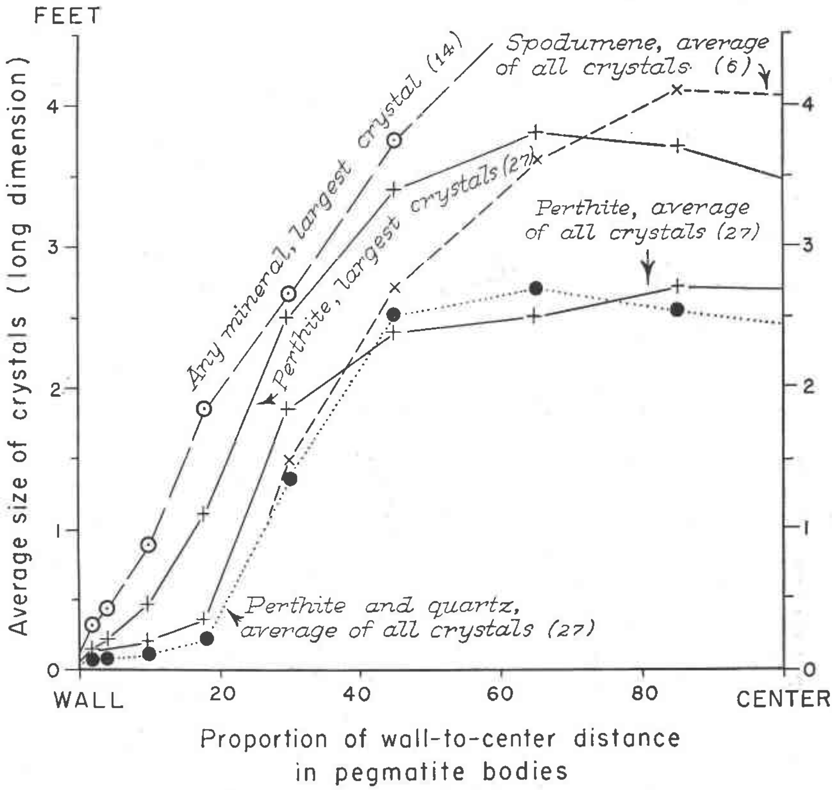

FIG. 12. Curves showing some general grain-size variations in large, zoned pegmatite bodies in the Hualapai, Bagdad, and White Picacho districts of western Arizona. Each curve represents an average of measurements made on the number of pegmatite bodies shown in parentheses; none of these bodies is less than 40 feet in maximum outcrop breadth. Each point on the "any mineral" curve represents an average that may involve more than one mineral species.

ORIGIN OF THE PEGMATITE FRAMEWORK

The crystallization of pegmatite minerals has been discussed by several generations of investigators, and various theories of genesis have been advanced to account for the characteristic structural, textural, and compositional features of pegmatite bodies. Excellent summaries of these theories have been provided by Kemp (26), Johannsen (25, pp. 74–84), and Landes (29, pp. 41–56), and the subject needs no detailed review here. The origin of zoned pegmatite bodies has been most recently discussed by Cameron, et al. (8, pp. 97–106) and by Flawn (12, pp. 180–190), who reached the conclusion that these rocks are mainly the products of primary crystallization from a magma, under restricted-system conditions (i.e., conditions approaching those of a closed system). The zonal structure has been attributed to fractional crystallization and incomplete reaction between successive crops of crystals and rest-liquid. This view thus reflects, wholly or in large part, the earlier conclusions of Brögger (16, p. 230), Crosby and Fuller (10, p. 157), Warren and Palache (40, p. 146), Kemp (26, pp. 708–709, 722), Landes (29, pp. 53–55), and Shaub (37, pp. 684–688).

It is not the primary purpose of this paper to present in detail the arguments for an essentially magmatic, or "closed-system," origin of the minerals indigenous to pegmatite zones. In summary, however, this concept rests mainly, in the present writer's opinion, upon combinations of eight major features of occurrence:

1. Widespread structural evidence for emplacement of original pegmatite fluid by mechanical injection, in many instances accompanied by digestion of country rock.
2. Consistent evidence for a sequence of zone development from the walls of a pegmatite body inward to its center.
3. Remarkable detailed correspondence in sequences of mineral assemblages from one zoned pegmatite to another.
4. Correspondence between the sequence of essential-mineral development in zoned pegmatites with the sequence of the same mineral species in normal igneous rocks; the sequence of major minerals in zoned pegmatites is basically that of Bowen's reaction series.
5. Similarities of pegmatite fabrics to those of many normal igneous rocks, despite the marked differences in grain size.
6. Strong concentrations of rare elements in some masses of pegmatite.
7. General accordance, in occurrences thus far investigated, between quantitative distribution of rare elements within zoned pegmatites and the distribution predicted for such elements on theoretical grounds.
8. Lack of field evidence that zones in a given pegmatite body were developed by successive replacement of pre-existing rock.

All known features of pegmatite zones seem reasonably explainable on the basis of crystallization from a melt of low viscosity, with or without end-stage deuteric or hydrothermal activity. Many of these features also suggest that masses of pegmatite crystallized inward from the walls of an original chamber, under restricted-system conditions, rather than in some sort of channelway or thoroughfare under more open-system conditions. The pod-like form and concentric internal structure of many pegmatite bodies support this general concept.

Most geologists view the fluid that forms zoned pegmatite bodies as a silicate rest-liquid derived by differentiation during the end stages of crystallization of ordinary plutonic or hypabyssal igenous rocks. Such a fluid also could be drived directly or by differentiation from a palingenetic magma formed through melting of pre-existing rocks, or possibly might be a product of granitization processes. Many investigators, however, have raised serious objections to granitization as a means of accounting for zoned pegmatites. It cannot be denied that much pegmatite may well have been formed from pre-existing rocks through processes of replacement, *in situ*, by highly attenuated fluids, but the rocks that appear to be products of such pegmatitization do not contain giant crystals, nor are they characterized by the internal zoning described above. Pegmatites of this type therefore are not considered in this paper.

The discussion has centered thus far about pegmatite zones and the minerals indigenous to these zones, with little mention of those minerals that plainly were developed by replacement of earlier pegmatite minerals. There is considerable argument among geologists—even among those who agree that pegmatite zones were formed by fractional crystallization from a liquid—regarding the relative importance of replacement processes, especially during the latest stages of pegmatite formation. The general concept of a magmatic stage and one or more hydrothermal stages in the development of the so-called complex pegmatite, as so clearly outlined by Landes (29, pp. 44–56), is variously applied by different investigators. In particular, arguments center about the proportion of replacement material in a given mass of pegmatite, and as to whether the replacing fluids were of deuteric origin (i.e., did the pegmatite body "stew in its own juice" under restricted-system conditions?) or were hydrothermal solutions derived from sources outside the pegmatite body. These questions are significant in terms of the origin of giant crystals in pegmatite.

Origin of the Giant Crystals

The case for primary crystallization

Crystals of giant size have impressed many investigators as primary constituents of pegmatite zones, and hence as products of normal crystallization from a melt, magma, or other fluid. One of the principal reasons for this view is the consistency, from one pegmatite body to another, of the textural relations between the giant crystals and the framework of the pegmatite body in which they occur. These, moreover, are the relations that are typical of many masses of non-pegmatitic igneous rocks.

A given crystal of giant size ordinarily is larger than other crystals of the same mineral that lie nearer to the walls of the pegmatite body, and is about the same size or somewhat larger than those nearer the center of the body. Thus its size and position are fully compatible with the general textural relations within zoned masses of pegmatite, which show either a progressive inward coarsening to a maximum value at the center, or an inward coarsening to a maximum value, followed by some decrease in average grain size near the center. Interestingly enough, this last relation has been reported from many thick igneous dikes of nonpegmatitic rock, and has been interpreted for basaltic dikes by Winkler (41, pp. 562–574) in terms of magmatic crystallization. Naturally, however, Winkler's conclusions can be extended to zoned pegmatite bodies only in those occurrences where essentially closed-system conditions of formation can be established for the entire crystallization history of the pegmatite minerals involved.

Despite the impressive size of the typical giant crystal, it generally is surrounded by other crystals of comparable size, and hence is merely a part of a mineral aggregate with giant pegmatitic texture. This important feature is commonly overlooked, mainly because so many of the enormous crystals of perthite, spodumene, and other minerals occur in massive quartz, which comprises anhedral crystals whose own great size rarely is evident on casual inspection (Figs. 7, 8). Moreover, the quartz is shattered or partly granulated in the interior parts of many pegmatite bodies, which tends to obscure further its giant texture.

Some disparity in dimensions does exist, of course, between adjacent crystals of different mineral species, but this is common in most igneous rocks. Only in some very coarse-grained pegmatite with porphyritic texture is there a marked size difference between the giant crystal and its neighbors (Fig. 6), and here all significant textural relations at the crystal boundaries show plainly and consistently that the giant crystal developed first. This also is compatible with textural relations in more "normal" porphyritic igenous rocks with a much smaller general grain size, and may well reflect some departure from strictly closed-system conditions of formation.

Also meaningful is the consistent relation, in terms of composition and sequence of development, of giant crystals to the zonal structure of the containing pegmatite body. This is a reflection of the impressive consistency of mineral assemblages described in detail for zoned pegmatites by Cameron, et al. (8, pp. 59–70). The quartz-euhedral perthite zone of a given pegmatite body, for example, occurs nearer the walls than a quartz-spodumene zone in the same body, regardless of whether the perthite individuals are 6 inches or 6 feet in maximum dimension. The absolute size of the crystals is significant, to be sure, but is incidental to their relative size and to their sequence of development, and hence to their relative positions within the pegmatite body.

Well-defined trends in composition of mineral species can be recognized in many pegmatite bodies. Within such bodies, for example, the alkali content of the beryl, the lithium content of tourmaline and micas, the tantalum content and manganese-iron ratio in columbite-tantalite, and the proportion of albite in plagioclase commonly increase inward from the walls to the centers. These systematic variations seem most readily explainable in terms of fractional crystallization of pegmatitic liquid. The giant crystals reflect faithfully these trends, so far as their composition has been checked against that of other crystals of the same mineral species in the same pegmatite body.

The orientation of some huge crystals plainly indicates their inward growth from the walls of the containing pegmatite body. In describing spodumene crystals in contact with the outer, fine-grained part of the Silverleaf pegmatite in eastern Manitoba, Derry (11, p. 465) stated that they "increase in size away from the contact and those nearest to it are arranged with their long axes normal to the contact." A similar arrangement characterizes the spodumene laths near the walls of many pegmatite dikes in the Piedmont region of North Carolina, and Hess (20, pp. 954–956) has described and pictured some excellent examples. The fringing, or comb-like, arrangement of tapering spodumene crystals in the hanging-wall part of the Harding dike, in northern New Mexico, has been noted in a previous paragraph (Fig. 1). Tapering crystals of spodumene, tourmaline, perthite, and other elongate minerals are oriented perpendicular or nearly perpendicular to wall-rock contacts or to contacts between zones in many other pegmatite bodies.

Such crystals evidently began to develop from their pointed or thinner ends, and were progressively thickened as they extended inward toward the center of the pegmatite body. This direction of growth is indicated by the well-formed crystal faces at their thick ends, by some tendency toward a radiating, or stellate, arrangement of the crystals from their thin ends, and, perhaps most convincingly, by the disposition of "growth surfaces" within the crystals themselves. Excellent examples of such surfaces are present in elongate crystals of perthite in many pegmatite dikes of southern California. As described from the Mesa Grande district by Jahns and Hanley (23), these crystals are elongate, generally parallel to the *a*-axis, and taper rather uniformly from one end to the other. Their thin ends commonly lie at or near a wall of the enclosing dike, with their long axes perpendicular to the wall or nearly so. Many of these crystals contain phantoms, each of which is surfaced wholly or in part with a very thin, dust-like aggregate of mica flakes, schorl needles, or tiny crystals of salmon-pink garnet. The "dusted" surfaces mark successive stages in the growth of the perthite crystals (Fig. 13),

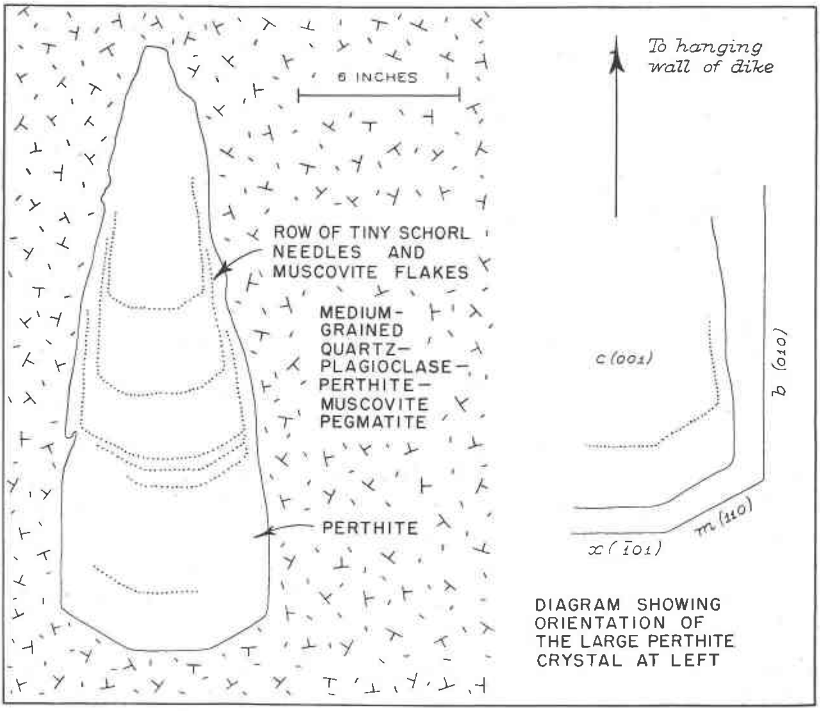

FIG. 13. Wedge-shaped crystal of perthite showing incomplete "phantoms," Mack mine, Rincon district, California. Crystal is elongate parallel to the *a*-axis, which is nearly normal to the hanging wall of the pegmatite dike.

and some are so continuously developed that well-faced phantom crystals are easily obtained by rough cobbing with a hammer. Similar phantoms (Fig. 14) are abundant in other pegmatite districts, both in southern California and elsewhere.

Finally, there seems to be a lack of direct evidence that the giant crystals grew by replacement of other minerals; indeed, most of their textural relations in the enclosing pegmatite indicate early development as phenocrysts, or essentially simultaneous crystallization with respect to immediately adjacent coarse-grained minerals. In other words, the giant crystals appear to be truly indigenous to the pegmatite zones in which they occur.

Fracture-fillings, as well as corrosion veins, pseudomorphs, and other replacement features are abundant and widespread in pegmatites, but these demonstrate attack and replacement *of the giant crystals*, generally yielding aggregates of younger, much finer-grained minerals. Examples of such replacement have been carefully described and discussed by

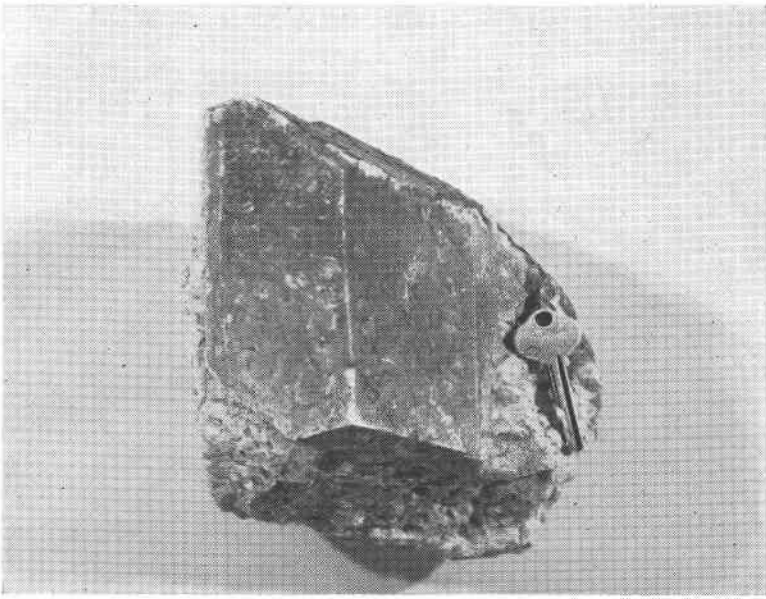

FIG. 14. "Phantom" crystal of perthite with graphically intergrown quartz, Chihuahua Valley, Riverside County, California. This crystal formed the central part of a much larger individual of graphic granite, part of which is still attached. The "phantom" faces are coated with thin scales of muscovite and tiny needles of schorl.

Schaller (35, pp. 274–275), Landes (27, pp. 371–398, 401–409; 28, pp. 549–558), Hess (18, pp. 293–296), Gevers (15, pp. 351–375), and many others. In contrast, there appears to be no comparable textural or structural evidence to indicate that the giant crystals themselves are pseudomorphous after other minerals, or that they developed by replacement of earlier solid material in any other way.

The case for replacement

Relations of individual crystals

In analyzing the numerous and well known arguments in favor of a replacement origin for giant crystals, one might begin by asking whether size alone is significant in this connection. Some investigators have suggested that there is a limit to the size that a crystal of a given substance can attain by growth under a given set of conditions, regardless of how much material is available for nourishment, and have theorized about the governing factors involved. Such limits might well exist, but they have not been established for growth of crystals from pegmatitic liquids, and it seems doubtful whether they could be set accurately on the basis of information now available. Further, there seems to be no theoretical basis for assuming that single crystals of a given rock-forming mineral can grow to greater size by replacing solid material than by developing directly from a solution; indeed, hundreds of experiments on crystal growth suggest that precisely the opposite may be the case, even though it must be admitted that conditions of growth in most laboratory experiments are not strictly comparable to those that probably obtained during the formation of minerals in intrusive igneous rocks. So far as pegmatite occurrences are concerned, few observers seem to have shrunk from the concept of huge perthite individuals crystallizing from a magma, and it scarcely seems reasonable to reject a similar origin for giant crystals of other minerals on the basis of their size alone.

Remarkably little *direct* evidence for growth of giant crystals by replacement has been recorded in the literature on pegmatities, although, as noted above, replacement relations between relatively fine-grained minerals and earlier, coarser-grained material have been described from hundreds of occurrences. Landes, who gave particular consideration to the origin of large crystals in several pegmatite districts, concluded that the huge spodumene "logs" in the Keystone, South Dakota, pegmatites were developed by replacement of earlier formed magmatic minerals. He pointed out (28, p. 548), in support of this conclusion, that these crystals "exhibit cross cutting relationship to the other minerals in the pegmatites," but frankly acknowledged that "in the Etta mine they are so huge that this characteristic is not easily observed, but in the Hugo mine a small spodumene crystal passes directly through a large apatite individual."

Evidently the cross-cutting relations of these giant crystals are not wholly convincing as evidence for replacement. Although the writer has had no opprotunity to examine these Black Hills occurrences in detail, he has made careful studies of fourteen large exposures of similar giant-textured quartz-spodumene pegmatite in the Southwestern States. In none of these occurrences was it possible to demonstrate a cross-cutting of quartz by spodumene in a manner suggesting replacement; instead, the quartz was found to occur as separate, diversely oriented crystals impinging on opposite sides of a given prism of spodumene (Fig. 15). Similar relations appear to be characteristic of the quartz and feldspars that are associated with giant prisms of tourmaline and beryl at other localities. And if these relations are as characteristic as they seem to be, one can only agree with Shaub (37, p. 681) that there is little structural evidence in pegmatites that indicates or even strongly implies transection of earlier solid material by giant crystals of elongate habit.

Even a demonstrable "penetration" or "separation" of one large indi-

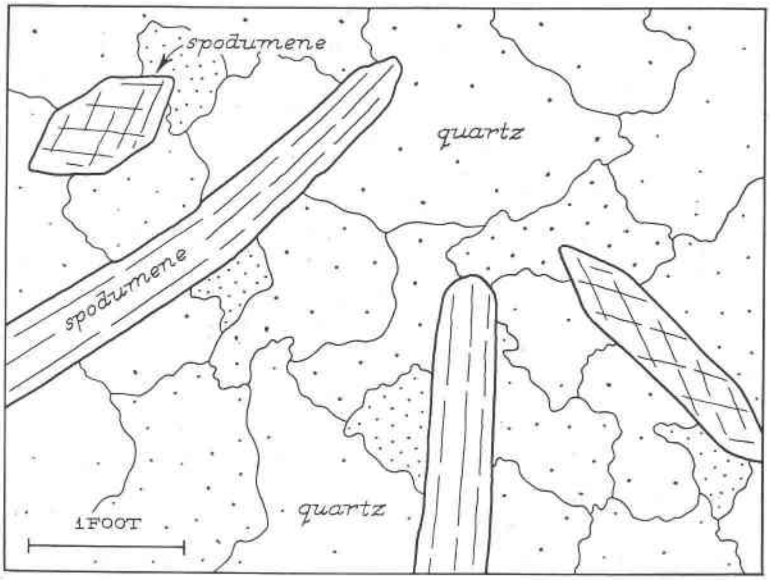

FIG. 15. Giant pegmatitic texture in quartz—spodumene pegmatite, Midnight Owl mine, White Picacho district, Arizona. Note how spodumene crystals are enclosed by an aggregate of diversely oriented, anhedral crystals of quartz. Contacts between quartz crystals are diagrammatic in detail, but nearly all are correct in position to within an inch.

vidual by another, as in the single occurrence specifically cited by Landes (28, p. 548), can be interpreted in more than one way. The same relations could be the result of nearly simultaneous crystallization from a liquid, with one crystal partly enveloping the other. The frequency of such occurrences would be a function of several factors such as the number, positions, and orientations of the crystal nuclei and the disposition of growth-rate vectors for the respective crystal lattices. Moreover, detailed examination of the mineral contacts in such occurrences from several pegmatite districts repeatedly reveals the presence of tiny apophyses, veinlets, and other features that suggest initial development of the "penetrating" crystal, followed by growth of the other crystal around it (Fig. 16).

Landes (28, p. 548) also noted irregular and abrupt changes in the thickness of the spodumene crystals in the Etta mine, and attributed these changes to differences in replaceability of the earlier minerals at whose expense the spodumene was formed. Although one might expect more even growth in a crystal forming from a liquid, as he suggested, a distinct uneveness does seem to be characteristic of many crystals that are developed very rapidly, particularly when they reach large sizes. As pointed out by Frondel (13, pp. 469–470), several investigators have remarked on the tendency of crystals to become irregular and highly imperfect when grown to large sizes in the laboratory. Perhaps more important with respect to the spodumene logs in the Etta mine is the possibility that they were competing for space with very large crystals of quartz and other minerals during a period of essentially contemporaneous growth, so that the irregularities of form might reflect to some degree the available space in a crystallizing mesh of extremely coarse texture. Minerals of much smaller grain size evidently developed later, and obscured some details of the earlier crystal boundaries.

Inclusions of other minerals are scattered through many giant crystals in pegmatite, and have been interpreted by some observers as residua of earlier crystals that were in large part replaced during growth of the giant hosts. These inclusions, which commonly are diversely oriented and show rounded, smooth surfaces, might be alternatively viewed as small, growing crystals that were caught and enclosed by the much more rapidly growing lattices of the giant hosts. One might expect such crystals to be subhedral or euhedral, however, as pointed out by Landes (28, p. 548).

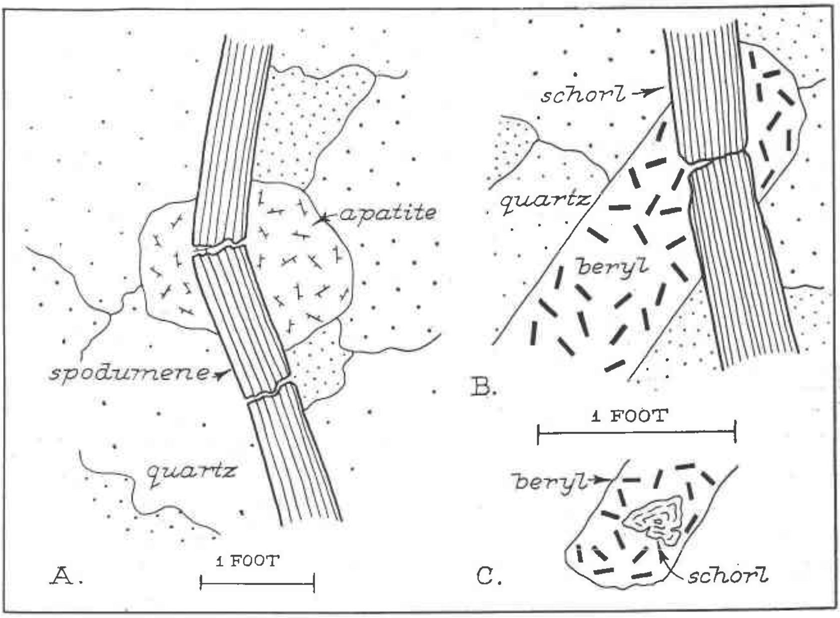

Fig. 16. Typical examples of older crystals "penetrating" younger crystals. *A*. Fractured prismatic crystal of spodumene, in part surrounded by younger crystal of apatite, Midnight Owl mine, White Picacho district, Arizona. *B, C*. Long prisms of schorl in part surrounded by younger crystals of beryl, Fano mine, Riverside County, California.

To the writer, they seem most readily explained in terms of very rapid crystallization of the host individuals from a silicate liquid, with entrapping of droplets and globules of the liquid (or of crystals and liquid) by these giant individuals; subsequent crystallization of the trapped liquid would yield inclusions that would nearly fill the rather smooth-walled spaces occupied by the globules of liquid. Upon crystallization, the included liquid should contribute some material to the host crystal and some to the final inclusion, in proportions depending upon the composition of the liquid. The actual occurrences are in accord with this, as nearly all the inclusions are mineralogically identical with the other large crystals that flank or partly enclose the giant hosts. Thus the spodumene crystals in giant-textured quartz-spodumene pegmatite commonly contain small, rounded inclusions of quartz (with very minor amounts of albite and other minerals).

The problem of support

How could a giant crystal be supported during its growth from a liquid? This question has been raised most frequently with reference to crystals of spodumene (see, for example, 18, pp. 290–295; 9, pp. 238–239; 28, pp. 547–549), whose specific gravity is distinctly greater than that usually adduced for a pegmatite magma. Several investigators who favor a replacement origin for such crystals have suggested that, had they been formed in a thin, watery pegmatite solution, they would have sunk rapidly in this liquid, even if originally attached to solid material. This view seems a little extreme, and may represent some confusion between the effects of specific gravity and those of viscosity of the solution.

Let it be assumed, however, that a combination of mechanical disturbance in the system and a difference of say 0.5 to 0.8 in specific gravity between spodumene crystals and the postulated enclosing liquid invariably were sufficient to cause detachment of the crystals and subsequent sinking in the liquid. It then would be necessary to call upon replacement inward from a single horizon in the pegmatite body to account for such fringing or comb-like arrangements as those so well exposed, for example, in the Harding mine (Fig. 1). This presents structural difficulties of the type summarized and discussed by Cameron, et al. (8, pp. 101–105) in connection with the genesis of pegmatite zones. Other advocates of a replacement origin have recognized the existence of "comb and concentric structures in the solidified pegmatites" (18, p. 291), and even have agreed to the significance of these structures in terms of primary crystallization, but in effect they have dismissed the matter by suggesting that such features are quantitatively unimportant.

The problem of support during crystallization from a liquid has been regarded as most critical in connection with those giant prisms that show no preferred orientation, and also with those that form huge, radial groups. It has been concluded, reasonably enough, that these crystals could not have grown in a liquid without some means of support. The assumed absence of such support, however, appears to rest wholly on an earlier assumption that large crystals, or crystal groups, of a single mineral were formed separately during a given period of time, without concomitant crystallization of any other mineral species. But is this

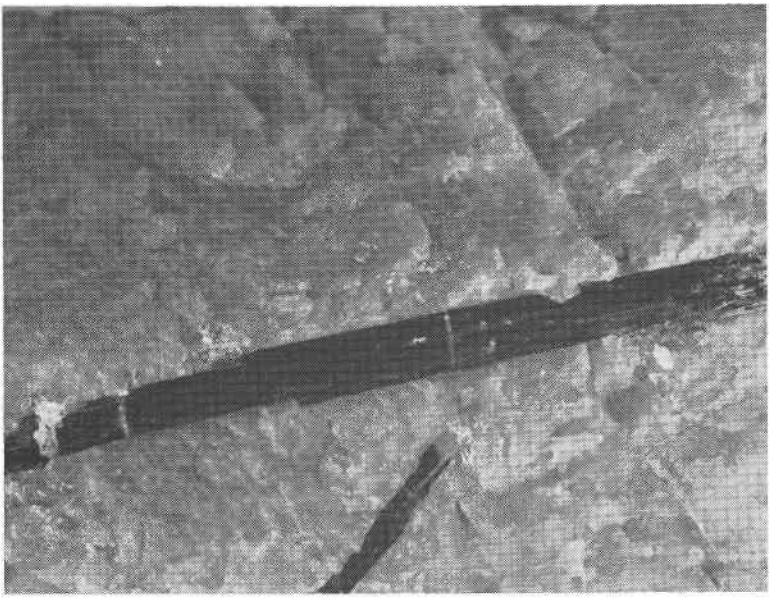

FIG. 17. "Healed-fracture" structure in black tourmaline, Southern Pacific silica quarry, Riverside County, California. The fractures are filled with quartz, which occurs in part as apophyses from the large crystals of quartz that flank the prisms of schorl. The large prism is about 3 inches thick.

earlier assumption trustworthy? The writer can see no reason why crystallization of two or more minerals should not have taken place penecontemporaneously to form a loose mesh whose interstices were progressively filled in by the growing crystals. Quartz is the most common mineral that is interstitial to giant crystals of spodumene and other minerals, and in such occurrences it forms giant crystals of its own. It appears to have developed with and slightly after the other minerals, so far as its known textural relations are concerned.

That support of the kind here suggested must have existed during development of many giant crystals is demonstrated by "healed-fracture" structures in numerous occurrences of spodumene, tourmaline, and other minerals of slender, elongate form. Typical examples, well exposed in the face of the Southern Pacific silica quarry near Neuvo, California, are shown in Figs. 17 and 18. Very large prisms of schorl here are broken along many irregular, transverse fractures that are filled with quartz, and some of the segments show evidence of rotation or other movement prior to the filling. The fractures have matching walls, and evidently were formed as simple tensional breaks, perhaps as a result

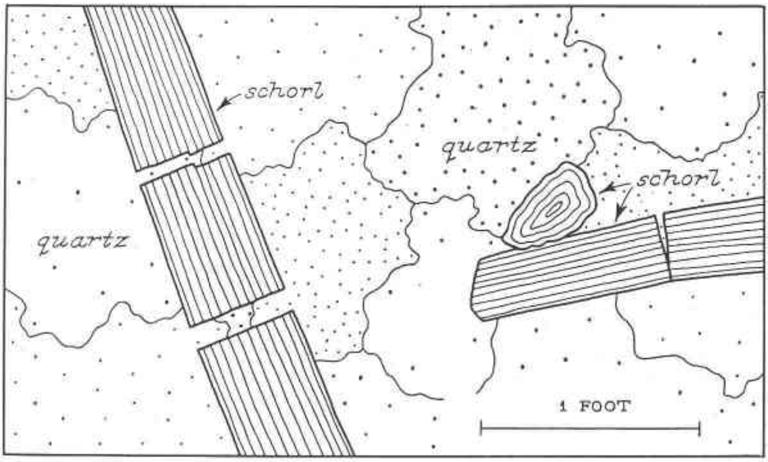

FIG. 18. "Healed-fracture" structure in very coarse-grained quartz—schorl pegmatite, Southern Pacific silica quarry, Riverside County, California. Fracture-filling relations indicate that the schorl prisms are older than at least some of the flanking anhedral crystals of quartz.

of minor disturbances in a very coarse but fragile crystal mesh of tourmaline and quartz. These fractures then were filled with quartz, much of which is crystallographically continuous with the giant quartz individuals that flank the schorl prisms. The filling thus appears to have been accomplished during the final stages of consolidation in the rock. These relations are not readily explainable in terms of a replacement origin for the schorl, especially as the fractures do not extend beyond the margins of the schorl crystals. It is not easy to imagine how the tourmaline prisms could have been fractured, pulled slightly apart, and in some instances disturbed on a larger scale after their development by replacement of solid pegmatite, without appropriate fractures appearing somewhere in the adjacent minerals.

The stellate, or rosette-like, arrangement of many giant crystals has been thought by some observers to pose a serious problem of support during any postulated growth from a liquid; indeed, Hess (18, p. 295) has stated that "radial disposition in three dimensions, with crystal terminations of the minerals at the outer ends, may, I believe, be accepted as a sign of replacement." This suggestion appears to have stemmed mainly from a study of huge spodumene rosettes in the Etta pegmatite of South Dakota, where many crystals several feet long radiate outward from small masses of fine-grained pegmatite into pegmatite that consists mainly of very large, anhedral crystals of quartz. In describing these fine-grained masses, Hess (19, p. 456) stated that " . . . they contain apatite,

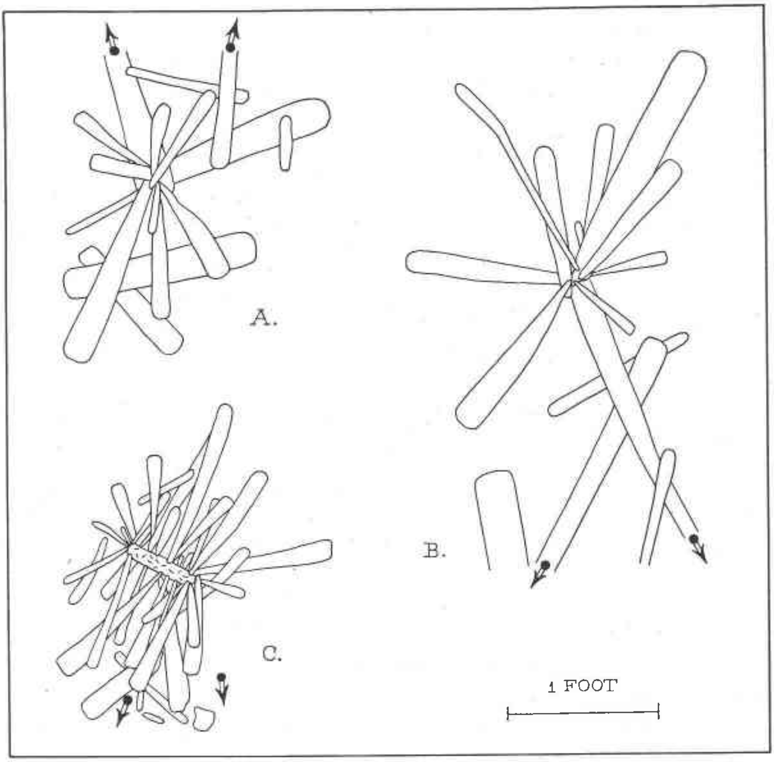

Fig. 19. Radial distribution of spodumene prisms in very coarse-grained quartz—spodumene—amblygonite pegmatite, Midnight Owl mine, White Picacho district, Arizona. Those prisms essentially coplanar with the exposed surfaces of the pegmatite are the only ones shown. Arrows indicate probable directions of attachment and support of crystals during growth; all sketches show relations on vertical faces of quarry. *A*. Growth from ends of two crystals attached to finer-grained pegmatite above. *B*. Growth from ends of crystal attached to finer-grained pegmatite below. *C*. Growth that may have begun as a crystal fringe from finer-grained pegmatite in hanging-wall part of pegmatite body, followed by detachment of a tabular mass of this pegmatite (with its fringe), sinking to a lower level, and completion of fringe on opposite side of the mass.

triplite, muscovite in plates an inch across, some quartz, potash feldspar, and other minerals, and are replaced masses of country rock."

If the spodumene crystals grew radially from masses of partly digested country rock, one might extend the problem back in time, and ask how these masses were supported within the pegmatite body. They might well represent detached fragments of wall rock that were scattered through a fragile, rapidly growing mesh of spodumene and quartz crystals. Detachment might have taken place after consolidation of the relatively thin outer zones of the pegmatite, or perhaps at an even earlier stage. Crystals of elongate habit could be expected to grow radially outward from the small masses of wall rock, the temperatures of which probably were slighly lower than that of the pegmatite fluid. Support would be provided by the crystal-bearing liquid or by the crystal mesh itself, perhaps very uncertainly at first but more and more stoutly as the crystals of both spodumene and quartz grew.

Similar, somewhat smaller-scale occurrences were studied by the writer in several pegmatite bodies in western Arizona, where outcrops and quarry exposures show evidence that some spodumene rosettes were supported during growth by other crystals of quartz and spodumene (Fig. 19). Such evidence is lacking in the exposures of other rosettes, to be sure, but this might be attributed to lack of complete exposure in three dimensions.

Other arguments

An argument commonly advanced to support the replacement theory is that random or erratic distribution of giant crystals and highly unsystematic variations in pegmatite textures are not easily explained in terms of fractional crystallization from a melt. This proposition might be true enough if such relations really were characteristic of pegmatites, but the mineralogical and textural variations in these rocks—especially where they involve crystals of giant size—are remarkably systematic. This has been pointed out in previous paragraphs, and has been noted and carefully documented by dozens of investigators during the past 80 years (8, pp. 11–13). The very absence of wholly erratic and unsystematic features from the zonal pattern of pegmatite bodies consitutes one of the strongest arguments for the development of the zones by primary crystallization from a magma.

The concentration of rare minerals, some of which form very large crystals, has been cited as evidence of the activity of hydrothermal solutions in many masses of pegmatite. Hess (18, p. 292), for example, has stated that "So far as I know, no suggestion adequately accounts for the excessive quantitites of minerals of low solubility such as the columbites, that, under these (magmatic) theories, must have been held in solution, and none satisfactorily explains the presence together of minerals considered as characteristic respectively of high and low temperatures." The term "solubility" is a little puzzling, as used in this statement, because the columbites, though almost insoluble in water, might well be very soluble in a pegmatitic rest-liquid developed during fractional crystallization of a granitic magma. The known segregation in a cooling magma of relatively rare elements such as beryllium, columbium, and lithium is accomplished mainly because these elements are not readily admitted into the crystal lattices of most common rock-forming minerals that are stable at high temperatures; ordinarily such elements cannot form lattices of their own until they are sufficiently concentrated in the rest-magma by fractional crystallization of other minerals. This bespeaks considerable solubility, whether these rare elements are fixed in crystals developed directly from the liquid or leave the liquid as constituents of hydrothermal solutions at some late stage during differentiation.

The occurrence together of minerals ordinarily regarded as forming in markedly different temperature ranges, such as perthite and cookeite or spodumene and zeolites, is readily explainable in terms of replacement, as Hess and others have suggested. Further, the textural relations of such minerals commonly indicate that one was formed largely at the expense of the other. In contrast to this, no giant crystals, or other minerals indigenous to pegmatite zones, are known to show such anomalous temperature or textural relations with respect to one another, and hence no recourse to hydrothermal replacement is needed to account for the observed associations.

Summary and Conclusions

Crystals of giant size, some of them weighing tons or even tens of tons and having maximum dimensions measurable in tens of feet, are constituents of pegmatite in many parts of the world. Perthite and spodumene form the largest known individuals, and among the other species whose crystals reach giant sizes are allanite, amblygonite, apatite, beryl, biotite, columbite, fluorite, hornblende, monazite, muscovite, petalite, phlogopite, plagioclase, quartz, topaz, tourmaline, and triphylite-lithiophilite.

Most of these huge crystals are euhedral, with characteristically simple habit and broad, rough faces. Some are regular in form, whereas others taper from one end to the other, or even from the central part toward both ends. Still others, like the spodumene "logs" in the Etta pegmatite of South Dakota, show irregular and abrupt pinchings and swellings. A few mineral species, notably quartz, form anhedral crystals of great size.

Some of the giant crystals are scattered individually through the mass of pegmatite in which they occur, and others are grouped. Those of elongate habit commonly form gigantic jackstraw-like aggregates, or are clustered in sub-parallel arrangements that appear on exposed surfaces of the containing pegmatite body as huge fringes. Groups of radiating crystals also are known, but are relatively rare.

Nearly all the crystals of exceptional size are found in zoned pegmatites, and appear to be primary constituents of the zones in which they occur. A few very large individuals occur in cavities or pockets that are younger than the surrounding solid pegmatite, but rarely are such crystals as large as other crystals that lie outside the cavities. The giant crystals of the pegmatite zones form phenocrysts in rock with porphyritic texture or are parts of non-porphyritic aggregates that have giant pegmatitic texture. The crystals show systematic trends in their distribution and size, and these trends are in full accord with all systematic structural and textural variations within the pegmatite body as a whole. Like the lithologic zones that contain them, they appear to have developed successively from the outer parts of a given pegmatite body inward toward its center.

Many investigators have concluded, on the basis of detailed study, that pegmatite zones were formed by fractional crystallization of a magma, with incomplete reaction between successive crops of crystals and rest-liquid (8, pp. 79–106). The giant crystals in pegmatites are here considered to be primary constituents of these zones, mainly on the basis of their distribution, textural and structural relations, and variations in composition.

The most convincing evidences of replacement within pegmatite bodies —mainly pseudomorphism, transection and corrosion of one mineral by another, and distribution of minerals in rock masses or along channelways that cut across earlier minerals or rock units—are readily applied to relatively fine-grained minerals that plainly are younger than the giant crystals. However, there appears to be little or no evidence for development of the giant crystals themselves by replacement of earlier pegmatite material. The criteria of hydrothermal activity so carefully outlined by Landes (28, pp. 538–539), for example, are not readily applied to the giant crystals, and most features specifically cited in favor of a replacement origin for such crystals seem more readily explainable in terms of primary crystallization from a liquid. Moreover, the usual arguments against a primary origin seem to be refutable in convincing terms by observed features of occurrence.

Available evidence, in the writer's opinion, indicates that nearly all the giant crystals were formed during what has been designated by most investigators the primary, or magmatic, stage of pegmatite development, and hence by crystallization from liquid under conditions that permitted remarkable growth of a relatively few individuals. These conditions will be discussed in some detail in a forthcoming paper. Suffice it to say here that the typical pegmatitic magma that yielded these enormous crystals must have been rich in hyperfusible constituents and probably had a very low viscosity. The crystals are thought to have been formed rapidly under restricted-system conditions involving rather delicate thermal and chemical balance. Temperatures almost certainly were below 600° C., and the confining pressures were sufficiently great to prevent major escape of volatile constituents during the period of giant-crystal development.

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